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The exploration of the planets is the modern counterpart to the exploration voyages of old. To reach the new world Columbus had to secure funding from Queen Isabella, outfit his three ships and set sail on a long journey. To explore the American Pacific Northwest, Lewis and Clark had a similar task of obtaining funding, purchasing equipment and going to points unknown, even though their path was across land and not sea. Today our journey is through space, rather than across land or sea, but we still travel with ships, now spaceworthy craft, rather than seaworthy. Our spacecraft are smaller than the ships of yore, crammed with electronics rather than provisions because man cannot go along on these journeys. We now rely on robots to be our eyes and ears at these distant worlds. Nevertheless, some aspects of exploration have not changed over the centuries. People are still fascinated by these unknown worlds and desire to explore them, and the process of obtaining the large sums of public moneys to finance these journeys still requires much pleading with authorities.

Saturn has long fascinated astronomers, planetary scientists, and the public at large, at first because of its prominent ring system and later because of its copious and varied moons, including Titan, one of the largest moons in the solar system, and the one having the most extensive atmosphere. Saturn, in fact, offers something for every discipline within the planetary sciences. While Saturn’s structure and composition are similar to those of Jupiter its smaller size produces a magnetic field that is much different to that of Jupiter. Saturn’s atmosphere has tremendous winds and storms like Jupiter, but the visible structure associated with these winds is generally veiled in an impenetrable haze. Saturn has a ring system vastly more developed than that of any other planet. It has a system of moons that are varied in their dynamical behavior, their apparent surface composition and interior structure, and atmospheric pressure. Surrounding this system is a large magnetic cocoon that protects Saturn from the direct effects of the solar wind. Now Saturn is to be probed with perhaps the most comprehensive single robotic mission ever flown to a planet, the Cassini-Huygens mission, respectively consisting of an orbiter (Cassini) and a probe (Huygens) provided (principally) by the two major partners NASA and ESA. This mission covers the full gamut of planetary discipline areas.

The orbiter carries the probe into orbit about Saturn. It then releases the probe into the atmosphere of Titan and relays the probe data back to Earth. After having accomplished its relay role, the orbiter continues to map the environment of Saturn for a total four years, and maybe more if an ‘extended mission’ can be performed.

Assembling a description of this ambitious mission has been almost as complex as the mission itself. We have split this special issue of Space Science Reviews into two volumes rather than attempt simultaneous publications of the entire set of articles. The articles in this first volume consist of three logical groups. The first five
articles describe the Cassini-Huygens mission, the Huygens probe, the Orbiter's tour around Saturn and the mission design. The next five articles describe the present state of understanding of Saturn environment and the science objectives of the mission. The last six articles describe the instrumentation and investigations on the Huygens entry probe that will make measurements of the atmosphere and perhaps the surface of Titan. These instruments will provide much of the initial science return of the mission and an exciting introduction to the evolving understanding of the Saturn system that the Cassini-Huygens mission will bring.

The purpose of these volumes is to provide interested planetary scientists with insight into the objectives of these investigations and how they are to be carried out. Whether these scientists are simply interested in the scientific results or in using the data themselves, they should find these articles helpful. The compilation of this volume is due to the efforts of many individuals, especially the referees and authors who worked together to develop what we hope is a readable and complete description of the mission. We especially wish to thank Anne McGlynn who assisted me in assembling this volume through much of its formulation.

C. T. RUSSELL
University of California
Los Angeles
August, 2002
THE CASSINI/HUYGENS MISSION TO THE SATURNIAN SYSTEM

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Abstract. The international Cassini/Huygens mission consists of the Cassini Saturn Orbiter spacecraft and the Huygens Titan Probe that is targeted for entry into the atmosphere of Saturn’s largest moon, Titan. From launch on October 15, 1997 to arrival at Saturn in July 2004, Cassini/Huygens will travel over three billion kilometers. Once in orbit about Saturn, Huygens is released from the orbiter and enters Titan’s atmosphere. The Probe descends by parachute and measures the properties of the atmosphere. If the landing is gentle, the properties of the surface will be measured too. Then the orbiter commences a four-year tour of the Saturnian system with 45 flybys of Titan and multiple encounters with the icy moons. The rings, the magnetosphere and Saturn itself are all studied as well as the interactions among them.

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Saturn is visible to the naked eye and virtually every ancient civilization noted its apparitions. Saturn is the second most massive planet in the solar system and it has the most extensive system of rings. It has a planet-sized satellite, Titan, that has a dense, veiling atmosphere. It has at least twenty-nine additional icy satellites. Each offers a world to explore. The Saturnian magnetosphere is immense. It maintains dynamical interfaces with the solar wind and with the atmosphere of Titan. The 
Cassini/Huygens mission makes both in situ measurements, and remote sensing observations of targets under favorable geometric and temporal conditions that are not available from Earth (e.g., range and angles of illumination and emission; events such as occultations and eclipses).

Progress in understanding the planets as bodies orbiting the Sun advanced with the invention of instruments to accurately measure celestial positions, and the subsequent cataloging of these precise observations. Developments in mathematics and the discovery of the theory of gravitational attraction provided a great leap forward. The pace of progress quickened with the invention of the telescope and its application to the sky by Galileo. Table I provides a brief chronology of the major events in the exploration of the Saturnian system. The advent of spacecraft exploration has again quickened the pace of discovery anew. It is expected that the availability of orbital observations and the atmospheric probing of Titan’s atmosphere by the Cassini/Huygens mission, will accelerate that pace of progress in gaining new knowledge.

1.1. NAMING THE MISSION AND THE SPACECRAFT

The overall mission and the Orbiter spacecraft (or mother ship) is named after the French/Italian astronomer Giovanni Domenico Cassini, who discovered several Saturnian satellites and ring features (including the Cassini division) in the period 1671–1685. The Titan atmospheric Probe is named after the Dutch astronomer Christiaan Huygens who discovered Titan in 1655. Portraits of these two scientists are shown in Figure 1.

The seventeenth century was a time of great scientific advances. Modern science was born and mankind’s view of the cosmos underwent the most rapid period of change since the beginning of recorded history. Giovanni Domenico Cassini (1625–1712) and Christiaan Huygens (1629–1695) helped to usher in the age by showing the incredulous public the new wonders of the sky, and of science. They changed our perception of the world. Both Cassini and Huygens came from well-to-do families – one in Italy, the other in Holland. Both received the best education available, both were extraordinarily industrious, and both performed most of their work in Paris, as members of the Royal Academy of Sciences established in 1666 by Louis XIV, the fabled Sun King. Huygens earned the invitation to join the Academy and the associated Royal Observatory as a result of having discovered
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>~800 BC</td>
<td>Assyrian and Babylonian observations</td>
</tr>
<tr>
<td>~300 AD</td>
<td>Mythological view of Saturn the god</td>
</tr>
<tr>
<td>1610</td>
<td>Galileo notes the ‘triple planet’ Saturn with his telescope</td>
</tr>
<tr>
<td>1655–1659</td>
<td>Huygens discovers Saturn’s largest satellite, Titan, and the true nature of the rings.</td>
</tr>
<tr>
<td>1671–1684</td>
<td>Cassini discovers a division in the ring, he also discovers the satellites Iapetus, Rhea, Dione and Tethys</td>
</tr>
<tr>
<td>1789</td>
<td>Herschel discovers satellites Mimas and Enceladus and notes thinness of the rings</td>
</tr>
<tr>
<td>1848</td>
<td>Bond and Lassell discover the satellite Hyperion</td>
</tr>
<tr>
<td>1850</td>
<td>Bond, Bond and Daws discover inner ring</td>
</tr>
<tr>
<td>1857</td>
<td>Maxwell proves that rings are not solid</td>
</tr>
<tr>
<td>1895</td>
<td>Keeler measures ring velocities</td>
</tr>
<tr>
<td>1898</td>
<td>Pickering discovers satellite Phoebe</td>
</tr>
<tr>
<td>1907</td>
<td>Comas Sola suggested Titan had an atmosphere</td>
</tr>
<tr>
<td>1932</td>
<td>Wildt discovers methane and ammonia on Saturn</td>
</tr>
<tr>
<td>1943–1944</td>
<td>Kuiper discovers methane and ammonia on Titan</td>
</tr>
<tr>
<td>1979</td>
<td>Pioneer 11 flies past Saturn</td>
</tr>
<tr>
<td>1980</td>
<td>Voyager 1 encounters Saturn</td>
</tr>
<tr>
<td>1981</td>
<td>Voyager 2 encounters Saturn</td>
</tr>
<tr>
<td>1989</td>
<td>Hubble Space Telescope’s Wide Field and Planetary Camera images Saturn</td>
</tr>
<tr>
<td>1995</td>
<td>Hubble Space Telescope’s Wide Field and Planetary Camera-2 images ring plane crossing</td>
</tr>
<tr>
<td>1996</td>
<td>Hubble images indicate that Titan’s surface is heterogeneous</td>
</tr>
<tr>
<td>1997</td>
<td>Cassini-Huygens launches</td>
</tr>
<tr>
<td>2004</td>
<td>Cassini-Huygens enters Saturn orbit, Huygens explores Titan</td>
</tr>
<tr>
<td>2005</td>
<td>Huygens Explores Titan</td>
</tr>
</tbody>
</table>

Titan and his observations of the rings of Saturn. Before joining the Academy, Huygens also had invented the pendulum clock, the first accurate timekeeping device. While still in Italy, Cassini gained fame by having measured the rotation periods of Jupiter and Mars, and for his extensive observations of the motions of the satellites of Jupiter, bodies that had been discovered by Galileo some fifty years earlier. In Paris, Cassini extended his precise observations to Saturn, discovering the satellites Iapetus, Rhea, Dione, and Tethys and structure in the rings. Towards the end of his life, Huygens returned to Holland where he continued pioneering work in mechanics and optics. Cassini stayed at the Paris Observatory where, in addition to conducting regular astronomical observations, he led the development of the new arts of geodesy and map-making.
The spacecraft are named after Giovanni Domenico Cassini (right) and Christiaan Huygens (left). They pioneered the exploration of the heavens in the seventeenth century. In the background on the right is the Paris Observatory under construction.

1.2. THE ORIGIN OF THE CASSINI MISSION

1.2.1. International Planning
The complex, cooperative undertaking, which is today’s Cassini/Huygens mission did not come into being overnight. It was the result of a process of many discussions and much careful planning that spanned many years. The formal beginning was in June 1982 when a Joint Working Group was formed by the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Science in the United States\(^2\). The charter of this Joint Working Group was to study possible modes of cooperation between the United States and Europe in the field of planetary science. The formation of the Joint Working Group and other significant events in the Cassini/Huygens chronology are listed in Table II. As can be seen from the chronology, the partners were cautious and did not enter lightly into the decision to carry out the Cassini/Huygens mission. Their perception was that this mission would be beneficial for the scientific, technological, and industrial sectors of their countries. The end result was an enterprise that from the initial vision to the completion of its nominal mission will have spanned thirty years!

The Cassini/Huygens mission is a joint undertaking by the National Aeronautics and Space Administration (NASA) in the United States and the European Space Agency (ESA). The overall mission is managed by the Jet Propulsion Laborat-
TABLE II  
Cassini/Huygens chronology

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
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| 1982     | The Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Sciences form a joint working group to study possible U.S. and European cooperation in planetary science.  
European scientists D. Gautier and W. Ip propose a combined Saturn Orbiter and Titan Probe mission to the European Space Agency (ESA) in response to a call for mission proposals. They suggest that the mission be carried out in collaboration with NASA. |
| 1983     | The Solar System Exploration Committee (SSEC) recommends NASA include a Titan Probe and radar mapper in its core program and should also consider a Saturn Orbiter.                                               |
| 1986     | ESA’s Scientific Program Committee approves Cassini for Phase A study, with a conditional start in 1987.                                                                                            |
| 1987–1988| NASA carries out further definition and work on the Mariner Mark 2 spacecraft and on the missions designed to use it: CRAF and Cassini.  
Titan Probe Phase A study.  
Start development of the facility instruments (ISS (J. Veverka), VIMS (T. McCord), RSS (C. Hamilton)) with advice and oversight by the CRAF scientific teams. |
| 1989     | Funding for CRAF and Cassini approved by Congress.  
ESA selects Cassini mission and names Probe Huygens.  
NASA and ESA release announcements of opportunity to propose scientific investigations for the Saturn Orbiter and Titan Probe.  
Selection of Orbiter and Probe investigations. |
| 1991     | NASA AO for INMS as a facility instrument. Selection of INMS investigations.                                                                                                                                               |
| 1992     | Funding cap on CRAF/Cassini; CRAF canceled and Cassini mission restructured to reduce costs. Launch rescheduled from 1996 to 1997. ISS, VIMS, and RSS become Cassini only instruments.                                                   |
| 1995     | House appropriations subcommittee targets Cassini for cancellation; the action is reversed.                                                                                                                               |
| 1996     | Integration and testing of spacecraft and instruments.                                                                                                                                                                  |
| April 21, 1997 | Ship Cassini spacecraft to Cape Canaveral, Florida  
Start of launch campaign.                                                                                                                                   |
| 1997     | Final integration and testing.                                                                                                                                                                                             |
| October 1997 | Launch from Cape Canaveral, Florida.                                                                                                                                                                                     |
TABLE II
Continued

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1998</td>
<td>First Venus gravity-assist flyby.</td>
</tr>
<tr>
<td>August 1999</td>
<td>Earth gravity-assist flyby.</td>
</tr>
<tr>
<td>December 2000</td>
<td>Jupiter gravity-assist flyby.</td>
</tr>
<tr>
<td>December 2001</td>
<td>First gravitational wave experiment.</td>
</tr>
<tr>
<td>June 12, 2004</td>
<td>Phoebe flyby. Closest approach is 2 000 km.</td>
</tr>
<tr>
<td>July 1, 2004</td>
<td>Arrival at Saturn. Saturn orbit insertion.</td>
</tr>
<tr>
<td>July 2008</td>
<td>Nominal end of mission.</td>
</tr>
</tbody>
</table>

ory (JPL), Pasadena, California. The Huygens Titan Probe was supplied by ESA (Clausen et al., 2002) while the main spacecraft, or Saturn Orbiter was provided by NASA (Henry, 2002). The Italian space agency (Agenzia Spaziale Italiana, or ASI), also a partner through a bilateral agreement with NASA, provided hardware systems for the Orbiter as well as instruments for both the Orbiter and the Probe. Other instruments on both the Orbiter and the Probe were provided by scientific groups, and/or their industrial partners, supported by NASA and by the national funding agencies of member states of ESA (Lebreton and Matson, 2002). The launch vehicle and launch operations were provided by NASA. NASA is also providing the mission operations and telecommunications via the Deep Space Network (DSN). Huygens operations are carried out by ESA from its European Space Operations Center (ESOC) in Darmstadt, Germany.

The objectives for the mission and the implementation approach were developed further by the work of the Joint NASA/ESA Assessment Study³ that was carried out in mid-1984 through 1985. This study group brought the scientific objectives for Cassini/Huygens into their present form and published them in the group’s final report (ESA, 1985). These objectives then became formally established when they were incorporated into both the NASA and ESA Announcements of Opportunity (ESA, 1989; NASA, 1989, 1991).

1.2.2. The Selection Process
Prior to the issuance of the Announcements of Opportunity, NASA and ESA carried out an informal dialogue regarding organization and management of the Cassini/Huygens mission. These understandings were formalized in a memorandum
of understanding between the agencies. The present organization of the mission evolved from this memorandum.

The selections of instruments and facility teams were coordinated between NASA and ESA. Investigations for the Huygens Probe were announced by ESA in September 1990, and NASA announced those selected for the Saturn Orbiter in November 1990. Both agencies also selected interdisciplinary investigations. The ESA Huygens selection was comprised of six principal investigator (PI) instruments and three interdisciplinary science (IDS) investigations. The NASA Saturn Orbiter selection was comprised of seven PI-instruments, four facility instruments, and seven IDS investigations. Absent from the proposed instruments was one capable of measuring the properties of the upper reaches of Titan’s atmosphere through which Cassini would fly many times. Such an instrument was regarded as critical to the mission, both from the scientific and engineering perspectives. NASA decided that such an instrument would be provided as a facility. Thus in May 1991 NASA issued a second Announcement of Opportunity. This one was for the Ion and Neutral Mass Spectrometer (INMS) Team Leader and Team Member positions. The results of that selection were announced in February 1992, bringing the facility instrument count to five. Summaries of the investigations are shown in Tables III and
IV. The corresponding instrumental techniques and measurements are summarized in Tables V and VI.

The originally envisioned Cassini and Huygens spacecraft were to be optimum for making various types of measurements. While the main spacecraft (Orbiter) would be 3-axis stabilized, the instruments would be accommodated by a ram platform, a turntable, an optical calibration target, and a scan platform. A separate steerable antenna would be provided for the communications link with Huygens allowing the Orbiter remote sensing instruments to observe the entry of Huygens into Titan’s atmosphere. Figure 2 shows a sketch for this early, ambitious design. Unfortunately, these features did not survive through the development phase of the spacecraft. In early 1992, the Cassini project was required to meet a new set of NASA budgetary constraints. The team at JPL reconfigured the mission and the Saturn Orbiter. As a result, engineering complexity has been traded for later operational complexity. At the same time the scientific objectives for targets of opportunity (asteroid flyby, Jupiter flyby, and cruise science (NASA, 1989, 1991; Lebreton, 1991) were given up. This was part of an effort to control development costs and the cost of operation during the first few years in flight. A new plan was established in which the start of scientific data acquisition would wait until two years before arrival at Saturn, i.e., well after the Jupiter flyby.

Fortunately the Cassini/Huygens spacecraft had a perfect launch and the spacecraft has performed superbly well in flight. The Cassini/Huygens team has a high degree of skill in flawlessly carrying out spacecraft maneuvers. Presently they are developing software programs that will enable the operation of the spacecraft with a high degree of efficiency at Saturn. The engineering team is exercising the spacecraft now in order to have all of the routine operations perfected before reaching Saturn. Once in orbit about Saturn the pace of operations will increase greatly and a smoothly operating spacecraft and operations team will be necessary in order to meet the challenge of performing the many scientific observations.

1.3. WHY GO TO SATURN AND TITAN?

In embarking upon this voyage to Saturn we are following a basic, evolutionally nurtured, instinct to explore our environment. Whether this exploration results in the discovery of resources, or the recognition of hazards, or merely provides a sense of place or accomplishment, being familiar with our environment has always proved to be beneficial. It is not surprising, therefore, that such exploration is a hallmark of growing, thriving societies. The expeditions that were mounted by the Old World to explore the New World provide recent examples. There are parallels between those now completed voyages of exploration and the voyages in the newly opened era of Solar System exploration. Available technology, skilled labor, possible benefits, costs, risks, and trip duration continue to be the chief considerations in deciding whether or not to undertake these trips. These factors were weighed for
<table>
<thead>
<tr>
<th>Investigation/Acronym</th>
<th>Scientist/Affiliation</th>
<th>Brief Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cassini Plasma Spectrometer (CAPS)</strong></td>
<td>D. Young (PI), Southwest Research Institute</td>
<td><em>In situ</em> study of plasma within and near Saturn’s magnetic field</td>
</tr>
<tr>
<td>Cosmic Dust Analyzer (CDA)</td>
<td>E. Grün (PI), Max Planck Institut für Kernphysik</td>
<td><em>In situ</em> study of ice and dust grains in the Saturn system</td>
</tr>
<tr>
<td>Composite Infrared Spectrometer (CIRS)</td>
<td>V. Kunde (PI), NASA Goddard Space Flight Center</td>
<td>Temperature and composition of surfaces, atmospheres, and rings within the Saturn system</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Magnetosphere and Plasma</td>
<td>M. Blanc (IDS), Observatoire MidiPyrénées</td>
<td>Interdisciplinary study of plasma circulation and magnetosphere-ionosphere coupling</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Rings and Dust</td>
<td>J. Cuzzi (IDS), NASA Ames Research Center</td>
<td>Interdisciplinary study of rings and dust within the Saturn system</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Magnetosphere and Plasma</td>
<td>T. Gombosi (IDS), University of Michigan</td>
<td>Interdisciplinary study of the plasma environment in Saturn’s magnetosphere</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Atmospheres</td>
<td>T. Owen (IDS), University of Hawaii</td>
<td>Interdisciplinary study of the atmospheres of Titan and Saturn</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Satellites</td>
<td>L. Soderblom (IDS), US Geological Survey</td>
<td>Interdisciplinary study of the satellites of Saturn</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Aeronomy and Solar Wind Interaction</td>
<td>D. Strobel (IDS), Johns Hopkins University</td>
<td>Interdisciplinary study of aeronomy in the Titan and Saturn atmospheres</td>
</tr>
<tr>
<td>Ion and Neutral Mass Spectrometer (INMS)</td>
<td>H. Waite (TL), Southwest Research Institute</td>
<td><em>In situ</em> compositions of neutral and charged particles within the Saturn magnetosphere</td>
</tr>
<tr>
<td>Imaging Science Subsystem (ISS)</td>
<td>C. Porco (TL), University of Arizona</td>
<td>Multispectral imaging of Saturn, Titan, rings, and the icy satellites to observe their properties</td>
</tr>
<tr>
<td>Dual Technique Magnometer (MAG)</td>
<td>D. Southwood (PI), Imperial College</td>
<td>Study of Saturn’s magnetic field and interactions with the solar wind</td>
</tr>
<tr>
<td>Magnetospheric Imaging Instrument (MIMI)</td>
<td>S. Krimigis (PI), Applied Physics Laboratory</td>
<td>Global magnetospheric imaging and <em>in situ</em> measurements of Saturn’s magnetosphere and solar wind interactions</td>
</tr>
<tr>
<td><strong>Cassini Radar (RADAR)</strong></td>
<td>C. Elachi (TL), Jet Propulsion Laboratory</td>
<td>Radar imaging, altimetry, and passive radiometry of Titan’s surface</td>
</tr>
</tbody>
</table>
Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
---|---|---|
Radio and Plasma Wave Science (RPWS) | D. Gurnett (PI), University of Iowa | Measure the electric and magnetic fields and electron density and temperature in the interplanetary medium and within the Saturn magnetosphere |
Radio Science Subsystem (RSS) | A. Kliore (TL), Jet Propulsion Laboratory | Study of atmospheric and ring structure, gravity fields, and gravitational waves |
Ultraviolet Imaging Spectrograph (UVIS) | L. Esposito (PI), University of Colorado | Spectra and low resolution imaging of atmospheres and rings for structure, chemistry, and composition |
Visible and Infrared Mapping Spectrometer (VIMS) | R. Brown (TL), Jet Propulsion Laboratory | Spectral mapping to study composition and structure of surfaces, atmospheres, and rings |

*IDS = Interdisciplinary Scientist; no instrumentation is provided by an IDS, but data from several PI or TL investigations will be used.
PI = Principal Investigator; each PI proposed the team and was responsible for providing the instrumentation for the investigation.
TL = Team Leader; each TL utilizes a facility instrument provided as part of the spacecraft systems; team members were individually selected by NASA.

*Cassini/Huygens*, both in Europe and in the United States, and we jointly decided to go.

In going to Saturn with *Cassini/Huygens* we will also be satisfying a cultural desire to obtain new knowledge. This drive is very strong and our society places very high value on knowledge. The resources expended in creating new knowledge through inventions, research, and scholarship are treated as investments. With *Cassini/Huygens* we do not have to wait for our arrival at Saturn. The return of new knowledge has already occurred. The challenge of this mission has resulted in new technological developments and inventions. Some of these have already been spun-off to new applications whose benefits are being realized now. Nevertheless, the main return occurs when *Cassini/Huygens* reaches Saturn. The mission explores a new part of the solar system, but we learn more than just facts about the Saturnian system. By comparing what we learn with complementary information about Earth, we learn how processes behave and can apply that new knowledge across the solar system. The laws of physics and chemistry are the same everywhere. Thus, for example, knowledge gained about the Saturnian magnetosphere or Titan's atmosphere and weather may turn out to have beneficial terrestrial applications.
<table>
<thead>
<tr>
<th>Investigation/Acronym</th>
<th>Scientist/Affiliation</th>
<th>Brief Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol Collector Pyrolyser (ACP)</td>
<td>G. Israel (PI), CNRS, Service d'Aéronomie</td>
<td><em>In situ</em> study of clouds and aerosols in the Titan atmosphere</td>
</tr>
<tr>
<td>Descent Imager and Spectral Radiometer (DISR)</td>
<td>M. Tomasko (PI), University of Arizona</td>
<td>Temperatures and images of Titan’s atmospheric aerosols and surface</td>
</tr>
<tr>
<td>Doppler Wind Experiment (DWE)</td>
<td>M. Bird (PI), Universität Bonn</td>
<td>Study of winds from their effect on the <em>Probe</em> during the Titan descent</td>
</tr>
<tr>
<td>Gas Chromatograph and Mass Spectrometer (GCMS)</td>
<td>H. Niemann (PI), NASA Goddard Space Flight Center</td>
<td><em>In situ</em> measurement of chemical composition of gases and aerosols in Titan’s atmosphere</td>
</tr>
<tr>
<td><em>Huygens</em> Atmospheric Structure Instrument (HASI)</td>
<td>M. Fulchignoni (PI), Observatoire de Paris-Meudon</td>
<td><em>In situ</em> study of Titan atmospheric physical and electrical properties</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Titan Aeronomy</td>
<td>D. Gautier (IDS), Observatoire de Paris-Meudon</td>
<td>Interdisciplinary study of the aeronomy of Titan’s atmosphere</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Titan Atmosphere-Surface Interactions</td>
<td>J. Lunine (IDS), University of Arizona</td>
<td>Interdisciplinary study of Titan atmosphere-surface interactions</td>
</tr>
<tr>
<td>Interdisciplinary Scientist (IDS) – Titan Organic Chemistry</td>
<td>F. Raulin (IDS), Université Paris – Val de Marne</td>
<td>Interdisciplinary study of Titan’s chemistry and exobiology</td>
</tr>
<tr>
<td>Surface Science Package (SSP)</td>
<td>J. Zarnecki (PI), University of Kent</td>
<td>Measurement of the physical properties of Titan’s surface</td>
</tr>
</tbody>
</table>

*IDS = Interdisciplinary Scientist; no instrumentation is provided by an IDS, but data from several PI or TL investigations will be used. PI = Principal Investigator; each PI proposed the team and was responsible for providing the instrumentation for the investigation.

The *Cassini/Huygens* mission also provides other more indirect benefits. By bringing people of different countries together to work toward a common goal, mutual understanding and common values are promoted. The internationality of *Cassini/Huygens* permits a wider range of talented engineers and scientists to apply themselves to the challenges of this mission. In addition to those directly involved, about three quarters of a million people from more than eighty-one different countries have involved themselves directly in this mission by requesting that their signatures and messages be placed aboard *Cassini/Huygens* for the trip to Saturn. For these many reasons, *Cassini/Huygens* can be regarded as an investment, one
TABLE V
Cassini orbiter instrumental techniques and measurements

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Participating countries</th>
<th>Measurements</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical remote-sensing instruments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Infrared Spectrometer (CIRS)</td>
<td>U.S.A., Aust., Fr., Ger., It., U.K.</td>
<td>High resolution infrared spectra, 10–1400 cm(^{-1})</td>
<td>Spectroscopy using 3 interferometric spectrometers</td>
</tr>
<tr>
<td>Imaging Science Subsystem (ISS)</td>
<td>U.S.A., Fr., Ger., U.K.</td>
<td>Photometric images through filters, 0.2–1.1 (\mu)m.</td>
<td>Imaging with CCD detectors; 1 wide angle camera (61.2 mr fov); 1 narrow angle camera (6.1 mr fov)</td>
</tr>
<tr>
<td>Ultraviolet Imaging Spectrograph (UVIS)</td>
<td>U.S.A., Fr., Ger.</td>
<td>Spectral images, 55–190 nm, occultation photometry, 2 ms; H and D spectroscopy, 0.0004 nm resolution</td>
<td>Imaging spectroscopy, 2 spectrometers</td>
</tr>
<tr>
<td>Visible and Infrared Mapping Spectrometer (VIMS)</td>
<td>U.S.A., Fr., Ger., It.</td>
<td>Spectral images, 0.35–1.05 (\mu)m (0.073 (\mu)m res.), 0.85–5.1 (\mu)m (0.166 (\mu)m res.); occultation photometry</td>
<td>Imaging spectroscopy, 2 spectrometers</td>
</tr>
<tr>
<td>Radio remote-sensing instruments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RADAR</td>
<td>U.S.A., Fr., It., U.K.</td>
<td>Ku-band RADAR images (13777.5 MHz); Radiometry, &lt;0.5 K resolution</td>
<td>Synthetic aperture radar; radiometry with a microwave receiver</td>
</tr>
<tr>
<td>Radio Science Subsystem (RSS)</td>
<td>U.S.A., It.</td>
<td>Ka, S, and X bands; frequency, phase, timing, and amplitude</td>
<td>X- and Ka-band transmissions to Cassini; Ka-, S- and X-band transmissions to the Earth</td>
</tr>
</tbody>
</table>

that is providing both immediate benefits as well as the expectation of many more to come.

1.4. GOAL AND OBJECTIVES

The primary goal of Cassini/Huygens is to ‘conduct an in-depth exploration of the Saturnian System’ (NASA, 1989).

Three trail blazing spacecraft, Pioneer 11, Voyagers 1 and 2, have already visited Saturn. Each flew rapidly through the Saturnian system. They sent back to
us eye-opening data. Titan, in particular, was revealed as an entirely new world, a unique object. While we learned much that we did not know, these data also introduced us to many puzzling effects. As a result many new questions have been posed. The early probes did not give us a good understanding of Titan, or of many other elements of the system. An in-depth study was in order.
<table>
<thead>
<tr>
<th>Instruments</th>
<th>Participating countries</th>
<th>Measurements</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Huygens Atmospheric Structure Instrument (HASI)</strong></td>
<td>It., Aust., Ger., Fin., Fr., Nor., Sp., U.S.A., U.K., ESA</td>
<td>Temperature: 50–300 K. Pressure: 0–2000 mbar. Gravity: 1 μg–20 mg AC E-field: 0–10 kHz, 80 dB at 2 μV m(^{-1}) Hz(^{-0.5}). DC E-field: 50 dB at 40 mV/m Electrical conductivity: (10^{-15}) Ω/m to (∞). Relative permittivity: 1 to (∞). Acoustic: 0–5 kHz, 90 dB at 5 mPa</td>
<td>Direct measurements using ‘laboratory’ methods.</td>
</tr>
<tr>
<td><strong>Gas Chromatograph and Mass Spectrometer (GCMS)</strong></td>
<td>U.S.A., Aust., Fr.,</td>
<td>Mass range: 2–146 amu Dynamic range: &gt;10(^8) Sensitivity: 10(^{-12}) mixing ratio Mass resolution: 10(^{-6}) at 60 amu</td>
<td>Chromatography and mass spectrometry: 3 parallel chromatographic columns; quadrupole mass filter; 5 electron impact sources</td>
</tr>
<tr>
<td><strong>Aerosol Collector and Pyrolyzer (ACP)</strong></td>
<td>Fr., Aust., U.S.A.</td>
<td>2 samples: 150–45 km, 30–15 km altitude</td>
<td>3 step pyrolysis: 20°C, 250°C, 650°C</td>
</tr>
<tr>
<td><strong>Descent Imager and Spectral Radiometer (DISR)</strong></td>
<td>U.S.A., Ger., Fr.</td>
<td>Upward and downward spectra: 480–960 nm, 0.87–1.7 μm, resolution 2.4–6.3 nm; down-ward and side-looking images: 0.66–1 μm; solar aureole photometry, 550 nm, 939 nm; surface spectral reflectance (Allan Variance)(^{1/2}): (10^{-11}) (in 1 s), (5 \times 10^{-12}) (in 10 s), (10^{-12}) (in 100 s), corresponding to wind velocities of 2 m/s to 200 m/s, <strong>Probe</strong> spin</td>
<td>Spectrophotometry, imaging, photometry, and surface illumination by lamp.</td>
</tr>
<tr>
<td><strong>Doppler Wind Experiment (DWE)</strong></td>
<td>Ger., It., U.S.A.</td>
<td>Doppler shift of <strong>Huygens</strong> telemetry signal, signal attenuation</td>
<td></td>
</tr>
<tr>
<td><strong>Surface Science Package (SSP)</strong></td>
<td>U.K., It., U.S.A., ESA</td>
<td>Gravity: 0–100 g. Tilt: ±60°. Temperature: 65–100 K. Thermal conductivity: 0–400 mW m(^{-1}) K(^{-1}). Speed of sound: 150–2000 m/s. Liquid density: 400–700 kg m(^{-3}). Refractive index: 1.25–1.45</td>
<td>Impact acceleration; acoustic sounding, liquid relative permittivity, density and index of refraction</td>
</tr>
</tbody>
</table>
With the dedication of the *Galileo* mission to the Jovian system, Saturn became the next logical target. Not only would this new mission study the individual objects (i.e., planet, satellites, rings, and magnetosphere) but it also would study the interactions between and among them.

1.4.1. System Science

The list of scientific objectives for *Cassini/Huygens* is extensive. There are specific objectives for each of the types of bodies in the system – the planet itself, the rings, Titan, icy satellites, and the magnetosphere. Not only is *Cassini/Huygens* designed to determine the present state of these bodies, and the processes operating on or in them, but it is also equipped to discover the interactions that occur among them. These interactions are important. An analogy can be drawn to a *mechanical clock*. A clock has many parts. However, a description of each part and the cataloging of their mechanical properties, alone, completely misses the essence of a clock. *The essence is in the interactions between the parts.* So it is for much of what *Cassini/Huygens* will be studying in the Saturnian system.

The ability to do ‘system science’ sets the superbly instrumented spacecraft apart. The very complex interactions that occur in systems such as those found at Jupiter and Saturn can only be addressed by such instrument sets. This is because many of the phenomena to be studied are sensitive to a large number of parameters. There are well known examples where the measurement being made is simultaneously dependent upon *location, time, directions to the sun and planet, the orbital configurations of certain satellites, magnetic longitude and latitude,* and *solar wind properties.* To deal with such complexity, it is necessary that the spacecraft have the right types of instruments in order to make all of the necessary measurements and that those measurements be made simultaneously. Identical conditions very seldom, if ever, recur.

Requiring that the instruments be able to operate simultaneously has a major impact upon spacecraft resources, such as electrical power. This requirement plus the need for a broad-based, diverse collection of instruments sized to be able to detect the low densities and weak signals of the Saturn environment is the reason why the *Cassini/Huygens* spacecraft is one of the largest planetary spacecraft to date.

2. Scientific Objectives

The lineage of the *Cassini/Huygens* objectives can be traced back to the meetings of the Joint Working Group in 1982. Objectives were established for the planet, the rings, the magnetosphere, the icy satellites and Titan.
2.1. SATURNIAN SYSTEM OBJECTIVES IN THE NASA AND ESA ANNOUNCEMENTS OF OPPORTUNITY

The list of scientific objectives covers the present state of these bodies, the processes operating on or in them and the interactions that occur among and between them. The objectives judged to be of the highest level in importance were part of both the NASA and ESA Announcements of Opportunity for this mission and were the criteria against which the selected investigations were measured. They also have provided the standard against which priorities for taking data were set. The objectives in the following lists are not prioritized and no significance that should be attached to the order of their appearance.

2.1.1. Titan
Titan is the major focus of the mission. It will be studied by both the Huygens Probe and the Cassini Orbiter. The scientific objectives are to:

- Determine abundances of atmospheric constituents (including any noble gases; establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere.
- Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photochemistry of the stratosphere; study formation and composition of aerosols;
- Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan’s atmosphere; search for lightning discharges;
- Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite;
- Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

While the formal set of scientific objectives is the same for both Probe and Orbiter, several additional constraints apply with respect to the synergistic gathering of data. ‘In the design of the Huygens measurements and Orbiter observations it is highly desirable that the value of the whole set of data be maximized’. To strive for this synergistic effect, there are some specific objectives that have been identified:

- ‘Each time the Orbiter will fly by Titan, it will perform a set of atmosphere and surface remote-sensing observations which will include re-observations of the atmosphere and surface along the flight path of the Probe.
- In this respect the Probe data will provide a reference set of data which will be used to ‘calibrate’ the Orbiter observations. The Probe data will be used, together with the Orbiter data, for studying spatial and seasonal variations of the atmosphere composition and dynamics.’

(ESA, 1989).
A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Lebreton and Matson (2002).

Titan has interesting modes of interaction with its immediate environment which can have two different states. The size and shape of the Saturnian magnetosphere depends upon the pressure of the solar wind. An increase in the solar wind pressure pushes the front of the magnetosphere (i.e., bow shock, magnetopause) closer to Saturn and visa versa. Titan's orbit passes through the region over which these changes occur. When Titan is at inferior conjunction (as seen from the Sun) it may be either inside or outside of the magnetosphere. The interaction with its plasma environment should be quite different in these two situations. Understanding how Titan interacts with its varying environment is an objective of the working group on the magnetosphere, atmosphere and plasma science (MAPS) (Blanc et al., 2002).

2.1.2. Magnetosphere
Specific Cassini objectives for magnetospheric and plasma science are to:

- Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of Saturn Kilometric Radiation (SKR).
- Determine current systems, composition, sources, and sinks of magnetosphere charged particles.
- Investigate wave-particle interactions and dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interactions with the solar wind, the satellites, and the rings.
- Study the effect of Titan's interaction with the solar wind and magnetospheric plasma.
- Investigate interactions of Titan's atmosphere and exosphere with the surrounding plasma.

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Blanc, et al. (2002). In addition the icy satellites have interesting interactions with the magnetosphere. Not only do they absorb particles from the magnetospheric plasma, but they can also contribute material to the magnetosphere. Furthermore, upon their solid surfaces are written their histories and by extrapolation that for much of the Saturnian system.

2.1.3. Icy Satellites
The known icy satellites have radii from 10 to 765 km. Over this size range different processes operate and the relative importance of some of the processes is a function of the satellite's size. Thus the satellites provide good examples for studying how such bodies are formed and evolve. Apart from their intrinsic interest, the icy satellites (and Titan) record the geologic history of the system through the records that have been 'written' on their surfaces by impacting objects. Specific Cassini objectives for icy satellite science are to:
• Determine the general characteristics and geological histories of the satellites.
• Define the mechanisms of crustal and surface modifications, both external and internal.
• Investigate the compositions and distributions of surface materials, particularly dark, organic rich materials and low melting point condensed volatiles.
• Constrain models of the satellites’ bulk compositions and internal structures.
• Investigate interactions with the magnetosphere and ring systems and possible gas injections into the magnetosphere.

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Lunine and Soderblom (2002). As satellites become smaller they start to approach the size domain of ring particles. In fact, some of the smaller icy satellites are embedded in the rings. There they define resonances and participate in other phenomena that establish the ring structures we observe.

2.1.4. Saturn’s Ring System
Saturn has by far the best-developed ring system in the solar system. Knowledge gained by studying these rings will be applicable to ring systems and planetary disks that occur elsewhere in the universe. Specific Cassini objectives for ring science are to:
• Study configuration of the rings and dynamical processes (gravitational, viscous, erosional, and electromagnetic) responsible for ring structure.
• Map composition and size distribution of ring material.
• Investigate interrelation of rings and satellites, including imbedded satellites.
• Determine dust and meteoroid distribution in the vicinity of the rings.
• Study interactions between the rings and Saturn’s magnetosphere, ionosphere, and atmosphere.

A discussion of these requirements, as well as some more specific objectives that can be derived from them, can be found in the article by Cuzzi et al. (2002).

2.1.5. Saturn
Jupiter and Saturn provide examples of objects in the large-planetary size range that, presumably, occur throughout the universe. Saturn is known to be very different from Jupiter. We have the opportunity to study Saturn’s properties with Cassini. The rotationally axisymmetric magnetic field arising from inside governs the magnetosphere and participates in all of the interactions with the other elements of the system. Finally, completing the circle of interactions, the energetic particles in the magnetosphere crash into Saturn’s atmosphere giving rise to aurora. Specific Cassini objectives for Saturn are to:
• Determine temperature field, cloud properties, and composition of the atmosphere of Saturn.
• Measure the global wind field, including wave and eddy components; observe synoptic cloud features and processes.
• Infer the internal structure and rotation of the deep atmosphere.
• Study the diurnal variations and magnetic control of the ionosphere of Saturn.
• Provide observational constraints (gas composition, isotope ratios, heat flux, etc.) on scenarios for the formation and the evolution of Saturn.
• Investigate the sources and the morphology of Saturn lightning (Saturn Electrostatic Discharges (SED), lightning whistlers).

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Owen and Gautier (2002).

2.2. FURTHER DEVELOPMENT OF OBJECTIVES BY THE PROJECT SCIENCE GROUP

Further development of the AO scientific objectives for Cassini/Huygens has been carried out by the Project Science Group (PSG) and the Huygens Science Working Team (HSWT). These groups, chartered by the AOs, are the Program's scientific advisory bodies. They work on specifying more detail than embodied in AO requirements themselves and in keeping the requirements up to date with respect to any new developments. In the PSG this work was done by a set of committees called Discipline Working Groups (DWG) specializing in each set of requirements and co-chaired by Interdisciplinary Scientists as was envisioned in the AO. The results of their work can be found in later articles in this volume: ‘Cassini-Huygens Investigations of Satellite Surfaces and Interiors’, ‘Saturn’s rings: Pre-Cassini Status and Mission Goals’, ‘Magnetospheric and Plasma Science with Cassini-Huygens’, and ‘Touring the Saturnian System: The Atmospheres of Titan and Saturn’.

The PSG and the HSWT also have the responsibility to translate the requirements into strategies for observing and measuring. The workload is shared by the four DWGs, special working groups, and instrument scientific investigation teams under the direction of the PIs and TLs. The strategies are, in turn, translated into specific instrumental observations and measurements by the scientists and the engineering and operations staffs of the individual instruments. All of these steps are closely coordinated with the spacecraft operations staffs at JPL and ESOC (for Huygens instruments).

3. Cassini and Huygens Spacecraft

3.1. THE CASSINI ORBITER SPACECRAFT

At the time of launch, the mass of the fully fuelled spacecraft was about 5636 kg. As shown in Figures 3 to 5, Cassini consists of several sections. Starting at the bottom of the ‘stack’ and moving upward, these are the lower equipment module, the propellant tanks together with the engines, the upper equipment module, the twelve-bay electronics compartment, and the high-gain antenna (HGA). These are
all stacked vertically on top of each other. Attached to the side of the stack is an approximately three-meter diameter, disk-shaped spacecraft, the Huygens Probe. Cassini/Huygens accommodates some twenty-seven different scientific investigations which are supported by eighteen specially designed instruments, twelve on the Orbiter and six on the Huygens Probe. (These investigations are listed in Tables V and VI. Also, see the more detailed discussions of the Orbiter instruments which comprises the second volume of this series). Most of the Orbiter’s scientific instruments are installed on one of two body-fixed platforms. These are called the remote-sensing pallet and the particles-and-fields pallet. The 11-meter-long boom supports sensors for the Dual Technique Magnetometer (MAG) experiment. Three skinny, ten-meter-long, electrical antennae point in orthogonal directions. These are sensors for the Radio and Plasma Wave Science (RPWS) experiment. At the top of the stack is the large, 4-meter-diameter high-gain antenna. Centered and at the very top of this antenna is a relatively small low-gain antenna. Another low-gain antenna is located near the bottom of the spacecraft.

Electrical power for the Cassini spacecraft and instruments is provided by three Radioisotope Thermoelectric Generators (RTG). RTGs are lightweight, compact spacecraft power systems that are extraordinarily reliable. They are not nuclear reactors and they have no moving parts. They provide electrical power through the natural radioactive decay of plutonium (Pu-238, a non-weapons-grade isotope). The heat generated by this natural process is changed into electricity by solid-state thermoelectric converters. A drawing of a Cassini RTG is shown in Figure 6.

RTGs have provided electrical power for some of the space program’s greatest successes, including the Apollo lunar landings and the Viking landers on Mars. RTGs made possible the Voyager explorations of Jupiter, Saturn, Uranus and Neptune, as well as the Pioneer missions to Jupiter and Saturn. RTG power sources are enabling the Galileo mission to Jupiter and the international Ulysses mission studying the Sun’s polar regions. The Cassini mission, given its scientific objectives, available launch systems, travel time to its destination and Saturn’s extreme distance from the Sun, required the use of three RTGs.

The temperatures of the various parts of the spacecraft are maintained within their required values by several means: (1) insulation and blankets, (2) reflective coatings, (3) shade provided by other parts of the spacecraft, (4) heat produced by the normal operation of the device, (5) electric heaters, and (6) small, radio-isotope heaters.

Two-way communication with Cassini is through the Deep Space Network (DSN) via an X-band radio link, which uses either the 4-meter-diameter high-gain antenna (HGA), or one of the low gain antennae. The high-gain antenna is also used for radio and radar experiments and for receiving signals from Huygens. At Saturn, communications will be via the HGA.

Cassini is a three-axis-stabilized spacecraft. Either reaction wheels or the set of 0.5 N (Newton) thrusters can change the attitude of the spacecraft. Attitude changes will be done frequently because the instruments are body-fixed and the
whole spacecraft must be turned in order to point them. Consequently, most of the spacecraft activities are made without a real-time communications link to Earth. The data are recorded on two solid-state recorders, each of which has a storage capacity of about two gigabits.

The Solid State Recorder (SSR) is the primary data storage and retrieval device for the Orbiter. The spacecraft is equipped with two SSRs each of which is expected to have a usable capacity of 1.8 Gigabits at end of mission. The nominal effects of solar and cosmic radiation have been taken into account when estimating the end of mission capacity. The SSR will store spacecraft telemetry and Attitude Articulation and Control (AACS), Command and Data Subsystem (CDS), and instrument memory-loads in separate partitions. All data recorded on and played back from the SSR is handled by the CDS.

Figure 3. The Cassini spacecraft. At the top is the high-gain antenna that is 4 m in diameter. The structure at the bottom is the adapter that attaches the spacecraft to the launch vehicle. It is jettisoned after launch.
3.2. THE HUYGENS TITAN PROBE

The *Huygens Titan Probe* is destined for entry into Titan’s atmosphere. It carries a capable, diverse, set of instruments for measuring atmospheric and surface properties. The *Huygens Probe System* also has another part, the *Probe Support Equipment* (PSE), which is permanently attached to the *Cassini Orbiter*. The PSE includes a *spin-eject device* that releases a strong spring-loaded mechanism that simultaneously propels the *Probe* away from the *Orbiter* and imparts to it a spin about its axis of a little more than 5 rpm. Separation occurs with a relative velocity of 0.3 to 0.4 m/s. Altogether, the *Probe* weighs about 305 kg and the *Probe Support Equipment* is only about 35 kg. *Huygens* is a very bluntly shaped conical capsule with a high drag coefficient. It consists of a *descent module* that is enclosed by a *thermal-protection shell* to protect the *Probe* from the heat generated during atmospheric entry.
Figure 5. The Cassini spacecraft (view as in Figure 4) showing the engine cover deployed. This cover protected the nozzles from micrometeorites during the transit of the asteroid belt.

Figure 6. Cut-away drawing of a Radioisotope Thermoelectric Generator (RTG). Three of these provide electricity for the thousands of tasks that Cassini will perform at Saturn.
The Probe Data Relay Subsystem (PDRS) provides the one-way communications link between the Probe and the Orbiter and includes equipment installed on both spacecraft. The elements that are part of the PSE are the Probe Support Avionics (PSA) and the Radio Frequency Electronics (RFE) which includes an ultra-stable oscillator (USO) and a low-noise amplifier. For redundancy, the Probe carries two S-band transmitters, both of which transmit during descent, each via its own antenna. The telemetry in one link is delayed by about six seconds with respect to the other link in order to avoid loss of data if there should be brief transmission outages. Reacquisition of the Probe signal would normally occur within this interval.

3.3. FLIGHT OPERATIONS

The flight operations of the Cassini mission operations are carried out at Mission Control Center, Jet Propulsion Laboratory (JPL) in Pasadena, California. The data are collected via NASA’s deep space network and stored on computers at JPL. The spacecraft health and status are routinely assessed. The operations of the Cassini instruments are distributed. The instrument teams analyze their respective instrumental data and prepare instrumental operation sequences at their home institution and transmit them to JPL for uplink. During the main mission phase, from the start of the Saturn encounter phase until the end of the mission, the Orbiter instrument teams will interact daily with the team at JPL. The flight operations of the Huygens Probe are carried out from ESA’s European Operations Centre (ESOC) in Darmstadt, Germany. Here the Huygens Probe Operations Centre (HPOC) has been established. All Huygens-related mission activities are carried out from the HPOC (e.g., periodic in-flight checkouts, communication equipment characterization and testing, and software modification and testing). When the Huygens telemetry returns it will be routed to the HPOC, where it will be ‘decoded’ to retrieve the instrument data which will be sent to the appropriate Huygens investigators.

4. Scientific Instruments

Cassini/Huygens accommodates some twenty-seven major scientific investigations that, in turn, are supported by eighteen specially designed instruments, twelve on the Orbiter and six on the Huygens Probe. A drawing showing how some of the probe instruments are packaged on the Huygens instrument platform is shown in Figure 7. Other instruments are attached on the bottom side of this platform. Lebreton and Matson (2002) present more detail on the Probe payload in a following article.

The Cassini Orbiter has the most capable and sophisticated set of instruments of any spacecraft sent to the outer Solar System. Many of the instruments have multiple detectors, or even several whole instruments as subsystems. Some were
built with articulation capability in order to assure optimum pointing for data acquisition. Compared to earlier spacecraft instruments, many Cassini instruments use much broader-bandpass data acquisition. Rather than obtain the spectrum of a spot, for example, they obtain spectra for all the pixels in a whole scene. Rather than measure one or a few energies, or frequencies, they are focused on obtaining the whole spectrum as a function of time. The wavelength ranges of the imaging sensors and the energy ranges of the particle investigations are shown in Figure 8. With few exceptions, all of the instruments will be obtaining large amounts of data, enough to fill Cassini’s 4 Gb per day bits-to-Earth capacity during ‘high-activity’ days.

There are two general classes of instruments on the Orbiter, those that make in situ measurements and those that carry out remote sensing. The in-situ instruments are mounted at several locations on the spacecraft. CAPS, INMS and MIMI are on the fields-and-particles pallet, Figure 9. The CDA, INCA (part of MIMI), and the RPWS components are mounted on the body of the spacecraft. MAG has its own boom. The fields of view, where appropriate, for these instruments are shown in Figures 10 and 11.

Figure 7. A drawing showing the layout of Huygens’ instruments.
The optical remote sensing instruments are mounted on a separate pallet, Figure 12. All of these instruments have built-in telescopes. Their fields of view on the sky are shown in Figure 13. Other remote sensing instruments are the RADAR and the RSS. Of course, these use the high-gain antenna. INCA, already discussed as part of MIMI is also a remote sensing instrument that images ions and neutrals and it is mounted on the body of the spacecraft. Detailed discussions of these instruments can be found in following articles by the instrument teams.
Figure 9. The fields-and-particles pallet. This triangular, horizontal structure provides mounting points for most of the fields-and-particles instruments.

Figure 10. The fields of view on the sky for the fixed (i.e., non-articulating) fields-and-particles instruments.
THE CASSINI/HUYGENS MISSION TO THE SATURNIAN SYSTEM

**Figure 11.** The fields of view on the sky for articulating fields-and-particles instruments. Each of these instruments can use a motor to change the pointing of its ‘bore sight’ or instrumental field of view. All directions which can be viewed are shown in the above plot.

**Figure 12.** The remote sensing pallet is largely obscured by the instruments that it supports. All of the optical remote sensing instruments as well as the star trackers are mounted on this pallet.

### 5. Launch and Cruise Phase

Although *Cassini/Huygens* officially had no cruise science phase, much has been accomplished by the mission on its way to Saturn. At this writing the spacecraft has passed Jupiter and is now on the way to Saturn. We digress for a moment to discuss the journey thus far before returning to the discussion of the objectives to be pursued at Saturn.
Figure 13. The fields of view on the sky for the remote-sensing optical instruments.

5.1. LAUNCH

Launch is both an ending and a beginning. Nowhere can you find a more profound test of the work that has been done. Nowhere is there a more dramatic event to mark changing program priorities. Nowhere is there more hope. Nowhere more tension. A successful launch is everything. These were the thoughts of many at the Cape Canaveral Air Force Station on the 15th of October, 1997. The launch vehicle was the Titan IVB with two stout Solid Rocket Motor Upgrades (SRMU) attached to its lower stage. A Centaur rocket sat on top of the propulsion stack as the uppermost stage, Figure 14. This system puts Cassini/Huygens into Earth orbit and then, at the right time injects it upon its interplanetary trajectory.

The ‘core’ Titan vehicle has two stages. The SRMUs are anchored to the first, or lower, stage. These ‘strap-on’ rockets burn solid fuel, whereas the Titan uses liquid-fuel. The Centaur is a versatile, high-energy, cryogenic-liquid-fueled upper stage with two multiple-start engines. The performance of the Titan IVB/SRMU-Centaur system is capable of placing a 5760-kg payload in a geostationary orbit. On top
of all this propulsive might sits Cassini/Huygens, protected for its trip through the lower atmosphere by a 20-meter-long payload fairing.

Lift-off from Cape Canaveral Air Force Station, launch complex 40 was at night. The launch sequence, shown in Figure 15, began with the ignition of the two SRMUs. They lifted the whole stack off of the pad. About ten seconds after liftoff, the stack continued to accelerate, and then, it started to tilt and rotate. The rotation continued until the required azimuth was reached. At plus two minutes the first stage of the Titan was ignited. The altitude was approximately 192 000 feet. A few seconds later the two, now spent, SRMUs were jettisoned. One-and-a-half minutes passed. At an altitude of 360 000 feet, the payload fairing was let go. It was about five and a half minutes into the flight when an altitude of 549 000 feet was reached. The first stage of the Titan separated at this altitude and the second stage fired. At launch plus nine minutes the second stage had burnt out and dropped away. Then the Centaur ignited and boosted the remaining rocket-and-spacecraft stack into a parking orbit and turned off its engines. Sixteen minutes later the Centaur ignited for a second time. The burn lasted between 7 and 8 minutes. Then the Centaur separated from the spacecraft. Cassini/Huygens was now on an interplanetary trajectory, headed for swingbys of Venus, Venus again, Earth, Jupiter, and at last, orbit about Saturn. It was a perfect launch! The interplanetary trajectory is shown in Figure 16.
Launch events

Figure 15. The sequence of events for launch into orbit above Earth.

Figure 16. The Cassini cruise trajectory to Saturn.
TABLE VII
Venus and Earth flybys

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5.2. VENUS SWINGBYS

Paradoxically Cassini/Huygens did not immediately head for the outer solar system but went inward toward Venus to pick up additional gravitational assistance because even the great thrust of the Titan-Centaur was insufficient to propel the massive spacecraft on its way to Saturn. Two Venus swingbys would be necessary followed by an Earth gravity assist plus one at Jupiter before the spacecraft had sufficient energy to climb far enough out of the Sun’s gravitational potential well to reach Saturn. The purpose of observations made during Venus 1, Venus 2 and Earth swingby are shown in Table VII.
These flybys provided the Cassini Program with its first experience in designing coordinated scientific observations during a planetary encounter. These activities also exercised some of the scientific instruments as well as various operational capabilities of the spacecraft.

At the time of launch the plan was for the spacecraft to have very little activity until its approach to Saturn. Consequently, scientific observations were minimal during the first encounter of Venus that occurred on April 26, 1998, just six months after launch. Scientific data were obtained by the Radio and Plasma Wave Science instrument (RPWS) in a search for lightning (Gurnett et al., 2001), and the Radio Science team (RSS) serendipitously captured the electron density profile of Venus’ ionosphere while supporting telecommunications to Earth.

All of the sequence design had to be done by hand or with rudimentary software tools. The software for automation in spacecraft control and planning so necessary for the successful mission at Saturn did not exist at the time of launch. It was planned that development would be carried out over the years as Cassini/Huygens cruised to Saturn.

Many factors contributed to restrictions in the allowable spacecraft attitude for scientific observations during this early phase of the mission. The orientation of the spacecraft was constrained to keep the Huygens probe, aligned with the \(-X\)-axis, in the ecliptic and in the direction of the spacecraft velocity to provide a shield from micrometeoroids. The high-gain antenna (HGA) is aligned with the spacecraft \(-Z\)-axis and is usually pointed toward the Sun so as to shade the rest of the spacecraft. As long as the HGA remains Sun-pointed, any roll attitude about the \(Z\)-axis is allowable as long as it does not change the thermal characteristics of the spacecraft. Pitch maneuvers (about the \(X\)-axis) and yaw maneuvers (about the \(Y\)-axis) could be done to obtain a desired orientation, but might result in bringing thermally sensitive spacecraft components into sunlight. Thus, these maneuvers would require analysis of the thermal effects in order to assess whether or not they could be allowed. To further constrain spacecraft pointing, telecommunications during inner cruise were generally restricted to one of the two low gain antennas on the spacecraft (i.e., LGA-2) which is aligned with the \(-X\)-axis of the spacecraft. When LGA-2 is in communication with Earth, the allowable roll attitude is further restricted. In addition, sunlight, either direct or reflected from bright planets, must be kept out of the field of view of the two Stellar Reference Units (SRU) which provide the stellar navigation data used for attitude control. These are aligned with the \(+X\)-axis of the spacecraft. Radiators for the Visual and Infrared Mapping Spectrometer (VIMS) and Composite Infrared Spectrometer (CIRS) are aligned with the spacecraft \(x\)-axis and also have specified limits for their exposure to sunlight. All these constraints were accommodated when choosing the spacecraft attitude for the Venus-2 and Earth flybys.

The second swingby of Venus occurred at an altitude of 598 km at 20:30:07 UTC on June 24, 1999. The spacecraft approached from the dusk-side of the planet. The flyby provided a unique opportunity for the fields and particles instruments
to study the interaction of the solar wind with Venus, a planet with no intrinsic magnetic field. Cassini/Huygens has a much more capable fields and particles payload than previous Venus missions. Since the flyby was at a low altitude, Venus’ ionosphere could be reached. CAPS, MAG, MIMI and RPWS were powered on several hours before closest approach. The MIMI CHEMS sensor made measurements in the ionosheath and stagnation region at Venus and detected a number of energetic species, possibly pickup O⁺ and C⁺ ions. MIMI was able to detect energetic neutral atoms escaping from Venus’ atmosphere with its ion and neutral camera (INCA). Plasma waves in the vicinity of Venus were measured over a broad frequency range and with increased sensitivity by RPWS. The high sampling rate allowed RPWS to again search for evidence of lightning, as they did during Venus-1. The magnetometer remained stowed in its canister because Cassini/Huygens was still too close to the Sun to expose its boom material to the heat of sunlight. During the Venus flyby the MAG was activated primarily to help identify boundaries such as the bow shock crossings in support of other instruments. Inbound and outbound bow shock crossings were nonetheless detected by significant jumps in magnetic field strength. The inbound bow shock crossing on the dusk flank was detected at approximately 19:20 UT and the outbound bow shock crossing at 20:40 UT, just 10 minutes after closest approach.

Several hours prior to the flyby at 14:40 UT the spacecraft performed a roll about the Z-axis of -34.4 degrees to allow the optical remote sensing instruments to view the planet. During the period around closest approach, the optical remote sensing instruments were pointed to the nadir. ISS, UVIS, and VIMS were sequenced to observe during the relatively short period (approximately 12 minutes) the planet was in their fields of view. Most of the ground track occurred over the night side of the planet where VIMS reported the first detection of thermal emission from the Venusian surface at 0.85 and 0.90 μm (Baines et al., 2000).

A 20 mrad deadband was maintained through the Venus flybys⁴. For the Earth swing-by it was lowered to 2 mrad in order to accommodate the optical remote sensing observations of the Moon. Tracking passes on NASA’s Deep Space Network of antennas (DSN) were scheduled at 1 per day on approach to Venus but increased to 3 passes per day to support the flyby. Nearly continuous DSN coverage was obtained during the Earth flyby.

5.3. Earth Swing-by

Four, planned, trajectory-correction maneuvers were executed in the fifty-four days between the Venus-2 and Earth flybys. The final corrections occurred seven days before reaching Earth. As a safety measure, the Earth-avoidance strategy had Cassini/Huygens aimed far away from Earth so that a collision with it was impossible. Consequently, as the range between the spacecraft and Earth decreased, it was necessary to successively increment the spacecraft path evermore inward, toward Earth, until, at last, it reached the correct swing-by distance to put it on the proper
trajectory to Jupiter. The closest approach occurred at 03:28 UT on August 18, 1999 at an altitude of 1163 km over the southern Pacific Ocean.

In order to prepare for making observations, the VIMS IR-radiator and optics covers were jettisoned two days before closest approach. Shortly thereafter the 11-meter-long magnetometer boom was unlatched and allowed to deploy. Since launch the boom had been stowed in a cylindrical canister mounted along the Y-axis of the spacecraft. With the high gain antenna pointed toward the Sun, the entire canister was shaded. Deployment in the inner heliosphere (less than 0.97 AU from the Sun) was prohibited because the boom would become too warm and exceed its temperature tolerance. However, the magnetometers needed to be operational during the Earth swing by to obtain data in Earth’s magnetosphere that would be critical for their calibration.

The magnetometer boom consists of inner and outer sections that deploy by what could be described as a telescoping action. The inboard section fully unfurls first and then the unfurling of the outboard section is initiated. The boom is springy and provides all of the force needed for its own deployment. It is unlatched and unfurls by itself. Viscous dissipation in a rate limiter keeps the boom segments from coming out too fast. The fluxgate magnetometer is mounted at the end of the inboard section and the helium magnetometer is mounted on the end of the outboard section. As anticipated, the boom deployed flawlessly on August 16, two days prior to the closest approach to Earth.

Earth’s magnetosphere is the best-characterized space plasma and each of the fields and particles instruments was able to obtain data for the purpose of calibration as well as scientific investigation. Some of the instruments were turned on several days before Earth closest approach and thus also obtained data while the spacecraft was in the solar wind. The inbound bow shock signaling entry into Earth’s magnetosphere was detected at 01:51 UT on August 18 at a distance of 15.1 Re. Although the spacecraft orientation was not optimal for CAPS to obtain the best view of the plasma distributions to which they are sensitive, CAPS was able to identify all the magnetospheric boundaries from the inbound bowshock to the ionosphere. Boundary layer flows from the magnetopause, suprathermal plasma from the plasmasphere on the dayside, and ring current/plasma sheet structures were measured. MIMI’s INCA sensor obtained energetic neutral atom images of Earth’s ring current. Also, bursts of energetic magnetospheric ions from the long, dawn-sheath passage far downstream (58 to 392 Re) of Earth were observed. RPWS successfully validated their wave-normal analysis capability by which they can determine the orientation of plasma wave fronts and polarization. They were also able to demonstrate the direction finding capability that was needed for their calibration at Jupiter in late 2000 to early 2001. In addition, Cassini/Huygens’ rapid traversal enabled an excellent set of radio- and plasma-wave data that represents a ‘snapshot’ of the terrestrial magnetosphere. Once the boom was successfully deployed, the magnetometer team accomplished several calibration and scientific objectives. Earth’s well-known magnetic field was used for calibration. The Sci-
ence Calibration and Alignment Subsystem (SCAS), which produces a magnetic field vector in a direction that is accurately known, was operated several times to obtain information about the alignment of the magnetometer boom with respect to the spacecraft axes.

At 21:28 UTC, the day before the closest approach to Earth, the spacecraft was rolled 104.3 degrees about the z-axis. This allowed the Moon to traverse the fields of view of the ORS instruments. ISS, UVIS, and VIMS observed the Moon, which was at quarter phase, for as long as it was in their fields of view. For the WAC this was the longest, being about 29 minutes. Later, after Earth closest approach, the Moon was in the FOV of the VIMS solar port for approximately an hour and a half, allowing the acquisition of important calibration data.

After closest approach the flyby geometry was such that the high-gain antenna pointed at Earth. This allowed several minutes for the RADAR to transmit and receive a track of data that started over the southeastern Pacific Ocean and extended across South America. The main motivation for this measurement was to perform an end-to-end test using Earth as a target. These data allow the verification of instrumental parameters and calibration. This was the last opportunity for such testing before the first RADAR observations of Titan during the Saturnian tour.

The flyby took place during an interval when the solar wind was relatively fast, ~600 km/s, and the interplanetary magnetic field had extended episodes of strong southward fields, up to 7 nT. Accordingly, Earth's magnetosphere was generally in a disturbed state during the encounter (Burton, et al., 2001).

Cassini/Huygens exited the magnetosphere on the dawn flank and returned to the solar wind at 55-65 Re. The fields and particles instruments including UVIS were able to collect data through opposition in mid-September. At this time the geometry permitted use of the high gain antenna while it continued to function as a Sun shield. Models of the distant geomagnetic tail predict that it is aberrated or deflected from the Sun-Earth line due to the motion of Earth about the Sun and upstream magnetic field and solar wind conditions (Bennett et al., 1997). Using such a model, it was predicted that Cassini/Huygens could pass through Earth's distant tail. Suggestive but inconclusive signatures of the deep tail were seen up to 6000 Earth radii downstream in the particle LEMMS data. A post-Earth trajectory change maneuver was performed thirteen days after the swing-by to set Cassini/Huygens on its proper course to fly by Jupiter on December 30, 2000.

5.4. THE JOVIAN FLYBY

The flyby of Jupiter produced more than just a gravitational assist for the spacecraft. Operations during this encounter served as a dress rehearsal for operations to be carried out later at Saturn. During the Saturnian tour, flybys occur frequently and the operational procedures must work perfectly. The lessons learned by exercising the spacecraft and instruments at Jupiter will greatly improve performance at Saturn. The trajectory for the flyby is shown in Figure 17 and compared with
predictions for the location of the bow shock and the magnetopause. In Figure 18 the trajectory of Cassini/Huygens is compared with the orbit of Galileo.

The Cassini/Huygens spacecraft flew by Jupiter on December 30, 2000, at a distance of 137 Jovian radii ($R_J \sim 71,490$ km; altitude = 9,794,130 km), *en route* to Saturn for an arrival in 2004. Observations of Jupiter and the Jovian system spanned a six-month period, that began on October 1, 2000. Unique among the many scientific results of these observations are those which came from measurements conducted jointly using two spacecraft, Cassini/Huygens and Galileo. This is the first time that two spacecraft have been simultaneously near and inside the magnetosphere of a giant planet. Since December 1995, Galileo has been in orbit about Jupiter, carrying out scientific investigations. Galileo is a dual-spin spacecraft with a full complement of remote sensing and *in-situ* fields and particles instruments. Also, observations were coordinated with researchers using the Hubble Space Telescope (HST), Chandra the Very Large Array (VLA) of radio antennae,
The locations of Cassini and Galileo during joint observing campaign. Tick marks on the Cassini/Huygens trajectory are daily positions whereas those for Galileo are for every fifth day. Other investigators used Hubble, Chandra, and Earth-orbital and ground-based instruments to observe the Jovian system at the same time. The campaigners were rewarded by a data set that is a discovery treasure trove.

The Deep Space Net (DSN), which is part of NASA's spacecraft communications system, and a number of ground-based astronomical observatories.

From Galileo's point of view, the collaborative work with Cassini/Huygens began on October 26th. For the next 100 days, Galileo collected data continuously as it moved from the solar wind, through the bow shock and magnetopause, into the middle and inner magnetosphere, and then back out through these regions and into the solar wind again. Approximately 60–70% of the data came down in real time and the remainder were recorded on tape. While some of the recorded data was returned to Earth in late December, the rest had to wait until the February to May 2001 when playback conditions were favorable.

Collaborations during the flyby period included a solar wind-Jupiter magnetosphere-aurora investigation involving Cassini, Galileo and the Hubble Space Telescope (HST), and a study of Jupiter's synchrotron emission involving the Cassini RADAR, the Very Large Array (VLA), the Deep Space Network (DSN), and the Goldstone Apple Valley Radio Telescope Project (GAVRT).

The extended approach and departure periods offered Cassini's optical remote sensing instruments (ORS) opportunities to carry out many observations. Unlike Galileo, Cassini/Huygens had an excellent communications link with Earth. The
luxury of a very high data rate at the Jovian encounter allowed some detailed investigations of short-term variations or changes to be carried out. These include time-lapse movies of: (1) Jupiter's atmosphere (both inbound and outbound), (2) Io's torus, (3) Io in eclipse, and (4) the very faint Jovian rings. Other important observations included characterization of Io's dust stream(s), satellite spectral reflectance data, and Jupiter's synchrotron emission in a spectral range difficult to study from Earth. Below we briefly discuss some of the observations made at Jupiter. They serve to illustrate the richness of the observations we expect when the spacecraft reaches Saturn.

5.4.1. Magnetosphere

The observations made by Cassini/Huygens are making important contributions to our knowledge of the Jovian magnetosphere. Some of these resulted from the unique advantage of the Galileo spacecraft being able to make similar measurements simultaneously. Other results were enabled by coordinated observations from Earth. These are discussed below, starting with Cassini/Huygens' measurements of the solar wind as it approached the Jovian magnetosphere.

A primary goal was to compare a solar-wind-dominated magnetosphere (e.g., Earth), and a magnetosphere dominated by rotation (e.g., Jupiter), to Saturn, for which both the solar wind and rotation are likely to be important magnetospheric drivers. Inbound Cassini measured the solar wind while Galileo measured deep in the magnetosphere. Outbound, the roles became reversed with Galileo measuring the solar wind while Cassini was in and out of the magnetosphere many times as it traveled along the dusk flank. The simultaneous measurements of the solar wind and magnetosphere allowed variations in the magnetosphere to be correlated with changes in the interplanetary environment. Although numerous reconfigurations and substorm-like activities were observed by Galileo prior to Cassini/Huygens' flyby, there had been no way to associate these events as a response to changing conditions in the solar wind impinging upon the magnetosphere.

Cassini/Huygens was the first spacecraft to explore the dusk flank of the Jovian magnetosphere. Of special interest were the processes of magnetic field draping (measurements by MAG), flow dynamics (measurements by CAPS), detached-plasma shedding (measurements by CAPS, and MAG), the generation of upstream waves (measurements by RPWS), and the shaping of the overall magnetic topology (measurements by MIMI, CAPS, and MAG). Cassini/Huygens, flight trajectory and fluctuations in solar wind pressure and rotation of the Jovian magnetic field caused the spacecraft to cross the bow shock and the magnetopause repeatedly. In all, there were 44 bow shock crossings and 6 crossings of the magnetopause! The locations and dynamics of these boundaries are important for an overall understanding of Jovian magnetospheric dynamics and they place significant constraints on magnetospheric models.

CAPS sensitivity and mass resolution permitted the first detailed compositional analysis of Jupiter's thermal magnetospheric plasma in the outer regions of the
magnetosphere. CAPS can easily resolve ion species associated with oxygen, sulfur, potassium and related molecules such as $S^+_2$ and $SO^+_2$. CAPS and MIMI can also distinguish between singly charged and multiply charged ions and thus establish the ratio of the two. This information helps to constrain the location and strength of sources, transport processes, and the mechanisms by which the middle and inner regions of the magnetosphere are populated with hot plasmas. RPWS monitored Jovian radio emissions and plasma-and radio-wave phenomena associated with the Jovian bow shock, dusk magnetosheath and possibly from the dusk magnetopause and magnetosphere. It remotely sounded the structure of the Io torus by using measurements of Faraday rotation and observations of the location and frequency of the narrow-band kilometric radiation. Multipoint observations by Cassini/Huygens and Galileo have provided the data for a better understanding of the beaming properties of Jovian radio emissions.

Cassini’s MIMI instrument includes an energetic neutral atom camera (INCA). Energetic neutral atoms typically arise from charge exchange interactions between a neutral atom and an energetic ion trapped in the magnetic field. Upon charge exchange the ion is neutralized and is no longer bound by the magnetic field. It leaves the site of the reaction at high speed. Imaging these neutrals permits the direct observation of the charge exchange reactions. This allows some inferences of the spatial, energy, and mass distributions of the trapped ion populations. MIMI also provided in situ measurements of the more energetic species encountered by the spacecraft. These complement measurements by CAPS over a large range of energy (up to 130 MeV). Cassini coordinated observations with the Very Large Array (VLA) radio telescope and took advantage of the flyby to map Jupiter’s synchrotron radiation. Cassini’s RADAR operated as a radiometer at a wavelength of 2 cm while the VLA mapped emission at wavelengths of 20 and 90 cm. This provided comparative measurements of the relativistic electron population in Jupiter’s radiation belts and enabled the most nearly complete estimate of their energy spectrum (up to 50 MeV) and density of the electrons in the radiation belts made to date. Observations of synchrotron emission provide the only remote probe of high-energy electrons in Jupiter’s inner radiation belts.

Jupiter’s aurora has been observed to vary on short time scales, from minutes to days. This variability is thought to be due to the combined influence of internal magnetospheric processes and external, solar-wind-driven changes. Unlike terrestrial aurora that are solar-wind-driven, Jupiter’s auroral morphology shows dependencies on both the solar wind and Jupiter’s rotation. The HST (Hubble Space Telescope) carried out coordinated observations in order to correlate changes in the intensity and morphology of Jupiter’s aurora with the state of the solar wind as measured by Cassini. Inbound to Jupiter, Cassini monitored the solar wind while Galileo measured magnetospheric properties and HST imaged the aurora. Outbound, Cassini monitored the nightside aurora while Galileo monitored the solar wind and HST observed the dayside aurora. This data set permits solar wind
influence on auroral intensity and structure to be separated from changes due to internal magnetospheric processes.

5.4.2. Atmospheric Structure and Dynamics
Atmospheric observations of Jupiter studied atmospheric kinematics and meteorology over time scales ranging from hours to months, measured wind velocities and life cycles of atmospheric features, and monitored interactions of storms and jets. These data will improve our knowledge of the 3-dimensional structure of the atmosphere and the global energy balance. Information was obtained on the distribution of oxygen compounds and higher order-hydrocarbons. CIRS searched for new spectral features and globally mapped the thermal structure and aerosol loading of the stratosphere, as well as obtaining some information on temporal variability. Wind shear and eddy signatures in the thermal field give information on the attenuation or propagation of tropospheric kinematics into the stratosphere. Cassini/Huygens helped to establish a link between daytime storm features and moist convection, as evidenced by lightning, at night. Adequate lightning statistics were gathered to link moist convection to cyclonic shear zones. Jovian dayglow and nightglow emissions were also measured.

Inbound, a ‘Zoom Movie’ was built up by acquiring Optical Remote Sensing (ORS) (i.e., CIRS, ISS, UVIS, and VIMS) data for all odd rotations of Jupiter from −90 to −20 days, plus one even rotation every 120 hours. ISS and VIMS imaged every 60° of longitude while data was acquired more or less continuously by CIRS and UVIS.

The inbound sequences were interrupted when scientific operations were suspended in order to investigate an out-of specification signal from the Attitude Control System. It was found that one of the spacecraft’s reaction wheels required more torque at very low rpm than expected. This problem was resolved by changing the operating range for the wheels so that low rpm rotation rates would be avoided.

Outbound, a zoom movie was acquired from +20 to +90 days, for all odd rotations of Jupiter, plus one even rotation every 120 h. Both the bright crescent and the dark hemisphere were observed.

Observations of Jupiter’s atmospheric thermal emission and synchrotron emission were obtained shortly after Jupiter closest approach (∼137 R_J distant from Jupiter). Two cm wavelength maps were obtained by using RADAR operated in its radiometer mode and slewing the spacecraft repeatedly across the emission region (∼8 R_j in width). Two 10-hour maps covering all Jovian longitudes were obtained (one for each polarization). The resolution of the maps is approximately 0.25 R_J (Bolton, et al., 2002).

5.4.3. Jovian Rings
The Jovian ring is very faint and difficult to observe due to its proximity to the planet. Cassini/Huygens’ objectives were to investigate the interaction between Jupiter’s small satellites and its ring to assess the sources and sinks of ring ma-
terial. A joint experiment was carried out with Galileo to characterize the three-dimensional structure of the rings by imaging them at the same time from two different perspectives. A watch was maintained for any temporal variability. Two ring ‘movies’ were taken, the first inbound at \(-18\) days with a duration of \(40\) h, and the other outbound at \(+16\) days, for \(39\) h. The solar phase angle reached \(\sim 0\) deg during the inbound movie, which allowed observations of the ‘opposition effect’, a backscattering effect closely related to the values of certain photometric parameters. Although Cassini’s spatial resolution could not compete with that of Galileo, the spectral range, available phase angles, and temporal coverage offered the opportunity to acquire valuable data, complementary to that obtained by Galileo.

5.4.4. Galilean Satellites and Himalia
Cassini/Huygens was blessed by an opportunity to obtain data on Himalia, a small satellite that heretofore had escaped observations by Galileo due to the lack of a favorable opportunity. Himalia was observed at a range of \(4.4 \times 10^6\) km for a duration of \(\sim 3\) h. VIMS obtained the first visible to near-IR reflection spectrum of Himalia (Brown et al., 2002). The purpose of this observation was to determine surface composition. ISS obtained some images that are useful for assessing Himalia’s rotation rate and size (\(\sim 160\) km diameter).

The timeline featured relatively dense coverage for Io and Europa, and relatively sparse coverage for Ganymede and Callisto. However, Cassini was able to observe both Europa and Callisto at near 0° phase angle and measure the surge of their opposition effects.

A search was carried out for new infrared spectral features. VIMS has nearly double the spectral resolution of Galileo’s NIMS and obtained spectra of the Galilean satellites in order to improve the determinations of their surface compositions, particularly the compositions of the non-icy components. It has been suggested that this component is rich in hydrated salts (i.e., magnesium and sodium sulfates) and they may be a signature left by water that came to the surface from an ocean below (McCord, et al., 2001).

In the visual, ISS acquired phase angle and polarization data to improve knowledge of the phase function and thereby physical characteristics of the surface such as grain size and packing. ISS also observed Io while it was in Jupiter’s shadow in order to examine the morphology and temporal variability of eruptive plumes, atmospheric airglow, and volcanic hot spots. At this time a very impressive set of images was obtained enabling a movie that shows changes in optical emission that come from changing interactions between the magnetosphere and Io’s very thin exosphere.

5.4.5. Io’s Torus
Closely related to Io’s exosphere are the two tori that are centered on Jupiter. One is composed of neutral atomic and molecular species and the other is composed of ions. They orbit at Io’s distance from Jupiter and are thought to originate from
Io. Measurements of the emissions from these species are used to study the sources and sinks of material, its composition, its dynamical behavior, and its dependencies on local time, Io’s phase, Jovian longitude and Io’s degree of volcanic activity. In a 5-day period, 70 h was spent monitoring Io’s torus and UVIS collected enough data to produce a torus movie showing stimulated emission from some ion species.

5.4.6. **Dust**

To measure the general dust populations, CDA remained on for most of the Jovian flyby, as well as the months and years during cruise. In 1992 *Ulysses* discovered collimated dust streams coming from Jupiter. Later observations with *Galileo* showed that Io was the source. Jupiter’s magnetospheric plasma charges dust particles coming from Io. These are then accelerated by Jupiter’s corotational magnetic field.

*Cassini’s* CDA is the most capable dust instrument that has observed these particles. CDA can measure their flux (≈1 per month to ≈10⁴ s⁻¹), mass (≈10⁻¹⁶ to ≈10⁻⁶ gm; ≈0.1 to ≈10 μm diameter for common silicates), velocity (1–100 km s⁻¹), charge (≈ 3 × 10⁻¹ to ≈ 3 × 10⁻¹² Coulomb), and composition (resolving power of ≈70 M/dM). The measurement of the chemical composition of the dust is a new capability that CDA brings to this problem, and it may yield further insight into Io’s volcanic activity. Coordinated measurements were made by *Cassini* and *Galileo* to separate temporal and spatial effects discernible in the structure of the dust stream by using data from two spacecraft. This coordinated experiment is illustrated in Figure 19. Much to the surprise of everyone, velocities turned out to be in the 300–400 km/sec range (Srampa, *et al.*, 2001). Mechanisms to attain such high dust velocities are being studied.

5.5. **GRAVITATIONAL WAVE AND GENERAL RELATIVITY RADIO EXPERIMENTS**

On its voyage between Jupiter and Saturn, *Cassini/Huygens* will carry out gravitational wave searches during the three successive oppositions of the spacecraft, beginning in December 2001. These are Doppler-tracking, radio experiments that involve two-way Ka-band tracking of the spacecraft by the Deep Space Network (DSN). Propagating, polarized gravitational fields are predicted by all theories of relativistic gravity. These waves change the distance between separated (known) masses and shift rates at which separated clocks keep time. Compared to electromagnetic waves, gravitational waves are extremely weak. Detectable amplitudes of these waves are only generated by astrophysical sources. In the *Cassini/Huygens* experiments the distances between the spacecraft and Earth are large compared to the wavelength. Because of this, there will be, in general, three distinctive components to the gravitational wave signature (in a relative-Doppler versus time plot). This experiment is sensitive to low frequency gravitational waves (0.1 to 10⁻⁴ Hz). Observations during the first opposition (December 2001–January 2002) went well.
Figure 19. The configuration for the two spacecraft dust experiment. The radiant of dust stream from Io and intersect the trajectories of Galileo, first, and then Cassini/Huygens. The time it takes the dust to fly between the spacecraft can be measured by observing the temporal modulation of the density of the stream. Particle velocities turned out to be hundreds of kilometers per second, a value much higher than thought to be possible.

The fractional frequency stability (e.g., Allan variance) of the radio system has been measured and was better than its manufactured specification.

During two conjunctions of the spacecraft with the Sun, a series of radio propagation measurements will be made using two-way X-band and Ka-band DSN tracking. These will provide the basis for a test of general relativity, as well as obtain data on conditions in the solar corona.
6. The Cassini/Huygens Mission at Saturn

The Cassini/Huygens mission has three main phases at Saturn: arrival and insertion into orbit, the Huygens mission, and the orbital tour. Each of these will now be discussed.

6.1. Arrival at Saturn and Insertion into Orbit

Months before reaching Saturn, Cassini begins making synoptic observations in order to refine our knowledge of Titan and to characterize the rings and the planet as early in the mission as possible. As soon as a few tens of pixels are available across Saturn’s disk the first characterization of the atmosphere with Cassini’s instruments can be started. This early work will establish the first point in Cassini’s kinematic coverage. It will also obtain the information we need for all targets in order to refine our knowledge of (remote sensing) instrumental sensitivities as a function of wavelength and other parameters. As the range to Saturn continues to decrease it will be opportune to make a movie showing the kinematics of the atmosphere.

Phoebe, the target of our first flyby in the Saturnian system, is reached on 11 June 2004. At this time the range to Saturn is still some 11.3 million kilometers. Phoebe has a modest diameter of 150 km. It has a rotation period of about 9.4 h and an orbital period of 550 days. Phoebe is unusual because of its inclined, retrograde, and chaotic orbit. This is strong evidence that it and a dozen recently discovered small satellites were interplanetary objects that have been captured perhaps from the Kuiper-belt. Measuring the density of Phoebe is key to assessing its bulk composition. There is some evidence from albedo measurements that there may be craters on the surface of Phoebe. This flyby is Cassini’s only encounter with Phoebe because this satellite is so distant from Saturn that Cassini cannot afford to expend the propellant needed to visit it again, later in the mission. The flyby of Phoebe occurs 19 days before SOI and the corresponding Sun-Earth-spacecraft angle is six degrees. The Phoebe distance at closest approach will be 2000 km and the phase angle will be less than 90°.

The trajectory of the spacecraft as it approaches the rings and planet is shown in Figure 20. The spacecraft is beneath the E ring from about 4.5 h to 2.75 h before periapsis. The spacecraft passes through the gap between the F and G rings at 1.86 hours before periapsis and again at 1.90 h after periapsis in the descending direction. During this arrival trajectory, the spacecraft will be at its closest to Saturn and the inner rings. The closest approach is 0.3 Rs (1 Rs = 60,330 km); the next closest is 1.7 Rs which occurs at several times late in the tour. Consequently, the initial pass of Saturn is a unique opportunity for making key observations.

Figure 20 shows the arrival trajectory from a view point above Saturn. Note that the trajectory just grazes the solar and Earth occultation zone behind the planet. This means the spacecraft will be in sunlight for the entire SOI sub-phase. The Earth occultation zone is not significant because the spacecraft will have turned
Figure 20. Saturn Orbit Insertion (SOI) geometric relationships. The view is from above Saturn's north pole. After launching from Earth, the placing of Cassini/Huygens into orbit is the most important event. The proximity to the planet and the rings makes this a uniquely valuable period for scientific measurements.

of the Earth-line before the first ring plane crossing. The SOI burn begins soon after the ascending crossing and ends at approximately Saturn closest approach. The maneuvers before SOI are planned to insure the proper spacecraft trajectory for the orbit insertion maneuver. Maneuvers after SOI are to correct for errors in the insertion burn itself. The B-plane delivery error at the orbit insertion point is expected to be less than 130 km (one sigma). The SOI maneuver itself occurs on 1 July 2004, and is timed so that a normal burn will end just after closest approach.

Cassini/Huygens will be the fourth spacecraft to pass through the rings of Saturn. A region known to be free of particles has been chosen. Any debris to be encountered during the ring plane crossings is expected to be of small size and very low mass (e.g., smoke) which the spacecraft has been designed to withstand. The orbit insertion burn slows the spacecraft and allows it to be captured into orbit about Saturn. The SOI burn will occur earlier in time (than optimum for minimizing propellant usage) so that the burn will end near the closest approach to Saturn. This allows time for post-periapsis remote sensing of the rings. Otherwise, should the
burn fail to execute as planned, this time will be used to fire the second engine and complete the maneuver to attain Saturnian orbit.

The SOI maneuver itself is a 97-minute main engine burn with a total $\Delta V$ of 633 m/s. An accelerometer will end the burn when the required velocity change has been obtained. The spacecraft will be steered at approximately a constant angular rate with the engine gimble actuator to keep the main engine pointed near the velocity vector in order to maximize the thrust efficiency during the burn. Thus the spacecraft will turn approximately 40° in all during the burn.

During the SOI burn itself, only fields, particles, and wave instruments will be operational. It is necessary to keep high power margins for the critical burn event; also, the fixed pointing and spacecraft vibrations during the main engine firing would degrade remote sensing. After the burn has ended and the sloshing in the fuel tanks has subsided (<5 minutes), the spacecraft will be rolled 60–70° to allow the ORS instruments to view the Saturn inner rings that are not in shadow. The ORS viewing angle is 20–30° from nadir. This look-angle is a compromise between the desires of the MAG investigation and the ORS instrument investigations. At this time Cassini/Huygens is the closest to Saturn and this is also the only time that this portion of the planet’s magnetic field will be available for measurement. It is also the best time to view the rings up close.

6.2. HUYGENS PROBE MISSION

The first two orbits about Saturn are used to set up the necessary trajectory for deploying the Huygens Probe on the third orbit. On December 16, 2004, three days after the end of the second orbit, the Probe Targeting Maneuver places Cassini/Huygens on a course that will intersect Titan. The Orbiter then turns to aim Huygens at Titan. On December 25th the Probe is released. The spin-eject mechanism simultaneously ejects the Probe and imparts to it a 5 rpm axial spin. The two spacecraft separate with a relative velocity of 0.3 to 0.4 m/s. Twenty-two days later, January 14, 2005, Huygens will reach Titan. Meanwhile, the Orbiter fires an engine and executes the Orbiter Deflection Maneuver. This sets a course to fly by Titan at an altitude of 60,000 km and at the right time for receiving transmissions from Huygens.

The general situation for this part of the mission is depicted in Figures 21 and 22. The spin-stabilized Probe is targeted to enter Titan’s atmosphere at latitude −10.7° and 199° west longitude. Winds during the descent will determine the exact landing location. Windage is expected to be almost entirely in longitude. Depending upon the direction and intensity of the wind, the position of the landing could differ from the above longitude by plus or minus half a dozen degrees or so.

The Orbiter is turned to point and track the HGA on the expected Probe entry point. The Probe support avionics (PSA) are configured to receive data. Orbiter instruments will be turned off. Huygens enters the atmosphere 2.1 h before the Orbiter will reach its closest approach to Titan. The Probe has a thermal-protection
Figure 21. Events and trajectories leading up to the delivery of Huygens. Three orbits are needed to set Cassini on the correct trajectory so that it can meet Huygens exacting requirements for entering Titan’s atmosphere. PRM is the periapse raise maneuver; PTM is periapse trim maneuver; ODM is the Orbiter deflection maneuver that keeps the Orbiter from following Huygens into Titan.

shell to protect it from the enormous flux of heat generated during atmospheric entry. Atmospheric entry is a tricky affair. Entry at too shallow an angle can cause the Probe to skip out of the atmosphere and be lost, whereas too steep of an angle will result in it being burned up in the atmosphere. The designed flight path entry angle is ~64 degrees. Once the Probe has decelerated to about Mach 1.5, the aft cover is pulled off by a pilot parachute. An 8.3-m diameter main parachute is then deployed to initiate a slow and stable descent. The main parachute slows the Probe, allowing the decelerator/heat shield to fall away as it is released. To limit the duration of the descent to a maximum of 2.5 h, the main parachute is jettisoned at entry +900 s and a smaller, 3.0 m diameter, drogue chute is deployed for the remainder of the descent. The entry and descent sequence is illustrated in Figure 23, which shows the major events of Huygens’ mission. The batteries, and all other resources, are designed for a maximum mission duration of at least 153 min. This corresponds to a descent time of 2.5 h plus 3 min.

The Probe measures atmospheric properties in situ as it descends by parachute to the surface. Throughout the descent, the HASI (Huygens Atmospheric Structure Instrument) will measure more than a half dozen physical properties of the atmosphere. It will also process signals from the Probe’s radar altimeter in order to gain information about surface properties. The Gas Chromatograph and Mass Spectrometer (GCMS) will determine the chemical composition of the atmosphere as a function of altitude. The Aerosol Collector and Pyrolyzer (ACP) will capture aerosol particles, pyrolyze them, and send the effused gas to the GCMS for analysis.
The Descent Imager and Spectral Radiometer (DISR) will measure the propagation of sunlight in the atmosphere. This instrument will also image the cloud formations and the surface. As the surface nears, the DISR will switch on a bright lamp and measure the spectral reflectance of the surface. Throughout Huygens’ descent, the Doppler shift of telemetric signal will be measured by equipment on the Orbiter in order to determine the atmospheric winds, gusts, and turbulence (the Doppler Wind Experiment, DWE). In the proximity of the surface, the Surface Science Package (SSP) is active. Its accelerometer characterizes the impact of touchdown. In the atmosphere SSP measures the local velocity of sound, electrical permittivity, temperature, and thermal conductivity. If the landing is into a liquid, SSP will measure density, velocity of sound, and index of refraction.
The data are transmitted in two separate streams, and both are recorded redundantly on each SSR. In all, there are four copies, not counting any duplication between the two Huygens communication channels. The maximum length for the expected descent time is 2.5 h. At this time the Orbiter is slightly pass closest approach (first tick mark in Figure 22) and Huygens will be on the surface. For about two hours the Orbiter will listen for transmissions from the surface. At ~2.4 h after periapsis the Orbiter, as seen from the Probe, will pass over the horizon. Soon thereafter, the Orbiter will turn the high-gain antenna towards Earth and begin transmitting the recorded data. The complete, 4-fold redundant set of Probe data will be transmitted twice. Verification of receipt of the data on the ground will be made independently by JPL and ESOC.

6.3. THE ORBITAL TOUR

After the delivery of Huygens, Cassini is put on orbits that take it to the icy satellites, explore much of the volume of the magnetosphere, and to high latitudes to observe the rings. Cassini uses close flybys of Titan both to study Titan and
The tour consists of 76 Saturn-centered orbits. They are navigated by using propulsive maneuvers and 45 Titan-gravity-assist flybys. The size of these orbits, their orientation to the Sun-Saturn line, and their inclination to Saturn’s equator are gauged to assist in meeting the scientific requirements. These include: Titan ground-track coverage, targeted flybys of icy satellites, Saturn, Titan, and ring occultations, maximum orbit inclination, and ring-plane crossings. Titan is the only satellite that is large enough to provide significant gravity-assisted orbit changes.

The design of the Cassini orbital tour was a complicated and challenging activity. It is a very aggressive tour compared to that in the Cassini AO. Its success in yielding many opportunities, in part, helps to compensate for the handicap that was introduced early in 1992 when the instrument platforms were deleted from the spacecraft design as a cost-saving measure.

The tour is shown in Figure 24. The outer dotted circle corresponds to the orbit of Iapetus. The various segments of the tour are color-coded. White indicates the period of 2004 July 1 to 2005 February 15 and includes SOI, the Probe release, and Huygens mission. Violet is 2005 February 15 to 2005 April 1. Orange is from
2005 April 01 to 2005 September 7 and includes a series of important occultation sequences. Green is 2005 September 7 to 2006 July 22 and gives the petal rotation and magnetotail petal. Blue goes from 2006 July 22 to 2007 June 30 and includes a 180-degree transfer. Yellow is 2007 June 30 to 2007 August 31 and includes apoapsis rotation in order to get certain icy satellites flybys. Red goes from 2007 August 31 until the end of mission (2008 July 1) and is chiefly the high inclination sequences.

In addition to the deliberately targeted flybys, there are unplanned or serendipitous flybys that occur as a result of the tour geometry. Many of these are close enough to provide valuable opportunities for observations. On these occasions, ranges can be less than 100,000 km. At that range the pixel resolution of Cassini's narrow-angle camera is about 0.6 km. This is substantially better than that achieved by Voyager for most of the icy satellites. Wolf (2002) will revisit mission and tour design in more detail in a later volume.

7. Data return and Distribution to the Scientific Community

What will we do with all of the data that Cassini/Huygens will collect? Upon the first inspection they are checked to see if the downlinks were successful and if the respective instruments appear to be functioning correctly. The instrument teams peruse the data for obvious surprises. Some of these may be new discoveries. If they are newsworthy they go onto a fast track for release to the world. Meanwhile, the data also go to the respective scientific teams and investigators. These are the people who are responsible for the initial analysis and study of the data. They render the results into forms appropriate for publication in the scientific literature. However, because of the continuing spacecraft operational chores and because of the very large amount of data that Cassini will return, they can only scratch the surface in terms of developing the scientific results in the data. One year after receipt of the data by the Cassini scientific teams, the data become available to everyone via NASA's Planetary Data System. At this time the whole worldwide community of scientists has the data available for its use and everyone is able to participate in the further exploitation of the data. But, in reality, the challenge of interpreting all that has been measured, photographed, and returned has just begun. The further analysis of these data over the years to come will be the continuing legacy of the Cassini and Huygens missions.

Notes

1. As of summer 2001, observations suggest the presence of additional satellites but their orbits are presently unknown. Undoubtedly there are many additional small, as yet undetected, satellites.
2. The membership of the Joint Science Working Group which supported the phase-A activities as follows: M. Allison (Goddard Institute for Space Studies, New York, USA); S. Bauer
(Karl Franzens Universität, Graz, Austria); M. Blanc (Centre de Recherches en Physique de l’Environnement, St. Maur, France); S. Calcutt (Dept. of Atmospheric Physics, Oxford, UK); J. Cuzzi (NASA Ames Research Center, Moffett Field, USA); M. Fulchignoni (Università ‘La Sapienza’, Rome, Italy); D. Gautier (Observatoire de Paris, Meudon, France); D. Hunten (University of Arizona, Tucson, USA); W. Ip (MPI für Aeronomie, Katlenburg-Lindau, Germany); T. Johnson (Jet Propulsion Laboratory, Pasadena, USA); H. Masursky (US Geological Survey, Flagstaff, USA); P. Nicholson (Cornell University, Ithaca, USA); T. Owen (State University of New York, Stony Brook, USA); R. Samuelson (NASA Goddard Space Flight Center, Greenbelt, USA); F. Scarf (TRW, Redondo Beach, USA); E. Sittler (NASA Goddard Space Flight Center, Greenbelt, USA); B. Swenson (NASA Ames Research Center, Moffett Field, USA). D. Gautier, W. Ip and T. Owen acted as ‘lead scientists’.

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4. ‘Deadband’ is an attitude control term for the maximum angular deviation in spacecraft attitude that can occur before eliciting a corrective response from the attitude control subsystem (ACS). To reduce the frequency of these cycles (and thus reduce propellant consumption), the deadband during cruise was set to a conservative value of 20 mrad on each of the three axes. The size of the deadband can be reduced if more accurate pointing is required.

5. A special series of eleven papers on the Venus and Earth flybys is in J. Geophys. Res. – Space Physics, 106, 30,099–30,279.

6. The interface altitude for atmospheric entry is taken to be 1,270 km.

7. All petal plots are shown in the MPF (MIMI Planning Frame) reference frame with the sun on the +X axis. The MPF is a rotating frame is defined as follows: (i) the Z-axis is along Saturn’s polar axis (i.e. the Z-axis of the planet’s body-fixed reference frame); (ii) the Y-axis is obtained as the unit vector along the cross product of the Z-axis and of the planet’s center to Sun vector; (iii) the X-axis is computed as the cross product of the Y- and Z- unit vectors. On the XY plots, the inner dotted line is a circle whose radius corresponds to the semi-major axis of Titan’s orbit.
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References


Appendix I: Saturn System Mythology, by Ladislav E. Roth

Until the middle of the nineteenth century, the satellites of Saturn bore numerical designations only. In 1847, John Herschel proposed that the satellites be named after Saturn’s ‘brothers and sisters, the Titans and Titanesses’. Titans and Titanesses were brothers and sisters not of Saturn, but of Kronos, Saturn’s Greek counterpart. Hesiod, Homer’s younger contemporary, gives us the earliest family history of the tribe of the Titans. Using some of Hesiod’s own words, here is an outline of the story. In the beginning, there was Chaos, and after him came Gaia (the Earth). Gaia’s first-born was Ouranos (the Sky), the ‘one who matched her every dimension’. Gaia ‘lay with Ouranos, and bore him Okeanos, Koios, Krios, Hyperion, Iapetus, Theia, Rhea, Themis, Mnemosyne, Phoebé, and Tethys’. Her youngest-born was the ‘devious-devising Kronos, most terrible of her children’. Hesiod assigned the name Titans to the enumerated twelve children. Kronos, upon urging from Gaia, attacked his father Ouranos with the sickle she provided. Following the attack, Kronos became the supreme ruler of the world.

Kronos took Rhea as his wife. She bore him five children. Remembering the fate of his father, Kronos swallowed each child right after it was born. Zeus was the sixth-born. To save the baby, Rhea tricked her husband into swallowing a stone instead. At some later point, Kronos was made to regurgitate the stone and the five children he swallowed. (Hesiod does not say when and how.) With his siblings’ help, Zeus initiated a rebellion against Kronos and the Titans. The Titans suffered a defeat in a terrible battle during which ‘all earth was boiling’. Zeus imprisoned the defeated gods in Tartaros, ‘a moldy place, at the uttermost edges of the monstrous earth’ and, along with his Olympian allies, assumed the lordship over the world. Although Kronos’ rule passed, it was long remembered as the Golden Age of mankind, when people ‘lived as if they were gods, their hearts free from all sorrow, without hard work or pain’. Saturn, a Latin deity perhaps associated with farming, received some of the attributes of Kronos. The Romans adopted also the
legend of the golden age. In their version, Saturn was the king of Italy in the long
forgotten days when, as in the age of Kronos, life was all play and no work.

John Herschel gave the name Titan to the moon of Saturn which was discovered
first and which happened to be the largest. The other four moons discovered
in the seventeenth century he named Iapetus, Rhea, Dione, and Tethys. The minute
inner satellites first observed by his father, John Herschel chose to name Enceladus
and Mimas. Two satellites found in the nineteenth century received the names of
Hyperion and Phoebe. The remaining satellites known at present were discovered
in the twentieth century. They include Janus, Pan, Atlas, Prometheus, Pandora,
Epimetheus, Telesto, Kalypso, and Helene. Of the eighteen named satellites, only
Iapetus, Rhea, Tethys, Hyperion, and Phoebe bear the names of Saturn’s ‘broth­
ers and sisters, the Titans and Titanesses’. A brief description of the meaning of
the satellites’ names is given below. The satellites are listed in the order of the
increasing distance from Saturn.

Pan- Half-goat, half-human, the Arcadian Pan was worshipped as the patron of
shepherds and as the personification of nature.

Atlas- Son of Iapetus. After the defeat of the Titans, Zeus ordered Atlas, ‘at Earth’s
uttermost places, near the sweet-singing Hesperides’ to uphold the vault of the
sky. Hesiod refers probably to the Pillars of Hercules, the edge of the world
known to the ancient Greeks

Prometheus- Hesiod presents Prometheus, son of Iapetus, as an immortal who
sided with the mortals and as a prankster who liked to annoy his cousin Zeus.
The ultimate annoyance was stealing ‘the far-seen glory of weariless fire’ and
giving it to mankind. For this, Zeus fastened Prometheus to a mountain in the
Caucasus, and he let loose on him ‘the wing-spread eagle, and it was feeding
on Prometheus’ imperishable liver, which by night would grow back to size
from which the spread-winged bird had eaten in the daytime’.

Pandora- The world’s first woman. Creating Pandora was the punishment Zeus
meted out to mankind for Prometheus’ brazen acts of disobedience. Pandora
arrived equipped with a jar that contained all the misfortunes, curses and
plagues. Once the lid was lifted, the evil asserted itself in the world. ‘Hope
was the only spirit that stayed there, in the unbreakable closure of the jar, this
was the will of the cloud-gathering Zeus’.

Epimetheus- Son of Iapetus, brother of Prometheus, husband of Pandora. Pictured
as weak-minded, he is the one who lifted the lid on Pandora’s jar.

Janus- An exalted Roman god, a figure of great antiquity and obscure origin.
Always represented as having two faces, one looking forwards, the other back­
wards, Janus presided over the past, present, and future, over gates, doorways,
entrances, and beginnings in general, and over war and peace. At every sac­
rifice, in every prayer, he was the first god invoked, taking precedence before
Jupiter. When war was declared, the portals to the sanctuary of Janus on the
Forum were opened. They were shut again on the declaration of peace. During
the entire history of Rome, this happened on a handful of occasions only. As the most ancient of kings, Janus is supposed to have given the exiled Kronos a warm welcome in Italy, and to have offered him a share of the royal duties.

**Mimas**- One of the Giants, children of Gaia born of the blood of Ouranos.

**Enceladus**- One of the Giants, children of Gaia born of the blood of Ouranos. Giants, the last race of Hesiod’s monsters, were beings of enormous size and invincible strength. Later depictions show them as having hideous faces, bristling beards, hanging hair, skins of wild animals for garments, tree trunks for weapons, and twin serpents for legs.

**Tethys**- The youngest of Titanesses, Tethys married her brother Okeanos, and bore him three thousand Okeanides, the ‘light-stepping’ sea-nymphs, and ‘as many Rivers, the murmurously running sons’.

**Telesto**- A daughter of Tethys and Okeanos, an Okeanide.

**Kalypso**- A daughter of Tethys and Okeanos, an Okeanide. For Homer and other authors, she is a daughter of Atlas. In the course of the Odysseus’ tortuous return to Ithaca, his ship ran aground on the fabled island of Ogygia, the home of the lonely Kalypso. Odysseus kept her company for seven years, after which he departed ‘on a jointed raft’.

**Dione**- Dione presents a problem in the genealogy of the Greek gods. To Hesiod, she is a daughter of Tethys and Okeanos, and thus an Okeanide. She is mentioned in a number of other incarnations; for instance as a daughter of Ouranos and Gaia (this would make her a Titaness), or as a daughter of Kronos, or of Atlas. In some localities she was also worshipped as the wife of Zeus (instead of Hera).

**Helene**- The divinely beautiful wife of Menelaos, the king of Sparta, Helen (Helene) was abducted by Paris, the son of Priam, the king of Troy. Over Helen the Greeks fought the all-destructive Trojan War.

**Rhea**- A Titaness, married to her brother Kronos.

**Titan**- Not a single deity, but a generic name for the enumerated children of Ouranos and Gaia. (Ouranos and Gaia had more children, not just the Titans and the Giants.)

**Hyperion**- The fourth-born Titan, Hyperion took for a wife his sister Theia. ‘Theia brought forth great Helios and shining Selene, the Sun and Moon, and Eos the Dawn who lights all earthly creatures and the immortal gods who hold the white heaven’. Solar and lunar deities, dominant in the affairs of other ancient civilizations, played a minor part in the religious life of ancient Greeks.

**Iapetus**- Iapetus, a Titan, took Klymene, his niece, the ‘light-stepping daughter of Okeanos, to be his wife’. Their sons were Atlas, Prometheus, and Epimetheus.

**Phoebus**- Phoebus, a Titanness, bore to her brother Koios the goddess Leto, ‘the gentlest of all who are on Olympus. Leto, who had lain in the arms of Zeus, bore Apollo and Artemis, children more delightful than all the other Olympians’. In later antiquity, Phoebus was honored as the goddess of the Moon.
THE HUYGENS PROBE: SCIENCE, PAYLOAD AND MISSION
OVERVIEW

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Abstract. Huygens is an entry probe designed to descend under parachute through the atmosphere of Titan, Saturn’s largest moon, down to the surface. The main Huygens science mission phase occurs during the 2–2¹/₂ hours parachute descent. Measurements will also be conducted during the 3 min entry and possibly up to about one hour on the surface if Huygens survives the landing impact. The Probe’s payload comprises six instruments. The Huygens Probe is provided by the European Space Agency (ESA) for the joint NASA/ESA Cassini/Huygens mission to Saturn and Titan. This paper provides an overview of the Huygens mission and a concise description of the payload as an introduction to the papers which describe the Huygens investigations in this volume.


1. Introduction

Huygens is an entry probe designed to study the atmosphere and the surface of Titan, the largest moon of Saturn. The Huygens scientific objectives are to carry out detailed in situ measurements of the physical properties, the chemical composition and the dynamics of the atmosphere and to provide a local characterisation of the...
The Cassini/Huygens spacecraft was launched from Cape Canaveral, Florida, aboard a Titan-4B Centaur rocket on 15 October 1997. After an interplanetary voyage of 6.7 years, the spacecraft is targeted to arrive at Saturn in early July 2004. The Saturn Orbit Insertion manoeuvre will place it in orbit around the planet on 1 July 2004. Following the discovery of an anomaly in the Probe-to-Orbiter telecommunication system in 2000 (Clausen et al., 2002), a reference revised Huygens mission scenario was worked in 2001. The reference revised Huygens mission plan calls for the Probe mission to be executed in mid-January 2005, on the third orbit around Saturn. Following the Huygens mission, the Orbiter will continue its intensive 4-year exploration of the Saturnian system along 78 orbits around Saturn. 45 of the orbits include targeted flybys of Titan with altitudes as low as 950 km above the surface.

The exploration of Titan is at the very heart of the Cassini/Huygens mission. Titan encounters are used for making the gravity-assist orbit changes that shape the orbital tour around Saturn. During each Titan flyby, the Orbiter will perform a set of in situ and remote sensing observations of the surface, the atmosphere and
the plasma environment. The detailed *in situ* data set acquired by the Probe and the global coverage that will be provided by the Orbiter observations during the targeted flybys will provide a unique wealth of new scientific information. It will substantially increase our knowledge of Titan, the enigmatic planet-sized moon shrouded by a thick, hazy and chemically active atmosphere.

This paper is intended to give an overview of the Huygens mission, and to provide an introduction to the more detailed papers related to Huygens contained in this volume. It is organised as follows. In section 2, a brief history of the development of the Cassini/Huygens mission is given. In section 3, a mission overview is provided. The scientific objectives of the Huygens Probe are described in section 4. Then, in section 5, the main characteristics of Titan are reviewed, with an emphasis on the ‘engineering’ knowledge of Titan that was needed to design the Probe mission. The main features of the payload are described in section 6. An overview of the Huygens mission profile is provided in section 7. The accommodation of the payload and the operational constraints are discussed in section 8. The Huygens flight operations are explained in section 9. A brief overview of the data analysis phase and of the data archive plans is given in section 10. Aspects of the Huygens mission recovery activities relevant to this paper are discussed in Section 11.

### 2. The Mission’s Historical Development

The development of the Cassini/Huygens mission, a complex and ambitious venture between NASA and ESA, required substantial scientific, technical and programmatic planning efforts over several years. In the late seventies and early eighties, NASA studied several scenarios for a mission to Saturn as the next natural step to follow the Galileo Orbiter/Probe mission at Jupiter in the detailed exploration of the giant planets. The Cassini mission, in its present form, was originally proposed to ESA as a collaborative initiative with NASA in response to a regular call for mission ideas released by ESA’s Directorate of Science. The mission was proposed in November 1982 by a team of European and American scientists lead by D. Gautier, W. Ip, and T. Owen. A mission to Saturn and Titan was also identified as a priority mission for cooperation between the United States and Western Europe in planetary exploration by the Joint Working Group set-up by US National Research Council and the European Science Foundation (see report on ‘US-European Collaboration in Space Science’, National Academy Press, 1998). After an initial assessment in early 1983, the proposed mission was subjected to a 1-year joint ESA/NASA assessment study starting in mid-1984 (ESA SCI(85)1, 1985; ESA SCI(86)5, 1986). Very early in the study phase, the Titan Probe was identified as ESA’s potential contribution to the international Cassini mission. Its estimated cost envelope was within ESA’s financial budget allocated to the first medium-size mission of the Horizon 2000 Programme (Bonnet, 1990). It was also within the technical capabilities of the European space industry, which had limited ex-
xperience in planetary missions, mainly acquired with the Giotto mission. It was subsequently selected by ESA for a competitive Phase-A study in 1986, but the start of the Phase-A was delayed by a year to allow programmatic adjustment with NASA. The Phase-A study was conducted from November 1987 to September 1988 (ESA SCI(88)5, 1988; Lebreton and Scoon, 1988; Lebreton, 1990; Lebreton, 1992; Lebreton and Matson, 1992).

The Titan Probe was selected by ESA’s Science Programme Committee in November 1988 as the first medium-size mission (M1) of the Horizon 2000 long-term space science plan. During the selection process, The Titan Probe was named Huygens, in honour of the Dutch Astronomer who discovered Titan in 1655. Within NASA, Cassini was included in the CRAF (Comet Rendezvous and Asteroid Flyby) /Cassini programme, which was approved in the 1990 budget.

CRAF/Cassini was subjected to NASA’s annual budget exercise and only the development of Cassini went ahead, as CRAF was cancelled by the Administration for budgetary reasons in January 1992. As part of the process, the Cassini mission was greatly restructured in early 1992 to meet a revised annual funding profile. The modified Cassini-alone programme was authorised in May 1992. As a result of the restructuring, the two articulated Orbiter science platforms and the articulated dedicated Huygens relay antenna (Jaffe and Lebreton, 1992) were deleted. The Orbiter instruments became body-mounted, but several instruments added their own articulation to temper the losses of the platforms. The Huygens radio receivers were then directly interfaced with the Orbiter High Gain Antenna (HGA). Huygens was essentially unhurt by the restructuring process. During this exercise, the possibility of launching the spacecraft in two sections on separate Shuttle missions for on-orbit assembly before dispatching it on its interplanetary journey was also evaluated. This scenario did not prove to be practicable.

The selection of the Orbiter and Probe investigations was subjected to coordinated planning. ESA and NASA released a joint Announcement of Opportunity in October 1989 calling for investigations on the Probe and the Orbiter, respectively. Both payloads were selected in close coordination between ESA and NASA, and with the European National Agencies that provided funding for specific hardware contributions. The Probe and Orbiter payload selections were announced by ESA and NASA, respectively in September and November 1990. In addition to hardware investigations, ESA and NASA selected respectively three and seven Interdisciplinary Scientist Investigations. The selected nine Huygens investigations are listed in Table I. During the investigation selection process, the Italian Space Agency (ASI) initiated a bilateral collaboration with NASA that provided for significant augmentation of the Orbiter payload capabilities beyond what NASA alone could fund, in areas of prime interest to the Italian scientific community. This bilateral effort also included the provision by ASI of a major Orbiter element: the 4-band (S, X, Ku, Ka) High Gain Antenna (HGA).

During the Phase-A study, the need for using planetary gravity-assist manoeuvres was identified in order to inject the spacecraft towards Saturn, as no laun-
cher existed in the Western World that was powerful enough to send it directly to Saturn. Three launch opportunities were identified; each included a Jupiter flyby in addition to Venus and Earth flybys. A flyby of Jupiter is required to reach Saturn in a reasonable time: 6.7 years, instead of 9–10 years. At the time of the joint CRAF/Cassini programme, Cassini was scheduled for launch during the second opportunity, in April 1996. After CRAF’s cancellation, the possibility of accelerating the programme and launching in December 1995 was looked at, but the October 1997 launch opportunity was eventually selected as it was the only one of the three that was compatible with NASA’s budget profile available for developing the Cassini spacecraft.

### 3. Overview of the Cassini/Huygens Mission

The Cassini/Huygens mission is designed to explore the Saturnian system and all its elements: the planet and its atmosphere, its rings, its magnetosphere and a large number of its moons, including Titan and most of the icy satellites. The mission will emphasize Titan, Saturn’s largest moon and the Solar System’s second largest (after Jupiter’s Ganymede), and the only satellite with a thick atmosphere.

An important aspect of the Cassini/Huygens mission is the study of the interaction and interrelation of the Saturnian System elements. For example, studying the interrelation between the rings and the icy satellites, and the interaction of the satellites and of Titan’s ionosphere with Saturn’s magnetosphere are key objectives.

### TABLE I

List of the nine Huygens investigations

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Principal Investigator or Interdisciplinary Scientist</th>
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<tbody>
<tr>
<td>Gas Chromatograph and Mass Spectrometer (GCMS)</td>
<td>Hasso Niemann, NASA/GSFC Greenbelt, MD (USA)</td>
</tr>
<tr>
<td>Aerosol Collector and Pyrolser (ACP)</td>
<td>Guy Israel, SA Verrieres-le Buisson (F)</td>
</tr>
<tr>
<td>Descent Imager and Spectral Radiometer (DISR)</td>
<td>Marty Tomasko, LPL, Univ. of Arizona, AZ (USA)</td>
</tr>
<tr>
<td>Huygens Atmosphere Structure Instrument (HASI)</td>
<td>Marcello Fulchignon, Observatoire de Paris-Meudon and Univ. Paris 6, Paris (F)</td>
</tr>
<tr>
<td>Doppler Wind Experiment (DWE)</td>
<td>Michael Bird, Univ. Bonn, Bonn, (D)</td>
</tr>
<tr>
<td>Surface Science Package (SSP)</td>
<td>John Zarnecki, Open University, Milton Keynes, (UK)</td>
</tr>
<tr>
<td>The Aeronomy of Titan</td>
<td>Daniel Gautier, Observatoire de Paris-Meudon, Paris (F)</td>
</tr>
<tr>
<td>Titan Surface-Atmosphere Interactions</td>
<td>Jonathan Lunine, LPL, Univ. of Arizona, AZ (USA)</td>
</tr>
<tr>
<td>Titan’s Organic Chemistry and Exobiology</td>
<td>François Raulin, LISA, Univ. Paris 12, Paris (F)</td>
</tr>
</tbody>
</table>
The Cassini/Huygens spacecraft (Figure 2) was launched on 15 October 1997 by a Titan 4B/Centaur rocket from Cape Canaveral Air Station in Florida. With a launch mass of 5650 kg, it was too massive for a direct injection towards Saturn. The flight to Saturn requires gravity assists from three planets (Figure 3): Venus (April 1998 and June 1999), Earth (August 1999) and Jupiter (December 2000). Along this trajectory, the flight time to Saturn is slightly less than 7 years.

The Cassini/Huygens spacecraft is scheduled to arrive at Saturn on 1 July 2004. The arrival date was optimised to allow a targeted flyby of distant moon Phoebe nineteen days earlier. The most critical phase of the mission after launch is the
Saturn Orbit Insertion (SOI) manoeuvre, on 1 July 2004. Not only is it a crucial manoeuvre, but it is also a period of unique Orbiter science activity. At that time, the spacecraft is as close as it ever will be to the planet, only 0.3 Saturn Radius (Rₕ) above the cloud top. Ring plane crossings (both before and after periapsis) occur in the gap between the F and G rings at a distance of about 2.66 Rₕ. The SOI part of the trajectory provides a unique observation geometry for the rings and a unique opportunity to study the magnetism of Saturn.

The Huygens Probe is carried to Titan attached to the Saturn Orbiter (Figure 4). After SOI, the Orbiter will be placed on an initial orbit that encounters Titan in late October 2004. On the subsequent orbit, 48 days later, another targeted encounter of Titan occurs. The details of the first two Titan encounters have been worked such that the Orbiter will be placed on the appropriate trajectory for the Huygens Probe mission during the third orbit targeted encounter. The Probe will be released about 22 days before Titan encounter (Figure 5). Shortly (typically 4–5 days) after Probe release, the Orbiter will perform a deflection manoeuvre and place itself on the required trajectory for the optimum radio link geometry during the Probe descent and the surface phase. The Orbiter will be about 60 000 km above Titan at closest approach. The communication window is required to last at least 3 hours, but it may last longer, until the Orbiter flies over the horizon, for continuing re-
receiving data if the Probe continues to transmit radio signals after touch down. As it was not be possible to optimise the link geometry for the whole duration of the communication window, the Orbiter trajectory was selected so as to optimise it for the Prime Huygens mission which includes the whole descent and at least 3 min on the surface. A descent time of between 2 and $2^{1/2}$ hours is expected. The communication window will therefore be optimised for the first 153 min of data transmission.
Figure 5. The Huygens release orbit. Huygens will be released from the Orbiter on the third orbit around Saturn.

4. Huygens Scientific Objectives

The scientific objectives of the Cassini/Huygens mission at Titan (ESA SCI(89) 2, 1989) are to:

- Determine abundance of atmospheric constituents (including noble gases); establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere;
- Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photo-chemistry of the stratosphere; study formation and composition of aerosols;
- Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan’s atmosphere; search for lightning discharges;
- Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite;
- Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

Huygens’ goals are to make a detailed in situ study of Titan’s atmosphere and to characterise its surface along the descent ground track and near the landing site.
The objectives are to make detailed *in situ* measurements of atmospheric structure, composition and dynamics. Images and other remote sensing measurements of the surface will also be made during the descent through the atmosphere. The parachute phase will start at an altitude of about 165 km. After a descent of about 135 min, the Probe will impact the surface at 5–6 m/s. As it is hoped that Huygens will survive for at least a few minutes after touch-down, the payload includes the capability for making *in situ* measurements for a direct characterisation of surface at the landing site. If everything functions nominally, the Probe batteries can supply half-an-hour, or possibly more, of electrical energy for an extended surface science phase that would be a bonus for the mission. The current mission scenario, as shown in Figure 6, foresees the Orbiter listening to the Probe for more than 3 h, which includes at least 30 min on the surface, as the maximum descent time is expected to be $2^{1/2}$ hours. A surface phase of only a few minutes would allow a rapid characterisation of the state and composition of the landing site. An extended surface phase would allow a detailed analysis of the physical and chemical composition of samples of surface material.
5. Titan

5.1. General Characteristics

Titan is the second largest moon of the solar system and it is the only one with a thick atmosphere. The atmosphere was discovered in 1907 by Spanish astronomer José Comas Solà (Comas Solà, 1908), who observed disc edge darkening features and suggested that they were due to an atmosphere, although its existence was not confirmed until 1944, when Gerard Kuiper discovered gaseous methane through spectroscopic observations (Kuiper, 1944). The major constituent is molecular nitrogen. The surface pressure is about 1.5 bar (i.e., 1.5 times the Earth’s). Until the mid-1970s, methane was believed to be the major constituent but the Voyager measurements in November 1980 replaced it with N₂ (Hunten et al., 1984) as was already suspected from models in the late 1970s. The presence of N₂ makes Titan’s atmosphere more like the Earth’s than any other solar system body. However, it is much colder: the surface temperature is 94 K and the temperature of the tropopause, at an altitude around 45 km, is about 70 K. Other major constituents are CH₄ (a few %) and H₂ (0.2%). It is speculated that argon could also be present in quantities ≤6% (Courtin et al., 1995). The presence of nitrogen and methane makes Titan’s atmosphere most interesting to explore.

The photo-dissociation of CH₄ and N₂ in Titan’s atmosphere, driven by solar UV radiation, cosmic rays and precipitating energetic magnetospheric particles, gives rise to a complex organic chemistry. Titan orbits Saturn at 20.3 Rₛ, which occasionally brings it outside the large Kronian magnetosphere when solar wind pressure pushes the magnetopause inside Titan’s orbit. Most of the time, however, Titan is inside Saturn’s magnetosphere, which underlines the importance of the energetic electrons as an energy source for its upper-atmosphere photochemistry. As a result of this complex photochemistry, the atmosphere also contains ethane, acetylene and more complex hydrocarbon molecules. Chemical reactions in the continuously evolving atmosphere provide possible analogues for the prebiotic chemistry that was at work within the atmosphere of the primitive Earth about 3.8 billion years ago, before the beginning of life. Titan’s atmosphere is too cold for life to evolve in it, but the mission does offer the unique opportunity to study prebiotic chemistry on a planetary scale (Owen et al., 1997).

Voyager cameras could not see Titan’s surface through the hazy, opaque atmosphere in the visible wavelength range. Despite the availability of low-resolution maps obtained by the Hubble space Telescope (Smith et al., 1996), and subsequently by ground-based observations using advanced adaptive optics (Combes et al., 1997, Coustenis et al., 2001), the nature of the surface remains largely unknown. Like Earth, it could be partially covered by lakes or even oceans, but in this case a mixture of liquid methane and ethane. However, it may be a dry surface, with underground liquid methane reservoirs continuously re-supplying the atmosphere’s gaseous methane.
Figure 7. Cross section of the Titan low stratosphere and the thermosphere illustrating the various processes that may be at work in the atmosphere and on the surface.

The processes that are believed to be at work in the atmosphere of Titan and on its surface are illustrated in Figure 7.

5.2. PHYSICAL PROPERTIES OF TITAN

Physical properties of Titan are listed in Table II.

5.3. TITAN ENGINEERING MODELS

The design of the Huygens Probe mission required the establishment of several Titan ‘Engineering models’ that provided a sound engineering basis for various
trade-off and performance calculation studies during the Probe development. These models were worked thanks to a close working relationship between the Huygens scientists who provided the knowledge (and the speculations) and the Huygens engineering team which provided the engineering wisdom (and the necessary engineering conservatism) which undoubtedly led to a robust Probe design in many areas. The engineering models are all documented in ESA SP 1177. They are briefly described below.

5.3.1. The Titan Atmosphere Thermal Profile
Several major design features of the Huygens Probe (in particular the heat shield and the 3-parachute descent subsystem) required the establishment of a reliable model capable of predicting the state of the atmosphere of Titan at the time of the Probe mission. The most important regions relevant to the Probe design are the altitude range below about 500 km where the Probe peak deceleration takes place and the region below 200-180 km down to the surface, where the parachutes are deployed. Such an 'engineering' model of Titan’s atmosphere was established in 1986 (Lellouch and Hunten, 1987, Lellouch and Hunten, 1997) during the Phase-A study (Figure 8). The model is based on a careful re-analysis of the radio occultation data and the infrared measurements that constrained the lower atmosphere profile (below 200 km) and the UV measurements at ~1400 km above the surface. Seasonal variations were taken into account to provide an envelope of the possible atmosphere profiles from an altitude of 1270 km down to the surface. The large uncertainties that were built in the Lellouch-Hunten model in the upper troposphere were further constrained by a new ‘engineering’ model that was established in 1994 (Yelle, 1994; Yelle et al., 1997), especially in an attempt to provide a more realistic thermal profile of the upper atmosphere in the altitude range of prime interest for constraining the lowest safe altitude for the Orbiter flyby (950 km)
prior to obtaining new in situ measurements that will be collected by the Orbiter during the first few Titan flybys. The analysis of the Probe entry trajectory may also provide new constraints in the density profile of Titan’s atmosphere in the altitude range below 600–700 but possibly at higher altitude depending upon the complexity of the dynamics of the Probe during entry.

5.3.2. Upper Atmosphere Composition
The possible presence of argon in Titan’s atmosphere has been a major design constraint for the heat shield, as the presence of argon, a chemically inert gas, would significantly contribute to an increase of the radiative heat flux during the entry (Huygens technical report (1992), unpublished). The heat shield was designed to be compatible with the maximum argon content put forward by the Lellouch-Hunten model (21%). The upper limit was subsequently reduced to 14% and 10% (Strobel et al., 1992, Strobel et al., 1993) and then to 6% (Courtin et al., 1995) to the growing satisfaction of the designers of the Huygens heat shield as its performance margin increased as the argon abundance decreased.

Figure 8. Titan atmosphere models (Lellouch-Hunten: LH and Yelle: Ye) used as the engineering models for designing the heat shield and the parachutes. The models comprise three profiles taking into account all uncertainties in the thermal profile.
5.3.3. Wind Model
The presence of zonal wind will affect the parachute descent trajectory. In the original mission scenario (Lebreton and Matson, 1997), a proper estimation of the zonal wind was of paramount importance for designing the Probe-to-Orbiter radio relay link geometry, and for specifying the pointing of the Orbiter receiving antenna during the Probe descent. In the revised mission scenario, the wind effects are less important. The adopted wind model was derived from an analysis of the latitudinal thermal gradients measured by Voyager (Flasar et al., 1981; Flasar et al., 1997). This model provides the amplitude of the zonal wind versus altitude, but it does not predict whether the wind blows West-to-East or East-to-West. The landing site may be displaced by up to several hundreds km in longitude due to the winds (Bird et al., 1997, Flasar et al., 1997, Kazeminejad et al., 2002), which contributes a large fraction of the dispersion in the landing ellipse. Because the Orbiter never gets closer than 60,000 km to Titan, the effect is more the limitation of the beam pattern of the transmitting antenna rather than any HGA mis-pointing. This is illustrated in Figure 6, which shows the link geometry and the uncertainties associated to Probe drift or HGA mis-pointing. Although there is growing evidence that the wind may be prograde (Kostiuk et al., 2001), for the purpose of mission design, it is still assumed that there is equal probability that the wind may be either prograde (wind blowing from West-to-East) or retrograde (East-to-West). The wind models and their effect on the probe trajectory are being re-assessed as part of the optimisation studies of the revised mission scenario (Kazeminejad et al., 2002).

Ground-based observers are setting up several observation programmes that are aimed at improving our knowledge of Titan’s winds before the Probe mission. The Cassini/Huygens science team is also exploring the capabilities of the Orbiter payload to provide a reliable wind measurement before the Probe mission.

5.3.4. The Lightning and Triboelectric Charging Hazard Model
Lightning is thought to be a common phenomenon in planetary atmospheres. On Earth, lightning occasionally presents a danger to aircraft. Although there is no evidence of lightning activity on Titan, the probability of lightning occurring in the atmosphere of Titan has been estimated and taken into account for the design of the Probe. Using conservative assumptions based on a scaled Earth-like lightning strike model, it has been established that the probability of a lightning strike with energy of $10^6$ J during the Huygens descent is $<1\%$ (Lorenz, 1997; Grard, 1997). Protection against lightning strikes of this size has been designed into the Huygens Probe (McCarthy and Hassan, 1996, McCarthy et al., 1997).

5.3.5. Wind-Gust Model
The presence of a wind gust during the descent under parachute would trigger an oscillatory pendulum movement in the probe-parachute system. Excessive pendulum motion would interrupt the radio-link between the Probe and the Orbiter. A wind-gust model based on a scaled Earth model was constructed by the Huygens
prime industrial contractor. It provided an engineering input to assess the stability of the parachute during the descent and to take into account the parachute maximum swing angle for the radio relay link calculations. Furthermore the parachute has been designed to provide effective damping should an oscillation be triggered. Under the assumed wind-gust conditions, the oscillation damping would occur in less than 4 s. A 6-sec buffer has been included in one of the two redundant data channels to minimize the effect of a data transmission interruption due to a gust of wind (Clausen et al., 2002).

5.3.6. Gravity-Wave and Wind-Shear Models
An upper limit for vertical shear in horizontal winds has been derived from the critical Richardson number criterion. A maximum temperature perturbation expected from the Yelle engineering model atmospheres (Yelle et al., 1997) has been estimated from linear saturation theory of gravity waves by Strobel and Sicardy (1997). Those models provided a sound engineering basis for studying the probe stability under parachute descent. They will be later used to derive the sensitivity of the HASI accelerometer to density fluctuations during the entry and descent (Ferri, private communication, 1998).

5.3.7. The Moist-Convection Model
Icing could occur if Huygens should traverse a moist convective cloud, as it does for an aircraft in the Earth’s atmosphere. For estimating the amount of methane ice that could deposit on the front of the Probe, a model that predicts the occurrence and properties of moist convective clouds in the troposphere of Titan has been established (Lunine and Awal, 1997). The model predicts that upward velocities of the order of 10 m/s are possible in plumes up to altitudes of roughly 30 km. However, based on the available convective flux, such ‘methane-nitrogen’ thunderstorms must be rare in Titan’s atmosphere. Taking this model into consideration, it was concluded that the Probe icing was of little concern for the design of Huygens. However, the risk of icing was taken into consideration for the placement of the radar altimeter antennae which were originally located on the Probe foredome; they are now mounted on the periphery of the Probe (see Section 8) so that they will not be exposed to the main gas flow stream during the descent.

5.3.8. Surface Radar Reflectivity
In order to help the designers of the Huygens Probe radar altimeter, a model has been established for the plausible range of radar reflectivities that might be expected on Titan’s surface, in particular in the working wavelength range of the Huygens radar (~2 cm). The parameter of interest is the specific back-scatter cross-section at normal incidence. The proposed model yields a range of 0.1 to 100 for back-scatter cross section averaged over the altimeter beam pattern (Kirk and Lunine, 1997).
5.3.9. *S-band Signal Attenuation in Titan’s Atmosphere*

The two redundant Probe data streams are transmitted to the Orbiter over 2 separate S-band radio channels. Bird (1997) established that the attenuation of S-band radio signals in Titan’s atmosphere was expected to be negligible (~0.02 dB at Probe touch down). The same attenuation calculations have been applied to the ~15 GHz signal of the radar altimeter and it was found that the maximum two-way vertical attenuation would not exceed 0.3 dB.

6. **The Huygens Payload**

The Huygens payload consists of six instruments provided by Principal Investigators. The main characteristics of the payload are listed in Table III, and the payload engineering parameters are provided in Table IV. A brief description of each instrument is given below; more detailed descriptions are in the individual instrument papers in this volume.

6.1. **The Gas Chromatograph and Mass Spectrometer (GCMS),**

(Niemann et al., 1997, Niemann et al., 2002)

The Gas Chromatograph Mass Spectrometer (GCMS) is designed to measure the chemical composition of Titan’s atmosphere from 170 km altitude (~0.1 mbar) to the surface (~1500 mbar) and determine the isotope ratios of the major gaseous constituents. GCMS will also analyse gas samples from the Aerosol Collector and Pyrolyzer (ACP) and will investigate the composition (including isotopic ratios) of several candidate surface materials.

GCMS is a quadrupole mass spectrometer analyser with a secondary electron multiplier detection system and a gas sampling system that provides continuous direct atmospheric composition measurements and batch sampling through three gas chromatograph (GC) columns. The mass spectrometer employs five ion sources that sequentially feed the mass analyser. Three ion sources serve as detectors for the GC columns and two are dedicated to direct atmosphere sampling and gas sampling for the ACP respectively. The instrument is also equipped with a chemical scrubber cell to prepare samples for noble gas analysis, and a sample enrichment cell for selective measurement of high boiling-point carbon-containing constituents. Its mass range is 2–141 amu and the nominal detection threshold is for a mixing ratio of 10^-8.

GCMS has also the capability, thanks to its heated inlet, to determine the chemical composition of a vaporised surface material sample in the event that landing allows the collection and transmission of data for several minutes from the surface.


<table>
<thead>
<tr>
<th>Instruments</th>
<th>Participating countries</th>
<th>Measurements</th>
<th>Techniques</th>
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</thead>
<tbody>
<tr>
<td>Huygens Atmospheric Structure Instrument (HASI)</td>
<td>It., Aust., Ger., Fin., Fr., Nor., Sp., U.S.A., U.K., ESA/SSD</td>
<td>Temperature: 50–300 K. Pressure: 0–2000 mbar Gravity: 1 μg–20 mg AC E-field: 0–10 kHz, 80 dB at 2 μV m⁻¹ Hz⁻⁰·⁵ DC E-field: 50 dB at 40 mV/m Electrical conductivity: 10⁻¹⁵ Ω/m to 10⁻⁶ Ω/m</td>
<td>Direct measurements of the atmosphere physical and electrical properties. Probing of the surface electrical properties.</td>
</tr>
<tr>
<td>Gas Chromatograph and Mass Spectrometer (GCMS)</td>
<td>U.S.A., Aust., Fr.</td>
<td>Mass Range: 2–146 dalton Dynamic range: &gt;10⁸ Sensitivity: 10⁻¹² mixing ratio Mass resolution: 10⁻⁶ at 60 dalton</td>
<td>Chromatography and mass spectrometry: 3 parallel chromatographic columns; quadrupole mass filter; 5 electron impact sources</td>
</tr>
<tr>
<td>Aerosol Collector and Pyrolyzer (ACP)</td>
<td>Fr., Aust., U.S.A.</td>
<td>2 samples: 150–45 km, 22–15 km altitude</td>
<td>3 step pyrolysis: ambient (~0°C), 250 °C, 600 °C</td>
</tr>
<tr>
<td>Descent Imager and Spectral Radiometer (DISR)</td>
<td>U.S.A., Ger., Fr.</td>
<td>Upward and down-ward violet photometer, visible (480–960 nm) and IR (0.87–1.7 μm) spectrometers. Down-ward and side-looking imagers: 0.66–1 μm: solar aureole photometer, 550 nm, 939 nm; surface spectral reflectance</td>
<td>Spectrophotometry; imaging; photometry, solar sensor; surface illumination by lamp</td>
</tr>
</tbody>
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### TABLE III
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<thead>
<tr>
<th>Instruments</th>
<th>Participating countries</th>
<th>Measurements</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Wind Experiment (DWE)</td>
<td>Ger., It., U.S.A.</td>
<td>(Allan Variance)(^{1/2} \times 10^{-11}), ((in 1 \text{ s})), (5 \times 10^{-12}) ((in 10 \text{ s})), (10^{-12}) ((in 100 \text{ s})), corresponding to wind velocities of (2 \text{ m/s}) to (200 \text{ m/s}); signal attenuation; probe spin</td>
<td>Doppler shift of Huygens telemetry signal, signal attenuation; spin signal modulation</td>
</tr>
<tr>
<td>M.K. Bird, University of Bonn (D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Science U.K., It., Package (SSP) U.S.A., J.C. Zarnecki ESA/SSD University of Kent Canterbury (UK)</td>
<td></td>
<td>Gravity: (0\text{–}100 \text{ g.}), Tilt: (\pm 60^\circ)</td>
<td>Simple laboratory-type measurements: impact acceleration; acoustic sounding; liquid relative permittivity; density and index of refraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature: 65–100 K.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal conductivity: 0–400 mW m(^{-1}) K(^{-1}).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Speed of sounds: 150–2000 m/s.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid density: 400–700 kg m(^{-3}).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Refractive index: 1.25–1.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acoustic sounder: 0–500 m</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE IV
Main engineering parameters of the Huygens payload

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mass (kg)</th>
<th>Power typical peak (Wh)</th>
<th>Energy (during descent) (Wh)</th>
<th>Typical data rate (bit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HASI</td>
<td>6.3</td>
<td>15/85</td>
<td>38</td>
<td>896</td>
</tr>
<tr>
<td>GCMS</td>
<td>17.3</td>
<td>28/79</td>
<td>115</td>
<td>960</td>
</tr>
<tr>
<td>ACP</td>
<td>6.3</td>
<td>3/85</td>
<td>78</td>
<td>128</td>
</tr>
<tr>
<td>DISR</td>
<td>8.1</td>
<td>13/70</td>
<td>42</td>
<td>4800</td>
</tr>
<tr>
<td>DWE</td>
<td>1.9</td>
<td>10/18</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>SSP</td>
<td>3.9</td>
<td>10/11</td>
<td>30</td>
<td>704</td>
</tr>
</tbody>
</table>

6.2. THE AEROSOL COLLECTOR AND PYROLYSER (ACP), (Israel et al., 1997, Israel et al., 2002)

ACP is designed to collect aerosols which the GCMS analyses for their chemical composition. It is equipped with a deployable sampling device that will be operated twice during the descent in order to collect an aerosol sample in two different altitude ranges: the first sample from the top of the atmosphere down to about 40 km,
and the second sample in the cloud layer from about 23 km down to 17 km. After extension of the sampling device, a pump draws the atmosphere and its aerosols through a filter in order to capture the collected aerosols. At the end of each collection period, the filter is retracted into a pyrolysis furnace where the effluent from the captured aerosols is analysed, first at ambient (≈0°C) temperature, subsequently heated to 250°C and then to 600°C in order to conduct a step-wise pyrolysis. The volatiles vaporise first at the lowest temperature. The more complex less volatile organic material, and finally higher-temperature organics in the particles are pyrolysed, leaving only more refractory material if any. The pyrolysed products are flushed into GCMS for analysis, thereby providing spectra for each analysis step.

6.3. THE DESCENT IMAGER/SPECTRAL RADIOMETER (DISR), (Tomasko et al., 1997, Tomasko et al., 2002)

The Descent Imager/Spectral Radiometer (DISR) is the optical remote-sensing instrument aboard Huygens. It comprises a set of upward and downward looking photometers, visible and IR spectrometers, a solar aureole sensor, a side-looking imager, and two down-looking imagers: a medium-resolution and a high-resolution imager. It also is equipped with a Sun sensor that will measure the Probe spin rate.

DISR makes measurements in the range 0.3 to 1.7 μm. The scientific objectives of DISR are to study:
- The thermal balance and dynamics of the atmosphere of Titan
- The distribution and properties of aerosol and cloud particles
- The nature of the surface
- The composition of the atmosphere.

This broad range of scientific objectives is achieved by measuring the brightness of sunlight in Titan’s atmosphere with three different fields of views, in several directions and at various spectral resolutions. DISR measures the solar radiation using silicon photodiodes, a 2D silicon charge-coupled-device (CCD) detector and two InGaAs near-IR linear array detectors. The sensor head is mounted on the outer rim of the Probe, on the equatorial platform. A set of optical fibres feed light collected by the foreoptics from different directions and in different spectral regions to the various detectors.

Small vanes have been placed on the foredome of the Probe to allow it to spin in a controlled manner during the descent. This rotation allows the imagers to build-up 360-degrees panoramic pictures. By recording several panoramas during the last part of the descent, it may be possible to infer the Probe’s drift (if surface features are seen), hence to derive the wind.

Titan is about 10 AU’s from the Sun. That means that the amount of sunlight striking the upper atmosphere is 1/100th of that at Earth. Atmospheric absorption and scattering further reduces the light level at Titan’s surface by about a factor of 10. A useful comparison is that Titan’s surface illumination during day-time is about 350 times that of night-time on Earth with a Full Moon. While the surface
illumination is adequate for imaging, DISR will turn on a lamp a few hundred metres above the surface to provide enough light in the methane absorption bands for spectral reflectance measurements. These measurements will provide unique information for studying the composition of the surface material.

Evaluation of the gas flow around the descent module during the 1 min time gap between the back cover separation and the heat shield release showed there was a small risk of contaminating DISR’s optical windows. In order to prevent contamination of the DISR optics, a protective cover was added to the sensor head. It will be ejected shortly after the heat shield is released. Should its release mechanism fail, the cover is provided with optical windows that would still allow measurements with it in place, although with some loss in quality.

6.4. THE HUYGENS ATMOSPHERE STRUCTURE INSTRUMENT (HASI),
(Fulchignoni et al., 1997, Fulchignoni et al., 2002)

HASI is also a multi-sensor instrument. It is intended to measure the atmosphere’s physical properties, including its electrical properties. Its set of sensors consists of a 3-axis accelerometer, a redundant set of a coarse and a fine temperature sensor, a multi-range pressure sensor, a microphone, and an electric field sensor array. The set of accelerometers is specifically optimised to measure entry deceleration for the purpose of inferring the atmosphere structure during the entry.

The electric field sensor consists of a relaxation probe to measure the atmosphere’s ionic conductivity and a quadrupolar array of electrodes for measuring the permittivity of both the atmosphere and of the surface material. In the active mode, it uses the mutual-impedance probe technique for permittivity measurements. In the passive mode, two electrodes of the quadrupolar array are also used as an electric antenna to detect atmospheric electromagnetic waves, such as those produced by lightning.

Several of HASI’s sensors require accommodation on booms. The temperature and pressure sensors are mounted on a 15-cm long fixed stub, which is long enough to protrude into the free gas flow. The electrical sensors are mounted on a pair of 60-cm long deployable booms in order to minimise the shielding effects of the Probe body. The capability for processing the radar altimeter surface-reflected signal (the altitude sensor is provided as part of the Probe engineering system, as described later), was added to HASI late in the programme. This additional function allows it to return information about the surface topography and radar properties below the Probe along its descent track.

6.5. THE DOPPLER WIND EXPERIMENT (DWE), (Bird et al., 1997, Bird et al., 2002)

The primary scientific objective of the Doppler Wind Experiment is to determine the direction and strength of Titan’s zonal winds. A height profile of wind velocity will be derived from the residual Doppler shift of the Probe’s radio relay signal as
received by the Cassini Saturn Orbiter. This will be corrected for all known Probe and Orbiter motion and signal propagation effects. Wind-induced motion of the Probe will be measured to a precision better than 1 m/s starting from parachute deployment at an altitude of \( \sim 165 \) km down to the surface. As secondary objectives, this investigation is also capable of providing valuable information on Probe dynamics (e.g., spin rate and spin phase) during the atmospheric descent, as well as the Probe’s location and orientation up to and after impact on Titan’s surface.

DWE uses one of the two redundant chains of the Probe-Orbiter radio link (Jones and Giovanoli, 1997, Clausen et al., 2002). It required the addition of two ultra-stable oscillators (USOs) to one of the two channels of the Probe data relay subsystem. The Probe transmitter USO (TUSO) provides a stable carrier frequency for the Probe-to-Orbiter radio link; the Receiver USO (RUSO) aboard the Orbiter provides an accurate reference signal for the on-board Doppler processing of the received carrier signal. The Probe’s drift with the wind will induce a measurable Doppler shift in the carrier signal. The wind-induced Doppler shift will add to the other deterministic frequency shifts that are induced in the signal. The strongest source of Doppler is due to the Orbiter-Probe range variation.

The radio relay link channel that is provided with the TUSO and the RUSO is also equipped with the same standard oscillators that equip the other radio relay link channel. It provides an alternative configuration if the performance of either the TUSO or the RUSO would have degraded during the 7-year cruise. Selecting between the DWE USOs (the default configuration) and the standard oscillators will be done during the Probe configuration activity before its release from the Orbiter.

6.6. THE SURFACE SCIENCE PACKAGE (SSP), (Zarnecki et al., 1997, Zarnecki et al., 2002)

SSP consists of a suite of laboratory-type sensors for determining the physical properties of the surface at the impact site and for providing information on the composition of the surface material. SSP includes a force transducer for measuring the impact deceleration, and sensors to measure the index of refraction, temperature, thermal conductivity, heat capacity, speed of sound and dielectric constant of the (liquid) material at the impact site. The SSP also includes an acoustic sounder that is turned on a few hundred metres above the surface for sounding the atmosphere’s bottom layer and the surface’s physical characteristics before impact. If Huygens lands in a liquid, the acoustic sounder will be used in a sonar mode to probe the liquid depth. A tilt sensor is included to indicate the Probe’s attitude after impact. Although SSP’s objectives are mainly to investigate the surface, several sensors will contribute significantly to the studies of atmospheric properties during the whole descent phase.
7. The Huygens Mission Profile

In the original mission profile, the Probe mission was planned to be carried out during the first Titan flyby in November 2004 (Lebreton and Matson, 1997). Following the discovery of an anomaly in the Huygens telecommunication system a recovery mission scenario was implemented (Clausen et al., 2002); see also section 10. The Probe mission will be carried out during the third targeted Titan encounter after Saturn Orbit Insertion. Thus, there are several opportunities for observing Titan from close range before the Probe mission. The Probe landing site will be observable from close range on both the first and the second flybys. Although it is not anticipated that the new knowledge about the Titan environment gained prior to the Probe mission will be used to adjust the Probe mission parameters, those observations will help to see the Huygens observations in their global context. The last significant Probe activity before Probe separation will be the loading of the on-board timers that will wake-up the Probe’s computers at a pre-determined time prior to entry into Titan’s atmosphere. Before Probe release, the composite Orbiter/Probe is placed on a trajectory that intercepts Titan. The Probe has no manoeuvring capability itself. It will be released at a pre-determined time. This activity will take place without radio contact with the Earth because the Cassini/Huygens orientation required for Probe release is not compatible with maintaining a link with the Earth. The Probe will separate from the Orbiter at a relative velocity of 30 cm/s and with a spin rate of 7 rpm for stability during the 22-day coast and the entry. Five days after Probe release, the Orbiter will perform a deflection manoeuvre, so as not to enter the atmosphere of Titan itself. This manoeuvre will also place the Orbiter on a trajectory above Titan that will provide the required geometry for communication during the Probe mission.

The 2.75 m diameter heat shield and the back cover will protect the enclosed descent module from the expected radiative and convective heat-fluxes generated during the entry. The peak heat-flux is expected in the altitude range below 350 km down to 220 km, where Huygens decelerates from about 6 km/s to 400 m/s (Mach 1.5) in less than 2 min. The detection of the entry deceleration peak will be used to reset the starting time of the pre-programmed descent sequence. At Mach 1.5, the parachute deployment sequence will be initiated. It starts with the firing of a pyrotechnic device that deploys the 2.59 m diameter pilot chute which, in turn, pulls away the aft cover and deploys the main chute. After inflation of the 8.3 m diameter main parachute, the front heat shield is released so that it falls away from the Descent Module. Then, there is a 30 s delay to ensure that the shield is sufficiently far away to avoid instrument contamination. Now the GCMS and ACP inlet ports open and the HASI booms deploy. The DISR cover is ejected 2 min later. The main parachute is sized to pull the Descent Module safely out of the front shield. After 15 min, it is jettisoned to avoid a protracted descent, and a smaller, 3.03 m diameter parachute is deployed. The descent will last between 2 and 2 1/2 hours.
The major events of the entry and descent sequence are illustrated in Figure 9. The predicted altitude profile range is shown in Figure 10, where the middle curve indicates the nominal profiles and the two other curves define its envelope, taking into account the Lellouch-Hunten atmospheric model and the descent calculation uncertainties. After Huygens separates from the Orbiter, its electrical power comes from five primary batteries that have a total capacity of at least 1800 Wh. The battery capacity has been sized for a mission duration of 153 min, corresponding to a maximum descent time of $2\frac{1}{2}$ h plus at least 3 min on the surface. However, the batteries and all other resources are sized with a comfortable margin. The mission can still be fully carried out if one battery should fail. Margin has also been included for battery capacity losses which depend mainly upon the temperature history of the battery cells.

Huygens transmits its data on two channels at a constant 8 kbit/s to the overflying Orbiter. Cassini points its HGA to a predefined location on Titan’s rotating surface, nominally for a full 3 h period to allow for data reception after landing. Data from the surface could last for 43 min for a nominal descent time of 137 min. The Probe data are stored on-board the Orbiter in its two solid-state recorders for later transmission to Earth. This is done soon after after Huygens has completed its mission.
Figure 10. Range of altitude profile as calculated using the three atmosphere profiles of the Lellouch-Hunten model.

8. Payload Accommodation

8.1. MECHANICAL ACCOMMODATION

The Huygens payload is accommodated on the ‘payload platform’ as shown in Figure 11. The overall accommodation of the payload sensors that require direct access to Titan’s atmosphere is illustrated in Figure 12.

ACP and GCMS are both single-box instruments with their inlet ports near the Probe apex to allow for direct access to the atmosphere. Each instrument has an exhaust tube projecting through the top platform. ACP and GCMS are linked by a temperature-controlled gas conduit to transfer ACP pyrolized products to GCMS for analysis. The electronic units of the two instruments are connected through a dedicated serial link that will allow their synchronised operation.

The DISR sensor head is mounted on the platform’s periphery to accommodate its fields of view and scanning requirements. Cooling of the IR detector will be provided by the convective flow of gas around the sensor head and a thermally conducting strap attached to the external structure of the Probe which is expected to be near atmospheric temperature. The electronics assembly is mounted on the platform’s interior. The DISR sensor head is enclosed under a protective cover. The cover will be ejected within 2 min after heat shield release.
In the entry configuration, the HASI accelerometers are located near the Probe’s centre of gravity, in order to provide the best sensitivity for measuring the Probe dynamics during entry. The HASI pressure and temperature sensors are mounted on a fixed stub; the electrical sensors are mounted on two deployable booms. One of HASI’s sensor is a microphone; it has been installed on the outer periphery of the Descent Module, such that it is protected from direct aerodynamic flow. All HASI sensors are connected to a central electronics box, which contains the signal-conditioning pre-amplifiers and the data processing functions. The electric
antenna pre-amplifiers are housed in two small boxes located as close as possible to the sensors inside the Descent Module, in order to minimise the length of the connecting cable.

SSP consists of two boxes: the ‘Top Hat’ structure that accommodates all but two of the sensors, and an electronics box. The ‘Top Hat’ is mounted below the platform, allowing for sensor wetting in case of landing in a liquid. It is connected to the SSP electronics (on the top of the platform) via a harness through the platform. The ‘Top Hat’ is also instrumented with a pylon designed for effective transmission of the impact deceleration to the force transducer on the platform. Two sensors are directly mounted on the electronics box: the tilt meter and an accelerometer.

DWE’s TUSO is also accommodated on the experiment platform, while RUSO is accommodated in the part of Huygens that remains attached to the Orbiter (Probe Support equipment, PSE) which houses the radio receivers.

8.2. PROBE SPIN REQUIREMENTS

Huygens spins during the descent to provide the azimuth coverage needed by several sensors. The spin information is used in real-time by DISR especially for the final part of the descent for optimising the imaging the surface. This mode of operation allows DISR to adapt the timing of consecutive frames during the mosaic image-taking cycle. The spin is induced by a set of 36 vanes mounted on the bottom
part of the foredome (Figure 12). The spin rate is measured by accelerometers covering the range 0–15 rpm with an accuracy of 0.1 rpm. The expected spin profile is shown in Figure 13.

8.3. PROBE ALTITUDE MEASUREMENTS

During the early descent, instrument operations are run by a timer based on the Probe clock. The descent timer is initialised at the end of the entry. However, to guarantee maximising scientific return, operations in the last part of the descent are based on the measured altitude above the surface rather than time. Furthermore, as

Figure 13. Spin profile envelope prediction during the descent. The different curves correspond to different friction coefficient assumed in the bearing of the device (swivel) that decouples the parachute rotation from that of the probe.
impact survival is not guaranteed by the Probe’s design, maximum scientific return can be achieved from the last few kilometres of the descent and possibly for the crucial first few seconds after impact if the altitude is reliably known on-board the Probe. In order to satisfy these requirements, the Probe’s altitude is measured below $\sim 25$ km by a set of two radar altimeters operating in the Ku-band (15.4 GHz and 15.8 GHz). The altitude measurements are processed by an algorithm in the Probe’s central computer. A default time-based altitude table remains as a back-up in case of a temporary loss of radar lock, e.g. one caused by a higher-than-nominal pendulum motion.

8.4. THE DESCENT DATA BROADCAST (DDB) PULSE

Several key housekeeping parameters are generated by the Probe on-board computers and distributed to all payload instruments. The Probe time, the measured spin and the altitude are broadcasted every 2 s to all experiments for their use during descent. The DDB altitude information is used by DISR, HASI and SSP to optimise their measurement cycles.

8.5. PROBE TARGETING REQUIREMENTS

Targeting requirements come from the needs of the payload and aspects of system design, such as the telecommunications geometry and the design of the heat shield ablative material, which are affected by the location of the entry point. DISR imposes requirements on the Sun Zenith Angle (SZA), which should lie within 35–65°, taking into account a 10° margin to encompass uncertainties about pendulum motion under parachute. The descent should occur over Titan’s sunlit hemisphere to satisfy the lighting requirements for the imagers and the spectrometers. DWE requires maximisation of the zonal wind component along the Probe-Orbiter line of sight. The heat-shield is designed for an entry angle range between 60 and 68°. All considered, a nominal entry angle of $-64°$ was selected. The Probe mission geometry is illustrated in Figure 14. The nominal landing, excluding all dispersions, will occur at latitude 10.7 S and longitude 160 E. The two ellipses include the dispersion if winds are assumed. Figure 15 shows the predicted landing spot on an image obtained by the Hubble Space Telescope (Smith et al., 1996). Huygens will land westward of the bright feature visible in all surface images. The variations of the parameters during the descent most relevant to the payload are illustrated in Figure 16.

8.6. ENTRY MEASUREMENTS

HASI is the only instrument that performs scientific measurements during the atmospheric entry. The Probe-to-Orbiter radio link will only be established a few minutes after main parachute deployment and heat-shield separation. The HASI
9. Flight Operations

Huygens operates autonomously after separation from the Orbiter (Sollazzo et al., 1997). The radio link to the Orbiter is one-way, telemetry only. Huygens will make no scientific measurements before arrival at Titan. It is nominally switched off during the cruise. Telecommands can be sent independently to the Probe itself, when still attached to the Orbiter, or to the Huygens Probe Support Avionics that remains attached to the Orbiter after Probe separation. Probe telecommands are sent via an umbilical (which also provides electrical power to the Probe). Telecommands are used during biannual Probe checkout sequences for exercising health monitoring functions, for performing the maintenance of payload mechanical devices, and for specific instrument calibration activities. After separation from the Orbiter, during the 22-day coast, only a triply-redundant timer will be operating. It will wake-up Huygens shortly before the predicted entry into Titan’s atmosphere. The loading of the value of the timer’s duration and the chemical activation of the batteries entry data, the Probe system data acquired during Probe switch on, and all housekeeping data acquired by the other instruments that are switched on prior to entry, will be buffered. They will be interleaved with the real time data packets that will be transmitted after the link is established.
Figure 15. Huygens landing site uncertainty ellipse (bottom left) superposed on the Hubble image of the surface of Titan (Smith et al., 1996). The upper right ellipse shows the landing site before probe mission modification.

that power the Probe after separation will be the last activities initiated by ground command. The revised mission requires the Probe Support Avionics equipment to receive continuously telecommands to maintain the radio receivers in a non-Doppler mode as during a Probe checkout, because the reduced Doppler is no more compatible with the default Doppler mode.

Probe operations and the analysis and distribution of the telemetered data are controlled from a dedicated control room, known as the Huygens Probe Operations Centre (HPOC), at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. Here, command sequences are generated and transferred by
Figure 16. Evolution of the main mission parameters during the Probe descent.

dedicated communication lines to the Cassini Mission Support Area at the Jet Propulsion Laboratory (JPL), Pasadena, California. There, the Probe sequences are merged with commands to be sent to other subsystems and instruments of the Orbiter for uplink via NASA’s Deep Space Network (DSN). Probe telecommands are stored by the Orbiter and forwarded to the Probe Support Equipment (PSE) at specified times for immediate execution. As a consequence of the distance between Earth and Saturn (up to 160 min is required for round-trip radio communications), Huygens real time operations were never envisaged.

Data collected by the Probe and passed to the PSE via the umbilical (during the attached phase) or the radio relay link (during the descent phase) are formatted by the PSE and forwarded to the Orbiter’s Command and Data Subsystem (CDS). The Orbiter redundantly stores the Huygens data in its two solid-state recorders for later transmission to DSN ground stations on Earth. From the ground station, the data are forwarded to the Cassini Mission Support Area where Probe data are separated from other Orbiter data before being stored in the Cassini Mission database. Operators in the HPOC access the Cassini database to retrieve Probe data via a Science Operations and Planning Computer.

Subsystem housekeeping data are used by ESOC to monitor Probe performance, while data from the science instruments are extracted for forwarding to the investigator teams. During the cruise, these data are shipped to the scientists’ home
institutes by CD-ROM (the prime medium) and by network data line. After analysing these data, the investigators meet with the operations team to assess the health of the payload and to define the activities for the following checkout period.

The investigators were located at HPOC for the first in-flight checkout activities, 8 days after launch. They will also be located at HPOC for supporting the pre-separation activities and the Probe mission phase. The co-location of the science teams and the flight operations teams will allow to expedite access to the instrument data and will facilitate interaction among the various teams. Accommodation is provided for the computer and data analysis equipment for the science teams to reduce and interpret their data at HPOC. During the Probe mission phase, quick look data plots will be made available within a few hours after data reception at HPOC.

9.1. DATA ANALYSIS AND ARCHIVING

The raw Huygens data will be provided to the Huygens Principal Investigator (PI) teams on CD-ROM after the mission is over. It is the responsibility of each PI team to process the data and to provide a reduced data set for allowing a coordinated analysis of the Huygens data set. The Huygens Science Working Team (HSWT) intends to produce a commonly agreed descent profile within weeks of the event to allow all experimenters to analyse their data and interpret their measurements in an efficient, self-consistent way. A subgroup of the HSWT, the Descent Trajectory Working Group (DTWG), has been set up to plan the data analysis that leads to establishing the Probe’s descent profile in Titan’s atmosphere (D. Atkinson, 1998).

The HSWT manages the overall Huygens science activities. It advised the Huygens Project team on all science-related matters during the Probe’s development. During the cruise, it meets periodically to assess the payload’s performance and to prepare itself for the Huygens mission and data analysis phase. The HSWT played a key role during the Huygens mission recovery studies. It advised the Huygens Mission Team on all science aspects of the scenarios under study. Activities will peak during the Huygens mission phase, as it coordinates the analysis and interpretation of the Probe data. It will also play an important role in planning the post-Huygens mission observations of Titan by the Orbiter, and it will participate in joint Probe/Orbiter investigations data analysis and interpretation studies.

The initial uncertainty ellipse of the Probe’s landing site may be as large as $\pm 10^\circ$ in longitude. The HSWT will work in coordination with the Orbiter teams to reduce the uncertainty of the Probe descent trajectory to allow a proper coordinated analysis of the Probe and Orbiter data sets and to help plan the observations of the Probe landing site by the Orbiter radar and remote sensing instruments after the Probe mission.

The Huygens data set will be archived within the ESA planetary data archive that is being developed to support the archiving of the data expected from the ongoing ESA planetary missions (Rosetta, Mars Express/Beagle-2, SMART-1). The
Huygens data set will form an integral part of the Cassini/Huygens data archive that is being defined by the Cassini Project Office at JPL. This will provide an optimised data set for future synergistic studies using Probe and Orbiter data.

10. Huygens Recovery Mission Design

The Huygens Probe is subjected to two types of in-flights tests during the Cruise (see Figure 3). Bi-annual Probe checkouts are carried out to perform a regular payload maintenance and calibration. Probe checkout sequences mimic as closely as possible the sequence that will run during the descent; however, the Probe-to-Orbiter radio link is simulated through an umbilical. Probe Relay Tests have been designed to execute in-flight end-to-end tests of the receiving functions of the Probe-to-Orbiter telecommunication system. During Probe Relay Test, the Huygens elements that will remain on-board the Orbiter after Probe separation are configured in mission mode. The Probe radio transmission signals are simulated by using a NASA Deep Space Network antenna that sends to Cassini’s HGA a signal like the one the Probe is expected to send during its descent. It was during the first Probe Relay Test, carried out in February 2000, that the Huygens receiver anomaly was discovered (Clausen et al., 2002). The Probe Relay Test results confirmed the expected carrier level performance, and provided a unique opportunity to calibrate the Doppler Wind Experiment, (Bird et al., 2002). However an unexpected behaviour was observed at sub-carrier and data stream level. In particular, the receivers performed nominally at zero Doppler, but showed anomalous behaviour (with loss of data) when simulated mission Doppler (~5.6 km/s) was applied to carrier, sub-carrier and data stream. The investigation studies that were subsequently performed revealed that the bandwidth of the bit synchronizer of the Huygens receiver was too small to accommodate the Doppler shift of the data stream frequency expected during the mission.

A dynamic model of the receiver symbol synchroniser was developed as a function of system-level parameters:

- Link performance in terms of signal-to-noise ratio ($E_b/N_0$)
- Symbol transition probability ($P_t$)
- Doppler Frequency shift, $\Delta F$, due to the relative velocity between Probe-and-Orbiter

The results of the modeling work for channel A are shown in Figure 17. There are small differences between the two channels. The performance of channel B are slightly better than those of channel A.

The signal-to-noise ($E_b/N_0$) can be adjusted by changing the Probe-Orbiter distance. The expected symbol transition probability ($P_t$) in the science data is of the order of 50%, indicating an efficient coding of the data. The probability of symbol transition can be increased by inserting strings of ‘zeros’ in the data streams. This, however, decreases the effective science data return. The Doppler shift ($\Delta F$) can be
Figure 17. Huygens radio receiver dynamic model results. The receiver works properly if the received signal transmitted by the Probe remains in-between the two thick lines. Data losses occurs if the signal falls in the shaded areas.

decreased by modifying the Probe-Orbiter communication geometry. The thermal performance of the clock driving the frequency \( F_0 \) of the transmitted data stream was also characterized. It showed that, by controlling the temperature of the clock, the frequency \( F_0 \) of the data stream could be manipulated favourably so as to decrease the transmitted frequency, which is equivalent to a Doppler shift decrease when the signal is received on-board the Orbiter.

The proposed Huygens mission recovery solution makes use of a combination of variations in the four system parameters listed above (\( E_s/N_0, P_t, \Delta F, F_0 \)). In particular it required a new Orbiter trajectory for the Probe mission that minimized the radial component of the Probe-Orbiter velocity. The Titan flyby altitude was adjusted in combination with the above for allowing the received signals to fall within the range where the receiver performance is acceptable. At the time of writing, we are still investigating whether or not it is technically feasible to adjust the transmitted data stream frequency by pre-heating the Probe before entry. If the received signal falls outside the working range of the receivers, data loss may occur (Clausen et al., 2002). The capability to insert ‘zero’ packets is being built into the Probe on-board computers. Trade-off studies are on-going as to whether the selected recovery mission implementation solution requires making use of this additional feature.
Figure 18. Probe transmitting antenna gain pattern for channel A (left) and channel B (right). The polar plots show the azimuthal gain variation for an elevation angle of 30°.

A baseline reference recovery mission was established in June 2001. A link geometry radically different from the one selected before launch (Lebreton and Matson, 1997) was chosen. During the Probe mission, the Orbiter is now flying on a trajectory parallel to that of the Probe, but at a large distance (Figure 6). At the start of the mission the Doppler effect is reduced to about 2/3 of its value compared to the original mission. At Titan closest approach, the Doppler effect is zero. The Doppler-shift reverses sign after closest approach. So ideally one should have an Orbiter Delay Time (ODT) of 1 1/2 hour such that the 3-hour Probe relay link window is symmetric around closest approach and the Doppler effect is minimum. However, due to Probe Aspect Angle (PAA) constraints the ODT had to be selected to a value of around 2.1 hours. The Probe aspect angle is a very critical parameter because of the Probe antenna gain pattern (Figure 6). Beyond 60° elevation, the gain drops sharply but it remains acceptable up to 80°. The variation of the Probe transmitting antenna gain pattern is shown as function of the elevation angle in
Figure 19. Radio link performance during the mission, assuming the winds are prograde. The black thick line shows the performance limit of the receiver when the data transition is about 50% (same as thick line in Figure 17). The dotted lines above the thick line indicate the performance limit when data packets (1 up to 5 out of 7) of ‘zeros’ are inserted in the transmitted data stream. The shaded region delimits the variation of the signal level expected during the mission, including the modulation induced by Probe spin. At the start of the mission, the signal level varies between about 12–14 dB due to spin and various uncertainties. At the end of the mission, the signal level is expected to vary between 2 and 10 dB also due to spin. The spin variation increases significantly towards the end of the mission as the Probe Aspect Angle increases beyond 60 deg.

Figure 18. In this figure, we also show the spin variation of the antenna gain. When Probe B-plane angle and Orbiter B-plane are identical, the Probe Aspect Angle roughly equals the Probe entry angle. Details are shown in Figure 6. The Probe Aspect Angle is somewhat smaller, because the angle to local vertical is less at touch-down than at entry. During the descent, the Probe aspect angle is increased by the Titan rotation and by prograde winds; it is however decreased by retrograde winds. The expected link performance for the reference recovery mission, which assumes prograde winds, is illustrated in Figure 19. The influence of the wind direction uncertainty is illustrated in Figure 20, which shows the link performance assuming retrograde winds.
Figure 20. Same as Figure 19, but winds are assumed to be retrograde. The higher signal towards the end of the mission is due to the fact that the Probe Aspect Angle does not increase as much as it does when the winds are prograde.

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The Cassini/Huygens mission required the dedication of many individuals to make it happen. It would be impossible to acknowledge in person all our colleagues who contributed to the development of this international mission. The international collaboration has played a key role in the life of the Mission. We deeply acknowledge the three ‘fathers’ of the mission, D. Gautier, W. Ip, and T. Owen who submitted the original idea to ESA and to NASA. We also would like to pay tribute to many colleagues in ESA, NASA/JPL, and in industry who made it happen, despite the slow route it took at times, and allowed it to become a reality in a very inspiring collaboration spirit. Special thanks are expressed to Boris Smeds from ESOC, whose expertise and skills lead us to discover the radio receiver problem and helped to find a solution for it. Ellis Miner provided useful comments on the manuscript. We thank the two referees for the very constructive comments which were very helpful for improving the manuscript.
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TOURING THE SATURNIAN SYSTEM

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Abstract. The Cassini mission to Saturn employs a Saturn orbiter and a Titan probe to conduct an intensive investigation of the Saturnian system. The orbiter flies a series of orbits, incorporating flybys of the Saturnian satellites, called the ‘satellite tour.’ During the tour, the gravitational fields of the satellites (mainly Titan) are used to modify and control the orbit, targeting from one satellite flyby to the next. The tour trajectory must also be designed to maximize opportunities for a diverse set of science observations, subject to mission-imposed constraints. Tour design studies have been conducted for Cassini over a period of several years to identify trades and strategies for achieving these sometimes conflicting goals. Concepts, strategies, and techniques previously developed for the Galileo mission to Jupiter have been modified, and new ones have been developed, to meet the requirements of the Cassini mission. A sample tour is presented illustrating the application of tour design strategies developed for Cassini.

1. Introduction

The successful launch of the Cassini spacecraft on October 15, 1997 has set the stage for a spectacular investigation of the Saturnian system. Cassini will be the first mission to visit Saturn in the more than two decades that will have elapsed since the Voyager flybys in 1980 and 1981.

After its insertion into orbit about Saturn, the Cassini orbiter will conduct a 4-year orbital tour of Saturn, its rings, satellites, and magnetosphere. A large portion of the mission’s scientific objectives are accomplished during this nominal mission, and the design of the tour trajectory is an important factor in achieving these objectives.

The tour contains approximately 45–55 close, ‘targeted’ flybys of Saturnian satellites. A targeted flyby is one where the orbiter’s trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) at closest approach, in order to use the satellite’s gravitational influence to produce a desired change in the trajectory. Most of the targeted satellite flybys in Cassini tours are Titan flybys, for two reasons: first, Titan is the satellite of highest priority for science observations; second, Titan is also the only satellite massive enough to make the large modifications in a spacecraft’s orbit required for orbit control in the tour.
TABLE I
Saturnian satellite data

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Ra (RS)</th>
<th>Rp (RS)</th>
<th>Smaj axis (RS)</th>
<th>Period (days)</th>
<th>Inc. (deg)</th>
<th>Radius (km)</th>
<th>$\mu$ (km$^3$/s$^2$)</th>
<th>Synodic period wrt Titan (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mimas</td>
<td>3.077</td>
<td>3.069</td>
<td>3.08</td>
<td>0.95</td>
<td>0.01</td>
<td>198.80</td>
<td>2.50</td>
<td>1.007</td>
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<td>Enceladus</td>
<td>3.943</td>
<td>3.936</td>
<td>3.95</td>
<td>1.37</td>
<td>0.01</td>
<td>249.10</td>
<td>5.60</td>
<td>1.503</td>
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<tr>
<td>Tethys</td>
<td>4.892</td>
<td>4.882</td>
<td>4.88</td>
<td>1.89</td>
<td>1.09</td>
<td>523.00</td>
<td>44.10</td>
<td>2.141</td>
</tr>
<tr>
<td>Dione</td>
<td>6.263</td>
<td>6.254</td>
<td>6.25</td>
<td>2.73</td>
<td>0.02</td>
<td>560.00</td>
<td>77.30</td>
<td>3.3</td>
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<tr>
<td>Rhea</td>
<td>8.742</td>
<td>8.738</td>
<td>8.75</td>
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<td>0.00</td>
<td>764.00</td>
<td>173.40</td>
<td>6.32</td>
</tr>
<tr>
<td>Titan</td>
<td>20.842</td>
<td>19.679</td>
<td>20.26</td>
<td>15.95</td>
<td>0.36</td>
<td>2575.00</td>
<td>8978.10</td>
<td>(N/A)</td>
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<td>Hyperion</td>
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<td>22.97</td>
<td>24.55</td>
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<td>1.01</td>
<td>141.50</td>
<td>1.00</td>
<td>63.697</td>
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<tr>
<td>Iapetus</td>
<td>60.689</td>
<td>57.412</td>
<td>59.02</td>
<td>79.33</td>
<td>15.42</td>
<td>718.00</td>
<td>116.90</td>
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<td>Phoebe</td>
<td>249.546</td>
<td>179.885</td>
<td>214.66</td>
<td>550.30</td>
<td>152.01</td>
<td>110.00</td>
<td>0.86</td>
<td>16.429</td>
</tr>
</tbody>
</table>

Ra, Rp, Smaj axis: Apoapsis, periapsis, semimajor axis of satellite orbit w.r.t Saturn.
RS = Saturn radii; 1 RS = 60330 km

The Saturnian satellites other than Titan are referred to as the ‘icy satellites’. Observing the icy satellites is an important tour objective. Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, and Iapetus (the most important ones) are within reach of the spacecraft during the tour. Phoebe (which orbits beyond the spacecraft’s apoapsis) will be visible on approach to Saturn before insertion into orbit. Table 1 shows some parameters of interest (including gravitational parameter $\mu$) for Titan and the main icy satellites.

Targeted flybys of Titan are capable of making large changes in the orbiter’s trajectory. A single targeted Titan flyby can change the orbiter’s Saturn-relative velocity by up to 850 m s$^{-1}$. For comparison, the total $\Delta V$ available from the orbiter’s thrusters is about 500 m s$^{-1}$ for the entire tour.

Each targeted flyby is used to target the orbiter to the next flyby. The abundance of aimpoints at each satellite encounter makes possible a large number of tours, each of which may satisfy many of the scientific objectives in different ways. While it is relatively easy to design a tour to satisfy any single scientific requirement, it is difficult to design a single tour which completely fulfills all the requirements, because the trajectories needed to satisfy different scientific requirements are often dissimilar.

Tour design involves maximizing science return in competing scientific areas while satisfying mission-imposed constraints. This is a complex task, as experience in designing satellite tours for the Galileo mission to Jupiter showed. Tour design studies have been conducted for Cassini building on the wealth of experience.
TOURING THE SATURIAN SYSTEM

Figure 1. Initial orbit geometry. The orbiter continues along the tour trajectory after the Huygens probe mission is complete.

gained from Galileo. Trades between areas of scientific interest and methods of meeting constraints are examined here, and a sample tour is presented.

The Cassini spacecraft carries the Huygens atmospheric probe, which is released into the atmosphere of Titan after the sequence of events diagrammed in Figure 1.

Upon arrival at Saturn, a maneuver is performed to slow the spacecraft and insert it into orbit about Saturn. Near the first apoapsis, another maneuver is performed which simultaneously raises the periapsis distance from Saturn and targets the spacecraft to the desired flyby aimpoint at Titan. Closer to Titan, the spacecraft (orbiter and probe) is maneuvered onto a Titan impact trajectory. The orbiter then separates from the probe and performs a maneuver which deflects it away from impact onto the desired flyby trajectory. The probe continues on the impact trajectory, enters the atmosphere, and relays its data through the orbiter to Earth as the orbiter flies overhead. After the probe mission is completed, the orbiter continues on the tour trajectory.

2. Scientific Objectives

The scientific investigations to be performed by the Cassini orbiter can be divided into five areas: Saturn, the rings, the Saturnian magnetosphere, Titan (Saturn’s largest satellite), and the icy satellites (those other than Titan).
2.1. SATURN

Observations of the vertical structure of Saturn’s atmosphere (temperature, composition of major and minor species, distribution of aerosols), cloud features and global dynamics in the Saturnian atmosphere can be made mostly by remote sensing in different wavelength ranges. While radio, submillimeter, and far IR observations of Saturn’s thermal emission can be done everywhere, visible and UV observations of solar reflected radiation can be done only of sunlit portions of Saturn. Observations at solar phase angles of 15 deg or less for periods of 20 h or more (two rotational periods of Saturn) are of particular interest to allow movies of the atmosphere to be made.

Radio science experiments as well as images can shed light on Saturn’s atmosphere. When the orbiter passes behind Saturn as viewed from Earth, radio signals from the orbiter are not instantly cut off. Instead, they are refracted by the dense Saturnian atmosphere on their way to Earth. Because a great deal of information on the atmosphere, ionosphere, and magnetic field may be gleaned by analysis of the refracted polarized signals, passes behind Saturn are desired in the tour. Such passes are called occultations of Earth by Saturn, as viewed from the orbiter.

Improving our knowledge of Saturn’s internal structure is also a major scientific objective of the mission. In addition to the constraints on the internal structure given by atmospheric measurements, key information can be obtained from the determination of the set of moments of the planetary gravity and magnetic fields. To measure these moments, orbits with periapses as low as possible, distributed as evenly as possible in latitude and longitude, are needed.

2.2. RINGS

Passes behind the rings provide the opportunity to use distortions in the radio signal from the orbiter to determine ring composition and particle size. These passes are referred to as ring occultations. One particularly desirable type of ring occultation, shown in Figure 2, occurs when the orbiter passes directly behind the center of the planet (and the rings) from one side to the other with both occultation entry and exit occurring close to Saturn’s equator. This is referred to as an ‘equatorial occultation.’ Several equatorial occultations are desired in the tour. These are crucial for determination of ring properties and are one of the highest science priorities of the mission.

At the beginning of the tour, the ring plane appears tilted about 25 deg as viewed from Earth. The tilt of the Earth decreases monotonically to about 7 deg by the end of mission, meaning that the rings appear much closer to edge-on as viewed from Earth. The quality of the occultation measurements degrades significantly as the ring tilt decreases since differentiation between the rings disappears when the rings are viewed edge-on. Therefore, the equatorial ring occultations are desired as soon as possible during the mission. Additionally, the spacecraft should be as close as possible to Saturn during these occultations to achieve good spatial resolution.
allowing determination of particle sizes in the rings. Stellar occultations are also important for determining ring properties; however, the large number and wide distribution of usable stars is such that including stellar occultations is not a driving factor in the design of the orbital tour trajectory.

Rings are also studied by imaging them at a variety of wavelengths, to analyze sunlight scattered from or transmitted through the rings. For this purpose it is important to cover a range of phase angles as broad as possible. In particular, viewing the rings from above is also important. At Saturnian latitudes of 55 deg or higher, the rings are visible around the entire disk of Saturn. Since maximum latitude is equal to orbital inclination, achieving an inclination of at least 55 deg is a high priority for ring science.

2.3. MAGNETOSPHERIC SCIENCE

Studying the Saturnian magnetosphere and its interaction with Saturn’s upper atmosphere, satellites, rings, and gas and dust tori is a high-priority goal. Saturn’s magnetosphere can be studied by a combination of in-situ characterization of plasma, charged particles, fields and waves, and of remote sensing of Saturn’s auroral, radio and neutral atom emissions. These measurements must cover all main magnetospheric plasma domains as well as their boundaries with the solar wind with a local time and latitude coverage as broad and complete as possible. For this reason, the orbiter must cover as large a region around the planet as possible over as large a range of distances as possible (including a number of high-inclination orbits).

Of particular interest are passages through the Saturnian magnetotail, which streams outward from Saturn in the direction opposite the Sun in a shape roughly resembling a windsock. The region of greatest scientific interest, the plasma sheet where most of the magnetotail plasma resides, lies approximately within 3 Saturn radii (RS) of Saturn’s magnetic equator at distances of 40 RS or greater from Saturn on the nightside. An inclination of a few degrees is required to fly through the center of the magnetotail since the Saturn-Sun line is inclined to the equatorial plane.
As magnetic field lines intersecting Saturn’s auroral region are the seat of the acceleration of auroral particles and of the emission of Saturn’s Kilometric Radiation (SKR), passages at altitudes as low as possible are highly desired (down to 3 or 4 RS). The auroral region lies at approximately 75–80 deg N, which means an inclination of 75–80 deg must be achieved in order to pass through the field lines associated with the aurora. Inclinations this high are achievable only during short-period orbits, for reasons which will be discussed.

Satellite ‘wakes’ are created as charged particles trapped in Saturn’s magnetic field sweep by the satellites. Saturn’s magnetic field rotates with Saturn at a rate faster than the rotation rates of the satellites around Saturn. Therefore, the wakes stream out in front of each satellite. Several passages through Titan’s wake are desired, as well as through the wakes of icy satellites. Wake passes are achieved with flybys near a satellite’s equator over the satellite’s leading edge. As the following discussion will show, such flybys reduce orbital period. Another region of interest is the magnetic flux tube of each satellite. Plasma moving by a satellite generates a wave in Saturn’s magnetic field that propagates in a region located approximately over a satellite’s poles, but tilted toward the direction of motion of the satellite. Passages through flux tube regions are achieved by flying nearly over a satellite’s pole.

2.4. TITAN

Titan is Saturn’s largest moon. A dense atmosphere hides its surface from view. Both the surface and atmosphere of Titan are of great scientific interest. The Huygens probe is designed to provide in situ observations of the atmosphere. Occultations of Earth by Titan, as viewed from the orbiter, are desired for the information they can provide on Titan’s atmosphere and ionosphere. Several occultations are desired, with entry/exit points spread out over a wide range of latitudes and longitudes, allowing sampling of points throughout the atmosphere.

The Cassini orbiter carries a radar to map the surface of Titan. During each close approach, a radar swath is taken which covers a small portion of Titan’s surface. To maximize the area mapped on Titan’s surface, it is necessary to incorporate as many Titan flybys as possible in the tour and to arrange them so that the orbiter flies over different parts of the surface. The ground track of the spacecraft during a flyby depends on the gravitational assist accomplished during the flyby (see section 3 for a detailed explanation).

In-situ measurements of Titan’s upper atmosphere and ionosphere by the Magnetospheric and Plasma Science instruments are also of high interest. These measurements should be made as deep in the atmosphere as spacecraft safety constraints permit; and should cover a variety as large as possible of Titan latitudes, Titan local times, and Saturn local times in order to make it possible to separate the different sources and sinks of Titan’s ionosphere and exosphere.
2.5. SATURN’S ICY SATELLITES

Satellites other than Titan are also objects of considerable scientific interest. Images of these satellites could contribute to the unlocking of some of the mysteries surrounding these bodies. Desired icy satellite flybys in the order of priority expressed by Cassini science teams are Enceladus (first encounter), Iapetus, Enceladus (second encounter), Dione, Hyperion, Rhea, and Enceladus (third encounter)\(^3\). Three targeted Enceladus flybys are included in this list because Enceladus is a particularly intriguing satellite. It has a particularly smooth surface (it is the brightest body in the solar system), and Saturn’s E ring has an increased particle density in the vicinity of Enceladus’ orbit. Iapetus’ leading edge is much darker than its trailing edge, for reasons unknown. Prolonged viewing of the boundary between the light and dark regions (i.e. viewing from either the approach or departure asymptote rather than near closest approach, where time available for observation is short) under good lighting conditions is desired. Dione appears to have a diverse surface composition; its position in Saturn’s magnetic field may offer an especially good chance to observe magnetospheric wake interactions. Hyperion is irregularly shaped, and a close flyby is desired in order to accurately determine its mass. Mimas is the closest satellite to Saturn. Observations of interactions between Mimas and the rings are desired, as well as images of its large impact crater.

Because flybys of the less-massive icy satellites can make only small changes in the spacecraft’s orbit, targeted icy satellite flybys must be achieved essentially ‘on the way’ from one Titan flyby to another, making the incorporation of close flybys of icy satellites in Cassini tours a challenge. To fly by any of the smaller icy satellites whose gravitational assist can be considered negligible (Hyperion, Mimas, Enceladus), the spacecraft must depart Titan on a trajectory which returns it directly to Titan. Otherwise, the icy satellite flyby cannot change the orbit enough to return the spacecraft to Titan and the tour cannot continue. To fly by the larger icy satellites (Tethys, Dione, Rhea, Iapetus), the spacecraft must depart Titan enroute to the icy satellite in an orbit very much like one which returns it directly to Titan; however, the small amount of gravitational assist available from these icy satellites requires a less restrictive set of conditions to be met on departure from Titan.

In addition to the dependence on the satellite’s mass, the difficulty of achieving a targeted flyby of an icy satellite depends on the satellite’s accessibility during the tour (i.e. the distance at which it orbits Saturn) and its synodic period with respect to Titan. The shorter the synodic period, the more frequently opportunities to encounter the satellite occur (see Table 1).

For example, Dione orbits close enough to Saturn, is massive enough, and its synodic period is short enough to allow a targeted flyby almost anytime during large segments of the tour. By contrast, although Hyperion’s orbit is close enough to Saturn to be reached by the orbiter during a large portion of the tour, Hyperion’s small mass and long synodic period make incorporating a targeted flyby of Hyperion (without prohibitively large \(\Delta V\)) much more difficult.
Tour Design Concepts

During the tour, the gravitational fields of satellites are used to make large alterations in the trajectory. The concept of gravitational assist has been previously discussed in detail\textsuperscript{3,4,5} and employed in previous missions. In brief, a satellite flyby can change the direction, but not the magnitude, of the orbiter’s velocity relative to the satellite. This change in the direction of the satellite-relative velocity vector can change both the direction and the magnitude of the orbiter’s velocity vector relative to the central body (Saturn, in the case of the Cassini tour). Since gravitational assist is fundamental to tour design, it is explored in greater detail in this section.

In the vicinity of a satellite, the orbiter’s trajectory approximates a satellite-centered hyperbola. The satellite-relative velocity vector along the incoming asymptote of this hyperbola (called $V_{\infty}$) is computed by subtracting the satellite’s velocity relative to Saturn from the orbiter’s. The orbiter approaches from ‘infinity’ (i.e., a point far enough from the satellite to be outside its gravitational influence) with a satellite-relative speed of $V_{\infty}$. It gathers speed as it nears the satellite, attaining its greatest satellite-relative speed at closest approach to the satellite. The satellite-relative speed of the orbiter decreases to $V_{\infty}$ as it departs along the outgoing asymptote. The angle between the incoming and outgoing asymptotes is referred to as the bending angle. The flyby altitude necessary to achieve a given bending angle is determined by the following equation:

$$\sin(\alpha/2) = 1/(1 + r_p V_{\infty}^2/\mu)$$

(1)

where $\alpha$ is the bending angle, $r_p$ is the closest approach radius, $V_{\infty}$ is the satellite-relative speed at infinity along either asymptote, and $\mu$ is the satellite’s mass. The orbiter’s Saturn-relative velocity after the flyby is then obtained by adding the satellite’s Saturn-centered velocity to the orbiter’s post-flyby $V_{\infty}^+$. The vector diagram shown in Figure 3 illustrates how a change in direction of the $V_{\infty}$ vector can result in a change in both magnitude and direction of the orbiter’s Saturn-centered velocity. Because of energy conservation, the satellite’s Saturn-relative speed decreases if the flyby increases the orbiter’s Saturn-relative speed (and vice versa). But, since the satellite is so much more massive than the orbiter, the change in the satellite’s speed is insignificant.

According to the above equation, the more massive the satellite, the greater the bending angle. Since Titan is the only satellite of Saturn massive enough to use for orbit control during a tour, Cassini tours consist mostly of Titan flybys. This places restrictions on how the tour must be designed. Each Titan flyby must place the orbiter on a trajectory which leads back to Titan. The orbiter cannot be targeted to a flyby of a satellite other than Titan unless the flyby lies almost along a return path to Titan. Otherwise, since the gravitational influence of the other satellites is so small, the orbiter will not be able to return to Titan, and the tour cannot continue.
Flybys can be used to achieve ‘orbit pumping,’ that is, changing the orbital period with respect to Saturn, or ‘orbit cranking,’ changing the orbit without changing its period (that is, changing eccentricity and inclination while keeping the semimajor axis constant). Orbit pumping and cranking are discussed in detail in Ref. 4. Increasing the period (referred to as ‘pumping up’) with respect to the central body is accomplished by flying behind a satellite’s trailing edge. Decreasing the period (pumping down) involves flying ahead of its leading edge. Figure 3 illustrates orbit pumping. The gravitational assist obtained from a single satellite flyby may consist of pure pumping, pure cranking, or pumping and cranking components. The total bending angle (obtained from both pumping and cranking components) must not exceed the value obtained from the bending equation at the minimum allowed flyby.
Flyby location | Energy (period) increasing flyby ("pumping up") | Energy (period) decreasing flyby ("pumping down")
--- | --- | ---
Inbound (pre-periapse) | Clockwise | Counterclockwise
Outbound (post-periapse) | Counterclockwise | Clockwise

*Note:* Clockwise rotation is in the direction from the initial orbit orientation (with apoapsis nearly over the dawn terminator of Saturn) toward the anti-sun direction.

*Figure 4.* Rotation of line of apsides due to orbit pumping, for an outbound Titan flyby.

altitudes. If the plane of the pre-flyby Saturn-centered orbit is near Saturn’s equator, pure pumping produces a near-equatorial satellite flyby and pure cranking produces a near-polar flyby.

Flybys which change the orbital period also rotate the line of apsides (the line connecting the periapsis and apoapsis points) and change the distance of the periapsis from Saturn. The direction in which the line of apsides is rotated depends on whether the period is increased or decreased and on whether the flyby occurs before Saturn-relative periapsis (‘inbound’) or afterwards (‘outbound’). Figure 4 shows that an outbound, period-reducing flyby (from orbit A to orbit B) rotates the line of apsides clockwise, and an outbound period-increasing flyby (from B to A) rotates the line counterclockwise.

Orbit cranking is illustrated in Figure 5. As the figure shows, in pure orbit cranking the pre- and post-flyby velocity magnitudes relative to Saturn are the same, as are the pre- and post-flyby velocity magnitudes relative to the satellite.
Since the Saturn-centered speeds are the same before and after the flyby, the pre- and post-flyby orbital periods are also the same.

The figure shows that in pure cranking, the locus of all possible $V_\infty$ vectors after a flyby is a sphere centered at the head of $V_{sat}$, and the locus of all possible $V$ vectors is a sphere centered at the tail of $V_{sat}$. Using a series of pure-cranking flybys, the heads of the $V_\infty$ and $V$ vectors can be placed anywhere on the circle of intersection of these two spheres. (A single flyby can move these vectors over only a small arc in the circle, due to bending angle limitations.)

Pure cranking changes orbital inclination and eccentricity together, while conserving semimajor axis length (keeping the period constant). If the plane of the pre-flyby Saturn-centered orbit is near Saturn’s equator, cranking causes a large inclination change and a small eccentricity change. If the pre-flyby orbital plane is significantly inclined to the equator, cranking causes a small inclination change and a large change in eccentricity (that is, periapse and apoapse radii change while the semimajor axis length remains constant).
3.2. Transfer Orbits of 180 and 360 Deg

The plane of the transfer orbit between any two flybys is formed by the position vectors of the flybys from Saturn. If the angle between the position vectors is other than 180 or 360 deg (as is usually the case), the orbital plane formed by these two vectors is unique and lies close to the satellites’ orbital planes (except for Iapetus’), which are close to Saturn’s equator. If the transfer angle is either 360 deg (i.e., the two flybys occur with the same satellite at the same place), or 180 deg, an infinite number of orbital planes connect the flybys. In this case, the plane of the transfer orbit can be inclined significantly to the planet’s equator. Any inclination can be chosen for the transfer orbit, as long as sufficient bending is available from the flyby to get to that inclination.

It can also be said that if a spacecraft’s orbital plane is significantly inclined to the equator, the transfer angle between any two flybys forming this orbital plane must be nearly 180 or 360 deg.

3.3. 180-Deg. Transfer Flyby Sequence

It is possible to construct a sequence of Titan flybys which rotate the line of apsides not by pure pumping as illustrated above, but by first increasing inclination using pure cranking, then accomplishing a 180-deg. transfer between Titan flybys, then reducing inclination using pure cranking. Such a sequence of flybys is called a ‘180-deg. transfer sequence’, an example of which is shown in Figure 6. In order to facilitate the incorporation of a large number of Titan flybys in the tour, orbit period is generally kept constant and short at 16 days (1 spacecraft revolution : 1 Titan revolution) during the pure cranking segments, although it is possible to use other values of orbital period which are resonant with Titan’s period.

As inclination is raised, periapsis radius increases and apoapsis radius decreases until the orbit is nearly circularized at an inclination of about 60 deg. The orbiter’s trajectory then crosses Titan’s orbit at not one, but two points (the ascending and descending nodes), making possible a 180-deg transfer from an inbound Titan flyby to an outbound Titan flyby (or vice-versa). After this 180-deg transfer is accomplished, several pure-cranking flybys reduce inclination as quickly as possible to near Saturn’s equator. This 180-deg transfer flyby sequence (raising inclination, accomplishing the 180-deg transfer, then lowering inclination again) takes about a year and rotates the line of apsides about 120 deg. Rotation is clockwise if the inclination-raising flybys are inbound and the inclination-lowering flybys are outbound; rotation is counterclockwise if the situation is reversed.

During pure cranking, Titan flyby altitudes are usually kept at the minimum allowed value of 950 km in order to maximize gravitational assist and to provide opportunities for low-altitude science observations.
3.4. MAXIMUM ACHIEVABLE INCLINATION

At a given orbital period (i.e., constant magnitude of \( V \) at encounter), inclination is maximized when the plane formed by \( V \) and \( V_{\text{sat}} \) is normal to the satellite’s orbital plane (see Figure 5). The maximum inclination for any given value of orbital period is then equal to the angle between \( V \) and \( V_{\text{sat}} \). This leads to the following relationship, obtained from the law of cosines, which can be used to specify the maximum inclination achievable at any orbital period:\(^4\):

\[
in_{\text{max}} = \arccos[(V_{\text{sat}}^2 + V_-^2 - V_{\infty}^2)/2V_{\text{sat}}V_-]
\] (2)
where $i_{\text{max}}$ is the maximum inclination, $V_{\text{sat}}$ is the magnitude of Titan’s velocity, $V$ is the magnitude of the orbiter’s Saturn-centered velocity before the flyby, and $V_{\infty}$ is the hyperbolic excess speed (the magnitude of the $V_{\infty}$ vector) with respect to Titan. As inclination is increased during a series of pure-cranking flybys, the theoretical maximum inclination is approached asymptotically. The first few flybys raise inclination most of the way, and the last few degrees of inclination require several flybys.

If the inclination to Saturn’s equator is high, pure pumping changes the inclination significantly in addition to changing the period. Reducing the period increases the inclination; increasing the period reduces the inclination.

Since $V$ is a function of the spacecraft’s orbital period, reducing period increases $i_{\text{max}}$ if $V_{\text{sat}}$ and $V_{\infty}$ are fixed. However, period cannot be allowed to drop below a minimum value imposed by the following considerations: the spacecraft’s periapsis cannot be allowed to dip below approximately 2.7 RS due to increased probability of hitting ring debris, and its apoapsis must be at least as far from Saturn as Titan’s orbit in order to continue encountering Titan. This minimum period is about 7.1 days.

Figure 7 shows the variation of $i_{\text{max}}$ with orbital period. In the figure, $V_{\text{sat}}$ is held constant at 5.573 km/s, the value associated with a circular orbit at a distance equal to Titan’s semimajor axis. Also, $V_{\infty}$ at Titan is held constant at 5.500 km/s, which is its approximate value at the start of the tour. This figure shows that if the minimum orbital period in the tour is 7.1 days, the maximum inclination achievable in the tour is about 73 deg. In practice, $V_{\infty}$ at Titan can vary by a few hundred m s$^{-1}$ during the tour due to the gravitational assist from icy satellite flybys and the eccentricity of Titan’s orbit. This can cause the maximum inclination achieved during a sample tour to vary by several degrees from the values shown in the figure.

Examination of this figure provides the genesis of the strategy used to increase inclination in Cassini satellite tours. Both pumping and cranking must be employed to maximize inclination. Pure cranking is first used to raise inclination at a constant period to near the $i_{\text{max}}$ value for that period. The orbital period is then pumped down, increasing $i_{\text{max}}$. Cranking can then resume until near the new $i_{\text{max}}$ value. This process is repeated until reaching the maximum inclination at the minimum 7.1-day period.

### 3.5. ORBIT ORIENTATION

The angle measured clockwise at Saturn from the Saturn–Sun line to the apoapse is referred to as the ‘orbit orientation’. This is an important consideration for observations of the magnetosphere (for which sampling of a wide variety of orientations is desired) and of Saturn’s atmosphere. The time available for atmospheric observations on Saturn’s lit side decreases as the orbit rotates toward the anti-sun direction.
Arrival conditions at Saturn fix the initial orientation at about 90 deg (i.e. apoapse nearly over Saturn’s dawn terminator). Due to the motion of Saturn around the Sun, the orbit orientation increases with time, with the apoapse rotating clockwise at a rate of about 1 deg/month for a total of 48 deg during the 4-year tour. Period-changing targeted flybys that rotate the line of apsides may be used to add to or subtract from this ‘drift’ in orbit orientation.

3.6. INCLINATION REQUIRED FOR OCCULTATIONS OF SATURN

Saturn’s equatorial plane is tilted 28 deg to the ecliptic. The declination of Earth with respect to the Saturnian equator is zero only at two points in Saturn’s orbit about the Sun. To an Earth-based observer, the rings appear edge-on only at those two points. As it happens, the rings never appear edge-on during the tour. At the time of the Cassini spacecraft’s arrival, the declination of Earth is −25 deg; four years later, it is −7 deg. Unless the declination of Earth is near zero, a spacecraft orbiting in Saturn’s equatorial plane does not pass behind Saturn as viewed from Earth. In this case, occultations of Earth by Saturn as viewed from the orbiter can be achieved only by inclining the orbital plane to the equator. Targeted satellite flybys are needed to raise the inclination to the required value.
The value of the inclination required to achieve a diametric occultation (that is, to pass directly behind the center of Saturn as viewed from Earth) is a function of the tilt of Saturn’s equator viewed from Earth, and the angle between the Saturn–Earth line and the line of nodes (the line connecting the points where the orbiter crosses Saturn’s equator). A schematic illustration of this relationship is provided in Figure 8. For a given equatorial tilt angle, the inclination required to obtain a diametric occultation is minimized when the line of nodes is perpendicular to the Saturn–Earth line. Because Titan’s orbital plane is close to Saturn’s equator, Titan flybys occur close to the line of nodes. It is desirable, therefore, to locate inclination-raising flybys nearly perpendicular to the Earth line to minimize the inclination (and therefore, the number of flybys) required to obtain occultations.

Non-diametric occultations (passages behind Saturn, but not behind the center of the planet) can occur at inclinations several degrees from the value required for diametric occultations. These provide less information on Saturn’s atmospheric structure than occultations close to or directly behind the center of the planet, however.
3.7. NONTARGETED FLYBYS

If the closest approach point during a flyby is far from the satellite, or if the satellite is small, the gravitational effect of the flyby can be small enough that the aimpoint at the flyby need not be tightly controlled. Such flybys are called ‘nontargeted.’ Flybys of Titan at distances greater than 25,000 km and flybys of icy satellites at distances of greater than a few thousand kilometers can be considered nontargeted flybys. However, for icy satellite flybys at distances of up to a few thousand kilometers targeting to a specific flyby aimpoint is usually necessary to achieve scientific objectives, even though the satellite’s gravitational influence is small. Opportunities to achieve nontargeted flybys of smaller satellites occur frequently during the tour. These are important for global imaging.

4. Constraints

In addition to having to satisfy multiple scientific objectives, the tour is subjected to various constraints. Some of these originate in the laws of orbital mechanics; others are unrelated to those physical laws. Constraints are imposed due to the limits of hardware capabilities, instrument reliability, operational necessities, and budgetary concerns.

Arrival conditions. The arrival conditions at Saturn are fixed by the interplanetary trajectory. The spacecraft arrives at Saturn on 1 July, 2004. This date was chosen for reasons of performance and because it permits a flyby of Phoebe on approach to Saturn. The spacecraft arrives from an orbit near the ecliptic plane, at an inclination of approximately 17 deg to Saturn’s equator. A propulsive maneuver is executed to insert the spacecraft into orbit about the planet.

Maximum duration. The tour’s maximum duration has been set at 4 years for budgetary reasons. The nominal tour must be finished 4 years after insertion into orbit about Saturn.

Ring plane crossing. The orbiter must avoid crossing the ring plane within regions in the ring system in which the probability of damage due to particle impacts is unacceptably high. The probability of mission loss must be less than 0.3% until probe mission completion, 1 percent until 1 year after probe mission completion, and 5% at the end of the tour. The Cassini project convened a major workshop in early 1996 at which Saturnian debris was reassessed and particle models were produced to assess the probability of impact. The models incorporate data taken during 1995–1996 from edge-on observations of the rings. Software has been developed incorporating these particle models in which damage to spacecraft subsystems is also modeled. This software shows that the risk constraint is easily met for several sample tours, including the one presented here.
Titan minimum flyby altitude. Titan’s atmosphere imposes a minimum flyby altitude constraint. Thermal and attitude control considerations due to atmospheric drag are the limiting factors. For the sample tour presented here, the lower altitude limit is assumed to be 950 km.

Minimum time between flybys. The time interval between targeted flybys must be long enough to allow time for tracking and incorporation of pre- and post-flyby statistical maneuvers. However, the large numbers of Titan flybys desired by science teams reduce the time between flybys which places stress on the ground system and may introduce significant operational risk of failing to complete a specified tour. For the Galileo mission to Jupiter, the minimum acceptable interval between flybys was set at 35 days. Cassini, endowed with a more advanced ground system and the benefit of Galileo experience, has reduced this minimum time interval at 16 days, with the proviso that the number of consecutive 16-day intervals is limited to four. After four successive 16-day intervals, an interval of 48 days between flybys, or alternately 2 intervals of ~32 days each, is required. This constraint may be violated once per tour. In addition, no maneuvers, flybys, or occultations are permitted during a 9-day period starting the Saturday morning before the Christmas holiday until the end of day on the following Sunday. One violation of this ‘holiday constraint’ is also permitted during the tour.

Solar conjunction. Doppler tracking data is degraded below Sun-Earth-Probe (SEP) angles of 5 deg due to solar interference and is unusable below ~3 deg. No maneuvers associated with flybys are permitted at times when SEP is below 3 deg. Additional time periods on either side of the conjunction limit are also reserved for post-flyby cleanup and pre-flyby navigational maneuvers. The end result is that for a span of 18.3 days centered about superior conjunction, no targeted flybys are permitted. For the Cassini tour, superior conjunctions occur on July 8, 2004; July 23, 2005; August 7, 2006; and August 22, 2008.

Available propellant. Only a limited amount of propellant is available for tour operations. Propellant is used only to provide small adjustments to the trajectory necessary to ensure desired flyby conditions, to turn the orbiter in order to obtain scientific observations, or to communicate with Earth. At a 95% confidence level, the amount of propellant available for the tour is estimated to be able to accomplish a total ΔV of 503 m s⁻¹; at a 75% confidence level, the estimated ΔV capability is 583 m s⁻¹.

Possibility of in-flight anomalies. The possibility of disruption of the tour by flight or ground system anomalies must be considered in the design of the tour. An anomaly onboard the orbiter could cause the orbiter to miss executing a trajectory correction maneuver at the intended time, resulting in the need to use extra propellant at a later time (after recovery from the anomaly) to get back to the desired
TOURING THE SATURIAN SYSTEM

trajectory. The ΔV penalty from several (perhaps more than one) such occurrences could be high enough to necessitate a tour redesign in flight. The satellite tour must be designed so that the probability of an inflight redesign due to missed maneuvers is acceptably low.

5. Methods and Software

While the basic concepts used in tour design are straightforward, the process of arriving at an estimate of the tour trajectory precise enough to be considered flyable is heavily dependent on software and modern high-speed computing hardware. The initial stages of tour design require fast (but not necessarily precise) trajectory computations for study purposes. This initial estimate must eventually be refined into an estimate of the nominal trajectory precise enough to be flyable, and which also minimizes propellant expenditure.

Since Titan is the only Saturnian satellite massive enough to use for orbit control in a tour, initial tours composed of only Titan flybys were constructed and evaluated by science teams. Such ‘Titan-only’ tours were limited to 3.5 years duration to reserve 6 months for inclusion of about six close icy satellite flybys as well as meet other constraints such as restrictions on flyby and maneuver times. These Titan-only tours were quickly designed using the STOCK5 program in an Excel spreadsheet environment. These tours demonstrate most of the basic science observation geometry of a complete 4-year tour with the significant exception of demonstrating the number and quality of targeted icy satellite flybys. Analysis gave the tour designers confidence that given 6 months, a desirable set of icy satellite flybys could be incorporated. This approach was not possible for the Galileo tour design, since for Galileo tours, four massive moons were utilized for gravity assist instead of a single moon.

The STOUR6 program was used to design tours incorporating icy satellite flybys based on those designed with STOCK. Icy satellite flyby opportunities were identified using the VTOUR7 program. VTOUR identifies ballistic icy satellite flyby opportunities once a Titan-to-Titan transfer orbit is specified. STOUR is highly interactive and is designed to enable the user to evaluate various trajectory options quickly. The tour is designed one flyby at a time. At each flyby, the user chooses from a set of aimpoints presented by the program, each of which leads to a different subsequent flyby. At any point in the tour, if the user is dissatisfied with the trajectory, he or she can return to any previous flyby and choose a different set of encounters after that flyby. In this fashion, the user can quickly evaluate which trajectory options best achieve the scientific objectives of the tour without violating the mission constraints. The result of the initial design stage is a mathematical representation of each orbit in the tour as an ellipse about Saturn (and, when near a flyby, a hyperbola about the flyby satellite). Third-body effects such
as the oblateness of Saturn and the gravitational effect of the Sun, which must be modeled in order to successfully fly the trajectory, are so far unaccounted for.

The initial representation of the trajectory is then used as a ‘first guess,’ to start the optimization process in the CATO⁸ program. In this program, flybys are ‘control points’ from which trajectory segments are numerically integrated forward and backward to ‘breakpoints’ between flybys. The integrator includes multibody gravitational effects, Saturn’s oblateness, and some nongravitational effects. Initially, discontinuities in both position and velocity appear at the breakpoints. To achieve a final trajectory that is continuous in position, constraints are imposed on the optimization requiring that position discontinuities at breakpoints be zero. The velocity discontinuities represent maneuvers that are necessary to fly the trajectory. The optimization algorithm varies the flyby times and aimpoints on successive iterations to minimize the weighted sum of the ΔVs, in the process driving many maneuvers to zero. The estimate of total deterministic ΔV resulting from this process is almost always less than that obtained from the initial design stage. The result of the optimization can be used as a nominal estimate of a flyable trajectory.

6. Sample Tour

The sample tour presented here is the result of several years of iteration between Cassini tour designers, other project personnel, and science teams.

This tour contains 44 targeted Titan flybys and 7 targeted flybys of icy satellites. Three targeted flybys of Enceladus and one each of Hyperion, Dione, Rhea, and Iapetus occur, in addition to 27 nontargeted flybys of icy satellites. The spacecraft completes 72 revolutions about Saturn, as well as 33 occultations of Earth by Saturn and 17 occultations of Earth by Titan (as viewed from the spacecraft).

Figure 9, referred to as a ‘petal plot’ because of the resemblance of the orbits to the petals of a flower, shows how the orbit is rotated about 270 deg from the initial orientation to near the sun line (local noon) in the sample tour. The figure shows the view from Saturn’s north pole. In the coordinate system used in the figure, the direction to the Sun is fixed (toward the top of the page). Only 48 deg of this rotation is from the ‘drift’ in orbit orientation due to Saturn’s motion about the Sun; the remainder is the result of targeted flybys. Figure 10, a view from just above Saturn’s equator near the Sun line, shows the profile of orbital inclination more clearly.

The tour provides opportunities for radar coverage of various portions of Titan, as shown by the ground tracks on Titan’s surface in Figure 11. Similar flybys (for example, inbound/period-reducing flybys) have similar ground tracks. Conflicting scientific requirements and orbiter operating constraints prevent taking radar swaths every flyby.

A tabular summary of encounters for this tour, showing the sequence of targeted encounters and some objectives accomplished at each encounter, is presented in
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Figure 9. Petal plot of sample Cassini tour, viewed from Saturn's north pole. Orbits are plotted in a rotating coordinate system, with the Saturn–Sun direction fixed at the top of the page.

Figure 10. View of sample tour from near noon orientation, just above ring plane.
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Figure 11. Orbiter ground tracks on Titan’s surface within 2 hours of closest approach. East longitudes are shown, points are plotted at 1 minute intervals, and closest approach locations are circled.

Table 2. In the table, 1 Rs (Saturn radius) = 60 330 km, Ran = radius from the center of Saturn to the ascending node of the spacecraft’s orbit, Rdn = radius from the center of Saturn to the descending node. ‘Flight time’ is the time in days between each targeted encounter and the next.

As the table shows, the sample tour violates the ‘holiday constraint’ imposed by operations three times rather than once. Simply adding time by inserting extra revs about Saturn in the tours which violate this or other timing related constraints is not possible without sacrificing the targeted icy satellite flybys downstream which are dependent on time critical phasing and/or failing to complete the tour. This tour also violates the constraint on the number of consecutive 16-day intervals between flybys (between Titan-21 and Titan-35) and includes one interval of less than 16 days (between Titan-35 and Iapetus-1) to illustrate the potential science gains of doing so. Sample tours have been designed which meet these constraints, at the expense of science return9.

6.1. PHASE I

The first three Titan flybys reduce period and inclination. The orbiter’s inclination is reduced to near zero with respect to Saturn’s equator only after the third flyby; therefore, these three flybys must all take place at the same place in Titan’s orbit. These period-reducing flybys were designed to be inbound, rather than outbound, to accomplish the additional goal of rotating the line of apsides counterclockwise. This moves the apoapse toward the Sun line in order to provide time for observations of Saturn’s atmosphere.
## TABLE II
Sample tour profile

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<th>Time</th>
<th>Inc.</th>
<th>Ran</th>
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<td>(d)</td>
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Phase IV

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<th>Flight Revs</th>
<th>Period</th>
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<th>Time (d)</th>
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The ΔV required to fly this tour is shown in Table 3 at both the 95% and 75% confidence levels.

After the inclination has been reduced to near Saturn’s equator, a targeted flyby of Enceladus is achieved on the way to an outbound flyby of Titan. Changing from an inbound to an outbound Titan flyby here orients the line of nodes nearly normal to the Earth line. As previously discussed, this geometry minimizes the inclination required to achieve an occultation of Saturn. Here, the minimum inclination required is about 22 deg. The Titan-4 and Titan-5 flybys (both outbound) increase inclination to this value. The second of these also changes period to 18.2 days. At this period, seven orbiter revolutions and eight Titan revolutions are completed be-
before the next Titan flyby, producing seven near-equatorial occultations of Earth by Saturn (one on each orbit). On all eight of these revolutions, the orbiter crosses Saturn’s equator near Enceladus’ orbit; on the fourth revolution, the second targeted flyby of Enceladus occurs. Enceladus’ gravity is too weak to displace inclination significantly from the value required to achieve occultations. After accomplishing these occultations, Titan-6 reduces inclination once again to near Saturn’s equator, targeting to Titan-7 which completes the first 1.2 years of the tour.

6.2. PHASE II

The outbound Titan-7 flyby increases period slightly to 18.4 days, taking advantage of a rare opportunity to achieve targeted flybys of both Hyperion and Dione before returning to Titan, as shown in Figure 12. The spacecraft completes slightly more than 1 revolution after Titan-7 before encountering Hyperion ~19 days later. Less than 1 revolution and ~16 days after Hyperion, the spacecraft encounters Dione, returning to Titan less than 1 revolution and ~16 days later for the Titan-8 flyby.

Titan-8 targets to an additional targeted icy satellite flyby, of Rhea. A series of alternating outbound/period-reducing and inbound/period-increasing flybys is then used to rotate the orbit clockwise toward the magnetotail. Passage through the magnetotail region occurs after Titan 14. This passage is not through the center of the region of interest (which is displaced from the equatorial plane because the Sun line is inclined to the equator) because inclination is not increased. However, at or near the apoapsis distance of 68RS, the spacecraft’s passage near the equatorial plane does traverse the region of interest.

<table>
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<th>Deterministic $\Delta V$ (m/s)</th>
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<th>75% confidence level</th>
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<td>Total $\Delta V$ (m/s)</td>
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<td>$\Delta V$ margin (m/s)</td>
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Figure 12. Flybys of Hyperion and Dione between Titan-7 and Titan-8 show how targeted icy satellite flybys must occur ‘on the way’ from one Titan flyby to another.

6.3. PHASE III

The Titan-16 flyby begins a 180-deg transfer flyby sequence. As inclination is raised, the tour briefly departs from pure cranking at a constant 16-day orbital period to satisfy the operations-imposed limit on the number of consecutive 16-day intervals between flybys. The 48-day ‘break’ period enhances science return by providing important close-in ring observation opportunities at about 55 deg. inclination. After this 180-deg transfer is accomplished, the next seven Titan flybys, all of which are outbound, are used to reduce inclination to near Saturn’s equator. This 180-deg transfer flyby sequence starts with apoapsis nearly opposite the Sun and finishes with apoapsis between the Sun line and Saturn’s dusk terminator. After inclination is lowered to near the equator, the line of apsides is rotated further clockwise to place the line of nodes close to the Sun line at the Titan-35 flyby, the start of the next phase.

6.4. PHASE IV

The final phase of this tour is a ‘maximum inclination flyby sequence’ whose principal goal is to raise inclination to as high a value as possible for ring ob-
servations and in-situ fields and particles measurements (about 75 deg. here, as previously discussed). This maximum inclination sequence starts with Titan-35, which is also used to take advantage of an opportunity to target to Iapetus. The resulting Iapetus flyby provides the desired opportunity for prolonged viewing of the boundary between the light and dark regions from an asymptote. Placement of the line of nodes close to the Sun line orients the orbits during this maximum-inclination flyby sequence nearly toward the Sun, away from the magnetotail, to ensure several occultations of Earth by Saturn and the rings at close distances.

During this flyby sequence, first, orbit cranking and then, orbit pumping (after a moderate inclination has been achieved) are used to increase inclination, eventually reducing the orbit period to 7.1 days (nine orbiter revolutions : four Titan revolutions). The closest approach altitudes during this sequence are kept at the minimum allowed value to maximize gravitational assist at each flyby. The last targeted icy satellite flyby, of Enceladus, is achieved between Titan-41 and Titan-42 at an inclination of 57 deg. and a period of 10.6 days (3 orbiter revolutions : one Titan revolution).

The tour ends on 1 July 2008, 4 years after insertion into orbit about Saturn. The aimpoint at the last flyby, on 28 May 2008, is chosen to target the orbiter to a subsequent Titan flyby to provide the opportunity to proceed with more flybys during an extended mission, if resources allow.

7. Conclusions

The diverse scientific objectives and multiple constraints of the Cassini mission make designing a satellite tour that can fulfill the promise of this exciting mission an interesting challenge. The large experience base in tour design accumulated during the Galileo mission to Jupiter helps in meeting this challenge. However, differences between the Saturnian and Jovian environments and the scientific objectives of Cassini and Galileo make the Cassini tour quite different from the Galileo tour. The use of more sophisticated tour design techniques (e.g., flyby sequences which achieve a 180-deg transfer and which maximize inclination) are necessary to achieve the full potential of the Cassini mission. The sample tour presented here illustrates the integrated application of these techniques to produce the desired result.

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
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References


AN INTRODUCTION TO THE DESIGN OF THE CASSINI SPACECRAFT

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Abstract. In October of 1997 NASA launched its largest interplanetary spacecraft to date. The Cassini spacecraft will arrive at Saturn in July of 2004 and begin a four year tour of that planetary system. After the spacecraft arrives it will separate into an orbiter and a probe. The Huygens Probe, developed by the European Space Agency, will follow a ballistic trajectory into the atmosphere of the moon Titan. The orbiter will relay signals received from the probe back to Earth and then begin the tour. This article provides an introduction to the design of the Cassini spacecraft. The major engineering functions of mechanical configuration, power generation and distribution, telecommunications, information system, pointing and course correction, and some other miscellaneous design features are discussed. A description of the engineering elements of the Huygens Probe is also provided.

1. Introduction

The Cassini spacecraft was launched on October 15, 1997 from Cape Canaveral aboard the Titan IVB rocket shown in Figure 1.

This article describes the engineering elements of the Cassini spacecraft. Separate sections describe the following subjects: spacecraft system overview, mechanical configuration, power generation and distribution, telecommunications, information system, pointing and course correction, miscellaneous design features, and the Huygens Probe.

2. Spacecraft System Overview

The Cassini spacecraft is the largest interplanetary spacecraft built by NASA. It stands 6.8 m (22.3 ft) tall with a high gain antenna 4 m (~13 ft) in diameter. At launch the spacecraft weighed about 5655 kg (12470 pounds) of which 2523 kg was dry mass and 3132 kg was propellant. Table 1 lists the 12 instruments carried by the orbiter and the 6 instruments carried by the probe. Figure 2 shows the spacecraft in the cruise configuration, that is, the configuration of the spacecraft after the last Earth flyby on its way to Saturn. The cruise configuration is noteworthy because the boom for the magnetometer and antenna for the Radio and Plasma Wave Science experiment are deployed and the Huygens Probe is still attached. Figure 3 shows the spacecraft during preparations for launch.

Figure 1. Titan IVB Rocket (photo courtesy of NASA).

3. Mechanical Configuration

Figure 4 shows several of the major structural elements of the Cassini orbiter. The orbiter has 8 major mechanical assemblies:

<table>
<thead>
<tr>
<th>Structural Element</th>
<th>Assembly</th>
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<td>High Gain Antenna</td>
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<tr>
<td>Magnetometer Boom</td>
<td>not shown in Figure 4</td>
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<td>Upper Shell Structure</td>
<td>USS</td>
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<td>Remote Sensing Pallet</td>
<td>RSP</td>
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<td>Fields and Particles Pallet</td>
<td>FPP</td>
</tr>
<tr>
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<td>PMS (not shown in Figure 4)</td>
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<tr>
<td>Lower Equipment Module</td>
<td>LEM</td>
</tr>
</tbody>
</table>

The HGA sits atop the spacecraft. It is a 4 m diameter, parabolic, cassegrain feed antenna constructed of graphite epoxy layers and an aluminum honeycomb core. The HGA assembly also includes the low gain antenna #1 (LGA1), a pair of sun sensors, several feeds for the Radar instrument, and a receive path for the Huygens Probe signal. The HGA serves as the primary antenna for orbiter communications. Additional information about the performance characteristics of the HGA is provided in the section about the spacecraft telecommunications system.
Below the HGA is the electronics bus. The electronics bus features 12 bays and a ‘penthouse’. Each bay consists of an outboard shear plate, an inboard shear plate, and stringers connecting these plates. Within the bays are housed the majority of the spacecraft electronics. The penthouse is mounted to the top of bus bay #11. It is another electronics bay housing additional electronics for the Radar instrument. Bay #1 is on the spacecraft +X axis, i.e., behind the remote sensing pallet. The bay numbers increase in the clockwise direction if viewed from above. The contents of the 12 bays are listed in Table 2.
**Figure 2.** Cassini Spacecraft in Cruise Configuration.

**TABLE II**

Contents of orbiter electronics bays

<table>
<thead>
<tr>
<th>Bay #</th>
<th>Assemblies Within Bay</th>
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<tr>
<td>Bay 1</td>
<td>attitude control computers, sun sensor electronics</td>
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<tr>
<td>Bay 2</td>
<td>power distribution</td>
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<tr>
<td>Bay 3</td>
<td>power subsystem remote engineering units, power control, shunt regulator, pyro</td>
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<tr>
<td>Bay 4</td>
<td>science calibration, magnetometer, and radio &amp; plasma wave electronics</td>
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<tr>
<td>Bay 5</td>
<td>radio system amplifiers</td>
</tr>
<tr>
<td>Bay 6</td>
<td>transponders, command detectors, ultra-stable oscillator electronics, telemetry control units</td>
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<td>Bay 7</td>
<td>radio frequency instrument electronics</td>
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<tr>
<td>Bay 8</td>
<td>command and data subsystem electronics</td>
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<td>Bay 9</td>
<td>solid state recorders, backdoor ALF injection loader</td>
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<td>remote sensing pallet remote engineering units, radar electronics</td>
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<td>imaging science electronics, accelerometer</td>
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<tr>
<td>Penthouse</td>
<td>additional radar electronics</td>
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</table>
The electronics bus is constructed of aluminum. The top of the electronics bus is covered by an electrically conductive cap to create a Faraday cage.

The magnetometer boom (see Figure 2) is mounted to the top of the electronics bus. It is the same design used on the Galileo spacecraft. After the last Earth flyby it was deployed from a canister to its full length of 10.5 m. The boom is constructed of 3 fiberglass longerons and supporting cross members and has a triangular cross-section. The boom is home to inboard and outboard magnetometer sensors. The inboard sensor is located about half way out the boom.

The upper shell structure (USS) connects the bottom of the electronics bus to the propulsion module. It is a conic section of aluminum to which the following assemblies are mounted: remote sensing pallet, the CDA instrument, an articulated reaction wheel assembly, the RPWS antenna assembly, the MIMI INCA and electronics, the ultra stable oscillator, and the probe support electronics. The com-
The combination of the electronics bus and upper shell structure is referred to as the upper equipment module (UEM).

The remote sensing pallet (RSP) shown in Figure 5 and fields and particles pallet (FPP) shown in Figure 6 are two aluminum structures attached to the USS that support science instruments. The RSP supports the ISS NAC, ISS WAC, VIMS, CIRS, UVIS, and two stellar reference units. The fields and particles pallet supports the INMS, the CAPS, MIMI CHEMS, and MIMI LEMMS.

The propulsion module subsystem (PMS) shown in Figure 7 attaches to the bottom of the USS. The primary structure is a cylindrical, semi-monocoque, aluminum shell. Housed within this shell are 2 tanks for bipropellants. Attached to the outside of the shell are a helium tank, spherical monopropellant tank, four thruster booms, two main engines, two pressurant control components assemblies, two propellant isolation components assemblies, and an electronics bay.

The bottom of the spacecraft is named the lower equipment module (LEM). It is also made of aluminum. Attached to the LEM are 3 radioisotope thermoelectric
generators (RTG), 3 reaction wheels (RWA), low gain antenna #2 (LGA2), and a deployable and retractable cover for the main engines.

The spacecraft structural coordinate system origin is on the spacecraft centerline in the plane defined by the interface between the electronics bus and the upper equipment module. The +X axis points radially outward in the direction of the stellar reference units’ boresights (which is perpendicular to the remote sensing boresights). The +Y axis points in the direction of the magnetometer boom. The +Z axis points down toward the main rocket engines.
4. Power Generation and Distribution

Power generation and distribution is provided by the Power and Pyrotechnics Subsystem (PPS). Figure 8 is a block diagram of the PPS.

The source of electrical power is 3 radioisotope thermoelectric generators (RTGs). Figure 9 shows a cutaway drawing of an RTG. Each unit uses the heat produced by 10.9 kg of plutonium dioxide to generate about 300 W of electrical power at beginning of mission. By the end of the 11 year nominal Cassini mission the output power will degrade to a total of about 640 W.

Power is distributed around the spacecraft by a single power bus. The power bus is controlled to a nominal 30 volts by a shunt regulator. Excess power is directed to a shunt radiator mounted on top of the electronics bus. Both the high and low (return) rails of the bus are isolated from spacecraft chassis by 2 kohms.
Figure 8. Power and Pyrotechnics Subsystem.

Figure 9. Radioisotope Thermoelectric Generator.
This feature makes the bus tolerant to single shorts to chassis. Transient loads are accommodated by filter capacitors connected to the bus.

Electrical loads are connected to the power bus by solid state power switches (SSPS). These switches feature controlled ramp-up of voltage to loads and hardware controlled automatic shutoff in the event of overcurrent. Each switch can deliver up to 3 amps. Monitors of the on/off state, trip state, and load current through each switch are available in telemetry. The switches switch both the high and low (return) rails of the circuit. In addition, no single failure within a switch can prevent its being switched off. There are 192 SSPSs on the spacecraft.

The PPS also supplies power for pyrotechnics. Two block redundant pyro switching units consisting of capacitor banks and associated electronics perform this function. A silicon controlled rectifier on the high side and an enable relay on the return side switch each pyro circuit. Potentially mission catastrophic events are inhibited by additional critical enable relays that can be positioned only by hardware decoded uplink commands.

The PPS includes several fault protection features. The PPS control electronics include hardware to detect and recover the spacecraft from system undervoltages. The switches to many loads are automatically switched off if the bus voltage drops below a preset threshold. Switches for mission critical loads are left on following undervoltages and are automatically switched on if both elements of a redundant set are off. An example of this is the watchdog timer for the Command and Data

### TABLE III
Antenna functions

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Mode</th>
<th>Frequency (GHz)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGA</td>
<td>Transmit</td>
<td>7.175 ±0.025</td>
<td>Telecommunications</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>8.425 ±0.025</td>
<td>Telecommunications</td>
</tr>
<tr>
<td></td>
<td>Ka-band Transmit</td>
<td>32.028 ±0.1</td>
<td>Science (RFIS)</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>34.316 ±0.1</td>
<td>Science (RFIS)</td>
</tr>
<tr>
<td></td>
<td>Ku-band Transmit &amp; Receive</td>
<td>13.7765 ±0.005</td>
<td>Science (RADAR)</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>13.800 ±0.1</td>
<td>Science (RADAR)</td>
</tr>
<tr>
<td></td>
<td>S-band Transmit</td>
<td>2.298 ±0.005</td>
<td>Science (RFIS)</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>2.097 ±0.005</td>
<td>Probe Relay</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>2.118 ±0.005</td>
<td>Probe Relay</td>
</tr>
<tr>
<td>LGAs</td>
<td>X-band Transmit</td>
<td>7.175 ±0.025</td>
<td>Telecommunications</td>
</tr>
<tr>
<td></td>
<td>Receive</td>
<td>8.425 ±0.025</td>
<td></td>
</tr>
</tbody>
</table>
Subsystem (CDS) processors. The control electronics also include hardware to isolate an RTG from the power bus in the event the RTG suffers an internal short.

Power for the PPS electronics is provided by block redundant general purpose power supplies that put out power at ±5 V and ±12 V.

5. Telecommunications System

The combination of the Antenna (ANT) and Radio Frequency Subsystems (RFS) provides the telecommunications function for the spacecraft.

The ANT subsystem consists of the HGA, LGA1, LGA2, and associated waveguides. Figure 10 is a block diagram of the ANT subsystem. The HGA and LGA1 are mounted on top of the spacecraft facing along the −Z axis. The LGA2 is mounted on the lower equipment module facing along the −X axis. The HGA provides both engineering and science functions. The LGAs serve only engineering functions. The functions and associated frequencies are summarized in Table 3.

The HGA and LGAs feature right hand and left hand circularly polarized ports for the telecommunications function. Key performance parameters of the antennas are shown in Table 4.

The HGA provided by the Agenzia Spaziale Italiana is an example of the international cooperation within the Cassini program.
The RFS translates radio signals to digital data and digital data to radio signals. It also generates one-way or turns around ranging signals used for navigation. Figure 11 is a block diagram of the RFS. The RFS can receive data, transmit data, receive ranging, and transmit ranging simultaneously or perform any of these functions alone.

Uplink data arriving from an antenna pass through waveguide transfer switches and a diplexer before reaching the receiver within the Deep Space Transponder (DST). The receiver demodulates the 7175 MHz uplink signal and passes the 16 kHz subcarrier signal to the Command Detector Unit (CDU). The CDU demodulates the
subcarrier signal and outputs digital command data, clock, and lock signals to the CDS for interpretation.

Downlink data in non-return-zero digital format is received by the Telemetry Control Unit (TCU) from the CDS at rates from 5 bps to 249 kbps. The TCU modulates this data onto a 22.5 kHz, 360 kHz, or biphase-L subcarrier. An optional convolutional code of constraint length 7 and rate 1/2 or length 15 and rate 1/6 can also be added by the TCU. An exciter within the DST receives the output of the TCU and modulates the subcarrier onto an X-band carrier signal. There are 3 frequency sources for the exciter: auxiliary oscillator, ultrastable oscillator, or receiver controlled oscillator. The DST outputs to a 3 dB hybrid power splitter to both traveling wave tube amplifiers (X-TWTA). The amplified signal is then passed from the powered TWTA through the diplexer and waveguide switches to the selected antenna.

The DST's exciter can generate differential one-way ranging signals used for navigation. There are two tones that can be selected for this function. The DST can also perform turnaround or two-way ranging. The exciter receives a ranging signal from the ground and feeds this signal to the exciter. The exciter remodulates the received ranging signal at one of two indices onto the downlink carrier signal.

Some key RFS parameters are listed in Table 5.

### Table V

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink data rates</td>
<td>7.8125 to 500 bps</td>
</tr>
<tr>
<td>Receiver threshold</td>
<td>-156 dBm</td>
</tr>
<tr>
<td>Receiver noise figure</td>
<td>2.5 dB</td>
</tr>
<tr>
<td>Uplink frequency tracking range</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Uplink frequency acquisition range</td>
<td>±650 Hz</td>
</tr>
<tr>
<td>CDU threshold (Eb/No ratio)</td>
<td>12.59 dB</td>
</tr>
<tr>
<td>RF output power</td>
<td>20 W</td>
</tr>
</tbody>
</table>

6. Information System

Figure 12 is a block diagram of the spacecraft information system. The assemblies listed in Table 6 are distributed throughout the spacecraft and combine to form the information system.

Elements of the information system communicate over the active portion of redundant MIL-STD-1553B serial data buses. The data buses are redundant pairs of twisted shielded wires. The bus bandwidth is 610 kbps. The clock rate is 1 MHz.
Figure 12. Spacecraft Information System.
TABLE VI
Assemblies of spacecraft information system

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command and Data Subsystem</td>
<td>CDS</td>
</tr>
<tr>
<td>Bus Controller</td>
<td>BC</td>
</tr>
<tr>
<td>Critical Controller</td>
<td>CRC</td>
</tr>
<tr>
<td>Engineering Flight Computer</td>
<td>EFC</td>
</tr>
<tr>
<td>Engineering Unit</td>
<td>EU</td>
</tr>
<tr>
<td>Hardware Command Decoder</td>
<td>HCD</td>
</tr>
<tr>
<td>Reed Solomon Downlink</td>
<td>RSDL</td>
</tr>
<tr>
<td>Solid State Recorder</td>
<td>SSR</td>
</tr>
<tr>
<td>Cross Strapped Bus Adapter</td>
<td>XBA</td>
</tr>
<tr>
<td>Remote Engineering Unit</td>
<td>REU</td>
</tr>
<tr>
<td>Bus Interface Unit</td>
<td>BIU</td>
</tr>
<tr>
<td>Unique Interface Unit</td>
<td>UIU</td>
</tr>
<tr>
<td>Telemetry Processing Module</td>
<td>TPM</td>
</tr>
<tr>
<td>Data Bus</td>
<td></td>
</tr>
</tbody>
</table>

TABLE VII
Engineering flight computer parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>1750A</td>
</tr>
<tr>
<td>Software language</td>
<td>Ada</td>
</tr>
<tr>
<td>Word size</td>
<td>16 bits</td>
</tr>
<tr>
<td>Total RAM</td>
<td>8.2 Mbits</td>
</tr>
<tr>
<td>PROM</td>
<td>131 kbits</td>
</tr>
<tr>
<td>Throughput</td>
<td>1.28 MIPS</td>
</tr>
</tbody>
</table>

Data on the bus are Manchester II biphase encoded. Signal amplitudes range from 11.5 volts (logic ‘1’) to −11.5 volts (logic ‘0’).

The 1553 standard calls for a single master of the data bus. This function is performed by the CDS BC. The BC orchestrates the distribution of commands, telemetry, and spacecraft intercommunication messages by outputting commands or calling for inputs over the bus. All of the remote terminals connected to the bus are slaves to the BC. The BC’s are in turn controlled by the CDS EFCs over a CDS internal bus. Some key parameters of the EFC are listed in Table 7.
Some remote terminals such as science instruments are connected to the bus through BIUs. The BIU comes in several forms. In addition to a standard BIU there are the RFS UIU and the CDS and AACS XBAs that have all the features of the standard BIU plus some high rate data transfer capabilities. Other remote terminals such as the PPS are connected to the bus through REUs (a.k.a., TPM for the propulsion subsystem’s interface and EU for the command and data subsystem’s interface). Both the BIUs and REUs have the following interfaces: digital interface to the 1553B bus, discrete status lines to the users, discrete command lines to the users. The REUs also have voltage and temperature interfaces with users.

Data for realtime transmission are formatted by the EFC into transfer frames, optionally encoded with Reed-Solomon code within the RSDL, and sent to the RFS for translation into a radio signal. Over 9000 telemetry channels have been defined.

Data to be recorded is formatted into unencoded transfer frames by the EFC and sent to one of two SSRs. Each SSR has a capacity of 2 Gbits in the form of dynamic random access memory. Because this memory is vulnerable to radiation effects, the SSRs are encased in vaults of half-inch thick aluminum.

The CDS/SSR interface is capable of exchanging data at up to 1.5 Mbps although no software data mode has been defined to operate at this speed. The SSR memory space can be divided by command into as many as 16 partitions. The partitioning protects data from being overwritten and allows for segregation of incoming data into types, e.g., engineering and science data. Data can be recorded onto the SSRs by four different modes: read-write to end, circular buffer, first in first out, and direct memory addressing. Different modes can be used in different partitions simultaneously. Data can be simultaneously recorded and read out from the same partition. All science data are buffered in the SSR before transmission. Instrument health measurements known as ‘housekeeping telemetry’ are transmitted realtime.

The SSR is also used to store multiple copies of the flight software loads for the CDS, attitude control computers, and instruments. These copies are used in the event radiation corrupts a RAM load of any of these elements.

The CDS also coordinates uplinked commands. Most commands are processed by CDS software. Commands can stand alone and be tagged for delayed or immediate distribution. Commands can also be embedded in sequences. Approximately 2.4 Mbits of RAM is reserved in each CDS for storage of sequences. Up to 256 sequences can be stored. Up to 64 sequences can be simultaneously active. A maximum of 128 commands per second can be sent on the data bus; although, not all of these can originate from sequences as some of this capability has been reserved for fault responses. Over 1100 command stems have been defined.

A few commands need no software interpretation. These commands are interpreted by the HCD. Commands recognized by the HCD are routed to the CRC where latching relays are set. Such commands enable or disable critical events such as release of the probe release or powering off of critical hardware.
7. Pointing and Course Correction

Figure 13 is a block diagram of the Attitude and Articulation Control Subsystem. Figure 14 is a block diagram of the Propulsion Module Subsystem (PMS). Both subsystems feature block redundancy of critical elements including the main rocket engine. Together, these two subsystems provide the pointing and course correction functions for the spacecraft. The orbiter is designed for 3-axis stable operation. Some key system parameters are listed in Table 8.

The brain of the attitude control loop is the Attitude Flight Computer (AFC). The computer selected is the same computer used in the CDS. This computer controls a separate subsystem 1553 data bus for the AACS sensors and control mechanisms. Table 9 lists the principal flight modes of the AACS software. The normal mode during cruise is Home Base. Transitions are made to various other modes to perform maneuvers or fine pointing operations. The AFC software includes an extensive set of fault protection monitors and responses to manage the configuration of the subsystem.
Figure 14. Propulsion Module Subsystem.
TABLE VIII
Pointing and course correction parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe release pointing</td>
<td>30.2 mrad</td>
</tr>
<tr>
<td>HGA pointing</td>
<td>4.0 mrad</td>
</tr>
<tr>
<td>Probe relay pointing</td>
<td>3.5 mrad</td>
</tr>
<tr>
<td>Imaging science pointing</td>
<td>2.0 mrad</td>
</tr>
<tr>
<td>Radar pointing</td>
<td>1.3 mrad</td>
</tr>
<tr>
<td>Pointing stability (1 second)</td>
<td>8 microrad</td>
</tr>
<tr>
<td>Pointing stability (1 hour)</td>
<td>280 microrad</td>
</tr>
</tbody>
</table>

TABLE IX
AACS software modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Means of Attitude Determination</th>
<th>Attitude Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pause</td>
<td>None</td>
<td>Idle</td>
</tr>
<tr>
<td>Coast</td>
<td>IRU</td>
<td>Idle</td>
</tr>
<tr>
<td>Detumble</td>
<td>IRU</td>
<td>RCS</td>
</tr>
<tr>
<td>Find_Sun</td>
<td>IRU, SSA</td>
<td>RCS</td>
</tr>
<tr>
<td>Center_Sun</td>
<td>IRU, SSA</td>
<td>RCS</td>
</tr>
<tr>
<td>Find_Stars</td>
<td>IRU, SSA, SRU</td>
<td>RCS</td>
</tr>
<tr>
<td>Home_Base, Inertial_RCS</td>
<td>IRU</td>
<td>RCS</td>
</tr>
<tr>
<td>Home_Base, Inertial_RWA</td>
<td>IRU</td>
<td>RWA</td>
</tr>
<tr>
<td>Home_Base, Cruise_RCS</td>
<td>SRU</td>
<td>RCS</td>
</tr>
<tr>
<td>Home_Base, Cruise_RWA</td>
<td>SRU</td>
<td>RWA</td>
</tr>
<tr>
<td>ME_DeltaV</td>
<td>IRU</td>
<td>ME/RCS</td>
</tr>
<tr>
<td>RCS_DeltaV</td>
<td>IRU</td>
<td>RCS</td>
</tr>
</tbody>
</table>

An important inclusion on the AACS data bus is the valve drive electronics (VDE). This allows the AFC to command the propulsion elements without having to use the spacecraft data bus, thereby improving the response time of the control loop.

Attitude positions and rates are determined using several AACS sensors. Stellar reference units (SRU) provide the primary source of attitude knowledge. Sun sensors (SSA) seed the star identification algorithm for the trackers and furnish an emergency attitude reference. Inertial reference unit gyros (IRU) measure rates during major course correction burns and turns. A single accelerometer (ACC)
TABLE X
AACS sensor parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRU field of view</td>
<td>15 deg × 15 deg</td>
</tr>
<tr>
<td>SRU-based attitude knowledge</td>
<td>1 mrad (3 axis, rates &lt; 0.3 deg s(^{-1}))</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>5.6 Mv stars</td>
</tr>
<tr>
<td>Stars in catalog (in AFC)</td>
<td>5000</td>
</tr>
<tr>
<td>SSA field of view</td>
<td>60 deg × 60 deg</td>
</tr>
<tr>
<td>SSA range</td>
<td>0.6 to 10.06 AU</td>
</tr>
<tr>
<td>SSA-based attitude knowledge</td>
<td>26 mrad (2 axis)</td>
</tr>
<tr>
<td>IRU type</td>
<td>hemispherical resonating</td>
</tr>
<tr>
<td>IRU drift rate</td>
<td>&lt;1 deg h(^{-1})</td>
</tr>
<tr>
<td>IRU drift rate stability</td>
<td>&lt;0.06 deg h(^{-1}) (8 h period)</td>
</tr>
<tr>
<td>IRU resolution</td>
<td>0.25 microrad</td>
</tr>
<tr>
<td>IRU full performance range</td>
<td>&lt;2 deg s(^{-1})</td>
</tr>
<tr>
<td>IRU degraded performance range</td>
<td>&lt;15 deg s(^{-1})</td>
</tr>
<tr>
<td>ACC range</td>
<td>&gt;± 1.12 g</td>
</tr>
<tr>
<td>ACC resolution</td>
<td>0.002 g</td>
</tr>
</tbody>
</table>

provides closed loop time out of major burns. Table 10 lists some of the key parameters of the AACS sensors.

Attitude is controlled using either reaction control thrusters (RCS) or reaction wheels (RWA). The thrusters are used for coarse pointing control, the reaction wheels for fine control (2 mrad, 99% radial). There are block redundant branches of eight thrusters pointed in the spacecraft +Z and +Y directions mounted in four clusters. There are three primary and one backup reaction wheels. The backup wheel is mounted on an articulating platform so that it can be positioned to compensate for the loss of any of the three primary wheels. Each wheel is capable of storing greater than 36 Nms of momentum and producing greater than 0.14 Nm of torque under certain conditions.

Table 11 lists some key parameters of the thruster system. The propellant is hydrazine. The feed system is a blowdown type with a single recharge. Helium is used as the pressurant. A membrane is employed within the hydrazine tank to serve as the propellant management device.

For course corrections of magnitude less than 1 m s\(^{-1}\) to 5 m s\(^{-1}\) the thrusters described above are used. For course corrections greater than 5 m s\(^{-1}\) such as orbit injection, one of two redundant main engines is used. These engines burn the bipropellants nitrogen tetroxide and monomethyl hydrazine. Each engine is gimbaled to keep the thrust through the spacecraft center of mass. The propellants
are stored in two tanks. Each tank features a vane-type propellant management device. The system can be operated in a blowdown or pressure regulated mode. The pressurant is helium and is supplied from a single tank. The pressurant system features pyrovalve ladders to prevent the mixing of fuel and oxidizer vapors. Mixing of propellant vapors is one of several possible causes for the loss of the Mars Observer spacecraft. Table 12 lists some key parameters of the main engine system.

8. Miscellaneous Design Features

Several miscellaneous features of the orbiter are worth noting. Attached to the bottom of the orbiter is a cover for the main engines. This cover is deployable and retractable like a baby carriage cover. It is used to protect the main engines from micrometeoroid strikes. The insides of the engine nozzles have thin thermal coatings that are particularly vulnerable to micrometeoroid damage.

Several approaches are taken to control temperatures on the orbiter. Electrically conducting and grounded multilayer thermal blankets are used extensively. Many of these blankets include a special layer of material to provide protection from micrometeoroids. A number of special paints are used. A particularly challenging painted surface is the HGA that has an allowable temperature range of about −200 to +125 degrees Celsius. Thermostatically controlled louvers are mounted

### TABLE XI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel load at launch</td>
<td>132 kg</td>
</tr>
<tr>
<td>Thrust per thruster</td>
<td>1 N (0.2 lbf)</td>
</tr>
<tr>
<td>Maximum burn duration</td>
<td>120 min</td>
</tr>
<tr>
<td>Thruster cycles</td>
<td>270 000</td>
</tr>
<tr>
<td>Throughput per thruster</td>
<td>25 kg</td>
</tr>
<tr>
<td>Minimum impulse bit</td>
<td>&lt;0.015 N-s</td>
</tr>
<tr>
<td>Fuel tank volume</td>
<td>11 350 in³</td>
</tr>
<tr>
<td>Fuel tank maximum operating pressure</td>
<td>420 psig</td>
</tr>
<tr>
<td>Fuel tank pressure at launch</td>
<td>367 psia</td>
</tr>
<tr>
<td>Fuel tank pressure at recharge</td>
<td>237 psia</td>
</tr>
<tr>
<td>Pressurant tank volume</td>
<td>14 340 in³</td>
</tr>
<tr>
<td>Pressurant tank maximum operating pressure</td>
<td>3720 psig</td>
</tr>
<tr>
<td>Recharge tank volume</td>
<td>418 in³</td>
</tr>
<tr>
<td>Recharge tank maximum operating pressure</td>
<td>3600 psig</td>
</tr>
</tbody>
</table>
on the outboard shearplates of many electronics bus bays to control the temperature swings associated with cycling power. Electrical heaters are used in many places. Software algorithms control some of these heaters. Radioisotope heater units, 1 W pellets of plutonium dioxide, are used in other places such as the thruster clusters to limit the amount of electrical power required. Waste heat from the RTG’s is channeled onto the exteriors of the main propellant tanks. Finally, there are several surfaces that are used to shade other parts of the spacecraft. The HGA is the most important of these. Whenever the distance from the spacecraft to the Sun is less than 2.7 AU, the HGA is pointed at the Sun to shade the spacecraft. This attitude is maintained except for short periods for trajectory correction maneuvers. The Huygens Probe is pointed at the Sun to shade the spacecraft during maneuvers.

9. Huygens Probe

The Huygens probe weighs 319 kg and is 2.7 m in diameter. During flight to Saturn it receives power from the orbiter for occasional checkouts. On November 6, 2004 it will be pointed at Titan and released by orbiter-initiated pyrotechnics. A spin eject device will spin up the probe to about 7 rpm as it is released. Probe support equipment (PSE) remains onboard the orbiter to receive and translate the radio signals from the Probe.

On January 14, 2005 it is expected that the Probe will enter Titan’s atmosphere. A coast timer set by the orbiter just before orbiter/probe separation will awaken the probe avionics about 15 min before encountering the atmosphere. A series
of deployments and jettisons of parachutes and engineering assemblies follows eventually culminating with a landing on Titan’s surface. The descent is expected to take 20 to 150 min. The probe may survive another 30 min on the surface.

As shown in Figure 15 the probe has six major structural assemblies. The front shield is made of tiles of silica fibers attached to a honeycomb shell with insulating foam sprayed on the back of the shell. The front of the shield ablates to provide thermal protection from the 1 MW m\(^{-2}\) flux as the probe decelerates from about Mach 20 to Mach 0.6. The front shield is jettisoned at around 160 km altitude. The fore dome provides thermal protection for the rest of the descent. Spin vanes attached to the fore dome provide a controlled spin rate for camera observations. The experiment platform and top platform are aluminum honeycombs supporting

*Figure 15. Huygens Probe Structure Assemblies.*
Figure 16. Top of Probe Experiment Platform.

Figure 17. Bottom of Probe Experiment Platform.
the instrument and engineering subsystem packages. The instrument locations on
the experiment platform are shown in Figure 16 and Figure 17. The after cone and
back cover are aluminum structures completing the package. The back cover is
detached by the deployment of the first of three parachutes.

The principal elements of the Descent Control Subsystem are three parachutes.
The first or pilot chute is 2.59 m in diameter and pulls the back cover away. The
8.3 m main parachute is deployed as the back cover is pulled away. This chute
decelerates the probe to about Mach 0.6. The third drogue parachute is only 3.0 m
in diameter so that the probe drops to the surface before running of power.

The probe sequence is controlled by block redundant Command and Data Man­
agement Units (CDMUs). Total memory is about 20 kbits. Three redundant timer
units and two redundant g-switches are used to trigger sequencing. Software is in
the Ada programming language.

Five lithium-sulphur dioxide batteries power the probe avionics. Total capacity
is about 1600 W-hr. One of these batteries can fail without compromising the
mission. The Power Conditioning and Distribution Unit (PDCU) supplies power
at 28 V. The peak load during descent is somewhere 300–400 W. A Pyro Unit
provides redundant sets of lines for 13 devices.

The probe has redundant S-band transmitters and antennas. One is left hand
circularly polarized, the other right hand. Identical data is transmitted from both
transmitters; however, a six second delay is used between transmissions to reduce
the chance of data loss due to link gaps. The orbiter HGA receives both signals.
Probe support avionics on the orbiter convert the radio signals to digital data. Probe
data is redundantly recorded on the orbiter SSRs.

10. Web Sites

Additional information about the Cassini Orbiter and Huygens Probe can be found
at the following web sites:
http://sci.esa.int/huygens

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THE HUYGENS PROBE SYSTEM DESIGN

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Abstract.

The Huygens Probe is the ESA-provided element of the joint NASA/ESA Cassini/Huygens mission to Saturn and its largest moon Titan. Huygens is an entry probe designed to enter Titan’s atmosphere and descend under parachute down to the surface. The Probe is carried to Titan on board the Cassini Saturn Orbiter. Huygens is dormant for 7.2 years, during the interplanetary journey and during the first 6 months around Saturn. It is activated about every 6 months for an in-flight checkout to verify and monitor its health and to perform a periodic maintenance and calibration of the payload instruments. The Probe will be targeted to Titan and released from the Orbiter about 3 weeks before the Titan encounter on the third Orbit around Saturn. During the 3-week coast phase the Probe is ‘OFF’, except a timer unit that has the task to awaken Huygens before it enters Titan’s atmosphere. The Probe’s aeroshell will decelerate it in less than 2 minutes from the entry speed of about 6 km s\(^{-1}\) to 400 m s\(^{-1}\) (Mach 1.5) at an altitude of 150–180 km. From that point onwards, a pre-programmed sequence will trigger the parachute deployment and the heat-shield ejection. The main part of the scientific mission will then start, lasting for a descent of 2–21/2 hours. The Orbiter will listen to the Probe for a total duration of at least 3 hours, which includes time to receive data from the surface, should the Probe continue to transmit data after touchdown. Huygens’ transmissions are received and stored aboard the Orbiter for later retransmission to the Earth.

This paper presents a technical description of the elements of the Huygens Probe System. The reader is invited to refer to the companion paper (Lebreton and Matson, 2002) for further background information about the Huygens mission, and the payload. The early in-flight performance of the Probe is briefly discussed. During in-flight testing in 2000, a technical anomaly was found with the Probe-to-Orbiter telecommunication system that required a change in the Huygens mission scenario designed before launch. It required also a change in the Orbiter trajectory during the Probe mission. This change was achieved by modifying the initial Cassini/Huygens orbits around Saturn. At the time of writing, details of the implementation of the revised Huygens mission scenario are still being worked.

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1. The Huygens Technical and Programmatic challenges

The Huygens Probe is the European Space Agency (ESA) first planetary atmospheric entry mission. It is part of the joint NASA/ESA Cassini Huygens mission to Saturn and Titan. Several of the technologies required for Huygens were very different from those needed for more traditional satellite missions (Hassan et al., 1994, Hassan et al., 1997). The development of Huygens presented a considerable challenge both to ESA and to European Industry. Special systems such as the Thermal Protection System and parachutes had to be developed specifically for the entry into Titan’s atmosphere. These factors and ESA’s geographical-return requirements presented special management challenges, which had to be solved in order to achieve the prescribed objectives. Following several years of studies (Lebreton and Matson, 2002), the industrial development activities of the Huygens Probe started in early 1990, and followed the schedule illustrated in Figure 1. The main industrial contractor, Aerospatiale (now Alcatel Space), Cannes, France, was selected at the end of 1990 and the detailed definition phase (phase B) started in mid-January 1991. The composition of the industrial Team was finalised at the end of Phase-B. As Figure 2 shows, it represents a very broad spectrum of European space industries with some involvement of US industry in very specific areas.

The overall Cassini/Huygens mission is managed by the Jet Propulsion Laboratory (JPL) for NASA. Early during phase B, clear programmatic and technical interfaces were established between ESA and JPL which allowed both ESA’s Huygens Probe and NASA/JPL’s Cassini Saturn Orbiter to proceed on parallel tracks with well identified interface definition and validation milestones.
Figure 2. The Huygens industrial consortium is spread all over Europe and includes firms in the US.

2. The Huygens Probe System and its mission

The Huygens Probe has been designed to be carried to Titan by the Cassini Saturn Orbiter with all its equipment in the OFF state. The Huygens Probe System consists of the Probe itself and the Probe Support Equipment (PSE). The Probe will detach from the Orbiter and enter into Titan’s atmosphere three weeks later, whereas the PSE will remain attached to the Orbiter. The PSE consists of the electronics necessary to track and recover data from the Probe during its descent and to process this data for recording on the Orbiter solid-state recorders, for later transmission to Earth when the Cassini-Earth link will be re-established after the Probe mission is over. The PSE also provides a command and data link to the Probe whilst the latter is attached to the Orbiter.

Following its launch in October 1997, the Probe System remains in a dormant state for seven years as the Cassini/Huygens spacecraft follows its cruise trajectory via Venus (twice), Earth and Jupiter, before finally entering the Saturnian system in late June 2004 (Figure 3). During the cruise phase, Huygens is activated for its scheduled bi-annual health checks. These in-flight checkouts, which last between 3 and 4 hours, have been designed to follow as closely as possible the pre-programmed descent scenario. The purpose of those bi-annual health checks (called Probe checkouts) is to perform periodic instrument maintenance and regular payload sensor calibration. Additionally, the PSE alone can be activated to support in-flight end-to-end testing of the receiving elements of the Huygens telecommu-
communication system. Such end-to-end tests are carried out by using a NASA Deep Space Network Antenna to mimic the Probe radio transmissions. The Huygens receiver anomaly was discovered as a result of the first end-to-end relay test carried out in February 2000 (see section 8.3).

On reaching Saturn, the composite Cassini/Huygens spacecraft will enter a highly eccentric capture orbit around the planet. The first two orbits around Saturn are used to prepare for the required geometry that needs to be achieved to conduct the Huygens mission on the third orbit (Figure 4). Prior to Probe release, the composite Orbiter/Probe will be targeted on to a collision path to Titan. About 22 days before Titan encounter, the Probe will be released from the Orbiter. It will then enter into coast phase. Five days after Probe separation, the Orbiter will initiate a deflection manoeuvre to avoid Titan itself and to be placed on a trajectory optimised for the acquisition of Probe data during descent and while on the surface. The communication window with the Probe is designed to last at least 3 hours for a maximum descent time of 2½ hours.

Prior to the Probe separation from the Orbiter, a final health-check will be performed and the coast timer will be loaded with the precise time necessary to ‘wake-up’ the Probe systems prior to encountering Titan’s atmosphere. For 22 days, the Probe will coast to Titan with no possibility of changing the attitude parameters acquired at separation. The only unit electrically active during the coast is the triple redundant wake-up timer.

At the end of the 22-days coast period, the Probe will be switched ON via its timer. At the time of writing, two options are being pursued for the implementation of the revised Huygens mission. The first option includes an early switch ON of the
Probe to allow a long warm-up of the Probe equipment, in particular of the clock that generates the data-stream modulation frequency. A warm-up time of 4 hours is being studied. The second option is based on the old mission baseline (Lebreton and Matson, 1997) that foresees Probe switch-on 25 min prior to entry.

The Probe switch-on event will activate the on-board computers, which will then take control of the on-board operations. After system initialisation, the payload instruments will be activated in a pre-programmed sequence. A set of Probe parameters, called the broadcast data block, will be distributed to all the payload instruments. Thus, they use the same reference parameters for sequence initialisation. It contains such information as: Probe time, spin rate, internal temperature, altitude and special-event flags. The Probe descent sequence will be activated based on the detection of the entry deceleration peak. A pilot chute, and then a main chute, will be deployed in sequence in the supersonic regime (Mach 1.5). The heat-shield will be released 30 s after passing through Mach 1. At this point the Orbiter will be about 2 h away from closest approach to Titan which will be about 60 000 km above the surface. The geometry during the Probe mission is illustrated in Figure 5. Data transmission to the Orbiter will be initiated 45 sec after deployment of the main parachute. The housekeeping and the science data are formatted by the Probe on-board computers and transmitted to the Huygens receivers on-board the Orbiter via the hot-redundant, two-channel, Probe-Orbiter radio link. Each telecommunication channel is designed to support a constant data rate of 8 kbps. The data will be received by the Huygens PSE via the Orbiter High Gain Antenna and packetized for relay to the Orbiter’s on board computer that will store them on its solid-state recorders for later transmission to Earth.

3. The Huygens Model Philosophy

The design and verification activities of Huygens required several development models to be built. The Huygens model philosophy was to achieve the most com-
Figure 5. Orbiter trajectory during the Probe mission. For reference, the old baseline trajectory is also indicated.

Complete verification possible that the Probe system meets the mission requirements within the cost envelope and the tight schedule constraints imposed by the launch window. Four models were developed at system level:

3.1. THE STRUCTURAL, THERMAL & PYRO MODEL (STPM)

Its purpose was to qualify the Probe design (including all mechanisms activated by pyrotechnic devices) for all structural, mechanical and thermal requirements. After launch, the STPM is being used as an exhibition model.

3.2. THE ENGINEERING MODEL (EM)

This model was used to verify the electrical performances of the Probe, including the payload instruments, and to test the electrical and functional interfaces with the Orbiter. After launch, the EM has been installed at the Huygens Probe Operations Centre, in ESOC, Darmstadt, Germany, ESA’s Flight Operations Centre for use as a testbed to support the Probe flight operations activities. EM payload unit interfaces were upgraded to flight standard to increase the system reliability of the EM testbed.
3.3. THE BALLOON DROP TEST MODEL

This model was known as the ‘Special Model#2’ (SM2). Early in the programme, another Special Model (SM1) was foreseen but eventually not built. The SM2 was used for a complete validation (demonstration) of the descent sequence in the most realistic way achievable on Earth. The SM2 was carried aloft a stratospheric balloon and dropped from an altitude of 35 km (Jaekel, et al., 1998). It allowed the verification, 30 months before launch, of the design of all the mechanisms of the descent control subsystem (heat shield separation, parachute deployment). All SM2 mechanisms were of flight standard. After launch, the SM2 is also being used as an exhibition model.

3.4. THE FLIGHT MODEL (FM)

All flight units were specifically built for integration into the FM Probe. None of the units built in the FM were used for instrumenting any of the three models previously described.

Flight spare units of all electrical subsystems, and of all payload instruments, were also built in order to minimise Probe refurbishment delays in case of a unit failure during critical phases of the integration activities of the FM. After launch, flight spare units were integrated into the EM Probe to make it function as realistically as possible like the flight model. Payload flight spare units are being maintained at respective Principal Investigator laboratories for calibration and measurement validation tests.

The main milestones and the major standard reviews carried out at ESA level are indicated in the overall development schedule in Figure 1. Additional joint ESA/JPL reviews were included in the development schedule as required by the specific nature of the Orbiter/Probe interfaces. Huygens was also subjected to the External Independent Review system put in place by NASA for Cassini/Huygens.

4. Overall Huygens Configuration

The Huygens Probe System (Clausen and Sainct, 1994; Jones and Giovanoli, 1997) consists of two principal elements: (i) the Huygens Probe itself, the element that will detach from the Saturn Orbiter and enter in the atmosphere of Titan; (ii) the Probe Support Equipment (PSE), the Huygens element that will remain attached to the Orbiter after Probe separation, and will provide the radio relay link functions with the Probe. The Huygens system has been optimised to make it robust to uncertainties of Titan’s environment (Carton et al., 1995).
4.1. THE HUYGENS PROBE

The mass breakdown of the Huygens Probe System is provided in Table I. The Probe (Figure 6) consists of two elements: The aeroshell and the Descent Module. The aeroshell is wrapped into a multi-layer thermal protection for the cruise phase. It is made of two parts: the front-shield and the back-cover. The Descent Module comprises two platforms, a fore-dome and an after-cone.

The Descent module is enclosed in the aeroshell like a cocoon. The aeroshell and the descent module are attached to each other by mechanisms at three points. The aeroshell is jettisoned after entry, releasing the Descent Module. The various elements are described in more details below.

4.2. THE PROBE SUPPORT EQUIPMENT (PSE)

The Probe Support Equipment consists of:
- Two redundant Probe Support Avionics (PSA) electronic boxes;
- Two redundant radio Receiver Front End's (RFE);
- The Doppler Wind Experiment (DWE) Receiver Ultrastable Oscillator (RUSO);
- The Spin Eject Device (SED);
- The harness (including the umbilical connector) providing power, command and RF and data links between the PSA, Probe and Orbiter during the cruise phase.

The Probe is installed on the Orbiter by the supporting ring of the Spin Eject Device (Figure 7). The ring is equipped with guide rails. Spring loaded pyrotechnic
The Huygens probe system design

Table I
Huygens mass budget

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Probe</th>
<th>PSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRSS</td>
<td>78.75</td>
<td></td>
</tr>
<tr>
<td>BCSS</td>
<td>16.13</td>
<td></td>
</tr>
<tr>
<td>SEPS</td>
<td>11.40</td>
<td>10.29</td>
</tr>
<tr>
<td>DCSS</td>
<td>12.13</td>
<td></td>
</tr>
<tr>
<td>ISTS</td>
<td>41.41</td>
<td></td>
</tr>
<tr>
<td>THSS</td>
<td>20.60</td>
<td>1.50</td>
</tr>
<tr>
<td>EPSS</td>
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<td></td>
</tr>
<tr>
<td>PHSS</td>
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<td></td>
</tr>
<tr>
<td>CDMS</td>
<td>23.10</td>
<td></td>
</tr>
<tr>
<td>PDRS</td>
<td>6.04</td>
<td>16.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Probe</th>
<th>PSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUSO/RUSO</td>
<td>1.90</td>
<td>1.90</td>
</tr>
<tr>
<td>SSP</td>
<td>4.87</td>
<td></td>
</tr>
<tr>
<td>GCMS</td>
<td>17.20</td>
<td></td>
</tr>
<tr>
<td>HASI</td>
<td>5.77</td>
<td></td>
</tr>
<tr>
<td>DISR</td>
<td>8.07</td>
<td></td>
</tr>
<tr>
<td>DISR cover</td>
<td>3.63</td>
<td></td>
</tr>
<tr>
<td>ACP</td>
<td>6.18</td>
<td></td>
</tr>
<tr>
<td>Fasteners, etc</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Balance mass</td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>318.32</td>
<td>29.99</td>
</tr>
</tbody>
</table>

Devices maintain the Probe in place on the ring. The umbilical cord links the Probe to the Orbiter and provides all electrical connections – Electrical power, RF link, and temperature monitoring – between the Probe and the Orbiter when they are attached during the cruise. Upon firing at Probe separation, the umbilical will be disconnected and the Probe will separate from the Orbiter with a small relative velocity of 0.3 m s⁻¹ and a spin of 7 RPM.

The overall Probe System configuration and its interfaces with the Orbiter is shown functionally in Figure 8. The subsystem breakdown is illustrated in Figure 9. Each subsystem is described in detail below.
Figure 7. Huygens Probe Accommodation on the Orbiter (A Probe development model and the Orbiter mechanical mock-up model are shown in this figure).

Figure 8. Huygens Probe System architecture. The acronyms used are explained for clarity. PSA: Probe System Avionics; S/S: subsystem; TUSO: Transmitter Ultrastable Oscillator; RUSO: Receiver Ultrastable Oscillator; HGA: (Orbiter) High Gain Antenna; RFE: Receiver Front End; TF: Transfer Frame.
5. Mechanical and Thermal Subsystems

The Huygens Probe is designed to enter into an atmosphere whose profile and chemical composition are specified by ‘engineering models’. The design of the aeroshell, which consists of the front shield and the back cover, is the result of various engineering trade-off studies (Patti, 1995).

5.1. Front Shield Subsystem (FRSS)

The 79 kg, 2.7 m diameter, 60-degree half-angle coni-spherical front shield is designed to decelerate the Probe in Titan’s upper atmosphere from about 6 km s\(^{-1}\) at entry to a velocity equivalent to about Mach 1.5 (\(~400\) m s\(^{-1}\)) by around 160 km altitude. Tiles of ‘AQ60’ ablative material – a felt of phenolic resin reinforced by silica fibres – provide protection against the entry thermal flux up to 1.4 MW m\(^{-2}\). The shield is then jettisoned and the Descent Control Subsystem (DCSS) is deployed to control the descent of the Descent Module (DM) to the surface. The FRSS supporting structure is a Carbon Fibre Reinforced Plastic (CFRP) honeycomb shell. It was also designed to protect the DM from the heat generated during entry. The AQ60 tiles are attached to the CFRP structure by adhesive CAF/730. Prosial, a suspension of hollow silica spheres in silicon elastomer, is sprayed dir-
ectly on the aluminium structure of the FRSS rear surfaces, which are expected to experience heat fluxes ten times lower than those to be experienced by the front shield.

5.2. BACK COVER SUBSYSTEM (BCSS)

The Back Cover (BC) protects the DM during entry, and carries multi-layer insulation (MLI) for the cruise and coast. A hole in it ensures depressurisation during Launch and repressurisation during entry. As it does not have stringent aerothermodynamic requirements, it is a stiffened aluminium shell of minimal mass (11.4 kg) protected by Prosial (5 kg). It includes: (i) an access door for late integration and forced-air ground cooling of the Probe; (ii) a break-out patch through which the first (drogue) parachute is fired; iii) a labyrinth sealing joint with the Front Shield, which provides a non-structural thermal and particulate barrier.

5.3. DESCENT CONTROL SUBSYSTEM (DCSS)

The DCSS controls the descent rate to satisfy the scientific payload’s requirements, and to provide the attitude stability to meet the requirements of the Probe-to-Orbiter RF data link and the stability requirements of the descent imager. The DCSS is activated nominally at Mach 1.5, at about 160 km altitude. The sequence (Figure 10) begins by firing the Parachute Deployment Device (PDD) to eject the
pilot chute pack through the Back Cover’s break-out patch, the attachment pins of which shear under the impact. The 2.59 m diameter Disk Gap Band (DGB) pilot chute inflates behind the DM and pulls the Back Cover away from the assembly. As it goes, the Back Cover pulls the 8.30 m diameter DGB main parachute from its container. This canopy inflates during the supersonic phase in order to decelerate and stabilise the Probe through the transonic regime. The Front Shield is released at about Mach 0.6. In fact, the main parachute is sized by the requirement to provide sufficient deceleration to guarantee a positive separation of the Front Shield from the Descent Module. The main parachute is too large for a nominal descent time shorter than 2.5 hours, a constraint imposed by battery capacity, communication geometry between the Probe and the Orbiter, and thermal performances of the DM in Titan’s atmosphere. It is therefore jettisoned after 15 min and a 3.03 m diameter DGB stabilising parachute is deployed. All parachutes are made of kevlar lines and nylon fabric. The main and the stabiliser chutes are housed in a single canister on the DM’s top platform. Compatibility with the Probe’s spin is ensured by incorporating a swivel using redundant low-friction bearings in the connecting riser of both the main and stabiliser parachutes.

5.4. Separation Subsystem (SEPS)

The Separation Subsystem (SEPS) provides: (i) mechanical attachment and electrical connection to, and separation from the Orbiter; (ii) the transition between the entry configuration (‘cocoon’) and the descent configuration (DM under parachute). The three SEPS mechanisms are connected on one side to Huygens’ Inner Structure (ISTS) and on the other side to the Orbiter’s supporting struts. As well as being the Probe-Orbiter structural load path, each SEPS fitting incorporates a pyronut for Probe-Orbiter separation, a rod cutter for front shield release and a rod cutter for Back Cover release.

Within the SEPS, the Spin Eject Device (SED) performs the mechanical separation from the Orbiter:

- Three stainless steel springs provide the separation force;
- Three guide devices, each with two axial rollers running along a T-profile helical track, ensure controlled ejection and spin, even in degraded cases such as high friction or a weak spring;
- A carbon fibre ring accommodates the asymmetrical loads from the Orbiter truss and provides the necessary stiffness before and after separation;
- Three pyronuts provide the mechanical link before separation.

In addition, the Umbilical Separation Mechanism (USM) of three 19-pin connectors, which provide Orbiter-Probe electrical links, is disconnected by the SED.
5.5. **INNER STRUCTURE SUBSYSTEM (ISTS)**

The ISTS provides mounting support for the Probe’s payload and subsystems. It is fully sealed except for a vent hole of about 6 cm² on the top. It consists of:
- A 73 mm thick aluminium honeycomb sandwich experiment platform which supports the majority of the experiments and subsystems units, together with their associated harnesses;
- A 25 mm thick aluminium honeycomb sandwich top platform which supports the Descent Control Subsystem and the two Probe RF transmitting antennas, and forms the DM’s top structure;
- The After Cone and Fore Dome aluminium shells, linked by a central ring;
- Three radial titanium struts, which interface with the SEPS and provide thermal decoupling between the Probe and the Orbiter, while three vertical titanium struts link the two platforms and transfer the main parachute deployment loads;
- 36 spin vanes on the Fore Dome’s periphery, which provide spin control during descent through aerodynamic interaction with the atmosphere;
- The secondary structure for mounting experiments and equipment.

5.6. **THERMAL SUBSYSTEM (THSS)**

The PSE is thermally controlled by the Orbiter. The Probe’s thermal subsystem (THSS) must maintain all experiments and subsystem units aboard the Probe within their allowed temperature ranges during all mission phases. In the vacuum of space, the THSS partially thermally insulates the Probe from the Orbiter. It ensures only small variations in the Probe’s internal temperatures, despite variation in the solar flux from 3800 W m⁻² (near Venus, but only during short periods as the Probe is normally shadowed under the Orbiter’s High Gain Antenna) to 17 W m⁻² (approaching Titan).

As shown in Figure 11, Probe thermal control is achieved by:
- A Multi-Layer Insulation (MLI) blanket surrounding all external areas, except for the small ‘thermal window’ in the Front-Shield (see below);
- 35 Radioisotope Heater Units (RHUs) on the experiment platform and the top platform providing about 1 W each all the time;
- A white-painted 0.17 m² thin aluminium sheet on the front shield’s forward face which acts as a controlled heat leak (about 8 W during cruise). It reduces the sensitivity of thermal performances to the MLI efficiency.

The MLI is burned and torn away during entry. The temperature is controlled by the ‘AQ60’ high-temperature tiles on the front-shield’s front face, and by Prosial on the front shield’s aft surface and on the Back Cover. During the descent phase, thermal control is provided by foam insulation and gas-tight seals. Lightweight open-cell Basotect foam covers the internal walls of the DM’s shells and the top platform. This prevents convective cooling by Titan’s cold atmosphere (70 K at
THE HUYGENS PROBE SYSTEM DESIGN

Figure 11. The Probe's thermal control system. RHU: Radioisotope Heater Unit; MLI: Multi Layer Insulation.

Figure 12. Huygens Probe Electrical Power Subsystem (EPSS). BDR: Battery Discharge Regulator; SSPS: Solid State Power Switch; The power lines (POWs) from the Orbiter to BDR's sections are called: Pow1: SSPS1 to BDR1; POW2: SSPS 2 + SSPS 3 to BDR 2; POW3: SSPS 4 to BDR 3; POW4: SSPS 5 + SSPS 6 to BDR 4; POW5: SSPS 7 to BDR 5.

45 km altitude, 94 K on the surface) and it decouples the units mounted on the experiment platform from the cold aluminium shells. Gas-tight seals around all elements protruding through the DM's shell minimise gas influx. In fact, the DM is gas tight except for a single 6 cm² hole in Top Platform that allow equalisation of pressure during launch and entry through the atmosphere of Titan.
6. Electrical Power Subsystem (EPSS)

6.1. Description

As shown in Figure 12, the Electrical Power Subsystem (EPSS) consists of three main elements which will now be discussed.

6.1.1. Batteries

Five batteries provide the mission's electrical power. Each battery consists of two modules of 13 L\textsuperscript{2}SO\textsubscript{2} (7.6 Ah) cells in series. The expected utilisation of the available battery energy during the mission (no pre-heating option) is detailed in Table II. The pre-heating option of the recovery mission requires an additional 400 Wh, which is available thanks to ample margin available if all 5 batteries are healthy.

6.1.2. The Power Conditioning & Distribution Unit (PCDU)

The PCDU conditions the power and distributes it via a regulated main bus, with protection to ensure uninterrupted operations even in the event of a single failure inside or outside the PCDU.

During the cruise, electrical power is provided by the Orbiter. The PCDU isolates the batteries. The five interface circuits connected to the Orbiter's Solid State Power Switches (SSPSs) provide Probe-Orbiter electrical isolation and voltage conversion between the SSPS output and the input of the PCDU's Battery Discharge Regulator (BDR) circuits. The BDRs adapt the power from either the Orbiter or the batteries and generate the 28 V for the bus. This is controlled by a centralised Main Error Amplifier (MEA). The power is distributed by active current limiters. The current limitation level is set for each user and with ON/OFF switching capability. The Mission Timer, however, is supplied by three switchable battery voltage lines through series fuses or, when the PCDU is powered by the Orbiter, by dedicated output voltage lines of the Orbiter interface circuits. The PCDU also provides a protected +5 V power supply used by the Pyro unit to generate the bi-level status telemetry of the selection relays and for the activation circuit that switches ON the Pyro unit's power intercept relay.

6.1.3. The Pyro Unit (PYRO)

The pyro unit consists of two redundant sets of 13 pyro lines, directly connected through protection devices to the centre tap of two batteries. Safety requirements are met by three independent levels of control relays in series, as well as by active switches and current limiters controlling the firing current (Figure 13). The three series relay levels are: (i) energy intercept relay (activated by PCDU at the end of the coast phase); (ii) arming relays (activated by the arming timer hardware triggered by a measured deceleration threshold during entry); (iii) selection relays (activated by Command and Data Management Unit, CDMU, software). In ad-
### TABLE II

<table>
<thead>
<tr>
<th></th>
<th>Coast (22 days)</th>
<th>Pre-entry entry (18 min)</th>
<th>Descent w/o proximity sensor (80 min)</th>
<th>Descent with proximity sensor (73 min)</th>
<th>Energy (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDRS (on Probe)</td>
<td>0.272</td>
<td>10.98</td>
<td>82.61</td>
<td>82.61</td>
<td>214</td>
</tr>
<tr>
<td>CDMS</td>
<td>0.272</td>
<td>26.39</td>
<td>26.39</td>
<td>37.73</td>
<td>246</td>
</tr>
<tr>
<td>EPSS (incl. Pyro)</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
<td>5</td>
</tr>
<tr>
<td>Payload</td>
<td>60</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>325</td>
</tr>
<tr>
<td>PCDU losses</td>
<td>25</td>
<td>47.3</td>
<td>47.3</td>
<td>47.3</td>
<td>128</td>
</tr>
<tr>
<td>Harness losses (0.5%)</td>
<td>0.50</td>
<td>1.45</td>
<td>1.51</td>
<td>1.51</td>
<td>4</td>
</tr>
<tr>
<td><strong>Power total</strong></td>
<td><strong>0.272</strong></td>
<td><strong>125</strong></td>
<td><strong>339</strong></td>
<td><strong>351</strong></td>
<td></td>
</tr>
</tbody>
</table>

Pre-separation checks

**Required Energy (nominal)**

Failure assumed: single Probe unit fails ON

: single experiment fails ON

972

85

110

**Required Energy (assuming failed units)**

**Available Energy (assuming failed batteries)**

Energy loss due to assumed battery failures:

1 string (of 10) failed

1 cell (of 5) in each string failed

355

520

**NOMINAL BATTERY CAPACITY**

(5 fresh batteries)

2059


dition, safe/arm plugs were provided on the unit itself for safety during ground operations.

### 6.2. In-flight Operational Modes

The configuration of the EPSS depends upon which operational mode the Probe is in. The following configurations are available:
6.2.1. Cruise
The EPSS is OFF during the whole cruise, except for periodic Probe checkout operations. There is no power at the Orbiter interface and direct monitoring by the Orbiter allows verification that all the relays are open.

6.2.2. Cruise Probe checkout
The EPSS is powered by the Orbiter for cruise Probe checkout operations. The 28 V bus is regulated by the EPSS BDRs associated with each Orbiter SSPS; a total of 210 W is available from the Orbiter and all the relays are open. In addition 52 W are available from the Orbiter to power the PSE.

6.2.3. Mission Timer loading
Following the loading (through the Orbiter) of the expected coast time duration into the Mission Timer Unit, battery ‘depassivation’ is performed to overcome any energy loss due to chemical passivation process during cruise. Before Probe separation, the EPSS timer relays are closed to provide electrical power to the Mission Timer Unit from the batteries and the Orbiter power is switched OFF.

6.2.4. Coast
Only the Mission Timer Unit is supplied electrical power by the batteries through specific timer relays during the coast phase. The EPSS is OFF and all other relays are open.
6.2.5. **Probe Wake-up**

At the end of the coast, the Mission Timer Unit wakes-up the Probe by activating the EPSS. Input relays are closed and the current limiters powering the CDMU are automatically switched ON as soon as the 28 V bus reaches its nominal value (other current limiters are initially OFF at power up). The pyro energy intercept relay is also automatically switched ON by a command from the PCDU.

6.2.6. **Entry and Descent**

All PCDU relays are closed and the total power (nominally 300 W; 400 W maximum) is available on the 28 V distribution outputs to subsystems and instruments. The Pyro Unit performs the selection and the firing of the squibs, activated by CDMU commands.

7. **Command and Data Management Subsystem (CDMS)**

The data handling and processing functions are divided between the Probe Support Equipment (PSE) on the Orbiter and the CDMUs (part of the CDMS) in the Probe.
(Figure 14). The Probe Data Relay Subsystem (PDRS) provides the RF link function for this purpose, together with the data handling and communication function with the Orbiter’s Control and Data Subsystem (CDS) via a Bus Interface Unit (BIU). During the ground operations and cruise checkouts, the Orbiter-Probe RF link is replaced by an umbilical connection. The CDMS has two primary functions: (i) autonomous control of Probe Operations after separation; (ii) management of data transfer from the equipment, subsystems and experiments to the Probe transmitters for relay to the Orbiter. For these functions, the CDMS uses the Probe On-board Software (POSW), for which it provides the necessary processing, storage and interface capabilities. The driving requirement of the CDMS design is such that it is intrinsically single point failure-tolerant. As a result of the highly specific Huygens mission (limited duration and no access by telecommand after separation), a very safe redundancy scheme has been selected. As shown in Figure 14, the CDMS therefore consists of:

- Two identical CDMUs;
- A triply redundant Mission Timer Unit (MTU);
- Two mechanical g-switches (backing up MTU);
- A triply redundant Central Acceleration Sensor Unit (CASU);
- Two sets of two mechanical g-switches (backing up CASU);
- A Radial Acceleration Sensor Unit (RASU) with two accelerometers;
- Two Radar Altimeter proximity sensors, each consisting of separate electronics, transmitting antenna and receiving antenna.

The two CDMUs each execute their own Probe Operations Software (POSW) simultaneously and are configured with hot redundancy (Chain A and Chain B). Each hardware chain can run the mission independently. They are identical in almost all respects; the following minor differences facilitate simultaneous operations and capitalize on the redundancy:

- The telemetry is transmitted at two different RF carrier frequencies (resp. 2040 and 2097.955 MHz);
- The chain B telemetry is delayed by about 6 s to avoid loss of data should a temporary loss of the telemetry link occur (e.g., due to an antenna mispointing as the Probe swings back and forth beneath the parachute).

Each CDMU chain incorporates a health check (the results are reflected in the ‘Processor Valid’ status flag) which is reported to the experiments in the Descent Data Broadcast (DDB) message. A chain declares itself invalid when two bit errors in the same memory word, an ADA exception or an under-voltage on the 5 V line occurs within the CDMU.

7.1. COMMAND AND DATA MANAGEMENT UNIT (CDMU)

Each CDMU includes a MAS 281 16-bit 1750A micro-processor running at 10 MHz, with 64 kword PROM storing the POSW and 64 kword RAM used for the
POSW and other dynamic data when the CDMU is ON. A memory management unit was implemented for providing memory flexibility and some growth potential during development. Direct Memory Access (DMA) is provided to facilitate data transfer between the memory and the input/output registers, thus relieving the microprocessor of repetitive input/output tasks. The RAM-stored program memory is protected against single error occurrence by an Error Detection And Correction (EDAC) device, which detects and corrects single bit errors and reports any double bit errors to the Processor Valid function. TM/TC management is based on an internal On Board Data Handling (OBDH) bus in order to standardize the internal interfaces, which are based on the classical Central Terminal Unit (CTU) and Remote Terminal Units (RTUs) approach.

In addition to conventional CDMS functions, the CDMUs implement the following Huygens-specific functions:

- The arming timer function which sends pyro arming commands following a specific hardware-managed timeline, thus offering full decoupling from the POSW operation;
- Sending of the Processor Valid signal to payload experiments via the Descent Data Broadcast (DDB), indicating the health of the nominal CDMU (unit A);
- Reprogrammability through the use of 16 kword of Electrically Erasable PROM (EEPROM), thus allowing patching of the POSW if necessary;
- EDAC error count reports on internal data transfers;
- Capability, through specific 16 kword of RAM, to delay one telemetry chain by a few seconds.

7.2. MISSION TIMER UNIT (MTU)

The MTU is used to activate the Probe at the end of the coast phase. In order to obtain a single point failure-free design, it is based on three independent hot redundant timer circuits followed by two hot-redundant command circuits. Two mechanical g-switches provide a backup to the MTU. MTU electrical power is supplied directly via three 65 V supply lines, one for each timer board, from independent batteries. During the pre-separation programming activities, when the Probe is still connected to the Orbiter, all three timers are programmed with the exact predicted duration of the coast phase via serial memory load interfaces from one of the two CDMUs. Each of the three timer boards can be loaded independently from either CDMU. The programmed values can be verified by the serial telemetry channels. When the MTU programming activity is finished, the CDMUs and all other Probe systems except the MTU are turned off. The Probe is separated a few days later. During the coast of about 22 days, the programmed timer register is decremented by a very precise clock signal. The MTU consumes about 300 mW during this period as only the necessary circuits (CMOS-based) are powered. When the command board majority voting detects either both g-switches active or at least two of the three ‘time-out’ signals received, five High Level Commands (HLCs) are issued sequentially from each board to the PCDU in order to switch on both
CDMUs. The timer then returns to a standby mode. The two g-switches, which ensure Probe wake-up in the event of atmospheric entry without the time-out signal from any of the timer boards, are purely mechanical devices that close when deceleration reaches a level of 5.5–6.5 g.

7.3. CENTRAL ACCELERATION SENSOR UNIT (CASU)

The CASU measures axial deceleration at the centre of the experiment platform during entry. The signal is processed by the CDMU to calculate the time for parachute deployment (To). The CASU operates within 0–10 g and uses a scale factor of 0.512 V g⁻¹. Its main building blocks are:

- Power circuit: two hot-redundant input power lines make it single point failure-tolerant in both the nominal and the redundant power line;
- Three accelerometer analogue signal conditioning blocks. A low-pass filter with a 2 Hz cut-off is used and the analogue output from each block is routed to both CDMUs.

In addition, the design prevents failure propagation from one conditioning chain to the other; it withstands permanent short circuit conditions without any degradation; and it is single-point failure-tolerant to the input power supply line.

Back-up detection of To is performed separately for both CDMUs by two pairs of mechanical g-switches in case the prime CASU system is inoperative. The threshold values for each pair of g-switches are 5.5 g and 1.2 g.

7.4. RADIAL ACCELERATION SENSOR UNIT (RASU)

The RASU measures radial acceleration at the periphery of the experiment platform. The signal is processed by the CDMU’s to provide the Probe spin rate for insertion into the DDB distributed to experiments. The RASU is designed to measure spin acceleration within 0–120 mg with a 41.67 V g⁻¹ scale factor. The design is based on the CASU unit but it includes only two accelerometers.

7.5. RADAR ALTIMETER UNIT (RAU)

The RAU proximity sensor uses two totally redundant altimeters operating with frequency-modulated carrier wave at 15.4 GHz and 15.8 GHz for measuring the altitude above Titan’s surface, starting from about 25 km. Each of the four antennas (two per altimeter) is a planar slot radiator array providing an antenna gain of 25 dB with a symmetrical full beam width of 7.9°. A continuous signal modulated in frequency with a rising and falling ramp waveform is transmitted; the received signal has a similar form, but delayed by the two-way propagation time after reflection on Titan’s surface. Hence the range to the target (Titan’s surface) is proportional (with a linear frequency modulation ramp) to the instantaneous frequency shift between the transmitted and received signals. The received signal waveform is also
provided to the Huygens Atmospheric Structure Instrument (HASI) for further on board processing for establishing Titan’s surface roughness and topography.

8. **Probe Data Relay Subsystem (PDRS)**

The PDRS (Figure 15) is Huygens’ telecommunications subsystem, combining the functions of RF link, data handling and communications with the Orbiter. It transmits science and housekeeping data from the Probe to the Huygens PSE on board the Orbiter, which are then relayed to the Orbiter CDS via a Bus Interface Unit. In addition, the PDRS is responsible for telecommand distribution from the Orbiter to the Probe by umbilical during the ground and cruise checkouts. The PDRS consists of:

- Two hot-redundant S-band transmitters and two circularly polarised Probe Transmitting Antennas (PTAs) on the Probe;
- A Receiver Front End (RFE) unit (enclosing two Low Noise Amplifiers and a diplexer) and two Probe Support Avionics (PSA) units on the Orbiter.

The Orbiter’s High Gain Antenna (HGA) acts as the PDRS receiving antenna. In addition, as part of the Doppler Wind Experiment (DWE), two ultra stable oscillators – The Transmitter Ultra Stable Oscillator (TUSO) on the Probe and the
Receiver Ultra Stable Oscillator (RUSO) on the Huygens PSE – are available as reference signal sources to allow the accurate measurement of the Doppler frequency shift in the Probe-Orbiter RF carrier signal. The PDRS electrical architecture is fully channelised for redundancy, except that TUSO and RUSO are connected to only one chain (chain A).

The RF signal is composed of a residual carrier signal (at either 2040 or 2097.955 MHz) that is phase-modulated by a subcarrier signal at 131072 Hz. The data-stream is PCM encoded on the subcarrier. The symbol stream rate is 16384 symb s⁻¹. The signal data rate is 8192 bit per second. The clock driving the carrier frequency is either a Temperature Controlled Oscillator (TCXO) or an instrument-provided Ultrastable Oscillator (on channel A only). A dedicated CDMU temperature-controlled crystal provides the reference frequency for the subcarrier and data modulation clock.

8.1. PROBE SUPPORT EQUIPMENT (PSE)

8.1.1. Receiver Front End (RFE)
The RFE is comprised of:
- Two Low Noise Amplifiers (LNAs) linked to the Orbiter’s HGA to amplify the acquired RF signal by 20 dB using two cascaded FET stages;
- Two RF inputs: one linked to the HGA, the other via a coupler and used during checkout to link a dedicated transmitter output (on the Probe) to the RFE via the umbilical;
- A pre-selection filter (coaxial cavity type with six poles);
- An isolator;
- An output attenuator (fixed value).

In addition, owing to the HGA’s shared use with the Orbiter, a bandpass filter (the TX filter) and a circulator protect the LNA chain B by isolating the Orbiter’s S-Band Transmitter (SBT) and the Probe’s S-band receiver, which both use the HGA. These two modes are mutually exclusive.

8.1.2. Probe Support Avionics (PSA)
The two RFE outputs are sent to the two redundant PSAs, which perform detection, acquisition (based on a 256-point Fast Fourier Transform algorithm), tracking, signal demodulation and data handling and management. The PSA data handling architecture is divided between analogue and digital sections. The analogue section performs signal down-conversion from S-band to the IF frequency. The IF signal is digitized and the samples processed by the digital section. The digital section performs:
- Digital Signal Processing (DSP), i.e. the signal acquisition and tracking task based on FFT analysis and frequency acquisition;
- Viterbi decoding of the digital signal and delivery of the decoded transfer frame to the data handling section at 8192 bit/s
Data handling, that consists of:

- Transforming the received transfer frame into a telemetry packet;
- Generating internal PSA housekeeping data (including the synthesised frequency information) in a packet format controlling and managing communications with the Orbiter CDS via a Bus Interface Unit (BIU);
- Distributing the telecommands from the Orbiter BIU interface.

The digital section is composed of the following main modules:

- The receiver digital module, consisting of the UT1750 microprocessor, 8 kword RAM and 8 kword PROM, and the receiver signal processing ASIC;
- The interface digital module, using GaAs devices for Numerically Controlled Oscillator (NCO) and Digital to Analogue Converter (DAC) functions;
- The Support Interface Circuitry (SIC) module, which comprises: (i) the 8 kword EEPROM to memorise software patches; (ii) the 32 kword PROM containing the Support Avionics Software (SASW) and the testing, telecommand, telemetry and umbilical interfaces; (iii) the MAS 281 microprocessor module used by the SASW;
- The BIU module that controls communications between the PSA and the Orbiter’s 1553 bus.

8.2. PROBE TRANSMITTING TERMINAL (PTT)

The PTT is comprised of two transmitters and two Probe antennas. Each transmitter includes a Temperature Controlled Crystal Oscillator (TCXO), a synthesiser and BPSK modulator module, and a 10 W Power Amplifier module using Automatic Level Control (ALC) for 40.2 dBm nominal output power (end-of-life, worst-case, including ageing). The reference oscillator for the Phase Locked Loop (PLL) synthesiser is either an (internal) Voltage Controlled Crystal Oscillator (VCXO) with a temperature compensating network or the (external) TUSO signal. The selection between these reference sources is made before separation from the Orbiter. The TUSO will be selected unless a failure is detected in it before separation.

The two transmitting antennas linked to the transmitters (dual chains without cross-coupling) are quadrifilar helix designs. The four spirals are fed at the bottom of the helix in phase quadrature. Left Hand Circular Polarisation (LHCP) is used for signal transmission at 2040 MHz and Right Hand Circular Polarisation (RHCP) for transmission at 2097.955 MHz. The minimum gain for the antennas, mounted on the top platform, is 1.6 dB (channel A) and 1.8 dB (channel B) at all Probe-Orbiter aspect angles between +20° and +60°. The transmitting antenna gain varies as a function of the azimuth and elevation angle as shown in Figure 16.
8.3. HUYGENS RECEIVER ANOMALY

8.4. ANOMALY OVERVIEW

The main component of the Huygens-to-Cassini communications link are shown at high level in Figure 17.

The symbol Synchronizer is a classical Data-Transition-Tracking-Loop (DTTL). A design fault in the DTTL results in poor phase tracking (and ultimately cycle slipping) in the DTTL. The Viterbi decoder's synchronization performance depends on certain settings that are controlled by the Frame Synchronizer, which is implemented in the PSA as a four-state machine. The data corruption mechanism depends strongly on the behavior of this finite state machine as well as its coupling to the Viterbi Decoder's node synchronization settings.

The Huygens communications link anomaly and its consequences are illustrated in Figure 18. The bit synchronizer has a bandwidth which is too narrow to accommodate the Doppler shift of the data stream frequency, due to relative Orbiter-Probe motion. At a certain combination of parameters frequency offset ($\Delta f_s$), signal to noise ($E_s/N_0$) and data transition density ($P_t$) cycle slips occur. These cycle slips
cause data corruption, on board synchronization detection failures and on ground decoding failures.

8.5. HUYGENS RECOVERY APPROACH

Cycle slips depend on the combination of three parameters: $\Delta f_s$, $E_s/N_0$ and $P_t$ in a perfectly deterministic way. The first two parameters depend on the relay link geometry, thus the mission profile. It is also possible to shift the transmitted frequency by controlling the temperature of the temperature controlled crystal oscillator in the CDMU (see section 8). It requires switching ON the Probe a few hours prior entry. A 4-hour pre-heating option is being considered. The third parameter, $P_t$, can only be varied by inserting strings of ‘zeros’ in the data stream, thus at the expense of the effective science data rate. The proposed solution makes use of adjustments of the 3 parameters. The mission recovery profile is further discussed in Lebreton and Matson, 2002.

9. Software

9.1. SOFTWARE CONCEPT

The Huygens software consists of that running in the Probe CDMS, referred to as Probe On-Board Software (POSW), and that within the PSA on the Orbiter, referred to as the Support Avionics Software (SASW). Two copies of the data handling hardware (CDMU and PSA) run identical copies of POSW and SASW. There is no cross-trapping between the two chains. The software is based on a top-down hierarchical and modular approach using the Hierarchical Object-Oriented Design (HOOD) method and, except for some specific, low-level modules, is coded in ADA. The software consists, as much as possible, of a collation of synchronous processes timed by a hardware reference clock (8 Hz repetition rate). In order to avoid unpredictable behaviour, interrupt-driven activities are minimised. Such a design also allows a better visibility and reliability of the software. Limited
reprogramming capability is provided to accommodate POSW modifications and RAM failure recoveries. The processes are designed to use data tables as much as possible. Mission profile reconfiguration and polling of experiment science-data packet can be changed only by modifying these tables. This is possible via the use of an Electrically Erasable Programmable Read Only Memory (EEPROM). In order to avoid a RAM modification while the software is running (which can lead to unpredictable behaviour and unnecessary complexity), direct RAM patching is forbidden. The POSW communicates with the SASW in different ways depending on mission phase. Before Probe separation, the two software subsystems communicate via an umbilical that provides both command and telemetry interfaces. The Huygens Probe cannot be commanded after separation, and its telemetry is transmitted to the Orbiter via the PDRS RF link. A certain degree of autonomy was designed into the software that will allow it to adapt the mission profile to the Titan environment (Dechezelles et al., 1994).

The overall operational philosophy is that the software controls the nominal mission from power-up without checking its hardware environment or the Probe’s connection or disconnection. The specific software actions or inhibitions required for ground or flight checkout must therefore be invoked by special procedures, activated by the delivery of specific telecommands to the software. To achieve this autonomy, POSW’s in-flight modification is autonomously applied at power-up by using a non-volatile EEPROM. At power-up, the POSW validates the CDMU EEPROM structure and then applies any software patches stored in the EEPROM before running the mission mode. If the EEPROM proves to be invalid at start-up, no patches are applied and the software continues based on the software stored in the CDMU ROM. A number of other checks are also carried out at start-up (e.g. a DMA check and a main ROM checksum), but the software will continue execution attempts even if the start-up checks fail.

At the time of writing, POSW modifications (software patches) are under study as part of the on-going work related to the implementation of the revised Huygens mission scenario. S/W patches will be applied to both chains. Those patches will be loaded in the EEPROM’s before Probe separation. The overall reliability of the S/W patches loading and the consequences at mission level of an unsuccessful patch loading on either chain are being assessed as part of the decision process for implementing the pre-heating option.

9.2. POSW FUNCTIONS

The three functions of the POSW are described below.

9.2.1. Probe Mission Management

– Detecting time T₀ as entry begins, based on the Central Accelerometer Sensor Unit (CASU) signals;
Forwarding commands at the correct times to the subsystems and experiments according to the pre-defined mission timeline;

- Computation of the Probe dynamical state from sensor readings sending Descent Data Broadcasts to the experiments.

9.2.2. Telemetry Management

- Collecting and recording housekeeping data;
- Generation of housekeeping packets from the housekeeping data;
- Collecting experiment packets according to a pre-defined polling scheme;
- Transmitting transfer frames to the PDRS.

9.2.3. Telecommand Management

- Reception of TC packets from the PSE (only while attached to the Orbiter);
- Execution of commands related to these TC packets;
- Forwarding of commands to the experiments.

9.3. POSW OPERATIONS

Control of the Probe, which involves the activation and forwarding of commands to experiments and subsystems, is driven by a pre-defined set of tables called the Mission Timeline Tables (MTTs). They define the actions to be performed as a function of time. The pre-To MTT is activated at Probe wake-up. It controls the Probe until the post-To MTT is activated by the POSW’s detection of To. The experiments perform most of their activities autonomously based on the mission phase data computed within the POSW and sent to all the experiments every 2 s as a Descent Data Broadcast (DDB) packet. The DDB contains the time, spin rate (computed by the POSW from the RASU signal or, in the event of failure, from a pre-defined look-up table) and altitude (initially taken from a look-up table based on the time elapsed since T0, but later in the descent by processing RAU data). The telemetry management function involves the acquisition and transmission of Probe telemetry as packets. Whether they are housekeeping or experiment packets, they are all 126 bytes long. They are forwarded to the SASW in the form of transfer frames comprising header information followed by seven packets and then Reed-Solomon code words, making a total frame size of 1024 bytes. Housekeeping data are acquired from the subsystems (and from the software itself) at different rates according to a pre-determined packet layout, and are loaded into four packets every 16 s. One of the packet types is buffered and issued 6.4 min later as ‘History’ housekeeping for transmitting information acquired during the entry phase when the radio link is not established. Experiment data are acquired according to a pre-defined polling strategy and the resulting packets are loaded into the transfer frames.

The selection of the appropriate type of telemetry packet to include in each of the seven slots in a frame is managed by the polling sequence mechanism on a
Polling Step 1

Figure 19. Payload telemetry sharing among the five instruments that provide science data packet. The sixth instrument, DWE provides only HK data that are embedded to the Probe System HK data packets.

major acquisition cycle of 16 s (equal to 128 Computer Unit Times) driven by the Polling Sequence Table (PST) and the Experiment Polling Table (EPT). The PST defines if housekeeping or experiment packets are to be included in the transfer frame currently under construction. However, it does not select which experiment is to be included. The EPT defines a prioritised scheme for the collection of experiment data. The table is invoked whenever the PST requests experiment data for the transfer frame and is read in a cyclical manner. It consists of a sequential list of the payload experiments, with the number of occurrences of each experiment in the table providing the polling priority. By this method, the CDMS and the POSW are protected against failure modes in the experiments that could affect the data production rates. Each experiment is guaranteed an opportunity to supply data at, as a minimum, its nominal data rate. Furthermore, this polling scheme automatically optimises the data return by reallocating the TM resource in the absence of a ‘packet ready’ status flag from an experiment when expected. Three EPTs provide different polling priorities during the descent’s various stages, switching from one table to the next at a pre-set time, Figure 19.

9.4. SASW FUNCTIONS

The SASW’s main purpose is to provide communications between the Probe and Orbiter. For the SASW, there is no difference between receiving Probe telemetry via the umbilical or via the RF subsystem. All the differences are handled by the
PDRS receiver part of the PSA equipment. The SASW provides the following functions:

9.4.1. **Telecommand Management**
- Reception of TC packets from the BIU that interfaces with the Orbiter CDS;
- Execution of commands related to these TC packets;
- Forwarding TC packets to the CDMS (including experiment telecommands) while attached to the Orbiter.

9.4.2. **Telemetry Management**
- Collecting PSE housekeeping data;
- Transmitting PSE housekeeping packets and modified CDMS frames to the Orbiter via the BIU.

9.5. **SASW OPERATIONS**

Communication between the SASW and the Orbiter CDS is via a MIL-STD-1553 bus using a BIU. Received telecommands are placed in BIU memory for the SASW to read; the SASW places telemetry packets in BIU memory for transmission by the BIU over the Orbiter’s CDS bus. The SASW examines any received telecommands to determine their destination address. Those destined for the Probe (subsystems or experiments) are transmitted over the umbilical TC link. Those for the PSA are handled by the SASW. The SASW handles the reception of Probe telemetry via a Frame Data Interface (FDI). Telemetry from the Probe is transmitted to the SASW either by the umbilical RF link when the probe is connected or by the Probe Relay Link (PRL) after separation. The SASW also generates its own telemetry in the form of housekeeping packets, containing PSA status information and status data collected from the PDRS subsystem.

10. **Probe in-flight commissioning**

10.1. **BI-ANNUAL IN-FLIGHT PROBE CHECKOUTS**

Following the launch of the Cassini/Huygens spacecraft on 15 October 1997, in-flight checkouts have been successfully carried out about every 6 months. A maximum time lapse between two successive checkouts is 8 months as required for instrument maintenance activities and system constraints. Overall, the performance of the Probe subsystems and of the payload during the checkout activities has been nominal. The first three Probe checkouts have been carried out in the nominal attitude configuration of the Cassini/Huygens spacecraft that is flown in the inner Solar System; i.e. in the High Gain Antenna-to Sun attitude. Solar radio noise picked up by the HGA injected noise in the Huygens receivers. A Huygens receiver
calibration test sequence was executed on 28 May 1998 with the HGA turned away 12° away from the Sun. This test was successful and allowed to confirm the health of the Huygens receivers. The history of the radio receiver AGC measurements obtained during the first in-flight checkouts is illustrated in Figure 20.

10.2. END-TO-END PROBE RELAY TEST

An End-to-End Probe Relay Test was performed in February 2000 with the objective of verifying and calibrating the performance of the receivers. The NASA Deep Space Network DSS-24 Goldstone station was used to transmit radio signals mimicking the ones expected to be transmitted by the Probe during its descent. This end-to-end test uncovered unexpected behaviour by both Huygens receivers while receiving Mission representative data transmission.

10.3. PROBE THERMAL PERFORMANCE DURING CRUISE

The Orbiter is continuously monitoring key Probe temperatures during the whole Cruise phase. The first years of temperature measurements of the Huygens Probe and of its interfaces with the Cassini Saturn Orbiter is plotted in Figure 21. The thermal performances of the Huygens Probe are within a few degrees of the pre-flight predictions. It demonstrates the robustness of the Huygens Probe Thermal design, (Cluzet et al., 1998). The excellent thermal performances of the Probe during the first 3 years allowed the Probe to be used as a secondary heat-shield for the whole spacecraft during the jovian observation campaign.

11. The Probe EM at HPOC/ESOC

The Huygens Flight Operations are conducted from the Huygens Probe Operations Centre (HPOC), ESOC, Darmstadt, Germany (Sollazzo et al., 1997). The one-time
Figure 21. Huygens Probe Temperature variation during the cruise during the first 8 months in 2000. The increase in temperature at the Probe-Orbiter interface (curves labelled SEPS 1 to 4), and in the Probe interior (curve labelled PCDU1 and PCDU2), which occurs on DOY 30, is due to the transition from HGA-to-Sun to HGA-to-Earth. The predicted temperatures are also shown for about one month after the transition to the attitude HGA-to-Earth. The measured temperatures are a few degrees lower than predicted.

The occurrence nature of the Huygens mission called for special ground facilities for testing and validating any modification of the on-board software that may be required as part of the bi-annual checkout activities and also for Probe configuration prior to its release.

The Huygens Engineering Model (see section 3 above), has been refurbished by the inclusion of flight-spare units and hardware upgrades to make it representative of the Flight Model Probe. It resides at HPOC, (Figure 22), to support the in-flight operations activities. It is used to rehearse any modified checkout sequence. Should it be required, it will be used as a testbed for on-board software maintenance activities.

The EM test bed has already been effectively used to support the diagnostic of the effect of the solar radio noise on the Huygens receivers that was observed during the first in flight checkouts. It was also extensively used during characterisation of the receivers anomaly. It will be maintained operational until after the Huygens mission has been completed.

Notes

2. Now Alcatel Space.
Acknowledgements

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References


CASSINI-HUYGENS INVESTIGATIONS OF SATELLITE SURFACES
AND INTERIORS

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Abstract. The Saturnian system contains 18 known satellites ranging from 10 km to 2575 km in radius. In bulk properties and surface appearance these objects show less regularity than the sparser Jupiter system. The Galilean-sized moon Titan sports a dense atmosphere of nitrogen and methane which renders surface observations difficult, but also makes this moon intriguing from the standpoints of climate change and exobiology. The Cassini-Huygens mission will make extensive observations of the satellites over a range of wavelengths, as well as using in-situ sampling of satellite environments (and in the case of Titan, sampling of atmosphere and surface). The goals of these extensive investigations are to understand the bulk properties of the satellites, their surface compositions and evolution through time, as well as interactions with the magnetosphere and rings of Saturn. This knowledge in turn should provide a deeper understanding of the origin of the Saturnian system as a whole and underlying causes for the distinctive differences from the Jovian satellite system.

1. Introduction

The Saturnian system contains 18 known satellites larger than 10 km in radius, nine of which exceed 100 km in radius (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, Phoebe), and one of which is much greater than 1000 km in radius (Titan). Physical and orbital properties of these objects, where known, are summarized in Table 1. The Saturnian system contains the most satellites of any planetary system, is much less regular than that of the Jovian system, but much more so than Neptune’s entourage. It contains the solar system’s second largest moon, Titan, which at a radius of 2575 km is edged out only by Jupiter’s Ganymede, in size and density sits neatly in between Ganymede and its near twin in bulk properties, Callisto, and contains a nitrogen atmosphere four times denser at its base than is sea level air density on Earth. The massive ring system comprises a countless number of small ‘satellites’ whose orbits are sculpted in places by the gravitational perturbations of satellites both interior and exterior to the rings. These include the six ring-region satellites Pan, Atlas, Prometheus, Pandora, and

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the co-orbitals Janus and Epimetheus. Thus the Saturnian ensemble of moons is unrivaled in its number or variety. Furthermore, with a number of moons in dynamical interaction with the massive rings, and one moon rich in gaseous nitrogen and organic molecules, the Saturnian system may have more to tell us about solar system history than do the moons of the three other giant planets.

TABLE I
Physical and orbital properties of the Saturnian satellites

<table>
<thead>
<tr>
<th>Name</th>
<th>Mean orbit radius ($10^3$ km)</th>
<th>Eccentricity of orbit</th>
<th>Inclination, degrees</th>
<th>Object radii, km</th>
<th>Density (g cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan</td>
<td>133.58</td>
<td>?</td>
<td>?</td>
<td>&lt;10&gt;</td>
<td>?</td>
</tr>
<tr>
<td>Atlas</td>
<td>137.64</td>
<td>0.000</td>
<td>0.3</td>
<td>19×17×14</td>
<td></td>
</tr>
<tr>
<td>Prometheus</td>
<td>139.35</td>
<td>0.002</td>
<td>0.0</td>
<td>74×50×34</td>
<td></td>
</tr>
<tr>
<td>Pandora</td>
<td>141.70</td>
<td>0.004</td>
<td>0.1</td>
<td>55×44×31</td>
<td></td>
</tr>
<tr>
<td>Epimetheus</td>
<td>151.42</td>
<td>0.009</td>
<td>0.34</td>
<td>69×55×55</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>Janus</td>
<td>151.47</td>
<td>0.007</td>
<td>0.14</td>
<td>97×95×77</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>Mimas</td>
<td>185.52</td>
<td>0.020</td>
<td>1.5</td>
<td>199</td>
<td>1.14 ± 0.03</td>
</tr>
<tr>
<td>Enceladus</td>
<td>238.02</td>
<td>0.004</td>
<td>0.0</td>
<td>249</td>
<td>1.01 ± 0.02</td>
</tr>
<tr>
<td>Tethys</td>
<td>294.66</td>
<td>0.000</td>
<td>1.1</td>
<td>523</td>
<td>1.21 ± 0.17</td>
</tr>
<tr>
<td>Telesto</td>
<td>294.66</td>
<td>0.0</td>
<td>1 ?</td>
<td>15×13×8</td>
<td></td>
</tr>
<tr>
<td>Calypso</td>
<td>294.66</td>
<td>0.0</td>
<td>1 ?</td>
<td>15×8×8</td>
<td></td>
</tr>
<tr>
<td>Dione</td>
<td>377.40</td>
<td>0.002</td>
<td>0.0</td>
<td>560</td>
<td>1.44 ± 0.07</td>
</tr>
<tr>
<td>Helene</td>
<td>377.40</td>
<td>0.005</td>
<td>0.2</td>
<td>17×16×15</td>
<td></td>
</tr>
<tr>
<td>Rhea</td>
<td>527.04</td>
<td>0.001</td>
<td>0.4</td>
<td>764</td>
<td>1.33 ± 0.10</td>
</tr>
<tr>
<td>Titan</td>
<td>1221.85</td>
<td>0.029</td>
<td>0.3</td>
<td>2575</td>
<td>1.88 ± 0.01</td>
</tr>
<tr>
<td>Hyperion</td>
<td>1481.1</td>
<td>0.104</td>
<td>0.4</td>
<td>205×130×110</td>
<td></td>
</tr>
<tr>
<td>Iapetus</td>
<td>3561.3</td>
<td>0.028</td>
<td>14.7</td>
<td>718</td>
<td>1.21 ± 0.12</td>
</tr>
<tr>
<td>Phoebe</td>
<td>12952.</td>
<td>0.163</td>
<td>150</td>
<td>115×110×105</td>
<td></td>
</tr>
</tbody>
</table>

Compiled data from a number of sources (Peale, 1992; Buratti, 1997; Thomas, 1997). Radii of the principal axes are given for irregular objects; < > indicates mean radius; ? indicates unknown or uncertain.

Understanding the nature and history of the Saturnian moons is a major goal of the Cassini-Huygens mission. Titan as an object is so complex that it is a mission goal unto itself, being the target of the Huygens probe as well as sole gravitational perturber for shaping the four-year tour of the Cassini Saturn Orbiter. In this paper we provide an abbreviated description of the many multi-disciplinary observations planned for the moons of Saturn, including Titan. The paper does not attempt a review of current knowledge in the literature: the IUGG five year reviews (McKinnon, 1987; Schemk, 1991; Lunine, 1995) and other references (Morrison et al., 1986) well serve this purpose. Our goal is rather to give the reader an understanding
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of the complexities and opportunities associated with Cassini-Huygens satellite observations during the planned four-year orbital tour.

2. Brief Summary of Satellite Properties

Voyagers 1 and 2 in 1980 and 1981 provided the bulk of our knowledge of Saturn’s satellites, built on a foundation of telescopic observations stretching back to Christian Huygens’ discovery of Titan in 1655. Bulk quantities such as radius and mass are determinable from ground-based observations of the satellite disks and of the mutual gravitational perturbations of the orbits. The Voyager imaging system greatly improved many of the orbital tracking measurements, and direct measurement of the perturbation of the spacecraft’s path by Titan afforded a very precise mass determination of that giant satellite. Because the Voyager complement of instruments did not include a high spectral resolution reflectance spectrometer, surface composition of the satellites has been determined up to now by ground-based and Earth-orbital studies. While such observations have produced high quality data sets, they are limited essentially to hemispherical spatial resolution. Spatially resolved compositional information will be extracted from the visible and near-infrared mapping spectrometer (VIMS), ultraviolet imaging spectrometer (UVIS) and composite infrared radiometer spectrometer (CIRS) instruments on the Cassini Saturn Orbiter (hereafter, the orbiter). The composition and physical state of Titan’s atmosphere was explored in fair detail through the combined measurements of the Voyager radio science experiment, infrared interferometer spectrometer, ultraviolet spectrometer and the imaging science and plasma experiments. Remote sensing data of Titan’s surface at hemispherical resolution from Earth and the Hubble Space Telescope has in recent years given us preliminary information unavailable from the Voyager experiments.

The Saturnian satellite system can be divided roughly into three groups of satellites using the decadal size categories defined in the introduction. The smallest class includes satellites embedded in, and immediately exterior to, the ring system as well as so-called co-orbitals of larger moons. The satellite Pan perturbs A-ring particles to create the Encke division, while gravitational perturbations of Janus and Epimetheus appear to define the outer edge of that ring. Epimetheus and Janus share an orbit that lies somewhat outside the classical ring system, between the F ring and very tenuous G ring, but may have been strongly perturbed by the evolving rings. Pandora and Prometheus orbit on either side of the F ring and ‘shepherd’ particles gravitationally to form that narrow ring. Many more small moons that perturb the rings may yet await discovery; see the articles by Cuzzi et al. and Porco et al. in this issue for further details on ring-satellite interactions. The intermediate-sized satellite Tethys shares its orbit with Telesto and Calypso, which may be fragments of a collision of an object with Tethys. Likewise, Dione shares its orbit with the much smaller Helene. The orbital interactions between
Janus and Epimetheus allow a rather precise determination of their densities which are well below the value of water ice. Either these bodies are made of exotic low density ices or, more likely, they are highly porous agglomerations of water ice with little rock.

The next decade of size encompasses the so-called ‘intermediate’ Saturnian satellites; with one exception these bodies likely formed in or close to their current orbits, though several have been modified strongly by subsequent collisions. All were photographed by Voyagers 1 and 2 at varying levels of spatial resolution and each object has a distinctive appearance, as summarized below (Batson, 1984; Squyres and Croft, 1986):

- **Mimas**, the smallest and innermost of the intermediate Saturnian satellites, lies between the tenuous G and E rings of Saturn. Heavily cratered across its surface, Mimas’s most striking feature is the crater Herschel, at 130 km in extent almost 1/3 the diameter of the satellite, and perhaps 10 km deep. Little in the way of evidence for tectonic activity is seen on a surface dominated by impacts. The best Voyager imaging resolution on Mimas exceeded 2 km/pixel.

- **Enceladus** is only slightly larger than Mimas but wholly different in appearance. While the north polar region is heavily cratered, northern midlatitude and equatorial regions show vast smooth plains interspersed with linear features. Enceladus is extremely bright and appears to have been extensively and recently resurfaced over large areas; this satellite might be the source of the tenuous E-ring seen by Voyager. The origin of the extensive activity is unknown but could be a result of past tidal interactions with neighboring satellites and Saturn (Lissauer et al., 1984). About 10% of the surface was imaged at better than 2 km/pixel resolution by Voyager.

- **Tethys** is over twice the diameter of Enceladus but apparently less active geologically; the most distinctive features apart from heavily cratered terrains are the 500 km diameter crater Odysseus and a huge trough, Ithaca Chasma, extending over at least 270° of the satellite. Their origins may be related (Moore and Ahearn, 1983). None of the surface was imaged at resolutions above 2 km/pixel, and most of the images lie between 5–20 km/pixel.

- **Dione** is slightly larger than Tethys but has a higher bulk density. The surface has the highest brightness contrasts outside of the Iapetus bright-dark dichotomy and an intricate assemblage of bright wispy markings that cut through the trailing hemisphere. This poorly understood and only modestly resolved (no better than 5 km/pixel) region contrasts with the more heavily cratered and better-imaged Saturn-facing hemisphere; the leading hemisphere was photographed at low resolution only.

- **Rhea** is the largest of the intermediate Saturnian satellites and is heavily cratered across much of the surface image by Voyager. Wispy markings do appear across part of the surface, that face away from Saturn, but interpretation of their nature is hampered by poor resolution (generally 10 km/pixel or worse)
on that hemisphere. The cratered terrain was imaged at high resolutions of 1 km/pixel or better.

- Iapetus is almost the size of Rhea and also heavily cratered; however the hemisphere which lies in the direction of orbital motion (‘leading’) is almost 25 times darker than the trailing hemisphere and about as dark as cometary nuclei and other primitive surfaces. The dark material is reddish and likely carbon-bearing; opposing models of endogenic emplacement and exogenic deposition by impact remain untested. The Voyager imaging system could discern features only on the bright, trailing hemisphere, but even here the resolution was never better than about 8 km/pixel.

- Hyperion is relatively dark, shaped irregularly, and tumbles chaotically (Wisdom, 1987); it was seen at low imaging resolution by Voyager.

- Phoebe, the most distant of the intermediate satellites and poorly imaged by Voyager, is nearly as dark as the dark material on Iapetus, and could well be its source. The loose retrograde orbit and dark reddish color of this satellite suggest strongly that it is a captured object, but the source region of capture (local solar nebula planetesimals, Kuiper Belt, etc.) cannot be ascertained with the present data.

Ground-based spectroscopy has detected water ice on the surfaces of Mimas, Enceladus, Tethys, Dione, Rhea, Iapetus and Hyperion (Cruikshank et al., 1998). Known densities vary from that of Enceladus, consistent with nearly pure water ice (but with large error bars) to the well constrained value of 1.4 g cm$^{-3}$ of Dione. These densities suggest rather large ice-to-rock ratios in the satellite interiors, perhaps higher than what would be allowed under models of standard solar nebula chemistry in which the large abundance of carbon monoxide sequesters much of the oxygen needed to make water. Instead, the densities are close to those predicted for a cosmochemical mixture of water ice and rock formed in a relatively reducing nebula where the bulk of the carbon is in the form of methane and most of the oxygen is available to make water. (See Lunine and Tittemore, 1993, for a review of this subject with comprehensive references). Essentially nothing is known of the densities of the more ‘irregular’ of the intermediate satellites, Phoebe and Hyperion.

This bewildering menagerie of properties of the intermediate satellites stands in seeming contrast to the situation at Jupiter, where four large bodies, grading outward in composition from rock to ice-rich, suggest a miniature solar system characterized by long-term regularity (Canup and Ward, 2002). However, such regularity may be misleading, as current understanding of the impact history of the outer solar system suggests that collisional processes should be and have been at play in all the systems of the giant planets. Indeed, the common thread that ties together the properties of the intermediate Saturnian satellites is collisions: The massive ring system, the heavily cratered surfaces including two (Mimas, Tethys) with giant craters whose causal impactors lay not far below the threshold of moon-disrupting bodies, the evidence for the ancient fragmenting of the parent moon
of Hyperion (Farinella et al., 1990), the dark coating (apparently deposited) on Iapetus, the irregular fragments co-orbiting with Tethys and Dione, and the apparent capture by Saturn of a large interloper called Phoebe are all testaments to the importance of collisions in the evolution of solid material in orbit about Saturn.

Moving up yet one more decade in size to Titan brings to hand yet another mystery: why does Saturn possess only one Galilean-sized moon? Though Ganymede and Callisto are larger than Io and Europa, all four bodies contain roughly the same amount of rocky material, as if all were destined to be the same size were ice available at the orbits of the forming Europa and Io or, in an opposite view, were it not for the fact that high-speed collisions blasted the ice off of the inner two Galilean moons (Shoemaker and Wolfe, 1982). Titan’s radius and density fit neatly in between the values for Ganymede and Callisto, which themselves differ by only 10% in radius and 5% in density. All three of these satellites, if made principally of rock and water ice, are somewhat rock-rich compared to the intermediate-sized Saturnian satellites but are so massive that accretional heating could have vaporized back to the surrounding nebula much of the water during the later stages of their accretion. Indeed, for this reason Ganymede, Callisto and Titan may represent the upper limit in massiveness of satellites that can be produced from a mixture of rocky and icy planetesimals; at their size the gravitational potential energy per gram is comparable to the latent heat of sublimation of water ice (Stevenson et al., 1986). This does not, however, explain why Saturn has one satellite and Jupiter two (or, potentially, could have had four). It is tempting to consider the difference in mass between Jupiter and Saturn, a factor of three, which would lead to very different amounts of solid material bound in the gravitational wells of these forming giants (Canup and Ward, 2002). Perhaps the raw materials for the satellites of Saturn were not abundant enough to produce more than one Titan in the time available for accretion; certainly this is consistent with the absence of such objects around Uranus and Neptune, Triton almost certainly being a captured body from a Pluto-like orbit. Alternatively, stochastic differences in timing of disruptive impacts during satellite formation in the Jupiter and Saturn systems might also be invoked to explain the abundance of massive moons around Jupiter and their paucity at Saturn.

Regardless of its genesis, Titan is extraordinary because it possesses a thick atmosphere of molecular nitrogen with an admixture (10% near-surface, 1.5% in the stratosphere) of methane. At a surface temperature of 95 K and pressure of 1.5 bars, the bottom of Titan’s atmosphere is four times denser than the air at sea level on Earth, and exceeded among the four solid bodies with significant atmospheres only by Venus’s massive carbon dioxide blanket. The thick atmosphere pushes the level at which ultraviolet sunlight is absorbed by methane to hundreds of kilometers above the surface. There, some of the products of methane photolysis irreversibly form heavy hydrocarbon and nitrile polymers, with escape of hydrogen, and these orange hazes block the view of the surface at optical wavelengths. Thus the Voyager imaging system, equipped with vidicon tubes that could not see into the near-infrared, was unable to penetrate deep into the atmosphere or see the
surface. Observations from the Hubble Space Telescope and large ground-based systems (reviewed by Lorenz and Lunine (1997)) indicate a variable surface in which water ice is present in at least some regions; Earth-based radar experiments are consistent with this view (Campbell et al., 2002).

The mystery associated with Titan’s surface is tied up in the methane photochemistry. Voyager ultraviolet and infrared observations showed clearly the presence of methane, hydrocarbon and nitrile products of that molecule’s photolysis, and a corona of atomic hydrogen produced from the breakup of methane and escaping to space. Calculations based on independently generated photochemical models predict that the atmospheric inventory of methane present today will be depleted in about 1% of the age of the solar system (Yung et al., 1984). If the presence of methane is not a recent, freak occurrence but is a long-term feature requiring resupply from somewhere, then over the age of the solar system of order hundreds of meters of photochemical products should have accumulated on the surface. The primary product, ethane, is a liquid at the Titan surface temperature of 95 K. Thus there should be hundreds of meters of liquid hydrocarbons filling craters and other basins on Titan, more if a reservoir of methane is dissolved in the ethane so that a steady-state chemical cycle of methane destruction and hydrocarbon production can be sustained in the future over geologically long timescales. This view, driven by the Voyager atmospheric observations, seems to be contradicted by the remote sensing data that show no evidence for liquid hydrocarbons, though the nature of the dark parts of the surface remain undetermined. Perhaps the liquids are stored in a porous ice crust (Stevenson, 1992), all of the photochemical models are wrong, or the remote sensing data are as yet not sensitive enough to detect low-lying basins of the liquid hydrocarbons or coatings of the solid hydrocarbons interspersed among exposures of a water ice or mixed ice-silicate crust. Or, perhaps methane photolysis is an episodic and relatively rare occurrence over Titan’s history, making the present atmosphere something of an anomaly (Lorenz et al., 1997). Resolution of this problem, perhaps the outstanding question surrounding how Titan’s surface and atmosphere have interacted through time, depends in large part on compositional and morphological mapping of Titan’s surface at high spatial resolution, a job for which Cassini-Huygens is (as described below) superbly equipped.

3. Objectives for the Cassini-Huygens Observations of Satellites

The fundamental science objectives for the Cassini-Huygens exploration of the Saturnian satellites are to:

- determine the general characteristics and geologic histories of the icy satellites;
- determine what processes change the surface and near surface of the icy satellites, including both external and internal processes;
• investigate the makeup and distribution of surface materials, especially dark material like that on the leading hemisphere of Iapetus and low melting point ices;
• provide observational constraints on the internal structure and makeup of the moon;
• investigate how the icy satellites interact with the magnetosphere and the ring system and whether the icy satellites act as sources for material in the magnetosphere;
• complete the inventory of Saturn’s satellite system.

Additionally there is a set of mission objectives for Titan. The two relevant to study of Titan’s surface and its interaction with the atmosphere are to

• determine whether the surface is liquid or solid, quantify its geologic history and composition, characterize the surface morphology, collect data that will help determine the internal structure of Titan;
• determine the abundances of gases in the atmosphere, establish isotopic ratios for the most abundant elements, provide information that might lead to better understanding of how Titan formed and evolved.

The science objectives will be achieved through complementary observations by multiple instruments on the orbiter and, in the case of Titan, through experiments on the Huygens probe as well. Each instrument is described in its own article elsewhere in this special issue; in the two sections that follow we summarize their planned observations of the satellites and Titan.

4. Observations of the Satellites of Saturn

The observations of the satellites of Saturn will be accomplished on a number of flybys by the orbiter at varying distances from selected bodies; Titan will be the subject of three to four dozen flybys (driven by its role as orbit perturber) and is covered below in a separate section. Because of the inherent limitations of a four-year tour, not all satellites could be covered uniformly. Therefore, an interdisciplinary ‘Satellites Working Group’, chaired by the authors, met multiple times over the Cassini program development period to establish priorities. Because of Enceladus’s extensive resurfacing, which may have been driven by episodes of tidal heating, close examination of this object is deemed of great importance to an understanding of the dynamical and geological history of the Saturnian moons. Additionally recent activity may have brought to the surface low melting point ices still available for detection by the VIMS experiment. Thus of high priority is at least two flybys of Enceladus at $\sim 2000$ km flyby distance each, corresponding to highest spatial resolution in the narrow angle camera of the imaging science subsystem (ISS) of order ten meters per pixel. Because of its potential record of catastrophic impacts and deposition of relatively primitive material into the Saturnian system, the dark region of Iapetus and its interface with the bright area are
also key targets. Hence a close (~2000 km) flyby over the sunlit boundary between
the bright and dark terrains on Iapetus is a high priority. Other Satellite Working
Group priorities include measuring at moderate range (~30,000 km) the brightness
of Enceladus in the short wavelength visible and ultraviolet at zero phase angle,
where the opposition surge due to surface microphysics is seen; observing Mimas,
Tethys, Dione (particularly its wispy trailing side), Rhea, Hyperion at flyby dis­
tances less than 10,000 km (corresponding to ISS narrow angle camera resolution
of order a hundred meters per pixel) and sun phase angle between 10° and 40°;
dawn terminator crossings of large satellites for temperature and hence thermal
inertia measurements; close flybys of the night side of Enceladus to allow thermal
infrared searches for hot spot features. The close flybys are desirable not only
for high-resolution imaging and near-infrared mapping with the remote-sensing
experiments but also for charged-particle sampling and the precise determination
of masses, as described below.

The plasma experiments on the orbiter have the opportunity to sample satellite
material directly and determine the interaction of each body with the magneto­
sphere. The Cassini Plasma Spectrometer (CAPS) will perform remote sensing
measurements of surface compositions by analyzing sputtered ions as well as ions
from neutral torus pick-up, and will characterize the contribution of satellites to the
particle population of the magnetosphere. These objectives are achieved through
close flybys (better than 10,000 km) through the co-rotation wakes of the satellites.
The Cosmic Dust Analyzer (CDA) can also obtain information on the composi­
tion of satellite surfaces through analysis of ejected dust particles on very close
flybys and will quantify the role of dust impacts in modifying satellite surfaces
through measurement of the dust distribution throughout the Saturnian system.
The Dual Technique Magnetometer (MAG) will search for intrinsic magnetic fields
of the satellites and quantify the interactions between satellites and the magneto­
sphere (wakes, wave generation, etc.). The Magnetospheric Imaging Spectrometer
(MIMI) can map (image) the spatial distribution of neutral and charged particles to
detect and analyze satellite exospheres as well as investigate the absorption of en­
ergic ions and electrons by satellite surfaces and consequent sputtering of neutral
particles. The Ion Neutral Mass Spectrometer (INMS) could detect neutral atoms
and ions during close flybys of satellite surfaces that are undergoing sputtering or
other erosional processes. Mapping of hydrogen Lyman-alpha emission by UVIS
will constrain sources of particles, including Saturnian moons, being detected by
in-situ particles and fields instruments. The plasma experiments along with UVIS
will also, collectively, investigate the relationship between the satellites and rings
of Saturn, particularly the G and E rings.

The electromagnetic remote sensing experiments that will examine the surfaces
of the satellites are, in order of wavelength, the UVIS, ISS, VIMS, CIRS, and
RADAR. UVIS will map physical and chemical differences across satellite sur­
faces by their ultraviolet reflectance, with darkening an indication of surface aging
and magnetospheric modification. Surface reflectivity versus wavelength can be
used to detect non-water-ice species contained in the surface. The fine structure and
degree of compaction of surface materials is constrained by determining surface
phase function. UVIS observations during drifts across satellite limbs will search
for tenuous atmospheres, and gaseous emissions connected with surface activity.

The ISS investigation of the icy satellites will explore geodesy, global geology,
geologic history, spectral and physical properties, and local geomorphology of
selected areas. ISS will obtain high-resolution, multi-color (filter) images of se-
lected intermediate Saturnian satellites out to 1 micron wavelength (Voyager being
limited to \(\sim 0.6\) microns), regional (1 km/line pair) and global scale coverage to
as complete a level as allowed by the tour for the intermediate and small satellites,
stereo and polarization imaging of selected targets. Phase angle coverage will be
designed to allow for mapping of color differences (low phase angle) and morpho-
logy of surface features (moderate to large phase angles). Color and polarization
measurements will distinguish between endogenic and exogenic surface modifi-
cation. Determination of satellite shapes will aid in constraining interior models.
Transient events such as eruptions will be looked for on Enceladus and other
moons. The small satellites Janus and Epimetheus will be imaged if possible and a
search undertaken for undiscovered satellites associated with rings and the Trojan
regions. \(F\) and \(E\) ring observations will explore the relationship of these rings to
nearby satellites.

VIMS will map the surface spatial distribution of mineral and chemical species
on the surfaces of satellites at wavelengths in the range 0.85–5.1 microns, over 256
wavebands, as well as 96 wavebands in a visible channel from 0.35 to 1.05 microns.
Observations will address the global geological characteristics of the satellites, de-
termine the composition and distribution of satellite surface materials, especially
organic-rich deposits and volatiles, constrain the origin of the dark material on
Iapetus, provide data required to estimate the internal composition and structure of
the icy satellites, study the relationship between Enceladus and the \(E\)-ring, study
the physical properties of the surfaces of the inner satellites as suppliers of mag-
etospheric material, and look for sputtered ion emissions. VIMS is boresighted
with ISS and sequence design in terms of satellite phase-angle coverage, selection
of regions to be imaged, etc., will consider the synergy afforded by the high spatial
resolution of ISS and high spectral resolution of the VIMS images.

By virtue of its wavelength range in the mid- to far-infrared, CIRS can retrieve
information from the upper several centimeters of the regolith of icy bodies, in-
cluding thermal properties. Determination of the temperature behavior below the
surface in a spatially resolved fashion provides a boundary condition for thermal
evolution models and can detect areas of recent activity (warm or high thermal
inertia ices). Particularly exciting in this regard is the possible detection of regions
of current or recent activity on Enceladus. CIRS could detect hot spots above
184 K several square kilometers or more in extent. Further, CIRS will provide
long-wavelength spectra of satellite surfaces at resolutions of better than 5 km for
the closest flybys, providing data on the composition of organics and volatiles com-
SATELLITES AND INTERIORS

Complementary to the shorter wavelength and higher spatial resolution VIMS data sets. Complementary to the CIRS measurements are those of the RADAR in its passive radiometry mode, which is directly sensitive to temperatures down to about a meter below the surface of icy satellites. Because the instrument design is optimized to the large disk of Titan, radiometry of the icy satellites will depend upon the tour design and close flyby opportunities. A minimum distance of 8,000 km from Mimas is required, and 50,00 km for Rhea or Iapetus in order to obtain a useful signal.

The Radio Science Instrument (RSS) is capable of providing precise spacecraft tracking during flybys of ice satellites. Improved masses and hence definitive densities for the intermediate-sized satellites will answer the question of how variable is the rock to ice ratio from one object to another. This in turn is key to understanding how regular or stochastic the accretion process might have been, whether the rock fraction is dependent on final size or distance from Saturn or is distributed randomly around some mean value. The larger satellites (Rhea, Iapetus) can have the low-degree-and-order-gravity fields determined, which in turn allows internal structure models to be constructed. Combined with information from the MAG instrument on the presence or absence of a magnetic field, these data allow inferences on the structural and thermal evolution of the satellite interiors. RSS extinction observations will constrain the distribution of dust particles in the Saturnian system, while Earth occultations by the satellites will permit searches for evidence of atmospheres or ionosphere, though expected densities are below the detection limits.

5. Observations of Titan Pertaining to its Surface

Titan as a large moon with an atmosphere constitutes a mission goal unto itself, with objectives involving the interior, surface, lower and upper atmospheres, exosphere and interaction with the Saturnian magnetosphere. Thus very extensive observational plans have been made for the three to four dozen Titan passes expected during the mission, as well as the descent of the Huygens probe to Titan’s surface. Here we outline orbiter and complementary probe instrument investigations directed specifically to an understanding of Titan’s surface and interaction with the atmosphere. The requirements for Titan surface studies on the orbital tour design, as recommended by the Surfaces Working Group, include enough Titan flybys to map 30% of the surface by RADAR, in addition to at least 12 Titan flybys devoted to mapping by other orbiter remote-sensing instruments, two close RSS gravity flybys of Titan each at Saturn apoapse and periapse (see below), as well as other requirements pertaining to geographic distribution for mapping. These are in addition to requirements levied for the atmospheric and magnetospheric-interaction investigations at Titan developed by the respective working groups. These requirements are intended to be guides only as there is considerable uncertainty.
about what we will learn about Titan from each of the experiments. Following a
good selection of observations in the first few orbits, the project should be prepared
to significantly revise and rework observational strategies.

CAPS, INMS, and MIMI will make measurements specifically directed to the
upper atmospheric composition, interaction with the Saturn magnetosphere and
solar wind (within which Titan is embedded part of the time). These observations,
along with RSS occultation searches for a Titan ionosphere, bear on the escape
rates of atmospheric constituents from Titan and, integrated over the age of the
solar system, on the total amount of mass of major and minor species lost through
steady-state processes. This in turn constrains how the atmosphere and surface have
evolved over long timescales, and sets limits on initial volatile abundances in the
surface-atmosphere system. RPWS and ISS searches for lightning in the Titan atmo­
sphere will set limits on the amount of convective activity in the troposphere and
hence contributions to vertical mixing of condensable constituents such as meth­
ane; such measurements provide global context for the electrical activity searches
of the Huygens Atmospheric Structure Experiment (HASI). Further, the HASI
measurements of atmospheric temperature and pressure along the probe descent
trajectory will be complemented by RSS Earth-occultation and CIRS determina­
tions of temperature profiles through Titan’s atmosphere at several latitudes and
longitudes. This information is key to linking the surface and atmosphere energy
balance through atmospheric thermal and dynamical models.

Two instruments address the internal structure of Titan and its thermal evol­
uation. A search by MAG for an intrinsic magnetic field will determine whether
Titan’s interior is like Ganymede’s in this respect. RSS doppler tracking during
Titan flybys will determine the low-degree-and-order- gravity field of Titan, and
hence constrain the extent of differentiation of the interior. Furthermore, because
Titan’s orbit is eccentric, the satellite is subject to a periodic tidal stress. Dual fre­
quency doppler tracking during flybys occurring near Titan periapse and apoapse
around Saturn will allow this distortion to be measured which in turn will con­
strain the dynamical value of the tidal Love number and hence the rigidity of
the interior (Rappaport et al., 1996). In principle, because the rigidity difference
is large between a substantially molten versus a solid Titan, such a measurement
could distinguish between a Titan rich in low-melting-point volatiles and one that
is largely just water ice and rock. This provides a key constraint on the origin of
the volatiles comprising the surface and atmosphere of Titan. Should Titan prove
to have an interior structure similar to Ganymede’s, yet be devoid of an intrinsic
magnetic field, the constraint on Titan’s composition may well prove important in
rationalizing the difference between the two.

Remote sensing measurements of Titan’s surface will be undertaken by ISS,
VIMS, CIRS and RADAR on the orbiter, and on the probe by the Descent Imager
Spectral Radiometer (DISR), as well as an engineering radar altimeter (returning
data through HASI) and acoustical sounder on the surface science package (SSP).
From Earth-based observations (Smith et al., 1996) it is established that the near-
**Figure 1.** Spatial resolution versus coverage for the remote sensing instruments on the orbiter and probe, modified and updated from Lorenz (1994). A typical run of spatial resolution versus coverage is given for the labeled instruments; ‘Radar & IR Lightcurves’ and HST (Hubble Space Telescope) refer to Earth-based observations, DISR SSP sounder (note 9) and Probe Radar Altimeter are on Huygens, and the remaining experiments are on the orbiter. The extensions to the ISS Narrow Angle Camera curve are based on two different assumptions about image motion compensation. Notes qualifying aspects of the curves (labelled by number) are given in upper left. To the right are shown areas (position on horizontal axis), and required spatial resolutions for useful investigation, of various geological processes; the projected area of Titan’s disk and the total surface area are given for reference. Acronyms not defined in text: SAR=synthetic aperture radar (the orbiter RADAR experiment), FOV=field of view, IMC=image motion compensation, IR=infrared.

Infrared capabilities of ISS and VIMS should allow them to image the surface through the haze and in between the methane absorption bands, with ISS providing higher resolution but suffering from more haze scattering shortward of its 1 micron limit. The run of spatial resolution versus image area for these experiments matches well to that of DISR, as shown in Figure 1. VIMS provides spectral compositional discriminators of surface materials, while the RADAR in its active and passive radiometric modes will provide supporting data on physical properties and composition of the surface and immediate subsurface. The altimetric mode of the RADAR could be combined with images to generate three-dimensional information on selected areas. CIRS will map the temperature of Titan’s surface at thermal infrared wavelengths where the atmospheric opacity is a minimum.
DISR will not only provide contextual pictures in the vicinity of the probe impact site, but will collect near-infrared data of one part of the surface from close range and using a white light lamp, important for calibrating and providing ground-truth in interpreting the VIMS spectra. Likewise, the radar altimeter and acoustic sounder will provide information on the probe impact region that can be compared with the global imaging to be obtained by RADAR. The major operational limitation on the multiple modes of surface imaging is the number of flybys of Titan and inability to run all the instruments simultaneously. This is a particular problem for the RADAR, which produces narrow strips across the surface and can be operated in active imaging mode only near closest approach; thus each RADAR pass covers about 1% of the surface.

From the multi-wavelength mapping of the surface will come information on the geomorphology of Titan's surface, including the nature and extent of resurfacing processes, areal coverage of the surface by solid and liquid hydrocarbons, depth of liquid layers (directly from the acoustic sounder and indirectly from profiling of partially drowned crater basins), and crater size-frequency distribution. The last may be of particular value in understanding the evolution of Titan's surface and atmosphere given that the current atmosphere is dense enough to shield the surface from impactors below a certain size (Engel et al., 1995). If Titan’s supply of atmospheric methane has not been constant over time, being depleted perhaps by photolysis, then episodes of atmospheric thinning or collapse (Lorenz et al., 1997) could be evident in a crater size-frequency distribution biased toward smaller sizes than expected for the current atmospheric density (Ivanov et al., 1997). The orbiter and probe mapping of the surface will provide the opportunity to build a self-consistent picture: for example, should the surface coverage of organic compounds be much less than predicted from photochemical models (Yung et al., 1984), one would look to the cratering record to see evidence of long episodes of a thinner (methane-absent) Titan atmosphere.

Essential to an understanding of Titan’s surface is detailed measurement of the isotopic, elemental and molecular composition of the atmosphere, because mass and energy exchange between surface and atmosphere ensure they evolve in a coupled fashion over time. Principal orbiter instruments for compositional determination are UVIS, VIMS and CIRS. Techniques include direct spectroscopy as well as solar and stellar occultations (in combination with RSS Earth occultations to derive temperature structure). Adding to these measurements are the direct samplings of the Huygens Probe Gas Chromatograph and Mass Spectrometer (GCMS), which will analyze atmospheric gases and, through the Aerosol Collector and Pyrolyzer, cloud and haze particles as well. The Surface Science Package will make direct and indirect samplings of surface materials, complementing the direct atmospheric measurements from the Probe. Finally, the INMS samples the very highest atmosphere directly. A few of the vast number of key measurements include argon to nitrogen ratio, to determine the origin of Titan’s nitrogen; isotopic abundances including deuterium to hydrogen, which provides information on environments of
formation as well as total photolyzed methane over time (Pinto et al., 1986); and assays of the complex organic chemistry in gases and grains to understand the full cycle of methane photolysis and its implications for pre-biotic chemistry on Titan’s surface. A fuller description of the significance of atmospheric measurements from Cassini-Huygens is given in the articles by Raulin and Owen and Gautier in this issue.

Perhaps more than any other aspect of the mission, the Titan flybys provide extraordinary opportunities for cooperative and synergistic measurements, in which data from multiple instruments provide a deeper understanding of the phenomena under investigation. At the same time, this confluence of opportunities inevitably results in conflict, because the orbiter cannot utilize all of its instruments at the same time or even on the same flyby of Titan. These conflicts occur in the satellite flybys as well. As described in the next section, resolving these conflicts in part required developing orbital tours with the largest number of possible science opportunities.

6. Saturn Satellites and the Orbital Tour

After delivering the probe to Titan in late December, 2004, the orbiter will continue a four-year nominal mission of exploring the Saturn system. To achieve a wide range of orbital elements, which provide close satellite flybys, views of the rings, magnetospheric exploration and opportunities to conduct occultations of Saturn, rings and Titan requires large energy changes in the orbit. This is achieved through close flybys of Titan followed by expenditure of rocket fuel to shape orbits whose energies have been altered by the Titan flybys. Titan is the only object orbiting Saturn which is massive enough to alter the spacecraft momentum. Thus unlike in the Jovian system, all orbits must involve a return to Titan so as to enable its use for subsequent, repeated orbit adjustments.

When the orbiter spacecraft was redesigned in 1992 to save development costs, removal of the remote-sensing platform, other pallets and additional changes complicated the operation of the spacecraft. The body-fixed antenna and instruments require that for the most part data be collected and stored during an observation, to be relayed later when the antenna is pointed toward Earth. Geometrical and operational conflicts among instruments were created by the change, for example, the inability to point the main antenna for radar measurements simultaneously with the ISS, VIMS and UVS observations of the target. Radio science mass measurements require the spacecraft to remain fixed inertially, preventing tracking of the target for pointing and image motion compensation. Thus on each satellite or Titan flyby, only a subset of the instruments can be operating during the precious time near closest approach.

These limitations created significant problems in achieving the mission’s promised science goals and placed a burden on the tour design team to create an orbital
tour rich enough in observing opportunities for all instruments and science disciplines so as to achieve most or all of the objectives. Beginning in 1992 and extending through the launch period in late 1997, the JPL tour design team worked with the Cassini-Huygens Project Science Group (PSG) in an intensive effort to define science requirements, translate these to tour requirements, and then design tours to meet the objectives within the constraints of maneuvering fuel and other spacecraft limitations. The development process was iterative, with trial tours evaluated by the PSG and consequently altered. Significantly, the expertise in using a variety of second-order effects in the Saturn system (planet oblateness, other satellites, etc.) to make orbit changes more efficiently was significantly enhanced during the tour-design process, primarily through software improvements at JPL but also through the ideas of PSG participants, especially Yves Langevin (Paris Obs.).

In the end, 19 types of tours were evaluated, distinct in the basic geometry of the orbit changes over four years as well as in other assumptions and ‘tricks’ employed by the design team. A final comprehensive evaluation by the PSG and its discipline working groups, together with Cassini Project evaluation of operability issues led to the so-called T-18 class of tours being selected. Within these are approximately a half dozen different tour varieties, all characterized by a similar initial 18 months but then diverging in coverage, orbit inclination changes with time, and other factors.

TABLE II
Basic Tour Parameters Relevant to Satellites for Tour 18-5

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<td>4</td>
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<td>45</td>
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</tbody>
</table>

Notes: Data from Cassini Project. Flyby distance d given in kilometers. Titan flyby distances are preliminary; following orbiter mapping of the upper atmospheric density using INMS, close approach distances will likely be decreased.

Table 2 lists the parameters relevant to Titan and icy satellite observations of T18-5 as an example of a tour that satisfies most of the science objectives associated with the Saturn satellites. The reader is cautioned that this is one of many tours
that have been generated, is given by way of example only, and that additional improvements to the tour candidates were being made by the project while this paper was in press. Small changes to the tours can lead to significant alterations in the number and nature of the satellite flybys, and a final decision on which tour to fly is contingent on further study by the engineering and science teams. The design process itself, lengthy and heavily consumptive of engineering time, nonetheless stands as a prime example of the value of thorough and extensive interfaces between mission scientists and engineers, and has honed skills and software useful in the planning of future missions requiring gravity assists (such as a future Europa Orbiter).

Acknowledgements

Much of the description of instrument objectives and mission design details was extracted from Cassini mission ‘orange books’ prepared by JPL and by the various instrument teams. The authors thank Prof. Carolyn Porco for improving the accuracy of the manuscript, Dr. Ralph Lorenz for providing the figure, and Drs. Roberto Orosei and Dale Cruikshank for correcting the English. We are most grateful to Dr. Amanda Hendrix, JPL, for revising and correcting Table II. The first author is grateful to Dr. Angioletta Coradini for hosting his stay at the Istituto di Astrofisica Spaziale, Rome, during which time this article was written. Preparation of the paper was supported by the Cassini Project and Consiglio Nazionale delle Ricerche (Italy).

References

SATURN’S RINGS: PRE-CASSINI STATUS AND MISSION GOALS

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Abstract. Theoretical and observational progress in studies of Saturn’s ring system since the mid-1980s is reviewed, focussing on advances in configuration and dynamics, composition and size distribution, dust and meteoroids, interactions of the rings with the planet and the magnetosphere, and relationships between the rings and various satellites. The Cassini instrument suite of greatest relevance to ring studies is also summarized, emphasizing how the individual instruments might work together to solve outstanding problems. The Cassini tour is described from the standpoint of ring studies, and major ring science goals are summarized.

1. Introduction and Overview

In November 1980, and again in August 1981, identical Voyager spacecraft flew through the Saturn system, changing forever the way we think about planetary rings. Although Saturn’s rings had been the only known ring system for three centuries, a ring system around Uranus had been discovered by stellar occultations from Earth in 1977, and the nearly transparent ring of Jupiter was imaged by Voyager in 1979 (the presence of material there had been inferred from charged particle experiments on Pioneer 10 and 11 several years earlier). While Saturn had thus temporarily lost its uniqueness as having the only ring system, with Voyager it handily recaptured the role of having the most fascinating one (Figure 1).

The Voyager breakthroughs (through 1984, when a series of review chapters appeared) included spiral density and bending waves such as cause galactic structure (Figure 2a); ubiquitous fine-scale radial ‘irregular’ structure, with the appearance

of record-grooves (Figure 2b); complex, azimuthally variable ring structure; empty gaps in the rings (Figure 2c), some containing very regular, sharp-edged, elliptical rings and at least one containing both a small moonlet and incomplete arcs of dusty material; shadowy ‘spokes’ that flicker across the main rings (Figure 3); and regional and local variations in particle color (Figure 4). One of the paradigm shifts of this period was the realization that many aspects of planetary rings, and even the ring systems themselves, could be ‘recent’ on geological timescales. These early results are reviewed and summarized in the Arizona Space Science series volumes ‘Saturn’ (Gehrels and Matthews 1984) and ‘Planetary Rings’ (Greenberg and Brahic 1984), in Brahic (1984), and by Cuzzi (1983). An excellent review of ring dynamics at a formative stage is by Goldreich and Tremaine (1982). The reader is referred to these review articles for an introduction to overall ring properties and physics. Table 1 summarizes nominal ring dimensions and properties.

From the mid 1980’s to the time of this writing, progress has been steady, while at a less heady pace, and some of the novel ring properties revealed by Voyager 1 and 2 are beginning to be better understood. It is clearly impossible to cite, much less review, every advance over more than a decade; however, below we summarize the main advances in understanding of Saturn’s rings since the mid 1980’s, in the context of the Cassini Science Objectives as described in the Announcement of Opportunity. Other review articles during this time period include Borderies (1989),
Figure 2. Characteristic structures in Saturn’s rings: (a) spiral density and bending waves, typical of the A ring, (b) ‘irregular structure’, typical of the B ring, (c) gap-and-ringlet structure, typical of the C ring and Cassini Division (from Lissauer and Cuzzi 1985).
Figure 3. Typical ‘spokes’, appearing relatively dark at low phase angles (bottom panel) and relatively bright at high phase angles (top panel) due to the scattering properties of the half-micron radius spoke particles relative to the surrounding macroscopic particles. From Cuzzi et al. 1984.
Figure 4. Ring color variations with radial location. Top panel: Overall ring optical depth from stellar occultation data, showing main ring regions: C ring (74,510–92,000 km), B ring (92,000–117,580 km), Cassini Division (117,580–122,170 km), and A ring (122,170–136,780 km). Middle panel: ring reflectivity or $I/F$ in the Voyager green filter (revised from EC96 to reflect Johnson-Buratti calibration); Bottom panel: ratio of reflectivity in Voyager Green filter to that in Voyager UV filter (Voyager 'atmospheric' calibration, revised as described in section 3.2). Figure from Estrada et al. (2003).
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Satellite masses and radii derived from Burns 1986 except as noted.

bSatellite masses and radii derived from Burns 1986 except as noted.

cMasses estimated by Cuzzi et al. 1984.


eRosen et al. 1991b.

2. New Observations

Ground-based stellar occultations detected ‘arcs’ of ring material orbiting Neptune, starting in 1984 (see Nicholson et al. 1995 and Porco et al. 1995 for review and discussion). This suggested the need for dynamical mechanisms of azimuthal confinement of ring material in addition to radial confinement (as in the Uranian rings).

The Voyager Uranus and Neptune encounters occurred in 1986 and 1989, respectively (Science 233, 1-132; Science 246, 1361-1532; Uranus and Neptune ring systems reviewed by French et al. 1991, Esposito et al. 1991, and Porco et al 1995). The Neptunian ring arcs were confirmed. Both of these ring systems were found to be composed of a series of narrow, dusty rings embedded in a broader, very low density, more diffusely structured, sheet of tiny dust particles. The ring material is darker, in both cases, than that comprising Saturn’s rings (Ockert et al. 1987, Ferrari and Brahic 1994, Karkoschka 1997). In both systems, families of ringmoons were discovered, including several lying within the nominal ‘Roche zone’ of the parent planet.

In 1989, Saturn’s rings occulted a very bright (albeit rather large – 20 km apparent diameter) star, 28 Sagitarii (Hubbard et al. 1993, French et al. 1993, Harrington et al. 1993). In addition, several stellar occultations were observed by HST, with complex trajectories that potentially contain information about azimuthal as well as radial ring structure (Elliot et al. 1993).

The ring plane crossings of the Earth and Sun in 1995 and 1996 provided important new insights into the time-variable structure of the F ring clumps and the properties of the G ring particles, and revealed anomalous orbital behavior of the nearby moons Prometheus and Pandora (see section 3.5).

An extended series of HST color observations of the rings, as they open up, has been conducted (French et al. 1998a, Cuzzi et al. 2002). Spokes were observed in these images, and the spoke particle size determined (French et al. 1998a). The ring color was also determined in 8 filters, from the near-UV at 0.25 micron extending out to 1 micron – a great improvement over the Voyager dataset (although at lower spatial resolution). Earlier HST data, obtained with the aberration-uncorrected WF/PC, have been analyzed by Poulet et al. (1999). Also as of this writing, new spectrophotometric observations of the rings have been obtained in the near-infrared using the IRTF (Poulet et al. 2002a), and at visual wavelengths using the HST/STIS combination (D. Cruikshank, PI; under analysis).

Galileo has returned several new images of the Jupiter ring, which show structure not seen in the Voyager images. Amongst other results, these new data confirm the tiny nearby ringmoons Metis and Adrastea as sources of main ring material, as well as establishing Amalthea as the parent of the gossamer ring and Thebe as a parent of an even less obvious ring (Ockert-Bell et al. 1999, Burns et al. 1999, de Pater et al. 1999). In addition, NIMS data imply that the particle size distri-
bution is considerably steeper (richer in small particles) than previously believed (McMuldroch et al. 2000, Brooks et al. 2003).

The Planetary Data System Discipline Node for Planetary Rings was established and has become a repository for a large amount of archival information on ring systems, including that noted above (Showalter et al. 1996; http://ringmaster.arc.nasa.gov).

3. Cassini Ring Science Objectives

The science objectives of Cassini are briefly described below. Recent advances since the mid-1980’s are noted, and key outstanding problems are summarized.

3.1. CONFIGURATION AND DYNAMICS

One of the most important questions about the rings is the cause of their abundant, complex structure. The ‘record groove’ structure in the A and B rings, the hauntingly regular banded structure in the C ring, and the ‘kinks’ in the F ring, remain unexplained. 

Spiral density waves and ‘wakes’: Spiral density waves are triggered at orbital resonances with moons, and propagate by virtue of the ring’s self gravity. Several studies were completed concerning the propagation and damping of spiral density waves (Shu et al. 1985, Borderies et al. 1986). The different appearance of waves in the B and A ring may be understood in terms of differing particle random velocities and elasticities (Shu et al. 1985); that is, the more slowly damping waves in the B ring indicate smaller random velocities for the particles than in the A ring regions where the waves damp more rapidly. Many weak spiral density and/or bending waves were discovered in the Voyager Radio Science data and analyzed in detail (Marouf et al., 1986, Gresh et al. 1986, Rosen et al. 1991a,b), but several of these wavelike features remain unidentified (Marley and Porco 1993). An outstanding problem is the lack of a full treatment of coupled spiral density wave propagation, damping, and ‘dredging’ or transport of material by angular momentum transport (Shu et al. 1985). The dredging issue has been touched on by Molnar and Dunn (1995), and recent attempts at wave damping and particle random velocities (ring thickness) were made by Rosen and Lissauer (1988) and Chakrabarti (1989). Given the importance of this physics to protoplanetary disk physics, it is a little surprising that it hasn’t received more attention.

Saturn’s embedded moon Pan was discovered in the Encke gap by virtue of the ‘wakes’ it leaves in adjacent material (Cuzzi and Scargle 1985, Showalter et al. 1986, Showalter 1991). In fact, the traces of Pan’s wake have now been detected many orbits ‘downstream’ in material well separated from Pan (Horn et al. 1996). Wakes are generated by varying kinematics of perturbed particle orbits, and are negligibly affected by ring self gravity (Cuzzi and Scargle 1985, Showalter et al.
The detailed properties of wakes are of great interest, as they provide a good way to explore local ring collisional dynamics (Lewis and Stewart 2000). Perhaps advances along these lines might help explain why, at one longitude at least, it seems the edge of the Encel gap becomes ‘detached’ in a way that is incompatible with RSS data (discussed by Cuzzi et al. 1984; see, e.g., Showalter et al. 1986). Gap-embedded moonlets were inferred in the Cassini division based on what appeared to be ‘wakes’ (Marouf and Tyler 1986) but imaging analysis of the region casts doubt on the wake interpretation (Flynn and Cuzzi 1989) and the moonlet inference; the true cause remains one of the many unsolved problems of Saturn’s ring structure.

**Irregular structure:** The fine-scale radial brightness variations in the A and B rings (Figure 2b) are not compatible with simple scattering models in which particle volume density is low; in fact they might indicate spatially variable particle volume density (Dones et al. 1989, 1993; Salo and Karjalainen 2002). Changes in volume density are expected from collisional dynamics: i.e., high optical depth regions, where the particles collide more frequently, probably have smaller random velocities and are therefore more densely packed than low optical depth regions for the same degree of stirring by large particles. The traditional way of constraining particle volume density is through the ‘opposition effect’ of the rings, a sharp brightening within a degree or so of zero phase angle (see French et al. 1998b and Poulet et al. 2002b for recent results and references). However, alternate explanations exist related to the porosity of the surface layers of each ring particle, or coherent scattering in the regolith surface (Mishchenko and Dlugach 1992, Hapke 1990, Hapke and Blewett 1991 – see also section 4.1). Poulet et al. (2002b) show that coherent backscattering is a preferred explanation for the ring opposition effect, implying that other approaches must be used to constrain ring volume density or packing fraction. Brightness variations as a function of ring opening angle and phase angle are another way to do so. Cuzzi et al. (2002) show how most of the optically thinner rings behave like a classical, many-particle-thick model, but that the outer two-thirds of the B ring, and the optically thick inner A ring, behave in a way that is expected from a more closely packed, lower porosity region as predicted by models (Dones et al. 1989, Salo and Karjalainen 2002).

In the outer 1000 km of the B ring lies a unique region where the irregular radial structure is not only variable with longitude, phase angle, and/or time (Smith et al. 1982), but also shows much finer scales than seen elsewhere (Horn and Cuzzi 1996, Cuzzi et al. 1984). No satisfactory explanation exists for the irregular structure, although various local transport processes and forces have been proposed. The most viable hypotheses include moonlet perturbations (Lissauer et al. 1981), ‘viscous overstabilities’ (Borderies et al. 1985, Longaretti and Rappaport 1995, Salo et al. 2002, Schmidt et al. 2002), and ballistic transport (Durisen et al. 1992). Other studies along the lines of ‘slow’ instabilities in dense rings have been done by Osterbart and Willerding (1995) and Schmit and Tscharnuter (1995), but these seem to indicate finer scale structure (comparable to the ring scale height) than the
observed irregular structure. Mosqueira et al. (1999) have developed and applied a scaling approach to the dynamics, and used a smooth-particle-hydrodynamics (SPH) code to increase the range of global numerical simulations of collective effects in dense rings. More laboratory or even theoretical study of the properties of impact ejecta from particle surfaces of different types would also be valuable, to better enable predictions by the ballistic transport theory (e.g., Arakawa and Higa 1996).

Isolated ringlets: Narrow isolated ringlets are seen in the C ring and Cassini Division (Figure 2c) – in fact in all ring systems – with a wide range of properties. We now understand how the sharp edges of the Uranian epsilon ring, at least, are maintained or ‘shepherded’ by individual resonances due to external satellites (Porco and Goldreich 1987, Goldreich and Porco 1987). Other narrow, eccentric ringlets, such as the other Uranian rings, are becoming more well understood as ‘modes’ in which momentum transport and the accompanying energy dissipation can reach equilibrium when the particle streamlines are arranged in a certain way (Borderies et al. 1985; reviewed by French et al. 1991 and Porco 1990). The effects of resonances on initiating narrow structures have been explored numerically by Hänninen (1993) and Hänninen and Salo (1992, 1994, 1995), and analytically by Rappaport (1998). The roles of viscosity and self gravity in maintaining these structures continue to be discussed, as improved analytical and numerical models are developed; Longaretti and Rappaport (1995) discuss the role of ‘viscous overstabilities’ in forming narrow, eccentric rings, finding that this process cannot form an eccentric ring from a circular one. The stranded F ring, as well as the discontinuous and kinky Encke gap ringlets, probably result from different physics (discussed in section 3.5).

Ring arcs: Following the discovery of azimuthal structure in the Neptunian system, hypotheses were advanced to explain satellite perturbations which could lead to azimuthal structuring or confinement of ring material, in addition to the radial confinement previously studied for narrow rings. The essential physics of these is creation of azimuthally variable potential energy minima and maxima in the frame rotating with the ring material, about which material can then librate as do Jupiter’s Trojan asteroids (Lissauer 1985). The preferred hypothesis until recently (Goldreich et al. 1986, Porco 1991) relies on corotational resonances with a moon which has a slightly inclined orbit (see Porco et al. 1995 for a review). More recent observations covering a longer time baseline (Terrile et al. 1998, Roddier et al. 1998, Sicardy et al. 1999, Dumas et al. 1999) have shown that the arcs have a slightly different mean motion than is consistent with the most promising confining resonance (Porco 1991), and a variant on the original model has been suggested by Namouni and Porco (2002). Fortya and Sicardy (1996) and Hänninen and Porco (1997) have shown that particles can escape corotational trapping and can either escape the arcs entirely or find their way to adjacent sites, compatible with a hypothesis that the arc material may be created by a disruption event and evolve, even if slowly (Esposito et al. 1997). Hänninen and Porco (1997) have also illustrated the
importance of nearby vertical resonances in minimizing the collision rate among arc particles and enhancing stability, and Salo and Hänninen (1998) studied the role of self gravity of the arc material. These new insights will be valuable in understanding the properties of azimuthally variable narrow rings that Voyager actually discovered first in Saturn’s rings (in the Encke gap, the Cassini Division, and the F ring region).

**Viscosity:** The primary mechanism for transferring angular momentum within and throughout Saturn’s rings is viscosity in the presence of Keplerian shear. The ring viscosity is a combination of random particle motions, as in classical kinetic theory, and collisions. Ring viscosity has now been modeled with allowance for finite particle sizes, close packing of particles, and the effects of mutual self gravity (Wisdom and Tremaine 1988, Mosqueira 1996, Mosqueira et al. 1999). A substantial contribution arises due to collisions between finite size particles in regions of large optical depth, causing a monotonic increase in viscosity with optical depth. This prevents the simple viscous instability (Lin and Bodenheimer 1981, Ward 1981) which had been envisioned for a system in which the viscosity has a local maximum at some intermediate optical depth (reviewed by Porco 1995 and Cuzzi 1995). Improved analysis of ring particle size and vertical structure from the Voyager radio science observations (Zebker et al. 1985) implies that the vertical thickness of the rings is only a few times the size of the larger (several meter radius) particles, which sets the velocity dispersion of the ring particles (less than 1 cm/s).

**Meteoroid bombardment:** The role of meteoroid bombardment in determining the structure, composition, and evolution of (at least parts of) Saturn’s rings has been extensively developed (Ip 1983; Morfill et al. 1983; Durisen 1984, Lissauer 1984, Durisen et al. 1989, 1992, 1996; Cuzzi and Durisen 1990). The vast surface area of the rings, relative to their mass, makes them highly sensitive to meteoroid bombardment. The above papers by Durisen and coworkers propose that the morphology seen at the inner edges of both the A and B rings, involving an abrupt inner edge, a linear ramp, and several plateaus nearby, and perhaps even some irregular structure on the high-optical depth side, might result from the special kind of ‘ballistic transport’ of ejecta associated with meteoroid bombardment. Meteoroid bombardment may also play a role in ring composition (section 3.2), in producing sporadic F ring clumps (section 3.5), and in spoke formation (see below). A revision and reanalysis of the flux hitting the rings was presented by Cuzzi and Estrada (1998), and a new analysis of multi-spacecraft data has been done by Landgraf et al. (2002) (see section 3.3).

**Electromagnetic influences:** A series of studies has suggested that magneto-gravitational instabilities favor loss of material from various parts of the rings to the planet (Northrop and Hill 1982, 1983; see reviews by Grün et al. 1984a and Connerney 1986). At least one of these ‘special’ boundaries corresponds to otherwise unexplained changes in ring spatial structure and scattering properties (see, e.g., Horn and Cuzzi 1996). The role of electromagnetic perturbations on tiny, charged dust grains was elucidated and applied to the structure of Jupiter’s ring (Schaffer and
‘Spokes’ (Figure 3; Grün et al. 1984b, 1992) are believed to result from a combination of impact and electromagnetic phenomena (Goertz and Morfill 1983, Goertz 1984). The electromagnetic aspects have been further elucidated (Tagger et al. 1991) and the properties of the spoke particles better constrained (Doyle and Grün 1990). There is a clear connection, as yet unexplained, between the spokes and Saturn’s planetary magnetic field; maximum spoke abundance and activity is correlated with the longitude of an active Kilometric Radiation source (Porco and Danielson 1982, 1984; also see Cuzzi et al. 1984). The role of meteoroid impacts has also been further studied by Cuzzi and Durisen (1990), who explained the role of the shadow region (it is the region of maximum impact velocity for heliocentric projectiles of large eccentricity and inclination) and also suggested that there might be a variation of spoke abundance with orbital season, depending perhaps on the ring orientation to incoming projectiles. While there has been no published mention of spokes in HST images at large ring opening angles, definite spoke activity has been observed from HST at low opening angles (French et al. 1998a) and recently, faint traces of spokes have been observed at moderate opening angles as well (R. French, personal communication, 2002).

Studies were conducted of the processes by which ring material absorbs magnetospheric particles, as part of several ‘Ring Hazard’ studies carried out under the auspices of the Cassini Project (see also section 3.4). These studies (Ring Hazard Working Group 1991, 1996) treat simultaneous absorption and diffusion of magnetospheric species, and combine imaging, magnetospheric, and spacecraft dust impact data sets into a fairly coherent picture of the faint material populating the ring plane. These results were used to constrain the ring plane crossing strategy for the spacecraft and, while not published in the open literature, are useful and available through the Cassini project or the Rings PDS Node. Canup and Esposito (1997) and Burns and Gladman (1998) present portions of the Ring Hazard Study results that constrain the ring plane crossing strategy.

3.2. COMPOSITION AND SIZE DISTRIBUTION

For decades, it has been known that water ice is likely to be the principal constituent of Saturn’s rings. However, the known variations in color and albedo across the main rings require the presence of other constituents, in amounts that vary with location. Reviews of ring composition are in Esposito et al. (1984) and Dones (1997).

Ices, silicates, organics? Photometric analysis of the A, B, and C rings, with some interpretation as to the nature of the ring particle surfaces and vertical ring structure, has been presented by Doyle et al. (1989), Cooke (1991), and Dones et al. (1993). Data presented by Clark (1980) and Karkoschka (1994) might show a very weak 0.85 micron absorption feature (see also Clark et al. 1986). However,
Poulet and Cuzzi (2002) confirm this only in the C ring. Estrada and Cuzzi (1996; EC96) analyzed the radial variation of color across the main rings in three Voyager (visual) wavelengths; unfortunately the plots in EC96 contained incorrect calibration constants. The revised ring colors (Figure 4, retaining the Voyager ‘atmospheric’ calibration discussed by EC96) are less red. Doyle et al. (1989) constrain the abundance of non-icy material from visual wavelength data; Cuzzi and Estrada (1998) extend and refine this analysis, and incorporate it with an evolutionary model which shows how meteoroid bombardment causes the color and composition of the rings to evolve with time.

Both Doyle et al. (1989) and Cuzzi and Estrada (1998) conclude that observed ring particle compositions are not compatible with exposure to current estimates of interplanetary debris over the age of the solar system. Cuzzi and Estrada (1998) infer from the observed ring properties that the reddening agent is more likely to be an ‘intrinsic’ organic tholin-like material than a silicate, and suggested Carbon as a spatially variable darkening agent based on ballistic transport calculations. More sophisticated regolith radiative transfer modeling by Poulet and Cuzzi (2002), Poulet et al. (2002a) support reddish organics as the preferred reddening agent for the rings, and Carbon as the preferred darkener. Poulet et al. (2002a) also find that the fractional amount and fine-scale spatial distribution of the Carbon varies with location (being more intimately mixed with ice in the C ring) and that an additional as-yet unidentified non-icy substance must be added to the C ring as well. The darkening material might be ‘extrinsic’, dark, neutrally colored carbaceous material, or it might be intrinsically developed by an unknown mechanism. Recent work by Poulet et al. (2002c) cautions us about the role of model biases in the Interference of regolith composition.

HST results (Cuzzi et al. 2002) also reveal an unexpected increase of the ring redness with phase angle (but not with opening angle), which is larger than is seen for, at least, Europa (Helfenstein et al. 1998) and invalidates the interpretation of the Voyager G/UV ratio by Cuzzi and Estrada (1998) as purely an albedo effect (that is, phase functions can apparently vary with wavelength). The newly calibrated Voyager results (Figure 4; see also Estrada et al. 2003) are compatible with this effect. A new analysis for the ring particle albedo and phase function has recently been done by Poulet et al. (2002b) using data over a range of phase angles. They find that the phase reddening is plausibly attributed to the unusually large roughness of ring particles – probably lumpy, clustered transient objects – which accentuates the phase angle dependence of multiple intraparticle scattering, as suggested by Cuzzi et al. (2002). The new HST results include evidence for regional variation of composition from several new passbands. Color ratio radial profiles imply the presence of different materials responsible for absorption at these and other wavelengths with rather different radial distributions.

Microwave emission is highly sensitive to small amounts of non-icy material spread uniformly throughout the ring particles. Epstein et al. (1984) limited the abundance of silicates to 10% by mass; recent studies by Grossman (1991; see
also Grossman et al. 1989) indicate the non-icy material fraction might be even lower – perhaps as low as 1%. Even more recent observations confirm these low ring brightnesses and the cause as scattering of Saturn’s thermal emission and the cold of space (de Pater and Dickel 1991, Molnar et al. 2002, van der Tak et al. 1998) and seem to agree on a weak East-West asymmetry in the ring brightness. The cause of this is not known at present, but might be related to the same trailing wake structures advocated to explain similar effects at visual wavelengths (e.g., Colombo et al. 1976, Dones et al. 1993). The usual framework for interpreting microwave observations, including radar reflectivity, is a more-or-less classical scattering layer (modified to account for finite thickness; Cuzzi et al. 1980, Zebker et al. 1985). However, recent suggestions that some of the large radar reflectivity of the Galilean satellites might be due to a coherent backscatter opposition effect (Mishchenko and Dlugach 1992, Hapke 1990, Hapke and Blewett 1991) might merit more consideration in the ring radar context as well.

Photometry of the D ring (Showalter 1996, Marley and Porco (1993)), E ring (Showalter et al. 1991), F ring (Showalter et al. 1992), and G ring (Showalter and Cuzzi 1993, Throop and Esposito 1998) is discussed further below.

**Particle size distribution:** A new approach to analysis of stellar occultation data was developed that provides good constraints on the size of the largest local particles at very high spatial resolution (Showalter and Nicholson 1990). Fluctuations in the brightness of an occulted star are observed that are above the levels predicted by Poisson statistics; these are interpreted in terms of uneven filling of the star’s Fresnel zone (about 20 m on a side) by objects at the large size end of the particle size distribution. Interesting comparisons can be made between these results and more direct measurements of ‘largest’ typical particle size, such as from Voyager radio occultations (Tyler et al. 1983, Marouf et al. 1983, Zebker et al. 1985). Agreement is not always as good as might be hoped, and improvements in the technique are probably indicated, but it shows how stellar occultation experiments can complement radio occultation measurements, providing high spatial resolution information on the abundance and size of the largest particles. More recent analysis of the 28 Sagitarii occultation constrains the lower end of the size distribution; the B ring particles are larger than 30 cm, while the size distribution extends further into the cm-size range in the other rings (French and Nicholson 2001). In the Cassini era, given a fuller understanding of the polarizing properties of irregular particles, currently puzzling polarization observations (Dollfus 1996) might become better understood.

The evolution of particles and clumps of particles by collisional sticking and growth, with spins and tidal and/or collisional disruption, has been studied analytically (Araki 1988, 1991b; Longaretti 1989). Laboratory studies have been done which constrain the plausible range of ice particle stickiness at low relative velocities for a variety of surface conditions (Bridges et al. 1996, Supulver et al. 1997, Higa et al. 1996). Numerical simulations of combinations of dynamical and collisional behavior of rings (and more general N-body systems) which include
realistic inelasticities have shown the formation of transient clumps (Salo 1991, 1992a,b, 1995; Richardson 1994). These large structures are reminiscent of, but larger than, the ‘dynamical ephemeral bodies’ postulated for the 5–10 meter-sized ring particles themselves by Davis et al. (1984). The large fluctuations observed in stellar occultation data (Showalter and Nicholson 1990) might be related to these structures. More quantitative discussion of their relative abundance will be needed before we can determine if such structures are significant contributors to remote observations of ‘particle size’ from radio or stellar occultations.

**Diffuse rings and tiny grains:** The E ring is now fairly well understood as dominated by micron-sized grains, based on a large number of complementary ground-based and spacecraft observations (Burns et al. 1984, Showalter et al. 1991); especially diagnostic are its blue color and vertically extended spatial distribution (discussed further in section 3.4).

Recent observations and modeling studies of the G ring (Throop and Esposito 1998, Meyer-Vernet et al. 1998, Nicholson et al. 1996) have revised our beliefs regarding the size and radial distribution of material in that region. Van Allen (1983) had concluded that the radial width of macroscopic material (capable of absorbing magnetospheric protons) was only around 500 km; Showalter and Cuzzi (1993) had reconciled this with Voyager images which clearly show a much broader feature by suggesting that the visible 5000 km wide ring is merely a broad dusting of tiny grains surrounding a narrower core of large objects. Showalter and Cuzzi (1993) also concluded from the (admittedly sparse) phase angle distribution of Voyager images that the diffuse Voyager G ring probably contained dust with a very steep ($r^{-6}$) size distribution. The newer results and analyses change these beliefs as follows: (a) the G ring material is confined to a relatively narrow vertical layer across its entire radial extent, as opposed to the obviously vertically extended E ring (Nicholson et al. 1996), (b) the G ring material is red-to-neutral in color, as opposed to the distinctly bluish hue of the E ring (Throop and Esposito 1998), and (c) reanalysis of Voyager PRA data showing impacts on the Voyager 2 spacecraft as it traversed the periphery of the G ring (Meyer-Vernet et al. 1998) are incompatible with the steep size distribution and dominance by tiny, submicron grains found by Showalter and Cuzzi (1993). Since several lines of argument find the E ring to be composed primarily of micron-sized particles (section 3.4), these results suggest that the G ring is not similarly composed, and that macroscopic material permeates the entire radial width of the G ring (which may still be compatible with the analysis of Van Allen 1983). The recent conclusions are all compatible with a distributed moonlet belt model covering the entire width of the G ring (Canup and Esposito 1997), doubtlessly coexisting with a complement of tiny dust grains as seen in Voyager images.
3.3. DUST AND METEOROIDS; LOCAL AND INTERPLANETARY

The influence of meteoroid bombardment on ring structure and composition has been discussed above in several places. While important uncertainties will require resolution by Cassini, especially in regard to the net flux and composition of the projectiles, some progress is being made. A collection of the different data sources, with a non-physical interpretation in terms of dynamical populations, was presented by Divine (1993). The Galileo and Ulysses missions have measured the abundance of tiny grains in the outer solar system (see, e.g. Grün et al. 1997 and references therein). A recent review combining the results from all remote spacecraft observations to date is by Landgraf et al. (2002; see below).

Recent observations of water in the stratospheres of Saturn and the other gas giants, interpreted with the aid of model photochemical calculations, place interesting constraints on the meteoroid mass flux (Feuchtgruber et al. 1997, Moses 1998, Moses et al. 1998). The (one-sided) mass flux implied is compatible with a recent reassessment by Cuzzi and Estrada (1998): about $5 \times 10^{-17}$ g cm$^{-2}$ sec$^{-1}$ prior to gravitational focussing by the planet. Galileo and Ulysses have found a population of plausibly interstellar grains (Grün et al. 1997); Dones (1997) questioned whether the mass flux at Saturn (as inferred from Pioneer) could be considerably lower – if the interstellar grains contain larger members than commonly assumed, their impact velocity on the Pioneer dust sensors is sufficiently higher than that of ambient projectiles to offset their smaller masses. Landgraf et al. (2002), however, found that these grains are probably too small and too few to significantly affect the mass flux into the rings, which is dominated by much larger (100 micron radius) objects. Showalter (1998) obtains a constraint on cm-sized particles in fair agreement with the fluxes suggested by Cuzzi and Estrada (1998) based on his interpretation of transient dust clouds ejected from the F ring strands at high velocity as meteoroid impacts. Another interesting finding by Landgraf et al. (2002) is that the interplanetary material at Saturn appears to have a significant prograde, ecliptic component, which will incur a larger gravitational focussing factor than the higher relative velocity Oort cloud objects assumed by Cuzzi and Durisen (1990) and Durisen et al. (1992, 1996).

Overall, the mass and velocity distribution of the dominant projectiles at Saturn are key goals for the Cassini CDA; the velocity distribution affects the gravitational focussing and longitudinal impact distribution, and the mass and composition will limit the ring age (Doyle et al. 1989, Cuzzi and Estrada 1998; see sections 3.2 and 4.1).

3.4. RING-ATMOSPHERE/IONOSPHERE/MAGNETOSPHERE INTERACTIONS

The outer, diffuse E, F, and G rings interact with Saturn’s magnetosphere, and the main rings interact with Saturn’s ionosphere as well as, perhaps, its atmosphere. The structure and particle properties of Saturn’s E ring (section 3.2) make a clear case for a particular combination of meteoroid ejecta, solar radiation pressure, and
charged particle dynamics in producing this unique structure (Horanyi et al. 1992; Hamilton and Burns 1993a, 1994). Essentially, particles of size narrowly localized to one micron radius, orbiting in the magnetosphere, attain a charge-to-mass ratio just sufficient for Lorentz forces to cancel out their orbital precession rate. The orbital eccentricities of this narrow range of particle sizes are then pumped to high values by solar radiation. The E ring does seem to have a particle size distribution narrowly confined to just this size range, based primarily on its blue color (Showalter et al. 1991 and earlier references therein). This model would predict at least some similarly diffuse rings associated with the other icy moons (A. Cheng, personal communication, 1996), and in fact there does seem to be an unmodeled component just interior to the orbit of Tethys (Showalter et al. 1991).

Radial variations in the abundance of various magnetospheric species have been used to constrain several properties of ring regions, because tiny amounts of ring material can produce noticeable depletions of rapidly mirroring charged particles (Van Allen 1983, 1984; Cuzzi and Burns 1988, and two ring hazard studies available through the Cassini project). A new model of microsignatures (longitudinally confined, radially narrow depletions) and macrosignatures (axisymmetric, radially broad depletions) has been presented by Paranicas and Cheng (1997). Evidence for longitudinally variable material in the E ring region remains controversial (see Van Allen 1984 for a discussion of the charged particle data, and Roddier et al 1998b for a puzzling visual detection of an ‘arc’ in adaptive optics data). Key uncertainties in interpreting microsignatures in terms of absorbing material include the poorly known identity and diffusion coefficients of the relevant magnetospheric species, and these will be important goals for Cassini MAPS.

A connection has been demonstrated between the rings and the atmosphere/ionosphere of Saturn, in that water vapor ejected from the rings by meteoroid bombardment impinges on the planetary stratosphere and ionosphere, with dramatic effects on electron density. The abundance of this water can, in principle, be used to constrain the meteoroid flux and loss of matter from the rings (Connerney and Waite 1984). Preliminary results have been reported for a direct observation of elevated water abundance in latitudes connected to the rings, which is compatible with a large water mass loss rate (Fouchet et al. 1996); however, the transport process, and the chemistry and loss processes within the stratosphere, are highly complex and need to be modeled carefully before implications can be drawn about water mass loss from the rings (e.g. Moses 1998, Moses et al. 1998). Pospieszalskaya and Johnson (1991) calculated a rather dense possible ring atmosphere (10^4 cm^{-3}) due to meteorite bombardment, but assumed a meteoroid flux on the high end of the likely range. HST observations implying that the neutral OH ‘atmosphere’ of the rings is about 600–700 atoms cm^{-3} (Hall et al. 1996) supported earlier inferences of a neutral H atmosphere at the same density from Voyager (reviewed by Cuzzi et al. 1984). Estimates by Ip (1995a) had been much lower. Ip (1995b) also estimated the visibility of ejecta during the 1995–1996 ring plane crossings, but no attempt has yet been made to compare these with the observa-
tions. However, more recent observations and analyses by Richardson et al. (1998) and Jurac et al. (2002) appear to conclude that these inferences might have been contaminated by material further out in the system (around the orbit of Enceladus) that the earlier, edge-on, Voyager and HST observations were necessarily looking through. Jurac et al. (2001, 2002) find that this amount of OH, if generated by magnetospheric sputtering of material near the orbit of Enceladus, requires a larger target area than the visible E ring grains (in fact, 30–60 times larger than Enceladus itself), which is narrowly confined to the orbit of Enceladus. It can be shown that, if loss of vapor by collision to the main rings is the dominant loss mechanism, meteoroid bombardment at the current nominal rate of $5 \times 10^{-17}$ g cm$^{-2}$ sec$^{-1}$ (one-sided, unfocused) probably falls short by a factor of 3–30 in maintaining a main ring atmosphere of 600–700 atoms cm$^{-3}$ over a region as thick as a Saturn radius. Perhaps the larger gravitational focussing factors associated with a significant ecliptic population might help close this gap. Hall et al. (1996) also noted that their observations might indicate an abrupt increase in density just outside of the main rings, which is consistent with the subsequent models of Richardson et al. (1998). Nevertheless, remote observations are hard pressed to detect material very close to the ring plane (< 0.1 Saturn radius), and there might be surprises in store for Cassini. Direct measurement of the density of the ring atmosphere by Cassini would be an important independent constraint on the meteoroid flux, in addition to their other intrinsic values.

3.5. RING-SATELLITE RELATIONSHIPS; RING ORIGIN/EVOLUTION

The origin and evolution of ring systems is so closely connected to ‘ring-satellite relationships’ that we merge these two Cassini science goals.

As described in previous sections, Saturn’s main rings (as well as other ring systems) are significantly evolved in composition and structure. On geological timescales, it has long been believed that dynamical evolution of the rings under moonlet torques removes both the rings and the inner ringmoons from their current locations in times much shorter than the age of the solar system (Goldreich and Tremaine 1982, Lissauer et al. 1985, Esposito 1986). As also discussed above, it has more recently been realized that meteoroid bombardment will alter the ring structure and composition on comparably short timescales. Ip (1984), Lissauer (1984) and Cuzzi and Durisen (1990) show that angular momentum dilution by infalling material can be important in causing orbits of ring material to decay. Northrop and Connerney (1987) suggest that the entire C ring might erode into the planet via small, charged grains ejected by impacts. While both the dynamical and the meteoroid effects have their uncertainties, they independently point in the same direction and to comparable ring ages of $\sim 1/10$ the age of the solar system. The general problem of ‘short timescales’ in planetary rings, and specifically in Saturn’s rings, was recently reviewed by Cuzzi (1995) and by Dones (1997), who differ on the robustness of the arguments for a recent origin of Saturn’s rings (see
Figure 5. Schematic of the ringmoon systems of the four giant planets (from Nicholson and Dones 1991), showing how rings and moons intermingle even across the nominal Roche limit.

In another perspective, Poulet and Sicardy (2001) suggest that ongoing differential orbital evolution of inner ringmoons can lead to both transient mutual resonant trapping and mutual, possibly disruptive, collisions which can both slow the orbital evolution, and regenerate the A ring occasionally. In any case, to infer ring origin, we must peer back through all this evolution and time variation.

Many of the issues of ring origin and evolution are closely linked to the existence of nearby ‘ringmoons’ - 1-100 km sized bodies which dynamically interact with the rings and/or provide source material to replace mass rapidly lost in small particles. It is now clear that the four gas giants are surrounded by systems in which rings and moons are intermingled; this is illustrated in Figure 5 (Nicholson and Dones 1991). The moonlet Pan was inferred and subsequently discovered orbiting within the Encke gap in Saturn’s A ring (section 3.1). The inner ringmoons
of Saturn (including the probably misnamed ‘F ring shepherds’ Prometheus and Pandora, and the coorbital satellites Janus and Epimetheus) seem to have unusually low internal densities —0.3 to 0.6 g cm\(^{-3}\) (Rosen et al. 1991b, Yoder et al. 1989, Nicholson et al. 1992). HST observations, starting in the 1995-1996 ringplane crossing epoch, have revealed anomalous dynamical behavior for both Pandora and Prometheus (Nicholson et al. 1996, Bosh and Rivkin 1996, de Pater et al. 1996, Bauer et al. 1997, French et al. 1999). Pandora shows a small regular oscillation which is due to a nearby resonance with Mimas (French et al. 1999). It has been known for a few years that these moons show occasional jumps in their longitudes relative to those predicted from Voyager orbital elements (Bosh and Rivkin 1996, Nicholson et al. 1996). It has recently become evident that both Pandora and Prometheus undergo sporadic and nearly instantaneous changes in their semimajor axis (at least) which seem to be correlated, with both moons getting slightly closer to the F ring simultaneously (French et al. 2002). Encounters with the F ring alone (Murray and Giuliani-Winter 1996) don’t seem to be able to explain this behavior.

Figure 6. The observing profile of the baseline tour (T18-5).
It is clear that the dynamics of the region is more complex than previously believed (Goldreich and Rappaport 2003).

The collisional and dynamical evolution of ‘moonlet belts’, in which visible dust grains are generated by mutual collisions between and extrinsic bombardment of large, possibly unseen, parent bodies, while sweepup and even reaccretion continuously operate, has been studied in a series of papers aimed at the F ring region of Saturn (Cuzzi and Burns 1988, Poulet et al. 1998, Barbara and Esposito 2002), as well as at the ring-moon systems of Uranus and Neptune (Colwell and Esposito 1992, 1993). Early work along these lines had been done in the Jupiter ring context by Burns et al. (1980). Models have also been applied to Saturn’s G ring (Showalter and Cuzzi 1993, Canup and Esposito 1997). The recent G ring results of Throop and Esposito (1998) are compatible with a moonlet belt hypothesis. Canup and Esposito (1995) modeled the accretion of objects closer to the planet, even inside the Roche limit.

The F ring will provide Cassini with perhaps its best example of a dynamically evolving ringmoon belt. There have been theoretical and observational studies of the current F ring strands (Lissauer and Peale 1986, Murray et al. 1997). Furthermore, the F ring is now known to be highly time variable, in that bright clumps in the ring come and go on a range of timescales (Showalter 1998). Specifically, the several bright ‘knots’ seen by Voyager 1 do not correlate with those seen by Voyager 2, and one bright region in a series of Voyager 2 frames is seen to generate new clumps on a daily timescale, which move at different orbital rates from the main clump which generates them (Showalter 1998, Bosh and Rivkin 1996, Nicholson et al. 1996). Showalter (1998) suggests that some of these clumps form by extrinsic impacts into the F ring; Poulet et al. (1998) and Barbara and Esposito (2002) suggest that some or all form by collisions between large F ring objects. Cuzzi and Burns (1988) proposed that microsignatures seen near, but not in, the F ring may be transient debris generated by collisions between unseen members of a moonlet belt surrounding the rings, which could be stirred by ultimately chaotic perturbations from Pandora and Prometheus (Scargle et al. 1993), and that the F ring itself may be a recent, unusually large, collisional product. Intriguing clues do exist for uncatalogued objects lying outside of the F ring itself but in the general region of potential interaction (Kolvoord et al. 1990, Harrington et al. 1993, Gordon et al. 1996, McGhee et al. 2001). A difficulty with this concept is the apparent lack of the fine dust one would expect to be associated with such collisionally generated debris (Showalter, personal communication, 1998). Clearly, there is considerable ‘action’ awaiting Cassini in this regard (see also Borderies 1992). It might even be that the Encke gap contains a scaled-down moonlet belt; two radially distinct ‘ring arcs’ are to be found in the Encke gap (Ferrari and Brahic 1997), which share many features with the kinky F ring (see Cuzzi et al. 1984, p. 151).

**Constraints on ring origin?** Theoretical estimates of the lifetimes of moons and moonlets in and around ring systems indicate their lifetimes are shorter than the age of the solar system (Colwell and Esposito 1992, 1993); thus ongoing creation
of narrow rings and ringlets, such as in the Uranian and Neptunian systems, or the G ring of Saturn, could readily follow occasional disruption of parent moonlets. This concept was first discussed by Harris (1984). Specific application to the disruption lifetimes of the inner moons of Saturn was presented by Lissauer et al. (1988). Saturn’s rings continue to present a hurdle for recent creation, due to their very large mass (about the mass of Mimas). Lissauer et al. (1988) estimate from crater abundances that the likelihood of disrupting a Mimas-size precursor in the last $10^8$ years is rather small - about a percent. In this set of models, the compositional properties of the rings would be expected to be closely related to those of the inner moons of Saturn. Recent models for the origin and evolution of the inner Saturnian moons have been developed by Mosqueira and Estrada (2003 a,b).

Alternatively, Dones (1991) reconsidered the plausibility of tidal (classical Roche style) breakup of a heliocentric object, and retention of some fraction of the debris (a scenario similar in some ways to comet Shoemaker-Levy’s recent encounter with Jupiter), and found a probability comparable to that of impact disruption (or perhaps higher if SL9-like cases are considered; Dones, personal communication, 1999). Cuzzi and Estrada (1998) suggested that the color/compositional properties of the rings differ from those of the Saturnian moons, and resemble those of Triton more closely; they suggested that this favors tidal breakup of an extrinsic, heliocentric object rather than impact disruption of a native-born resident of the system. The revised ring colors emerging from reanalysis of the original Estrada and Cuzzi (1996) results (Estrada et al. 2003, section 3.2), show that a systematic color difference still exists between the rings and the inner moons. However, recent compositional modeling by F. Poulet (personal communication, 2002) indicates that the ice/tholin mix for the rings might not be qualitatively dissimilar from that characterizing Rhea in spite of the substantial difference in their redness, removing some of the motivation for the extrinsic hypothesis. Additional research into the different compositions of bodies in the Saturn system, as compared to bright heliocentric objects, and the fragmentation of realistic bodies on realistic trajectories, would certainly be welcome.

4. Instrumental Approach

Details of the science investigations are described in the individual papers by the instrument teams. Below we present high-level introductions to the main contributions of the different instruments to ring science objectives.

The UltraViolet Imaging Spectrometer (UVIS) will provide spectral images of the rings, constraining the location and distribution of water ice vs. other materials; a strong absorption edge shown by water ice will be prominent in the properties which will be studied. Because it has the shortest wavelength, UVIS images will be sensitive to the smallest dust particles. UVIS will also measure H,D, and O to characterize ring evolution, water loss, ring atmosphere, history, and current
ring-magnetosphere interactions. Perhaps the primary contribution of UVIS to ring science will be its stellar occultation capability. Observing stellar occultations in the UV greatly reduces ring background, since the rings are extremely absorbing in the UV; the Voyager stellar occultation (of the UV star δ Scorpio) provided the highest spatial resolution of any instrument (the Fresnel zone on the rings was only tens of meters across). For δ Sco, Cassini UVIS has 50 times the sensitivity of the Voyager PPS with 5 times smaller resolution. Two kinds of information are derived from these data: highly detailed, fine resolution scans of the optical depth of ring material, including our best observations of spiral density waves and sharp ring edges, and constraints on the radial variation of the abundance of large ring particles (those with size comparable to the Fresnel zone; Showalter and Nicholson 1990). UVIS will also use its overlapping High Speed Photometer and Far UV fields of view in rapidly sampling mode to attempt to detect impact flashes from meter-sized (spoke-forming) impacts in the shadowed portion of the rings (e.g., Artemieva et al. 2000, Dunham et al. 2000).

The Imaging Science System (ISS) is the highest resolution two-dimensional imager on the Orbiter and will provide unique information on variation of structure with radius, azimuth, and time; the ISS Narrow Angle Camera (NAC) and its Wide Angle Camera (WAC) have typical resolution of 6 and 60 microradians, respectively. The ISS cameras are far more sensitive than the Voyager cameras, and one expects many small moonlets will be discovered in gaps within the rings, and perhaps outside the rings in and around the F and G ring regions. Furthermore, the ISS has the unique ability to cover a very broad range of azimuth in one observation. Greatly improved dynamical models will result from the high accuracy observations of mean motion, inclination, and eccentricity of ringmoons. Images in multiple filter bands will provide good constraints on ring particle composition with excellent spatial resolution. Variability of ring brightness with observing geometry (phase angle, illumination angle or solar elevation angle, and viewing elevation angle) will constrain the local volume density of the rings, and thus the local dynamics and viscosity. Highly sensitive detection of tiny amounts of microscopic dust at high phase angles will map out regions of active collisional evolution.

The Visual and Infrared Mapping Spectrometer (VIMS) will provide unique information on the detailed spectral fingerprints of different materials in the rings, from their diagnostic lattice vibration features. Distinction between icy, silicate, and perhaps even organic material will be possible. Information about ring particle regolith grain size will be obtained from the depths of different absorption features. The VIMS instrument has a 0.5 millirad (mr) pixel size, as well as a high resolution mode having 0.25 mr resolution in one dimension – well suited for ring studies. Its field of view is variable from the size of the NAC field of view (6 mr) to 32 mr, and can be targeted independently within this range. In addition, VIMS has created a capability for stellar occultations which is in principle comparable to the capability of UVIS (some software issues remain to be resolved); observations of an entirely
different stellar population (bright infrared stars) can be conducted in water ice absorption bands. The wide difference in wavelength between these occultations and the UV stellar occultations of UVIS will constrain the relative abundance of fine dust particles in the rings, which are effective at blocking UV radiation but not IR radiation.

The Composite Infrared Spectrometer (CIRS) is a Fourier transform spectrometer that measures thermal radiation from 10 to 1400 cm\(^{-1}\) (1 mm to 7 \(\mu\)m), with a spectral resolution that can be set from 0.5 to 20 cm\(^{-1}\). The far infrared portion of the spectrum (17 \(\mu\)m to 1 mm) is measured using thermopile detectors which collect radiation through a 4 mr FOV. The middle infrared section is measured using two focal planes (7 \(\mu\)m to 9 \(\mu\)m and 9 \(\mu\)m–17 \(\mu\)m) each with a 1 \(\times\) 10 array of HgCdTe detectors. Each detector has a 0.3 mr FOV. Observations of the ring temperatures at thermal wavelengths (the 100 K ring temperature has peak emission at 30 \(\mu\)m wavelength), especially how they vary diurnally as a function of ring optical depth, radius, and solar elevation angle, can provide constraints on local ring dynamics (history of particles moving from lit to unlit faces of the ring). The composition and/or porosity of the regoliths of ring particles might vary with location, and these data will provide another handle on separating this variation from other effects. In principle, the millimeter channel can sense emission emerging from throughout the ring material (the absorption pathlength for millimeter emission in ice at 100K is several meters), and even small radial variations in mixing fraction of non-icy material will be mapped. However, sensitivity at the very longest wavelengths (1 mm) might be less than hoped for, so the effective upper limit on wavelength might be 500 \(\mu\)m.

The Microwave Radiometer, part of the Radar system, will sense ring radiation at 2 cm wavelength, using the high-gain antenna with a resolution of 6.5 mr. Radiation at 2 cm wavelength contains, in addition to thermal emission, a somewhat larger component due to diffuse scattering of the planetary thermal emission than found at 1 mm wavelength, and will complement the CIRS observations. The 2 cm wavelength radiometer will sense thermal emission throughout icy particles smaller than about 5 meters.

The Radio Science Subsystem (RSS) uses multiple wavelength (0.94, 3.6, and 13 cm) occultation and bistatic-scattering observations to map ring structure and determine ring physical properties. The wavelengths are ideally matched to the centimeters-to-meters radius distribution of ring particles, which dominate ring opacity and mass. The observations provide the unique capability of mapping the relative abundance of the 1 to 20 cm radius particles within individual ring features, as well as determination of the full size distribution and vertical thickness of broad ring features that can be resolved in the signal spectra. Multiple high-resolution optical depth profiles obtained at different viewing geometries and times will provide ‘tomographic’ mapping of the variability of radial, azimuthal, vertical, and temporal ring structure, important for quantitative characterization of physical and dynamical processes. The larger ring opening angle, multiple occultation op-
portunities, and three wavelength capability will permit significant improvements over the Voyager RSS observations, particularly for the optically thick B Ring which blocked the Voyager radio signals over most of its width.

The Cosmic Dust Analyzer (CDA) will directly sense the composition of ‘ring’ material that it encounters, such as in the E (and perhaps G) rings. It will also provide essential data on the mass flux, particle size distribution, composition, and orbital elements of interplanetary and circumplanetary projectiles that continually bombard the rings. This information is critical to unraveling the role of meteoroid bombardment in evolving the structure, composition, and even the age of the main rings, as alluded to above.

Other contributions to understanding the rings will be made by the extensive suite of particle and field experiments, as in previous missions. For example, observations of microsignatures and macrosignatures as functions of magnetospheric particle species and energy, can tell us much about the presence of clumps of debris too transparent to be observed by remote sensing instruments. Also, measurements of pulses of ionized material created when tiny particles hit the spacecraft have proven to be highly sensitive to very small amounts of tiny particles in the ring plane. The tenuous ‘ring atmosphere’ will be sensed when Cassini is very close to the planet. These and other contributions to ring science are detailed in the papers by the respective instruments.

4.1. EXAMPLES OF HOW INSTRUMENTS MIGHT BE USED TOGETHER TO SOLVE OUTSTANDING PROBLEMS:

Answering the ‘big questions’ of, for instance, the origin and age of Saturn’s rings will require combining the observations from most of the instruments on the spacecraft.

A combination of occultation and imaging data led to the discovery of the Encke gap moonlet; similarly, we expect that discovering and studying ever tinier moonlets in and around the rings will be best done by combining imaging (direct detection; indirect detection from edge waves; detection of time-variable clumps from collisions, etc) with stellar and radio occultations (detection of wakes in surrounding material - strongly variable with longitude). In a similar way, unraveling the nature of the irregular structure, including the distinction between angular and temporal variation, will require a variety of images and stellar and radio occultations at different times and longitudes.

Studies of very low optical depth moonlet and debris belts, such as the G ring and perhaps material near Lagrange points, can best be done by combining the great sensitivity of magnetospheric particles to absorption by tiny amounts of matter (as detected by the MAPS instruments) with direct deep imaging searches.

Recent work has shown that evolution of the color and composition of the rings under meteoroid bombardment might provide a significant constraint on the origin and age of the rings. Models of the process require the radial variation of both ring
optical depth and ring particle size variations (which, along with optical depth, determine surface mass density) with location. Particle size variations are obtained from stellar occultation fluctuations, or by comparison of optical depth from optical and radio wavelength occultations. Models of radial variation of ring composition will use color data from imaging broadband filters, reflection spectra from VIMS, and/or total thermal emission from CIRS millimeter-wave and/or centimeter-wave Radiometer data.

Ring viscosity, a critical evolutionary parameter, will be established from combining several different observations: local (radially variable) volume density measurements may be inferred from imaging the opposition effect and by comparing ring brightness over a range of phase angles. If the opposition effect indeed constrains the ‘packing density’ of the rings, it will then constrain the particle relative velocity which is essential for understanding the fine scale structure and its local dynamics. Or, the opposition effect might simply refer to the particle surface structure as mentioned in section 3.1. It is thought that these possibilities can be distinguished by adequate coverage of the effect as a function of illumination, viewing, and phase angles, wavelength, and possibly polarization. RSS measurements of ring optical depth at several ring tilt angles will constrain vertical ring structure, hence the relative velocities of the largest particles, which carry most of the ring mass; CIRS measurements of particle diurnal (and eclipse) heating/cooling will tell us the ease with which particles migrate vertically in the ring, another measure of ring viscosity.

Compositional evolution involves ring viscosity as constrained from multi-instrument observations. In order to convert ring evolutionary age in dimensionless units, obtained from modeling color profiles using all these data, to an actual ring age requires absolute interplanetary and circumsaturnian projectile mass fluxes and velocity distributions, which will come from CDA. CDA will also provide a better estimate of the composition of the interplanetary projectiles, a key unknown of the model.

5. Cassini Tour

The Rings working group met in July 1995 to forge a coherent set of prioritized science requirements, emphasizing those which drove tour geometry.

We categorized our requirements as Priority I (Excellent, must have), priority II (Very Good, should have), and priority III (Good, want to have). These are the same classes of priority as widely used by peer review panels. We had extensive debate across the teams as to what distinguished must have (uniqueness, new observational geometry, new instrument, critical resolution threshold, time baseline, etc) from should have (multiple wavelengths, longitudes, times), or want to have (‘complete coverage of...’, ‘maximum range of...’, ‘fill in phase space of...’, etc). This pri-
oritization did provide us with a convenient way of making numerous decisions concerning tours and defending our decisions.

In the brief paragraphs below, we present a simplified version of the science requirements which drove tour geometry (the more detailed requirements are documented in project reports). From these different science needs, metrics were derived to judge the relative quality of candidate tours. Many important science goals are not specifically called out herein (see instrument team reports), but we do mention a few supportive science goals where appropriate, or where the combination of all requirements together provides knowledge that none of them does individually (such as photometry) but the key geometries are individually justified on the grounds of unique and essential science. The requirements are in rough priority order.

5.1. ‘MUST HAVE’ RING OBSERVING GEOMETRIES FOR THE CASSINI TOUR

(1) Adequate time in nearly diametric Earth occultations as early in the tour as possible, with spacecraft distance approximately 5–6 Saturn radii ($R_S$) behind the planet. These are ‘dayside apoapse’ revs.

This geometry simultaneously provides three of the most critical observing geometries for ring science, and is therefore one of the highest priority ‘must have’ tour elements. Diametric Earth occultations, with the spacecraft at 5–6 $R_S$ behind the planet, provide RSS with the required radial resolution to explore known classes of structure in both the direct and the ‘scattered’ signals (each providing structural information for different size particles). In addition, only while the sun is occulted by Saturn can ISS obtain the unique, high resolution, very high phase angle observations which so strongly delineate clumps and kinky ringlets, as well as extremely low-optical depth dust-sized material. In these orbits, the Sun is also occulted by the rings and planet as seen from the spacecraft, providing unique information on ring composition for VIMS and UVIS. Finally, this same geometry also provides observing times when the opposition effect can be observed moving across the rings. The requirement to have these 6–7 revs as soon in the mission as possible derives from the fact that the ring opening, as seen from Earth, decreases with time, and the denser regions rapidly become impenetrable to RSS (the slant angle appears in an exponential). It is not currently known, for example, just how opaque the densest parts of the B ring are! This geometry, together with the geometry provided by (3), (4), and (5), provides an adequate range in viewing angle coverage of the rings as solar illumination angle varies from highest to lowest.

(2) Adequate time at high resolution (range < 6 $R_S$), observing the lit face at low phase angle ($< 45^\circ$) and moderate s/c latitude (45° or more). These are ‘nightside apoapse’ revs (this requirement was subsequently bifurcated into two slightly different geometries).

High resolution, lit face, high latitude observations are critical geometries needed to address several key unknowns related to the question of the origin and
The temporal evolution of observable ring structure, and the distribution and gravitational influence of embedded and external satellites, are other key current unknowns in this regard. The combination of high latitude and high resolution stated above is required for ISS to make better-than-Voyager measurements, over a range of ring orbital longitudes, of certain fine scale ring features which are known to be azimuthally and/or temporally variable; the cause of this structure is currently unknown and determining its origin and evolution is one of the highest priorities for ISS. Low phase angle observations are required so that these observations can simultaneously accomplish the science objectives of both discovering, and determining the orbital elements of, satellites in the (roughly) dozen known genuine gaps in the rings, and in studying the structure, kinematics and dynamics of gap-embedded ringlets. (Small embedded satellites are easiest to detect and observe at moderate-to-low phase angles.) High-resolution observations from high latitudes will probably be obtainable in polar orbits late in the mission, but this will only provide one of (minimally) two points needed (i) to distinguish time variation from spatial variation for ring feature observations, and (ii) to determine the rates of changes of the orbital elements of newly discovered satellites. Consequently, it is essential that there are opportunities for these geometries to occur in the early-middle part of the tour, to provide a good time baseline with ‘polar orbit’ observations, most likely at the end of the tour.

(3): Adequate time at high inclination (60–70°) with low periapse (3–5 $R_S$) (which turn out to be satisfied primarily by a ‘Polar Orbit Sequence’).

The B ring is so dense that its optical depth has never been measured over a considerable fraction of its radial extent at resolutions on which structure is known to occur. Stellar occultations by UVIS and VIMS will provide not only the ultimate in structural information but also, from detailed analysis, information about particle size distributions at both micron- and meter-scales. Only this sequence provides sufficiently numerous stellar occultation opportunities at sufficiently high signal-to-noise ratio to allow measurement of structure and particle properties in high optical depth regions at full radial resolution (20 m). The combination of small distance from Saturn and high inclination (close proximity to the rings at high latitudes) ensures the occurrence of tens of high quality UV stellar occultation opportunities (bright O and B stars) because the rings cover a large angular extent.
and have a large opening angle relative to the line of sight. Our investigations of other geometries have shown that the quality of occultations available at moderate inclinations (such as the ‘diametric Earth occultation’ sequence of element (1), or typical Titan 180° transfer orbits as described in section 5.2.2) is significantly worse for two reasons: the rings are more opaque because they are more oblique to the occultation path, and their smaller apparent size reduces the number of candidate stars. For various reasons, it appears that ‘polar orbits’ are best situated near the end of the tour. Sunward apoapsis for the polar orbit sequence is preferred for three reasons related to ring studies. First, it allows UVIS and VIMS ring stellar occultations to occur across the rings in Saturn’s shadow, which provides the lowest possible background. Second, it provides optimum viewing by CIRS (with adequate radial resolution near periapse) of the shadowed region which is most diagnostic of ring thermal properties. Third, nightside periapse provides several times better resolution for profiling ring structure using the direct component of the RSS occulted signal. Several decent, although not diametric, chords across the rings can be obtained in this geometry. Fourth, the near-polar geometry provides adequate time and resolution to enable radiometry of the rings with the 2 cm-wavelength Radar feeds. Centimeter-wavelength radiometry is the only way to penetrate the entire volume of ring material and detect ‘buried’ materials of non-icy composition. The large Radiometer beamwidth requires close observing distances to resolve known structure of interest. This geometry, together with the geometry provided by (1), (4), and (5), provides an adequate range in viewing angle coverage of the rings as solar illumination angle varies from highest to lowest. Finally, to the extent that this geometry provides solar occultations, ISS will be able to obtain a time baseline on temporal evolution of dusty, fine-scale structure using high phase angle observations (relative to element 1 above).

(4): A second series of 3–4 Earth occultations; ring opening angle (from Earth) of 14–18° with range < 5–6 Rs antisunward.

The driving requirement here is for RSS to obtain unique information at tilt angles between the maximally open geometry found early in the mission (bullet 1), and the nearly ‘edge-on’ configuration in which Voyager observed them, which is approached at the end of the Cassini mission. The nominal target tilt angle here is in the range 14–18°. The combinations of observations obtained this way will allow unique information to be inferred about ring vertical thickness and structure in all three main ring regions. It is difficult to obtain the full complement of information from RSS data if the geometry is not tuned to mitigate Doppler smearing of the scattered signal. We believe this can be alleviated by some moderate optimization of occultation tracks within opportunities obtained just before, during, or after a suitably oriented Titan 180° transfer or other inclined sequence. For example, occultation tracks can be adjusted to begin and end off the planet, and/or to cross the rings in a configuration which is roughly diametric. Also, orbital tour ‘tweaks’ at this stage may once again allow the ring opposition effect to be observed by ISS at a different solar elevation angle, allowing much stronger constraints to be placed
on ring vertical structure and distinguishing ring packing density influences from particle regolith effects.

(5): Adequate time in two widely spaced epochs (prior to mid-mission and after mid-mission) with S/C latitude > 30–45°, distance to rings < 14 $R_s$, and phase angle < 90°.

This element provides the critical time baseline and coverage needed for ISS to perform orbit determination of the myriad small embedded satellites that Cassini is sure to discover and the structure they cause, amongst other goals. For instance, high accuracy in orbit determination is needed to measure the acceleration of nearby ringmoons away from the rings – a key measure of ring lifetime. It is also needed to separate moonlet orbital inclination from eccentricity – important for azimuthal confinement of ‘arcs’. Furthermore, resolved images of small moonlets, and their orbital changes, as they gravitationally interact with other moons and ring material, will provide the only means of determining the moonlet densities. This geometry, together with the geometry characterized by (1), (3), and (4), provides an adequate range in viewing angle coverage of the rings as solar illumination angle varies from highest to lowest. Furthermore, it provides another key time point for numerous stellar occultations. Occultations in this geometry will be less numerous and generally have a lower signal to noise ratio than during the polar orbits for reasons discussed under bullet (3). However, if the distance from Saturn is larger, the occultations will be slower and thus low and moderate optical depth regions can be studied with higher sensitivity.

5.2. BRIEF ILLUSTRATION OF HOW CANDIDATE TOURS SATISFY RING REQUIREMENTS

Several candidate tours were developed by the Mission Design Team (MDT) in response to the geometric requirements of the various science working groups and disciplines, including the Rings Working Group (RWG). These candidate tours have three distinct stages of interest to ring science, which are, naturally, stages containing inclined orbits. An example of these stages is illustrated in Figure 6, which is for the tour originally named T18-5 - which has been adopted by the PSG except for small tweaks which remain to be worked out.

5.2.1. Early Inclined Sequence

In order to satisfy the first RWG ‘must-have’ observation (Section 5.1), the tour includes an early inclined sequence with the node of Cassini’s orbit chosen nearly perpendicular to the Saturn-Earth line. This geometry produces nearly ansa-to-ansa diometric occultations for RSS and highly diagnostic illumination and observation geometry for the suite of optical remote sensing (ORS) instruments. The sequence captures the rings near their maximum tilt angle, allowing for an unprecedented opportunity to observe all ring features - including the dense B ring.
All candidate tours were optimized to include this sequence, with the RSS team working with the MDT to achieve optimization of the radio occultations. Tour T18-5 is superb from this standpoint, and at the time of this writing has been selected as the baseline mission tour.

5.2.2. Titan 180° Transfer Sequence
In order to satisfy the diverse set of geometries needed to meet Cassini's broad science goals, the orbital petal of the spacecraft must be maneuvered to different orientations with respect to the Saturn-Sun direction. This is normally described by changes in the apoapsis phase angle. The orientation of the initial set of orbits is set by the arrival geometry of the spacecraft. The MDT identified a rapid means of achieving a rapid change in apoapsis phase angle by a series of orbits called a Titan 180° transfer (see chapter by Wolf, this volume). These sequences can be divided into two stages: an 'up-leg' stage where Cassini flies by Titan at the spacecraft's ascending node (increasing Cassini's orbital inclination and raising its periapse), and a 'down-leg' stage where the flyby is at the descending node (decreasing the inclination while lowering the periapse again). These orbits provide high inclinations and also relatively high periapse altitudes.

Critical ORS opportunities to distinguish time and angle variation of fine scale structure occur during the up-leg (to be used in combination with the late, high-inclination sequence, see below). The up-leg stage provides sufficient time for an initial characterization of fine scale ring structure that is known to be either azimuthally or temporally variable (or both), satisfying another 'must have' science goal for rings. This structure, often in opaque ring regions, must be observed with high resolution, in backscatter, and on the lit face of the rings. These observations will need to be compared with those that are provided in the final high inclination tour sequence, and so perform a critical time-baseline function. Figure 6 shows that tour T18-5 includes some repeated revs in its single Titan 180° transfer sequence at this critical geometry.

Important RSS opportunities to characterize optical depth dependence and forward ring scatter on the ring opening angle, and hence determine vertical ring structure, occur during the down-leg (when the tilt of the rings as seen from earth is at an intermediate value of about 15°). The timing of this sequence and the number of repeated revs have important implications for both of these objectives. For this class of orbits, there may be a tradeoff between optimal occultation track geometry and optimal Doppler contour alignment.

5.2.3. Final High Inclination Sequence
Candidate tours end with the spacecraft in a highly inclined orbit with a low periapse. This geometry is critical to producing the numerous stellar occultation opportunities which are needed for the finest scale studies of ring structure (and particle size). This geometry translates into being close to the planet at high sub-spacecraft latitude, so that the rings present a large target for stellar occultations, and the
opaque regions unstudied by Voyager can be probed with good sensitivity. Also, in this geometry ORS captures the other critical part of its observing time in which to study fine scale structure in opaque rings, and azimuthal variations requiring high resolution (requirements 2 and 5, section 5.1). In addition, CIRS requires this geometry to map thermal changes over a ring particle orbit, and RSS requires the low ring tilts provided by this tour stage to observe tenuous ring features (C ring and Cassini Division) and out-of-plane ring features (such as bending waves).

The critical features of this sequence are the high inclination and low periapse altitude. Because this geometry satisfies several ‘must have’ rings requirements (2, 3, and 5), the total number of hours in this ‘close-in, high-up’ geometry must be great enough that the different goals can be met. Because of the low periapse, the amount of time in this geometry on each rev is relatively small, and competition for observing time in this highly favorable geometry for ring observations requires as many revs at as high an inclination as possible. In tour T18-5, this sequence also includes new multiple RSS ring occultation opportunities, though this is not in general a feature of this sequence, and depends on the precise orientation of the orbital petals.

### 6. Special Opportunities

#### 6.1. SATURN ORBIT INSERTION (SOI)

The brief period immediately following the main engine burn at initial closest approach has been of prime interest for ring science since the pre-Cassini days of the Joint Working Group. During this period, the spacecraft skims the unilluminated side of the rings, with vertical elevation of 10,000–30,000 km. This is nearly an order of magnitude closer than at any other time during the mission. Even though the smear rate is a few m/second during this time, the ORS instruments are all sufficiently sensitive that unique new observations can be made with sufficiently short exposure times that smear is not a limitation. The importance of this observing geometry to ring science is easily stated: there are known radial and azimuthal variations in ring structure and composition that will only be resolvable at this time by ORS instruments. CIRS will map the radial variation in ring particle composition at the resolutions of 40–100 km for the far infrared and 3–8 km for the middle infrared. VIMS will resolve radial structure on the several tens of km scale where distinct color and albedo variations are known to exist throughout the rings. ISS, with 6 microradian pixels, should be able to resolve the 100 m-scale transient density wakes believed to be responsible for the A ring azimuthal brightness asymmetry.

Several studies by the Rings Working Group have shown that a scan of the entire main ring system can be obtained within time constraints, and that ample data volume and signal to noise are available to provide a truly unique data set
spanning the extreme UV to the far IR for comparison with all other Cassini data. Over a several year time period, these goals have been merged with measurements of the planetary magnetic field and ring ‘atmosphere’ which can be done only at this unique time.

6.2. JUPITER ENCOUNTER

The opportunity to study Jupiter with new instruments (either more sensitive than, or not carried by, Galileo) and excellent spatial resolution (better than HST) allowed Cassini to address some important and still unresolved problems regarding the faint Jovian ring system. Although there are some spectral observations of the jovian ring (Nicholson and Matthews 1991, Neugebauer et al. 1981, Meier et al. 1999), the composition of the material comprising the jovian ring remains unknown. Cassini returned more than 10 times the number of ring images obtained by Galileo over a wider range of phase and elevation angle than previously. ISS color coverage was greatly expanded over that of Voyager or Galileo, and also made use of polarization measurement capability (diagnostic of tiny grains). ISS and VIMS characterized the color and angular scattering behavior of the rings. The sparse Galileo images indicated the ring has an azimuthally and/or temporally varying structure, which is too poorly characterized to understand (Ockert-Bell et al. 1999); were these ‘spokes’ in Jupiter’s ring? ISS took ‘movies’ to resolve this question and looked for new moons in the Jovian vicinity. Using data collected over several tens of hours in the far infrared, CIRS tried to ascertain the particle size distribution from the deviation of the spectral emission distribution from a blackbody, and to detect silicate absorption features in the mid or far infrared. While Voyager-based photometric analyses support flatter distributions (Showalter et al. 1987), analyses of the Galileo NIMS data indicate steeper distributions (McMuldroch et al. 2000). Brooks et al. (2001) indicate a way of reconciling these disparate models. It is known that fine dust grains are flying away from Jupiter (Grün et al. 1993, 1996). If the source of any of the dust sampled by CDA were uniquely identified as the ring or ringmoons, the ring composition might be measured directly. Unfortunately, severe data losses resulting from a spacecraft anomaly, and scattered light from the planet, have hampered ISS, CIRS and VIMS efforts to interpret their data as of this writing and tour planning has taken priority over data analysis. However, preliminary results from CDA appear to show that Io, rather than the ring, is the primary contributor of ejected fine grains discovered by Galileo (Hamilton and Burns 1993b, Horanyi et al. 1993, Graps et al. 2000, 2002).

Acknowledgements

Cassini has so far benefitted from the talents and hard work of too many individuals to cite here. Beyond the obvious critical contributions of the highly successful spacecraft, launch, and operations teams, we acknowledge the outstanding work
of the Cassini Mission Design Team in helping us through so many varied and complex tours. We thank Luke Dones for key contributions early in the tour assessment process, and Joe Burns, Ed Danielson, and Mark Showalter for discussions concerning Jupiter’s ring system prior to publication. We also acknowledge the valuable support of Kevin Beurle, Ken Bollinger, Jim Bradley, Kevin Grazier, and Brad Wallis in helping us understand the properties of the tour candidates, and Joe Burns and Luke Dones for very thorough reviews of the manuscript.

References


MAGNETOSPHERIC AND PLASMA SCIENCE WITH CASSINI-HUYGENS


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Abstract. Magnetospheric and plasma science studies at Saturn offer a unique opportunity to explore in-depth two types of magnetospheres. These are an ‘induced’ magnetosphere generated by the interaction of Titan with the surrounding plasma flow and Saturn’s ‘intrinsic’ magnetosphere, the magnetic cavity Saturn’s planetary magnetic field creates inside the solar wind flow. These two objects will be explored using the most advanced and diverse package of instruments for the analysis of plasmas, energetic particles and fields ever flown to a planet. These instruments will make it possible to address and solve a series of key scientific questions concerning the interaction of these two magnetospheres with their environment.

The flow of magnetospheric plasma around the obstacle, caused by Titan’s atmosphere/ionosphere, produces an elongated cavity and wake, which we call an ‘induced magnetosphere’. The Mach number characteristics of this interaction make it unique in the solar system. We first describe Titan’s ionosphere, which is the obstacle to the external plasma flow. We then study Titan’s induced magnetosphere, its structure, dynamics and variability, and discuss the possible existence of a small intrinsic magnetic field of Titan.

Saturn’s magnetosphere, which is dynamically and chemically coupled to all other components of Saturn’s environment in addition to Titan, is then described. We start with a summary of the morphology of magnetospheric plasma and fields. Then we discuss what we know of the magnetospheric interactions in each region. Beginning with the innermost regions and moving outwards, we first describe the region of the main rings and their connection to the low-latitude ionosphere. Next the icy satellites, which develop specific magnetospheric interactions, are imbedded in a relatively dense neutral gas cloud which also overlaps the spatial extent of the diffuse E ring. This region constitutes a
very interesting case of direct and mutual coupling between dust, neutral gas and plasma populations. Beyond about twelve Saturn radii is the outer magnetosphere, where the dynamics is dominated by its coupling with the solar wind and a large hydrogen torus. It is a region of intense coupling between the magnetosphere and Saturn’s upper atmosphere, and the source of Saturn’s auroral emissions, including the kilometric radiation. For each of these regions we identify the key scientific questions and propose an investigation strategy to address them.

Finally, we show how the unique characteristics of the CASSINI spacecraft, instruments and mission profile make it possible to address, and hopefully solve, many of these questions. While the CASSINI orbital tour gives access to most, if not all, of the regions that need to be explored, the unique capabilities of the MAPS instrument suite make it possible to define an efficient strategy in which \textit{in situ} measurements and remote sensing observations complement each other.

Saturn’s magnetosphere will be extensively studied from the microphysical to the global scale over the four years of the mission. All phases present in this unique environment – extended solid surfaces, dust and gas clouds, plasma and energetic particles – are coupled in an intricate way, very much as they are in planetary formation environments. This is one of the most interesting aspects of Magnetospheric and Plasma Science studies at Saturn. It provides us with a unique opportunity to conduct an \textit{in situ} investigation of a dynamical system that is in some ways analogous to the dusty plasma environments in which planetary systems form.

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Appendix A 336
1. Introduction

Cassini, the second orbiter mission to a giant planet, will be a unique opportunity to conduct an in-depth study of a planetary magnetosphere other than Earth’s and Jupiter’s. For this purpose the spacecraft carries a very sophisticated complement of plasma and field instruments. During its four-year exploration of the Saturnian system along an orbital tour that will provide a broad coverage in local time, latitude, and radial distances, Cassini is likely to lead to a very comprehensive description of Saturn’s magnetosphere, and should solve some of the most intriguing questions that this very special magnetospheric system poses.

Our actual knowledge of Saturn’s magnetosphere is based on a very limited set of observations. First of all are the plasma, particles and fields measurements obtained along the Pioneer 11 and Voyager 1 and 2 trajectories (see Figures 11 and 12 in the text). In addition to in situ measurements, these fly-bys also provided a limited access to the ionosphere profiles of Saturn through radio occultation data. The PWS instrument was able to provide remote sensing data on Saturn’s radio emissions, essentially Saturn’s Kilometric Radiation (SKR). The crossing of Titans’s wake by Voyager 1 returned to the Earth the only existing data on Titan’s interaction with the magnetosphere, while the subsequent radio occultation of Titan’s ionosphere made it possible to place at least an upper limit on its peak electron density. In addition to the spacecraft fly-by data, remote sensing measurements from Earth, its orbit, or by other interplanetary probes provided additional information on Saturn’s gas clouds, aurora and radio emissions following the Voyager era.

From this limited source of information, one can characterize Saturn’s magnetosphere by comparison to the family of planetary magnetospheres already explored in some detail, essentially the magnetospheres of the Earth and of the giant planets, to determine in what sense it shares common characters with them, and in what respect it is unique. To this end, let us explore the specific features of planetary magnetospheres.

i) An ‘intrinsic magnetosphere’ is generated by the interaction of the planetary intrinsic magnetic field with a plasma flow (generally the solar wind, or a stellar or planetary wind). The result of the interaction is to confine the planetary field inside a cavity, the magnetosphere, separated from the external flow by a sharp boundary, the magnetopause.

Saturn has an intrinsic magnetic field, which is compared in Table I (from Bagenal (1992)) to those of the other planets: its surface equatorial intensity of 0.21 Gauss is roughly comparable to those of the other planets, and only Jupiter stands out with a significantly larger value, reaching 14 Gauss at its maximum. Saturn is unique in that its dipole axis is nearly aligned with its rotation axis. Consequently the rotational modulation of its magnetic field should be small, essentially reflecting the effects of the non-dipole moments of the field. These effects are probably significant, however, since a planetary spin modulation is observed on
TABLE I
Comparison of planetary magnetic fields

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter(^a)</th>
<th>Saturn(^a)</th>
<th>Uranus(^a)</th>
<th>Neptune(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius, (R_{\text{Planet}}) (km)</td>
<td>6373</td>
<td>71,398</td>
<td>60,330</td>
<td>25,559</td>
<td>24,764</td>
</tr>
<tr>
<td>Spin Period (Hours)</td>
<td>24</td>
<td>9.9</td>
<td>10.7</td>
<td>17.2</td>
<td>16.1</td>
</tr>
<tr>
<td>Magnetic Moment/(M_{\text{Earth}}) (^b)</td>
<td>1</td>
<td>600</td>
<td>50</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Surface Magnetic Field (Gauss)</td>
<td>0.31</td>
<td>4.28</td>
<td>0.22</td>
<td>0.23</td>
<td>0.14</td>
</tr>
<tr>
<td>Dipole Equator, (B_0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0.24</td>
<td>3.2</td>
<td>0.18</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.68</td>
<td>14.3</td>
<td>0.84</td>
<td>0.96</td>
<td>0.9</td>
</tr>
<tr>
<td>Dipole Tilt and Sense</td>
<td>+11.3(^\circ)</td>
<td>-9.6(^\circ)</td>
<td>-0.0(^\circ)</td>
<td>-59(^\circ)</td>
<td>-47(^\circ)</td>
</tr>
<tr>
<td>Distance (A.U.)</td>
<td>1(^d)</td>
<td>5.2</td>
<td>9.5</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>Solar Wind Density (cm(^{-3}))</td>
<td>10</td>
<td>0.4</td>
<td>0.1</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>(R_{\text{CF}})</td>
<td>8 (R_E)</td>
<td>30 (R_J)</td>
<td>14 (R_S)</td>
<td>18 (R_U)</td>
<td>18 (R_N)</td>
</tr>
<tr>
<td>Size of Magnetosphere</td>
<td>11 (R_E)</td>
<td>50–100 (R_J)</td>
<td>16–22 (R_S)</td>
<td>18 (R_U)</td>
<td>23–26 (R_N)</td>
</tr>
</tbody>
</table>


\(^b\)\(M_{\text{Earth}} = 7.906 \times 10^{25}\) Gauss cm\(^3\) = 7.906 \times 10^{15}\) Tesla m\(^3\).

\(^c\)Note: Earth has a magnetic field of opposite polarity to those of the giant planets.

\(^d\)1 AU = 1.5 \times 10^8\) km.

radio emissions and trapped particle fluxes. The magnetopause shapes of the Earth, Jupiter and Saturn have been modeled by Maurice and Engle (1995), taking into account the contribution of the internal plasma pressure on the pressure balance with the solar wind (Figure 2). They appear very similar when their sub-solar magnetopause distances are scaled to the same length, except that the calculated jovian magnetopause is significantly ‘blunter’ than the Earth’s, because of the effect of a plasma disk and associated current disk. Saturn’s magnetopause appears intermediate, revealing a significant internal plasma pressure.

**ii) Planetary magnetospheres trap plasma and energetic charged particles of internal and solar wind origins on their closed magnetic field lines.**

As an illustration, Figure 3 shows the populations of trapped ions in the intermediate energy range, from about 30 keV to a few MeV, in the different planetary magnetospheres. Data on the Earth’s magnetosphere come from the ISEE spacecraft, and data on the giant planets from the Voyager LECP instrument. Locations of the upstream planetary shock (labeled S) and of the magnetopause (labeled M) are indicated, showing the exact extent of the planetary magnetopause in each panel. One can see the solar wind ion population at very low energies on the two sides of each magnetosphere, and characteristic enhanced ion fluxes inside the magnetospheric cavities. The radial positions of the satellites are also indicated. The ion fluxes in this specific energy range are weaker at Saturn than at Earth and Jupiter, but significantly stronger than at Uranus and Neptune. The bulk of the solar
Figure 1. ‘Artist’s view’ of Saturn’s magnetosphere, showing the diversity of processes and interactions taking place within the magnetospheric cavity. Courtesy of D. Mc Comas, Los Alamos National Laboratory.

Figure 2. When scaled to the same subsolar magnetopause distance to the planet’s center, the differences in the geometries of the magnetospheres of the Earth, Jupiter and Saturn, as calculated by Maurice and Engle (1995), become apparent. Saturn’s magnetopause shape is closer to the Earth’s, and the jovian magnetopause stands out as much ‘blunter’ than the other two, as a direct result of the presence of its intense equatorial current ring.
Figure 3. Radial distribution of fluxes of ions of intermediate energies (30 keV to a few MeV), in cgs units, in the magnetospheres of the Earth (from ISEE measurements) and of the giant planets (as measured by the LECP instrument on board Voyager during the planetary fly-bys). The locations of the planetary upstream shock (S), of the magnetopause crossings (M) and of the radial positions of the main satellites are also indicated.
### Table II
Plasma characteristics of planetary magnetospheres

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Density (cm$^{-3}$)</strong></td>
<td>1–4000</td>
<td>&gt;3000</td>
<td>-100</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Primary Sources</strong></td>
<td>$O^+$, $H^+$</td>
<td>$O^{n+}$, $S^{a+}$</td>
<td>$O^+$, $H_2O^+$ $H^+$</td>
<td>$H^+$</td>
<td>$N^+$, $H^+$</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>Io</td>
<td>Dione, Tethys</td>
<td>H cloud</td>
<td>$H^+$</td>
<td>Triton</td>
</tr>
<tr>
<td><strong>Secondary Sources</strong></td>
<td>$H^+$</td>
<td>$H^+$</td>
<td>$N^+$, $H^+$</td>
<td>$H^+$</td>
<td>$H^+$</td>
</tr>
<tr>
<td>Source Strength (ions/s)</td>
<td>$2 \times 10^{26}$</td>
<td>$&gt;10^{28}$</td>
<td>$10^{26}$</td>
<td>$10^{25}$</td>
<td>$10^{25}$</td>
</tr>
<tr>
<td>(kg/s)</td>
<td>5</td>
<td>700</td>
<td>2</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>Days$^b$</td>
<td>10–100</td>
<td>30 days</td>
<td>1–30</td>
<td>~ 1 day</td>
</tr>
<tr>
<td></td>
<td>hours</td>
<td>days</td>
<td>- years</td>
<td>days</td>
<td></td>
</tr>
<tr>
<td><strong>Energetic Neutral Atom</strong></td>
<td>Fluxes$^d$</td>
<td>$\sim 100$</td>
<td>$\sim 440$</td>
<td>$\sim 240$</td>
<td>&lt;12</td>
</tr>
</tbody>
</table>

$^a$Chappell et al. (1987).  
$^b$Filling time for plasmasphere.  
$^c$Convective time outside plasmapause.  
$^d$In units of (d/R$p)^{-2}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$, after Krimigis et al. (this issue).

Wind ions and of the cold plasma, located below 30 keV, is missing in this diagram, but it has been partly observed by other detectors at lower energies. A summary of these observations is given in Table II, again taken from Bagenal (1992). Just as we found at higher energies, Saturn’s absolute plasma densities, on the order of a few 100 particles/cm$^3$ at most, are intermediate between the significantly higher values found at Earth and Jupiter and the much smaller densities of the plasma populations of Uranus and Neptune.

### iii) Planetary ionospheres

Planetary ionospheres, which are tenuous plasma domains generated by photon and energetic particle irradiation of the upper atmospheres of planets, are an important element of magnetospheric systems. In addition to their own interest, they are important plasma sources, and regulate magnetospheric dynamics by their electrical properties.

Planetary atmospheres contain regions or layers of partially ionized plasma called ionospheres. All bodies in the solar system which possess significant atmospheres also possess ionospheres (see Nagy and Cravens, 1998; Schunk and Nagy, 2000). The main ionization sources are photo ionization by extreme ultraviolet (EUV) solar photons and electron-impact ionization by electrons with energies that exceed the neutral atom or molecule’s ionization potential. The electrons can be photoelectrons or energetic electrons originating in a planetary magnetosphere or in the solar wind. Each ionosphere provides a distinct plasma source of specific composition to its magnetosphere. Ionospheres have been detected both on Saturn and on its moon Titan, whose atmosphere is dense enough to support a collisional...
ionospheric layer. It has been suggested that ionospheric-type plasma also exists in the tenuous atmosphere associated with the rings system. With three different ionospheres inside its magnetospheric cavity, Saturn is a unique environment from the point of view of ionospheric physics.

iv) The electrodynamical coupling of a planetary ionosphere with the outer magnetosphere and its boundaries with the solar wind is at the origin of a broad variety of dynamical phenomena, including the generation of electrostatic potential differences, electric current flows and charged particle acceleration along magnetic field lines. These phenomena in turn produce a broad spectrum of so-called auroral emissions, which are a common feature of planetary magnetospheres.

Auroral emissions from Saturn have been observed in the radio, IR, visible and UV wavelength ranges. Saturn’s auroral radio emissions are much less intricate than Jupiter’s: they simply consist of one northern and one southern kilometer X mode source (SKR), with respectively right-hand and left-hand circular polarizations. As shown in Figure 4 (Zarka, 1998), where the average spectra of the auroral...
radio emissions of five magnetized planets (including the Io-Jupiter emission) are compared, the SKR spectrum covers a frequency range similar to that of the Earth, Uranus and Neptune radio emissions. The broad spectral range of Jovian radio emissions reflects the higher amplitude of the Jovian surface field, which results in a higher electron cyclotron frequency near the planet. The SKR average intensity is 5–10 times higher than that of the Earth’s auroral radio emissions, and second only to that of Jovian radio emissions, which are driven by a much larger solar wind input.

Saturn’s aurora (in the UV, visible and IR) appears to be less intense, as the Saturnian magnetosphere is both more distant and less active than the Jovian one. The few observations available from Voyager UVS and more recently from the Hubble Space Telescope indicate that the Saturnian aurora appears to be about one order of magnitude fainter than the jovian aurora. It emits mainly in the far UV, in the Lyman-α line of atomic hydrogen and in the Lyman and Werner bands of H₂. It seems to be organized in two ovals at about 80° latitude, dominated by bright ‘hot spots’ on the morning side.

v) Planetary magnetospheres develop complex electrodynamic interactions with their planet’s satellites when they are located inside the magnetospheric cavity. The nature of these interactions depends on the magnetic and electrical properties of the satellites, on the presence, density and composition of a satellite atmosphere/ionosphere and on the properties of the incident flow of magnetospheric plasmas and charged particles.

Saturn’s magnetosphere displays two different types of satellite interactions, with the icy satellites and with Titan, to which one should add its interactions with rings and dust particulates. For the purpose of comparison, Table III summarizes our knowledge of the characteristics of satellite interactions for Jupiter and Saturn. It shows the characteristic magnitudes of the incident flow, conveniently expressed in terms of Alfvénic (\(M_A\)) and sonic (\(M_S\)) Mach numbers, and the nature of the obstacle. The interactions with the icy satellites, as well as the jovian satellite interactions, are sub-Alfvénic and supersonic. The interaction with Titan is subsonic and super-Alfvénic (we call it ‘transonic’ in the remainder of the text), and the obstacle is the atmosphere and the ionosphere of this satellite. For these reasons Titan’s magnetospheric interaction is a unique case, which produces a true ‘induced magnetosphere’ in the magnetospheric flow (and at times in the magnetosheath or even the solar wind flow).

vi) Magnetospheric plasmas are fed by a broad variety of plasma sources, which differ in each particular magnetosphere.

At Earth, for instance, only two sources exist: the solar wind and the terrestrial ionosphere. At Jupiter, the significant sources of plasma which Galileo has found to be associated with Ganymede, Europa, and even Callisto are probably indicative of what we might expect for the icy satellites at Saturn. But these are dwarfed by Io, which is most likely the dominant jovian plasma source. The jovian ionosphere, however, may also be an important plasma source (Nagy et al., 1986). Saturn
TABLE III
Known characteristics of satellite/magnetosphere interactions at Jupiter and Saturn

<table>
<thead>
<tr>
<th></th>
<th>$M_S$</th>
<th>$M_A$</th>
<th>Nature of the obstacle</th>
<th>Magnetized or not</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Atmosphere. Ionosphere/solid surface</td>
<td></td>
</tr>
<tr>
<td>Jovian satellites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Io</td>
<td>1.65</td>
<td>0.30</td>
<td>Yes$^1$/yes</td>
<td>?</td>
</tr>
<tr>
<td>Ganymede</td>
<td>2.4</td>
<td>0.48</td>
<td>No/yes</td>
<td>Yes$^4$</td>
</tr>
<tr>
<td>Europa</td>
<td>1.75</td>
<td>0.39</td>
<td>Yes$^2$/yes</td>
<td>Probably not</td>
</tr>
<tr>
<td>Callisto</td>
<td>2.4</td>
<td>0.94</td>
<td>No/yes</td>
<td>No</td>
</tr>
<tr>
<td>Kronian satellites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titan</td>
<td>0.57</td>
<td>1.9</td>
<td>Yes/solid + lakes or oceans?</td>
<td>no</td>
</tr>
<tr>
<td>Tethys</td>
<td>1.24</td>
<td>0.25</td>
<td>No/yes</td>
<td>unknown</td>
</tr>
<tr>
<td>Dione</td>
<td>1.31</td>
<td>0.46</td>
<td>No/yes</td>
<td>unknown</td>
</tr>
<tr>
<td>Rhea</td>
<td>1.29</td>
<td>0.56</td>
<td>No/yes</td>
<td>unknown</td>
</tr>
<tr>
<td>Enceladus</td>
<td>2.4</td>
<td>0.14</td>
<td>No/yes</td>
<td>unknown</td>
</tr>
</tbody>
</table>

$^1$See Saur et al. (1999).
$^2$See Kliore et al. (1997), Saur et al. (1998).
$^3$The figures for the galilean satellites are taken from Neubauer (1998).
$^4$For the discovery of Ganymede’s magnetic field, see Kivelson et al. (1996), Gurnett et al. (1996).

Probably displays the largest diversity of sources: in addition to the solar wind and the planetary ionosphere, there are two other dominant plasma sources in the vicinity of the equatorial plane, which are directly related to the satellite interactions we just described. The first, in the external magnetosphere, is Titan which probably provides mainly $\text{H}^+$ and $\text{N}^+$ ions; the second, in the inner magnetosphere, is constituted by the neutral gas torus produced from sputtering of the surfaces of icy satellites and rings. It mainly provides ions of the dissociation products of water molecules. As Table II shows, these satellite sources alone are comparable in intensity to the total source of ions at Earth, but much smaller than the Io source at Jupiter.

vii) Each magnetospheric ion species is connected to its sources and sinks by transport processes acting on different scales. These may also differ strongly from one magnetosphere to another and need to be specifically identified.

Large-scale plasma circulation in planetary magnetospheres is generally described to first order as the superposition of the planetary corotation flow and of large-scale flow vortices, usually called ‘magnetospheric convection’, driven by the interaction of the outer magnetosphere with the solar wind. We know solar-wind-driven convection is important at Earth, and planetary corotation dominates the dynamics of the jovian magnetosphere. The case of Saturn is probably intermed-
ate, but very little is known about it, except that corotation dominates up to at least 6 Saturn radii from the planet center along the Voyager fly-by trajectories. In addition, small-scale motions and plasma instabilities may also significantly contribute to the redistribution of the different ion species throughout the magnetosphere: the characteristics of plasma transport at Saturn are basically unknown to-day, and should be a subject of intense research during the CASSINI years.

Saturn’s magnetosphere looks intermediate between the terrestrial and the jovian magnetospheres from the point of view of its plasma and field characteristics: its magnetic field topology or the absolute amount of trapped plasma are more similar to the Earth’s; its plasma circulation regime is probably similar to the jovian one. So what is really unique about Saturn’s magnetosphere is the variety of its interaction processes with the other components of Saturn’s environment. Saturn offers two magnetospheres in one, an ‘induced magnetosphere’ at Titan and an ‘intrinsic magnetosphere’ around Saturn itself, which we shall describe in this article. Figure 5 gives a schematic representation of the different components of the Saturn environment which interact with these magnetospheres, and indicates the section of this article dealing with them:

(a) Section 2 of this article will be entirely devoted to the description of Titan’s magnetospheric interactions: we first describe Titan’s ionosphere (section 2.1), which constitutes with its atmosphere an obstacle to the flow of the magnetospheric plasma (or at times of the solar wind or magnetosheath). We then study in section 2.2 Titan’s induced magnetosphere itself.

(b) Saturn’s magnetosphere itself is described in Section 3. We first start with a summary of the morphology of magnetospheric plasma and fields. Then we describe the interaction processes in each region, beginning with the innermost regions and moving outwards. We first describe the region of the main rings and their connection to the low-latitude ionosphere. Next the icy satellites, which develop specific magnetospheric interactions, are imbedded in a relatively dense neutral gas cloud which also overlaps the spatial extent of the diffuse E ring. This region constitutes a very interesting case of direct and mutual coupling between dust, neutral gas and plasma populations. Beyond about twelve Saturn radii is the outer magnetosphere, where the dynamics is dominated by its coupling with the solar wind and a large hydrogen torus. It is a region of intense coupling between the magnetosphere and Saturn’s upper atmosphere, and the source of Saturn’s auroral emissions, including the kilometric radiation. For each of these regions we identify the key scientific questions and propose an investigation strategy to address them.

Finally, we show in Section 4 how the unique characteristics of the CASSINI spacecraft, instruments and mission profile make it possible to address, and hopefully solve, many of these questions. While the CASSINI orbital tour gives access to most, if not all, of the regions that need to be explored, the unique capabilities of the MAPS instrument suite make it possible to define an efficient strategy in which in situ measurements and remote sensing observations complement each other.
Figure 5. This schematic representation of Saturn’s intrinsic magnetosphere (top) and of Titan’s induced magnetosphere (bottom) shows the different regions described in detail in this paper. Saturn’s magnetosphere interacts with all other components of the Saturnian environment. From the inner regions outwards, it interacts with the main rings and Saturn’s low latitude ionosphere (see section 3.2.1), with the icy satellites (section 3.2.2), with the inner gas torus and the E ring (section 3.2.3), with Saturn’s upper atmosphere and ionosphere along auroral field lines (section 3.2.4) and finally, in the outer magnetosphere, with the solar wind and extended hydrogen torus (section 3.2.5). Our discussion of Titan-related science will focus on Titan’s ionosphere (section 2.2) and Titan’s interactions with the surrounding plasma flows (section 2.3).
2. Titan’s Plasma and Magnetospheric Interactions

2.1. Uniqueness of the Problem

Titan’s interaction with its plasma environment is the only case in the solar system where a satellite with a substantial atmosphere (Hunten et al., 1984) characterized by an exobase well above the planetary surface interacts with the magnetospheric plasma. The plasma interaction is mostly of the atmospheric type (Neubauer et al., 1984), although a magnetic field of internal origin may play an important albeit secondary role as will be argued later. The three-dimensional picture of the plasma flow and its associated magnetic field in Titan’s vicinity is determined by the properties of the atmosphere, which at least at high altitudes is strongly influenced by the flow, and by the characteristics of the incident flow, which carries mass, momentum and energy into Titan’s surroundings. The energy input is enhanced by hot electrons flowing into the interaction volume along the field lines, particularly in the magnetosphere, and by solar UV photons. This interaction determines the loss of mass from Titan and constitutes an important source of magnetospheric plasma in the outer magnetosphere of Saturn. It also fixes the outer boundary condition of the atmosphere of Titan and contributes to the mass budget of this interesting atmosphere. In addition to its role for the Titan-Saturn system as a whole, it is also unique as a special case of a plasma interacting with an atmosphere. Because of its large scale height the atmosphere is an obstacle to the incident plasma flow, which is intermediate between the ‘hard’ target Venus and the very ‘soft’ target of a comet with substantial gas production. Titan is also unique, because it may be engulfed in the magnetospheric plasma with the Alfvén velocity and the speed of sound approximately equal to the flow velocity (see Table III) or in the magnetosheath of Saturn or even the solar wind, when Titan is near 12:00 in Saturn local time. A further unique aspect is the fact that the gyroradii of newly created heavy pick-up ions are larger than the satellite’s radius and are expected to lead to new flow effects in addition to substantial asymmetries. The carefully designed Titan tour and measurement programs will shed important light on many questions associated with these issues. The in situ measurements are done along specifically designed flyby trajectories, therefore theoretical modeling is needed to connect these observations. The models have to be three-dimensional, multi-fluid or even kinetic with sufficient resolution in configuration space and velocity space. The in situ measurements will be complemented by remote sensing of the upper atmosphere, e.g. by UV-observations, radio occultation studies of the ionosphere etc.

2.2. Titan’s Ionosphere

2.2.1. Present Knowledge and Open Questions

Titan’s atmosphere is dominated by molecular nitrogen (N₂) although a considerable abundance of methane (CH₄) is present (see review by Hunten, 1984). Many other species are present in lower abundances including ethane (C₂H₆), propane
molecular nitrogen is the most abundant neutral below an altitude of about 1700 km but methane becomes the dominant neutral constituent above this altitude. Molecular hydrogen (H₂) and atomic species such as N and H become dominant species further out in the exosphere. The only observational evidence of the existence of Titan’s ionosphere is the detection of the ionospheric peak region near the terminator by the radio occultation experiment onboard Voyager, with a peak electron density of 2400 cm⁻³ at an altitude of 1175 km (Bird et al., 1997). So our knowledge of Titan’s ionosphere nearly entirely rests upon theory and models.

At Titan, both photoionization by solar EUV radiation and electron impact ionization associated with magnetospheric electrons are thought to contribute to the creation of the ionosphere (cf., Cravens et al., 1992). Gan et al. (1992) used a two-stream electron transport code and Galand et al. (1999) used a multistream code to study how magnetospheric electrons, or atmospheric photoelectrons, interact with Titan’s ionosphere and atmosphere. The relative proportion of the two ionization mechanisms (EUV or magnetospheric electrons) at a particular location on Titan and at a particular time is a function of altitude, latitude and longitude, and also depends on the orbital position of Titan.

Many ion species are produced in Titan’s upper atmosphere due to the complexity of the neutral composition. The dominant ion species produced include N²⁺, N⁺, CH₄⁺, and CH₃⁺. In the main ionospheric region (altitudes less than about 1700 km) where the neutral density is high enough for chemistry to take place, the N²⁺, CH₄⁺, and CH₃⁺ ions originally produced are quickly converted by ion-neutral chemical reactions to a variety of other ion species, including such hydrocarbon species as C₂H₃⁺ and CH₃⁺ and nitrile species such as HCNH⁺ (Fox and Yelle, 1997; Keller et al., 1998). CH₃⁺ is also produced by the reaction of N₂⁺ ions with CH₄. For example, C₂H₄⁺ ions are produced from CH₃⁺ ions via reaction with methane, and C₂H₃⁺ in turn reacts with hydrogen cyanide (HCN) producing HCNH⁺. This ion species can further react with C₄H₂ (or other species) producing even heavier hydrocarbon species or it can dissociatively recombine. The molecular ion species produced in various ways then recombine with the thermal ionospheric electrons via dissociative recombination reactions.

Other loss processes have also been suggested for HCNH⁺ (Fox and Yelle, 1997). The full ion chemistry scheme for Titan’s ionosphere is quite complex and is not yet well understood. Several photochemical or one-dimensional models of Titan’s density structure have been constructed to study these chemical processes and the linkages to neutral photochemistry (see Table IV). The energetics of Titan’s ionosphere was modeled both by Gan et al. (1992), who focused on suprathermal electrons and on electron energetics, and by Roboz and Nagy (1994) who studied the ion and electron energetics at Titan. Temperatures within the ionosphere range from below 1000 K to above 10⁴ K. An example of predicted ion density structure in Titan’s ionosphere is shown in Figure 6.
TABLE IV
Recent Titan ionosphere models

<table>
<thead>
<tr>
<th>Model reference</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banaszkiewicz et al. (1999)</td>
<td>coupled upper atmosphere and ionosphere photochemical model</td>
</tr>
<tr>
<td>Keller et al. (1992; 1998)</td>
<td>photochemical model with detailed and updated hydrocarbon chemistry</td>
</tr>
<tr>
<td>Fox and Yelle (1997)</td>
<td>coupled upper atmosphere and ionosphere photochemical model</td>
</tr>
<tr>
<td>Gan et al. (1992)</td>
<td>2-stream electron transport and ionospheric electron energetics</td>
</tr>
<tr>
<td>Ip (1990)</td>
<td>one-dimensional MHD model of ram side</td>
</tr>
<tr>
<td>Keller and Cravens (1994)</td>
<td>1D hydrodynamic ionospheric wake</td>
</tr>
<tr>
<td>Keller et al. (1994)</td>
<td>1D ram side multi-species MHD</td>
</tr>
<tr>
<td>Cravens et al. (1998)</td>
<td>2D ram side 3-species MHD</td>
</tr>
<tr>
<td>Roboz and Nagy (1994)</td>
<td>energetics (electrons and ions)</td>
</tr>
</tbody>
</table>

At higher altitudes (above about 1700 km) where the neutral density is rather low, dynamical processes associated with rapid flow driven by the external plasma interaction start to become more important than chemical processes in controlling the ionospheric plasma distribution. The one-dimensional MHD models of Ip (1990) and Keller et al. (1994) demonstrated that the ionosphere of Titan is likely to be magnetized on the ram side due to the interaction of Saturn’s magnetospheric plasma with the ionosphere. The field structure and plasma behavior in the wake will be quite different and Keller and Cravens (1994) used a ‘polar wind’ type ionospheric outflow model to study this. 2-D and 3-D models are now also available, but they naturally focus on Titan’s magnetospheric interaction and will be described in Section 2.3.

2.2.2. Key Questions and MAPS Investigation Strategy
Considering the lack of observational data on Titan’s ionosphere, measurements from all the MAPS instruments, as well as from other Orbiter and Probe instruments, will be needed in addition to modeling work to discover and understand the ionosphere of Titan and its coupling to the neutral atmosphere and magnetosphere. The key questions to address are indeed very basic:

(1) What is the average morphology of Titan’s ionosphere and how is it determined by its coupling with Titan’s neutral atmosphere and with magnetospheric particles and fields?
(2) What is the variability of this ionosphere, and to what extent is it controlled by magnetospheric effects (importance and variability of energetic charged
particles as plasma sources, of its magnetization by the surrounding plasma flow, etc.)?

(3) How important are the different escape processes from Titan’s upper atmosphere and ionosphere, in the neutral or ionized phases, in the balance of magnetospheric plasma sources and for the long-term evolution of Titan’s upper atmosphere?

The ion neutral mass spectrometer (INMS) will measure both neutral density profiles in the upper atmosphere and ion density profiles in the ionosphere for species with mass numbers ranging from 1 amu up to 99 amu. This mass information will allow the chemical pathways controlling the ionosphere to be deduced. The vertical and horizontal structure of the ionosphere and upper atmosphere will also be determined by INMS. RPWS will determine the plasma density near and in the Titan ionosphere by measuring the upper hybrid resonance band. More importantly, RPWS includes a Langmuir probe added specifically to measure the electron density and temperature in Titan’s ionosphere. In addition to these very important parameters, however, modeling of the current-voltage relationship should provide information on the ion temperature, given the composition measured by INMS and/or CAPS, and a measure of the solar UV flux. The radio science experiment (RSS) will provide electron density profiles. CAPS will measure the distribution
functions of electrons and ions with energies up to 20 keV. The MIMI experiment will measure fluxes of energetic ions, electrons, and neutrals. These experiments will provide important information on energy inputs (and ionization sources) into Titan associated with magnetospheric particle populations. They will also provide information on the plasma velocities in and near Titan’s ionosphere. The UVIS experiment, by providing information on ultraviolet emissions from the upper atmosphere, will also tell us about both solar inputs and magnetospheric particle inputs into the upper atmosphere and ionosphere. The magnetometer experiment (MAG) will tell us the magnetic field topology around Titan and in its ionosphere. This topology, which largely controls the ionospheric dynamics and the energy inputs from the magnetosphere since the magnetic field guides magnetospheric electron motions, is the result of Titan’s interaction with the magnetosphere.

2.3. TITAN’S INTERACTION WITH THE MAGNETOSPHERE

2.3.1. Observational Knowledge
All our observational knowledge of Titan’s interaction with the magnetosphere is limited to the data obtained by Voyager 1 on November 12, 1980, which were published in special issues of Science (10 April 1981) and Journal of Geophysical Research (1 March 1982). The detailed reports on the observations made by the magnetic field experiment (Ness et al., 1982), the plasma wave instrument (Gurnett et al., 1982), the PLS plasma analyzer (Hartle et al., 1982) and the LECP charged particle detector (Mc Lennan et al., 1982) were summarized by Neubauer et al. (1984).

Let us give a brief overview of this unique data set, centered on the identifications of the main particles and fields signatures observed during the Titan fly-by. The Titan encounter occurred at 13.30 Saturn local time, along a trajectory which had a low inclination (8°) to Titan’s orbital plane, crossing it from north to south at a point very close to the closest approach, which occurred at a distance of 6959 km from Titan’s center (see Figure 1 of Neubauer et al. for the exact encounter geometry). The upstream magnetospheric flow conditions, as derived from the plasma data, corresponded to an Alfven Mach number of 1.9, and a sonic Mach number of 0.57, resulting in a fast Mach number of 0.55. For this ‘transonic’ situation, no upstream shock was expected in Saturn’s plasma flow. Voyager passed through the wake of Titan in Saturn’s magnetospheric plasma flow. This wake appeared to be shifted by 20° towards Saturn from the direction expected for exact corotating flow. As a result, the point of closest approach was very near the center of the wake, and the trajectory was not far from perpendicular to the wake axis, thus making the interpretation easier. Figure 7 shows a sketch of the different signatures observed, extrapolated from the V1 trajectory in a plane including this trajectory and perpendicular to Titan’s orbital plane, which is actually nearly orthogonal to the wake axis.
Figure 7. 2-D interpretation of plasma, particles, B-field and waves signatures observed by Voyager 1 during its encounter with Titan’s wake.

The magnetic field signature clearly showed an induced magnetotail configuration, with two lobes of opposite polarities closely matching the size of the Titan obstacle itself (fields towards Titan in the northern lobe, away from Titan in the southern lobe). They were separated by a sharp current sheet flowing away from Saturn near Titan’s orbital plane, and apparently closing through two sets of current sheets to the north and south of Titan’s orbital plane. This magnetic signature is consistent with the draping of Saturn’s magnetospheric field lines around the Titan obstacle. The two tail lobes were separated from each other and from the external plasma flow by regions of enhanced total plasma density (hatched areas in the figure) compared to the densities in the lobes and in the undisturbed magnetosphere.

A bite-out of the electron spectrum above 700 eV was observed in the PLS data over a region just slightly broader than the lobes, consistent with the absorbing or decelerating effect of Titan’s upper atmosphere on these hot electrons.

Another spectacular feature of the data was a strong asymmetry between the Saturn-facing and the anti-Saturn facing sides of this induced tail. On the Saturn-facing side, the lobe magnetic field appeared more intense, and the lobe appeared separated from the external flow by a sharp boundary carrying a narrow and localized electric current sheet. The picture is very different on the anti-Saturn facing
Titan/Magnetosphere interaction models

<table>
<thead>
<tr>
<th>Model reference</th>
<th>Type</th>
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<tbody>
<tr>
<td>Cravens et al. (1998)</td>
<td>2-D multi-fluid MHD</td>
</tr>
<tr>
<td>Ledvina and Cravens (1998)</td>
<td>3-D MHD</td>
</tr>
<tr>
<td>Kabin et al. (1999)</td>
<td>3-D MHD</td>
</tr>
<tr>
<td>Brecht et al. (1999)</td>
<td>Kinetic model (see Figure 2.3)</td>
</tr>
</tbody>
</table>

side: lobe fields appeared weaker, and they were separated from the undisturbed magnetospheric flow by a much broader boundary. This smooth transition actually extends over a width comparable to that of the tail itself, forming a sheath on only one side of Titan’s wake, which apparently includes the region of distributed currents closing the cross-tail currents to the north of the spacecraft.

The electromagnetic emissions detected by PWS supported the identification of these different plasma domains. The lobes were associated with a ‘tail noise’ very similar in morphology to the characteristic Broad Band Electrostatic Noise (BBEN) observed in the Earth’s magnetotail. Emissions in the sheath were dominated by a ‘sheath noise’, a low frequency electrostatic noise which has been interpreted as generated by fresh H\(^+\) pick-up ions extracted from Titan’s exosphere on its anti-Saturn side.

Finally, the analysis of PLS ion data appeared at least consistent with the expected geometry of the magnetospheric flow around the Titan obstacle. While H\(^+\), as previously indicated, seemed to be dominant outside Titan’s wake, a reduction in plasma flow speed was observed close to the tail boundary, consistent with mass loading of the flow by the addition of the heavier ions, such as N\(_2^+\), H\(_2\)CN\(^+\) and N\(^+\), extracted from Titan’s ionosphere.

The schematic representation of the VI encounter with Titan shown in Figure 7 rests upon implicit assumptions such as the symmetry of the wake about Titan’s orbital plane (which is basically orthogonal to the incident magnetospheric magnetic field). As for the interpretation in terms of draped field lines and the possible presence of pick-up ions in the sheath, it corresponds to a ‘reasonable’ 3-D extrapolation guided by our a priori physical understanding of Titan’s magnetospheric interaction, complemented by what we learnt from the few presently available numerical simulations.

2.3.2. The Contributions of Numerical Models
Numerical simulation studies of the Titan-magnetosphere interaction (see Table V) are still oversimplified, because of limitations in spatial resolution, limited consideration of the multi-ion chemistry and dynamics, and lack of consideration of the non-stationary features, which are essential to study electromagnetic induction
effects. But they are very useful for a first-order understanding and description of the Titan interaction, and as planning tools for the preparation of CASSINI observations. 3-D magnetohydrodynamic models have been developed by Ledvina and Cravens (1998) and by Kabin et al. (1999). A more detailed and multi-fluid model was developed in 2-D by Cravens et al. (1998), and in 3-D by Nagy et al. (2001). The 3-D models, for instance, reproduce many expected features, such as the region of magnetic pile-up on the upstream side, the draping of field lines and the formation of Alfvén wings, and the formation of an induced tail downstream. They also display significant differences, which to a large extent may be explained by the different numerical schemes and boundary conditions used. The first attempt at developing a kinetic model has been made by Brecht et al. (1999). Figure 8 shows, in the ideal plane of equatorial corotational flow, the calculated positions of the different ions in this model. Incident N\(^+\) ions are shown in the left-hand column. The positions of the pick-up ions, H\(^+\), N\(^+\) and C\(_2\)H\(_5\)\(^+\) are shown on the right-hand side, in panels (A), (B) and (C) respectively, for a case corresponding to 18.00 LT. The observed asymmetry between the two sides of the wake produced by finite gyroradius effects, which is evidently beyond the scope of ideal MHD models, is clearly seen in the figure.

2.3.3. Key Problems and MAPS Investigation Strategy

Even if we combine V1 encounter data and presently available simulation studies, we are left with enormous gaps in our understanding of Titan’s interaction with the Saturnian magnetosphere. CASSINI studies will have to address three major problems.

i) Determine the ‘average’ properties of Titan’s plasma environment and magnetospheric interaction.

We have summarized in Figure 9 what we can say to-day about Titan’s plasma environment. It schematically shows the interaction, for the case when Titan is in Saturn’s magnetosphere, in two orthogonal planes containing the direction of the incident flow vector: the ‘vertical’ plane containing the incident magnetic field, which is approximately perpendicular to Saturn’s equatorial plane, and the ‘horizontal’ plane perpendicular to it, which is close to the equatorial plane for a purely corotational flow. As the plasma runs into Titan’s atmosphere, it is loaded with mass by pick-up ions created from atmospheric neutrals by photoionization and electron collisional ionization. Thus the initial momentum is distributed over an increasing mass, corresponding to a deceleration of the incident plasma and an associated draping of the magnetic field lines frozen into the plasma. The mass-loaded plasma leaving Titan on the wake side thus forms an ion tail as indicated.

Mass is also lost via a neutral particle flux due to elastic collisions between fast ions and atmospheric neutrals (atmospheric sputtering) and via charge-exchange reactions, in addition to the classical atmospheric loss mechanisms. If the ionization rate is large enough and/or the momentum flux of the incoming flow is low enough, an ionopause will form separating an outer region threaded by Saturn’s
Figure 8. The ion positions calculated in the numerical kinetic model of Titan’s magnetospheric interaction developed by Brecht et al. (1999) are shown in the equatorial plane of the ideal corotation flow, which comes from above, with the unperturbed magnetic field perpendicular to the plane of the figure. The left-hand column shows the positions of original incident N⁺ ions, while the right-hand side panels show the positions of pick-up ions, H⁺, N⁺ and C₂H₅⁺ in panels (A), (B) and (C) respectively.
MAGNETOSPHERIC AND PLASMA SCIENCE WITH CASSINI-HUYGENS

Figure 9. A sketch of the interaction between Titan and the magnetospheric plasma flow is presented in two orthogonal planes containing the incident flow vector $v_o$: the plane containing the undisturbed magnetic field, and the plane perpendicular to it. The figure shows a magnetic field line as it is convected through Titan’s atmosphere, as well as horizontal flow lines around the obstacle and the region of pick-up ions on the anti-Saturn side. Mass loading slows down the plasma and leads to the draping with the formation of Titan’s tail and the tail current sheet. Ions are lost through the ion-tail. Some of the ion species are indicated.

magnetospheric field lines and an inner region, which is free from Saturnian magnetic fields but may contain magnetic fields of internal origin. If these conditions are not fulfilled, no ionopause forms and the magnetic field of Saturn will penetrate the atmosphere. The ionopause also represents a sheet of concentrated plasma currents.

In the ‘horizontal’ plane, the figure visualizes plasma flow lines which are diverted around the obstacle before continuing into the induced tail and around the flanks. On the side of the obstacle opposite to Saturn, ions picked-up from Titan’s extended exosphere are accelerated out of the exosphere by the large-scale electric field associated with the flow and then dragged downstream, whereas similar ions on the Saturn-facing side will tend to be precipitated into Titan’s atmosphere by the same electric field.

Further downstream, there is also a tail current sheet, as observed by Voyager 1, separating the northern and southern parts of the tail with essentially opposite magnetic field directions. In addition the tail will contain a north-south trending boundary between field lines draped over different hemispheres of Titan, as the incoming field lines separate at the stagnation point. If the plasma conditions are
very different on the two sides, this boundary may be easily identifiable, leading
to a four-lobe induced tail as it seems to have been the case at the time of the
V1 encounter (see Figure 7): because of variations in the relative directions of
the magnetospheric plasma flow and of incoming solar photons (separated by an
angle $\alpha$) the north-south boundary may be very pronounced at times. An additional
boundary is the outer boundary of the magnetotail, which may be referred to as the
tail magnetopause.

Other chemical boundaries may also exist. A bow shock was absent at the
Voyager 1 encounter but should obviously be looked for at each encounter, because
variations in the outer magnetosphere due to magnetospheric dynamics may lead to
occasional favorable conditions. As is clear from the discussion, the complicated
geometry destroys many symmetries found e.g. at Venus, where our angle $\alpha$ is
generally close to zero.

Three-dimensional observations of magnetic fields, plasma properties with
chemical resolution, energetic particles, neutral particles and plasma waves are
needed to disentangle the picture, ideally for all possible incident flow conditions.
However, a sufficient number of carefully selected flyby trajectories is sufficient
to describe the interaction, where they should be grouped by approximately equal
incident flow conditions. Special emphasis must be given to the description of the
various boundaries and current sheets alluded to above. To evaluate the mass losses
through the ion tail, good coverage of the plasma flow on the wake side is necessary
as a function of chemical species. For studies of the ionopause and the surrounding
regions, flyby orbits with very low altitudes at closest approach are important like
the nominal 950 km minimum altitude orbits of the Cassini mission.

The interaction picture will be different if the magnetosphere is sufficiently
compressed for Titan to be located in the magnetosheath or the solar wind. In the
latter case a pronounced bow shock is expected.

\textit{ii) Study the variability of Titan’s plasma environment.}

Titan is subjected to a strongly varying incident plasma flow due to variations
of the solar wind and the Saturnian local time at Titan varying through 24 hours
during the orbital period of 15 days. The analysis of the flow picture around Titan
will lead to erroneous results, if this is not taken into account.

For a stable solar wind with an average momentum flux, the magnetopause
will be at a stable location outside the orbit of Titan. Even then conditions at
Titan vary mostly because of the variation of the angle $\alpha$ between the direction
of corotational flow and incoming solar photons (Wolf and Neubauer, 1982). The
situation is shown schematically in Figure 10. It shows that magnetospheric flow
and ionizing photons from the sun provide the strongest ionization source in the
upstream region of the flow around 18:00 LT, where LT denotes local time. The
ionopause is expected to be best developed at this local time. Solar photons do
not contribute to the ionization in the upstream stagnation region around 6:00 LT.
The upstream ionopause may disappear in this case. Apart from the variation of $\alpha$,
magnetospheric plasma conditions will be dominated by Saturn’s inner tail plasma
population and magnetic field configuration around 24:00 LT. Here substorm-like phenomena may play a role. If now the variation of the solar wind is taken into account, the magnetopause configuration will change with the possibility of Titan being located in Saturn’s magnetosheath or even the solar wind. Obviously this will occur most easily near 12:00 LT.

Another interesting situation arises, when the sun is eclipsed by Saturn as seen by an observer on Titan. The sudden cut-off of sunlight will make interesting experiments possible with the upper atmosphere of Titan. This situation will occur near the equinoxes, e.g. at the end of 2008 or in 2009 just after the primary mission of Cassini.

Through the study of the variability of Titan’s ionosphere and magnetospheric interaction, it will be possible to partly disentangle the effects of the different parameters which play a role in the interaction of a non-magnetized atmospheric/ionspheric obstacle with an external plasma flow. For instance, by varying solar il-
lumination and consequently the density of the ionospheric layers, we shall learn about the role played specifically by the ionosphere as a planetary obstacle to the external flow. Variations in the characteristics of this external flow (Mach numbers, composition, temperature etc.) similarly have a strong effect on the geometry of the different interaction regions. The repeated study of Titan’s magnetospheric interaction during the CASSINI tour will make it possible, in principle, to explore rather extensively the parameter space of this very particular type of interaction between a flow and an obstacle. But for this exploration to be comprehensive enough, there is a need for a very good coverage of Titan fly-bys by the MAPS instruments throughout the mission.

iii) Contribute to the investigations of Titan’s interior.

Magnetic fields due to currents in Titan’s interior influence the interaction in various ways and can be diagnosed most easily by flybys at very low altitude. They can be used to probe Titan’s interior. In principle, dynamo magnetic fields or magnetic fields due to remanent magnetization could produce permanent fields in the frame fixed to Titan. An upper limit to a permanent dipole has been derived after the Voyager I encounter. Other interpretations are possible, although the ‘noise’ due to dynamic magnetic field variations in the outer magnetosphere makes a too detailed interpretation difficult. This is apart from the consideration that contemporary models of Titan’s interior do not allow large remanent magnetization because of the ‘icy’ outer shells.

After the discovery of a dynamo at the somewhat larger Jovian satellite Ganymede, one might be tempted to also expect at least a weak dynamo at Titan. However, Titan is not in a strong orbital resonance with the central planet as Ganymede is, and this resonance is suspected to play an important role in creating/maintaining a dynamo. Also, the evolution of Titan is likely to have been quite different from that of Ganymede.

There are probably better chances to observe an internal magnetic field due to electromagnetic induction in an electrolytically conducting ocean inside Titan. The inducing magnetic field could be the Saturnian magnetic field, which could periodically penetrate the Titanian atmosphere and ionosphere around 6:00 LT. This could also happen during the eclipses mentioned above. Again magnetic field measurements during very close encounters (950 km altitude for Cassini) are very important at the appropriate local times, as are MAPS measurements in general, in order to best understand the local plasma environment which will aid in identification of how any internal magnetic field is generated.
Figure 11. Trajectories of the Pioneer 11, Voyager 1 and Voyager 2 s/c, projected onto Saturn's equatorial plane. The average locations of the magnetopause (MP) and shock (S) are indicated, as well as their specific crossings during these three fly-bys. One can notice that only the noon and early morning sectors were explored.

3. Saturn's Plasma and Magnetospheric Interactions

3.1. LARGE-SCALE STRUCTURE AND DYNAMICS OF PLASMAS AND FIELDS

In order to set the stage for the discussion of the diversity of magnetospheric interactions operating in Saturn's magnetosphere, it is necessary to first give a brief overview of what we know of the large-scale distribution of its plasmas and fields.
The three planetary fly-bys provided us with a preliminary description of the magnetic field configuration, the main plasma domains and plasma wave emissions. Figure 11 shows their trajectories projected onto Saturn’s equatorial plane and Figure 12 shows the same trajectories in a Saturn latitude/radial distance coordinate system, represented in a Saturn meridian plane and overlaid with modeled magnetic field lines and ring current. As the figures show, these three fly-bys provided a very limited local time coverage of Saturn’s magnetosphere, basically limited to the noon and early morning sectors, but some coverage in latitude. These observations have sometimes been extended in space coverage by a variety of empirical or physical models.

3.1.1. Magnetic Field Configuration
As for all planetary magnetospheres, the magnetic field at Saturn can be described as the sum of the internal contribution to the planetary field, produced by the planet-
ary dynamo, and additional contributions from the ring current, magnetopause and magnetotail currents. Smaller and more localized contributions are also expected from currents flowing along magnetic field lines between the equatorial magnetosphere and the ionospheric hemispheres of Saturn, and from currents generated by the interactions with the satellites, rings and neutral gas and dust clouds.

The ring current carried by charged particles trapped in Saturn’s magnetic field has been detected extending from 8 Rs to 15.5 Rs near Saturn’s equatorial plane (Figure 12). The magnetopause has a subsolar point distance of about 23 Rs from Saturn’s center. The magnetotail has not been directly explored, and is only described by predictive models, such as the one of Behannon et al. (1981) shown in Figure 13. The tail should extend first symmetrically about Saturn’s equatorial plane, and then along the Sun-Saturn axis beyond a hinge point estimated to be located in the midnight meridian at about 30 Rs from Saturn in the anti-solar direction.

More detailed descriptions of Saturn’s magnetic field and associated boundaries are given in appendix A.

3.1.2. Plasma Domains

Saturn’s plasma domains were first discovered by Pioneer (Frank et al., 1980), and later analyzed in detail by the three charged particle investigations carried by Voyager: PLS, LECP and CRS.

The plasma science instrument (PLS) provided most of our current knowledge of the thermal plasma at Saturn up to about 6 keV (Bridge et al., 1981, 1982; Lazarus and Mc Nutt, 1983; Sittler et al., 1983; Richardson, 1986). Higher-energy particles were measured by the low-energy charged particle (LECP) experiment (Krimigis et al., 1981, 1982, 1983). The cosmic ray subsystem (CRS) covered energies greater than 1 MeV (Vogt et al., 1981, 1982). Altogether, the three instruments left a gap in energy coverage between about 6 and 22 keV which won’t be covered before CASSINI returns data from Saturn.

Let us summarize what we know of the electron and ion populations, their energy spectra and their fluid parameters.

Electron populations

A comprehensive analysis of electron observations, merging the information from the three investigations, has been performed by Maurice et al. (1996). Through a careful re-analysis and intercalibration of all available data, they have been able to produce composite energy spectra with a 15-min. time resolution all the way along the V1 and V2 trajectories. For each spectrum, using a logarithmic interpolation across the PLS-LECP energy gap, the authors systematically computed three moments of the electron distribution function, assumed to be isotropic: the electron density $n_e$, the electron pressure $P_e$, and the total electron return current density to the spacecraft, $F_e$, which is simply the intensity spectrum integrated in energy.
Figure 13. Representation of magnetic field lines in the noon-midnight meridian plane in the Saturn magnetotail model of Behannon et al. (1983), for the case when the sun is in Saturn’s equatorial plane.

Figure 14 shows the moments calculated in this way along the Voyager 2 spacecraft trajectory, together with the latitude of the spacecraft (lower panel) and the electron beta of the plasma (third panel). Open circles show the value of beta extrapolated to the magnetic equator assuming a constant pressure of the warm/hot electrons along field lines. The regions where beta reaches 1 nearly coincide with Connerney et al.’s (1981) model ring current. Densities and pressures regularly increase inward, until the orbit of Dione, and then decrease inward of it. A similar curve for Voyager 1 (see Figure 8 of Maurice et al.) shows that electron densities can reach higher values, up to 10 cm$^{-3}$, near the equatorial plane.
Figure 14. Voyager 2 electron density ($n_e$), electron pressure ($P_e$), electron beta ($\beta_e$), and electron return current density ($F_e$) plotted as a function of L shell with their 1-sigma uncertainty (solid circles). Open circles are used for the beta values extrapolated to the magnetic equator of each field line. The absolute value of the spacecraft latitude is shown in the bottom panel.
**Ion populations**

The Voyager PLS instrument had no direct capability to discriminate the different ion species. However, as long as the Mach numbers of the different ion species remained sufficiently greater than 1, each species gave a different and separable peak in the PLS energy spectra, from which one could determine the density (from the peak total intensity) and the temperature (from the peak width), whereas the comparison of the three Faraday cup records gave access to the ion drift velocity vector (e.g., Lazarus and Mc Nutt, 1983; Richardson, 1986). The analysis revealed the presence of two different mass components in the Voyager spectra, a light-ion component at mass 1 corresponding to protons, and a heavier ion component near 16 amu. It could not be determined, however, if this peak was composed of \( \text{O}^+ \), \( \text{OH}^+ \), \( \text{H}_2\text{O}^+ \) or a combination of them since the peak was broad enough to cover all these possibilities, or even \( \text{N}^+ \) at 14 amu. So this peak was arbitrarily treated as a single ion species, denoted ‘\( \text{O}^+ \)’ for simplicity. A detailed review of thermal plasma at Saturn has been published by Richardson (1998). Here we shall simply show one illustrative example of the original analysis of Richardson (1986): Figure 15 shows the ion drift velocity, reduced (from top to bottom) in terms of azimuthal, radial and vertical components in a reference frame linked to Saturn’s equatorial plane, and the temperatures and densities of the two ion species (bottom two panels), plotted as a function of L shell. The dotted lines on the drift panels show the corresponding components of the local corotation velocity. The striking feature emerging from these data is that the thermal plasma corotates with the planet only in the inner magnetosphere (inside \( L = 5.5 \) for Voyager 1 as seen in Figure 15, or inside \( L = 8.5 \) for Voyager 2). But it systematically moves more slowly than corotation outside these limits, reaching at times as low as 50% of the corotation speed. There is also an increase in the departure from corotation just outside the orbits of Dione and Rhea. In addition to these azimuthal flows, radial flows of significant magnitudes are also seen in the outer magnetosphere.

Using the distributions of ion densities, ion and electron temperatures along the spacecraft trajectories, Richardson and Sittler (1990) extrapolated the density distribution of each charged species to a full magnetic meridional plane by using the equation of pressure balance along field lines, for a range of L values extending to \( L = 12 \). The resulting density model is shown in Figure 16, in terms of iso-contours of proton, ‘oxygen’, and electron densities. One sees that the ion species are concentrated toward the equatorial plane, as a result of the effect of the centrifugal force acting on the plasma trapped in each magnetic flux tube. This effect is negligible for electrons, significant for the light ion and dominant for the heavier ion. In addition, the three species are coupled along each field line by a charge-separation electric field which restores quasi-neutrality. This field results in a lesser confinement of the heavier ion, which is partly pulled away from the equator by the electric field which couples it to the electron gas, while the light ion tends to ‘float’ away from the equator where its density has a local minimum, as one can see in the ‘proton’ panel. This model was extrapolated further outward.
Figure 15. Thermal ion moment profiles along the Voyager 1 trajectory deduced from the PLS data by Richardson (1986), assuming the presence of two ion masses: the three components of ion drift in the Saturn-centered cylindrical coordinate set are shown at the top, and the density and temperature of the two mass components at the bottom.
Figure 16. Isocontours of thermal $H^+$, $O^+$ and electron densities in Saturn's meridian plane in the model of Richardson and Sittler (1990), deduced from PLS data.
to $L = 20$ by Richardson (1995). These two studies used simplifying assumptions of constant temperatures and temperature anisotropies along field lines. A self-consistent calculation of the exact distribution of each species along field lines, allowing for distribution functions of arbitrary shapes and for temperature anisotropy variations, was later developed by Maurice et al. (1997) and applied to the special cases of Jupiter and Saturn.

**Plasmas and fields in the outer magnetosphere**

The region outside about $15\ R_\oplus$ in the equatorial plane and centered on Titan’s orbit appears to display a broad variety of dynamic phenomena and irregular structures. This is very probably because it is under the combined influence of the solar wind and its variability, the magnetic tail, Titan and its neutral torus. Let us describe the irregular structure of plasmas and fields in this domain.

Observations of regions of detached plasma were made by two of the three spacecraft flybys of Saturn. These signatures on the dayside inbound passes of the Voyager 1 and 2 spacecraft occurred whilst the magnetosphere was in an expanded and rather disturbed state as a result of relatively quiet solar wind conditions. The Pioneer 11 inbound pass occurred during a period when the solar wind was itself very disturbed, resulting in a very compressed and rather quiet magnetosphere.

The detached plasma regions are of higher density than the surrounding medium and of a much colder temperature. There are also corresponding signatures in the magnetic field, where a sharp dropout in the north-south component is mirrored by a corresponding dropout in the field magnitude (Dougherty, private communication). Such signatures are to be expected from simple pressure balance arguments. This cold detached plasma is observed in the hot outer magnetosphere in the rather turbulent region between the last magnetopause entry into the magnetosphere and the outer edge of the equatorial plasma sheet.

Four of these signatures observed during the Voyager 1 encounter in the vicinity of Titan have been interpreted as the spacecraft having crossed through remnants of the plasma plume of Titan (Eviatar et al., 1982). The observations were consistent with a gradual aging of the plume as well as dispersal of the plume in response to changing solar wind conditions. Closer in to the planet but still beyond the outer edge of the plasma sheet the plasma signatures have been described as detached plasma flux tubes which have broken off from the edge of the plasma sheet by the centrifugally driven instability (Goertz, 1983). For the Voyager 2 fly-by, Titan was in the magnetosheath during the inbound pass, yet numerous cold plasma enhancements, also associated with magnetic field drop-outs, were observed between entry into the magnetosphere and the outer edge of the plasma sheet.

Similar signatures of detached plasma flux tubes have also been observed in Jupiter’s dayside magnetosphere, again just beyond the outer edge of the plasma sheet (Southwood et al., 1995). Once detached from the planetary field the only forces imposed on the bubble will be those imposed by the external field. The magnetic pressure force compresses the bubble transverse to the external field but
exerts no force along the field direction and so the bubble expands in that direction. Dispersal of the plasma within the flux tube is likely as they evolve and observations which the Cassini orbiter will make at Saturn are crucial for allowing a better understanding of these flux tubes and their evolution at different local times and radial distances. Such phenomena are important since they are likely to represent evidence of dynamical processes occurring in fast rotating magnetospheres and may represent an important mechanism for loss of material from such magnetospheres.

**A summary picture of plasma regimes and flows**

From the set of available observations, a summary picture of magnetospheric plasmas in the middle and low latitude magnetosphere has been proposed by Sittler et al. (1983), as shown in Figure 17, adapted from their study. Due to the local time coverage of the inbound and outbound Voyager fly-bys, it can be established only for the noon sector (left-hand side of the figure) and for the dawn sector (right-hand side). The region of closed field lines of the magnetosphere can be divided radially into relatively homogeneous plasma domains. Going from the planet radially outward, the regions of dense plasma correspond to the inner plasma torus, certainly coupled to the rings and icy satellites as their main source, and then to the extended plasma sheet, extending basically from 8 to 12–15 $R_S$. Both temperatures and flow speeds of the ions increase outwards, with a trend which closely corresponds to corotation and pick-up ion energies up to about 6 $R_S$, and then progressively departs from exact corotation to display a significant sub-corotation. This region of relatively cool and dense plasma is embedded into a hotter and more...
tenuous plasma in the outer magnetosphere, which is not centrifugally confined to the vicinity of the equatorial plane as the cold plasma is. Between the outer edge of the extended plasma sheet and the magnetopause on the dayside, a very irregular plasma structure has been detected by Voyager, which may be partly composed of plasmas from Titan and of plasma ‘blobs’ centrifugally detached from the plasma sheet. The structure of this region is probably highly variable with solar wind conditions.

3.1.3. Plasma Waves
Saturn’s plasma wave spectrum shows strong similarities to those of other planetary magnetospheres (Kurth and Gurnett, 1991). The observations from the Voyager 1 flyby (Gurnett et al., 1981a) are summarized in Figure 18. This figure represents the 16-channel spectrum analyzer data in the form of a frequency-time spectrogram with the intensities of waves indicated by the color bar at the right plotted as a function of frequency and time. We’ve used a fitting algorithm to interpolate wave intensities between the coarsely-spaced spectrum analyzer channels; some features which appear to be rather broadband in this presentation are narrowbanded in fact. The observations are generally well-ordered by the electron cyclotron frequency $f_{CE}$ derived from the measured magnetic field and this characteristic frequency is provided as a white line overlaying the spectrogram. At the very
highest frequencies the low-frequency extent of the Saturn kilometric radiation, which will be discussed extensively in section 3.2.4., can be observed. One set of radio emissions which is not related to the kilometric radiation, however, occurs near closest approach at frequencies below $f_{\text{CE}}$ but above the local electron plasma frequency (Gurnett et al., 1981b). These are narrowband radio emissions in the frequency range of a few to 10 kHz based on high resolution wideband observations. That they are found in Figure 18 at frequencies below $f_{\text{CE}}$ means that they are propagating in the left-hand ordinary mode. Gurnett et al. (1981b) suggest that the frequency spacing between the narrowband lines implies that there may be some connection between the icy satellites and the generation mechanism of these waves.

Just above $f_{\text{CE}}$ on the outbound portion of the trajectory inside of about 8 Rs Voyager observes electron cyclotron harmonic emissions, called ECH in the remainder of the text (Kurth et al., 1983). The primary band observed is the so-called $3f_{\text{CE}}/2$ band just above the electron cyclotron frequency and below its harmonic. Also seen, however, is the upper hybrid resonance band which is a special case of the ECH bands between the harmonics of $f_{\text{CE}}$ near the upper hybrid resonance frequency. Below $f_{\text{CE}}$, especially near closest approach and near the equator crossing, are bands of whistler-mode hiss and chorus. A relatively intense feature right at the equator is likely to comprise both whistler-mode hiss and the response of the instrument to dust impacts (Barbosa and Kurth, 1993; Tsintikidis et al., 1985). Finally, the broadband emissions near the end of the plot in Figure 18 could be some combination of whistler mode or electrostatic waves (such as broadband electrostatic noise) associated with the near-tail region.

The ECH bands at Earth are occasionally observed at intensities of a few mV/m and are capable of pitch-angle scattering electrons of a few hundred eV to a few keV. However, the observed ECH bands at Saturn are quite weak, only about 30 $\mu$V/m and are unlikely to be an important loss mechanism for low-energy electrons. Similarly, Scarf et al. (1984) have calculated that the whistler-mode emissions near 1 kHz resonate with electrons near 2 keV, but are considerably weaker than required to cause strong diffusion. They also report that the flux of resonant electrons observed is well below the stable trapping limit, so this is not a surprising result. The magnetic equator is a location where certainly the ECH waves and to a lesser extent the whistler-mode waves tend to be most intense at other planetary magnetospheres. Because of the aligned magnetic dipole the Voyagers only sampled the near-equatorial region near 6 and 3 Rs, so it may be that an orbiter such as Cassini might find that there are either radial or temporal variations in the intensities of these emissions, which would increase their importance as a loss process for electrons (Kurth and Gurnett, 1991).

3.1.4. Saturn’s Ionosphere

Molecular hydrogen is the primary neutral constituent of the thermospheres of the giant planets (Jupiter, Saturn, Uranus, and Neptune), although atomic hydrogen is also present in the upper atmospheres and exospheres of these planets as well
as some methane (CH$_4$) in the lower thermosphere (cf., Atreya, 1986). Electron density profiles were measured in Saturn's ionosphere by the Pioneer 11 and Voyager 1 and 2 spacecraft by means of the radio occultation technique (see review by Waite and Cravens, 1987). The typical maximum electron density observed in Saturn's ionosphere was about $2 \times 10^4$ cm$^{-3}$ (cf., Waite and Cravens, 1987). The electron density profiles measured by Pioneer are shown in Figure 19. Radio occultations of the atmosphere or ionosphere of the outer planets are possible only near the terminators, which severely limits the available local time information on these ionospheres. However Kaiser et al. (1984) used radio measurements of the observed low-frequency cut-off of Saturn electrostatic discharges (SED) from lightning to determine the peak ionospheric electron density and its variation with local time (see Figure 20). The peak electron density deduced in this way at local noon is 10 times higher than radio occultation values at the terminator (i.e., dusk.

Figure 19. Electron density profile of Saturn's ionosphere deduced from Pioneer 10 radio occultation data. From Kliore et al. (1980).
Figure 20. Peak electron density versus local time in Saturn’s ionosphere. Data points are from the SED measurements of Kaiser et al. (1984) and the curves (A through E) are from the model of Majeed and McConnell (1996) for different water influxes and abundances of vibrationally excited H₂. Curve A is for a ‘standard’ model with no water influx and no vibrationally excited H₂. Model D has no vibrationally excited H₂ but does have a water influx of $5 \times 10^7$ cm$^{-2}$ s$^{-1}$. Model E has no water influx but does have vibrationally excited H₂. From Majeed and McConnell (1996).

or dawn). Kaiser et al. also noted that some ionospheric structure appeared to be linked to the rings. Infra-red observations of H$^+_3$ provide another source of information on the auroral region, indicating the presence of this important ionospheric species (Geballe et al., 1993).

H$^+_2$ is the main ion produced in all these ionospheres although some H$^+$ is also produced (cf., Schunk and Nagy, 2000). Photoionization by solar EUV radiation is the main ion source at low and mid-latitudes. Electron impact ionization by energetic magnetospheric electrons is thought to be the main ionization source in the auroral regions (see section 3.2.4 on auroral processes).

Just as in the E regions of the inner planets (Earth, Venus, and Mars), ion-neutral chemistry alters the ion composition. In particular, the following reaction quickly removes H$^+_2$:

$$H^+_2 + H_2 \rightarrow H^+_3 + H$$ (1)
TABLE VI
Main characteristics of Saturn Plasma/particles models

<table>
<thead>
<tr>
<th>Model reference</th>
<th>Main characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maurice et al. (1996)</td>
<td>Provides composite electron energy spectra with a 15-min resolution along the V1 and V2 trajectories for the energy range 10 eV–2 MeV.</td>
</tr>
<tr>
<td>Richardson and Sittler (1990)</td>
<td>Meridian plane distribution of thermal O(^+), H(^+) and electron densities deduced from PLS Voyager up to L = 12.</td>
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<tr>
<td>Richardson (1995)</td>
<td>Extrapolation of the previous model to L = 20, describing irregular structures in the outer magnetosphere.</td>
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TABLE VII
Main Saturn ionosphere models

<table>
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<tr>
<th>Model reference</th>
<th>Main characteristics</th>
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<tbody>
<tr>
<td>Connerney and Waite (1984)</td>
<td>1D chemical/vertical transport model including vibrationally excited H(_2) and ring water influx.</td>
</tr>
<tr>
<td>Majeed et al. (1991)</td>
<td>1D chemical/vertical transport model including vibrationally excited H(_2).</td>
</tr>
<tr>
<td>Majeed and McConnell (1996)</td>
<td>1D chemical vertical transport including vibrationally excited H(_2), water influx, and vertical ion drifts.</td>
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The H\(_3^+\) ions that result from this reaction are rapidly removed by dissociative recombination, and for this reason have relatively short lifetimes. H\(_3^+\) ions can also be removed in the lower ionosphere by reaction with CH\(_4\), thus forming CH\(_3^+\) ions. Subsequent photochemistry leads to the formation of heavier, more complex hydrocarbon ion species. Metallic ion species also probably exist in Saturn's lower ionosphere, just as they exist in the Earth's lower ionosphere where they are produced by the meteoritic source. Ionospheric models show that the main ionospheric peak is located in a 'F\(_1\)-type' region and that the major ion species near this peak is H\(^+\). The reason for this is that the chemical lifetime of ionospheric protons is quite long, whereas the other ion species have much shorter chemical lifetimes. The main chemical loss process for the H\(^+\) ion is the slow radiative recombination reaction allowing the H\(^+\) density (in what are called 'standard' models) to build up to rather large values. In fact, in order to bring calculated density values into line with the observed values, most theoretical models of Saturn's ionosphere (see Table VII) had to invoke additional loss processes for H\(^+\) such as removal by reaction with water molecules, presumably associated with the rings (Connerney and Waite, 1984) or by reaction with vibrationally excited H\(_2\) (Mc Elroy, 1973; Majeed and McConnell, 1991); see the review by Waite and Cravens (1987).
By analogy with the terrestrial ionosphere, Saturn’s ionosphere is likely to be extremely dynamic. Both vertical and horizontal ion drifts, associated with both neutral winds and magnetospheric electric fields, are likely to be present. Very little work has been carried out in this area. Majeed and McConnell (1996) adopted reasonable values of vertical ion drifts in their ionospheric model in order to ascertain the effects on the ionospheric density profile. They also included the effects of H\(^+\) loss by reaction with vibrationally excited H\(_2\) or with water. Figure 20 shows some of these results. Majeed and McConnell find that the model (with a reasonable choice of parameters) can reproduce the radio occultation profiles at the terminator but not the large diurnal variation evident in the SED data. Influx of water from the rings may help to increase the rate of loss of H\(^+\) ions, but this mechanism is not proven to actually operate.

**MAPS investigation strategy for the study of Saturn’s ionosphere**

It is clear that Saturn’s ionosphere remains very poorly understood although it may be an important source and/or sink of plasma for the magnetosphere and ring ionosphere and plays a role in magnetospheric dynamics via electrodynamic coupling effects of the ionosphere’s electrical conductivity. The Cassini mission can contribute to a greater understanding of Saturn’s ionosphere and its linkages to the lower atmosphere, to the magnetosphere and to the rings. To this end every opportunity will have to be used to measure electron density profiles from radio occultation. Critical information on particle fluxes (electrons, ions, neutrals, and dust, from low to high energies) into and out of the ionosphere will be obtained by a number of MAPS instruments (e.g., CAPS, MIMI). The analysis of SED’s by the wave instrument (RPWS), as demonstrated by Voyager experimenters, can also be a powerful sounding technique to determine the diurnal variations of the ionospheric layers. All these observational inputs will be much needed to develop a new generation of Saturn ionospheric models and try to reconcile the large discrepancies existing to-day between models and observations.

### 3.2. SATURN’S MAGNETOSPHERIC INTERACTIONS

#### 3.2.1. Interactions of the Inner Magnetosphere with the Ionosphere, Rings and Dust

A schematic representation of Saturn’s inner magnetosphere region is shown in Figure 21. This region is characterized by the strong coupling of three components: plasma populations, ring and dust particulates, and energetic charged particles from the radiation belts.

Plasmas of 3 different origins, from Saturn’s ionosphere (in blue), from the tiny rings’ atmosphere (in green) and finally from the icy satellites torus (in red), are likely to exist in this region. The existence of a specific component of the plasma, narrowly confined to the vicinity of the ring plane and related to the rings’ ionosphere, was first suggested by Eviatar and Richardson (1990, 1992) and later
Figure 21. The innermost magnetosphere is a region of strong mixing and interactions between the different plasma sources. The Saturn ionospheric source diffuses partly upward along field lines towards the equatorial plane, where it mixes with the plasma generated in the tiny rings atmosphere (green) and the icy satellites ion torus (red). Downward diffusion of water-group ions into the upper atmosphere of Saturn may play an important role in the balance of the ionospheric plasma itself.

confirmed by the detailed analysis of PLS data in the vicinity of the ring plane crossing, near 2.85 $R_s$, by Gan-Baruch et al. (1994). It showed a relatively dense plasma, with a peak density around 100 cm$^{-3}$, a large anisotropy of about 5, and a strong confinement within $\pm 0.3$ $R_s$ about the ring plane, consistent with the observed anisotropy. This observation confirmed the existence of a ring ionosphere,
predicted by Ip (1983) to result from the ionization of the tenuous H\textsubscript{2}O atmosphere of the rings, which was observed for the first time by Wagener and Caldwell (1986).

These three plasma populations of significantly different densities, temperatures and composition are partly superposed in the inner magnetosphere, as a result of a variety of diffusion processes: magnetic-field-aligned upward diffusion of ionospheric plasmas towards the equatorial plane, field-aligned downward diffusion of ring plasma towards the ionosphere, and probably some cross-field diffusion of the rings and icy satellites plasmas.

The second component of the region is constituted by the rings and dust particulates, which cover a broad range of sizes from 100 meter to sub-micron. The small-size component of this population is composed of dust particulates which may interact with the plasma in several ways, being subject to electrostatic charging under the effect of UV irradiation, bombardment by charged particles, and interaction with the plasma. This additional charged particle population constitutes, together with the ion and electron components, a very interesting ‘dusty plasma’ disk near the equatorial plane.

The third component of this region is constituted by the trapped energetic particles observed by Pioneer 11 (Simpson et al., 1980) and Voyager (Krimigis et al., 1983). Their strong interaction with the satellites and rings is very clearly evidenced by strong absorption features at the main satellite locations in their radial flux profile, and by a sharp inner edge right on the outer edge of the A-ring. This indicates they are absorbed by satellite surfaces and solid particles, a process in which they interact with these solid surfaces, producing energetic neutral atoms (ENA’s) via sputtering, charging, and probably inducing some surface erosion and modification (see Johnson, 1990, for a comprehensive analysis of the physical processes involved).

A diversity of mechanisms, which ultimately control the coupling between plasmas, dust and energetic particles, and in part the distribution of each of these components, are at work. We shall mention a few of the most important and interesting ones.

**Plasma transport**

As already mentioned, plasma transport along and across field lines plays a very important role in mixing the three plasma sources present, and therefore in defining the particular plasma regime as a function of radial distance and magnetic latitude.

Cross-field plasma transport, in this region which is essentially dominated by corotation, may exist if some modes for field line interchange motions are unstable. The resulting time scale for radial diffusion has been estimated to be very long, on the order of years, but some of these interchanges have been proposed to involve dust-plasma coupling, as will be seen later. It is this diffusion process which controls the degree of mixing between ring plasma and icy satellites plasmas near the outer edge of the rings system.
Field-aligned plasma transport has been studied with a high degree of sophistication in this region, because it controls the net exchange of ionized matter between the rings and Saturn’s ionosphere. A first kinetic model of plasma transport along field lines was developed by Wilson and Waite (1989). This steady-state model included gravitational, magnetic mirror, centripetal and ambipolar electric forces, as well as two plasma sources at the two ends of each modeled field line. In the equatorial plane, a warm water ion plasma simulated the rings ionosphere, whereas at the ionospheric foot of the same field line a cool hydrogen ion plasma simulated Saturn’s ionosphere. The model showed that the regime of plasma exchange was not the same throughout the rings system. Near the C ring, in the innermost part, the dominant ion was found to be H⁺, whereas over the outer B ring and the A ring access of ionospheric plasma to the ring plane was inhibited by the ambipolar electric field, and water ions remained dominant. The model results also showed that significant fluxes of water-derived ions, of up to 5 × 10⁷ cm⁻² s⁻¹, could be established and maintained through the outer edge of the B ring, thus giving some support to the hypothesis that water ions from the rings play a role in ion recombination in Saturn’s ionosphere (see section 3.1.4). A later study by Wilson (1991) made it possible to calculate the diurnal variations through a time-dependent model, and used the computed plasma densities to determine the charge state of dust particles in the rings system. As the plasma and charge state distribution are basically fixed with respect to the sun, the keplerian motion of dust particles through this fixed pattern must in principle generate magnetic field-aligned motions closing through the ionosphere, as initially proposed by Ip and Mendis (1983). Wilson’s calculation showed that the effect of this current system on ExB plasma drifts was negligible. Finally, a plasma transport model using the alternative technique of 16-moment equations was developed by Demars (1995) who explored a large fraction of the parameter domain for stationary conditions.

**Physics of dusty plasmas**

The vicinity of the plane of the main rings, as well as the volume of space occupied by the more diffuse E ring, are regions of strong coupling between plasma, dust particles and energetic charged particles. Under the effect of bombardment by these particles, of UV irradiation and of interactions with the plasma, each particle carries a net equilibrium electric charge which may be positive or negative depending on the environmental conditions. As a result, the ‘gas’ of dust particles becomes electrostatically coupled to the ambient plasma and forms what is currently called a ‘dusty plasma’, a complex system which has received increased interest over the last decade. Saturn’s magnetosphere and ring/dust system certainly offer one of the most interesting opportunities to study a natural dusty plasma in space.

**Dust-associated current systems.** This system has, for instance, the property of being a permanent current carrier. The drift motion of a charged dust particulate is a combination of keplerian motion in Saturn’s gravity field and of gyration/drift in
its corotating magnetic field. Since keplerian motion remains dominant over most of the mass spectrum of dust particles, there is a permanent relative drift among the charged dust particles in Saturn’s corotating frame. This drift is eastward inside the synchronous orbit, and westward outside of it, and therefore also carries a net azimuthal current whose direction depends on dust charge, size and location. As the ambient plasma parameters and charged particle fluxes vary with radial distance and local time, this azimuthal current may also vary in local time, leading to current divergence along magnetic field lines and its closure into the ionosphere, as initially proposed by Ip and Mendis (1983). Wilson (1991), however, showed that the resulting ExB drifts induced by this ionospheric current closure are negligible.

**Dust-associated waves and instabilities.** The presence of this ‘dusty’ azimuthal current is suspected to play a role in the development of a variety of instabilities and specific mechanisms. The most spectacular one is probably the generation of ‘spokes’, these sporadic radially-aligned albedo features which were observed by Voyager, as shown in Figure 22. A good concise summary of the observational characteristics of spokes can be found, for instance, in Tagger et al. (1991). As spokes appear dark in backscattered light, but bright in forward-scattered light, they must be formed by sub micron grains electrostatically levitated over the larger ring grains. They usually have a V shape, with the apex of the V at the synchronous orbit (in the B ring at a radius of $\sim 1100\,000$ km). In the initial stage of spoke formation, one edge of the V rotates at the keplerian frequency and the other one at the planetary rotation frequency. They appear most of the time at dawn on the disk and also seem to be created at a particular longitude, which corresponds to the preferential longitude for SKR generation.

Several theories for the generation of spokes have been elaborated, all founded on the specific properties of dusty plasmas. The model of Goertz and Morfill (1984) starts from the initial idea that spokes become visible when small micron-sized dust particles are elevated above the ring plane. According to the authors, this levitation is made possible locally by the injection of an additional source of dense trapped plasma in contact with the ring plane, which may be the neutral and ionized dense cloud generated by a meteor impact on the rings (Morfill and Goerz, 1982). Then the very local plasma density enhancement produces the elevation of dust above the ring plane necessary for spoke formation, but also carries a local enhancement of azimuthal electric current due to the differential drift of plasma and dust particles, as already explained. This current, which diverges on the eastward and westward edges of the plasma cloud, closes through the ionosphere via magnetic field-aligned currents and induces a radial ExB drift, which drags the initial plasma cloud away from the synchronous orbit for the case of a negative space charge of dust particles, and towards it for the opposite case. The radial spoke structure, in this theory, is then only the visible trace of the motion of the plasma cloud, which produces elevation of dust above the ring plane along its trajectory. This theory indeed explains several of the observed characteristics of spokes, in particular their
preferential appearance north of the ring in the active sector, which is consistent with the idea that they must be formed on the side of the ring facing the magnetic equator for the enhanced plasma cloud to be stably trapped.

Tagger et al. (1991) developed a more elaborate theory, in which they relate them to the particular characteristics of magnetosonic waves in a weakly ionized disk in keplerian rotation, embedded in a vertical magnetic field. These waves have been proposed to be at the origin of radial and spiral density waves in magnetized accretion disks.

The question of the origin of spokes belongs to a more general class of phenomena involving dust-plasma coupling, which must play a diversity of roles in the system. For instance the instability mechanism invoked by Goertz and Morfill (1984) for the formation of spokes has also been proposed, with some adaptation, to be the source of radial plasma transport in Saturn’s icy satellites torus (Morfill et al., 1993).
**Key problems and MAPS investigation strategy**

Two important scientific questions emerge from the analysis of our present knowledge of the region of the magnetosphere directly connected to the rings:

1. What is the net exchange of plasma, neutral species and dust particles between the rings, Saturn’s ionosphere and its inner plasmasphere, and what effect does this exchange have on the maintenance of the ionosphere and the evolution of the rings?

2. What are the mechanisms responsible for the formation of spokes on Saturn’s main rings?

Magnetic field lines connected to the main rings will be explored by Cassini only during the Saturn Orbit Insertion (SOI) phase. As shown by Mauk et al. (1998) in their Figure 5, the spacecraft on its inbound and outbound legs will cross the ring plane near 2.5 Rs and then fly above the main rings at an altitude lower than 0.5 Rs. This sequence will therefore be a unique opportunity to study rings/plasmas/ionosphere coupling by means of an observational strategy combining in situ and remote sensing measurements.

*In-situ measurements* will use the standard MAPS instrument complement to provide the characteristics of plasmas, dust, energetic particles and possibly neutral gas at the ring plane crossings and above. As the spacecraft will fly through field lines directly connected to the rings and the ionosphere of Saturn, the angular resolution of the particle instruments (CAPS, MIMI) will make it possible to really characterize the flows of the different plasma species between these two reservoirs, as well as to measure the populations of trapped electrons and ions. This should provide an important contribution to the question of the exchange of ions between the rings and Saturn’s ionosphere, and of the possible role of water-derived ions in ionospheric recombination.

*Close distance remote sensing measurements* will be of very special interest during SOI. While rings imaging by the different cameras on board will provide numerous constraints on the composition and size distribution of ring particles, ENA imaging by MIMI/INCA will provide a wealth of information concerning the dynamics of trapped energetic particles and their interaction with the rings (Mauk et al., 1998): constraints on the radial transport rates of energetic particles, a better determination of energetic particles impact rates on the rings and their effect on sputtering and erosion, and of the importance of rings as a sink of these particles. Finally, the measured energy spectra of the ENA emissions will provide an additional type of constraint on the size distribution of ring particles.

### 3.2.2. Interactions with the Icy Satellites

Whereas Hyperion, Iapetus and Phoebe interact directly with the solar wind, the inner icy satellites of Saturn, Mimas, Enceladus, Tethys, Dione and Rhea are imbedded in the inner magnetosphere of Saturn. The interaction of the magnetosphere’s fields and particles with these icy satellites, while being interesting by itself, can provide important information about their bulk and surface properties.
**Present knowledge**

The surfaces of these satellites are believed to be composed primarily of ice with a trace amount of O$_3$ being the only other identified species. Other suggested volatile constituents are CO$_2$ and NH$_3$ with dark components of the surface being possibly made of C and S chains. Models also suggest the presence of hydrated minerals like those found on the Jovian satellites (McCord et al., 1999; Carlson et al., 1999).

The effect of sputtering induced by energetic particle bombardment and bombardment by the ambient plasma permanently maintains tenuous atmospheres around these satellites. Because these atmospheres are expected to be optically thin they will not have ionospheres which are sufficient to prevent the flowing plasma from reaching the surface of the icy satellite. Satellite surfaces are also exposed to micrometeorite bombardment that produces a porous regolith as well as a vapor and the emission of particulates into Saturn’s magnetosphere. The chemical composition of the gas and particulate phases of these tenuous icy satellite environments is evidently related to their surface composition, though not in a straightforward way. Models of the atmospheres can be constructed based on knowledge of the energetic particle population originally provided by Voyager, and will be enhanced by Cassini and by knowledge of the physics of sputtering for potential surface species.

Each satellite as a whole, with its interior, surface and atmosphere, interacts with the magnetosphere’s plasmas and fields. The different mechanisms involved in this interaction are schematically shown in Figure 23. The sputtered atmosphere is represented as a blue cloud surrounding the icy satellite. The bombardment of the icy satellite by the hot plasma is shown by the red dots in the figure that also shows the formation of a plasma wake behind the icy satellite. Because the plasma is moving faster than the icy satellite the lower energy plasma ions and the hot electrons tend to preferentially bombard the trailing side of the satellite whereas the energetic heavy ions bombard more isotropically (Pospieszalska and Johnson, 1989). The energy spectrum of the sputtered particles is such that most of the sputtered molecules are on escape trajectories (Johnson, 1990). Therefore, as the ionization rate is low there also exists a toroidal neutral cloud co-orbiting with the satellite containing satellite surface species (see Johnson et al., 1989) which will be discussed in the next section.

Partial conversion of this neutral cloud and atmosphere to ions proceeds through ion pickup. Fresh pickup ions can be distinguished from the ambient plasma by their characteristic cycloidal motion which has a distinct energy-angle dependence, as shown by yellow dashed lines in Figure 23. These fresh pickup ions, with their unique energy-angle signature, provide the most direct information about the atmosphere composition. Pioneer (Smith and Tsurutani, 1983) and Voyager (Barbosa, 1992) observations showed the presence of ion cyclotron waves in the vicinity of Dione’s L shell and the frequency of the waves was consistent with the pickup ion being a heavy ion such as H$_2$O$^+$. These waves provide indirect evidence for the formation of pickup ions in the vicinity of Dione. The presence of ion cyclotron
waves in the vicinity of the pickup region is schematically shown by the wiggles in the magnetic field lines in Figure 23. The pickup process should also generate an ion beam instability (Ma et al., 1987) in the plasma, producing a broad spectrum of electrostatic waves which can be measured by Cassini.

If the satellite has a conductive interior then there may be a magnetic signature that could be measured by Cassini. This effect is schematically shown in Figure 23 by magnetic field lines getting hung up in the body of the satellite, complicating the interaction. Although we think this unlikely due to the small size of these satellites Cassini would be able to measure an internal field, if present and for close enough fly-bys, from which we could infer the presence of a dynamo operating in the core of the satellite. Since fast ions appear to dominate the sputtering process (Jurac
et al., 2001a), the field topology within the vicinity of the satellite is not expected to have a strong influence on the generation of the sputtered atmosphere.

**Key problems and MAPS investigation strategy**

Cassini fly-bys of the icy satellites will offer a unique opportunity to address two major scientific objectives of the mission:

1. Can we contribute to determining the surface composition of the icy satellites during close Cassini fly-bys from CAPS and MIMI data?
2. What are the modes of interaction between Saturn’s magnetospheric plasma flow and the icy satellites, and how do they depend on the net contribution to ion pick-up, the internal structure and conductivity, and possibly the state of magnetization of these satellites?

CAPS measurements of fresh pick-up ions produced by the tenuous sputtered atmospheres will be the main contribution of MAPS to the investigation of the surface geology of icy satellites. As indicated before, the specific energy-angle dependence of their fluxes should make it possible to distinguish them from the background magnetospheric plasma (Johnson and Sittler, 1990). Determinations of isotope ratios from the mass spectra and from the molecular composition measurements will also be critical inputs for estimating surface age. Therefore, the CAPS instrument will complement the surface geology data provided by VIMS. The RPWS Langmuir Probe will also contribute to the measurement of electron density and temperature near the icy satellites.

The characterization of surface-magnetosphere interactions will involve the whole suite of MAPS instruments. The CAPS instrument will measure the ambient plasma characteristics and its interaction with the satellite, in addition to the pick-up ions. This data set will provide information about the ionization processes for pickup ions such as charge exchange and electron impact ionization. The MIMI instrument will be able to measure the very energetic ions which are believed to provide a dominant contribution to the generation of the sputtered atmospheres of the satellites; their data should also show evidence of a wake forming behind the satellite indicating the net ion bombardment of its surface. MAG will be able to measure the presence of ion cyclotron waves in the pickup region. If the satellites are conductive, it will measure the perturbations in the magnetic field produced by the systems of d.c. currents and/or MHD waves – including possible Alfven wings – generated by their interaction with the magnetospheric plasma flow. It could also potentially measure the presence of an internal magnetic field if present. The RPWS instrument will measure whistler-mode emissions, electrostatic solitary structures, ion cyclotron waves, electrostatic electron cyclotron harmonic emissions, and upper hybrid waves created via the interaction of the icy satellites with the Saturnian magnetosphere, similar to effects observed near the Galilean satellites at Jupiter. All these measurements critically depend on the fly-by geometry, which will have to be studied very carefully to meet the MAPS objectives.
3.2.3. Interactions with the Neutral Gas and the E Ring in the Inner Plasma Torus

As described in Section 3.1, the inner plasma torus extends out to about 8 Rs, and is continued through the extended plasma sheet out to $L = \sim 13$ Rs. This region contains all the important plasma and neutral sources except Titan: the rings, the planet, and the inner icy satellites, whose magnetospheric interactions have just been described. It is characterized by a strong chemical and dynamical coupling between the plasma, the neutral gas and E-ring particles. Since the neutral gas, based on recent observational constraints, dominates the plasma in terms of local density, this is a very interesting and unique environment in which the variety of chemical and dynamical mechanisms involved in dust/gas/plasma coupling can be studied in depth at Saturn by a combination of in situ and remote sensing measurements.

Present knowledge: distribution of neutral gas and E-ring particles

Saturn’s magnetosphere is now known to be dominated by neutral gas throughout the region inward from 30 Rs. The presence of atomic hydrogen in significant amounts was predicted by McDonough and Brice (1973), who argued that a large atmosphere on Titan would produce a torus of H at 20 Rs. Atomic hydrogen was subsequently observed in a rocket experiment (Weiser et al., 1977), although no definition could be established on its distribution. The magnetosphere also contains large quantities of OH (Shemansky et al., 1993), in addition to atomic hydrogen, and by inference atomic oxygen in comparable amounts to OH. This neutral gas torus entirely covers the region of space covered by the diffuse E ring. Let us review the observational evidence.

Atomic hydrogen. The present determination of its distribution is derived from Voyager 1 post encounter observations of H Ly-α (Shemansky and Hall, 1992). The distribution is asymmetric in local time with most of the gas concentrated inside 15 Rs in the dusk region and with concentrations up to $\sim 150$ cm$^{-3}$. The latitudinal distribution is roughly $\pm 8$ Rs, and extends from Saturn’s atmosphere to $\sim 30$ Rs. The source of the atomic hydrogen is not definitively determined. A component must be provided by Titan, but according to Shemansky and Hall (1992), most of the H atoms are on ballistic trajectories exiting Saturn’s atmosphere. Based on the recent observations of OH, discussed below, H from the water products in the inner magnetosphere may also be important.

$H_2O$ products. The observed OH is assumed to be the product of $H_2O$ chemistry. The source may be complex with a number of components; sputtering from satellite and E ring grain surfaces by hot ions (Johnson et al., 1989), E-ring particle impacts (Hamilton and Burns, 1994), as well as meteoroid bombardment (Ip, 1983) and reactions at the rings (Ip, 1984a,b, 1995). The HST observations obtained in 1992 and 1994 with the Faint Object Spectrograph provide a large number of measure-
Figure 24. Iso-density contours of the OH cloud derived by Richardson et al. (1998) from Hubble Space Telescope Faint Object Spectrograph measurements under the assumption of axial symmetry about Saturn’s rotation axis.

ments from which an assumed azimuthally symmetric cloud has been constructed (Figure 24). The trend in the distribution suggests that the abundance peaks at \( \sim 4.5 \ R_S \). From the data at 1.8 \( \ R_S \) one can infer that there is no detectable OH above the rings because all of the observed line-of-sight abundance at 1.8 \( \ R_S \) can be accounted for by the gas in the region \( \gtrsim 3 \ R_S \). Atomic oxygen, which is much more difficult to detect, has not been observed, but it is calculated (Richardson, 1998) to be comparable in density to OH. The densities rapidly decrease inside of \( \sim 3 \ R_S \) and the inferred scale height of the cloud is comparable to the plasma scale height.

IUE observations by Festou and Shemansky (2000) provide a rough measure of latitudinal distribution. The Saturn system was spatially explored using the IUE long wavelength spectrograph (large slit) on 31 Oct–2 Nov. 1995. OH was positively detected along the equator between \( \sim 2.5 \ R_S \) and \( \sim 5.5 \ R_S \). In the equatorial plane, the mean brightness (10 by 20 arcsec slit) decreases from \( \sim 130 \ R \) to \( \sim 60 \ R \). There is some indication that OH emission could be weakly present at a point located \( \approx 1 \ R_S \) from the ring plane and \( 2.5 \ R_S \) from the planet center. This is consistent with a scale height of order 0.5 to 1 \( \ R_S \) of the OH emission at \( \sim 2.5 \ R_S \) in the equatorial plane.

**E-ring Grains.** The neutral gas in the inner magnetosphere is coupled not only to the plasma, but also to the population of solid particles which exist as charged grains in the E-ring and, in part, the G-ring. In fact the extent of the E-ring is determined by its interaction with the plasma, the Lorentz forces (e.g., Horanyi et al., 1992), and the lifetime of the grains which is determined by sputtering by the
trapped plasma. A recent analysis (Jurac et al. 2001b) indicates that in the region 3–6 Rs the E-ring is the dominant source of neutrals, but only if there are many more grains than seen optically. That is, there is apparently much more surface area than observed to be tied up in small sub micron grains. Such grains are readily transported in the magnetosphere and rapidly eroded by sputtering, hence, need to be replenished rapidly. In fact it is likely that there is a continuous spectrum of neutral sizes from atoms to molecules to molecular clusters and small grains. Since the grains are known to be charged there may also be charged clusters surviving in the vicinity of Enceladus and Mimas (Johnson et al. 1989). This is an interesting region having very low electron temperatures and low relative collision velocities between the co-rotating plasma and the neutrals.

Contributions from modeling
Saturn’s neutral gas torus results from a complex balance between source processes, chemical and photochemical reactions between neutral species and loss of these species. The main source mechanisms for neutrals, in addition to the outgassing of Titan’s atmosphere, are the collisions of energetic particles, corotating plasma, and micrometeorites with the ring particles and satellites, which sputter H$_2$O from the surfaces, as partly described in the previous section. The ion sputtering yields depend on the flux, energy, and mass of incoming particles (Johnson, 1990). Another mechanism suggested as a source of additional neutrals is collisions of E-ring particles with each other and with satellites embedded in the ring (which extends from 3–8 Rs) (Hamilton and Burns, 1994), but the magnitude of this source is not well determined. The neutrals orbit Saturn until lost via either ionization, dissociation, or collision with a ring particle or satellite. Plasma is formed when the neutrals orbiting Saturn are ionized by UV radiation, electron impact, or charge exchange. The plasma densities again result from a balance between the formation rates and loss rates due to recombination, charge exchange, collisions with satellites and ring particles, and transport processes.

Since the observational base is limited, models of the spatial distribution of density and composition of neutral and ion species have been developed. Monte Carlo schemes have been used to calculate the neutral distributions, which depend on the ejection energy from the sputtered surface and the lifetime of the neutrals (i.e., Johnson et al., 1989; Pospieszalska and Johnson, 1991; Ip, 1995; Jurac et al., 2001a). These studies show the neutrals and plasma are tightly confined to Saturn’s equator. Models of plasma transport and chemistry have been used to determine ion composition and transport rates (Barbosa, 1990; Shemansky and Hall, 1992; Richardson et al., 1986; Richardson, 1995, 1998). Figure 25 shows a chart of the ion and neutral processes; we show only the most important reaction paths for simplicity. Where multiple paths are important, we show a very rough magnetosphere-averaged percentage for each path. The actual percentage varies with position in the magnetosphere. These reactions, transport, and the distribution of ions and neutrals in latitude are a necessary component for an accurate model of
Figure 25. Schematic representation of the main chemical paths contributing to the balance of the inner torus. The irradiation agents acting on the different objects of the Saturn system are shown in light blue boxes. The sources and sinks are shown in yellow boxes. The approximate, spatially averaged, branching ratios of the different reactions are shown along the chemical paths.
the inner magnetosphere. A recent model which includes both neutrals and plasma was able to match both the plasma and neutral observations fairly well (Richardson et al., 1998). To fit both the neutral and plasma data, the total sputtered source of \( \text{H}_2\text{O} \) required from the rings and satellites is \( 1.4 \times 10^{27} \text{ s}^{-1} \), with the source strongly peaked near 4.5 \( \text{R}_\text{S} \), and the transport time is about 5 days at \( L = 6 \). Figure 26 shows the densities of the major ion and neutral species predicted by this model. The total neutral density is near 1000 cm\(^{-3}\) near 4.5 \( \text{R}_\text{S} \). OH is the densest neutral component inside 7 \( \text{R}_\text{S} \), outside 7 \( \text{R}_\text{S} \) H and O are most important. The ion densities increase inward with peak densities near 200 cm\(^{-3}\), with \( \text{O}^+ \) the dominant ion followed by \( \text{H}^+ \).

Several problems remain, however, before full consistency between the presently available data and model estimates can be achieved:

1. The neutral source required by the model is at least a factor of 4 greater than published sputtering estimates (Shi et al., 1995) and more than an order of magnitude larger than obtained from a recent reanalysis of the plasma LECP data (Jurac et al., 2001b). This led Jurac et al. (2001a) to suggest that very small ring grains in the E ring could provide a sufficient source of neutrals. More recently, using a new set of HST observations of the OH cloud, Jurac et al. (2002) showed that a vast majority of the \( \text{H}_2\text{O} \) molecules originates from Enceladus’ orbit, and attributed this to the presence of an unknown population of colliding small bodies.

2. Although the model fits the heavy ion observations very well, it predicts more protons than observed by a factor of 2–3 between 5 and 8 \( \text{R}_\text{S} \).

3. The model sets the ion and electron temperatures equal to those observed by Voyager. Recent work to model the temperatures shows that an electron energy source is needed to maintain the observed electron temperature and that slower transport, by about an order of magnitude, is needed to fit the observed ion temperature profile (Richardson, 1999). Part of the problem may come from the fact that the neutral model used is too simplistic and needs to be replaced with a Monte Carlo model which includes ion-neutral and neutral-neutral collisions and more accurately calculates the neutral distribution.

**Key problems and MAPS investigation strategy**

In view of the present very limited understanding of the magnetospheric interaction with neutral gas tori, two key questions will have to be addressed during the Cassini mission:

1. Can we quantitatively understand the observed distribution of neutral and ion species in the inner torus from the balance of plasma generation, loss and radial transport?

2. Does it provide constraints on poorly known quantities, such as satellite surfaces compositions, the sputtering rates from the icy satellites surfaces and from the E ring, and the key reaction rates along the chemical and photochemical paths?
Figure 26. Radial distribution of the equilibrium neutral and ion densities calculated in the model of Richardson et al. (1998), using a chemical scheme similar to the one shown in Figure 25.
An efficient plan to solve these questions should include three ingredients: critical laboratory measurements, the development of an improved physical model of the dynamical and chemical coupling between solid phases (satellite surfaces and ring particles), neutral gas tori and charged particle populations, and well-planned Cassini observations:

- a program of additional measurements of key parameters (sputtering and photochemical rates, reaction coefficients, etc.) should aim at reducing remaining uncertainties;
- an improved model describing the inner torus chemistry, transport and energetics, should be progressively developed, with the capability of assimilating new data throughout the Cassini mission lifetime.
- Cassini observations should monitor neutral and ionized species, E-ring characteristics, airglow emissions, observationally-derived sputtering rates of the icy satellites, and the time dependence of all these features over the lifetime of the Cassini mission to better understand their interdependence.

UVIS does not have the appropriate channel to detect the strong OH emission band at 308 nm, but it is expected to map the distribution of the inferred large abundance of atomic oxygen. Solar flux driven fluorescence in OH does have an infrared and radio spectrum, but an investigation is needed to determine if it is possible for CIRS and/or VIMS to measure the spectrum. Combined measurements by CAPS, CDA, INMS, MAG, MIMI, and RPWS will map the distributions of neutral, charged and dust particles.

3.2.4. Coupling of the Outer Magnetosphere to Saturn’s Upper Atmosphere and Ionosphere, and Related Auroral Processes

The regions of the upper atmosphere and ionosphere of Saturn located poleward of approximately 70° latitude, which correspond to the auroral zones and polar caps, are characterized by a strong coupling with the magnetosphere. Magnetic field lines emerging from these regions connect them directly to the outer magnetosphere, which includes the magnetotail on the nightside, and to its boundaries with the solar wind. The upper atmosphere and magnetosphere continuously exchange significant amounts of charged particles, net electric currents, angular momentum and energy along these field lines. Magnetospheric energetic particles accelerated or scattered along them precipitate into the upper atmosphere, where they generate electromagnetic ‘auroral’ emissions in several wavelength ranges, mostly radio (through plasma mechanisms) before their arrival into the atmosphere, and UV (through collisional and thermal excitation of neutrals) after interaction with it. Conversely, a fraction of ionospheric ions and electrons is extracted from the ionosphere by thermal and non-thermal mechanisms and constitutes one of the many sources of magnetospheric plasma. Energy deposited into the upper atmosphere via auroral particle precipitation and the joule heating of magnetospheric currents closing through the ionosphere are an important element of the energy balance of Saturn’s upper atmosphere. This local energy deposition may have important
effects on the chemical composition of the upper atmosphere, and may also be partly redistributed toward adjacent latitude regions via the induced thermal neutral winds. Just like at Earth or Jupiter, auroral regions are the most important region of mass, momentum and energy coupling between the solar wind, the magnetosphere and the planet’s upper atmosphere and ionosphere. Understanding their dynamical behavior is therefore critical to a quantitative description of Saturn’s space environment.

Auroral emissions
Since auroral emissions are our main, though very indirect, source of information about Saturn’s auroral upper atmosphere, it is a key objective to establish their morphology, identify their generation mechanisms, and understand how they are controlled by the solar wind and/or internal magnetospheric drivers.

Morphology of UV emissions. Saturn’s UV auroral structures have been observed only by the Voyager 1 & 2 ultraviolet spectrometer (UVS) experiments in 1980–1981, plus a few times by IUE between 1981–1985 (in the range 115–390 nm) and by HST (FOC & WFPC2) since 1994. Voyager findings are reviewed in the Saturn book chapter by Atreya et al. (1984). Being slit spectrometers, Voyager/UVS and IUE did not have imaging capabilities (except through scanning). As a consequence, they could not provide an accurate mapping of the UV auroral structures, but only approximate and indirect morphological information, such as the dependence of the intensity of precipitations upon magnetic longitude (or SLS), and an estimate of the low-latitude limit of the northern and southern auroral zones. The geometry of the northern aurora was deduced from modeling of these UV observations, as two ovals at about 80° N & S latitude. HST provided a few high-resolution (~0.1”) images of auroral UV ‘hot spots’, on the morningside of the planet (Gérard et al., 1995; Trauger et al., 1998) (see Figure 27). The spectrum of UV aurora allows, in principle, a diagnostic of the nature and energy of precipitating particles. The energy of precipitating electrons is estimated to be in the 1–10 keV energy range, lower than in the case of Jupiter. An average auroral electron energy influx of 2 $10^{11}$ W between 78° and 81.5° in each hemisphere is required to account for the UVS measurements in the Lyman and Werner H$_2$ bands.

Taken together, all UV observations of Saturn’s aurora suggest that (i) they are weaker than at Jupiter (~1 order of magnitude), (ii) they are subject to high short-term variability (maybe a substorm-like activity?), and possibly (iii) there may be a gradual decrease of their activity over the 80’s and 90’s (seasonal effects), but the sparsity of observations does not allow a definitive conclusion.

Morphology of Auroral Radio emissions. Saturn’s kilometric radio emission (SKR) has been observed quasi-continuously for 6 months with Voyager 1 and 2’s Planetary Radio Astronomy experiment (PRA), measuring the flux and circular polarization of incoming waves (I and V Stokes parameters) in the range 1.2–
Figure 27. (a) Revised SKR source locations (Galopeau et al., 1995), projected onto Saturn cloud tops (dark gray-shaded). They include high latitude regions (>80°) about noon LT and extend toward lower latitudes on the morning sector (down to 60°), and possibly in the evening sector. Northern and southern sources appear magnetically conjugate. Earlier SKR source determinations are indicated (in red & green/gray lines = (Kaiser et al., 1981; Kaiser and Desch, 1982); in black lines [Lecacheux and Genova, 1983]), as well as ‘Voyager’ UV auroral ovals (in light blue/gray shading). (b) Hubble Space Telescope UV observations of the northern auroras confirm these results, revealing bright spots in the morning-to-noon sector (Trauger et al., 1998).
1326 kHz. This constitutes our main source of information on the physical characteristics of SKR, as summarized in the Saturn book chapter by Kaiser et al. (1984), and in (Zarka, 1998; and references therein). Complementary information at low-frequencies (∼56 kHz) was obtained by the plasma wave experiment (PWS) onboard Voyager (cf. Scarf et al., 1984). SKR is also detected on a regular basis, although with very low intensity, in the data from the unified radio and plasma wave experiment (URAP) on board Ulysses, allowing for the study of its long-term variations.

SKR is very intense, reaching a flux density of $10^{-19}$ Wm$^{-2}$ Hz$^{-1}$ from 1 AU range (1–2.10$^{-20}$ Wm$^{-2}$ Hz$^{-1}$ on the average – cf. Figure 28), which corresponds to a brightness temperature from over 10$^{15}$ to 10$^{19}$ K. It is thus of nonthermal origin. Its average spectrum covers a frequency range from ∼3 kHz to >1200 kHz, consistent with cyclotron emission from the vicinity of Saturn’s poles where $|B|$ ∼ 0.4 G. The spectral peak is localized between 100 and 400 kHz (depending on the LT of the observer), and the observed spectra present a slow decrease towards lower frequencies (<100 kHz) and a steep one at higher frequencies (>600–1000 kHz). The total radio power emitted on the average is ∼10$^9$ W, while the instantaneous value can be more than 1 order of magnitude above the average one.

SKR has been found to originate from the northern and southern auroral regions of Saturn’s magnetosphere. Higher frequencies and intensities are produced from the northern hemisphere, probably related to a magnetic field anomaly (discussed below). The observed SKR polarization is consistent with pure 100% circular polarization from each hemisphere (Right-Hand from the North and Left-Hand from the South), and thus corresponds to X mode emission. Stereoscopic studies using simultaneous observations by Voyager 1 and 2 (separated by ∼140°) showed that the SKR beaming is instantaneously narrow (at timescales <1 min.) and at large angle from the magnetic field in its source regions, but that the beam flickers in time and illuminates on the average a much broader beam ∼2π sr. More recent reanalysis of SKR polarization variations allowed a better description of the instantaneous beaming as a hollow cone with 60°–90° half-apex angle (the emission being beamed along the cone walls).

The high intensity of SKR requires a nonthermal, coherent generation process. The many similarities of SKR with the Auroral Kilometric Radiation of the Earth suggests that the same mechanism is operating in both cases (as well as in the other magnetized planets’ auroral regions). The best candidate generation process is the cyclotron-Maser instability (CMI) through which the free energy of unstable keV electron populations is directly converted into radio waves, with an efficiency of up to 0.1–1%. In strongly magnetized plasmas ($f_{pe}/f_{ce} \ll 1$) the emission is mainly produced on the X mode near the local $f_{ce}$, and beamed at large angle relative to the source magnetic field. The condition $f_{pe}/f_{ce} \ll 1$ is fulfilled at Jovian high latitudes due to the high magnetic field intensity there (several Gauss). At Earth, it is fulfilled only in the so-called ‘auroral plasma cavities’, where the Viking spacecraft revealed filamentary, underdense regions spread along magnetic field lines, the origin of
Figure 28. SKR dynamic spectra in Voyager/PRA LF range (1.2–1326 kHz). (a) One Saturnian rotation is displayed, with the abscissas labeled in longitude (SLS – increasing westward, with a rotation period of 10 h 39.4 min). Increasing darkness indicates increasing intensity. Data were recorded from close range (a few to a few tens of planetary radii). (b) SKR fine sporadic structures at Voyager/PRA best time resolution (30 ms). It consists here exclusively of spikes shorter than 6 s and narrower than 20 kHz.

which is still unclear. At Saturn, the rapid rotation confines the magnetospheric plasma in a low-latitude disk so that the condition $\frac{f_{pe}}{f_{ce}} \ll 1$ is fulfilled at high latitudes above the ionosphere even in the absence of any auroral cavity.

Variability and external control of auroral emissions
The SKR dynamic spectra (frequency-time images) are modulated by the planetary rotation. SKR sources appear to be fixed in LT and turned ‘On’ and ‘Off’ (or at least strongly modulated) along with the rotation of the planet. Maximum emission occurs when a so-called ‘active’ sector at longitude (SLS) $\sim 100^\circ–130^\circ$, of yet unknown nature, passes about noon LT. Monitoring of the SKR occurrence, performed over a few years with Ulysses/URAP whose high sensitivity permits Saturn to be detected from several AU distance, revealed apparent fluctuations of Saturn’s rotation rate at the 1% level (Lecacheux et al., 1997) which are certainly linked to long-term variations of the SKR source locations. SKR power was found to be tightly correlated with the solar wind fluctuations, and especially with its
ram pressure, as clearly demonstrated by the extinction of SKR during Saturn immersions in the distant Jovian magnetotail. No temporal variations were un­ambiguously found at intermediate timescales (tens to hundreds of hours), which correspond to Saturn ‘substorms’, if they exist, neither was there any clear indication of a control of SKR occurrence or intensity by a satellite (e.g., Titan, Dione). At shorter timescales, smooth SKR, modulated in arc-shaped structures and narrow frequency bands (Figure 28a), is sometimes replaced by sporadic, instantaneously narrowband emissions at timescales as short as 1 second or less (Figure 28b). These fine structures are less prominent than in the terrestrial and Jovian cases, and have never been systematically studied.

The fact that both auroral UV and radio sources are fixed in LT and the tight solar wind control of SKR power strongly suggest that the main driver of auroral activity is the solar wind. The location of the most active auroral sources on the dayside of the planet suggests that the solar wind/magnetosphere interaction occurs primarily at the dayside magnetopause. For this reason Galopeau et al. (1995) suggested that electron acceleration may result from the parallel electric fields of surface waves generated through a Kelvin-Helmholtz instability at the dayside magnetopause, excited by the velocity shear of the solar wind flow. Signatures of these waves have been observed by Lepping et al. (1981).

Estimated characteristics of precipitating particles
Significant constraints on the energy of auroral particles can be deduced from model studies of auroral emissions. A theoretical model of the SKR spectrum (Galopeau et al., 1989), in which a simplified description of the SKR source region was introduced, was very successful in reproducing the details of observed SKR spectra (averaged over ~1 hour) within the observed ranges of the plasma disk and ionosphere scale heights, and for a perpendicular energy of auroral electrons $E_{\perp} \sim 1$–5 keV (Zarka, 1992) (Figure 29). Model calculations of the auroral UV spectrum are consistent with this determination. They indicate that the energy of electrons responsible for the observed auroral H$_2$ Lyman and Werner band emissions is between 1 and 10 keV, and that the Saturnian auroral UV spectrum can be reproduced through direct products of the $e^+ + H_2$ process only.

Locations of auroral emission sources
Early studies based on SKR occurrence, occultations, and intensity variations, have shown that SKR sources are fixed in LT, close to noon, and located at high latitudes, in the vicinity of the polar cusps of the planet (at the limit between closed and open field lines). This latitude range, about 75°–80°, was approximately correlated with that of Voyager/UVS-based determinations of the UV auroral ovals. A reanalysis of SKR polarization variations along Voyager 1 and 2 trajectories allowed determination of the SKR source location more accurately, or a more exact definition of the maximum projections of SKR sources on the planetary surface. The northern and southern sources were both found at very high latitudes (~80°, i.e. higher
than at Jupiter and Earth) at 12–13 h LT, but with extents towards lower latitudes (60°–70°) about ~9 h LT and marginally about 18–19 h LT (Figure 27a). These sources thus extend over L-shells of 4 to 130. Although constrained independently, the northern and southern sources appear magnetically conjugate on the average. Recent UV observations of Saturn’s northern aurora by the HST, displayed in Figure 27b, revealed bright spots closely matching the above radio source locations, i.e. dominantly on the morning side with latitude extents lower than 80°. The reason why ‘active’ LT seems to correspond to lower latitudes is unexplained.

In view of the Cassini tour, the regions of interest for auroral studies correspond, in projection onto the planetary surface, to the ‘Voyager’ auroral ovals at ~76°–82° plus the new SKR sources (at slightly higher latitude at 12 h–13 h LT, and including their lower latitude extents, especially on the morningside). In 3-D, these regions extend along magnetic field lines from the planetary surface up to ~5 Rs, which corresponds to the lowest observed SKR frequencies. SKR (and possibly also UV) sources are active only/mainly when the ‘active’ longitude sector ~100°–130°, of yet unknown nature, passes about noon LT.

Effects of auroral phenomena on Saturn’s upper atmosphere
Auroral phenomena are the source of intense energy deposition into Saturn’s upper atmosphere. As a result of this heat input the temperature in the upper atmosphere...
reaches \( \sim 600-800 \) K, much higher than the value that can be reached from solar UV heating only (\( \sim 200 \)). An estimated heat influx of \( \sim 3 \times 10^{-4} \) Wm\(^{-2} \) is required to heat the upper atmosphere to that temperature. Auroral electron precipitation is a possible heat source, as the estimated average precipitated power of \( 2 \times 10^{11} \) W in the northern and southern auroral regions represent \( \sim 6-9 \times 10^{-4} \) Wm\(^{-2} \). In the form of 1–10 keV electrons, these precipitations generate an exospheric temperature of 1600 to 650 K between 1500 km and 900 km (above the 1-bar level). Auroral energy deposition thus appears to be an important source of heating in Saturn’s high latitude thermosphere, but it cannot make a significant contribution to the heating of the entire thermosphere/exosphere region (unlike at Jupiter), even if the atmospheric circulation is able to distribute this energy with 100% efficiency over the entire planet. Joule heating, related to ionospheric electric currents via the Pedersen conductivity, is another candidate heat source (as at the Earth and Jupiter) which could provide half the required flux. The transfer of energy to the thermosphere is caused in this case by ion/neutral gas friction due to the \( \sim 10\% \) departure from corotation of the plasma in the outer magnetosphere beyond \( \sim 8 \) R\(_S\) (see Figure 15).

Auroral precipitations can also modify the composition of the auroral thermosphere, although on Saturn they do not seem to influence the global distribution of H atoms (while they cause a depletion at Jupiter). It is not clear if these modifications are of chemical or dynamical origin, as precipitations also influence the thermo-stratospheric circulation (winds, eddies, turbulence). Observations and circulation modeling favor the latter at Jupiter, where supersonic winds have been detected, and where thermospheric perturbations extend towards lower (non-auroral) latitudes. No information is yet available at Saturn.

Auroral precipitations are also responsible for the production of ‘polar hazes’. They emit in the near UV (\( \sim 200 \) nm), but strongly absorb the FUV reflected solar flux, and thus allow the detection of auroral FUV features. The generation mechanism for the polar haze observed at Saturn, whose spatial extent and variability are not well documented yet, is not understood. It may consist of enhanced reactivity of collision-produced hydrocarbon ions, or enhanced vertical mixing (deep-atmosphere species brought to surface).

**Key scientific questions and MAPS investigation strategy**

In spite of the Voyager, IUE, HST and Ulysses observations, our present knowledge of Saturn’s auroral zones remains poor, and the key questions regarding them are still very basic:

1. What is the detailed spatial distribution of auroral UV, IR and radio emissions, and their temporal variability at the different scales and what does it tell us about their possible control by external (solar wind) and internal (storms and substorms) processes?

2. What are the dominant ionosphere/magnetosphere coupling and particle acceleration mechanisms along auroral field lines?
(3) What role does the auroral upper atmosphere play in the regulation of magnetospheric plasma flows and the coupling of Saturn’s environment to the solar wind?

(4) What are the effects of auroral particle, momentum and energy deposition on the energy balance, dynamics and chemical composition of Saturn’s upper atmosphere?

An appropriate investigation strategy for MAPS to address these four questions must be two-fold:

- Advantage needs to be taken of the long duration of the mission to conduct a continuous monitoring (as much as possible) of the main auroral emissions, and of all airglow emissions that can provide information on the response of Saturn’s upper atmosphere to auroral energy input. This monitoring will be based on the continuous survey mode of RPWS and on the best possible coverage of auroral emission features in the UV and IR ranges. Additional observations of these emissions from Earth’s orbit, if carefully designed, will be an important contribution.

- Plan intense campaigns of *in situ* investigations of auroral magnetic field lines and particle acceleration regions during the very short periods of encounters with these field lines at high magnetic latitudes. As Figure 33 shows, the planned tour presently offers two such periods, one 23 to 25 months after SOI, corresponding to encounters with SKR generation regions, one 37 to 44 months after SOI during which the nightside auroral field lines will be crossed. The total observing time for these encounters will be very limited (a few hours throughout the mission), so we expect that MAPS investigations will be granted a high level of priority during these encounters, which will have to be planned just as carefully as a satellite encounter, for instance, considering the unique opportunity they offer for an *in situ* investigation of auroral processes.

The continuous remote sensing survey of auroral emissions will make it possible to cover all the relevant time scales in auroral variability, and to provide constraints on auroral emission control by the solar wind and internal magnetospheric processes. For instance the long periods of time spent by the spacecraft in the solar wind will be an ideal opportunity to study its influence. Similarly, large-scale dynamical phenomena studied in situ by the plasma and wave instruments will be correlated with auroral emission variations.

Many critical measurements can be performed during the crossing of the auroral zones and SKR generation regions, such as for instance:

- The nature and energy of precipitating particles causing UV and radio emissions.

- The search for faint UV/IR auroral emissions spots which could reveal satellite/magnetosphere electrodynamic interactions.

- Measurements of charged particle distribution functions: are they adequate for SKR generation, through CMI, and what do they imply in terms of precipitating/escaping charged particle sources and acceleration processes?
- Measurements of the level of wave electric fields in auroral regions: what constraints do they imply on SKR saturation levels? Is the level of electrostatic turbulence high?
- Measurements of radio wave polarization and beaming close to the SKR sources: is the polarization more linear than far from the source (propagation should circularize it)? Is the cone beaming angle smaller at high frequencies, as predicted by the theory?
- Are there auroral cavities (or filamentary cavities) in Saturn’s auroral regions?
- Radio direction-finding results at highest SKR frequency should help to locate accurately the HF SKR sources: do they correspond to the magnetic anomaly inferred by Galopeau and Zarka (1992)?
- Is the ‘active’ region at 100°–130° SLS a magnetic anomaly?

3.2.5. Coupling with the Solar Wind and the Hydrogen Torus in the Outer Magnetosphere

As for any other magnetosphere, Saturn’s magnetospheric structure, dynamics and energetics are determined by the combined effect of external forcing by the solar wind and internal forcing by planetary rotation, and the other internal sources of plasma and momentum. The Saturn case is particularly complex, because each of these factors is in a sense uniquely different. The solar wind, whose effect is particularly important in the outer magnetosphere, has quite different characteristics at Saturn than at Earth. Its density is much lower, the magnetic field magnitude is smaller, and the nominal Parker spiral gives a magnetic field that is almost completely azimuthal, with an angle of 85° of its direction to the Saturn-Sun direction. Its effect must combine with those of the internal plasma and momentum sources. In the outer magnetosphere, the dominant internal source is the neutral hydrogen torus. We focus in this section on the interactions between the solar wind, the magnetospheric plasma flow and this hydrogen torus.

The contribution of MHD simulations

With the development of advanced MHD simulation techniques, it has recently become possible to try to anticipate the dynamical behavior of Saturn’s magnetospheric system under a variety of solar wind conditions. Hansen et al. (1999) published a series of MHD simulations on this subject. The model used a state-of-the-art numerical code that solves the ideal MHD equations. This simplified model has been successful in providing a clear picture of global dynamics for various plasma flows.

The set of basic equations, the parametric description of plasma sources and sinks and the boundary conditions used are described in Hansen et al. (1999). The magnetic field model used is a pure dipole aligned with the rotation axis. In order to emphasize and understand the effects specifically associated with the hydrogen torus, the only included plasma source is the one produced by this torus. The system of MHD equations has been solved for three different IMF conditions that are
representative of the many possible configurations: southward, $\mathbf{B}_{sw} = (0,0,-B)$; northward, $\mathbf{B}_{sw} = (0,0,+B)$; and Parker spiral, $\mathbf{B}_{sw} = (-0.1 B,0.995 B,0)$, where $B$ is the magnitude of the interplanetary magnetic field ($B = 0.5$ nT in the simulation). Figure 30 shows the calculated steady-state distributions of mass, density and plasma flow vectors in the equatorial plane for the three values of the IMF considered. In each panel the filled circles represent the $3 \text{ Rs}$ surface at which boundary conditions were applied, and the other circles indicate the assumed inner and outer boundaries of the neutral torus.

Southward IMF. Since Saturn’s magnetic dipole has the opposite polarity from the Earth, the magnetospheric configuration for a southward IMF at Saturn is very similar to that at Earth for a northward IMF. The magnetic field lines are open to the solar wind magnetic field only over the small region occupied by the cusp and the closed magnetosphere extends approximately 125 Rs downstream, in a configuration very similar to Earth. The corotation flow of the near Saturn region interacts with the incident solar wind driven magnetospheric convection to create a stagnation region on the dawn side of the magnetosphere. The plasma resulting from the neutral torus builds up, creating a region of high density plasma near the equatorial plane with a peak value of nearly 14 times the solar wind mass density. A separatrix, located nearly along the outer boundary of the Titan torus in the dusk to midnight quadrant, separates circulating corotation flow from solar wind dominated flow. The structure of the flow and the location of the separatrix for this case seem to match the picture of Jupiter’s magnetosphere given by Vasyliunas (1983), although he gives a location for the x- and o-lines which do not exist for this steady state configuration. The density maximum in the noon-midnight meridian plane extends from roughly $L = 10$ to $L = 25$ and has a half thickness of 7 Rs, corresponding reasonably well to the extended plasma sheet measured by Voyager, although slightly larger and with a slightly higher density than measured.

Northward IMF. As expected, the magnetic field configuration for this case is also very similar to the corresponding case for Earth (e.g., southward $B_z$). There is a clear x-line located at 20 Rs that represents reconnection of the open magnetospheric field lines on the day side while at the same time a large region of the polar cap is open to the solar wind. The plasma density and velocity field for this case are quite different from the previous southward IMF case. There are now two stagnation regions, one to the dawn side and one to the dusk side. In each of these regions the flow is slowed and plasma density from the torus is allowed to build up. The locations of the peaks in density are nearly symmetric. On the dusk side the density peaks at 3.8 times the upstream density while on the dawn side the peak value is 2.5 times the density in the incident solar wind. The extended plasma torus can still be seen for this case, although the densities are lower and the half height is smaller. For this case, the separatrix between corotation flow and anti-solar flow is much more pronounced than for the southward IMF case. The separatrix is very
Figure 30. Calculated distributions of the plasma densities (left panels) and of the equatorial projections of the velocity field (right panels) in Saturn’s equatorial plane, as determined in the ideal MD simulation of Hansen et al. (1999) for three different IMF conditions: southward IMF (top), northward IMF (middle) and Parker spiral (bottom panels).
nearly a line located approximately 19 Rs down the tail, and falls very close to the x-line associated with the magnetic field reconnection.

**IMF along the Parker Spiral.** A Parker spiral IMF at the radius of Saturn is almost entirely azimuthal. This fact, combined with the planetary rotation, eliminates any of the near symmetries that existed for the previous IMF configurations, and so field lines and stream traces are not confined to planes. Even though this case is much more complicated, the magnetic field structure is very similar to that of the Earth for a Parker spiral IMF. The interaction region between solar wind driven magnetospheric convection and the corotation flow for this case is quite similar to that for the northward IMF case. There are again two stagnation regions, one on the dawn side and one on the dusk side of the magnetosphere with the dusk side having the higher mass density. The peak values are 4.7 and 5.6 times the upstream density. The extended plasma torus can again be seen for this case. The densities are intermediate between the first two cases and the size is also somewhere between the two. As in the northward IMF case, the separatrix is very nearly a line located approximately 20 Rs down the tail, and corresponds closely to the x-line associated with the magnetic field reconnection.

Figure 30 clearly shows the differences in magnetospheric structure for different IMF configurations. As is expected, the magnetic field structure seems very similar to the Earth while the velocity and plasma density fields are quite distinct from Earth and vary with IMF orientation. The flow structure for southward IMF follows the diagram given by Vasyliunas (1983) for Jupiter, but even for this case, the steady state structure does not match his picture exactly. For the other IMF orientations, a completely different and more complicated structure exists. In essentially all cases, corotation is seen to dominate out to at least 12 Rs from Saturn.

**Key scientific questions and MAPS investigation strategy**
The results of this simulation give us a first idea as to the large-scale distributions of plasmas and flows in the outer magnetosphere, and on their variability under changing solar wind conditions. They suggest that with the combined use of such simulations and the analysis of Cassini observations it will be possible to address the key questions concerning the dynamical behavior of the outer magnetosphere:

1. What is the importance of ion pick-up from the hydrogen torus as an internal source of magnetospheric plasma, and how does it operate at the microscopic and macroscopic scales?

2. How does ion pick-up compete with the other sources of plasma and momentum, namely the solar wind, Saturn’s ionosphere and planetary rotation, to determine the overall configuration of plasma distribution, composition and flow in the outer magnetosphere? How does this configuration vary with changing solar wind conditions?

To help us address these questions, observations should ideally provide:
- the large-scale distribution of the bulk parameters of the different components of the plasma in terms of moments of the electron gas and of the different ion species, derived from the particle instruments (CAPS and MIMI);
- direct measurements, or at least some constraints, on the main plasma sources: ionosphere and neutral gas tori (see previous sections);
- monitoring of the auroral upper atmosphere’s UV, radio and other emissions, to provide indications on the amount of energy deposited into the atmosphere and on its variability;

Detailed information on the ion mass distribution and chemical composition as a function of energy, and on the velocity-space distribution functions of the electrons and of the main ion species, as well as spectrograms of the local plasma wave modes, will also have to be acquired regularly to study the non-MHD aspects of the plasma dynamics.

The large fraction of time spent in the magnetosheath or in the free solar wind must be used to monitor their plasma flow characteristics. As seen from the MHD simulation (Figure 30), it will be very important to describe how the magnetosheath plasma flow connects to the internal magnetospheric flow through the magnetopause. In addition, a systematic monitoring of the variability of the free solar wind and of the response of auroral emissions to its variation will be an important ingredient in evaluating the degree of control of the solar wind on the auroral ionosphere. This can be done by combining in situ measurements of the solar wind with remote sensing of the auroral emissions and ionospheric densities.

Combining in situ and remote sensing measurements will indeed be one of the key elements of the MAPS investigation strategy, making it possible to permanently place the detailed analysis of local plasma and field characteristics in the broader context of the observation of the large-scale features of the main plasma reservoirs. The other key element is the implementation of a MAPS survey mode, providing continuous monitoring of the plasma and field characteristics throughout the tour at an appropriate temporal (and therefore also spatial) sampling rate. Continuity of data acquisition through the implementation of this mode is certainly one of the most important requirements of magnetospheric and plasma science.

4. Magnetosphere and Plasma Science with the CASSINI Instruments and Orbital Tour

Some of the outstanding scientific questions about Saturn’s magnetosphere and its coupling to the Saturn system have been introduced and discussed in the previous section. The CASSINI-HUYGENS mission offers two major key advantages to solve these questions, and certainly to open a large number of new ones, which we just cannot anticipate with our limited knowledge of the Saturnian system today: we expect to make real discoveries! The first advantage is the CASSINI orbital tour, which will effectively cross most or all of the magnetospheric regions of
4.1. EXPLORATION OF SATURN’S MAGNETOSPHERIC REGIONS BY THE CASSINI ORBITAL TOUR

The geographical coverage of the different regions of the magnetosphere by the tour is the first key ingredient of a MAPS strategy. Figure 31 displays a schematic break-down of the Saturnian magnetosphere into regions, and Table VIII indicates the name of each region, its geometric definition, and the percentage of time spent by the CASSINI spacecraft in the different domains along the presently selected nominal tour, tour T 18.5 (Wolf et al., this issue). A first comment is that only 53%
TABLE VIII

Definition of the different magnetospheric regions used in the Tour evaluation

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Residence time</th>
<th>Nominal tour</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSIDE MAGNETOSPHERE</td>
<td>53%</td>
<td>R-0 Innermost Magnetosphere</td>
<td>1%</td>
<td>L &lt; 5</td>
</tr>
<tr>
<td></td>
<td>R-1 Inner Magnetosphere</td>
<td>2%</td>
<td>5 &lt; L &lt; 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-2 Middle Magnetosphere</td>
<td>6%</td>
<td>8 &lt; L &lt; 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-3 Outer Magnetosphere</td>
<td>35%</td>
<td>L &gt; 15, X &gt; -30 Rs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-5 Tail Lobes</td>
<td>6%</td>
<td>L &gt; 15, X &lt; -30 Rs,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-6 Tail Plasma sheet</td>
<td>3%</td>
<td>L &gt; 15, X &lt; -30 Rs,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aur. Auroral Regions</td>
<td>~75 h</td>
<td></td>
<td>[</td>
</tr>
<tr>
<td></td>
<td>SKR SKR generation Regions</td>
<td>~4 h</td>
<td></td>
<td>[</td>
</tr>
<tr>
<td>OUTSIDE MAGNETOSPHERE</td>
<td>47%</td>
<td>MSH Magnetosheath</td>
<td>36%</td>
<td>Between magnetopause and shock</td>
</tr>
<tr>
<td></td>
<td>SW Solar Wind</td>
<td>11%</td>
<td>Outside the planetary shock</td>
<td></td>
</tr>
</tbody>
</table>

of the nominal tour time (extending over 44 months) is spent inside our ‘model’ magnetosphere, and 47% outside of it, including 36% in the magnetosheath and 11% in the free solar wind. The magnetosphere itself, for the purpose of mission planning, has been divided into 8 different domains. Domains R-0 to R-2 correspond to closed-field-lines, approximately symmetric regions around Saturn’s magnetic dipole axis. Regions R-0 and R-1 correspond approximately to the inner torus, and R-2 to the extended plasma sheet. Domain R-3, which excludes the magnetotail, corresponds to the outer magnetosphere. The boundary between the outer magnetosphere and the magnetotail has been defined as a plane orthogonal to the Sun-Saturn axis passing through the tail hinge point, located 30 Rs from Saturn in its equatorial plane in the midnight meridian. Located on the nightside of this boundary, the magnetotail is finally divided into its lobes (domain R-5) and its plasma sheet, which has been given an arbitrary extension of 5 Rs in either direction along the Z axis from the Z value of the hinge point. Finally, the auroral field lines domain has been defined as the regions of magnetic latitude larger than 70°, and closer than 5 Rs to the planet’s center. This very schematic magnetospheric geometry was defined by the MAPS working group to assist in the evaluation of
TABLE IX
Exploration of the main magnetospheric regions during the CASSINI nominal Tour

<table>
<thead>
<tr>
<th>Time in tour (Months)</th>
<th>Geometric Configuration</th>
<th>Magnetoospheric regions More particularly explored</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI</td>
<td>Passage above and through ring plane</td>
<td>Inner most magnetosphere, magnetically connected to the main rings</td>
</tr>
<tr>
<td>0–6</td>
<td>First orbits: Low inclination, high apoapsis</td>
<td>Dawnside equatorial magnetosphere</td>
</tr>
<tr>
<td>6–10</td>
<td>Medium inclination orbits dawn side</td>
<td>Middle and low latitude dawnside magnetosphere</td>
</tr>
<tr>
<td>10–14</td>
<td>Equatorial orbits. Rotation towards the nightside</td>
<td>Equatorial dawnside to nightside magnetosphere</td>
</tr>
<tr>
<td>14–22</td>
<td>Elongated orbits with Apoapsis on the nightside</td>
<td>Encounters with the tail plasma sheet</td>
</tr>
<tr>
<td>23–25</td>
<td>High inclination orbits</td>
<td>SKR generation regions and auroral zones</td>
</tr>
<tr>
<td>25–32</td>
<td>180° transfer from nightside to afternoon</td>
<td>Afternoon midlatitude magnetosphere</td>
</tr>
<tr>
<td>32–37</td>
<td>Low inclination orbits, apoapsis in the afternoon</td>
<td>Low latitude afternoon magnetosphere</td>
</tr>
<tr>
<td>37–44</td>
<td>High inclination orbits with apoapsis near noon</td>
<td>Nightside auroral zones</td>
</tr>
</tbody>
</table>

The candidate tours, and in order to check how and whether they fulfilled the MAPS tour requirements deduced from the different science objectives.

The presently selected tour, T 18.5, does a reasonably good job of satisfying most of these requirements, making it possible to explore the magnetosphere as a whole, as well as most of its key regions. Table IX proposes a segmentation of this tour into different periods corresponding to different properties of geographical coverage of the magnetosphere. Time is counted in months from SOI, and limited to the nominal tour duration. The variations in orbit configuration (central column) make it possible to successively explore the different regions indicated in the right-hand-side column of the table. In addition to the partial coverage of the middle and low latitude magnetosphere, which is achieved reasonably well by the progressive clock-wise rotation of the orbit orientation around Saturn, a few segments of the tour, corresponding to short explorations of very specific regions of high interest, need to be specifically pointed out. They are:

- the Saturn Orbit Insertion sequence (SOI), which will be our unique opportunity to explore the region of the inner magnetosphere which is magnetically connected to the rings system, and to measure Saturn’s magnetic field very close to the planet;
the segment between 14 and 22 months, which includes all the encounters with the tail plasma sheet;
- the short segment between 23 and 25 months, which includes the first period of encounters with the auroral field lines, and probably the only opportunities to cross or come close to the SKR generation regions;
- and, finally, a second period of high-inclination orbits, near the end of the mission, which will be the best opportunity to explore the nightside auroral zones.

Due to the high apoapsis of most of the orbits, the tour also offers many opportunities to explore the magnetopause and study its dynamics under the effect of variations in solar wind and/or in the magnetosphere. Figure 32, using the model magnetopause surface of Maurice and Engle (1995) shows the locations of the nominal inbound and outbound crossings for the dawn and dusk halves of the surface. As one can see, there will be essentially near-equatorial crossings on the dawn side, but a broader latitudinal exploration of the magnetopause on the dusk side and near noon.

As explained in section 3.2.4, the few hours spent inside the auroral zones and the SKR generation regions during the whole tour will be of outstanding interest for MAPS objectives. Figure 33 shows the locations of the footprint of the spacecraft, projected along Saturn’s magnetic field lines, during these short encounters with the auroral regions. One sees that, in the presently planned tour, field lines will be explored up to invariant latitudes of nearly 85 degrees. The local time coverage, though not complete, is reasonable as a consequence of the two different encounter periods (see Table IX). It is absolutely essential to preserve the relatively good quality of this encounter geometry through all possible adjustments of the tour.

4.2. CONTRIBUTIONS OF MAPS INSTRUMENTS TO THE DIFFERENT SCIENCE AREAS

The second key element in the MAPS investigation strategy is the combined operation of an outstanding suite of instruments. The instrument suite of interest to MAPS, which is summarized in Table X, allows the measurements of the electric and magnetic field (via RPWS and MAG), the plasma distribution functions of ions and electrons (via MIMI and CAPS) over a broad range of energies and consequently the flow velocities of each ion component, the dynamic spectra of plasma waves and radio emissions (RPWS), and even an energetic neutral atom (ENA) imaging capability which will provide global pictures of the plasma reservoirs in the inner magnetosphere and of the Titan/magnetosphere interaction, the INCA sensor of the MIMI investigation. In addition, the orbiter carries an ion and neutral mass spectrometer (INMS) and a radio science subsystem (RSS); the RSS will provide information on the ionospheres of Saturn and Titan while the INMS instrument will be mainly used to study the structure and composition of Titan’s interaction with Saturn’s magnetosphere. The Cosmic Dust Analyzer (CDA) will
Figure 32. Distribution of nominal magnetopause crossings along the T 18.5 tour on the dawn (upper panel) and dusk (lower panel) halves of the magnetopause, calculated using the model magnetopause of Maurice and Engle (1995) for a magnetopause ‘nose’ distance of 23 Rs along the X axis.
provide direct observations of particulate matter in the Saturnian system (CDA),
and the Ultraviolet Imaging Spectrograph (UVIS) will be a key instrument to study
the upper atmospheres of Titan and Saturn, the neutral gas tori, airglow and auroral
emissions. Detailed descriptions of each of these investigations are found in the
corresponding articles of this issue.

One of the important characteristics of this instrument suite for MAPS is its
ability to measure the three components of the electric and magnetic fields over a
broad frequency range, as shown in Figure 34. Thanks to some overlap between the
MAG instrument and the RPWS search coils, the magnetic field can be measured
over a frequency range from quasi-static to 12 kHz. The electric field measurements
are made over a frequency range from 1 Hz to 16 MHz. This will allow the studies
of the electromagnetic field with CASSINI to cover a broad range of interests,
from the study of Saturn’s internal structure through the monitoring of the d.c.
component of the magnetic field near the planet, to the analysis of SKR emissions,
and through the detailed study of the different electrostatic and electromagnetic
emissions generated in Saturn’s magnetosphere.
TABLE X
Cassini Science Investigations directly related to MAPS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPS</td>
<td>Cassini Plasma Spectrometer (D. T. Young) Measures composition, density, velocity and temperature of ions and electrons</td>
</tr>
<tr>
<td>CDA</td>
<td>Cosmic Dust Analyzer (E. Grün) Measures flux, velocity, charge, mass and composition of dust and ice particles from $10^{-16}$ to $10^{-6}$ g</td>
</tr>
<tr>
<td>INMS</td>
<td>Ion and Neutral Mass Spectrometer (J. H. Waite) Measures neutral species and low-energy ions</td>
</tr>
<tr>
<td>MAG</td>
<td>Dual Technique Magnetometer (D. Southwood) Measures the direction and strength of magnetic field</td>
</tr>
<tr>
<td>MIMI</td>
<td>Magnetospheric Imaging Instrument (S. M. Krimigis) Images Saturn's magnetosphere using energetic neutral atoms plus measures the composition, charge state and energy distribution of energetic ions and electrons</td>
</tr>
<tr>
<td>RPWS</td>
<td>Radio and Plasma Wave Science (D. A. Gurnett) Measures wave emissions plus electron density and temperature</td>
</tr>
<tr>
<td>RSS</td>
<td>Radio Science Subsystem (A. J. Kliore) Measures the density of Saturn's ionosphere</td>
</tr>
<tr>
<td>UVIS</td>
<td>Ultraviolet Imaging Spectrograph (L. W. Esposito) Measures ultraviolet emissions to determine sources of plasma in Saturn's magnetosphere</td>
</tr>
</tbody>
</table>

The remarkable MAPS capability of the mission can also be appreciated through the energy and direction-of-arrival coverage of the different types of particles encountered in the Saturnian environment along the CASSINI orbit provided by the particle instruments. CASSINI will indeed offer a very broad access to the three types of particles of interest, electrons, ions and neutrals, with the capability of separating ions and neutrals of different masses and even, in the case of the IMS sensor of CAPS, some access to the identification of the different chemical species. In addition, the RPWS Langmuir probe will provide electron density and temperatures of ionospheric plasmas and should work reasonably well near the icy satellites as well as the inner plasma sheet. The RPWS sounder should also provide an independent electron density measurement.

Cassini will also have access to the dust component of Saturn's environment, not only through the CDA, but also through RPWS. While the RPWS measurements do not include composition and can only crudely determine mass, they use the entire spacecraft as a target and should be able to do a reasonable job of measuring the dust flux of micron-sized and larger particles, regardless of spacecraft orientation.

The energy coverage of the CASSINI particle instruments can be seen in Figure 35. Thanks to some overlap of their energy range, the particle instruments provide a continuous coverage from about 0.010 eV to about 18 MeV (ions),
10 MeV (electrons) and 3 MeV (neutrals). They will thus allow the study of a very broad range of particle populations and their dynamics.

These instruments also have remarkable capabilities in terms of coverage of the velocity space of each particle species, by a combination of the 1-D or 2-D fields of views of the different sensors in velocity space with the additional orientation flexibility provided by turntables or actuators attached to the particle instruments.

The field of view (FOV) of the CAPS, INMS, MIMI and UVIS experiments is shown in Figure 36. The CAPS sensors (IMS, IBS and ELS) are mounted on a turntable, which through a windshield-wiper type motion around the spacecraft Z-axis allows the instruments to enlarge their FOV in the azimuthal direction. The MIMI LEMMS sensor is also mounted on a turntable, which provides a continuous rotation around the spacecraft Y-axis, allowing thus a complete coverage in elevation.

The FOVs shown in Figure 36 take into account the turntable rotations. As can be seen, the particle instruments onboard Cassini provide a good coverage of velocity space. When the spacecraft is in a spin mode, then the azimuthal coverage becomes complete (360°) over one spacecraft rotation (23 minutes), thus allowing
Figure 35. Energy range of the Cassini particle instruments for the different particles detected (ions, electrons, neutrals).

Figure 36. FOV (Field of View) of the CAPS, INMS, MIMI and UVIS experiments, with respect to the spacecraft body-built coordinate system. HGA corresponds to the High Gain Antenna.
one to retrieve the 3-D distribution functions of each particle species, averaged over this time interval, when temporal/spatial conditions in the medium allow.

Taken together, one of the remarkable properties of the MAPS instrument suite is that it combines local measurements along the orbit, providing a detailed but local analysis of the medium encountered, with remote sensing observations of the regions or components of key interest. As an illustration of this point, Table XI shows, for some of the most important topics of MAPS science, which instruments contribute to the local measurements or to the remote sensing measurements. It is quite remarkable that many of them, such as RPWS and MIMI for instance, contribute to both aspects.

### 5. Conclusions

Magnetospheric and plasma science in the Saturn system offers the unique opportunity to explore in depth particularly interesting examples of two types of magnetospheres: the ‘induced’ magnetosphere generated by the interaction of Titan with the surrounding plasma flow, and Saturn’s ‘intrinsic’ magnetosphere, the magnetic cavity generated by Saturn’s magnetic field interaction with the solar wind flow. This in-depth exploration of these two objects, conducted with the help of the most advanced and diverse package of instruments for the analysis of plasmas, energetic particles and fields ever flown to a planet, will make it possible to address and solve a series of key scientific questions concerning the interaction of these two magnetospheres with their environment.

During the more than 44 fly-bys of Titan planned over the duration of the mission, the key scientific questions will address two main topics:

<table>
<thead>
<tr>
<th>Plasma populations</th>
<th>Local measurements</th>
<th>Remote sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fields and waves</td>
<td>MAG, RPWS</td>
<td>RPWS</td>
</tr>
<tr>
<td>Dust/Plasma interactions</td>
<td>CDA, CAPS, MIMI</td>
<td></td>
</tr>
<tr>
<td>Neutral atmos./clouds</td>
<td>INMS, UVIS</td>
<td>UVIS</td>
</tr>
<tr>
<td>Ionospheres</td>
<td>INMS</td>
<td>RSS</td>
</tr>
<tr>
<td>Auroral emissions</td>
<td>RPWS, UVIS, VIMS, ISS</td>
<td></td>
</tr>
<tr>
<td>Ring/Plasma interactions</td>
<td>ISS, MIMI</td>
<td></td>
</tr>
</tbody>
</table>
5.1. TITAN’S IONOSPHERE

- What is the average morphology of Titan’s ionosphere and how is it determined by its coupling with Titan’s neutral atmosphere and with magnetospheric particles and fields?
- What is the variability of this ionosphere, and to what extent is it controlled by magnetospheric effects (importance and variability of energetic charged particles as plasma sources, of its magnetization by the surrounding plasma flow, etc.)?
- How important are the different escape processes from Titan’s upper atmosphere and ionosphere, in the neutral or ionized phases, in the balance of magnetospheric plasma sources and for the long-term evolution of Titan’s upper atmosphere?

5.2. TITAN/MAGNETOSPHERE INTERACTIONS

- What is the basic geometry of the interaction of Titan’s atmosphere with Saturn’s magnetized plasma flow?
- How does it vary with changing conditions in the upstream flow characteristics and with the geometry of local ionization sources?
- Is there a detectable intrinsic magnetic field at Titan, and if so what constraints does it provide on its internal structure?

Thanks to its broad coverage of the main magnetospheric regions, the 4-year tour of the Saturnian system will make it possible to study a magnetosphere which is in strong interaction with all other components of Saturn’s environment. The analysis of the broad diversity of these interaction processes will be one of the main themes of MAPS science during the Cassini mission. We have shown in this article how it can be naturally divided into several interaction domains, which roughly coincide with different regions of the Saturnian system, and what are the key scientific questions related to these interaction domains:

5.3. RINGS/PLASMA/IONOSPHERE COUPLING

- What is the net exchange of plasma, neutral species and dust particles between the rings, Saturn’s ionosphere and its inner plasmasphere, and what effect does this exchange play in the maintenance of the ionosphere and the evolution of the rings?
- What are the mechanisms responsible for the formation of spokes on Saturn’s main rings?
5.4. MAGNETOSPHERE/ICY SATELLITES INTERACTIONS

- Can we determine the surface composition of the icy satellites during close CASSINI fly-bys from CAPS and MIMI data?
- What are the modes of interaction between Saturn’s magnetospheric plasma flow and the icy satellites, and how do they depend on the net contribution to ion pick-up, the internal structure and conductivity, and possibly the state of magnetization of these satellites?

5.5. MAGNETOSPHERIC INTERACTIONS WITH THE INNER NEUTRAL GAS TORUS AND THE \textit{E} RING

- Can we quantitatively understand the observed distribution of neutral and ion species in the inner torus from the balance of plasma generation, loss and radial transport?
- Does it provide constraints on poorly known quantities, such as the sputtering rates of water products from the icy satellites surfaces and from the \textit{E} ring, or the key reaction rates along the chemical and photochemical paths?

5.6. COUPLING OF THE OUTER MAGNETOSPHERE TO SATURN’S UPPER ATMOSPHERE AND ASSOCIATED AURORAL PROCESSES

- What is the detailed spatial distribution of auroral UV, IR and radio emissions, and their temporal variability at the different scales and what does it tell us about their possible control by external (solar wind) and internal (storms and substorms) processes?
- What are the dominant ionosphere/magnetosphere coupling and particle acceleration mechanisms along auroral field lines?
- What role does the auroral upper atmosphere play in the regulation of magnetospheric plasma flows and the coupling of Saturn’s environment to the solar wind?
- What are the effects of auroral particle, momentum and energy deposition on the energy balance, dynamics and chemical composition of Saturn’s upper atmosphere?

5.7. COUPLING WITH THE SOLAR WIND AND THE HYDROGEN TORUS IN THE OUTER MAGNETOSPHERE

- What is the importance of ion pick-up from the hydrogen torus as an internal source of magnetospheric plasma, and how does it operate at the microscopic and macroscopic scales?
- How does ion pick-up compete with the other sources of plasma and momentum, namely the solar wind, Saturn’s ionosphere and planetary rotation, to determine the overall configuration of plasma distribution, composition
and flow in the outer magnetosphere? How does this configuration vary with changing solar wind conditions?

At the time of writing this article, the CASSINI spacecraft is flying past Jupiter towards Saturn, after its successful encounters with Venus and our Earth. All teams are now focusing their efforts on our joint goal, namely to plan and achieve a very successful mission, which will unravel some of the most fascinating mysteries of Saturn. As we fly towards Jupiter, to encounter it and then make our final turn toward Saturn, no doubt each of us dreams of the time, a few years down the road, when Saturn, Titan and their gas and plasma environments are going to appear more and more distinctly in our imagers. Figure 37, a synthetic view of the Saturn-Titan system as it will be seen by the MIMI/INCA imager, gives us a first idea of what we expect to see when we finally reach the spacecraft’s destination. Then the time will come to start to explore, discover and understand new and exciting phenomena. We hope that this article will have convinced the reader that Magnetospheric and Plasma Science, in strong interaction with all other disciplines, is going to play a major role in this exciting scientific endeavor.

Appendix A

MODELS OF SATURN’S MAGNETIC FIELD AND ASSOCIATED BOUNDARIES

The magnetic field at Saturn (B), as for all planetary magnetospheres, is the sum of contributions from various sources, foremost among them being the internal contribution ($B_p$) to the planetary field, whose intensity at Saturn is sufficient to hold off the solar wind pressure. The total field $B$ is the sum of $B_p$ and additional
### TABLE XII
Main characteristics of Saturn magnetic field models

<table>
<thead>
<tr>
<th>Model reference</th>
<th>Main characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field models</strong></td>
<td></td>
</tr>
<tr>
<td>Acuña and Ness (1980)</td>
<td>Dipole representation of internal field</td>
</tr>
<tr>
<td>Z3 (Connerney et al., 1982)</td>
<td>Higher-order representation of internal field from Voyager data</td>
</tr>
<tr>
<td>P1184 (Davis and Smith, 1986)</td>
<td>Higher-order representation of internal field from Pioneer 11 data</td>
</tr>
<tr>
<td>SPV model (Davis and Smith, 1990)</td>
<td>Combines data sources and features of Z3 and P1184 models</td>
</tr>
<tr>
<td>SPV-R (Ladreiter et al., unpublished)</td>
<td>Incorporates constraints on surface field from SKR data into a modified SPV model</td>
</tr>
<tr>
<td>Connerney et al. (1981, 1983)</td>
<td>Ring current model</td>
</tr>
<tr>
<td>Mauk et al. (1985)</td>
<td>Analytical representation of the shape of magnetic field lines near the equator</td>
</tr>
<tr>
<td>Maurice and Engle (1995)</td>
<td>Contribution of magnetopause currents to the field</td>
</tr>
<tr>
<td>Behannon et al. (1981)</td>
<td>Only existing model of the magnetotail contribution to the field. Uses a set of current loops</td>
</tr>
<tr>
<td><strong>Boundary models</strong></td>
<td></td>
</tr>
<tr>
<td>Slavin et al. (1983)</td>
<td>Simplified analytical representation of magnetopause and bow shock shapes from all Pioneer and Voyager MP crossings</td>
</tr>
<tr>
<td>Maurice and Engle (1995)</td>
<td>Provides the magnetopause shape and contribution to the magnetospheric field</td>
</tr>
<tr>
<td>Maurice et al. (1996)</td>
<td>Analytical representation of the Maurice and Engle magnetopause model</td>
</tr>
<tr>
<td>Mauk et al. (1992)</td>
<td>Representation of the shape of the distant tail and of the intensity of the lobe field</td>
</tr>
</tbody>
</table>

Contributions of Saturn's equatorial ring current ($B_{RC}$), magnetopause ($B_{MP}$) and magnetotail currents ($B_t$), and possibly more localized currents due to satellite and/or neutral cloud interactions with the magnetosphere ($B_I$):

$$B = B_P + B_{RC} + B_{MP} + B_t + B_I$$

Table XII summarizes the existing models of these different terms and their main characteristics, as well as the models of the magnetopause and planetary shock.

The internal contribution, $B_P$, to the Saturnian magnetic field may be approximated by a dipolar field of moment $\sim 0.21 \text{ G} \times R_S^3$ aligned within $\sim 1^\circ$ of Saturn's
rotation axis (Acuña and Ness, 1980; Ness et al., 1981, 1982). The polarity of Saturn's dipole, like Jupiter's, is opposite to that of Earth. The most remarkable aspect of Saturn's planetary field is the close alignment of Saturn's magnetic and rotation axes.

Higher order models of $B_p$ have been developed at Saturn, using the traditional spherical expansion of a scalar potential $V$ from which the planetary field is obtained, via $B_p = \nabla V$. The scalar potential can be written as a sum of Legendre functions with Schmidt coefficients. There has been several approaches to derive a set of Schmidt coefficients for the internal field:

1. The $Z_3$ internal field model of Connerney et al. (1982) based on Voyager data.
2. The $P_{1184}$ internal field model of Davis and Smith (1986) based on Pioneer 11 data.
3. The SPY internal field model by Davis and Smith (1990) which combines the data from all three encounters and the features of the $Z_3$ and $P_{1184}$ models.
4. The SPV-R model by Ladreiter et al. (private communication) which includes the first terms of the SPY model but uses as an additional source of information the constraint on the surface magnetic field intensity derived from the high-frequency cut-off of the SKR radio emission (see sections 2.3 and 3.6).

While models 1, 2 and 3 only include the axially symmetric dipole, quadrupole, and octupole terms, model 4 is variable with longitude.

The ring current contribution, $B_{RC}$, results from the combination of the magnetization current and of the azimuthal gradient and curvature drifts of trapped particles, which produces a net azimuthal current. This net current also corresponds to the pressure gradient part of the magnetization current. Two models representing the ring current (1) or including its effects on the total field (2) have been developed:

1. In the ring current model proposed by Connerney et al. (1981b, 1983), the ring current is an annular disk extending from 8 $R_S$ to 15.5 $R_S$ in Saturn's equatorial plane. The current is assumed to be distributed uniformly in $z$ throughout the total disk thickness of 6 $R_S$, and decreases with radial distances from Saturn as $J_\varphi = I_\varphi / \rho$, where $I_\varphi = 2.9 \times 10^6$ A/$R_S$, and $\rho$ is the radial distance to Saturn's center in Saturn radii. The total integrated ring current is $\sim 10^7$ A, only a few percent of the total current of the Jovian magnetodisk.

2. Mauk et al. (1985) have developed a procedure to calculate the local shape of field lines encountered near Saturn's magnetic equator. These authors have derived an analytical form of each field line: the radial distance to the planet is a polynomial (degree 4) expansion of the magnetic latitude. This model already includes the planetary field $B_p$, and covers the region from $\sim 7 R_S$ to $\sim 16 R_S$ within $\pm 2 R_S$ of the equator.

The magnetopause contribution, $B_{MP}$, to the total field, is produced by the currents flowing on the magnetopause surface, which contribute to the pressure balance between the magnetospheric plasmas and field and the shocked solar wind. It
varies strongly with the magnetopause distance to the planet, $R_{\text{sub}}$, and the latitude of the sun in the Saturn reference frame.

Maurice and Engle (1995) have developed a model of the solar wind interaction with Saturn’s magnetosphere, based on a numerical method developed by Mead and Beard (1964). They have been able to compute simultaneously the shape and size of the magnetopause, illustrated in this article by Figures 2 and 32, and the additional contribution to the total field ($B_{\text{MP}}$) from the surface currents. Inside the magnetosphere, $B_{\text{MP}} = -\nabla \phi_{\text{MP}}$.

The contribution, $B_T$, from the magnetotail was modeled by Behannon et al. (1983). Saturn’s magnetic tail is a very complex region. Its magnetic field geometry is not symmetric around the planet except for $\lambda = 0$. The stretching of the field lines along the tail direction can be attributed to cross-tail currents, which have to close on the magnetopause surface. The closure of the field lines in the tail is very sensitive to the detailed current distribution. However, as there was no traversal of the tail current sheet at Saturn, models of Saturn’s magnetic tail are necessarily speculative.

$B_T$ is expected to become significant beyond $\sim 10$ $R_S$. Saturn’s tail presumably extends to a large distance from Saturn in the down-stream solar wind direction ($x < -100$ $R_S$). Since cross-tail currents are driven by the solar wind, Saturn’s tail field is essentially aligned along the Sun-Saturn axis, while other internal contributions ($B_P$, $B_{\text{RC}}$) are symmetric with respect to the equatorial plane. A hinge of the tail field must result, with a hinge point located near $x = -30$ $R_S$ down the tail. In the model by Behannon et al. (1981), illustrated in Figure 13, the authors incorporate cross-tail currents which extend from $-16$ $R_S$ to $-100$ $R_S$ along the Sun-Saturn line and close onto the magnetopause. $B_T$ is computed by summation of the field due to a system of individual closed current loops. Individual loops are spaced at 1 $R_S$-intervals and carry an eastward current. The current has a $1/\sqrt{r}$ dependence, decreasing outward from $\sim 5$ A/km at $-16$ $R_S$. The average distant tail lobe field is $\sim 3nT$.

Models of the main magnetic boundaries of the magnetosphere.

The magnetopause shape, which results from the pressure balance between the magnetosphere and the shocked solar wind, has been modeled in three studies.

(1) Slavin et al. (1983) have fitted all Voyager and Pioneer magnetopause crossings (i.e. when $\lambda \sim 0^\circ$), scaled to a common mean dynamic pressure of the solar wind, to a unique second order curve. They have used a magnetopause shape which is given by $r = L/(1 + \varepsilon \cos \theta)$ where $\varepsilon$ is the conic eccentricity, $L$ the semi-latus rectum. A third parameter, $x_0$, is the position of the conic focus point along the $x$-axis. Polar coordinates ($r$, $\theta$) are determined from the point $x_0$. They have found $x_0 = 5$ $R_S$, $\varepsilon = 1.09$ and $L = 30.8$ $R_S$, which corresponds to $R_{\text{sub}} = 19.75$ $R_S$. This model is valid for $x > -20$ $R_S$.

(2) As already mentioned, Maurice and Engle (1995) have calculated the shape of Saturn’s magnetopause consistently with the $B_{\text{MP}}$ contribution. Later, Maurice et al., (1996) have derived an analytical parameterization of this surface for $R_{\text{sub}}$
values between $17 \, R_S$ and $45 \, R_S$, and possible $\lambda$ between $0^\circ$ and $+/-26.7^\circ$. This model is valid for $x > -30 \, R_S$ only.

(3) Macek et al. (1992) have computed the external shape of Saturn's distant magnetotail, using pressure equilibrium equations and conservation of momentum. Between $x = -100 \, R_S$ and $x \sim -4500 \, R_S$, their model provides the main features of the Saturnian magnetotail: elliptic dimensions in the $y$ and $z$ directions, and magnetic field intensity in the lobes, as functions of downstream distance.

The bow shock, upstream of Saturn's magnetosphere, is a transition layer within which a portion of the plasma flow energy is converted to internal energy, turbulence, and waves. Bow shock crossings are usually identified unambiguously from particle and field measurements.

Slavin et al. (1983) have fitted all Voyager and Pioneer bow shock crossings (i.e., when $\lambda = 0^\circ$), scaled to a common mean dynamic pressure of the solar wind (see also Slavin and Holzer (1981)). They used the same parametric shape as for the magnetopause, and found in their fitting procedure $x_0 = 6 \, R_S$, $\varepsilon = 1.71$ and $L = 55.4 \, R_S$, when the magnetopause is scaled at $R_{SUB} = 19.75 \, R_S$. The Slavin et al. (1983) model is the only existing representation of the bow shock.

References


TOURING THE SATURNIAN SYSTEM: 
THE ATMOSPHERES OF TITAN AND SATURN

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Abstract. This report follows the presentation originally given in the ESA Phase A Study for the Cassini Huygens Mission. The combination of the Huygens atmospheric probe into Titan’s atmosphere with the Cassini orbiter allows for both in-situ and remote-sensing observations of Titan. This not only provides a rich harvest of data about Saturn’s famous satellite but will permit a useful calibration of the remote-sensing instruments which will also be used on Saturn itself. Composition, thermal structure, dynamics, aeronomy, magnetosphere interactions and origins will all be investigated for the two atmospheres, and the spacecraft will also deliver information on the interiors of both Titan and Saturn. As the surface of Titan is intimately linked with the atmosphere, we also discuss some of the surface studies that will be carried out by both probe and orbiter.

1. Introduction

A comprehensive study of the atmospheres of Titan and Saturn has always been a major goal of the Cassini-Huygens mission. For this review of atmospheric science objectives, we decided to use the 1986 ESA Phase A Study as our guide. Our purpose is to show that the spacecraft that is now on its way to the Saturn system is indeed capable of fulfilling the original objectives established for the mission. We also want to preserve the essence of the Phase A Study in an easily accessible publication, as this is the document that won the approval of the mission from ESA and NASA.

Reviewing this study, we found that a few instruments in the strawman payload were ultimately not selected for the mission. Furthermore, our knowledge about Saturn and especially Titan has increased significantly in the last decade. Nevertheless, the original scientific objectives remain valid, so we have kept the basic format of the original document, revising the contents as appropriate.

During the early days of planning for this mission, well before even the Assessment Study was initiated, there was hope for a Saturn orbiter with two atmospheric probes - one for Saturn and one for Titan. Budget constraints quickly eliminated the Saturn probe from consideration, so the studies of Saturn’s atmosphere must be

¹Adapted from ESA/NASA Assessment Study: Cassini: Saturn Orbiter and Titan Probe, ESA Ref. SCI (85)1 (1985)
carried out by remote sensing. It is therefore very helpful that the trajectory of the spacecraft en route to Saturn permits a moderately close (140 RJ) flyby of Jupiter, because data from the Galileo Jupiter Entry Probe (see *Science*, Vol. 272, No. 5263, 10 May 1996; *J. Geophys. Res.* Vol. 103, No. E10, 1998) provides a beautiful way of calibrating the Cassini remote-sensing instruments during the flyby.

We expect a rich harvest of results from the Jupiter flyby, an enterprise that was also envisaged in the original Phase A Study. However the main focus of this report, mirroring that original study, is on Titan and Saturn, as it is the exploration of the Saturnian system that is the ultimate goal of Cassini-Huygens. Our focus remains the basic science objectives. We therefore ask the reader who is interested in the specification of instrument capabilities to consult the relevant articles in this issue that describe the individual instruments. We have cited these references as volume 1 or volume 2 in the first instance each instrument is mentioned. For the Huygens probe, additional instrument descriptions are collected in a special ESA report (ESA SP-1177, August 1997, ed. J. P. Lebreton).

## 2. Titan

The encounters by Voyager 1 and 2 (summarized by Hunten *et al.*, 1984) revealed the unique character of Titan in the solar system. Subsequent ground-based and Earth-orbital observations have added information about Titan’s surface and lower atmosphere, discovered additional atmospheric constituents (most notably CO, CH$_3$CN and H$_2$O), determined isotopic ratios, provided new determinations of atmospheric structure (see recent summary by Gautier and Raulin, 1997) provided low resolution maps of the surface in the near IR (Meier *et al.*, 2000) and the first evidence for clouds (Griffith *et al.*, 1998). We expect these additions to continue. Nevertheless, Titan will clearly remain an enigma in many respects, including the nature of its surface, the details of the complex photochemistry occurring in its stratosphere, and the origin and evolution of its atmosphere. The Cassini-Huygens Mission to Titan will address the major topics described in the following paragraphs.

### 2.1. The Atmospheric Composition of Titan

**2.1.1. The Troposphere**

2.1.1.1. *Scientific Problem: Determine the tropospheric composition of Titan, specifically the relative abundances with altitude of CO, Ar, N$_2$, H$_2$, and CH$_4$.* In contrast to the oxidized atmospheres of terrestrial planets, Titan’s predominantly nitrogen atmosphere is chemically reduced. The low tropopause temperature, around 70° K (see Figure 1) acts as a cold trap for most of the gases that could be present in the troposphere and limits their amount in the stratosphere unless they are formed there. Methane has been detected in the stratosphere in amounts that cannot exceed
3 or 4%, but it could have a mixing ratio as high as 10% at the 94° K temperature of the surface (Courtin et al., 1995). Collision-induced absorption by nitrogen, methane and hydrogen contributes to a mild greenhouse effect. The presence of argon is suspected for cosmogonic reasons, but it has not been firmly identified (Samuelson et al., 1981; Owen, 1982). The upper limit on a heavy, volatile, spectroscopically undetectable constituent such as argon has been steadily lowered until it is now ≤6% (at 3σ) (Courtin et al., 1995). This argon would be primordial 36Ar and 38Ar brought to the satellite during its formation; 40Ar produced by decay of 40K in Titan’s rocks should be less than 0.5% of the present atmosphere revised upward from <0.01% (Owen, 1982) owing to escape of nitrogen (see below). Accurate determinations of argon and other noble gases (and of their isotopes) are crucial to test theories of the origin of the atmosphere (section 2.5).

Carbon monoxide poses a similar set of problems. At the present time (2003), there are three different values for the CO mixing ratio: 60 ± 20 × 10⁻⁶ as determined from the 3-0 near-IR vibration-rotation band (Lutz et al., 1983; Courtin et al., 2000) 10±5 × 10⁻⁶ deduced by Noll et al. (1996) from the (1-0) fundamental at 4.8 μm, and 29±6 × 10⁻⁶, derived from microwave observations of the J (0-1), J(1-2), and J (2-3) rotational lines (Hidayat et al., 1998). Gurwell and Muhleman (1995), observing the J (0-1) rotational line, found a CO abundance of 50 ± 1 × 10⁻⁶, in good agreement with the (3-0) near-IR result. Further disagreement exists regarding the vertical distribution of CO, with Gurwell and Muhleman (1995) finding the gas uniformly mixed, and Hidayat et al. (1998) reporting a decrease in the CO concentration to a value of 5±4 × 10⁻⁶ at 350 km.

The CO abundance is important because of its role in atmospheric photochemistry and as a possible tracer of Titan’s original endowment of volatiles. CO is converted to CO₂ by the reaction.

\[ \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \]  

(1)

with the OH contributed by infalling H₂O (Samuelson et al., 1983). CO may be produced by the attack of OH on CH₄, or it may be a relic from the origin of the satellite (Samuelson et al., 1983; Lutz et al., 1983; Owen and Gautier, 1989). In either case, reaction (1) suggests that a detectable amount of CO₂ may have been deposited on Titan’s surface during the last 4.5 billion years.

Other tropospheric constituents include molecular hydrogen, which was found by Voyager to have a mixing ratio of about 0.1% (Courtin et al., 1995). This hydrogen is expected, it is a product of CH₄ dissociation and shows that this gas is being irreversibly destroyed in the atmosphere. Methane must condense in the troposphere if its partial pressure reaches the limit defined by the saturation vapor pressure law. The methane in the upper troposphere and ethane descending from the stratosphere (see 2.1.2) would be the principal constituents of any cloud cover that may exist below the tropopause.

The recent discovery of clouds on Titan by Griffith et al. (1998) using spectroscopy indicates that condensation indeed takes place, although the extent, fre-
Figure 1. A cross section of Titan's atmosphere, with various imagined surface features and a methane rainstorm introduced by the artist.
quency, and location (are they associated with surface relief?) of these clouds remains to be determined. AO imaging observations by Brown et al. (2002) and Roe et al. (2003) revealed cloud systems over the South Pole of Titan. Accurate values of the methane mixing ratio near Titan’s surface would help us to determine the nature of the condensed materials that must exist there (see Section 2.4). The lifetime of atmospheric methane is limited by photolytic destruction with subsequent production of other compounds (see 2.5). Strobel (1982) has estimated that the current atmospheric abundance of methane will disappear in $\sim 20 \times 10^6$ years. Hence there must be a source of this gas on the satellite, either in the form of outgassing from the interior or storage in a subsurface reservoir (Stevenson, 1992). Similarly, the discovery that $^{15}$N/$^{14}$N is 4.5 times the terrestrial value in Titan HCN (Marten et al., 1997; Meier et al., 1997; Hidayat, 1998) suggests that an as yet unspecified amount of N$_2$ has left the satellite (see 2.5). A determination of the exact composition of the current troposphere as well as the time-integrated atmospheric reservoir remain key problems. The fact that $^{12}$C/$^{13}$C is normal (Hidayat et al., 1997) suggests that a reservoir for CH$_4$ exists, as does the irreversible destruction of CH$_4$ by solar UV (Strobel, 1982).

2.1.2. The Stratosphere

2.1.2.1. Scientific Problem: Determine the vertical and horizontal abundance distributions of trace hydrocarbons, nitriles and oxygen bearing compounds in the stratosphere. Search for more complex organics including polymers in gaseous and condensed phases. In addition to CH$_4$, six hydrocarbons C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, C$_3$H$_4$, C$_3$H$_8$, C$_4$H$_2$) and five nitriles (HCN, HC$_3$N, CH$_3$CN, C$_2$N$_2$ and C$_4$N$_2$) have been detected in Titan’s stratosphere (see Gautier, 1997, and Gautier and Raulin, 1997, for a review, and more recently, Marten et al., 2002). Oxygen compounds are represented by CO, CO$_2$, and H$_2$O. Except for CH$_4$, CO and possibly C$_2$H$_4$, the amounts of the detected species are much higher than would be permitted by the saturation law at the tropopause temperature. This implies that they are formed at stratospheric levels and above from a complex photochemistry initiated by dissociation of methane, nitrogen and water vapor by solar UV photolysis and bombardment by cosmic rays and high energy electrons trapped in Saturn’s magnetic field. H$_2$O was recently detected by ISO (Coustenis et al., 1998), its presence, presumably from impacting particles, may be required to explain the formation of both CO and CO$_2$. Photochemical models predict the formation of observed hydrocarbons and nitriles from the radicals arising from CH$_4$ and N$_2$ dissociation (Strobel, 1982; Yung et al., 1984; Toublanc et al., 1995; Lara et al., 1996). Condensation of these photochemical products and other more complex compounds including polymers produce the aerosols that are responsible for the thick layer of smog surrounding the satellite. These aerosols absorb sunlight, leading to a temperature inversion and an increase of the static stability of the stratosphere (Figure 1).
Because of the short radiative time constant at upper atmospheric levels, the latitudinal temperature field should be distributed symmetrically about the equator at the equinox. However, an asymmetric temperature field was observed by Voyager at the 1 mbar level (Flasar et al., 1981). Latitudinal distributions of aerosol albedos were also observed to be asymmetric by Voyager 1 suggesting that a complex interaction exists between thermal, chemical and dynamical systems (Sromovsky et al., 1981). In particular, the remarkable change in the average albedo of the aerosols that occurs just at the satellite’s equator is unique in the solar system, as is its seasonal variation (Sromovsky et al., 1981; Caldwell et al., 1992). The distribution and composition of trace molecules and aerosols in Titan’s stratosphere is thus a key problem. The acquisition of these data by Cassini at the local solstice compared with Voyager data acquired at the equinox will permit a study of seasonal effects. Of particular interest is the distribution of the “parent” molecule CH₄ which may not be uniformly mixed horizontally in the stratosphere.

One of the most important results of the Voyager encounter with Titan was the discovery of three nitriles HCN, HC₃N and C₂N₂, subsequently joined by CH₃CN discovered from Earth (Bézard et al., 1993) and a later detection of C₄N₂ in the Voyager spectra (Samuelson et al., 1997). The synthesis of complex organic compounds from mixtures of simple gases of reducing composition has been extensively studied in the laboratory since the famous experiments of Miller and Urey over 45 years ago (Miller, 1955). Indeed, laboratory experiments have demonstrated that HCN is a precursor of purines (in particular adenine) which are among the building blocks of the nucleic acids in living systems on the Earth. Similarly, HC₃N leads to pyrimidines which are also present in nucleic acids. Although the composition of Titan’s atmosphere is certainly very different from that of the primitive Earth, (it is so much colder that water vapor is only present in the form of externally supplied traces), abiotic organic synthesis in the atmosphere of Titan offers a test of how a Miller-Urey synthesis works at low temperature on a planetary scale and what it produces over several billion years (Owen et al., 1992, 1997; Raulin, 1997; Raulin and Owen, 2002).

The key problem is thus to determine the abundances and distribution of organics in Titan’s stratosphere, to establish the degree of complexity these compounds have achieved (both in the atmosphere and in subsequent reactions in any liquids that may exist on the surface), and to determine the processes and pathways for producing them. A list of organic molecules likely to be present in Titan’s atmosphere on the basis of laboratory experiments is given in Appendix 1.

Almost all expected organics condense at the temperatures occurring in Titan’s lower stratosphere (Figure 1). They must form droplets or solid particles that will precipitate with the larger aerosols to the surface where they will accumulate. At tropospheric temperatures the organics have very low abundances in the gas phase; they must pass through the troposphere as aerosols. The analysis of the composition of aerosols in the lower stratosphere and/or the troposphere is thus of great importance.
2.1.2.2. **Capabilities of Cassini.** The Gas Chromatograph/Mass Spectrometer (GCMS) aboard the Titan Probe will measure the elemental and isotopic composition from about 170 kilometers altitude down to the surface (Niemann *et al.*, vol. 1). Through the use of a collector and pyrolyzer of aerosols (ACP) (Israel *et al.*, vol. 1), it will also be able to detect condensed organics. Search for organics in gaseous form and measurement of their vertical distributions can also be accomplished by this versatile instrument. The far infrared-submillimeter spectrometer (CIRS) aboard the Orbiter (Kunde *et al.*, vol. 2) will provide, at each encounter with Titan, the vertical distributions of HCN, HC$_3$N, C$_2$N$_2$ and of some hydrocarbons (C$_4$H$_2$, C$_3$H$_4$) at various locations on the satellite. CIRS will also determine isotope ratios such as D/H and $^{15}$N/$^{14}$N and will also permit the detection of (or determination of upper limits for) new species such as other nitriles that are expected to be present in Titan’s stratosphere (See Appendix 1). It will map the distribution of H$_2$O in the upper stratosphere to determine the pattern of ice particle infall. The UV solar flux penetration and the N$_2$ dissociation will be investigated with the UV spectrometer aboard the Orbiter (Esposito *et al.*, vol. 2). The thermal structure and the abundances of CH$_4$ and C$_2$H$_2$ in the upper atmosphere will be obtained by observing the sun or a star occulted by the limb of Titan (as successfully done by Voyager). A combination of occultations and IR measurements should help to shed some light on the temperature structure in this altitude range. VIMS (Brown *et al.*, vol. 2) will be able to study the CO fundamental at 4.7 μm and search for evidence of other minor constituents in the long optical paths to Titan’s surface that are available in near IR atmospheric windows. Both VIMS and the Imaging Science System (ISS) (Porco *et al.*, vol. 2) will be able to search for clouds in the troposphere and contrast features in the haze to track atmospheric motions. The Descent Imager and Spectrometer (DISR) will also study clouds and constituent abundances along the descent trajectory.

2.2. **THERMAL STRUCTURE AND METEOROLOGY OF TITAN’S ATMOSPHERE**

2.2.1. **Scientific Problem: Measure winds and temperatures; investigate general circulation and seasonal effects in Titan’s atmosphere**

Voyager infrared observations of Titan’s stratospheric temperature field imply the presence of 100 m s$^{-1}$ zonal winds, super-rotating some 5–6 times faster than the 16-day rotation of the satellite body itself (Flasar *et al.*, 1981). If this inference is correct, then Titan’s large-scale atmospheric motions may be in a class with those of Venus, which shows cloud-tracked wind speeds of comparable magnitude. Unlike Venus, however, Titan has a large (27°) obliquity more nearly comparable to that of the Earth and may, therefore, show substantial meteorological variations with changing seasons.

The super-rotating winds have been confirmed by the analysis of the occultation of the star, zeta Sgr by Titan (Sicardy *et al.*, 1990) and by the heterodyne infrared based measurements of Kostiuk *et al.* (2000). The latter authors measured the
difference in Doppler shifts of C$_2$H$_6$ lines at the opposite limbs of Titan, demonstrating for the first time that the zonal winds in the upper atmosphere are prograde. The general circulation of the atmosphere of Titan and its super rotation with respect to the ground have been modeled by Hourdin et al. (1995) who reproduced rather well the wind pattern obtained by Sicardy et al. (1990).

Progress in the study of these features requires direct measurements of the zonal winds, global mapping of temperature fields over a range of altitudes, and improved measurements of the vertical variation of clouds and aerosols. Zonal wind measurements will confirm the assumed balance between large-scale motions and north–south gradients in temperature previously applied to the analysis of Voyager infrared observations. Global maps of the temperature fields at an “instant” in time can then be used to extend the inference of thermal wind structure to other levels. The strength of seasonal fluctuations can be inferred by a comparison of Voyager and Cassini thermal measurements. Measured limits of the longitudinal variation of temperature will provide important information on the role of wave dynamics in the general circulation of Titan’s atmosphere. Global mapping of the vertical and horizontal distribution of hydrocarbons and nitriles will provide important boundary conditions on dynamical models of the middle atmosphere. Measurements near the surface (see Section 2.4) will provide further important clues about the possible role of moist (hydrocarbon condensation) convection in the Titan Meteorology.

2.2.2. Capabilities of Cassini

The tropospheric thermal structure will be mapped at each encounter of the Orbiter with Titan by the far infrared submillimeter spectrometer of CIRS. The stratospheric thermal structure will be studied by means of the CIRS spectrometer operating in the middle infrared. A large number of tropospheric and lower stratospheric temperature profiles will be provided by radio-occultation experiments (Kliore et al., vol. 2). The Huygens Probe will measure the local temperature from 170 kilometers altitude down to the surface (Fulchignoni et al., vol. 1). Doppler tracking of the Probe during its descent trajectory will provide a direct measure of the zonal winds at one location (Bird et al., vol. 1). Wind velocities will be determined to accuracies of 10 m s$^{-1}$ or better at an altitude of 170 km and 5 m s$^{-1}$ near the surface. Measurements of latitudinal temperature gradients can then be used to extend the zonal wind mapping into the troposphere. The cloud structure along the descent trajectory will be observed by the Descent Imager (Tomasko et al., vol. 1). Winds will also be measured directly by tracking clouds in the lower troposphere observed by the imaging system and by VIMS on the orbiter. The circulation in the stratosphere may be monitored if these same instruments identify structures in the haze layer. These measurements, along with determinations of the vertical distribution of CH$_4$ by the GCMS, will permit characterization of convective processes in the lower troposphere. Inference of the net solar flux as a function of height by the Descent Imager will provide information on the vertical distribution of heat sources that drive the atmospheric circulation.
The ultraviolet spectrometers on Voyagers 1 and 2 provided considerable information on Titan’s upper atmosphere through a solar occultation and studies of the day-time airglow (see Hunten et al., 1984 for a review). The radio occultation experiment yielded a marginal detection of an ionosphere, giving an upper limit of 3000 electrons cm\(^{-3}\) a few degrees from the terminator (Bird et al., 1997). The nature of Titan’s interaction with the magnetosphere leaves no doubt that an ionosphere exists. The upper atmosphere is mostly N\(_2\), with several percent of CH\(_4\) and a detectable amount of C\(_2\)H\(_2\). H and H\(_2\) are probably present in the unusual dayglow of Titan. Although this emission is confined to the dayside of the satellite, it is 5–10 times brighter than the glow that could be produced by the entire solar flux below 1000 Å (angstrom). Since the phenomenon is so mysterious, its investigation has a high priority. There is little doubt that the glow is excited by electrons with energies between 10 and a few hundred eV. Such electrons should be sought with in-situ instrumentation. These electrons are also the most likely source of Titan’s ionosphere, rather than solar EUV radiation. Ionization produced by the interaction of these low-energy electrons (∼100 eV) will consist primarily of N\(_2^+\) and N\(^+\) as indicated from airglow observations. The principal ions in Titan’s ionosphere, however, are expected to consist of nitrile (e.g., H\(_2\)CN\(^+\)) and hydrocarbon (e.g., CH\(_3^+\)) ions resulting from ion-molecule reactions between the originally formed N\(_2^+\) and N\(^+\) ions and CH\(_4\) present at ionospheric levels. Recombination of these ions will be a major source of the HCN present in Titan’s atmosphere. Jupiter’s inner magnetospheric composition and energetics are known to be dominated by heavy ions of S and O ejected from Io. Ejecta from Titan (and other satellites) should be similarly important to Saturn’s magnetosphere, though probably not dominant. A neutral torus of H atoms was detected by the Voyager Ultraviolet Spectrometer and H\(_2\) and N are expected as well along with H\(_2\)O and O from the icy satellites.

2.3.1. Capabilities of Cassini

The Orbiter will carry a full complement of remote-sensing and in-situ aeronomy instruments (Blanc et al., vol. 1). The UV spectrometer will examine the dayglow emissions, determine the global distribution of H around Titan, and map hydrocarbon distributions by observing stellar occultations. The ion and neutral mass spectrometers will determine the composition of the upper atmosphere (Waite et al., vol. 2).

Since many of the orbits pass through the upper atmosphere of Titan at altitudes down to 800 km, close to the ionization maximum, several separate sets of in-situ measurements will be accumulated over the four-year lifetime of the mission. Repeated radio occultations and UV observations of occultations of the sun and stars by Titan’s limb will add to this store of information. The mission design offers an opportunity to compare inferences from remote-sensing observations with
the “ground-truth” derived from the periodic in-situ measurements, including the
selected set carried by the Probe to the surface. Thus the global coverage available
from remote sensing can extend with confidence the localized but more detailed
coverage provided by the direct measurements.

2.4. TITAN SURFACE AND INTERNAL STRUCTURE

2.4.1. Scientific Problem: Determine the nature and the composition of Titan’s
surface; infer the satellite’s internal structure

The interiors of Titan and Saturn have been included in the charter of respons­
bilities for the Atmospheres Working Group. We are adding a discussion of the
surface of Titan here for both historic and scientific reasons. This topic was cer­
tainly included in the original Phase A Report, and in fact, the surface of Titan has
a particularly important connection with the atmosphere, both as a potential source
and reservoir for volatiles that can replenish the atmosphere, and as a repository
for condensates and aerosols that must constantly precipitate from the atmosphere.
(Additional details will be found in the article by Hunine and Soderblom.)

Titan boasts the largest unexplored surface in the solar system. This mysteri­
ous domain is perpetually masked by thick layers of aerosols that prevented the
Voyager cameras from recording any surface detail. However, this ubiquitous haze
can be penetrated at near infrared, infrared and radio wavelengths, with the result
that observations of Titan from Earth have succeeded in sensing the satellite’s
surface. Radar was the first to show that the surface is inhomogeneous, with a
higher reflectivity from the leading hemisphere (Muhleman et al., 1990). Near in­
fared observations discovered windows in the planet’s spectrum through which the
surface could be glimpsed, again revealing a brighter leading hemisphere (Griffith
et al., 1991; Lemmon et al., 1993). Subsequent studies with the Hubble Space
Telescope and ground-based adaptive optics established the outlines of a continent­
sized feature that appears to be responsible for this asymmetry in Titan’s surface
albedo (Smith et al., 1996; Combes et al., 1997; Meier et al., 2000). Evidently Titan
does not have a global ocean of hydrocarbons, as initially proposed by Lunine et al.
(1983).

This poses a problem, because the stratospheric production of nitriles, hydro­
carbons, and possibly other, more complex organics, with subsequent escape of
hydrogen into space, uses up methane that is not recycled. Thus it is necessary to
replenish this gas, either by outgassing from the interior (volcanism) or by evap­
oration from some large, subsurface reservoir, or both. The lifetime of the present
atmospheric methane abundance is only $20 \times 10^6$ years, indicating the severity of
the problem.

We expect the surface to include deposits of organic aerosols and icy grains of
CO$_2$ and H$_2$O, all of which will descend through the atmosphere as microscopic
particles. Even though there is not a global ocean, there must be ponds, lakes, or
even seas of liquid hydrocarbons, presumably dominated by ethane and propane,
as these are the most abundant condensible compounds produced by the photochemistry that we know. Thus the surface of Titan contains an important record of atmospheric processes, and may concentrate some constituents that are extremely rare in the atmosphere itself.

The properties of Titan’s interior are very poorly understood. Assuming that Titan consists of differentiated anhydrous chondritic rock and water ice, the density measured by Voyager (1.8 g cm\(^{-3}\)) suggests that the satellite has a bulk composition of about 50% rock and 50% ices but the internal structure remains unconstrained.

Models of the interior of Titan have been proposed by Stevenson \textit{et al.} (1986) and more recently by Grasset and Sotin (1996). These models include the probable occurrence of a thick subsurface ocean of H\(_2\)O, CH\(_4\) and NH\(_3\). It might be that these species escape, continuously or randomly, up to the surface through cracks in the crust, and replenish the atmosphere in CH\(_4\) (while NH\(_3\), if any, and H\(_2\)O would immediately condense at low surface temperatures). A recent model of the subnebula of Saturn supports this assumption (Mousis \textit{et al.}, 2002a,b).

2.4.2. Capabilities of Cassini

The radar aboard the Orbiter will be able to map the distribution of bodies of liquid hydrocarbons on the surface and to define surface topography (Elachi \textit{et al.}, vol. 2). The radar resolution (350–500 meters) will be sufficient to characterize the surface morphology and cratering record on the solid surface, in those areas of Titan where close radar passes occur. The VIMS instrument will be able to sense the surface through the several atmospheric windows that occur in the 0.9–5.0 \(\mu\text{m}\) (micron) spectral region, at a resolution of \(\sim\)1 km and the imaging system will exploit the short wavelength end of this range, reaching scales of \(\sim\)15 meters. The resulting spectrophotometry and imagery will provide additional details on surface morphology and constrain models for the composition of surface materials, including local variations caused by weather patterns. (One thinks here of the wind blown deposits of dark materials on Mars and Triton and the deposition of sediment by wind and water on Mars and Earth.) The Descent Imager (DISR) on the probe will achieve still higher resolution over the landing area, again delivering both images and spectroscopic data. The radar altimeter on the probe will provide local measurements of surface roughness and reflectivity with high spatial resolution. Comparing the probe results with the orbiter data should permit interpretations of the latter on smaller scales than those provided directly by the remote-sensing instrument. Gravity field measurements derived from the trajectories of the \(\sim\)40 scheduled encounters of the orbiter with Titan during the duration of the nominal four-year mission will permit the development of significant constraints on interior models of Titan.
2.4.3. Conditional Measurements If a Soft Landing Occurs

If the probe survives its landing, further refinements are possible by conducting experiments on the surface. These experiments must be carried out on a best effort basis; they are not mandated within the mission guidelines, even though there is a Surface Science Package explicitly included in the probe payload (see Zarenecki et al., vol. 1). In addition to the experiments included in that package, we point out the ability of the DISR to obtain images and spectrophotometric data that describe conditions in the immediate vicinity of the landing site, and measurements with the GCMS of surface composition that will be enabled by heating the projecting inlet tube. These compositional measurements may be among the most interesting ones provided by this instrument. A landing in a drift of aerosols will enable sampling of the most volatile constituents in a concentrated form unachievable during descent. A wet landing would permit a determination of concentrated photochemical products in the frigid hydrocarbon equivalent of Darwin’s “warm little pond” that saw the first steps in the chemical evolution that led to life on Earth (Owen et al., 1992, 1997; Raulin, 1997; Raulin and Owen, vol. 1). A more difficult scenario would be a landing on an outcrop of surface ice. If the probe survived and the heated inlet of the GCMS made contact with the ice, it might be possible to measure a value of D/H in Titan’s ice, an extremely interesting measurement from the standpoint of the origin and evolution of the satellite’s atmosphere (see following section).

2.5. ORIGIN AND EVOLUTION OF TITAN’S ATMOSPHERE

2.5.1. Scientific Problem: Determine the origin of $N_2$, $CH_4$, and CO in the atmosphere and the changes in atmospheric composition during Titan’s lifetime

Voyager observations exclude the possibility that Titan’s atmosphere was formed by direct retention of gases from the primitive solar nebula or from the Saturn sub-nebula (including an extended atmosphere of the forming planet). In these cases, the present Ne/N ratio in the atmosphere should be close to 1, which it is not (Owen, 1982). The current upper limit on the mixing ratio of Ne set by Voyager UV observations is 0.002 (Hunten et al., 1984). The idea that Titan’s atmosphere might have been contributed primarily by cometary impact (Griffith and Zahnle, 1995) is weakened by the observation that D/H in cometary $H_2O$, the dominant reservoir of hydrogen in comets, is $3.2 \times 10^{-4}$ (see, e.g., Meier and Owen, 2000, for a review of cometary data) whereas in Titan’s methane, it is closer to $10^{-4}$ (Coustenis et al., 1998). It is thus reasonable to think that Titan’s atmosphere was formed predominantly by outgassing of volatiles from planetesimals that formed the satellite. What were these volatiles?

This is one of the most interesting investigations that Cassini-Huygens will undertake as the answers have implications not only for Titan but Triton, Pluto and even the inner planets, as icy planetesimals (in the form of comets) must have
played a role in delivering volatiles to these bodies as well (Owen and Bar-Nun, 2001). In the interstellar cloud from which the solar system formed, approximately 70% of the nitrogen was in the form of N$_2$ with the rest in NH$_3$ and various organic compounds. The carbon was predominantly in grains, as amorphous carbon and organic compounds with up to 30% as CO and perhaps 3% as CH$_4$ (van Dishoeck, 1998; Ehrenfreund et al., 1998). Interstellar grains that fell into the nebula disk may have experienced significant heating due to the protosolar radiation field (Simonelli et al., 1997) and/or passage through the accretion shock (Cassen and Chick, 1997). In addition, surviving grains and vapor which entered into the nebula at great heliocentric distances may have been brought to the inner solar system by the systematic inflow of gas. Some mixing of the two components was an inevitable consequence of nebular mass and angular momentum transport (Cassen, 1994). Whatever the composition of the solar nebula at the heliocentric distance of Saturn, the formation of a subnebula around the forming planet may have resulted in modifications of the composition since the initial subnebula was inevitably denser and warmer than the surrounding solar nebula. The problem is to find the link between the composition of the subnebula and the fact that CH$_4$ and N$_2$ are presently the two major components of the atmosphere of Titan. Under the assumption that the atmosphere was formed by outgassing from the interior of the satellite, carbon and nitrogen must have been contained in grains that agglomerated to form Titan, but in what form? Several scenarios can be envisaged.

In the scenario advocated by Prinn and Fegley (1981), C and N are in the form of CO and N$_2$ respectively, in the subnebula, while most of the oxygen is in the form of H$_2$O. This is based on the assumption that all matter coming from the presolar cloud has been dissociated during the collapse of the cloud, and subsequently recombined in molecules in the hot inner part of the nebula. These molecules are transported by turbulence out to the region of formation of Saturn. An appropriate Saturn subnebula (namely much denser than the nebula) could permit in principle the conversion of CO into CH$_4$ and the conversion of N$_2$ into NH$_3$. Subsequently, when the subnebula cools down, H$_2$O first condenses, and at lower temperatures NH$_3$, followed by CH$_4$. Alternatively, as soon as H$_2$O condenses, water ice can form CH$_4$ clathrates and NH$_3$ hydrates (Lunine and Stevenson, 1985), or trap CH$_4$ and NH$_3$ through adsorption if the H$_2$O ice is in amorphous form. In this last case, the amounts and proportions of trapped gases are strongly dependent on local temperature (Bar-Nun et al., 1985). Grains containing CH$_4$ and NH$_3$ could subsequently form a subsurface ocean (see Section 2.4) and ultimately the primitive atmosphere of Titan. The last step of the process requires the photolytic conversion of NH$_3$ into N$_2$. To insure that, the temperature of the early atmosphere of Titan must have been not lower than 150 K to permit efficient evaporation and photolysis of NH$_3$ to produce the N$_2$ (Atreya et al., 1978).

The difficulty with this scenario is that the conversion of N$_2$ into NH$_3$, which strongly depends on pressure, requires a subnebula that is quite dense, the validity
of which has never been demonstrated. In fact, more recent models of the subnebula (e.g., Coradini et al., 1989) are not as dense as that used by Prinn and Fegley (1981). Accordingly, a second scenario considers that nitrogen was in the form of N₂ in the subnebula. The question is then to explain how N₂ was efficiently trapped in grains that formed Titan. Bar-Nun et al. (1985) and Owen and Bar-Nun (1995) argue that trapping of this gas by water ice requires very low temperatures. Lunine and Stevenson (1985) discuss in detail the formation of clathrates of N₂.

A solution to the difficulty of forming NH₃ in the subnebula is proposed in a third scenario (Owen, 2000). The nebula in the region of Saturn is assumed to have conserved at least a part of the NH₃ present in interstellar gas and grains. This ammonia would then be present in the subnebula and would have subsequently condensed as in the first scenario. Scenario 3 implies that NH₃ came from the outer part of the nebula without having been converted into N₂. It also implies that very little conversion of NH₃ to N₂ occurred in the subnebula prior to the formation of Titan.

The recent evolutionary model of a turbulent nebula elaborated by Mousis et al. (2002a,b) supports scenario 3. The authors found that the pressure in the Saturn subnebula must have been five orders of magnitude lower than that assumed by Prinn and Fegley (1981). As a result, CO could not have been converted to CH₄ or N₂ into NH₃ in the subnebula. Moreover, the calculated structure of the subnebula reveals that the mass of heavy elements was not large enough to form Titan where it is today. Therefore, Mousis et al. (2002a) argued that the CH₄ and NH₃ present in the driving feeding zone of Saturn around 10 AU were trapped at low temperature in the form of clathrate hydrate of CH₄, and hydrate of NH₃, respectively. These hydrates were incorporated in planetesimals embedded in the cold external part of the subnebula, which subsequently migrated inwards to form Titan.

How can we choose among these scenarios?

Measurements of noble gas abundances and isotopic ratios provide a means for discriminating between the primordial and photochemical models. The presence of a substantial amount of non-radiogenic argon (³⁶Ar and ³⁸Ar) and other noble gases would support the idea that most of the N₂ and CO we find in Titan today were brought in by the ices, either as clathrates or as adsorbed monolayers. On the other hand, a marked deficiency of primordial argon would support models suggesting that the nitrogen originated in the form of condensed NH₃ or other compounds. For example, the upper limit of 6% that we already have for Ar in the present atmosphere (Courtin et al., 1995) coupled with the isotopic evidence for nitrogen escape (see Section 2.1.1) leads to a value of Ar/N that is much less than solar. This means that Ar has been fractionated from nitrogen – as it has on Earth – which could only happen if Titan originally acquired its nitrogen in the form of compounds other than N₂. If the ice composing Titan contained the same proportion of NH₃ found in comets and in interstellar clouds – about 1% – outgassing could have produced an atmosphere of ~120 bars of N₂, so there is no shortage of nitrogen with this model!
The isotope ratios will provide further clues. We need to know how the fractionation and escape of N and H has taken place in the atmosphere, leading to the values we find today. Did the methane we find on Titan form in the subnebula? Was it included in the ice like NH$_3$? Or did it form during accretion, on the satellite itself? The answer may be found through a study of D/H in Titan’s H$_2$O, which would be the source of the hydrogen for in-situ methane production. Studies of D/H in other compounds besides CH$_4$ will help determine the extent of photochemical fractionation of these important isotopes. Mousis et al. (2002b) argued that the D/H ratio measured in Titan is representative of that in CH$_4$ in the cooling solar nebula at 10 AU, at the time when methane was trapped in the form of clathrate hydrates. This scenario constrains the value of D/H in methane ices falling from the presolar cloud into the early nebula.

2.5.2. Capabilities of Cassini
The GCMS aboard the Titan Probe will measure noble gas abundances and their isotopic ratios. It will also determine isotope ratios for the other abundant elements. The use of the gas chromatograph in combination with the mass spectrometer allows a clean discrimination between molecules and their fragments that would otherwise have overlapping charge-to-mass ratios. If the probe survives the landing, the concentration of condensed species on the surface will provide an additional increase in sensitivity. One issue to be considered then will be the possible confusion between ice crystals coming into the atmosphere from the outside and the ice that formed the satellite. The former may include cometary ice with a much higher D/H than is expected on Titan. Finding evidence of both types of ice would be extremely interesting.

3. Saturn

3.1. Introduction
Despite the apparent similarities between the two largest planets in the solar system, the Voyager encounters have revealed that Saturn is significantly different from Jupiter. The study of each planet will clearly benefit from comparative observations of the other. Following the Galileo mission to Jupiter in 1995–2000, Cassini will allow us a much deeper level of comparison between the two largest planets in our solar system. The reasons for apparent differences in internal structure and general circulation for example, can be studied in ways beyond the reach of the Voyager spacecraft. The potential for advancing our knowledge is further enhanced by the fact that Cassini will arrive at Saturn during a different season from that of the Voyager encounters. Furthermore, the Cassini flyby of Jupiter (closest encounter on 30 December 2000), en route to Saturn, allows a direct comparison of observations of the two planets with the same suite of instruments, calibrated at Jupiter by results from the Galileo entry Probe.
3.2. THE INTERIOR

3.2.1. Scientific Problem: Constrain the Extent of Interior Structure Differentiation and Its Coupling to the Atmospheric Circulation

Voyager observations of Saturn revealed an outer envelope depleted in helium with respect to a protosolar composition mixture and a strong internal heat source that is larger than can be accounted for by homogeneous cooling models. Assuming a methane-to-molecular hydrogen mixing ratio of $4 \times 10^{-3}$, Conrath et al. (1984) found $0.06 \pm 0.05$ for the He mass fraction, compared with $0.238 \pm 0.007$ for the He mass fraction on Jupiter, as determined by instruments on the Galileo probe (von Zahn et al., 1998; Niemann et al., 1998). However, the Voyager observations of Jupiter led to a lower value of $0.18 \pm 0.04$ for the He mass fraction on Jupiter, suggesting the presence of a systematic error in the Voyager results, which would affect the Saturn determination as well.

Saturn Voyager data have been reexamined by Conrath and Gautier (2000). Using a method of retrieval of the H$_2$/He ratio based on the differential spectral behavior of H$_2$–H$_2$ and H$_2$–He collision-induced absorption coefficients (Gautier and Grossman, 1972), these authors suggest that the mass fraction of He in the outer envelope of Saturn is about three times higher than the value previously inferred by Conrath et al. (1984) which was dependent on the radio occultation profile obtained by the Voyager spacecraft.

The occurrence of internal heat in Saturn, in spite of the fact that the planet should have lost the energy initially acquired at the time of its formation about two billion years ago is interpreted as resulting from the demixing of helium from metallic hydrogen in the deep interior of Saturn (Stevenson and Salpeter, 1977; Guillot, 1999; Hubbard et al., 1999). This separation which began late in the history of Saturn and the subsequent migration of helium droplets towards its center liberates gravitational energy responsible for the internal energy observed today (see Figure 2).

However, this internal energy depends upon the amount of helium that migrated from the outer envelope downwards toward the center of the planet since the formation of this object. Interestingly enough, two recent models of evolution of Saturn by Guillot (1999) and by Hubbard et al. (1999) both conclude that the abundance of helium in the envelope should be substantially higher than that derived by Conrath et al. (1984). The factor 3 increase deduced by Conrath and Gautier (2000) from their reanalysis of the Voyager data is consistent with these new evolutionary models.

3.2.2. Capabilities of Cassini

Saturn’s gravitational field will be measured throughout the Cassini orbital mission by radio tracking of the Orbiter trajectory at a variety of inclinations (Kliore et al., vol. 2). The radius of Saturn at low and high latitudes will be determined by a series of radio occultation measurements. These improvements in our knowledge of the
shape and gravitational field of the planet will provide further constraints on models for Saturn’s interior. The far infrared spectrometer will retrieve temperatures and their variation with latitude at the top of Saturn’s convection zone. Combined with radio-occultation retrievals, or independently, the infrared measurements will deliver a more accurate determination of the helium abundance. Thermal emission measurements by the Composite Infrared Spectrometer (CIRS) and observations of reflected solar energy by the near infrared spectrometer will be used to refine our knowledge of the global energy balance.

3.3. THERMAL STRUCTURE AND COMPOSITION


Voyager IRIS and Radio Science measurements have provided retrievals of vertical temperature structure at pressure levels between 1 and 1000 mbar. The Voyager IRIS data revealed latitudinal gradients in temperature in Saturn’s upper troposphere that are strongly correlated with the cloud-tracked winds, but could not be measured at higher levels. A north-south hemispheric asymmetry of temperature was also observed, indicating a seasonal response (at a time near the equinox) with moderate thermal inertia. The altitude range of the retrieval of tropospheric profiles from Voyager IRIS data was limited by the lack of measurements below 200 wavenumbers (λ > 50 μm). Ground-based microwave observations also show strong latitudinal variations in tropospheric temperatures at pressure levels of a few bars, including a pronounced warm band at northern mid-latitudes. These are difficult to interpret as kinetic temperatures owing to uncertainties in the NH₃ abundance, but may be diagnostic of vertical motions. IRIS determinations of the ortho-para ratio in Saturn’s upper troposphere have provided evidence for variations of this ratio with latitude, as recently demonstrated by Conrath et al. (1998).

IRIS determinations of the CH₄ abundance in the stratosphere indicate an enrichment of carbon amounting to approximately four-and-one-half times the solar abundance value (Courtin et al., 1984), which was supported by ground-based observations that indicate an enrichment of 4 ± 1 × solar (Karkoschka and Tomasko, 1992). However, more recently, Kerola et al. (1997) found an enrichment of 3 ± / − 1× solar. It is an important issue, as models for the origin of giant planet atmospheres predict that abundances of heavy elements should be greater on Saturn than on Jupiter (e.g., Pollack and Bodenheimer, 1989; Owen and Bar-Nun, 1995). However, Hersant et al. (2003) propose a scenario in which CH₄ and NH₃ were trapped by clathration and hydration in the feeding zone of Saturn, thereby
producing in the planet a carbon enrichment of 2.5, and a nitrogen enrichment of 2.0. Both values are less than those observed in Jupiter, in which Ar, Kr, Xe, C, N, S are all enriched by a factor 3 ± 1 compared to solar abundances tabulated by Anders and Grevesse (1989). What are thus the abundances of species other than methane observed in Saturn? (Owen et al., 1999). What is the enrichment of NH₃ on Saturn? Limited information on the deep tropospheric abundance of NH₃ on Saturn has been obtained from ground-based microwave measurements as well as from IRIS spectra. Indications of an NH₃ abundance near the saturation limiting value at 500–700 mbar were provided by Voyager radio occultation data. Various hydrocarbon constituents, such as C₂H₂, C₂H₆, C₃H₄, and C₃H₈ have been detected in Saturn’s stratosphere, but with only moderate spectral resolution and signal-to-noise ratio, which has prevented an accurate assessment of their abundances. (reviewed by Atreya [1986], Noll and Larson [1991] and Atreya et al., 2003). There are indications of significantly higher abundances of some constituents on Saturn that are also present on Jupiter, especially PH₃ which may be enhanced by an order of magnitude (Noll and Larson, 1991). ISO has found CO₂, H₂O and CH₃ in the stratosphere (Encrenaz et al., 1999). Several other as yet undetected molecules are expected to be present in Saturn’s atmosphere. If detected they would offer important clues to Saturn’s atmospheric chemistry.

It is widely recognized that an accurate determination of D/H can provide useful constraints on models for the origin and evolution of planetary atmospheres. As H₂ dominates all other hydrogen-bearing constituents by a large margin on Jupiter and Saturn, the value of D/H in the H₂ in these atmospheres should be almost identical to the value in the hydrogen that dominated the interstellar cloud from which the solar system formed. Neither of these giant planets is sufficiently massive to produce internal temperatures and pressures that would permit nuclear reactions converting D to ³He. The only disturbance of the original ratio would therefore come from other hydrogen compounds that were brought to the forming planet as solids (primarily in ices) in sufficient amounts.

The value of D/H on Saturn was given as D/H = \((1.7 + 1.9/ - 1.0) \times 10^{-5}\) by Gautier and Owen (1989) from an analysis of observations of bands of CH₄ and CH₃D (with correction for fractionation from hydrogen) by several different observers. More recently, Griffin et al. (1996) have reported D/H = \((2.3 + 1.2 - 0.8) \times 10^{-5}\) from observations of HD absorption lines by the Infrared Space Observatory (ISO). From the short wavelength spectrometer (SWS) of ISO Lellouch et al. (2001) derived D/H = \(1.85 + 0.85/ - 0.6\) \times 10\((-5)\) from HD, and a somewhat lower value from CH3HD. Using Jupiter for comparison, we point out that Mahaffy et al. (1998) derived D/H \((2.6 \pm 0.7) \times 10^{-5}\) from direct measurements of HD and H₂ in Jupiter’s atmosphere. This is significantly higher than the value of \(1.6 \pm 0.2 \times 10^{-5}\) found in local interstellar hydrogen today (Linsky, 1996), as expected from models for galactic evolution that predict the destruction of deuterium with time as a result of nuclear “burning” in stars.
Within the errors of the current D/H measurements, Jupiter and Saturn may exhibit the same value of D/H, in spite of the fact that Saturn appears to contain more heavy elements, and thus presumably more ices than Jupiter (Guillot et al., 1994). However, under the assumption that volatiles were trapped in the form of clathrate hydrates in the feeding zones of both Jupiter and Saturn, Hersant et al. (2003) predict that the enrichment in oxygen in Saturn should be almost twice less than in Jupiter (Gautier et al. 2002). Unfortunately, the O/H ratio is still unknown in both planets. Obviously it is very important to increase the precision of the D/H measurement on Saturn in order to decide whether or not the hydrogen reservoir in the planet has been enriched in deuterium from the condensed matter (predomin-
antly in the form of icy planetesimals) that formed the core and contributed excess heavy elements to the atmosphere. Coupled with more accurate determinations of the abundances of carbon, nitrogen and phosphorous, the deuterium measurement can then be used to estimate the mass of heavy elements contained in the planets and to characterize the composition of the planetesimals that delivered them.

3.3.2. Capabilities of Cassini

Spectral measurements from 10 to 1400 cm$^{-1}$ (7 to 1000 μm) will permit the determination of atmospheric composition and thermal structure between 100 and 1000 mbar as well as between 0.1 and 10 mbar. The planned 2004 arrival date will permit the measurement of atmospheric conditions near the solstice, providing an important seasonal comparison with Voyager observations. Good horizontal mapping and some vertical information on the ortho-para hydrogen ratio will be available from CIRS, partly by assessment of the relative strength of H$_2$–H$_2$ and H$_2$–He collision – induced absorption lines. The hydrogen dimer (H$_2$)$_2$, detected by Voyager, will also be spectrally analyzed at 16 and 28 μm, providing a very sensitive evaluation of its latitudinal variation. These determinations will significantly constrain the adiabatic lapse rate at deeper levels and also provide useful diagnostics of vertical motions. Latitudinal variations of methane emission will be measured in limb-sensing mode at levels up to 1 microbar, which will yield the kinetic temperature with a vertical resolution of one scale height. Vertical and horizontal distributions of C$_2$H$_2$, C$_2$H$_6$, and other hydrocarbons can also be obtained by limb sounding in the middle infrared.

Radio occultation measurements will provide an independent retrieval of thermal profiles at selected locations, permitting a determination of He/H$_2$ in conjunction with the infrared measurements. This ratio will also be directly retrieved by CIRS from IR measurements at long wavelengths.

Ammonia (NH$_3$) cloud optical depths will be mapped using spectral regions near 200 and 1000 wavenumbers and in the near infrared. The near infrared spectrometer will yield further important constraints on cloud properties including particle sizes and relative heights of different cloud layers.

Making many measurements of additional HD lines over four years at several locations on the disk of the planet (thereby permitting an improved evaluation of the cloud opacity), CIRS will easily be able to surpass the accuracy of the ISO determination. Improved modeling and calibration will further enhance this effort. In addition, D/H in methane can also be inferred from measurements of the CH$_3$D/CH$_4$ ratio. Comparing this D/H with D/H in H$_2$ may permit us to evaluate the isotopic enrichment factor in methane in the upper troposphere of Saturn (Lecluse et al., 1996). A precise determination of this factor would help us to discriminate among the various models of dynamics of the deep atmosphere, models that are presently only poorly constrained.

Information on the thermal structure and composition of the upper atmosphere will be acquired by observing the sun or a star at the planetary limb with the
ultraviolet spectrometer. The high-speed photometer will measure high-altitude atmospheric densities. Soundings of the deep atmosphere from 2–10 bar will be obtained by microwave radiometry. The opportunity for variable viewing geometry and, by use of the telecommunications dish, for high spatial-resolution observations will aid in separating kinetic temperature and variable abundance effects.

3.4. ATMOSPHERIC DYNAMICS AND GENERAL CIRCULATION

3.4.1. Scientific Problem: Perform cloud-tracked wind and correlated temperature measurements at all latitudes with sufficient time and longitude coverage to analyze eddy-mean flow exchanges. Constrain global scale temperature-density gradients at sub-cloud levels. Measure vertical wave propagation at selected latitudes

Voyager imaging observations of large-scale motions on Saturn revealed a super-rotating equatorial jet and at higher latitudes an axisymmetric and apparently long-lived pattern of counter-flowing jet streams. Although these features of the atmospheric circulation are qualitatively similar to observed motions on Jupiter, the Saturn jet streams are a few times stronger, somewhat wider, and more dominantly prograde, measured with respect to the planet’s rotation period. Two extreme model interpretations have been suggested for the general circulation of both giant planets. In one view the observed jet streams are the manifestation of counter rotating cylinders of convection, concentric with the planetary spin axis, and extending deep into the interior of the molecular hydrogen envelope. In the other view the observed motions are confined to a relatively shallow layer extending no more than a few scale heights below the cloud tops and supported by strong latitudinal gradients in temperature and composition (Figure 3). Further measurements will be required to distinguish between the two models. The Voyager observations of Saturn’s high wind speeds and its enormous equatorial jet provide an even greater challenge to theoretical understanding than the observations for Jupiter and have served to emphasize the distinction between the two extreme models illustrated in Figure 3. The diagnostic assessment of wave – mean flow exchange and cloud – temperature correlations are also more problematic for Saturn. Present knowledge cannot provide definitive answers to the most fundamental questions about the nature of the Saturn meteorology. How deep do the jet streams extend into the interior? How does the deep internal convection couple to the motions at the cloud tops? Do small scale horizontal eddies feed the large-scale jets or do the jets support the eddies? What is the role of moist latent heat-release and ortho-para hydrogen conversion in the global circulation balance?

Progress in answering these questions will require more elaborate measurements extended to longer time frames and other vertical levels of the atmosphere than were available from the flyby Voyager encounter. Voyager infrared measurements of north-south gradients in temperature just above the cloud tops imply a reduction of the wind speeds with altitude toward a net west-to-east directed flow.
Figure 3. Two alternative models for the general circulation of Saturn's atmosphere: (a) suggests that the circulation is driven in a rather shallow layer in the visible part of the atmosphere; (b) invokes deep convection following a pattern of concentric cylinders. (After Michael Allison.)
The extension of these measurements to higher levels of the upper stratosphere will offer important clues to the circulation balance at deeper levels. Long wave microwave sounding combined with radio occultation measurements of vertical temperature profiles will place important constraints on the horizontal gradients in temperature and composition. Measurements of the ortho-para hydrogen ratio and its variation with latitude will provide important information on the thermodynamic state of the wind layer and will be diagnostic of the vertical motion field. Measurements of zonal mean and eddy scale cloud velocities over several months of observations will characterize the zonal momentum balances. Studies of the motion of small-scale cloud features and waves will serve as an additional diagnostic of the wind structure at deeper levels.

3.4.2. **Capabilities of Cassini**

CIRS will provide horizontal temperature gradients in the upper troposphere and stratosphere that can be used in thermal wind analyses of the Saturn jet streams. This will permit characterization of the zonal wind field in both the troposphere and stratosphere, including inference of the vertical jet decay at high levels. Zonal thermal structure will be used to analyze tropospheric waves, while a combination of zonal structure and vertical structure with a resolution better than one scale height obtained from limb sounding and radio occultations will provide information on stratospheric wave propagation. These results, combined with a determination of possible latitudinal variations of hydrocarbon and ammonia abundances, can be used to define stratospheric circulation and transport. Extended visible imaging observations during dayside petal orbits of the Saturn disk will provide measurements of zonal winds in the upper troposphere and the localized motion of atmospheric waves and vortices (Porco et al., vol. 2).

Radio occultation measurements will provide data on the figure of Saturn, which, combined with improved determinations of the gravitational moments, will place important constraints on the rotational state of Saturn’s interior.
3.5. **Saturn’s Ionosphere**

3.5.1. **Scientific Problem:** Determine from radio occultations the diurnal variation of ionization. Establish the role of plasma transport as well as chemical processes associated with infalling of H$_2$O

Radio occultation observations from Pioneer 10 and Voyager 1 and 2 have established the existence of an ionosphere with a peak density of $\sim 2 \times 10^4$ cm$^{-3}$. In addition, the Voyager Planetary Radio Astronomy experiment (PRA) has provided an indirect measure of the diurnal variation of the peak ionospheric density through its observations of Saturn Electrostatic Discharges (SED), thought to originate from lightning in the lower atmosphere. The SED frequencies (which necessarily exceed the electron plasma frequency) also constrain the allowable diurnal variation to a maximum of greater than 10$^3$ cm$^{-3}$ around local noon and a minimum of less than 10$^3$ cm$^{-3}$ near dusk. Although these variations are suggestive of ion pair production by solar extreme ultraviolet radiation, there is an indication of rising electron densities during the night that is inconsistent with a simple photochemical explanation. It has been suggested that ion loss processes arising from the conversion of H$_+^+$ to H$_2$O$^+$ and H$_3$O$^+$, may be driven by an injection of H$_2$O from the icy rings. The possible role of plasma transport processes in controlling the height of the ionospheric peak also remains an unsolved problem. The recent discovery by ISO of CO$_2$ in addition to H$_2$O in Saturn’s upper atmospheric (Encrenaz et al., 1998) strengthens this interpretation and adds another molecule to be considered in this analysis.

3.5.2. **Capabilities of Cassini**

Repeated radio occultations of Saturn by the Cassini Orbiter are expected to provide a wealth of new ionospheric data. Ion chemistry (possibly including H$_2$O transport) can be studied by the UV spectrometer. CIRS will be able to map the destination of incoming H$_2$O or CO$_2$. SED’s containing ionospheric information will be observed by the plasma/radio wave experiment (Gurnett et al., vol. 2). Measurements of the polar wind and possible field-aligned flows from the ionosphere by the plasma instrument can provide direct information about the ion composition of Saturn’s ionosphere at high latitudes. Taken together, these data will contribute substantially to understanding the origin and variability of Saturn’s ionosphere.

4. **Summary**

It should be evident from this review that the capabilities of the spacecraft now on its way to Saturn and Titan are extraordinarily powerful and diverse. Additional details about the instruments on the probe, their scientific objectives and more background science for Titan can be found in the ESA Special Report (SP-1177) HUYGENS: Science, Payload and Mission (ed. J. P. Lebreton, ESA Publications,
# TABLE I
Organic Compounds Expected to Be Present in Titan’s Atmosphere

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Expected Mean Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrocarbons</strong></td>
<td></td>
</tr>
<tr>
<td>( \text{C}_3\text{H}_6 ) (propene) (^a)</td>
<td>(10^{-7}-10^{-8})</td>
</tr>
<tr>
<td>( \text{C}_3\text{H}_4 ) (allene) (^a)</td>
<td>(10^{-7}-10^{-8})</td>
</tr>
<tr>
<td>( \text{C}_3\text{H}_6 ) (cyclopropane) (^a)</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>( \text{C}_6\text{H}_2 ) (triacetylene) (^a)</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>( \text{C}_8\text{H}_2 ) (tetraacetylene) (^a)</td>
<td>(10^{-9}-10^{-10})</td>
</tr>
<tr>
<td>( \text{C}_4\text{H}_4 )</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>1,2-( \text{C}_4\text{H}_6 )</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>1,3-( \text{C}_4\text{H}_6 )</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>( \text{C}_4\text{H}_8 )</td>
<td>(10^{-8}-10^{-10})</td>
</tr>
<tr>
<td>( \text{n C}<em>4\text{H}</em>{10} )</td>
<td>(10^{-7}-10^{-9})</td>
</tr>
<tr>
<td>( \text{iso-C}<em>4\text{H}</em>{10} )</td>
<td>(10^{-7}-10^{-9})</td>
</tr>
<tr>
<td>( \text{C}_6\text{H}_6 )</td>
<td>&lt; about (10^{-9})</td>
</tr>
</tbody>
</table>

(related to \( \text{C}_2\text{H}_2 \) polymerization)

| **Nitriles**                           |                            |
| \( \text{C}_2\text{H}_5–\text{CN} \)    | < \(5 \times 10^{-7}\) \(^b\) |
| \( \text{CH}_2=\text{CH–CN} \)          | < \(2 \times 10^{-7}\) \(^b\) |
| \( \text{CH}_3–\text{CC–CN} \)         | < \(2.5 \times 10^{-7}\) \(^b\) |
| \( \text{n–C}_3\text{H}_7–\text{CN} \)  | < \(6 \times 10^{-8}\) \(^c\) |
| \( \text{iso–C}_3\text{H}_7–\text{CN} \)| < \(2 \times 10^{-8}\) \(^c\) |
| \( \text{cyclo–C}_3\text{H}_6–\text{CN} \)| < \(1.5 \times 10^{-8}\) \(^c\) |
| \( \text{HC}_5\text{N} \)              | < \(1.5 \times 10^{-8}\) \(^c\) |

| **O-Compounds**                        |                            |
| \( \text{HCO} \)                      | \(10^{-10}–10^{12}\)     |
| \( \text{H}_2\text{O} \)              | \(10^{-10}–10^{12}\)     |
| \( \text{CH}_3\text{OH} \)            | \(10^{-10}–10^{12}\)     |

\(^a\) May play an important role in Titan’s photochemistry and needs to be studied.

\(^b\) Likely to be in the range \(10^{-8}-10^{-9}\).

\(^c\) Likely to be in the range \(10^{-8}-10^{-10}\).

Noordwijk, The Netherlands, 1997) 364 pp. While the early hopes for a joint US/European mission to the Saturn System have been fully realized (Owen et al., 1983; Gautier and Ip, 1984; Owen et al., 1986), we regret that the planned follow-
up of a Saturn atmospheric probe (Owen et al., 1983, 1986; Swenson et al., 1987) is not in any current mission plan. Experience from the Jupiter probe has stressed the necessity of in-situ experiments if we are to achieve the level of precision required for meaningful comparative studies of the giant planets. In fact, it is now clear that we need missions with multiple probes to sample these atmospheres, so we can achieve a proper global picture. Multi-probe missions to all four giants, including Uranus and Neptune orbiters, are thus the logical next steps to follow Cassini-Huygens. Cooperation among the world’s space-faring nations will make such ambitious missions affordable, just as it has for Cassini-Huygens.

Acknowledgements


Appendix

Table I lists organic compounds not yet detected in Titan’s atmosphere but expected to be present at concentrations detectable from Cassini Huygens (Gautier and Raulin, 1997).

References


ORGANIC CHEMISTRY AND EXOBIOLOGY ON TITAN

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Abstract. Exobiology is not only the study of the origin, distribution and evolution of life in the universe, but also of structures - including at the molecular level, and processes – including organic chemical transformations - related to life. In that respect, with its dense nitrogen atmosphere, which includes a noticeable fraction of methane, and the many organic compounds which are present in the gas and aerosols phases, Titan appears to be a planetary object of prime interest for exobiology in the Solar system, allowing the study of chemical organic evolution in a planetary environment over a long time scale. We describe here some aspects of this extraterrestrial organic chemistry which involves many physical and chemical couplings in the different parts of what can be called 'Titan’s geofluid' (gas phase, aerosol phases and surface solid and maybe liquid phases). The three complementary approaches which can be followed to study such chemistry of exobiological interest are considered. Those are experimental simulations in the laboratory, chemical and photochemical modeling and of course observation, using both remote sensing and in situ measurements, which is an essential approach. The Cassini-Huygens mission, that offers a unique opportunity to study in detail the many aspects of Titan’s organic chemistry, is discussed and the many expected exobiological returns from the different instruments of the Cassini orbiter and the Huygens probe are considered.

1. General View

With a dense N$_2$-CH$_4$ atmosphere rich in organics, and the possible presence of hydrocarbon lakes on its surface, Titan appears to be a natural laboratory in which to investigate chemical evolution toward complex organic systems in a planetary environment over a long time scale. The Cassini-Huygens mission offers a unique opportunity to study in detail extra-terrestrial organic processes in this environment, and consequently this mission has important implications for the fields of exobiology and the origin of life on Earth.

1.1. EXOBIOLGY, EXTRA-TERRESTRIAL ORGANIC CHEMISTRY AND THE ORIGIN OF LIFE

Organic Chemistry is – generally speaking – the chemistry of carbon; it includes the chemistry occurring in living systems. With the development of space exploration, our knowledge of extra-terrestrial organic chemistry has been drastically
improved. It is now clear that organic chemistry is widely distributed in the universe. In particular, it is present on many planetary bodies of the outer solar system. Exobiology can be considered as the study of the origin, evolution and distribution of life in the universe. The synthesis and evolution of organics in planetary environments is an important aspect of Exobiology. It is one of the initial steps of the chemical evolution that must have preceded the formation of living systems on Earth. It is also an important source of organics in extra-terrestrial environments, such as Jupiter, Saturn and especially Titan.

Since the pioneering work of Stanley Miller (1953) demonstrating the possible abiotic formation of biomolecules as a part of the chemical evolution of a planetary environment, our knowledge of the processes that may have led to the emergence of life on our planet has been drastically improved. It now looks very likely that life appeared on the Earth after a long period of chemical evolution that preceded the development of terrestrial biology, involving the transformation of simple but reactive organic molecules, or their oligomers, into biomacromolecules through physical-chemical processes of increasing complexity. These organics, precursors of the prebiotic syntheses, are mainly small organic compounds with multiple bonds in their structures, such as nitriles and aldehydes, especially HCN, HC$_3$N, C$_2$N$_2$ and HCHO. The evolution of HCN in aqueous solution, through the formation of a tetramer, can produce adenine, one of the purine bases, which, like the pyrimidine bases, are the constituents of the nucleotides, building blocks of the nucleic acids in current living systems. HCN polymerization processes can also produce complex oligomers which, after hydrolysis, release purine and pyrimidine bases and amino-acids, the building blocks of proteins. Similarly, the chemistry of HC$_3$N in aqueous solution can produce pyrimidine bases while the aqueous chemistry of formaldehyde can produce the biological sugars (for a review, see Raulin, 1990). In addition C$_2$N$_2$ can act as a chemical agent, allowing the condensation of the monomers to form the biopolymers.

Thus from only a small number of different organic compounds as starting materials, the ‘prebiotic chemist’ can produce most of the building blocks of the biomacromolecules. However, extrapolation of those laboratory data to planetary environments is not obvious and many questions still remain to be solved. First, the possible origin of these organics on the primitive Earth is still controversial. They could have formed directly in the atmosphere, if it was reducing, or have been brought by meteoritic or cometary impacts (Chyba et al., 1990; Oro et al., 1997), or even have been formed together with biomonomers in primitive submarine hot springs (Shock et al., 1995, and refs. included).

How complex were the organics synthesized in the atmosphere of the primitive Earth? What were the relative roles of the different energy sources available in this environment, especially UV light and electric discharges? Were gas-solid chemical processes involved in the prebiotic chemistry? Were atmospheric organic syntheses efficient enough to provide the starting materials necessary for chemical evolution toward living systems? Did the dynamics of the atmosphere play a crucial role in
chemical evolution? What are the respective roles of the processes in gas phase and in solution and the influence of temperature? How far can prebiotic chemistry proceed in the absence of liquid water? More generally, to what extent can the results of laboratory experiments be extrapolated to the case of real planetary environments? By offering the possibility of studying on-going organic chemistry in a natural planetary environment over a very long period of time, the Cassini-Huygens investigation of Titan could provide answers to some of these questions.

1.2. TITAN

In spite of important differences (first of all from their surface temperatures), as pointed out by Clarke and Ferris (1997), several similarities between Titan today and the early Earth can be emphasized. In particular, both have a dense atmosphere, mainly composed of molecular nitrogen, and an environment very rich in organic compounds. Indeed, several of the conditions necessary for prebiotic chemistry to evolve toward complex organic systems are present on Titan:

1.2.1. A dense, mildly reducing atmosphere
Titan’s atmosphere is mainly composed (Hunten et al., 1984; Gautier, 1997; Gautier and Raulin, 1997) of nitrogen with a noticeable mole fraction of methane and a very low mole fraction of hydrogen. Simulation experiments in the laboratory (Table 1) suggest that such an atmosphere is one of the most favorable for the synthesis of organics (Raulin et al., 1982; Bossard et al., 1983; Thompson et al., 1991; Coll et al., 1995; de Vanssay et al., 1995).

1.2.2. The presence of methane
The existence of methane in Titan’s atmosphere is a major puzzle at present. This gas is destroyed so rapidly by photochemistry that the amount we see today will be gone in just $10^7$ years. Something must be replenishing this gas – a subsurface reservoir (tapped by volcanism?), or an external source (cometary impacts?). The presence of methane on Pluto and Triton poses a similar enigma (Cruishank et al., 1993; Owen et al., 1993). Given the probable importance of this gas for prebiological chemical evolution on Earth (Miller & Orgel, 1979; Sagan & Chyba, 1997; Kasting, 1997), understanding its origin on Titan has high priority.

1.2.3. The presence of several sources of energy in the atmosphere
UV light, energetic electrons from Saturn’s magnetosphere and cosmic rays, in particular, allow an efficient transformation of the main atmospheric constituents into more complex compounds (Strobel, 1982; Yung et al., 1984; Yung, 1987; Toublanc, 1992; Lara, 1993, Toublanc et al., 1995; Gautier, 1997).
TABLE I
Organics detected in Titan’s atmosphere and in simulation experiments related to Titan

<table>
<thead>
<tr>
<th>PRODUCTS</th>
<th>TITAN</th>
<th>UV</th>
<th>High energy (Arc &amp; Silent)</th>
<th>Elec. Discharges</th>
<th>Plausible prebiotic source of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>H, e, γ Room Temp. Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₆</td>
<td>M</td>
<td>M</td>
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<td>HC₄CN</td>
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</table>

M: main products; ≪: less abundant by one order of magnitude; ≪: by two orders or more.
(a): all isomers.
(b): only in low temperature silent discharge experiment (Coll et al., 1999).
1.2.4. *The presence of a low-temperature tropopause, coupled with the existence of atmospheric hazes*

The submicron particles of the haze may act as condensation nuclei, allowing the condensation of organics (Sagan and Thompson, 1984) and their transport, through aerosol precipitation, down to the surface of the planet (Figure 1). Such processes can protect the organics from further destruction in the gas phase (Frère, 1989; Frère et al., 1989) and could account for a noticeable loss rate of nitrogen (McKay, 1996).

1.2.5. *The possible presence of liquid hydrocarbons at the surface*

The principal product of atmospheric chemistry on Titan is ethane (Strobel, 1982; Yung et al., 1984; Lara et al., 1997). Ethane will condense at the temperature of Titan’s surface, as will propane and other photochemical products. One therefore anticipates ponds or lakes of liquid hydrocarbons at the surface, although a global ocean (Lunine et al., 1983; Lunine, 1993; Dermott and Sagan, 1995; Lunine, 1997; and refs. included) can now be ruled out by Earth-based observations (Griffith et al., 1991; Muhleman et al., 1993) including the more recent observations using adaptive optics (Combes et al., 1997), as well as HST observations (Smith et al., 1996). If they exist, such lakes may play an important role in Titan’s chemical evolution. By allowing partial or total dissolving of atmospheric organics, the liquid medium provides an additional way to protect the organics formed in the gas phase from destruction by the same sources of energy that produce them. In addition, high energy cosmic rays (Capone et al., 1983) reaching the surface of these hypothetical lakes or seas can induce new organic processes, involving the main constituents but also the dissolved minor species (Raulin, 1987; Dubouloz et al., 1989; and refs. included). In particular CO, and eventually NH₃ which could be synthesized from N₂-H₂ chemistry in the atmosphere or directly in the liquid bodies could lead to further syntheses. From this step, chemical evolution on Titan may have followed a very different path from that on the Earth (Raulin et al., 1992; 1995).

1.3. *Chemical couplings in Titan’s geofluid*

There must be strong couplings between the high atmosphere-low pressure and the lower atmosphere-higher pressure processes. Eddy diffusion should play an important role in these couplings, but the atmospheric aerosols will also contribute.

There must be similar strong couplings between the atmospheric processes occurring in the high atmosphere and the chemical evolution on Titan’s surface. The organic compounds formed by UV and magnetospheric electrons in Titan’s mesosphere and thermosphere, simple organics or hetero-oligomers, carried by diffusion down to the stratosphere act as condensation nuclei and induce the condensation of organic compounds of smaller molecular weight. The resulting particles precipitate down to the troposphere with dimensions increasing as altitude decreases. Their
Figure 1. Modelling of the low stratosphere aerosol: evolution of the chemical composition of the particle from 100 km down to the 50 km level (the corresponding particle size increases from about 0.3 μm up to a few μm).
layered structure is formed of compounds that are more and more volatile from their cores to their outermost layers. Haze particles in the stratosphere, they become hail in the high troposphere and rain in the low troposphere (Toon et al., 1988). These particles irreversibly carry most of the organics of very low vapor pressure from the high atmosphere down to the surface.

Because of such couplings, Titan’s organic chemistry must be considered as a whole. The Cassini-Huygens mission will have to study globally the chemical evolution going on in the three parts of what composes Titan’s prebiotic environment: the atmosphere, the aerosols and the surface. This total system could be called “Titan’s geofluid”.

Depending on the planetary environment, chemical evolution may proceed differently. On the primitive Earth in the presence of liquid water, prebiotic organic chemistry starting from simple reactive molecules allowed the emergence of life. On Titan, with very low temperature conditions, chemical evolution is still going on, but in the absence of liquid water. Studies of the prebiotic organic chemistry on this planetary body may provide information on the atmospheric processes that occurred on the primitive Earth. But such studies could also indirectly furnish important information on the role of liquid water in chemical evolution, since prebiotic chemistry on Titan has evolved in the absence of this universal solvent and source of oxygen atoms, which seems to be a requirement for the emergence of life as we know it. However, Titan’s hydrocarbon seas may have evolved in the presence of noticeable traces of dissolved ammonia, playing the role of water. If this were the case, there may be a pseudo-biochemistry still going on in Titan’s ocean (Raulin et al., 1992), where ammonia substitutes for water, and N-chemical groups substitute for O-chemical groups, giving ‘amono’ analogs (Molton, 1974) (Figure 2).

Is Titan’s chemistry even more complex than we expect? Are O atoms involved in the surface organic chemistry, because of dissolved CO and precipitated CO$_2$ (both CO and CO$_2$ are present in the atmosphere). Are there purine and pyrimidine bases present on Titan? Are there amino acids or their analogues? Are pseudopolypeptides included in Titan’s organic oligomers? To check such hypotheses and try to answer the many associated questions, it is necessary to study in detail Titan’s prebiotic geofluid. So far several organic compounds of prebiotic interest (i.e.: the evolution of which can yield bio-organics) have been detected in Titan’s atmosphere, but no bio-organics (such as amino-acids or purine or pyrimidine bases). If the Cassini-Huygens mission can demonstrate the presence of such organics on Titan, it will have strong implications for Exobiology.
2. Proposed Approaches and Expected Results

2.1. General Approach

To fulfill these objectives, we propose to use simultaneously and in a correlative way the data of most of the instruments on board the probe and several on the orbiter, in particular:

On the probe:
- GC-MS: The Gas Chromatograph-Mass Spectrometer will provide vertical concentration profiles of the main atmospheric constituents and of minor species, especially already detected and new organics, involved in the general evolution of Titan’s geofluid. If the probe survives the landing, the GC-MS will also give detailed information about the composition of any liquids or condensed volatiles that may be present on the surface.

- ACP/GC-MS: The Aerosol-Collector Pyrolyser coupled with the GC-MS will provide data on the chemical composition and relative abundances of the organic cores and condensed volatiles constituting the aerosols. If the probe survives the landing, this instrument can also examine the composition of liquid and solid volatile compounds that have accumulated on the surface.

Figure 2. Some biochemical molecules and their analogues in a 'no-O-but-N-atoms' biochemistry.
HASI: The Huygens Atmospheric Structure Instrument will provide temperature and pressure vertical profiles also essential to model the gas and aerosol phases.

DISR: The Descent Imager Spectral Radiometer will give information on the cloud structure and surface physical state and composition, but also on the photon fluxes versus altitude, crucial data to constrain photochemical modeling of the atmosphere.

SSP: The Surface Science Package will also provide data on the surface composition and physical state and on its main chemical composition, essential to model surface organic chemistry.

We will complement the probe results with observations from the orbiter that will continue through the duration of the mission. Through their coverage of the entire satellite, these observations will allow us to extend some of the probe results to global scales. The instruments of special interest for our purposes are:

A) VIMS: The Visual-Infrared Mapping Spectrometer will allow an examination of Titan’s surface through ‘windows’ between strong methane absorptions. In addition to searches for hydrocarbon lakes and aerosol drifts, this instrument can look for deposits of specific chemicals such as CO₂. It will also investigate lower atmosphere meteorology and help determine if there is an evident source for atmospheric methane (rapidly being depleted) and a hydrocarbon cycle, with clouds, rain and rivers of hydrocarbons.

B) The VIMS findings on the distribution of surface liquids will be supplemented by RADAR and Imaging Science System observations. The latter (ISS) will also help with lower atmosphere meteorology.

C) CIRS: The Consolidated InfraRed Spectrometer will search for additional trace constituents, thereby improving constraints on models of atmospheric photochemistry. It will also help define the vertical and horizontal distribution of these starting materials for prebiological chemical evolution.

The data provided by these instruments will be used, together with:

- Data from laboratory experiments simulating the evolution of models of the Titan atmosphere, carried out at low temperature. Such experiments are under development at LISA, with special emphasis on the products that have low stability at room temperature, but are stable at low temperature (Aflalaye et al., 1995; Coll et al., 1995; de Vanssay et al., 1995; Coll et al., 1997; 1999). These new experiments provide a much better simulation of conditions on Titan than the previous ones, as demonstrated by the recent detection of C₄N₂ (Coll, 1997; Coll et al., 1999); this compound was, before, the only trace organic observed in Titan’s atmosphere but not detected in Titan simulation experiments.

- Theoretical modeling, including photochemical modeling integrating chemistry and physics of the atmosphere.
2.2. GAS PHASE ORGANIC CHEMISTRY

From GC-MS data, it will be possible to obtain vertical concentration profiles of the already known atmospheric constituents, in particular CH$_4$, C$_2$H$_2$, C$_2$H$_6$, HCN, C$_2$N$_2$, HC$_3$N, CO, CO$_2$ and CH$_3$CN, but also those of many other, not yet detected organic compounds. The expected species include hydrocarbons such as butanes (C$_4$H$_{10}$), polynes (C$_6$H$_6$, C$_8$H$_2$) and higher hydrocarbons, and nitriles such as acrylonitrile H$_2$C$_2$HCN and HC$_4$CN (Figure 3). Data from HASI will also be taken into account, to check the presence or absence of electric discharges in the atmosphere, which may contribute locally to additional syntheses. Data on the winds and turbulence (Doppler wind Experiment) and on the clouds (DISR) will also be taken into consideration in the model, to constrain the meteorological parameters.

Using those data, together with the T.P. vertical profiles given by HASI, and with the help of kinetic modeling software currently used at LISA (FACSIMILE numerical integrator, which 'uses fixed-step implicit backward-difference predictor-corrector formulas of orders 1 to 5' (Curtis, 1979)), we should be able to develop a detailed model of the gas phase organic chemistry occurring in Titan’s atmosphere. Such modeling should allow us to verify the importance of the stratospheric pho-
tocatalytic dissociation of CH₄, and the effective coupling of UV and electrons in the primary processes of the chemistry of Titan’s atmosphere. But this modeling will also have to include the data from ACP/GC-MS related to the chemical composition of the cores of the atmospheric aerosols. The accurate measurement of the relative abundances of minor species, detected or not yet detected, will also provide information on the mechanisms involved in atmospheric organic syntheses. For instance, knowledge of the ratio of branched hydrocarbon chains/linear hydrocarbon chains, and an accurate assessment of the abundances and vertical distribution of the polyyynes (C₄H₂, C₆H₂,...) are important.

A particular emphasis will be given to CO and CO₂. The determination of the CO vertical concentration profile by GC-MS will provide information on the source of oxygen atoms on Titan, and, consequently, on the complexity of the satellite’s organic chemistry. For instance, if it is confirmed that CO is depleted in the high stratosphere relative to the troposphere, and if it appears that this is due to the presence of a source of CO on the surface (such as dissolved oceanic CO), then we can expect that oxygen is involved in the surface organic chemistry. Such a discovery would suggest that organic chemistry is more complex than expected, and that oxygenated purines or pyrimidines bases, or even amino-acids may be present in this medium. In addition, Ar and isotopic analyses by the MS part of the GC-MS instrument will provide information on the origin and evolution of Titan’s atmosphere. This will give additional indications on the possible presence of O-organics on Titan’s surface, depending on the origin of atmospheric CO.

The abundance of CO₂ at the surface of Titan will provide another constraint on the oxygen chemistry. The trace of CO₂ in the atmosphere is thought to be produced from CO by the reaction:

\[ \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \]

What is the source of the OH? With the discovery of H₂O in Titan’s upper atmosphere by ISO (Coustenis et al., 1998), it appears that most of the OH may come in to Titan by bombardment of ice particles. However, some of it could come from the dissociation of CO with subsequent attack of CH₄ by O(¹D) (Samuelson et al., 1983). Widespread, thick deposits of CO₂ would imply a large initial source of CO and the potential for additional oxygen chemistry (Owen and Gautier, 1989).

2.3. ORGANIC CHEMISTRY IN TITAN’S AEROSOLS

Using the data directly related to the gas phase, coupled with the temperature (T) and pressure (P) vertical profiles from HASI, it will be possible to model very accurately the condensation processes occurring in the stratosphere and troposphere.

ACP/GC-MS data will provide information on the bulk chemical composition of the stratospheric and tropospheric particles, with a discrimination between the cores of these particles and the outer layers of condensates. The chemical analysis
of the cores of the particles, by pyrolysis techniques, is of major importance for the scientific objectives.

The pyrograms obtained either with Pyr-MS or Pyr-GC-MS, give essential information on the nature of the pyrolysis fragments. This can be used to infer the chemical structure of the sample and as a guide to perform calibrations (by direct comparison of the pyrograms of standard samples with those of the unknown, using identical conditions of pyrolysis, and with the help of similarity coefficients, which can allow a secure identification). This technique has already been used successfully to analyze models of Titan's aerosol oligomers (Khare et al., 1981; 1984). Similar studies are developed by Raulin's team (Coll, 1997; Coll et al., 1997; Coll et al., 1999), using up-to-date gas chromatographic columns. Applied to Titan's aerosols, it will allow us to check if the core of the particle, assumed to be composed of oligomers formed in the high atmosphere, is constituted of only carbonaceous oligomers free of heteroatoms, or includes C+N oligomers. Such a measurement will have very important implications for our understanding of the primary processes occurring in the high atmospheric regions. It will be a way to determine the relative contributions of the photopolymerization and co-polymerization processes of CH₄, C₂H₂, C₂H₄ and HCN.

In addition, the use of an analytical pyrolysis cycle with several temperatures will allow evaporation and analysis of the volatile part of the collected aerosols without pyrolyzing either this part, or the core. With such analyses, it will be possible to detect minor atmospheric constituents undetectable in the gas phase, because they can be highly concentrated in the aerosol compared to the gas phase. It will also be possible to get information on the absolute quantity of aerosol collected in the atmosphere, and on the ratio of the core to the condensate parts. This will provide a major constraint for microphysical modeling of Titan's organic aerosol. Cloud structure data from DISR, and P,T vertical profiles, winds and turbulence data from HASI and DWE will also be used to constrain the models.

2.4. ORGANIC CHEMISTRY ON TITAN'S SURFACE

2.4.1. Organic Liquids

If there are lakes, ponds, rivers, etc. on the surface, it will be possible to derive their main composition from that of the atmosphere just above the surface, knowing temperature and pressure at the interface. This will be done by coupling the data related to the gas phase composition near the surface (GC-MS) with the data from HASI (T,P), assuming chemical equilibrium between the liquids and the atmosphere, provided the probe descent occurs over one of the ponds or lakes. The assumption of thermodynamic equilibrium will be checked by looking at the wind data (HASI and DWE), and at the atmospheric near surface mole fraction of C₂H₆ (GC-MS).

If the probe survives only a few seconds after impact into a liquid, the GC-MS will quickly provide information on the composition. We expect mostly semi-
quantitative measurements because of the possible selective vaporization of the samples and vapor transfer in the MS. Nevertheless, we will certainly be able to identify the main constituents. SSP will provide quantitative measurement of the index of refraction of the liquid, which is directly connected by an almost linear relationship to the $\text{CH}_4/\text{C}_2\text{H}_6$ ratio if these are the only two main constituents (Badoz et al., 1992). Comparisons of the values of primary liquid composition deduced from thermodynamical modeling of the liquid/atmosphere interface and the direct analyses from SSP and GC-MS will also allow us to check whether or not there is a quasi thermodynamic equilibrium between surface liquids and the atmosphere. The amplitude of the difference between model and observation can be correlated with the amplitude of the surface turbulence. This will provide information on the turbulence (zonal winds, temperature gradients, etc.) at the interface between ocean and atmosphere.

This set of data will also provide information on:

- The present and initial total volume of the lakes and ponds, since the current $\text{CH}_4/\text{C}_2\text{H}_6$ liquid ratio can be directly connected to the evolution of the liquid bodies;

- The average depth of the organic deposit at the bottom of the lakes and ponds, since that quantity is closely related to the temperature and main composition of the liquid;

By coupling the data characterizing the atmospheric aerosols to the data related to the main characteristics of the liquids, it is possible to deduce information on the minor constituents of the liquids. In particular, from an estimate of the flux of aerosols down to the surface, knowing their chemical composition, it will be possible to derive the downward flux of several of the minor atmospheric constituents to the surface. Then, knowing their solubility which can be estimated from thermodynamical calculations (Raulin, 1987; Dubouloz et al., 1989; Thompson et al., 1992), one can deduce for each of these solutes whether saturation is reached or not. In that case, their concentration should be equal to their solubility. Otherwise, if their downward flux is not high enough, their concentration is controlled by the flux. With a very fast surface sample analysis, GC-MS can also provide information on the nature and range of concentration of minor constituents. Comparison between the values given by thermodynamical calculations, and observed concentrations will give some indication about the presence of sinks or sources of minor constituents in Titan's lakes and ponds. This will also provide some clue about the occurrence of chemical reactions still going on in these liquids.

2.4.2. Solid Surface
Assuming the lander touches down on a solid surface, several different scenarios can be envisaged. The surface can have regions consisting of:
(a) A thick layer of fluffy material, consisting of aerosols that have ‘rained out’ of the atmosphere, accumulating as drifts in low-lying areas protected from near-surface winds.

(b) Exposed deposits of CO₂ ice, or terrains frosted by CO₂.

(c) Exposed H₂O ice, ‘bedrock’ possibly sculpted by rains and rivers of liquid hydrocarbons.

(d) Accumulations of debris impacting objects. In particular they could be dark carbon-rich icy fragments from Hyperion.

(e) Combinations of the above, such as drifts of aerosols cemented by hydrocarbon rains, overlying impact debris and frosted by CO₂.

The recent HST and ground-based observations of Titan’s surface (Smith et al., 1996; Combes et al., 1997) suggest that we may obtain some better information about these various possibilities before the Huygens probe is deployed in 2005. Observations of Titan with the Arecibo radar that will become possible in the next few years will add to this knowledge. However, all of these data will be obtained at resolutions that are far too coarse to predict exact conditions at the landing site.

If the probe survives the impact of landing, the GC-MS should be able to provide a chemical analysis of any of the candidate materials we have described. This could be one of the most important sets of data returned by the Cassini-Huygens mission. The GC-MS has a heated inlet tube that extends several mm beyond the probe’s outer skin. A landing in a fluffy drift of aerosols would therefore provide access to an unusually concentrated sample of the organic compounds that the atmosphere of Titan has produced during many hundreds of millions of years. Even a successful touchdown on water ice could provide useful information. The value D/H in crustal H₂O on Titan will provide a fundamental constraint on hypotheses for the origin of Titan’s methane: Was this gas formed on the satellite by impacts during accretion or was it formed in the Saturn sub-nebula and trapped in the icy grains from which Titan was subsequently made?

In addition to the GC-MS measurements, SSP, DISR and Radar data may also provide some indications on the chemical nature of the landing point. And, by subsurface sounding with the Radar, Cassini may be able to detect the presence of liquids or solids below the layer of fluffy material.

If the surface is made of solid rocks, (considered highly improbable), it is likely that the main information on the surface will be given by DISR data, just before the impact. If that information is unambiguous and clearly shows the presence of such a solid surface, then we will be faced with a number of tough questions: What is the source of those rocks? Where is the expected liquid ethane? Where is the methane reservoir?
3. Exobiological Conclusions

The Cassini-Huygens mission offers a unique opportunity to study the origin, nature and evolution of organic compounds as well as their distribution in the different parts of what could be called Titan’s ‘geofluid’. This includes the gas phase, liquid phase (seas, lakes), solid phase (sedimentary deposits) and condensed atmospheric phases (aerosols). All the instruments planned on board the probe, (and many of the instruments on the orbiter) will collect data of crucial importance for our understanding of Titan chemistry, especially organic chemistry.

By coupling these observational data with experimental (laboratory simulation) and theoretical (photochemical, microphysical and thermodynamical modeling) data, it will be possible to study and model:

- organic chemistry in Titan’s atmosphere, using kinetics and thermodynamics, and with the help of laboratory simulation experiments: nature, mechanisms of formation, relative abundances, distribution and level of complexity of the organic compounds in the gas phase.

- Titan’s aerosols: their formation, their chemical composition and structure, their vertical distribution, their possible chemistry, and evolution on the surface of Titan.
Titan’s lakes and ponds: their physical characteristics, chemical composition, the possible organic chemistry which can occur in this cold liquid medium under the action of high energy cosmic rays.

the interactions between the different parts of Titan’s ‘geofluid’ (Figure 4).

the consequences of these results for our theories of the origin of life on the Earth, and more generally for chemical evolution throughout the universe. These approaches will be developed in a complementary way. The Cassini-Huygens mission through its development, has already induced a large increase in the number of research programs devoted to Titan’s organic chemistry. Such current studies strongly demonstrate the importance of the implications of Titan’s organic chemistry in the field of exobiology and the origins of Life. They also show that many research groups want to contribute to the development of the mission, and to preparing the scientific community to use the mission data in an optimized way as soon as the Cassini-Huygens data will be available.

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References


THE CHARACTERISATION OF TITAN’S ATMOSPHERIC PHYSICAL PROPERTIES BY THE HUYGENS ATMOSPHERIC STRUCTURE INSTRUMENT (HASI)


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Abstract. The Huygens Atmospheric Structure Instrument (HASI) is a multi-sensor package which has been designed to measure the physical quantities characterising the atmosphere of Titan during the Huygens probe descent on Titan and at the surface. HASI sensors are devoted to the study of Titan’s atmospheric structure and electric properties, and to provide information on its surface, whether solid or liquid.

1. Introduction

The Huygens Atmospheric Structure Instrument (HASI) is one of the six experiments comprising the payload of the Huygens probe, which will be released by the Cassini spacecraft to descend onto Titan. During the descent and after the
landing, the instrumentation on board the probe will make measurements to investi­gate Titan’s environment. HASI has been designed to measure the physical quantities characterising Titan’s atmosphere, including the density, temperature, and pressure profiles, winds, turbulence and electric properties. HASI data will also contribute to the analysis of the atmospheric composition and provide information on the surface, whatever its phase: liquid or solid. HASI will monitor the acceleration experienced by the probe during the entire descent phase and will provide the only direct measurements of the ambient atmospheric pressure and temperature through sensors having access to the atmospheric flow. Electrical measurements will be performed in order to characterise the electrical environment on Titan and to detect effects connected to electrical processes, such as lightning and thunder. In situ measurements are essential for the investigation of the atmospheric structure and dynamics. Estimates of the temperature lapse rate can be combined with composition measurements to identify the presence of condensation and clouds, to distinguish between saturated and unsaturated, stable and conditionally stable regions. Variations in the density, pressure and temperature profiles constrain the atmospheric stability and stratification, thermal tides, waves and turbulence in the atmosphere. Moreover, the descent profile can be derived from temperature and pressure data as a function of pressure and altitude. The return signal of the Huygens radar altimeter is processed by the HASI electronics, providing an independent estimation of altitude and the spectral analysis of the signal yields information on the satellite’s surface.

In addition the HASI in situ measurements will provide a high-resolution reference for calibration of some remote sensing observations from the orbiter and the measurements of other Huygens experiments.

HASI is a multifunction experiment package originally proposed as an international collaboration including 17 institutions from 11 countries. HASI has been funded by the Italian Space Agency (ASI) and by other European institutions that provided hardware elements. The HASI subsystems and elements have been designed, developed, and built in the different institutes and by Officine Galileo (OG), Firenze, Italy.

2. HASI Subsystems and Sensor Packages

The HASI experiment is divided into four subsystems: the accelerometers (ACC); the deployable booms system (DBS); the stem (STUB) carrying the temperature sensors, a Kiel probe pressure sampling inlet, an acoustic sensor, and the data processing unit (DPU). The HASI subsystems, their acronyms, the institutions responsible for the management (together with the providers) and the elements included are summarised in Table I.

The scientific measurements are performed by four sensor packages: the accelerometers (ACC), the temperature sensors (TEM), the Pressure Profile Instrument
TABLE I
HASI subsystems

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Responsible Institutions (Providers)*</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployable Boom System (DBS)</td>
<td>SSD (LPCE/SSD)</td>
<td>PWA electrodes, Boom Magnetic Actuators, PWA preamplifiers (HASI-I)</td>
</tr>
<tr>
<td>Fixed stem (STUB)</td>
<td>UPD (UPD/FMI/IWF)</td>
<td>Temperature sensors, PPI Kiel probe, acoustic sensor</td>
</tr>
<tr>
<td>Accelerometers (ACC)</td>
<td>UKC (UKC)</td>
<td>Four accelerometers</td>
</tr>
<tr>
<td>Data Processing Unit (DPU)</td>
<td>OG (FMI/IWF/IAA/OG)</td>
<td>Electronics boards</td>
</tr>
<tr>
<td>Electrical Ground</td>
<td>OG (UPD/OG)</td>
<td>EGSE</td>
</tr>
</tbody>
</table>

*Refer to the authors’ affiliation for institute acronyms.

(PPI) and the Permittivity, Wave and Altimetry package (PWA) (see Table II). The block diagram of the HASI experiment is reported in Figure 1.

TEM, PWA sensors and the Kiel probe of PPI are mounted outside the Huygens probe by means of booms attached to the probe ring. The other HASI elements are placed on the probe experiment platform; see Figure 2 for HASI accommodation on the Huygens probe.

2.1. HASI SUBSYSTEMS

2.1.1. The Accelerometer Box (ACC)
The Accelerometer subsystem (ACC) consists of a small box (60×80×70 mm) placed at the centre of mass of the descent module of the Huygens probe (see Figure 3). The box contains four accelerometers, two temperature sensors and their conditioning electronics and is connected via a cable to the DPU where acceleration data are handled.

2.1.2. The Deployable Boom System (DBS)
The Deployable Boom Subsystem (DBS) consists of two units with release mechanisms, each carrying three PWA electrodes connected to two pre-amplifier boxes (HASI-I). The booms are stowed under the thermal shield during the interplanetary cruise and are released by a magnetic actuator (MCA) and deployed by a coil spring, at the beginning of the descent in Titan’s atmosphere (Figure 4).

The PWA sensors on each boom consist of two rings forming the receiving and transmitting antennas of the mutual impedance experiment (RX & TX), and a disk for relaxation probe measurements (RP) (see Figure 5). The receiving and the relaxation probes are connected to the preamplifiers contained in the HASI-I boxes (Grard et al., 1995).
HASI

Figure 1. Block diagram of the HASI experiment on the Huygens probe in descent configuration (for acronyms refer to Tables I & II).

2.1.3. STUB
The STUB consists of a stem fixed on the Huygens ring (Figure 6), which is under the thermal shield of the Huygens probe during cruise phase. The STUB ensures that the sensors (two thermometers and a Kiel probe) are appropriately located and oriented with respect to the gas flow during the measurements. A microphone, the PWA acoustic sensor, is fixed on the STUB flange.

2.1.4. Data Processing Unit (DPU)
The DPU is the HASI electronics box located on the Huygens experiment platform close to the STUB. It is composed of four functional blocks:
  - the PPI electronics board containing the pressure heads and the conditioning electronics;
  - the Radar Altimeter Extension (RAE) board which is mounted on the PPI board and processes the return signal of the Huygens proximity sensor, before these data are spectrally analysed by the PWA electronics;
  - the Permittivity, Wave and Altimetry (PWA) block (composed of two boards: analogue and digital) which provides the analogue signal conditioning and data conversion and processing for all PWA sensors;
  - the Experiment Power Data Handling block (composed of four boards and one motherboard), which provides the power supply for the HASI subsystems, interaction between the electronics boards, TEM and ACC sensors conditioning
Figure 2. HASI subsystems accommodation on the experiment platform of the Huygens probe. TEM, PWA sensors and the Kiel probe of PPI are mounted outside the Huygens probe. The booms, carrying the PWA sensors, are stowed under the thermal shield of the probe during the interplanetary cruise and are deployed at the beginning of the descent into Titan’s atmosphere. The STUB ensures that the temperature sensors and pressure inlet are appropriately located and oriented with respect to the gas flow during the measurements. The ACC box is located on the Huygens probe experiment platform, at the centre of mass of the Huygens probe in entry configuration.
### TABLE II
HASI sensor packages

<table>
<thead>
<tr>
<th>Sensor package</th>
<th>Acronym</th>
<th>Sensor type</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>Measured parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometers*</td>
<td>ACC</td>
<td>3-axes accelerometer (1 X-servo &amp; 3 piezo-resistive accelerometers)</td>
<td>1%</td>
<td>1–10 μg (high res.)</td>
<td>Atmospheric deceleration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9–9 mg (low res.)</td>
<td>Descent monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Response to impact</td>
</tr>
<tr>
<td>Pressure Profile Instrument</td>
<td>PPI</td>
<td>Kiel type pressure probe + capacitive transducers</td>
<td>1%</td>
<td>0.01 hPa</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>Temperature sensors</td>
<td>TEM</td>
<td>2 dual element Pt thermometers</td>
<td>0.5 K</td>
<td>0.02 K</td>
<td>Atmospheric temperature</td>
</tr>
<tr>
<td>Permittivity, Wave and Altimetry</td>
<td>PWA</td>
<td>Mutual Impedance AC field measurement</td>
<td>10%</td>
<td>10⁻¹¹ (Ωm)⁻¹</td>
<td>Atmospheric electric conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 μV/m (threshold)</td>
<td>Wave electric fields and lightning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relaxation probe</td>
<td>10%</td>
<td>1 min</td>
<td>Ion conductivity &amp; DC electric field</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25 ms</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 mV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(threshold)</td>
<td></td>
</tr>
<tr>
<td>Acoustic sensor</td>
<td></td>
<td></td>
<td>5%</td>
<td>10 mPa (threshold)</td>
<td>Acoustic noise due to turbulence or storms</td>
</tr>
<tr>
<td>Radar signal processing (FFT)</td>
<td></td>
<td></td>
<td>1.5 dB</td>
<td>40 m @ 24 km</td>
<td>Radar echoes below 60 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figures for resolution and accuracy are for the X servo accelerometer.

and data conversion, data acquisition and processing, and experiment data handling to the Probe Command Data Management System.

### 2.2. HASI SENSOR PACKAGES

#### 2.2.1. ACC
The Accelerometer subsystem consists of one highly sensitive single axis accelerometer (servo) and three piezoresistive accelerometers. The accelerometers are aligned parallel and perpendicular to the Huygens probe axis of symmetry. The servo is mounted at the Huygens probe’s centre of mass, in order to sense change in acceleration along the probe’s descent axis (X axis). The three piezoresistive accelerometers are mounted orthogonally, oriented along the probe’s X, Y, and Z
axes. Temperature measurements are carried out by two AD 590 sensors in thermal contact with the accelerometers.

The servo accelerometer (Sundstrand QA-2000-030) senses the displacement of a seismic mass and drives it back to a null position; the required current is a direct measurement of acceleration. This package is gas filled and sealed to provide damping of the proof mass when deflected. The servo accelerometer output is amplified by two non-inverting amplifiers providing two channel outputs. In addition, the two channels have a switchable range (high and low resolution) by means of a single analogue switch. The absolute accuracy of the sensor is ±35 μg in high resolution, high gain. The resolution is 1 to 10 μg, depending on the mode.

The piezo accelerometers (Endevco 7264A-2000T) consist of a suspended seismic mass supported by a cantilever whose displacement is determined by two strain-dependent resistances. The accelerometer is part of a Wheatstone bridge; the variation in voltage output produced when an external voltage is applied is dependent on acceleration. The strong dependence on temperature is compensated through the temperature measurement of the AD 590 sensor. The piezo accelerometers can resolve 0.1 g and provide an absolute accuracy of ±0.4 g. The accuracy of the temperature diodes is ±0.5 K.
2.2.2. TEM
The HASI temperature sensors (TEM) are dual element platinum resistance thermometers (Ruffino et al. 1996; Angrilli et al., 1996), manufactured by Rosemount Aerospace Inc., Minnesota, U.S. Each unit (Figure 7) is composed of a platinum-rhodium truss cage frame exposing the two sensing elements to the atmospheric flow. The principal sensor (fine) is a double platinum (Pt 99.999%) wire of 0.1 mm in diameter and 2 m in length, wound around a Pt-Rhodium frame from which it is insulated by a thin layer of glass. The secondary (coarse) sensor, designed as a spare unit in the case of damage on the primary sensor, is a thinner Pt wire (0.02 mm) annealed in the glass on the frontal side of the upper part of the frame. In order to include the TEM units in the global Huygens Faraday cage and to reduce electric noise, the sensors are coated with 25 μm of paralyne and 1 μm of gold. The two redundant TEM units are mounted on the STUB. The TEM sensors can resolve 0.02 K with an accuracy of 0.5 K at the best.

2.2.3. Pressure Profile Instrument (PPI)
The Pressure Profile Instrument includes sensors for measuring the atmospheric pressure during descent and surface phase (Harri et al., 1998). The atmospheric
Figure 5. One component of the Deployable Boom System with the PWA sensors. In Figure A, the boom is locked (cruise configuration under the thermal shield). In Figure B, the boom is deployed (descend configuration). The three PWA electrodes are visible: the two rings are elements of the receiving antenna (RX, at the tip) and transmitting antenna (TX) for mutual impedance measurements; the disk forms the relaxation probe (RP). The RX and RP electrodes are connected to the preamplifiers contained in the HASI-I boxes (visible in Figure A on the probe experiment platform).
Figure 6. View of the flight model of the HASI STUB fixed to the Huygens probe ring during the testing and verification campaign.

Figure 7. TEM sensor.
flow is conveyed through a Kiel-type pressure probe accommodated within a pitot tube, mounted on the STUB stem end, and is connected with a tube to the DPU, where the transducers and the related electronics are located (Figure 8). The Kiel probe has been designed to provide accurate measurements of total pressure (environmental plus kinetic pressure) even for variations in a flow inclination angle up to 45°. The pressure transducers are silicon capacitive absolute pressure sensors (Barocap) produced by the Vaisala Co, Helsinki, Finland. The Barocap consists of a small sensor head with associated transducer electronics. The varying ambient pressure deflects a thin silicon diaphragm in the sensor head, causing changes in the separation of two capacitive plates. The capacitance variation is converted into an oscillation frequency in the PPI electronics. Three types of Barocap, characterised by different thickness of silicon diaphragm, are used in order to cover the measurement range. The sensors with the thinnest diaphragms are used for high resolution, in the range $10^{-3} - 10^{-2}$ hPa. The temperature dependence of the Barocap response is compensated by measuring the sensor temperature with Thermocap sensors. PPI sensors are connected to three oscillator blocks based on Vaisala Multicaps, each having eight frequency input channels. The first group contains sensors for intermediate pressure measurements with sensibility range from 0 to 1200 hPa, the second group for high pressure (0–1600 hPa) and the third for low pressure (0–400 hPa). In each Multicap, two channels are reserved for reference capacitors, R1 and R2, used for the reconstruction of pressure measurement; the other channels are
for sensors (Barocap and Thermocap). The accuracy of the pressure measurement is about 1% and the maximum resolution is 0.01 hPa.

2.2.4. **Permittivity, Wave and Altimetry package (PWA)**

The PWA sensors are six electrodes and an acoustic pressure transducer (Grard et al., 1995). After the deployment of the booms, the two couples of the mutual impedance transmitter (TX) and the receiver (RX) electrodes form a trapezoid in the plane of the Huygens probe X-axis. The mutual impedance is measured by applying a sine wave pulse with amplitude 0.1–10 V at fixed frequencies (from 45 Hz up to 5.7 kHz after impact) on the two TX electrodes; amplitude and phase of impedance are computed using the analysis of the RX electrodes differential signal. A Fast Fourier Transform (FFT) is performed every 60 ms, with a 45 Hz spectral resolution in a 9.5 kHz bandwidth. The RX signal is also used in a passive mode to detect natural waves. The PWA quadrupolar probe will measure atmospheric electric conductivity due to the free electrons and detect wave emission in atmosphere and related phenomena such as lightning. Quasi-static electric field and ion conductivity will be measured through the relaxation probe. Positive and negative potentials will be applied between the descent module and the relaxation probe during a period of 1 s, every 1 min by closing switches; when the switches are open, the sensors and the vehicle discharge independently and return to their equilibrium potentials. From the measurement of these potentials as a function of time, positive and negative ion conductivities can be derived and the free electrons detected, if any. The relaxation electrodes are grounded at the end of the measurement sequence.

The acoustic sensor, mounted on STUB will detect sound waves to correlate with acoustic noise, turbulence, and meteorological events (pressure level threshold: 10 mPa).

The radar return signals of the Huygens Proximity Sensor, containing information on surface properties and altitude, are processed also by the Radar Altimeter Extension (RAE) board in the HASI experiment. The Huygens Proximity Sensor is composed of two Frequency Modulated Continuous Wave (FMCW) altimeter radars with redundant channels at 15.4 and 15.6 GHz respectively, operated to keep the intermediate frequency (IF) at 200 kHz. The transmitted signal is modulated in frequency with rising and falling ramp waveforms. Inside the RAE board, the radar return signal is converted to 10 kHz and filtered before passing to the PWA A/D converter and signal processor. The Huygens radar input signals in HASI/PWA (Figure 9) are the digital blanking signal and the analogue intermediate frequency signal (echo signal). The blanking signal is used to control the radar lock status and contains the altitude information, while information on surface properties can be retrieved from the analysis of the echo signal.

The PWA signal processor performs FFT, digital integration and data packetising and controls the data acquisition. The operational mode, and therefore the FFT analysis type, is selected depending on the altitude levels. An averaged spec-
Figure 9. Radar signals of the Huygens proximity sensor transmitted to HASI for processing and elaboration.

Spectrum is calculated separately for the rising and the falling ramp because of Doppler shift. Spectrum and altitude information of the return signal are added to the HASI data stream.

3. HASI Operations and Measurements

HASI will be the first instrument to perform measurements during the probe entry phase in Titan’s atmosphere. HASI is switched on during the coast phase of the Huygens probe to Titan, ten minutes before the beginning of the entry phase. At two minutes after switch-on and during the entire high-speed entry phase, from an altitude 1300 km down to 160 km (~4 min duration), acceleration data are sampled. After the probe has decelerated to Mach ~1, the entry phase ends and the probe device deployment sequence begins. In a period of three minutes the pilot parachute is fired to lift off the probe aft cover and inflate the main parachute; the frontal thermal shield is released falling away. From this moment, starting from 160-km altitude, the Huygens scientific instruments are exposed to Titan’s
atmosphere. The probe descent continues on parachute. At 120-km altitude, the main parachute is cut away and replaced by a smaller one. The complete descent will last 2 h and 15 min. At least, another 15 min are foreseen to perform surface measurements after landing, before the batteries run out and/or the probe relay link to the orbiter is lost. The Huygens mission scenario is reported in Figure 10.

Given the atmospheric mean molecular weight and the probe aerodynamics, vertical profiles of density, pressure, and temperature can be derived from the three axes accelerometer data (Seiff et al. 1980, 1997b, 1998). About one minute after the frontal shield release, the HASI booms are deployed and direct measurements of pressure, temperature and electrical properties are performed.

The sampling of HASI sensors is driven by a predetermined time sequence that is triggered by environmental conditions during descent. Proximity sensor sampling will start at 60-km altitude, but the probe system will continue to use the altitude table until both the radars lock (anticipated to be at about 30 km). In that part of the atmosphere, PPI will switch from low to medium sensitivity channels and then to its high-pressure channel. The PPI measurement cycle is organised in a sequence of normal and burst sessions; in normal mode, 9 samples are recorded in 43.2 s and average and standard deviation of five values are computed, in burst mode 19 samples for sensor are recorded in six seconds. The effective temporal resolution is between 2.4 and 4.8 s.
In the last km (HASI impact mode) the ACC will be reset to impact detection, acceleration data will be stored for transmission after the impact. In this last part of the atmosphere, only the TEM fine sensors will be sampled every 1.25 s in order to achieve a better vertical resolution. The normal sampling (4 measurements alternating fine and coarse sensors sample of TEM1 and 2 on a period of 5 s) will be selected again at the surface.

4. HASI Contribution to the Huygens Trajectory Reconstruction

Reconstruction of the probe entry and descent trajectory is needed in order to correctly interpret and correlate the results from all Huygens science experiments and to calibrate the remote sensing measurements from the orbiter instruments. HASI will measure the atmospheric pressure and temperature as well as the profile of axial and normal accelerations during the Huygens descent in Titan’s atmosphere, so that it will mainly contribute to the descent trajectory reconstruction analysis. Its acceleration data and then direct pressure and temperature measurements will provide fundamental information for reconstructing the height versus time profile.

Using the assumptions of hydrostatic equilibrium and the equation of state, pressure and temperature will be used to determine the probe descent velocity. During the entry phase, the determination of the atmospheric vertical profiles requires the reconstruction of the probe trajectory and of the velocity temporal history. The probe trajectory and attitude can be reconstructed by analysing vehicle acceleration by an accelerometer aligned parallel and perpendicular to the probe symmetry axis. During the high-speed entry phase, the probe entry track, velocity and altitude profiles, and attitude will be retrieved from acceleration data in redundancy with the measurements of the Huygens housekeeping accelerometers (these sensors are less accurate than the HASI ones).

During the descent, temporal velocity and altitude profiles will be derived from the pressure and temperature measurements performed by the HASI PPI and TEM, while the data of the three-axial accelerometer ACC will contribute to determine the probe drift and its motion induced by rotation and turbulence. In addition, the HASI elaboration of the radar return signal will provide an independent estimation of probe altitude and descent velocity in the troposphere approximately beneath 30 km. In the first part of the Huygens mission, during the probe entry in atmosphere (from about 1300 km to 160 km), the equations of motion will be integrated using the accelerometer data to derive probe velocity, flight path and azimuth angle as a function of time, starting from the probe initial conditions derived from navigation data and possibly imaging by the Cassini camera.

The parachute deployment and separation sequence and the opening of the thermal shell of the probe will imply an uncertainty on the trajectory determination. The accelerometer measurements could be saturated because of the pyro shocks, the cover releases, the chute deployment and separation and the jettison of the
thermal frontal shield beneath the probe could strongly affect the free fall of the probe, which in a few seconds (about 60 s) is changing its configuration. Then the probe will continue its descent dragged by the main parachute. From this point on, probe descent velocity can be derived primarily from HASI measurements of pressure and temperature, the assumption of hydrostatic equilibrium and the equation of state, and the known mean molecular mass (e.g., derived from the speed of sound measured by SSP):

\[
\frac{dz}{dt} = \frac{RT}{\mu g} \frac{\partial \ln P}{\partial t}
\]

(1)

Height versus time profile can be derived integrating the descent velocity or the hydrodynamic law:

\[
z = \int_{P_0}^{P} \frac{RT \ dP}{\mu g \ P}
\]

(2)

where \( P_0 \) is the pressure at the surface level. These techniques have been applied in the atmosphere of Mars, Venus and Jupiter (Seiff et al., 1980, 1997b, 1998).

In the lower atmosphere the Huygens radar altimeter, starting approximately at 33 km (the altitude at which the lock of the radar signal is foreseen), will derive the altitude from surface level and the descent velocity. The integration process of the equations of motion for the trajectory reconstruction is continuous, iterative and inverse, from the surface up to the beginning of the descent. The satellite surface is the lower boundary condition of zero velocity and ‘known’ altitude used to correctly scale the estimated values.

5. HASI Expected Results

The scientific measurements performed by HASI are designed to characterise Titan’s environment. The main scientific objectives are:

- Determine the atmospheric pressure and temperature profiles.
- Evaluate the density profile and molecular weight profiles.
- Determine the atmospheric electric conductivity and charge carrier profiles.
- Investigate ionisation processes.
- Survey the wave electric fields, atmospheric lightning and analyse the quasi-static electric fields leading to storm formation.
- Detect acoustic noise due to turbulence or thunder.
- Characterise the roughness, mechanical and electric properties of the surface material, whatever its phase, solid or liquid.

The three-axis accelerometer ACC, placed at the centre of mass of the Huygens probe, will record the atmospheric deceleration and the impact trace with a resolution as high as 1 \( \mu \)g. The total pressure and temperature will be monitored by
the PPI and TEM sensors, which sample the undisturbed field outside the probe boundary layer. The Kiel probe and the PPI capacitive gauges will sample the pressure with a resolution of 0.01 hPa, while the platinum wire thermometers, TEM, will measure temperature with an accuracy of 0.5 K and a resolution of 0.02 K.

HASI deceleration data will provide information about the energetic balance of the thermosphere and will contribute to the investigation of the physical conditions of the high stratosphere where methane dissociation takes place and the haze is formed (Hunten et al., 1984). About 1 min after the Huygens frontal thermal shield separation, at a height level of about 160 km, the HASI booms will be deployed and direct measurements of pressure, temperature and electrical properties will be carried out through Titan’s stratosphere and troposphere, down to the surface, for the entire duration of the descent (nominally 2 h and 15 min) and for at least 15 min after landing.

HASI data will contribute also to other investigations of Titan’s environment, such as atmospheric composition analysis and the study of the vertical distribution of organic and inorganic compounds. Moreover they will provide a reference for the calibration of some remote sensing observations from the orbiter (i.e. radio occultation, IR spectroscopy) and measurements of other experiments on-board the Huygens probe.

5.1. Atmospheric Structure

Determination of temperature and pressure profiles, also combining HASI measurements with data of other experiments, will help to define the atmospheric structure (Lellouch et al., 1990; Yelle, 1991), layer by layer composition (in particular to evaluate the CH₄ mixing ratio in the saturation region), the vertical concentration profile of organic and inorganic compounds (Coustenis et al., 1989, 1991, 1995a; Lara et al., 1996), and the partial pressure of saturated gas in order to detect the presence of tropospheric clouds (Toon et al., 1988) or supersaturation layers (Courtin et al., 1995).

During the entry phase in Titan’s atmosphere, the information on density, pressure and temperature will be derived indirectly from ACC deceleration measurements. In this phase the typical scale height \( H = \frac{RT}{\mu g} \) of Titan’s atmosphere is thought to be about 40 km; the descent velocity is expected to vary from 6200 m s⁻¹ to 400 m s⁻¹ (Table III). In order to obtain a good resolution, three or four measurements per scale height are necessary (Fulchignoni et al., 1997). The atmospheric density is directly related to the aerodynamic deceleration of the probe \(-a_p\):

\[
\rho(z) = -\frac{2ma_p}{C_D A V_r^2}
\]

where \( m \) is the mass of the entry vehicle, the aerodynamic drag coefficient \( C_D \) and the probe cross section area \( A \) are constants known from ground tests. \( V_r \) is the
probe velocity relative to atmosphere. Combining (3) with the hydrostatic equation, and knowing the molecular mean mass, temperature can be calculated. The pressure and temperature profiles measured during the descent can be incorporated into the hydrostatic law, to calculate the absolute heights from the surface of Titan as a function of time. These techniques have been applied for the investigation of other planetary atmospheres, e.g., Venus by Pioneer probes (Seiff et al., 1980), Mars by Pathfinder (Seiff et al., 1997b; Schofield et al., 1997), Jupiter by Galileo probe (Seiff et al., 1998).

Pressure and temperature measurements obtained during the parachute descent phase must be corrected taking the dynamic conditions into account. The dynamic correction of the measured profiles can be carried out with an iterative process described in Fulchignoni et al., (1997).

During the entry phase HASI will perform on average one acceleration measurement every 128 m; from these data, information on the upper stratosphere will be derived in order to investigate the physical conditions present in the region

### TABLE III
HASI Timeline, probe events and related dynamic conditions during the Huygens mission

<table>
<thead>
<tr>
<th>Time</th>
<th>Mission</th>
<th>Altitude</th>
<th>Vertical velocity</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>(min)</td>
<td>time</td>
<td>(km)</td>
<td>(m s(^{-1}))</td>
<td>(m s(^{-2}))</td>
</tr>
<tr>
<td>COAST</td>
<td>T0 − 22d 5 mn</td>
<td>Tsep</td>
<td>Probe separation from Orbiter</td>
<td></td>
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<tr>
<td></td>
<td>T0 − 18 mn</td>
<td>Tp</td>
<td>Probe power-up and CDMS activities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T0 − 10 mn</td>
<td>THasi</td>
<td>HASION (17:46 preT0)</td>
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<td></td>
<td>T0 − 8 mn</td>
<td>Tacc</td>
<td>ACC sampling start</td>
<td></td>
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<tr>
<td>ENTRY</td>
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</tr>
<tr>
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<td>max acc</td>
<td>4.13</td>
<td>170.24</td>
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Probe separation from Orbiter
Probe power-up and CDMS activities
HASION (17:46 preT0)
ACC sampling start
End of entry phase
Pilot chute deployed and inflation
Back cover release, main chute deployment & inflation
Front shield jettison
DISR cover jettison
T&k sampling; 1st BOOM release attempt start
1st BOOM release attempt end
2nd BOOM release attempt start
PWA sampling (mode A) start
Main chute jettison, stabiliser deployment & inflation
RADAR sampling, PWA mode C
tropo-pause
Medium p sampling start
High p sampling start
PWA mode D (no RP)
IMPACT mode
IMPACT SURFACE mode, PWA mode G
Loss of radio link
where CH$_4$ is photodissociated and the haze is formed (Hunten et al., 1984). In order to define the layer-by-layer composition of this part of the atmosphere, where more complex organic compounds are built up and some species could condense (Sagan and Thompson, 1984; Coustenis et al., 1995a), accurate local measurements of the stratospheric pressure and temperature profile are needed. To reach this goal, at least one measurement every 4 km was requested (Fulchignoni et al., 1997); HASI will take a measurement every half kilometre. Combining the HASI data with those of other experiments, it will be possible to derive the atmospheric chemical composition as a function of altitude, to provide the vertical concentration profile of inorganic and organic compounds and also to contribute to the analysis of the chemical composition of the aerosol gathered and analysed by the ACP (Israel et al., this issue) and GCMS (Niemann et al., this issue). Moreover HASI data will contribute to estimates of the mixing ratios to identify the condensates. In order to determine if the partial pressure of a specific compound is equal to its saturation vapour pressure and consequently if it could condense at a certain height, an accurate knowledge of the temperature conditions is needed. HASI could detect the presence of methane clouds at the level of the ‘cold trap’, where the minimum atmospheric temperature value is reached (the tropopause: 40 km, 71 K) (Lellouch et al., 1990; Yelle, 1991). At these heights the Huygens probe, dragged by the pilot chute, will continue to descend at a speed of about 15 m s$^{-1}$, so that HASI measurements will have a good spatial resolution on the typical scale height of about 16 km (at least one measurement every 35–40 m).

In the lower atmosphere HASI will accurately sample the pressure and temperature profiles (about one measurement every 5 m) in order to determine the vertical temperature lapse rate. Based on Voyager observations, the lapse rate is expected to be very close to the radiative equilibrium value; less than the dry lapse rate ($\frac{dT}{dz} = 1.3$ K/km) but larger than the moist lapse rate (McKay et al., 1997). Convective zone is expected to extend only a few kilometres above the surface (McKay et al., 1989). Direct detection of the temperature lapse rate will provide confirmation of the convective and condensation properties of the troposphere on Titan. Combining the HASI temperature data with the solar flux measurements performed by DISR (Tomasko et al., this issue), it will be possible to evaluate the thermal balance of Titan’s atmosphere.

HASI temperature and pressure sounding capabilities are reported in Figure 11 together with the temperature profile of Titan’s atmosphere as derived from the tropospheric structure model of Lellouch et al. (1990). HASI vertical resolution depends on the probe descent velocity and sensor sampling rate. In the upper atmosphere, where temperature and pressure are derived from acceleration data, HASI resolution is of the order of 2 km, then it will gradually decrease to a few meters in the troposphere. The two ‘inversions’ at 160 km and 115 km correspond to the deployment of pilot and drogue chutes.
Figure 11. HASI temperature and pressure sounding capabilities. The spatial resolution of temperature and pressure measurements derived from HASI data during the entry and descent in Titan’s atmosphere is reported as a function of the altitude from the surface level. The dashed line represents the vertical temperature profile (Lellouch et al., 1990).

5.2. ATMOSPHERIC DYNAMICS

Acceleration, pressure and temperature measurements provide information about wind, gravity waves and turbulence in the atmosphere or at least allow deducing if conditions leading to turbulence were present. Assuming that turbulence is important only when turbulent diffusion is stronger than molecular diffusion, the minimum turbulence intensity in Titan’s atmosphere can be estimated. In order to detect scale lengths associated to turbulence (min and max dimensions of the turbulence cell), the HASI accelerometer should measure scale lengths decreasing from a value of 50 km at 1000 km altitude down to 0.5 km at the troposphere (Fulchignoni, 1992). The actual HASI accelerometer capabilities ensure spatial resolution of 2 km at an altitude of 1000 km, and vary from 8 m at the tropopause down to 3 m in the last kilometres.

Variations in the density and pressure profiles, as well as in the temperature lapse rate, give information regarding atmospheric layering, atmospheric stability, wind, wave propagation and saturation. Latitude variations in the temperature lapse rate observed by Voyager confirmed the existence of strong zonal winds close to the 1 hPa level that could have speeds between 50 and 100 m s$^{-1}$ (Flasar et al., 1981). Analysis of the observations of the 28 Sagittarii stellar occultation by Titan in July 1989 has demonstrated the presence of zonal wind with equatorial speed of 100 m s$^{-1}$, and also of structures reminiscent of gravity wave propagation (Hubbard et al., 1993; Strobel and Sicardy, 1997). The oscillations in the derived density and temperature profiles are characterised by small amplitude with quasi-periodic vertical structures similar to gravity waves (Sicardy et al., 1999). Currently, the poor knowledge of Titan’s topographic elevation profile, wind system, and meteorology strongly constrains data interpretation in terms of gravity waves and the determination of the mechanisms that could produce gravity waves in Titan’s at-
mosphere. HASI will provide in situ atmospheric density, pressure and temperature vertical profiles as well as the topographic elevation profile and surface roughness through the analysis of the radar altimeter return signal. These measurements will lead to a better understanding of Titan’s environment and constrain the interpretation of the processes that occur in it, specifically in terms of waves and thermal tides.

Wind gusts in the atmosphere can be observed by monitoring the periodic oscillations of the probe-parachute system with the accelerometers and thus detecting any perturbations on these oscillations caused by wind (Seiff et al. 1993, 1997a). These results could be compared and confirmed by the measurements of the Doppler Wind Experiment (DWE) (Bird et al., this issue). The presence of thunderstorms or other meteorological phenomena, such as hail and rain (Lorenz, 1993), could be detected through the measurements made by the PWA acoustic sensor.

5.3. ATMOSPHERIC ELECTRIC PROPERTIES

Titan’s atmosphere undergoes a constant bombardment of galactic cosmic rays and Saturnian magnetospheric particles giving rise to free electrons and primary ions. These charged particles are subsequently captured by aerosol droplets and form heavy ions, which accumulate in tropospheric clouds. Friction, fragmentation, or collisions during convective activity may increase the charged particle number. Charge separation due to convection and gravitational sedimentation induces electric fields within clouds and between cloud layers and the surface.

Nitrogen and methane are the main atmospheric compounds in Titan’s atmosphere and the solar radiation flux input on Titan is only 1% of that on Earth (Borucki et al., 1984). Our knowledge of the electric properties of Titan’s atmosphere and an investigation of electrical phenomena associated with storm activity, such as electrical discharges, atmospheric currents, electric potential gradients, atmospheric conductivity and electrical charging of surfaces are necessarily exploratory.

The ionospheric electron density profile model, given in Figure 12, has been derived combining: (i) an upper layer due to the solar photon bombardment and the impact of magnetospheric electrons (Ip, 1990); (ii) a lower layer related to galactic cosmic ray ionisation (Borucki et al., 1987); (iii) a hypothetical intermediate layer (height ~ 500 km) due to meteoritic impacts (Grard, 1997). Lindal et al. (1983), on the basis of Voyager 1 radio occultation measurement, gave an upper limit of $3.5 \times 10^3$ cm$^{-3}$ for Titan’s electron density.

The conductivity of Titan’s atmosphere is probably higher than Earth’s, owing to the fact that nitrogen and other atmospheric molecules do not form negative ions on Titan. In Figure 13 the atmospheric conductivity profiles are estimated from the plasma density model of Borucki et al. (1987) and the pressure and neutral profiles of Lellouch et al. (1990).
Figure 12. Vertical profile of the electron density in Titan's atmosphere. The dashed line is the upper limit derived from Voyager 1 radio occultation data (Grard, 1997).

Figure 13. Models of ions (i) and electrons (e) conductivity profiles with and without aerosols (dashed and full line, respectively) (Grard, 1997).
Whistlers have been observed in the magnetosphere of other planets (e.g., Jupiter) and bear evidence of lightning activity (Rinnert, 1985). The absence of any substantial magnetic field on Titan does not allow waves to propagate in this mode; moreover, the electric fields may not be strong enough to produce lightning (Borucki et al., 1984) and the convection energy could be dissipated through corona effects. Some form of electrical discharges may however take place in the height range 0–35 km (Boruki et al., 1984; Navarro-Gonzales & Ramirez, 1998) and be the source of complex organic chemistry reactions.

The fact that no radio emissions were received during the Voyager 1 flyby, implies that lightning discharges on Titan are either infrequent or characterised by a different energy spectrum. An energy flash of the order of $10^6$ J, 200–1000 times fainter than that of a typical terrestrial lightning event, should have been detected by Voyager (Desch & Kaiser, 1990). Radio wave emissions could have been shielded by a meteoritic ionised layer (Grard, 1997), which still has to be detected. Evidence for lightning activity and corona effects will be investigated with HASI, but detection of the associated electromagnetic emissions will be a function of the probe descent profile, the average discharge rate, and the typical discharge energy (Grard et al., 1995).

The global effect of the electric phenomena could also excite the spherical resonant cavity limited by the satellite surface and the ionosphere lower boundary. The frequencies of the Schumann resonance are inversely proportional to the planetary body radius and 2.5 times greater on Titan than on Earth (Polk, 1982).

The scientific objectives of the measurements performed by the HASI PWA sensors package are: (i) studying the ionisation processes due to cosmic galactic rays, Saturn magnetospheric electrons and micrometeorites; (ii) investigating the electric charge production and transport mechanisms and determining the charge carrier density profiles; (iii) measuring electric fields and the ion and free electron conductivities, (iv) detecting and surveying wave electric fields and possible atmospheric lightning; (v) detecting acoustic noise due to turbulence and thunder (Grard, et al., 1995).

Some phenomena will be directly measurable, others will be inferred from the observations; for example, the presence of atmospheric currents can be deduced from the atmospheric conductivity and electric potential gradient. Electromagnetic waves with frequencies lower than 100 kHz are confined within the ionospheric cavity and can be detected only in situ (Grard, 1997). The Schumann resonance spectrum yields information about the intensity and global properties of lightning activity and electromagnetic fields. During the descent and after landing, the mutual impedance measurements performed with the PWA quadrupolar probe will give the electrical conductivity of the free electrons in the atmosphere, and the two relaxation probes will measure the ion conductivity and provide information about quasi-static electric fields. Electron and ion densities will be derived from the conductivities, with the knowledge of the atmospheric neutral density and temperature.
5.4. SURFACE AND ATMOSPHERIC BOUNDARY LAYER CHARACTERISATION

The surface of Titan is hidden under a thick photochemical haze, which prevents direct observations. Titan’s total density indicates rock and water ice as its principal components. The images of Ganymede and Callisto, satellites that have almost the same size of Titan, suggest that Titan’s surface should be characterised by craters and topographic variations of the order of 1 km (Lunine & Lorenz, 1996).

The presence of hydrogen in Titan’s atmosphere implies its continuous supply through the methane photolysis and, consequently, the existence of a methane reservoir. Lunine et al. (1983) proposed the existence of a global hydrocarbon ocean. Radar observations (Muhleman et al., 1995), near IR observations (Griffith et al., 1991; Coustenis et al., 1995b) and the HST images (Smith et al., 1996, Lemmon et al., 1995) which penetrated the haze, show that Titan’s surface is heterogeneous. These data argue against a global ocean, but are consistent with the presence of shallow lakes, formed by an accumulation of liquids in the bottom of crater basins (Lara et al., 1994). Albedo variations observed in the near IR from ground and from HST seem to indicate the presence of two types of terrain: one darker and the other brighter than water ice. The Huygens probe will land on the western edge of one of these bright spots, about the size of Australia and centred near the equator.

If the probe survives the impact without losing the radio link, the HASI data will contribute to the characterisation of Titan’s atmospheric boundary layer and surface, partly redundant with the experiment Surface Science Package (SSP) (Zarnecki et al., this issue).

ACC will detect the probe impact on Titan’s surface and will record the instant and impact trace, yielding indications on surface hardness. In the case of a ‘liquid’ landing, the accelerometer data will contribute to characterise the waves. The PWA quadrupolar probe will investigate the conductivity at ground level and, in case of liquid surface, the electric properties, conductivity and permittivity of the liquid. Pressure and temperature sensors will measure the surface conditions, contributing to the definition of the mean atmospheric molecular weight and the estimation of the amount of non condensable gas (e.g., nitrogen). In the presence of a liquid phase, the vapour pressure and the methane mixing ratios will be determined in order to evaluate the composition of the eventual sea or lake.

Spectral analysis of the radar altimeter return signals will provide the topography along the ground track of the Huygens probe descent, the medium- and small-scale surface texture and the spatial integrated value of the surface material permittivity. In general HASI data will help to discriminate between a liquid and a solid surface.
6. HASI Testing Campaign

The HASI experiment was tested following the assembly, integration and verification plan both at experiment and system levels, with the instrument integrated on the Huygens probe. Its performance was fully demonstrated through the qualification and acceptance test campaign, which included tests to simulate the extreme environmental conditions that the system will experience during the cruise phase and during the mission at Titan.

HASI sensors were characterised and calibrated at the subsystem level. In addition their performance has been verified through two balloon flights in Earth’s atmosphere. Titan’s atmosphere is thought to be very similar to Earth’s in terms of pressure, density, and thermal structure, although the temperature values on Titan are much lower. A stratospheric balloon flight represents an excellent opportunity to test and verify the HASI performance, providing a realistic functional test in aerodynamic conditions similar to those of the Huygens probe descent on Titan.

6.1. THE COMA SOLA\(^1\) BALLOON FLIGHT EXPERIMENT

The Instituto de Astrofisica de Andalucia in collaboration with the Instituto Nacional de Técnica Aerospacial (Spain) and the Centre National des Etudes Spatiales (France) organised the balloon flight of the COMAS SOLA experiment. The payload was a 1:1 mock-up of the Huygens probe on which all the HASI subsystems (refurbished breadboard or qualification models) and one Huygens radar altimeter unit have been integrated. The deployable booms carrying PWA electrodes, the radar altimeter receiving and transmitting antennas and the STUB were placed on the probe mock-up ring in the exact configuration of the Huygens flight model. The X-servo accelerometer, the electronic packages for data handling and storage of PWA, radar (RAE), pressure and temperature subsystems were located inside the mock-up, together with the battery and telemetry packages.

On December 1, 1995, a 35 000 m\(^3\) balloon launched from the Léon base (Spain), brought the COMAS SOLA experiment to an altitude of 30 km (Figure 14). A daylight flight was scheduled in order to reach the maximum possible height and to recover the payload immediately after the flight. The flight baseline foresaw a quick rise (speed ~ 5 m s\(^{-1}\)) up to the ceiling, a drift period (maximum 15 min) at the highest altitude and a parachute descent divided in two phases: at low (3 m s\(^{-1}\)) and at high (11 m s\(^{-1}\)) speed, respectively. The balloon position along its trajectory was tracked by GPS (Global Positioning System) and OMEGA (triangulation with ground stations) systems. In Figure 15, the flight profile of the COMAS SOLA balloon is reported as monitored by GPS. The payload landed after a 3-hour flight, at about 200 km from the launch site. Since it landed on a hilly slope, it overturned.

\(^1\)In honour of the Catalan astronomer José Comas Solà who, in 1908, deduced the existence of an atmosphere on Titan from the visual observation of the limb darkening.
Figure 14. Ascending phase of the COMAS SOLA balloon flight. The secondary balloon, which is lifting the probe mock-up, will be released later on, and the payload will continue its ascent dragged by the primary balloon. A damper has been fixed under the mock-up in order to damp the landing.
and storage systems was recovered in perfect shape with the exception of one of the DBS booms, which was damaged in the probe overturning.

The COMAS SOLA experiment allowed us to take data during the balloon ascent and descent phases in order to check the HASI sensors and the Huygens radar altimeter performance in dynamic and environmental conditions similar to those anticipated during the final part of the Huygens probe descent in Titan’s atmosphere. The results obtained represented an in-flight functional test of all the sensors, particularly the PWA, since electric measurements at ground level are strongly affected by the anthropogenic electromagnetic environment. The experiment provided an essential test for the radar altimeter operation, which revealed anomalous instabilities and irregularities in a previous balloon test operated by the Huygens project.

6.1.1. Temperature Profiles
The temperature measurements were obtained by the two TEM units mounted on the STUB; an additional PT100 thermistor was positioned as close as possible to TEM1, to be used as reference. Other temperature measurements were taken by the balloon housekeeping sensors and included in the telemetry data. All the sensors measured the atmospheric temperature conditions during the balloon ascending phase and the first part of the descent, corresponding to an altitude range...
Figure 16. Atmospheric vertical profile recorded between 0.8 and 30 km by the different temperature sensors of the COMAS SOLA experiment. Data are plotted as functions of time as recorded by the data logger used for data recording and storage (5000 s D.L. time = 10:25:39 TU balloon launch).

between 0.8 km and 30 km, with a 1 Hz sampling frequency. Atmospheric temperature profiles obtained from each of the TEM sensors and the PT100 thermistor (PT1) are shown in Figure 16, together with the profile derived from the balloon housekeeping temperature data.

The TEM measurements are more sensitive and are characterised by shorter time constants and better spatial resolution than the PT100: consequently, the TEM sensors recorded wider temperature variations compared to the average value. The profiles derived from the different sensors show a good correlation. From the spectral analysis of the profiles derived from the TEM fine and coarse sensors, we conclude that the dynamic behaviour of the sensors in atmospheric conditions is coherent with the results of the dynamic numerical model (Angrilli et al., 1997). Two major periodicities in the temperature variations have been detected corresponding to altitude scales of about 1400 and 450 m related to atmospheric features.

6.1.2. Pressure Profiles
A PPI-based subsystem was used to determine the pressure profile (Mäkinen et al., 1998). The Kiel probe, mounted at the STUB tip, was connected with the capacitive pressure sensors and the temperature sensors located inside the probe, within the electronic box. The pressure measurements combined with the simultaneous tem-
temperature measurements permit the reconstruction of the flight vertical trajectory and the pressure profile (Figures 17 and 18). Some turbulent phenomena have been detected.

6.1.3. Atmospheric Conductivity
The PWA subsystem was similar to the one included on the Huygens probe, in order to take advantage of the ideal testing conditions represented by the balloon experiment. Measurements of air conductivity, electric fields, and acoustic waves were carried out all along the flight duration, as well as for the processing of the radar echo signal. In the COMAS SOLA experiment, only one radar was used and the booms were fixed on the mock-up ring in deployed configuration.

The relaxation probes mounted on the booms have been used to perform two different measurements: (i) the measure of $\tau$, the relaxation time constant that gives an indication of the ion conductivity in the atmosphere, and (ii) the detection of electric fields, e.g. lightning. In the first case, the relaxation probe electrodes are charged at $\pm 5$ V and then connected to the PWA electrometer, in the second one,
the electrodes are connected to ground and the measured tension represents the electric field of the mock-up. Conductivity is obtained by dividing the dielectric constant $\varepsilon_0$ by the relaxation time $\tau$

$$\sigma = \varepsilon_0 / \tau (\Omega m)^{-1}$$

(4)

The wide range of results for the conductivity of Earth's atmosphere by different experiments in fair weather conditions have been fitted by Rosen & Hofmann (1981) by an empirical formula that gives the conductivity as a function of the pressure

$$\sigma_+ = 3789 P^{-0.6975} e^{-0.002899 P}$$

(5)

where $\sigma_+$ is in $10^{-4}(\Omega m)^{-1}$ and $P$ is the pressure in hPa.

As shown in Figure 19, conductivity at low altitude does not follow the theoretical model (5) and the values obtained during the ascent are different from those obtained during the descent. Conductivity values obtained from the charge decay curves are different at different time intervals and the observed differences depend on the altitude (i.e. the pressure) and vary with positive or negative charging ($\pm 5$ V). This peculiar behaviour of the relaxation probes during the COMAS
Figure 19. Vertical profiles of atmospheric ion conductivity as derived from one of the PWA relaxation probes during the COMAS SOLA balloon flight. The three profiles have been derived from the discharge curve starting from three different initial states: −5 V, 0 V, +5 V. The conductivity profile (5) (Rosen and Hofmann, 1981) is also reported together with the experimental data.
SOLA experiment is probably due to the distortion of the electric environment caused by balloon electrostatic charging (Grard, 1998).

6.1.4. Radar Altimetry
The objectives of the COMAS SOLA experiment for the radar altimeter were to analyse the instabilities and irregularities observed during the previous Huygens balloon drop test, investigate possible solutions, and test and verify the effect of the radar upgrade in realistic conditions. During the COMAS SOLA flight the radar had stability problems. The altimeter behaved nominally up to 16.5 km, but at higher altitudes, even in the presence of a strong return signal, instability in the control cycle produced a noisy blanking signal and losses of lock (see Figure 20). The non-linearity of the sweep ramp strongly limited the resolution for surface topography measurements. Good correspondence was obtained between GPS and radar altitudes.
Analysis of the COMAS SOLA results, combined with those obtained from other radar models, allowed the selection of some solutions and modifications to be implemented on the Huygens proximity sensor in order to optimise its performance. Integration time has been reduced in order to ensure the radar signal lock at higher altitudes, while the control cycle has been modified to achieve stability. A better dynamic synchronisation technique has been used to implement the efficiency of sweep ramp linearity and then to improve the resolution of topography measurements.

6.1.5. Acceleration Measurements
ACC was triggered to perform measurements during the descent phase and to detect the surface impact trace. This part of the balloon flight is the most representative of the Huygens mission at Titan and provided the opportunity to test the accelerometer performance and measurement cycle, especially the impact detection under real conditions. The accelerometer correctly detected the impact with the terrestrial surface and recorded the subsequent overturning of the mock-up.

7. First HASI Data from Space

During the Cassini cruise phase the Huygens probe is in sleep mode. Periodically, it is switched on to perform a health check. The probe, its subsystems and the experiments are tested in a mission simulation sequence in order to verify the health status. Eight days after launch, the Huygens probe was switched on for the first time and performed the first in-flight checkout successfully. Then, about every six months the probe is switched on and checked until the Saturn insertion orbit.

During the first in-flight checkouts, the HASI behaviour was nominal. The HASI sensors appear to be functioning within their nominal parameter range; the measurements are normal and consistent with the expected space environmental conditions. The ambient spacecraft acceleration conditions were outside the sensitive range of ACC sensors. The acceleration values sensed when ACC was set in the high-resolution range are of the order of 20 \( \mu \)g (the sensor offset at 0 g). ACC did not record any effects due to Cassini thruster activations for three-axes-stabilised spacecraft attitude control. The PPI pressure sensor readings were approximately 0 hPa and the constant capacitor readings close to nominal values, as expected in deep space vacuum conditions.

8. Conclusions

The HASI experiment is on its way to Titan. The in-flight health checks of the Huygens probe show that our instrument is in a very good shape. The success of prior atmospheric structure experiments (e.g., Pioneer Venus and Galileo ASI)
in achieving similar goals at other planetary bodies, reinforces the feasibility of HASI goals for Titan’s investigation. We are preparing the mission at Titan in order to maximise the scientific output, exploiting the results of new observations, theoretical and experimental models (new balloon flights, numerical modelling, laboratory simulations).

Acknowledgements


References


HUYGENS PROBE AEROSOL COLLECTOR PYROLYSER EXPERIMENT

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Abstract. ACP’s main objective is the chemical analysis of the aerosols in Titan’s atmosphere. For this purpose, it will sample the aerosols during descent and prepare the collected matter (by evaporation, pyrolysis and gas products transfer) for analysis by the Huygens Gas Chromatograph Mass Spectrometer (GeMS). A sampling system is required for sampling the aerosols in the 135–32 km and 22–17 km altitude regions of Titan’s atmosphere. A pump unit is used to force the gas flow through a filter. In its sampling position, the filter front face extends a few mm beyond the inlet tube. The oven is a pyrolysis furnace where a heating element can heat the filter and hence the sampled aerosols to 250 °C or 600 °C. The oven contains the filter, which has a thimble-like shape (height 28 mm). For transferring effluent gas and pyrolysis products to GCMS, the carrier gas is a labeled nitrogen ¹⁵N₂, to avoid unwanted secondary reactions with Titan’s atmospheric nitrogen.

Aerological tests under cold temperature conditions were conducted by using a cold gas test system developed by ONERA. The objective of the test was to demonstrate the functional ability of the instrument during the descent of the probe and to understand its thermal behavior, that is to test the performance of all its components, pump unit and mechanisms.

In order to validate ACP’s scientific performance, pyrolysis tests were conducted at LISA on solid phase material synthesized from experimental simulation. The chromatogram obtained by GCMS analysis shows many organic compounds. Some GC peaks appear clearly from the total mass spectra, with specific ions well identified thanks to the very high sensitivity of the mass spectrometer. The program selected for calibrating the flight model is directly linked to the GeMS calibration plan. In order not to pollute the two flight models with products of solid samples such as tholins, we excluded any direct pyrolysis tests through the ACP oven during the first phase of the calibration. Post probe descent simulation of flight results are planned, using the much representative GCMS and ACP spare models.

1. Introduction

Titan’s atmosphere is believed to be over geological times a permanent source of N-containing organic molecules (mostly nitriles) and of various hydrocarbons. Some of these species polymerize to form very complex organic chains which condense into aerosols. These aerosols are certainly the source of the yellowish haze which...
covers Titan’s surface. Organic molecules may condense on these aerosols, forming shells on the particles when they settle down into the atmosphere.

The main objective of the ACP experiment is to analyze the chemical makeup of the aerosol particles. For this purpose, the instrument will sample the aerosols during descent and prepare the collected matter (by evaporation, pyrolysis and gas products transfer) for analysis by the Huygens Gas Chromatograph Mass Spectrometer (GCMS). An ACP’s products transfer line (PTL) interfaces directly with an ACP-devoted GCMS feed tube. The GCMS is used by the ACP for about 20% of its operating time.

2. Scientific Investigation of Titan’s Aerosols

2.1. RATIONALE

The origin of Titan’s hazes is most currently attributed to photochemical processes occurring at high altitudes. Ions and radicals produced from N₂ and CH₄ by UV photolysis and energetic particles bombardment, recombine chemically, forming organics, some of which polymerize to create the aerosol.

Owing to the diversity of the possible energy sources and their related vertical distribution, different types of particles can occur with respect to the altitude ranges. The polymerization of C₂H₂ through the action of solar UV photons is expected, from current modeling, to yield C₂₅H₂ at altitudes larger than ~500 km. The synthesis, in large amounts, of polymers of the form (C₂H₂)n in the lower stratosphere may be considered as rather unlikely but depends on how acetylene polymerizes longward of 190 nm (Cabane et al., 1992; Chassefière & Cabane, 1995). In addition the formation of C-H-N oligomers by the action of suprathermal Saturn plasma electrons, around 900–1000 km, or of energetic radiation belt particles at 350–400 km altitude, is shown to be the most plausible mechanism for explaining the haze’s formation.

In the low stratosphere, aerosol particles settling down from the upper levels may act as condensation nuclei. Below ~80 km, this should lead to the deposition of thin layers (<0.01 µm) of condensed gases (e.g. HC₃N, HCN, C₄H₁₀) on the sub-µm particles. This first stage is followed by a more consistent increase in the particle size, up to a few µm, where the condensation of CO₂, C₃H₈, C₂H₂ and C₃H₆ occurs, between 67 and 63 km (Frère et al., 1990). The main condensation processes occur near the tropopause, with the condensation of C₂H₆ below 62 km, and in the troposphere where CH₄ and N₂ condense on the resulting particle, which may yield cloud droplets (~100 µm, see Toon et al., 1992). Another source of condensation nuclei may be the particles produced directly at these altitudes by the radiolysis of organic gases. Cosmic rays present a maximum of the energy deposition near 60 km and, as on Earth, lightning may exist in the low troposphere.

Two methods of producing Titan-like aerosols in the laboratory have been investigated:
The first involves identifying these aerosols with the complex organic material that is often observed in the laboratory from simulating the photolytic and radiolytic processes expected in Titan’s atmosphere. This material roughly corresponds to what Sagan’s group labels ‘tholins’ (Khare et al., 1984). The second route for producing the yellowish matter that might correspond to the aerosols of Titan, is by polymerizing organic molecules using UV. The best candidate is C₂H₂, which polymerizes more easily than C₂H₄ or HCN (Clarke & Ferris, 1997).

Confidence in the process is increased by the fact that the polymers assumed above can form the types of aggregates that are needed to reconcile polarimetric and photometric results (West & Smith, 1991; Cabane et al., 1993; Rannou et al., 1995; Rannou et al., 1997). Tholins obtained from the sparking of He-CH₄ and N₂-C₃H₂ mixtures have been studied, with the ACP experiment in mind, (Israel et al., 1991; see also Raulin et al., 1998; Coll et al., 1998). Until recently systematic physical/chemical data on tholins were available only from one type of tholins, produced in the Cornell group (Khare et al., 1984). However, chemical analysis of such tholins showed a contamination of the products by oxygen atoms. The experimental programs developed (Coll, 1997; Coll et al., 1997, 1998) use conditions which avoid such a contamination (irradiation system in a glove box under nitrogen atmosphere, allowing the recovery and sampling of tholins under inert atmosphere). Furthermore, Cornell’s tholins were produced within room-temperature conditions, far from Titan’s ones. Now, as shown on Figure 1, clearly, the chemical composition of the tholins strongly depends on the conditions (pressure, temperature, inert atmosphere). A valid parameter is the C/N ratio which varies from 1 to 11. Khare’s et al. (1984) tholins which were used for systematic spectroscopic analyses have a C/N ratio of 1.9, but with more than 10% contamination by O atoms. In the case of experimental conditions which seem to be the more representative of Titan’s atmosphere (low temperature, low pressure, absence of oxygen), the value is 2.8 (Coll, 1997; Coll et al., 1997).

The pyrolysis gas chromatography (Py-GC) of tholins produced at 77 K (Figure 2) shows that saturated and unsaturated carbon chains are included in their structure; N-containing groups appear in the case of N₂-CH₄ sparking. The thermal desorption profile of these tholins (Figure 3) clearly showed two peaks, the first one corresponding to the distillation of condensed species, the second one to the pyrolysis. The mass spectrometer (MS) study of the evaporated oligomers and

<table>
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<th>Experiment</th>
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<tr>
<td>Sagan et al, 1984</td>
<td>Room T</td>
<td>Low P</td>
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<td>1.9</td>
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<tr>
<td>Coll et al, 1995</td>
<td>Low T</td>
<td>High P</td>
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<td>McKay et al, 1996</td>
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<td>Low T</td>
<td>Low P</td>
<td>Airtight</td>
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Figure 1. Titan’s tholins C/N ratio from various simulation experiments.
Figure 2. Pyrolysis gas chromatography of the solid products obtained after four hours sparking a gas mixture containing 15 mbar of CH$_4$ (constant, at 77 K) plus 800 mbar of (A): Helium, (B): Nitrogen. Pyrolysis: 600 °C for 5 s; gas chromatography: column Poraplot Q 10 m × 0.32 mm ID (10 µm coating); temperature: isothermal 40 °C for 2 min, then programmed at 20 °C/min up to 180 °C, then isothermal 180 °C; carrier gas: H$_2$ at 2 ml/min.

Pyrolyzates showed that a wide range of alkylated aromatic compounds evolved from the sample, which indicates that such solids contain a 3-D polymer with a high degree of branching.

In other work (Ehrenfreund et al., 1995), the main peaks related to N-compounds observed by a GCMS analysis are HCN, CH$_3$CN, C$_2$H$_5$CN and longer chain nitriles. Only the saturated hydrocarbons are observed. The study of the evolution with temperature shows that HCN is a dissociation product during the whole Py-GC analysis process, which may imply that the nitriles can form thermostable structures in the tholins.

2.2. ACP SCIENTIFIC OBJECTIVES

Primary objectives, can be satisfied from measurements made during Probe entry by the ACP coupled with the GCMS:
1. Determine the chemical makeup of the photochemical aerosol, i.e. infer the relative numbers of constituent molecules (C, H, N, O) composing the aerosol.

2. Obtain the relative abundances of condensed organics (e.g. C₂H₂, C₂H₆, HC₃N, HCN) in a column average throughout the low stratosphere. Compare with the abundance of constituent molecules in the aerosol nucleation sites.

3. Obtain the relative abundances of condensed organics (principally CH₄, plus organics listed above) in a column averaged over the upper troposphere. Compare with the abundances of constituent molecules in the aerosol nucleation sites. Secondary objectives of fundamental interest can also be satisfied with the aid of additional information acquired by other Probe instruments (mainly the Descent Imager/Spectral Radiometer):

4. Obtain absolute abundance for all condensed species, averaged over the low stratosphere and upper troposphere respectively.

5. Determine the mean sizes of aerosol nucleation sites averaged over the low stratosphere, and compare with those in the upper troposphere.

6. Detection of non-condensable species, such as CO, eventually trapped in aerosols.
3. Functional Description

Figure 4 provides an overview of the ACP. The gas products transferred from the ACP are analyzed by the GCMS (Niemann et al., 1997). A sampling system is required for sampling the aerosols in the 135–32 km and 22–17 km altitude regions of Titan’s atmosphere. These altitude ranges refer to the Probe’s nominal descent profile (ESA 01/94).

Optimal sampling requires an inlet (sampling) tube (ST) extending beyond the boundary layer. This boundary layer was calculated by Aerospatiale during the Huygens Probe design and was found to be a few mm thick; the aerothermodynamic effects can be neglected since the filter’s bottom end protrudes 28 mm from the Probe’s fore dome. During sampling, the collecting target’s temperature must be as close as possible to that of Titan’s atmosphere in order to help retain the more volatile aerosol and cloud particle components (Lefebvre and Krauss, 1992).

The target is a filter (FIL), made in stainless steel (Beckaert ST10), that can be moved along the inlet tube by a ‘filter’ mechanism (FIM). A pump unit (PU) is used to force the gas flow through the filter. In its sampling position, the filter front face extends a few mm beyond the inlet tube. This increases aerosol collection by direct impaction at high altitude, where the pump does not operate (see appendix). Before descent, the filter is held in its storage position inside the oven (OV). During descent, the mechanism (FIM) can move the filter to its sampling position and return it into the oven.

The oven is a pyrolysis furnace where a heating element (OH) can heat the filter and hence the sampled aerosols to 250 °C or 600 °C. A motorized gate valve (GV) can be activated to close the furnace after filter retraction. Three normally closed monostable valves (V1, V2, VT) are mounted on the oven’s body. V1 supplies a labeled gas (15N2) to carry the gas sample from the oven to the transfer lines through V2. The venting valve VT allows the oven’s gas content to be drained off.

The pump unit (PU) is a drag fan which accelerates the flow of Titan’s atmosphere at a rate depending on altitude. An exhaust tube (ET), with a one-shot isolation valve (P2), allows the gas to be vented into Titan’s atmosphere. When it is switched off, PU acts as a flow-blocking device. The pressurization system for storing N2 gas and controlling its flow to the oven is supplied by a gas tank (GT) at 30 bar. Oven filling is controlled by a pressure transducer (PS) associated with valve V1 (see Section 5). A relief valve (RV, set at 4.1 bar) in the internal gas transfer line protects the GCMS against accidental ACP overpressure.

The whole internal circuit is pressurized during ground operations and the early part of the flight to Saturn. About three years after launch, the ACP’s internal circuit is evacuated by opening P2. The inlet tube end is closed by a sealing cover (SC), which will be opened at the beginning of descent. A connecting tube (Product Transfer Line, PTL) between the ACP and GCMS transfers the pyrolysis products. Valve P1 isolates the ACP internal circuit from the product transfer lines. This one-shot isolation valve is opened at the beginning of descent (To + 2 min) for an
Figure 4. Aerosol Collector Pyrolyser (ACP) schematic.
initial venting of the internal (ITL) and the external (PTL) exit transfer lines. The IVA one-shot valve (see below and Niemann et al., 1997) isolates the PTL at its GCMS extremity. A program allows V1, V2 and VT electrovalves, P1 and PTL to be heated using special heaters. The heating of V1 is controlled by a thermostat, activated when the temperature falls below $-5^\circ$C. This was shown to be necessary to prevent leakage due to the low temperatures during pumping.

4. Measurement Strategy

The operations sequences (Figure 5) result from the following requirements:

1. Determining the compositions of the particle cores (non-volatile and volatile components) is conducted mainly in the low stratosphere and down to the tropopause (above 30 km). In the higher part of the descent (above 80 km), it is expected that aerosols will be obtained by direct impaction on the filter. Below 80 km, where the pump becomes effective, the samples are obtained by filtration.

2. The second sample must be collected within the troposphere above the deep methane clouds (20 km).

3. Owing to mass constraints, the instrument is equipped with a single collector that must be used again after cleaning the oven, filter and product transfer lines.
4. The samples are analyzed by using the GCMS for a fixed portion of its life (approximately 20 min), knowing that this instrument must make at least one direct chromatographic analysis of the atmosphere’s composition before surface impact.

In addition, because of the very short descent profile (120 min minimum), it was decided to make three transfers for each sample, each transfer using the direct MS mode (Niemann et al., 1997). The transfers are done sequentially when the oven is at ambient temperature, at 250 °C and at 600 °C. Analysis of the aerosols using the full capacity of the GCMS and which requires about 10 min, implies the use of the three columns (Niemann et al., 1997). It is done only for the pyrolysis sequence (600 °C) after the first sampling. The gas transfer starts at To + 74 min (Figure 5) after the analysis of the content of the two gas enrichment cells programmed by the GCMS for Titan atmospheric gas analysis.

5. Sequences During Descent

The following sequences programmed during the descent phase are:

Sequence 1: Initial venting and preparation for the first sampling operation between ACP initialization (at To + 1 min 40 s) and the time when the filter reaches its sampling position (at To + 6 min 45 s, nominal altitude 130 km).

Sequence 2: First sampling in the low stratosphere. This period ends when the filter is retracted into the oven (GV locked) at To + 60 min 00 s (nominal altitude 32 km).

Sequence 3: Heating the filter (ambient, 250 °C, 600 °C) and gas product transfers to the GCMS at To + 74 min 00 s (nominal altitude 24 km).

Sequence 4: (a) Oven and transfer lines cleaning. The oven and filter are cleaned by extending the oven heating phase at 600 °C. This operation is followed by flushing the different gas transfer pipes. (b) Preparation for the second sampling operation with the filter in its sampling position at To + 77 min 00 s (nominal altitude 22 km).

Sequence 5: Second sampling in the upper troposphere. This period ends when the filter is retracted into the closed oven, at To + 89 min 00 s (nominal altitude 17 km).

Sequence 6: Heating the filter (ambient, 250 °C, 600 °C) and gas product transfers to the GCMS ends at To + 108 min 00 s (nominal altitude 9 km).

Sequence 3 is the first analysis sequence which deals with:

1. the preparation of aerosols for producing evaporates and pyrolysis products;

2. the transfer of gas products to the ACP line (feed tube to the GCMS);

3. the proper analysis, either by the direct MS mode or by the complete mode GCMS + direct MS (Niemann et al., 1997).

The program for aerosol preparation and transfer consists of three phases:
Phase (a): transfer of the gas products obtained while the filter is in the unheated oven. At the time of transfer, the filter has considerably warmed since oven closing, and the temperature gradient is sufficient to produce some evaporates.

Phase (b): transfer of gas products obtained after heating the filter to $T_f = 250 \, ^\circ C$. During the transfer time (1 min), the filter temperature is maintained by holding $T_f$ at 250 $^\circ C$.

Phase (c): transfer of the gas products obtained after heating the filter to 600 $^\circ C$.

Figure 6 is a schematic of the ACP-GCMS interface. In order to transfer the gas samples with minimal dilution from the effluent gas ($^{15}N_2$), each injection into the GCMS is done by pressurizing the oven to 2.5 bar with $N_2$ (V1 controlled, V2 closed) and then rapidly depressurizing it down to 1.9 bar (fast actuation of V2 and VAB). To ensure this ‘piston effect’, the pressure range is controlled by the software using the oven pressure sensor signal. At injection the estimated mass flow rate is 3 to 9 mg s$^{-1}$ at 2 bar $N_2$. A transfer of the sample is completed after 6 injections. The oven is then emptied in order to obtain a background analysis.

Sequence 6 is a copy of sequence 3 but during phase (c) only the MS mode is used. At the end of the transfer (phase c) of the products to the GCMS (To + 108 min), the ACP is prepared for being turned off until To+110min (8 km nominal altitude).

### 6. Mechanical Configuration

The instrument housing is made of aluminum alloy and consists of a single unit mounted on the lower part of the experiment platform. The rectangular box carries six attachment lugs on its base. The electronics system (ACPE) has its own struc-
ture attached at six points on one side of the instrument’s main body, in which the mechanical and pneumatic subsystem is located. Figure 7 shows the ACP unit with its electronic box, sampling tube and sealing cover.

The ACP’s overall dimensions are $220 \times 200 \times 206$ (H) mm. The ACP’s total mass is 6.07 kg, including the exhaust tube (40 g), the PTL (120 g) and the electronic box (2030 g).

The aerosols sampling inlet tube extends downwards to penetrate the Probe’s fore dome. To provide efficient evacuation of Titan’s atmospheric gas after sampling and filtering, the exhaust tube exits upwards, passing through the experiment platform and the top platform. By siting the ACP close to the GCMS, the inlet tube is close to the Probe’s axis and PTL is as short as possible (see Figure 8). A very strict procedure for limiting chemical contamination was followed during instrument fabrication. The objective values specified for the internal circuit of the gas transfer subsystem are 10 ppb for CO, CO$_2$ and the organic compounds expected during aerosol chemical analysis and 100 ppb for H$_2$O. The internal surfaces of all the transfer tubes have been passivated (‘silanised’). A cleanliness plan was followed first at the level of each equipment element and then at the instrument level. After assembly, the whole ACP was baked under vacuum for several days at 120°C. Also, organic materials were not used in the GV and filter mechanisms. Their bearings, in particular, are not lubricated.

In order to maintain the high cleanliness level during the instrument’s ground storage and its first part of the cruise, the ACP’s internal gas circuit was filled to
2.5 bar with pure nitrogen. The internal circuit is hermetically closed off, by three sealing devices, at the level of the sampling and exhaust tubes and at the interface between the ACP housing and the PTL. The specified instrument overall helium leak rate of $10^{-6}$ mbar l s$^{-1}$ was found to be sufficient to hold the gas circuit pressurized until a few months after launch.

The two apertures leading to the atmosphere are sealed by specially developed devices: the sealing cover (SC) for the sampling tube and the one-shot P2 valve for the exhaust tube. SC is screwed to the bottom of the sampling tube (ST); the tightness requirement is satisfied by a stainless steel O-ring gasket. The cap and spring, totaling 80 g, are held in position on SC's body by tin-silver solder. Ejection will be within 2 min after switching on the 53 W heater (SCH), as the alloy melts at about 150 °C. The P2 concept is identical: melting a brazing allows a spring to eject a sealing cap, freeing the outlet gas exhaust.

7. Integrated Mechanical System

Figure 9 shows the oven, the gate valve (GV) plus the mechanism which function is to translate the filter through the sampling tube. In the configuration shown, the filter is in its inner position. The sampling tube (ST) is a 70 mm-long, 45 mm-outer diameter aluminum cylinder that protrudes from the Probe’s fore dome in order to
Figure 9. Mechanisms and oven assembly.
position the filter directly in the gas flow, beyond the boundary layer. ST’s upper extremity is fixed to the GV, and the crushing of a metallic O-ring gasket provides a tight seal between the two devices. At the bottom of ST, a stainless steel gasket made of flat surfaces assembled into a bellows ensures a tight fit with the filter. The gas flow is thus forced to pass through the wire netting. The filter is a mesh, brazed at one end to a mounting ring that interfaces with the rack of the filter mechanism. The mesh is made of multiple layers of stainless steel fibers. The filter’s bottom end is a mesh disc laser-brazed to the mesh cylinder. This disc faces directly into the path of the gas and aerosols during sampling. When SC has been ejected and the filter is in its sampling position, the filter’s bottom end is 4 mm below the cone-shaped entrance, 28 mm from the external surface of the Probe’s fore dome.

7.1. OVEN DESIGN AND GAS TRANSFER SYSTEM

The oven is the core of the mechanism’s assembly shown in Figure 9. It has a dead volume of approximately 6 cm³. Its cylindrical main body forms a common piece with the GV main body. The oven contains the filter, which has a thimble-like shape (inner diameter 10 mm, height 28 mm, thickness 0.5 mm). The heating element, from Thermocoax, is a resistance heater protected by a stainless steel shield and rolled inside the inner filter volume.

In order to minimize chemical reactions with the walls, the oven inner surface body is gold-coated (few µm layer). The three injection valves are miniature solenoid valves made by Matra Marconi Space, procured with their Lee restrictor (Lee Jeva). They are monostable normally closed. Each one is made of stainless steel with Viton elastomer seats, which can withstand low temperatures (−25°C).

For transferring effluent gas and pyrolysis products to the GCMS, the carrier gas is a labeled nitrogen ¹⁵N₂, to avoid unwanted secondary reactions with Titan’s atmospheric nitrogen. The carrier gas is stored in a specially developed reservoir (GT) at 30 bar. The 55 cm³ cylindrical gas reservoir has a 32 mm diameter and its housing is made of 1 mm-thick stainless steel. The system is designed for a maximum pressure of 40 bar at 120°C; burst pressure is 160 bar. The oven is supplied through the one-shot P3 valve, specially developed and qualified by Industria. A solenoid actuates a needle that punctures a metal diaphragm to initiate carrier gas flow. The diaphragm is a few µm thick and is qualified for the large pressure differential (upstream flow 40 bar, downstream 2 bar). The same type of one-shot valve is used for P1, which isolates the ACP gas transfer system from the PTL and GCMS inlet tubing (see Figure 4). P1 was calibrated for identical pressures (3 bar) upstream and downstream.

7.2. THE FILTER MECHANISM (FIM)

The drawing of the FIM is shown in Figure 9. The filter mechanism concept is a rack and pinion mechanism, with magnet locking, that translates the filter, 120 mm along the sampling tube, from the sampling position outside the Probe to the oven
position inside the ACP. A stepper motor Sagem 21 PP drives the pinion. A Titanium sleeve between rotor and stator, around the stator protects the internal volume of the ACP from chemical contamination.

The total time from one end position to the other is 5.250 s, whatever the direction of filter displacement is. A bronze pinion gear transmits the rotation motion to the rack translation motion with the overall stroke of 120 mm. Two ball bearings are assembled on the common pinion and motor shaft with a preload insured by an annular ring. The rack, made in stainless steel, is guided inside a tube with two bronze sliding bearings located above and below the pinion. Inside the bottom bearing is a ceramic anti-rotation ball that moves in a groove machined in the rack. For rack preloading purpose, a cuproberyllium helical spring pushes the ball into the groove.

At the top of the rack, a magnet locks the rack to a mechanical stop in both end positions. During sampling phase, the 10 N magnetic force locks the rack to the mechanical stop and pushes the filter against a metallic bellows. During heating phase, product transfers phases (and also during the vibration phases at launch), the magnet provides a 13 N to 17 N magnetic force which locks the filter ring against the base of the oven. Electrical supply of the stepper motor is not required to lock the rack in both end of stroke positions. Displacement of the filter in both directions until a targeted position is commanded by driving the stepper motor with a pre-programmed step number. Two Hall effect sensors detect and provide the status of both filter end positions. When the filter is in its inner position, near the bottom of the rack, a collar crushes an elastomer (fluorosilicone) o-ring, insuring a $5 \times 10^{-4}$ mbar l s$^{-1}$ tightness of the oven to the FIM compartment even at the lowest temperature of $-50^\circ$C. The fluorosilicone type has been selected for its low outgassing rate. Also it can sustain long storage life time. Chemical cleanliness tests of the ACP show marginal pollution effect on pyrolysates analysis.

The tight overall housing of the FIM is made of titanium alloy. The FIM, which weights 370 g, has been manufactured by Mecanex (Switzerland).

7.3. THE GATE VALVE SYSTEM

The drawing of the gate valve is shown in Figure 10. The system is composed with the gate valve (GV) itself and the gate valve mechanism (GVM). It has been manufactured by SEP.

It is a guillotine valve type which translates in both direction, activated by the GVM. It opens the oven volume to free the passage of the filter between the sampling and heating position. The main components of the gate valve are:

- The valve main body which is common with the oven body. It is made of stainless steel.
- The roller plates made of high resistance stainless steel.
Figure 10. Gate valve.

- The stainless steel top clapper which receives a fluorosilicone o-ring seal. The same fluorosilicone type for FIM was selected and pollution contribution was tested marginal.
- The bottom clapper made of stainless steel.
- Two rollers made of cupro-beryllium.
- The return spring, made of cupro-beryllium, is located between the top and the bottom clapper. It exerts permanently a return force to maintain the two clappers against the two rollers.
- The main spring, made of cupro-beryllium, is 8 branches star shaped and attached to the bottom clapper. It bears on the top shoulder of the sampling tube, which is made of aluminum alloy and which is protected by a hard anodized oxidation.

During the closing motion of the valve, its stroke is decomposed in two parts. The first part, 23 mm along the GVM axis covers the valve access of the filter to the sampling tube (closing phase). The second part, 5 mm along the same direction, serves to bring the upper clapper against the bottom collar of the oven body (locking phase). The closing and locking operations of the gate valve are as follows: first the screw pushes the roller plates. (Since the return spring exerts a restoring force of 14 N, between the top and the bottom clapper, the clappers remain stuck against the rollers in the configuration corresponding to the minimum thickness of the valve configuration.) The gate valve is then freely translated toward close position. When
the gate valve reaches this position, the upper clapper stops at the mechanical stop, the screw continues to push the rollers’ plate, and the rollers start to move outside their grooves. The gate valve thickness increases until the rollers’ plate reaches the end position against the valve main body. The main spring provides the crushing force (387 N) and the upper clapper compresses the o-ring against the bottom collar of the oven body. Then the gate valve is in its locked and gas tight position.

In addition, two pairs of mechanical stops, respectively shrunk below the top clapper and above the bottom clapper, avoid any possibility of disengaging the roller plates and rollers from the top and bottom clappers. This gives more tolerance to a malfunction of the valve. A magnet mounted on the gate valve provides the status information on the valve position.

The gate valve mechanism performs a complete activation in less than 4 seconds. The mechanism is designed to power the gate valve screw with a minimal force of 250 N. Taking into account all mechanical safety margins, the actual force is measured to be between 500 and 900 N. It consists mainly of the motor and its shaft, a spur gear, the gate valve power screw, the bearings and the housing. The motor shaft has two deep grooved bearings mounted on to its shoulders. It transmits the motor torque to the input pinion which meshes with the wheel. The module has been fixed to 0.4 and the speed reducing ratio to 4. The screw-and-nut stage consists of a power screw and of the thread machined inside the wheel which acts as a nut. The power screw translates in the hollow axes of the wheel. The input pinion and the power screw are made of stainless steel, whereas the wheel is made of bronze. As for the FIM, the use of lubricant is avoided.

The GVM motor is a brushless DC motor ETEL Meti 111. A titanium sleeve, located between rotor and stator, surrounding the stator, protects the internal volume of the ACP from chemical contamination. Two Hall effect sensors detect the position of the rotor and serve as an input for the electronic drive which provides the proper square wave to the motor.

As for the FIM, the tight overall housing of the GVM is made of titanium alloy. The GVM which weights 373 g, has been manufactured by Mecanex (Switzerland).

8. The Sampling System

Owing to the high temperatures required for pyrolysing the organic compounds, the use of metallic mesh filters was necessary for collecting the aerosols (see Section 7). Tests were performed in low pressure chambers (at SA/CNRS and CNES) to evaluate the pressure drop produced by such metallic filters as the pump unit draws in Titan’s atmosphere. Using the cold gas test facility of CERT/ONERA in Toulouse (see below), it was possible to study the effect of low temperatures. The theoretical laws giving the variation of the pressure drop with temperature and total pressure (Fuchs, 1964; Pich, 1971) were verified and used to characterize the pump.
It was also necessary to evaluate the collection efficiency for sub-\(\mu\)m particles when metallic filters operate at reduced pressure. The tests were performed at the Institut de Protection et de Sureté Nucléaire/CEA, Saclay, using Na-Fluoresceine (Uranine) particles 0.15 \(\mu\)m. Such a particle size corresponds to the lowest efficiency of a fiber filter: for larger sizes, the impaction of particles inside the filter increases the efficiency (Suneja & Lee, 1974), for smaller sizes, capture due to Brownian diffusion predominates (Davies, 1952). These tests led to the choice of multi-layered Beckaert ST10 filters (porosity 80\%, thickness: 0.4 mm, fiber diameter 0.4 mm), which provide the best trade-off between efficiency and pressure drop for our experimental objectives. During the whole descent, aerosols can be collected by direct impaction (see appendix). Aerosols sampling by filtration is obtained during two active sampling periods at 80–32.5 km and 22–17 km nominal altitudes when the pump unit draws atmospheric gas through the filter.

8.1. DESCRIPTION OF THE PUMP

The pump (Figure 11), built by Technofan under subcontract to SEP, is a small, light weight unit of about 850 g and overall size 100 x 80 x 100 mm. The system consists of a casing, the first/second stage pump wheels and the electric motor. The internal assembly is mounted on a shaft carried on two bearings. The first and second stage pump wheels are mounted on the motor shaft and locked to the inner race of the front bearing by the shaft lock nut. The front bearing is mounted in a housing, integral with the casing, restraining the bearing outer race from axial and radial movement.

At the rear end of the pump, a rear bearing is held in an adjustable cover. Radial movement is restrained but axial movement is limited only by the pre-load from a compressive washer giving about 40 N around the outer race. As the dynamic mass of the shaft assembly is of the order of 125 g, the 40 N pre-load is sufficient to prevent axial movement up to 33 g applied axially to the shaft dynamic mass. The shaft is not free to move axially because it is restrained by the front end bearing housing and the bearing axial stiffness. The pre-load ensures that the axial and radial play in the bearings is taken up, allowing for greater stiffnesses against radial or axial movement.

The shaft assembly is completed by a second locknut that pre-loads the rear bearing inner race. The shaft and its bushes and abutments are of good quality stainless steel. The electric motor rotor is fixed in the middle of the shaft in the correct position with respect to the stator winding. The radial clearance between rotor and stator is only 0.3 mm. The winding is fixed permanently to the motor casing, which is purely cylindrical at this section. A titanium sleeve around the stator protects the internal parts of the pump (and sampling tubing) against chemical contamination.

At the pump front end, formed around the circumference of the motor cylindrical casing, is a housing to accommodate the front cover. They both form the first and second stage pumping cavities. Eight stainless steel bolts attach the front
cover to the housing. The front housing also provides the load path down to the two front attachment legs, which are equispaced around the shaft axis. Only one rear attachment leg is provided, and this is accommodated by the rear housing, which has a similar function to the front one in that it accepts a cover. Six bolts are used for the rear cover attachment. The front cover, front housing, cylindrical casing, rear housing and rear cover are all made of aluminum. In order to achieve the leak rate requirement \((10^{-7} \text{ mbar l s}^{-1})\) Viton seals were preferred to metal seals.
The motor is a brushless (permanent magnet) 3-phase auto synchronous motor from Norcroft. Hall effect sensors monitor the rotor position. The maximum electric power required for the pump is 69 W. The two bearings, mounted on the pump shaft, are deep-groove ball bearings. In order to satisfy a high rotation speed (about 25 000 rpm), no lubricant and a 10 h lifetime, ball bearings pre-loaded with stainless steel rings and balls, and a cupro-beryllium cage were envisaged. But development tests showed there was material transfer between rotating parts, thus jamming the bearings after few seconds operation at high speed. The bearings finally selected, use stainless steel balls and rings, and a Duroid 5813M cage (Duroid is a glass microfiber PTFE with MoS$_2$ as an additive). In operation, the MoS$_2$ coats the balls, forming a dry lubricant.

8.2. AERAULIC TESTS UNDER COLD TEMPERATURE CONDITIONS

Aeraulic tests were conducted on the pump unit by using the cold gas test system developed by ONERA at Centre d’Etudes et de Recherches de Toulouse (CERT). The test objective was to give inputs (transient values) to the evaluation of the pump unit performances during the descent. The cold gas test system consists of:

1. the cold gas generator: a liquid nitrogen reservoir, a cryogenic valve controlling liquid nitrogen flow, and a heat exchanger of a coiled pipe immersed in the liquid flow stream;

2. the test chamber of two 55 mm-diameter double-wall cylinders and two internal pipes to carry refrigerant fluid (the two movable cylinders are separated by a central flange);

3. an interface flange that connects the cold gas generator to the test chamber (the flange is screwed to an inlet cylinder fixed to the chamber and cooled by a liquid nitrogen helical pipe);

4. the accessory equipment: vacuum pump units, mechanical valves and electrovalves, and sensors (flow rate meter, pressure and temperature).

The test chamber can accommodate a large range of mass flow rates (20–200 mg s$^{-1}$) and of atmospheric pressure (from atmospheric pressure down to 30 mbar). Inside the chamber, the gas temperature at the exit tubing of the cold gas generator depends on the pressure (and Probe altitude) to be simulated. Three altitudes were selected for the pump aeraulic tests: 65, 40 and 22 km; the exit temperatures were $-100$, $-150$ and $-170^\circ$C, respectively. A first confirmation of the pump’s airflow performance was obtained and compared with the pump’s calculated dynamic characteristics. Moreover, temperature sensors were located in different parts of the pump housing and support, in order to validate the thermal modeling of the pump.
9. Electronic System

9.1. Hardware Design

The ACP's electronic system (ACPE) is composed of four functional blocks: power supply module, control unit, monitoring unit and drive unit. The mechanical structure consists of two stacked frames and a base plate, made of aluminium alloy. The first frame contains two printed circuit boards (PCBs), one for the control unit (ACPCU) and one for the drive unit (ACPDU), mounted face to face. The second frame, which has an integrated top plate, contains the monitoring unit PCB (ACPMU) and the components for the power supply module (Figure 12).

The Huygens probe supplies the ACP with three 28 V power lines: main lines ML1 and ML3 and protected line PL2. The power supply module provides the secondary power for the control unit and the monitoring unit by use of a DC/DC converter at ML1. Secondary output voltages are +5 and ±15 volts. ML3 and
PL2 are used to power the electromechanical devices with 28 V directly from the spacecraft power bus. The protected power line 2 is used to activate the one-shot-valves and the sealing cover. A short circuit protection provides the decoupling to the S/C power bus system. Additional input filter stages at the power lines minimize the noise emission and limit the inrush currents during power-on.

The drive unit supplies all electromechanical devices (electrovalves, heaters, motors) located inside the mechanical box. This module contains the high power FET’s and the logic to run the brushless DC-motors. Metallic layers, aluminium foils laminated at the top side of the PCB’s, support the heat exchange between the high power components and the structure. Since the electromechanical devices are directly powered from the spacecraft power bus, the drive unit must be galvanically isolated from the drive logic inside the control unit.

The monitoring unit contains the signal conditioner for the analogue signals as temperature and pressure. The sensors located inside the mechanical box and rooted in a separate harness. Hall effect sensors with digital output and end-switches are used to monitor the status of the electromechanical devices. All motors, valves and heaters are operated under software control.

The control unit contains the processor module, the interface to the spacecraft and the driver logic. The processor module is based on a 80C85 8-bit microprocessor, supported by the 80C37 direct memory access (DMA) controller. The system clock is set to 4.096 MHz. Two bipolar PROM’s, 8 kBytes memory each, are used for code storage. Two RAM chips, 8 kBytes each, are mapped to the same address space as the PROM and used for data storage and program execution. During start-up the program code, approx. 12 kBytes, is copied to the RAM area. After a successful memory check the ACP program is executed from the RAM and the PROM’s are switched off. The remaining 4 kBytes are available for intermediate data storage.

Communication with the Probe’s Command and Data Management Subsystem is performed via four hot-redundant interfaces. The memory load command channel (MLC) is used to receive tele-commands and descent data broadcast. All measurement data are transmitted via the packet telemetry data channel (PTD). Both, tele-command reception and data transmission, are executed under DMA control. Additional information concerning the instrument status is transferred through the status word channel (SW). Synchronization with the probe system is performed by use of the broadcast pulse (BP) together with the time information in the descent data broadcast. An additional interface, where synchronization pulses are sent to the GCMS instrument, guarantees the accurate timing of the GCMS and the ACP valves activation during gas transfer periods. The entire logic, used for the S/C interface, drive logic and the processor system is packed into two field programmable gate arrays of type ACTEL-1020A.

A 12-bit analogue-to-digital converter (ADC) with an in-built sample and hold amplifier (S&H) and two cascaded 8-channel multiplexers (MUX) are used to monitor analogue signals. A voltage comparator monitors continuously the pressure
signal and generates an interrupt in case of pressure overflow. The driver logic mainly contains latches and buffers to activate the opto-couplers. In-built timers control actuation time and generate the waveforms to run the stepper motors. The timing can be set to adapt to different motor types. An important task is the power management, which discriminates simultaneous activation of devices with high power consumption. A priority scheme is used to allocate power to the valves and heaters in the most efficient way.

9.2. SOFTWARE DESIGN

Onboard software is used by ACP's microcontroller to execute the automatic sequences, monitor the status and health of the various subsystems, acquire and interpret TC and format data for TM. Its main functions are to control the mechanical subsystem, collect data and transmit it to the Probe system, provide an interface to command ACP via the Probe, and perform descent measurements synchronized with the rest of the Probe.

The software synchronizes every two seconds to the onboard time code and executes the measurement step by step as defined in the time-line. Internal clocks on a higher frequency provided the base for the accurate timing. The main loop is activated every 125 ms, triggered by the broadcast pulse. In case of absence of the BCP, an internal timer provides a time base of 128 ms. Re-synchronization is performed with the next BCP or the time code in the descent data broadcast.

An additional clock initiates an interrupt every 4 ms and is used to control the exact duration of a valve activation. All instrument activities are time dependent. The only exception is the over-pressure control, which is initiated via interrupt and has the highest priority.

ACP'S software provides four different operational modes: descent; cruise checkout; ground test mode; engineering mode. The first three execute automatically on receipt of the appropriate mission flag and time code. The engineering mode is selectable by a specific TC, and is used mainly for integration and test phases. In this mode, all ACP functions could be activated individually by sending the appropriate TC. It is accessible during any automatic sequence. It can also be used to check specified mechanical devices during cruise, should any problem arise.

10. Specific Tests During Qualification

In order to qualify the instrument it has been necessary to undertake specific tests in addition to the environmental tests – vibration tests and thermal vacuum tests. This is mainly due to the special thermal constraint during the descent in Titan's atmosphere when the pump unit is activated. Besides it was necessary to demonstrate that the lifetime of the mechanisms can cover the total number of actuations
(approximately 50) required during ground tests and cruise phase and during the descent trajectory. The operation lifetime of 10 hours for the pump unit had also to be proved.

10.1. FUNCTIONAL TESTS UNDER TITAN’S ATMOSPHERE CONDITIONS

The objective of the test was to demonstrate the functional ability of the instrument during the descent of the probe and to understand its thermal behavior, that is to test the performance of all its components and mechanisms.

However, the operation of the one-shot devices such as the sealing cover was controlled separately during a special ‘destructive descent sequence’ of the ACP qualification model, done at SEP. To achieve the functional tests, the conditions – pressure and temperature with respect to time – which the ACP will encounter during its operational lifetime in Titan’s atmosphere, must be simulated as closely as possible. In fact, the pressure profile was exactly representative of the descent whereas the temperature was maintained constant around 80 K.

The tests have been conducted at ‘Service des Basses Températures’ du Centre d’Etudes Nucléaires de Grenoble (CEA-CENG). A special cryostat, as shown in Figure 13, has been designed which contains the whole ACP instrument. It consists of two chambers. The first one is the chamber where the ACP is mounted and inside which it was possible to simulate the thermal environment of the ACP ensured by the thermal control of the probe. It can be regulated at a given value between 0 °C and −20 °C, for each test. The other chamber contains the sampling zone in which the ACP inlet tube is plunging and where the temperature is maintained at −190 °C. The atmospheric pressure of the cryostat is common to the two zones and can be controlled to follow a calculated pressure profile corresponding to the expected descent profile of the probe in Titan’s atmosphere. During the test a complete operational sequence of the ACP can be commanded by the electronic unit of the ACP and its ground support equipment. The sequence includes of course not only the two pumping phases but also all the operations of oven heating and gas transfer dictated by the program software. In addition to the information (T, P and status) given through the ACP data transmission, we got complementary measurements obtained by a great number of sensors instrumented all along the cryostat parts. This was particularly needed to get empirical values to be compared with the thermal model of the ACP (internal and in interaction with the Probe).

Two different tests, one for the base plate controlled at −10 °C and one for the base plate controlled at −20 °C, have been found entirely successful, showing that the whole components of the ACP were operating correctly. In particular this is the case for the gate valve mechanism, in spite of a gate valve main body temperature found as low as −50 °C at the end of the pumping phase. Besides, the results of the tests allowed to revise the values obtained by our thermal modeling for the exchanged flux between the ACP and the Probe (16 W in the worst case instead of 40 W).
During Titan’s atmosphere tests at CENG, direct measurement of the pump’s characteristics by the use of a flow meter was excluded (because of the low level of its internal pressure drop when the pump starts). However, the quality of the thermal...
modeling made together by CNES Toulouse and CERT/ONERA, associated to the almost complete instrumentation of the ACP gas circuit during the tests, allowed a preliminary confirmation of the flow rate of the pump. Nevertheless, complementary tests were done at CENG in order to precisely calibrate, a posteriori, the ‘thermal flow meter’ whose role was played by the cryostat exhaust tube. To achieve this test, the tube was instrumented, as in the previous test, by two thermocouples immersed inside the gas flow, TEG 1 and TEG 2. The operation consists in running equivalent dynamic tests, using the same cryostat but in which ACP has been replaced by a cell, on which a heater was fixed to adjust the power input to the internal flow (P gas). The external laboratory pump mounted in the down stream flow is used either for controlling the pressure inside the cryostat, or to ensure the circulation through the cell and the exhaust tubes. The objective is to reproduce the thermal dynamic responses of the two main sensors, obtained during the previous tests (see Figure 14a). Two flow-meters located in the upstream flow of the cryostat are used to deduce the calibration curves. The resulting data on the performance of the pump are shown on Figure 14b, as well as the power inputs brought to the screen and the cell.

11. Science Validation and Calibration Test

11.1. PYROLYSIS TESTS

In order to validate the ACP’s scientific performance, pyrolysis tests were conducted at LISA on solid phase material synthesized from experimental simulation.

An ACP laboratory model was specifically developed for this sort of science validation and laboratory investigation. It is representative of the ACP, except for the pump unit and the gas tank, which are not mounted. It contains:

- the filter transfer mechanism (not motorized) to translate the filter into and out of the oven;
- the gate valve mechanism (not motorized) to close off the oven;
- the three monostable microvalves used (1) to vent the oven by pumping (VT) (2) to fill the oven with pure nitrogen piston gas (V1), and (3) to transfer the gas phase from the oven to the GCMS (V2).

The filter could be dismounted from its support and easily replaced. In order to protect the filter’s organic solid phase material from oxygen contamination, the following operations were carried out in a glove box filled with nitrogen:

- once removed from the reactor, the filter was mounted;
- gate valve was closed after enclosing the filter in the oven.

The organic synthesis by electrical irradiation of an N₂-CH₄ mixture requires a long reaction time (about 20 h). The reactor is a two-part glass vessel with two tungsten electrodes and a metallic filter in the lower part. It is filled at a total pressure of 900 mbar with a mixture of N₂ (800 mbar) and CH₄ (100 mbar). One of
Figure 14. Complementary tests, at CENG, to determine the gas mass flow obtained by the ACP pump unit. (a) Shows the evolution, during the simulated descent in Titan's atmosphere (see section 10.1), of the temperatures measured by the thermocouples TEG1 and TEG2. These curves were used as reference curves. During the complementary tests, the flow rates have been adjusted to obtain values of TEG1 and TEG2 which fit the reference curves. TET1 was a control temperature which was not used. (b) Shows the resulting data of tests: evolution of the gas mass flow rate during the Titan descent simulation test. The adjustment of the thermal profile of TEG2 was done by acting on the flow rate at N2 injection. The adjustment of the thermal profile of TEG1 was achieved by the regulation of the electric power \( P_{\text{gaz}} \) brought to the gas. \( P_{\text{écran}} \) is the electric power dissipated into the screen to simulate the probe platform temperature as controlled by the probe \((-10^\circ\text{C})\).
the electrodes is connected to a Tesla coil fed by a low current (80–100 mA) high
frequency (80–200 kHz) generator. The other electrode is earthen. Five irradiation
periods of about 4 h each were performed and, between each, the gas phase was
removed from the reactor and replaced by a new mixture of N<sub>2</sub>-CH<sub>4</sub> at 900 mbar
with the same ratio as the original. During irradiation, the bottom of the reactor
was cooled by liquid nitrogen. At the end of the synthesis, 2.3 mg of solids were
deposited on the filter.

Owing to the oven’s low leak rate (5.10<sup>-4</sup> mbar l s<sup>-1</sup>), we can be sure that
no oxygen contamination of the filter occurred during analysis. The analysis of
the 600 °C pyrolysis products, obtained with the ACP laboratory model, was done
using a Varian Saturn II GCMS (with helium as carrier gas) at an inlet pressure of
1.6 bar. The chromatographic capillary column was a CP-Sil-5 CB column of 25 m
length, 0.15 mm inside diameter and 1.20 µm film thickness from Chrompack. The
column temperature was controlled as follows: 30 °C for 20 min; raised from 30 °C
to 150 °C in 30 min at 4.0 °C/min; 150 °C for 10 min. The total mass spectra of the
GC peaks were thus collected over 60 min. The ion trap mass spectrometer was able
to detect masses of 10–226 AMU by using the electronic ionization mode. Under
the experimental chromatographic conditions chosen, only hydrocarbons from C<sub>4</sub>
to C<sub>10</sub> were analyzed. This excluded the light hydrocarbons (C<sub>2</sub> and C<sub>3</sub>) and the
heavy hydrocarbons (above C<sub>10</sub>).

The chromatogram obtained by the GCMS analysis shows many organic com­
ounds (Figure 15). Some GC peaks appear clearly from the total mass spectra.
The others are identified only when they are specific ions with a very high MS
sensitivity. According to their mass spectra, 23 gross formulas of more than 25 GC
peaks have been identified unambiguously. It immediately appears that no oxy­
genated organic compounds were detected, showing that the laboratory procedure
prevented oxygen contamination of the synthesized solid phase material.

In the proposed simulation test, we have observed that the main compounds
detected on the pyrogram are mono-aromatic hydrocarbons. The most concentrated
is benzene (C<sub>6</sub>H<sub>6</sub>), followed by toluene (C<sub>7</sub>H<sub>8</sub>) and C<sub>2</sub>-substituted benzene (C<sub>9</sub>H<sub>8</sub>,
C<sub>9</sub>H<sub>10</sub>, C<sub>9</sub>H<sub>12</sub>). One may conclude that these mono-aromatic hydrocarbons are the
major constituents of the synthesized solid phase material. If they are thermally
stable, they could be completely desorbed into the gas phase at 600 °C with no
variation of their structures. Thus the main constituents are the main compounds
desorbed and detected on the pyrogram.

One argument limits the validity of this result. Since a bi-aromatic hydrocarbon
is observed on the pyrogram (C<sub>10</sub>H<sub>8</sub>) and because of the chromatographic
conditions (choice of column), we cannot properly observe poly-aromatic hydro­
carbons. In a previous study, the pyrolysis of anthracene, which contains three
aromatic cycles, was performed with the same pyrolyser at 600 °C. The pyrogram
showed mainly benzene, toluene, ethenyl-benzene and C<sub>8</sub>H<sub>10</sub> isomers. It shows
that poly-aromatic hydrocarbons are decomposed at 600 °C in benzene and in sub­
stituted mono-aromatic hydrocarbons. The type of compounds detected on anthra-
Figure 15. Pyrogram of the solid phase material synthesized directly on to the filter.
cene pyrograms depends on the pyrolysis temperature. For example, it was shown that naphthalene (a bi-aromatic hydrocarbon) was clearly observed at a lower pyrolysis temperature. So it is quite possible that the mono-aromatic hydrocarbons detected on the pyrogram could be provided by the poly-aromatic hydrocarbons present in the solid phase material and thermally decomposed at 600 °C into mono-aromatic hydrocarbons.

We also detect a small amount of benzonitrile (C\(_7\)H\(_5\)N), which can be similarly produced by thermal decomposition of poly-aromatic compounds containing nitrogen atoms. Most of the nitriles observed on the pyrogram have also been detected in the gas phase synthesized by the simulation (acetonitrile: C\(_2\)H\(_3\)N, propenenitrile: C\(_3\)H\(_3\)N, butenenitrile isomer: C\(_4\)H\(_5\)N, butanenitrile isomers: C\(_4\)H\(_7\)N). The heaviest nitriles detected (pentenitrile isomer: C\(_5\)H\(_7\)N and pyrrole: C\(_4\)H\(_5\)N) could be provided by thermal desorption of the same compounds present in the solid phase or by thermal decomposition of the heaviest molecules. Finally, many hydrocarbons are detected on the pyrogram (C\(_4\)H\(_6\), C\(_4\)H\(_8\), C\(_5\)H\(_8\), C\(_5\)H\(_6\), C\(_6\)H\(_6\), C\(_6\)H\(_8\) and C\(_7\)H\(_{14}\)). They can be provided by the two sources cited above, or by the thermal polymerization of the lightest alkenes and alkynes.

Before performing the above pyrolysis tests, the procedure for testing the cleanliness of the ACP Flight Model, after delivery by SEP, was conducted. The instrumentation includes a very pure nitrogen gas reservoir, a flow regulator provided by the contractor, and the Varian Saturn II GCMS. A mixing ratio threshold of 50 ppb was measured for the significant gas components.

11.2. LABORATORY CALIBRATION OF THE INSTRUMENT

The program selected for calibrating the flight model is directly linked to the GCMS calibration plan carried out at GSFC. It will be used to relate quantitatively the pyrograms and the mass spectra to the effluent gases injected from the ACP. Several known concentration gas mixtures, containing expected Titan atmospheric species, were injected directly into the ACP feeding tube of the GCMS.

A second phase, which requires the gas to pass through the ACP oven first, has been limited to a few test species. Complete calibration will be performed, in the laboratories, on the spare models at the time of arrival on Titan. During this investigation, the oven will be heated accordingly with the software programs of the ACP and the GCMS, and filled at the pressure measured after the completion of each of the two aerosols’ sampling phases during the Probe descent.

12. Conclusion

The ACP/GCMS data will provide information on the bulk chemical composition of the stratospheric and tropospheric particles, with a discrimination between the core of these particles and the outer layers of condensates. The chemical analysis
of the core of the particle, by pyrolysis techniques, is of major importance for the scientific objectives. The pyrograms obtained either with Pyr-MS or Pyr-GC-MS, give precious information on the nature of the pyrolysis fragments. This can be used to infer the chemical structure of the sample and as a guide to perform calibrations (by direct comparison of the pyrograms of standard samples with those of the unknown, using identical conditions of pyrolysis, and with the help of similarity coefficients, which can allow a secure identification). Applied to Titan’s aerosols, it will allow us to check if the core of the particle, assumed to be composed of oligomers formed in the high atmosphere, is constituted of only carbonaceous oligomers free of heteroatoms, or includes C+N oligomers. Such a measurement will have very important implications for our understanding of the primary processes occurring in the high atmospheric regions. It will be a way to determine the relative contributions of the photopolymerization and co-polymerization processes of CH₄, C₂H₂, C₂H₄ and HCN.

In addition, the use of an analytical pyrolysis cycle with several temperatures will allow evaporation and analysis of the volatile part of the collected aerosols without pyrolyzing either this part, or the core. With such analysis, it will be possible to detect minor atmospheric constituents undetectable in the gas phase, because they can be highly concentrated in the aerosol compared to the gas phase. It will also be possible to get information on the absolute quantity of aerosol collected in the atmosphere, and on the ratio of the core to the condensate parts. This will provide a major constraint for microphysical modelling of Titan’s organic aerosol. Cloud structure data from DISR, and P, T vertical profiles, winds and turbulence data from the HASI and DWE will also be used to constrain the models.

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References


In the case where the Knudsen number:

\[ Kn = \frac{2 \lambda}{d_p} \]

(\(lambda: mean free path of air molecules\) is not smaller than unity, the Stoke’s law:

\[ F = -3 \pi d_p \mu u \]

has to be corrected by the Cunningham slip correction factor:

\[ C = 1 + a \, Kn + b \, Kn \exp(-c \, Kn^{-1}) \]
Figure 16. Stoke's number, \( St \), related to the diameter of the particles and therefore to the altitude of the Probe. When \( St > 1 \), particles are impacting the collector.

where \( a, b \) and \( c \) are related to the gas. Hence:

\[
St = \frac{\rho_p}{18 \mu} \frac{d_p^2}{\delta} \frac{u}{C}.
\]

If \( St \ll 1 \), the aerosols follow the flow lines and impaction does not occur. Conversely, if \( St \gg 1 \), the aerosols impact the collector. The Stoke's number has been calculated as a function of altitude and particle size for Titan's characteristics and with the expected probe velocity, assuming \( \delta = 1 \) cm; \( d_p \) is the aerosol particle diameter and \( z \) the altitude (Figure 16). Keeping in mind that the models give \( d_p \approx 0.4 \mu \text{m} \) at 160 km, \( d_p \approx 0.4 \) to 2 \( \mu \text{m} \) at 60 km, one can see that aerosol collection by impaction only will be difficult over a large part of the stratosphere. Below 60 km, impaction will occur if \( d_p \gg 6 \mu \text{m} \); but the uncertainties on the growth of particles due to ethane and methane condensation lead us to be cautious.
Figure 17. Sampling efficiency of a filter, E, in function of the diameter of the particles and therefore of the altitude of the probe.

2. SAMPLING ON FILTERS

Particle inertia increases the number of particles which penetrate the pipe. If the velocity is $u_s$ in the sampling pipe and if $u$ is the flow velocity outside the filter, the sampling efficiency will be $E = \frac{n_s}{n}$, where $n$ is the number density in the flow and $n_s$ the number density in the pipe. $E$ is related to $St$ by:

$$E = \frac{u}{u_s} \left( 1 - \alpha \right) + \alpha$$

with

$$\alpha \approx \left( 1 + St \right)^{-1}$$

In Figure 17, $E$ is shown as a function of $d_p$ and $z$ (for $u_s = 7$ m s$^{-1}$).

When particles are slowed in the pipe, the stopping distance is $x_s \approx \delta St$. In the case where $\delta \approx 1$ cm, $x_s$ can be read in Figure 16 by replacing $St$ by $x_s$ in centimetres. Particles then arrive on the filter at reduced velocity and the
eventuality of rebound is limited. The filters which will be used are made of multilayered stainless steel fibres (porosity $P_o \approx 0.8$, fibre radius $R \approx 2 \mu m$). In this case particles will be captured mainly by interception, increased by inertia effects, diffusion phenomenon being insignificant (Fuchs, 1964).
Abstract. The payload of the Huygens Probe into the atmosphere of Titan includes the Descent Imager/Spectral Radiometer (DISR). This instrument includes an integrated package of several optical instruments built around a silicon charge coupled device (CCD) detector, a pair of linear InGaAs array detectors, and several individual silicon detectors. Fiber optics are used extensively to feed these detectors with light collected from three frame imagers, an upward and downward-looking visible spectrometer, an upward and downward looking near-infrared spectrometer, upward and downward looking violet photometers, a four-channel solar aureole camera, and a sun sensor that determines the azimuth and zenith angle of the sun and measures the flux in the direct solar beam at 940 nm. An onboard optical calibration system uses a small lamp and fiber optics to track the relative sensitivity of the different optical instruments relative to each other during the seven year cruise to Titan. A 20 watt lamp and collimator are used to provide spectrally continuous illumination of the surface during the last 100 m of the descent for measurements of the reflection spectrum of the surface. The instrument contains software and hardware data compressors to permit measurements of upward and downward direct and diffuse solar flux between 350 and 1700 nm in some 330 spectral bands at approximately 2 km vertical resolution from an altitude of 160 km to the surface. The solar aureole camera measures the brightness of a 6° wide strip of the sky from 25 to 75° zenith angle near and opposite the azimuth of the sun in two passbands near 500 and 935 nm using vertical and horizontal polarizers in each spectral channel at a similar vertical resolution. The downward-looking spectrometers provide the reflection spectrum of the surface at a total of some 600 locations between 850 and 1700 nm and at more than 3000 locations between 480 and 960 nm. Some 500 individual images of the surface are expected which can be assembled into about a dozen panoramic mosaics covering nadir angles from 6° to 96° at all azimuths. The spatial resolution of the images varies from 300 m at 160 km altitude to some 20 cm in the last frames. The scientific objectives of the experiment fall into four areas including (1) measurement of the solar heating profile for studies of the thermal balance of Titan; (2) imaging and spectral reflection measurements of the surface for studies of the composition, topography, and physical processes which form the surface as well as for direct measurements of the wind profile during the descent; (3) measurements of the brightness and degree of linear polarization of scattered sunlight including the solar aureole together with measurements of the extinction optical depth of the aerosols as a function of wavelength and altitude to study the size, shape, vertical distribution, optical properties, sources and sinks of aerosols in Titan’s atmosphere; and (4) measurements of the spectrum of downward solar flux to study the composition of the atmosphere, especially the mixing ratio profile of methane throughout the descent. We briefly outline the methods by which the flight instrument was calibrated for absolute response, relative spectral response, and field of view over a very wide temperature range. We also give several examples of data collected in the Earth’s atmosphere using a spare instrument including images obtained from a helicopter flight program, reflection spectra of various types of terrain, solar aureole measurements including the determination of aerosol size, and measurements of the downward flux...
of violet, visible, and near infrared sunlight. The extinction optical depths measured as a function of wavelength are compared to models of the Earth’s atmosphere and are divided into contributions from molecular scattering, aerosol extinction, and molecular absorption. The test observations during simulated descents with mountain and rooftop venues in the Earth’s atmosphere are very important for driving out problems in the calibration and interpretation of the observations to permit rapid analysis of the observations after Titan entry.

1. Introduction

Optical measurements of solar radiation made inside Titan’s atmosphere can reveal a great deal about many important physical processes occurring there. Measurement of the absorption of ultraviolet light determines the amount of energy available to drive the photochemical reactions that lead to changes in atmospheric composition and to the production of atmospheric aerosols. Measurement of the brightness of the sky near the disk of the sun, the solar aureole, constrains the size, shape, composition, and distribution of aerosols and cloud particles and their optical properties. These properties of the aerosols control their ability to absorb sunlight and emit thermal infrared radiation. Measurements of the net flux of solar energy as a function of altitude determine the amount of sunlight absorbed in each layer of the atmosphere, yielding the net solar heating rate. Knowledge of the particle properties, gas composition, and temperature profile permit computation of the net radiative cooling rate. This combined with the solar heating rate provides the radiative forcing for atmospheric dynamics, which in turn can affect the distribution of aerosol and cloud particles and influence climate. The composition, thermal balance, dynamics, and meteorology of the atmosphere also affect (and are affected by) the properties of the planetary surface. Images of the surface in reflected sunlight together with near infrared reflection spectra can reveal the nature of the surface and its interactions with atmospheric processes.

The Descent Imager/Spectral Radiometer (DISR) is the optical instrument aboard the Huygens Probe that makes measurements at solar wavelengths. This instrument was developed in a collaborative effort by scientists from the US, France, and Germany. The list of Co-Investigators for the DISR experiment includes M. G. Tomasko, L. R. Doose, and P. H. Smith (of the University of Arizona), R. West (of the Jet Propulsion Laboratory), R. Solderblom (of U.S.G.S. in Flagstaff), B. Bézard, M. Combes, A. Coustenis, C. deBergh, and E. Lellouch (of the Paris Observatory (PO)), B. Schmitt (of the Institute of Glaciology in Grenoble, France), H. U. Keller and N. Thomas (of the Max Planck Institute for Aeronomy (MPAE) in Lindau, Germany), and F. Gliem (of the Technical Institute of Braunschweig (TUB), Germany). For the U.S. effort, our key aerospace partner was Lockheed Martin Aerospace (LMA) in Denver.

By including substantial hardware contributions from several institutions in Europe, a significantly more capable instrument was developed than would have
been possible using the resources of one country alone. DISR measures solar radiation using silicon photodiodes, a two-dimensional silicon Charge Coupled Device (CCD) detector (provided by H. U. Keller and our German investigators) along with two InGaAs near-infrared linear array detectors (provided by B. Bézard and our investigators from Paris). Fiber optics (developed by Lockheed Martin Aerospace with our U.S. investigators) connect the detectors to many separate sets of fore-optics that collect light from different directions and in different spectral regions. In this way the instrument can make a suite of measurements carefully selected to answer key questions concerning the nature of Titan’s surface and the composition, meteorology, thermal balance, and clouds and aerosols in the atmosphere of Titan.

The purpose of this paper is to describe the DISR instrument and the scientific investigation planned for its descent through Titan’s atmosphere on the Huygens probe. We have previously described (Tomasko et al., 1996, 1997) the design approach for the instrument. Here we concentrate on the properties of the instrument using measurements made after the instrument was completed, including some calibration measurements as well as measurements made from a helicopter and from the surface of the Earth. The scientific objectives of the experiment are outlined briefly in section 2 to set the context for the description of the instrumental approach summarized in section 3. Section 4 summarizes the measurements planned during the mission. Section 5 briefly summarizes the types of laboratory calibration data collected for the instrument. A final section shows a sample of data obtained from a test unit during our field test program on Earth, and serves to illustrate the ability of the flight experiment to meet our objectives at Titan.

2. Scientific Objectives

2.1. THERMAL BALANCE AND DYNAMICS

A basic objective of the DISR investigation is to measure directly the vertical profile of the solar heating rate. This will be done using measurements of the upward and downward solar flux over the spectral interval from 350 nm to 1700 nm between 160 km to the surface at a vertical resolution of approximately 2 km. The downward flux minus the upward flux gives the net flux, and the difference in the net flux at two altitudes gives the amount of solar energy absorbed by the intervening layer of atmosphere. Knowledge of the solar heating profile is necessary for understanding the thermal balance of Titan’s atmosphere.

The combination of the solar heating profile with the thermal cooling profile provides the net radiative drive for atmospheric dynamics. The radiative cooling profile will be modeled using the temperature profile and the opacity of atmospheric gases and cloud and aerosol particles at wavelengths in the thermal infrared. The gaseous composition and temperature profile will be measured by other Huy-
gens and Cassini instruments. The DISR measurements make an important contribution by determining the size, shape, optical properties, and vertical distribution of aerosol and cloud particles. Using models for the variation of particle properties and thermal profile over the surface of Titan, the variations of solar heating and thermal cooling over the disk can be computed. Once the solar heating and thermal cooling have been combined, model computations can be used to estimate the wind field from the radiative forcing.

Finally, DISR will measure the horizontal wind direction and speed as functions of altitude from sets of panoramic images of the surface obtained every few kilometers in altitude which will show the drift of the probe over the surface of Titan. Sets of 36 images covering nadir angles from $6^\circ$ to $96^\circ$ around a full $360^\circ$ in azimuth are obtained within two minute periods during imaging operations. Overlap between individual images, views of the horizon, and housekeeping observations of the orientation of the probe are available to determine the motion of the instrument platform relative to the vertical when these images were obtained. This information will be used to separate angular motion under the parachute from drift over the surface between the times of successive image panoramas. The measured wind speed and direction determined by DISR can be compared to the wind field computed from the net radiative forcing determined above.

### 2.2. Distribution and Properties of Aerosol and Cloud Particles

Several properties of the cloud and aerosol particles are important for understanding their interaction with the solar and thermal radiation field. The size of the particles compared to the wavelength of the radiation is important for understanding particle scattering. Measurements of both the forward scattering and polarizing nature of the aerosols on Titan have been used to show that spherical particles can not simultaneously explain these two types of observations (see Hunten et al., 1985). Information on particle shape in addition to size is therefore required for understanding particle scattering. The vertical distribution of the particles also influences the profiles of solar and thermal radiation. Finally, a suite of optical properties as functions of wavelength are needed to permit accurate computations of the interactions of the particles with radiation. These properties include the optical depth, single scattering albedo, and the shape of the scattering phase function. The variation of these optical properties with wavelength, together with determinations of size and shape, can yield the imaginary refractive index and thus constrain the composition of the particles.

DISR will measure many of these properties using combinations of measurements of small-angle scattering in the solar aureole in two colors, measurements of side- and back-scattering in two colors and two planes of polarization, measurements of extinction as a function of wavelength from the blue to the near infrared, and measurements of the diffuse transmission and reflection properties of layers in the atmosphere as outlined in sections 3 and 4.
2.3. NATURE OF THE SURFACE

The surface of Titan was hidden from view of the cameras aboard the Pioneer and Voyager spacecraft by the layers of small haze particles suspended in the atmosphere. Nevertheless, intriguing suggestions regarding the nature of the surface have been made (Lunine, 1993), including the possibility that the surface consists of a global ocean of liquid methane-ethane. Recent radar observations and direct observations at longer wavelengths by the Hubble Space Telescope (Smith et al., 1996; Lemmon et al., 1995) show that the surface is not a global ocean. The many fascinating surfaces observed by the Voyager mission on satellites of the outer solar system showed a surprising range of phenomena including craters, glacial flows, frost and ice coverings, and active geysers and volcanoes. These preliminary explorations of the small bodies of the outer solar system suggest that the surface of Titan may well also contain surprises.

DISR will determine the physical state (solid or liquid) of the surface near the probe impact site, and determine the fraction of the surface in each state. DISR will measure the topography of the surface, thus constraining some of the physical processes that have formed the surface. DISR will obtain reflection spectra of surface features from the blue to the near infrared in order to constrain the composition of the different types of terrain observed. In addition, DISR will image the surface at resolution scales from hundreds of meters (similar to those accessible from the orbiter) to tens of centimeters over as large an area as possible to permit studies of the physical phenomena occurring on the surface and to clarify the physical interactions of the surface and the atmosphere.

2.4. COMPOSITION OF THE ATMOSPHERE

The Huygens Probe contains a mass spectrometer/gas chromatograph to measure directly the composition of the atmosphere. Nevertheless, direct sampling techniques can give inaccurate mixing ratios for condensable constituents if a cloud particle enters and slowly evaporates in the inlet system, as happened during the Pioneer Venus mission (Hoffman et al., 1980). The DISR provides an important complementary capability for measuring the mixing ratio of methane, the most likely condensable constituent, using a technique that is not subject to this potential problem. The mixing ratio of methane will be obtained from the increasing depth of methane absorption bands as the gas path between the instrument and top of the atmosphere increases during the descent.

Methane can exist as a solid, liquid, or gas on Titan, and has been suggested to play a role in the meteorology of Titan similar to the role played by water on the Earth. The DISR measurements of the methane mixing profile will be analogous to a relative humidity profile on the Earth.

Finally, the atmosphere of Titan is believed to consist primarily of nitrogen, methane and argon. The DISR measurements of the mixing ratio of methane together with the determination of total mean molecular weight of the atmosphere by
radio occultation measurements made by the Cassini Orbiter will indirectly yield the argon to nitrogen mixing ratio as an important backup to the mass spectrometer measurements planned for the Huygens Probe.

3. Instrument Approach

3.1. Overview

In order to achieve this broad range of scientific objectives, it is necessary to measure the brightness of the sunlight in Titan’s atmosphere with several different spatial fields of view, in several directions, and with various spectral resolutions. For measurements of solar energy deposition, for example, measurements are needed of the downward and upward solar flux with broad and flat spectral sensitivity, and with a cosine zenith angle weighting. For determination of the composition of the surface, spectral resolution is desirable, and spatial information is necessary. For determination of the physical processes occurring on the surface, images are needed with very broad fields of view looking downward toward the surface. To determine the size distribution of aerosol particles above the altitude of the probe, upward-looking measurements are needed of the brightness of the region of the sky near the sun (the solar aureole) in at least two colors with modest angular resolution. Images looking outward toward the horizon are useful for sensing the presence of thin haze layers during the descent.

It was not possible to include in the limited payload of the Huygens Probe separate instruments devoted to each of these scientific measurements. Nevertheless, it has been possible to increase considerably the usefulness of the single Huygens optical instrument by making extensive use of fiber optics to collect light from different directions and bring it to a few centrally located detectors after various spectral or spatial analyses. In this way redundant electrical systems have been minimized, and moving mechanical parts have been all but eliminated. A parachute swivel and rotation vanes on the perimeter of the probe provide a rotating platform for direct and diffuse sensing as well as image mosaics. A summary of the locations of the fields of view and spectral coverage of the DISR optical measurements is given in Table 1.

The DISR instrument can be thought of as consisting of two halves, one using a charge coupled device (CCD) array detector and the other half built around a pair of linear near infrared array detectors. The pair of linear array detectors are at the focus of a small grating spectrometer as shown schematically in Figure 1. The grating spectrometer is fed by two optical fibers. One fiber looks down and a small lens is used to collect light from a 3° by 9° field of view centered at 20° nadir angle. This permits measurement of the intensity as a function of wavelength coming from this location on the ground. As the probe rotates, information is collected over the entire range of azimuth angles. Models are used for the variation of the intensity
### Table 1

Summary of DISR instruments

<table>
<thead>
<tr>
<th>Upward-Looking Instrument</th>
<th>Azimuth Range</th>
<th>Zenith Range</th>
<th>Spectral Range (nm)</th>
<th>Spectral Scale (per pixel)</th>
<th>Spatial Scale (per pixel)</th>
<th>Pixel Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violet Photometer (ULV)</td>
<td>170°</td>
<td>5°–88°</td>
<td>350–480</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Visible Spectrometer (ULVS)</td>
<td>170°</td>
<td>5°–88°</td>
<td>480–960</td>
<td>2.4 nm</td>
<td>–</td>
<td>8 x 200</td>
</tr>
<tr>
<td>Infrared Spectrometer (ULIS)</td>
<td>170°</td>
<td>5°–88°</td>
<td>870–1700</td>
<td>6.3 nm</td>
<td>–</td>
<td>132</td>
</tr>
<tr>
<td>Solar Aureole (SA 1)</td>
<td>6°</td>
<td>25°–75°</td>
<td>500±25</td>
<td>–</td>
<td>1°</td>
<td>6 x 50</td>
</tr>
<tr>
<td>Solar Aureole (SA 2)</td>
<td>6°</td>
<td>25°–75°</td>
<td>500±25</td>
<td>–</td>
<td>1°</td>
<td>6 x 50</td>
</tr>
<tr>
<td>Solar Aureole (SA 3)</td>
<td>6°</td>
<td>25°–75°</td>
<td>935±35</td>
<td>–</td>
<td>1°</td>
<td>6 x 50</td>
</tr>
<tr>
<td>Solar Aureole (SA 4)</td>
<td>6°</td>
<td>25°–75°</td>
<td>935±35</td>
<td>–</td>
<td>1°</td>
<td>6 x 50</td>
</tr>
<tr>
<td>Sun Sensor (SS)</td>
<td>64° cone</td>
<td>25°–75°</td>
<td>939±6</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downward-Looking Instrument</th>
<th>Azimuth Range</th>
<th>Nadir Range</th>
<th>Spectral Range (nm)</th>
<th>Spectral Scale (per pixel)</th>
<th>Spatial Scale (per pixel)</th>
<th>Pixel Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violet Photometer (DLV)</td>
<td>170°</td>
<td>5°–88°</td>
<td>350–480</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Visible Spectrometer (DLVS)</td>
<td>4°</td>
<td>10°–50°</td>
<td>480–960</td>
<td>2.4 nm</td>
<td>2°</td>
<td>20 x 200</td>
</tr>
<tr>
<td>Infrared Spectrometer (DLIS)</td>
<td>3°</td>
<td>15.5°–24.5°</td>
<td>870–1700</td>
<td>6.3 nm</td>
<td>–</td>
<td>132</td>
</tr>
<tr>
<td>High-Resolution Imager (HRI)</td>
<td>9.6°</td>
<td>6.5°–21.5°</td>
<td>660–1000</td>
<td>–</td>
<td>0.06°</td>
<td>160 x 256</td>
</tr>
<tr>
<td>Medium-Resolution Imager (MRI)</td>
<td>21.1°</td>
<td>15.75°–46.25°</td>
<td>660–1000</td>
<td>–</td>
<td>0.12°</td>
<td>176 x 256</td>
</tr>
<tr>
<td>Side-Looking Imager (SLI)</td>
<td>25.6°</td>
<td>45.2°–96°</td>
<td>660–1000</td>
<td>–</td>
<td>0.20°</td>
<td>128 x 256</td>
</tr>
</tbody>
</table>

with nadir angle, and the observations are used to constrain the upward solar flux at wavelengths from 850 to 1700 nm. The second feed fiber for the IR spectrometer looks at the bottom of a horizontal diffusing plate. The plate is surrounded by an external baffle that limits its field of view to zenith angles from 5° to 88° and to
Figure 1. Schematic layout of the infrared spectrometer. Separate fiber ribbons bring the light from a diffuser (looking up) and from a camera lens (looking down) to adjacent positions along the input slit of the spectrometer. A small mechanical shutter located just behind the input slit can be commanded open or closed to separately measure the dark current of the detector when it is warm and the total bright plus dark signal. The light leaving the grating spectrometer is focused on the pair of linear detectors. Also shown is a tipped glass plate which is oriented to partially compensate for the different efficiency of the grating for input light which is linearly polarized parallel or perpendicular to the grooves of the grating.

170° in azimuth. The baffle is termed a ‘bear’s ear baffle’ because of its appearance (see Figure 2). The diffusing plate makes the response of upward-looking IR spectrometer roughly proportional to the cosine of the zenith angle. Thus, the instrument measures half the diffuse downward flux plus the direct downward flux (when the sun is included in the field of view of the instrument) or only half the diffuse downward flux (when the probe has rotated so that the sun is behind the baffle).

The second half of the DISR instrument contains the CCO detector and the fiber optic bundle that feeds this detector. The fiber optic bundle is constructed so that different portions of the bundle are fed by different optical systems at the input end, but the light is all brought together in front of the CCO detector (see Figure 3). The gap between the end of the fiber optic bundle and the face of the CCO detector is <20 μm. The CCO pixels are 17 by 23 μm in size centered 23 μm apart both vertically and horizontally. Because the gap is smaller than a CCO pixel, not much resolution is lost across the gap between the end of the fiber optic conduit and the face of the CCO. The individual fibers in the fiber optic conduit are 8 μm in diameter, so several fibers feed each CCO pixel.

The sensitive area of the CCO array is 520 by 256 pixels times 23 μm for each pixel, or about 12 mm horizontally by 5.9 mm vertically. The fiber optic conduit is about 6 by 12 mm at this end and is mounted very close to the face of the CCO. From here the fiber optic conduit is separated into nine different bundles. Three
Figure 2. The shape of the ‘bear’s ear’ baffle which surrounds the diffuser of the upward-looking infrared spectrometer to define its limit its field of view to 170° in azimuth and to the range from 5° to nearly 90° in zenith angle. The region within 5° of the zenith is masked to avoid viewing the parachute.

Figure 3. The layout of the fiber optic conduit which brings light from the three imagers, from the four-channel solar aureole camera, and from the upward-looking and downward-looking visible spectrometer to the face of the CCD detector (right hand end of the conduit).
of the bundles (3.7 × 5.9 mm, 2.9 × 5.9 mm, and 4.0 × 5.9 mm lead to three separate lens systems pointed at central nadir angles of 14°, 31°, and 71°. The f/2.5 lenses at the end of each of these three fiber bundles focus an image on the front of each fiber bundle. The arrangement of the windows, lenses, image conduits, and the CCD detector is shown schematically in Figure 4.

Figure 5 shows the arrangement of the upward and downward-looking visible spectrometer windows, fibers, optics, and the CCD detector. Two separate fiber optic ribbons lead from the CCD detector to the focus of a small grating spectrometer. One of these ribbons feeds an area of 20 × 200 pixels (5 mm × 0.5 mm), while the other covers 8 by 200 CCD pixels. The thicker ribbon is used for the downward-looking portion of the visible spectrometer while the thinner ribbon is used for the upward-looking portion. At the input slit plane of the grating spectrometer, separate fibers lead to a small lens system that images the slit onto a 4° by 40° long region on the ground centered at 30° nadir angle. The other fiber leads to the bottom of a flat diffusing plate that is surrounded by an external ‘bear’s ear’ baffle that limits its field of view from 5° to 88° zenith angle and to 170° in azimuth. In addition, a 10° wide shadow bar extends down roughly the center of the field of view. Data can be collected when the sun illuminates the diffuser, or when the sun is behind the shadow bar or behind the back of the baffle. Combinations of these measurements can yield the direct and diffuse downward solar flux.

Figure 6 shows the schematic layout of the solar aureole system. Four 6 × 50 pixel regions of the CCD are fed by separate ribbons of fibers that are fed by lenses, filters, and polarizers to image a strip of sky 6° wide in azimuth and extending from
Figure 5. The schematic layout of the components of the upward and downward-looking visible spectrometer. The upward looking input views the bottom of a diffuser. The downward looking input uses a lens to project the entrance slit onto a $4^\circ \times 40^\circ$ region that extends from $10^\circ$ to $50^\circ$ nadir angle.

Figure 6. The schematic layout of the components of the solar aureole system. The beamsplitter is used to introduce light from the inflight calibration system into the four channels of the solar aureole system.
Figure 7. The schematic layout of the sun sensor. The three-slit reticle is deposited on the front of one of the plano-convex lenses next to the bandpass filter. The size of the optical elements are shown to scale in the upper left corner with a bar to indicate a size of 1 cm. The detector stimulus is used to inject pulses of light into the system to test functionality during cruise.

25° to 75° in zenith angle. These four strips are measured in two wavelength bands (near 500 and 935 nm). In each wavelength band, a linear polarizing analyzers are used to measure separately the horizontal and vertical components of linear polarization.

The separate grating spectrometers feeding the CCD and linear array detectors measure the upward and downward streaming solar flux from 480 nm to 960 nm and from 850 to 1700 nm, respectively. Two separate silicon detectors are used to extend the upward and downward flux measurements to the violet region between 350 and 480 nm. These individual detectors are placed behind diffusing plates mounted behind external ‘bear’s ear’ baffles. The upward looking violet photometer (ULV) is placed behind the diffuser used by the ULVS, and shares the same external baffle and shadow bar. The downward looking violet photometer (DLV) uses a separate diffuser and bear’s ear baffle.

Finally, a separate silicon detector, lens, and vertical slit assembly is used to determine when the instrument has rotated to the azimuth of the sun. The pulses generated by this system are used to control the azimuth at which measurements are made by the rest of the system. The schematic layout of this system is shown in Figure 7.
3.2. DETECTORS

Co-I Dr. H. U. Keller of the Max Planck Institute for Aeronomy (MPAE) in Germany is responsible for the CCD subsystem. LORAL Fairchild supplied the flight CCDs to the MPAE group. The data interface between the German and American electronics is at the output of the 12-bit analog-to-digital (A/D) converter.

The format of the CCD is shown in Figure 8. The CCD is a $512 \times 520$ pixel frame transfer device. It is divided into an image section and a memory, or storage, section, each $256 \times 520$ pixels in size. The image section contains antiblooming drains on the side of each pixel. The individual pixels are $17 \times 23 \, \mu m$ (sensitive area) on $23 \, \mu m$ centers. The CCD is fed by optical fibers from 9 optical subsystems: the HRI, MRI, SLI, ULVS, DLVS, and the four-channel SA radiometer (two colors in each of two orthogonal polarization states). The quantum efficiency of the CCD is $>50\%$ at the peak.

Exposure time is controlled by 0.5 ms shifts of the charge from the image section to the storage section of the chip which is covered by an opaque metal film. The exposure is the time between rapid shifts. No mechanical shutter is needed and no moving parts are used in this system. The full CCD frame is read out and digitized for imaging data, a process that takes about 2.2 seconds for the entire
frame. Only the first 49 columns are digitized for taking spectra and solar aureole measurements, thus shortening the readout time to about 300 ms when only these measurements are made.

After A/D conversion, the data are reduced from 12 to 8 bits/pixel by a square-root algorithm which balances the size of the quantization steps according to the distribution of shot noise in the observations. The image data are then compressed in a lossy hardware compressor by factors between 3 and 8:1. The hardware that accomplishes the lossy image compression was provided by Co-Investigator Dr. F. Gliem of the Technical Institute of Braunschweig, Germany. The spectral and solar aureole data from the CCD are compressed with a lossless software compression algorithm by a factor of about 2 and then buffered for transmission.

The dark current from the CCD is measured by the signals from the column of masked pixels along the edge of the chip. These data are read out and inserted into the telemetry stream once every few minutes. At Titan entry, the chip is at a temperature of some 260 K, and the dark current is a few percent of typical signals. After some 40 minutes of the nominal 140 minute descent, the detector cools to a temperature less than 200 K, and the dark current is essentially negligible.

The full well capacity of the CCD pixels is about 125,000 electrons. This is digitized at 30 electrons/step (before square-root compression). The read noise of the system is about 15 electrons. For all but the lowest signals, the data are shot-noise limited.

Two linear photodiode arrays (for the DLIS and the ULIS) along with their associated preamplifier electronics were provided by Co-I Dr. B. Bézard of the Paris Observatory. Each of the two arrays contains 150 individual InGaAs photodiodes bonded to a sapphire substrate and connected to CCD readout registers. The two modules are assembled on a ceramic base and are protected by a hermetically sealed titanium case which includes a coated sapphire window. A copper thermal lug bonded at the rear of the ceramic base and connected by a thermal strap to the exterior of the Huygens Probe is used for cooling the detector assembly. A silicon diode bonded onto the ceramic base provides a measure of the temperature of the focal plane array. Each pixel has a photo-active area of 38 by 300 μm. The pixel pitch is 52 μm. The detector arrays are used for detecting radiation with wavelengths from 850 to 1700 nm. Peak quantum efficiencies >80% were measured. The detector assembly was manufactured by Thomson-TCS (Saint Egreve, France). The general design is based on the technology used in the SPOT 4 satellite devoted to Earth observations (Bodin and Reulet, 1987). The IR preamplifier board in the sensor head and the clocking electronics (on a board in the DISR electronics assembly) were built by AETA (Fontenay-aux-roses, France).

Between readouts of the photodiodes, charge is accumulated both due to dark current and at a rate proportional to the flux of incident photons. Upon readout, this is digitized using a 14-bit A/D converter. The gain is 920 electrons per digital step with a full scale of some 14 million electrons. The dark current in the InGaAs diodes decreases roughly by a factor of 2.5 for every 10 K decrease in temperature.
Measurements at 270 K show dark currents in the range 0.5–2 pA. Somewhat larger dark currents are expected at Titan as a result of the impact of energetic protons during the cruise. The minimum time between reads is 8 msec, which is sufficiently short that only a small fraction of the wells contain dark current at the temperature (near 260 K) expected at the start of the Titan descent. After some 40 minutes, the temperature of the detector decreases to <200 K, and dark current is almost negligible.

A shutter mechanism (the only moving part in the entire DISR) at the entrance slit of the IR spectrometer permits separate measurements of the dark signal and the dark plus light signal throughout the descent. Spectra with shutter open and closed are both included in the telemetry stream. In addition, seven pixels at the beginning and end of the array are masked with an opaque resin and provide a measure of the typical dark current. In case of shutter failure, they would provide an estimate of the dark current that can be used to remove the dark signal from shutter-open spectra obtained at warm temperatures.

The readout noise has been measured to be ~1100 electrons for temperatures <270 K. The shot noise is generally lower than the readout noise. About 10% of the pixels exhibit, in addition, a 1/f noise due to defects in the p-n junction of the diode itself. Its amplitude is roughly proportional to the dark signal and amounts to 0.1 to 1% of the dark level.

The CCD and IR array spectrometers together cover wavelengths from 480 nm to 1700 nm. There is considerable interest in the radiation shortward of 480 nm which is strongly absorbed by the aerosols in the upper stratosphere. Since there are only extremely weak methane bands in this part of the spectrum, high spectral resolution is not required. Two silicon photodiodes, appropriately filtered so that the bandpass between 350 and 480 nm gives a relatively flat spectral response, measure the flux in the upward and downward-looking directions.

3.3. DISR SUB-INSTRUMENTS

3.3.1. Imagers
The design of the imagers is driven by several considerations. The range to Titan’s surface decreases by three orders of magnitude during the descent from 160 km at entry to only a few hundred meters at the last image. Even the maximum range of 160 km is orders of magnitude less than is typical for images of planetary surfaces obtained by any other technique, including close flybys. Thus, the usual requirement for high angular resolution, necessary for observations made at longer range, are much relaxed in our case. We have chosen a maximum angular resolution of 0.06°/pixel, similar to that of the naked human eye. This pixel size of about one milliradian gives a spatial scale of 160 m/pixel at start of descent and about 10 cm/pixel at 100 m. The low resolution overlaps that available from orbiters and the high resolution near impact is three orders of magnitude greater.
Given the limitation of only 256 pixels across the active area of the CCD detector, even this relatively low angular resolution would limit the coverage in a single image to 15°. In order to observe as large an area as possible on the surface, we have chosen to divide the long dimension of the CCD into three image frames centered at different angles from the nadir that together cover a range of nadir angles from 6.5° to 96°. This is done with the division shown in Figure 8. As the probe rotates, sets of three images can be obtained at 12 azimuths to give a panorama with full coverage over nadir angles from 6.5° to 75°. A set of 24 images in azimuth, obtained in two staggered sets of 12 in successive measurement sets, permits full coverage in azimuth for the most side-looking imager and also completes the mosaic from nadir angles of 6.5° to 96°. The footprints on the surface of the individual images in a panoramic mosaic are shown in Figure 9.

The size of the imager pixels and their nadir angles define the relationship between integration time and blurring due to probe rotation during the image exposure. We limit the integration time so that rotation during the exposure is $<1.5$ times the angular size of a pixel in the center of the field of view of the High-Resolution Imager. The blur in the other imagers is less than that in the HRI.

This limitation on integration time translates into a relation between the f/number of the optical system and the signal-to-noise (S/N) ratio in the images for a model of the brightness of the surface of Titan. We selected an f/2.5 system to permit S/N $>100$ at the rotation rate of 1.5 rpm expected at low altitudes for a nominal model of the surface of Titan and the quantum efficiency and transmission expected for the imaging system.

For good imaging, we require that the optical systems be capable of giving spot sizes (full width at half maximum) smaller than 2 CCD pixels. The spot size is produced by geometrical aberrations in the lenses, diffraction, and by the spreading of light between the back face of the fiber bundle and the surface of the CCD. Because the end of the fiber optic bundle is within 20 μm of the face of the CCD, spot sizes smaller than 2 pixels can be achieved.

The light is brought from the three separate lens assemblies to the face of the CCD by a fiber optic bundle produced by Collimated Holes, Inc. (CHI). The fibers are small compared to the 17 x 23 μm size of the active area of the CCD pixels, so that many (about 6) fibers feed each pixel. Extramural absorption is added between the clad fibers to absorb light that might emerge from individual fibers. The glass used for the fiber optic conduit is specially selected for resistance to darkening from energetic particle impact.

The spectral range of the imagers is limited to wavelengths between 660 and about 1000 nm. The long wavelength end is defined by the limit of the CCD detector. The short wavelength end is selected to prevent Rayleigh scattering by the atmosphere below the probe from dominating the signal due to light reflected directly by the surface. All three imagers have the same spectral range. Color can be added to the monochromatic images using measurements of spectral reflectivity of the surface measured by the DLVS. We plan to correlate the spectral measurements
Figure 9. A view of the ground as seen from an altitude of 10 km showing the boundaries of individual images which together make a panoramic mosaic. The dimensions along the vertical and horizontal axes are distances in km. DISR also measures the spectral reflection of the surface at 10° × 4° locations along the slit of the DLVS at each of the 12 azimuths. (The locations of these spectral measurements are only shown at 3 azimuths here for clarity.)

of several thousand surface points with the morphology of these points as seen in the images to produce a library of color as a function of the type of terrain (craters, canyons, lakes, stream beds, etc.) In this way color images of the surface can ultimately be made from our measurements.

As described below, we expect to obtain more than 500 separate images of the surface which can be assembled into 36-image panoramic mosaics every few km from the start of descent at an altitude of 160 km to the surface.
3.3.2. Visible Spectrometer

Measurements of the spectrum of the upward and downward streaming sunlight as functions of altitude during the descent support most of the scientific objectives of the DISR experiment including: (1) measurement of the profile of the absorption of solar energy; (2) measurement of the vertical profile of methane; (3) measurements of the optical properties, size, and vertical distribution of atmospheric aerosols and clouds; and (4) measurements of the composition and nature of the surface of Titan. Accordingly, significant effort and experiment resources have been devoted to this portion of the instrument.

The visible spectrometer uses separate fiber bundles to bring downward- and upward-streaming sunlight to adjacent positions along the entrance slit. The speed of the collimator and camera optics of the transmission grating spectrometer is f/2. A tipped flat plate is included in the beam just before the grating to decrease the sensitivity of the measured intensity to the state of linear polarization of the incident light. The spectral range is limited by a filter to wavelengths from 480 to 960 nm in first order. The upward and downward-looking spectra are focused on the ends of two fiber optic ribbons which join the fiber conduit used for the imagers. The spectra are spread over 200 CCD pixels in the spectral direction. The spectral spread function has a width (FWHM) of two pixels. The resulting resolving power of the spectrometer, \( \lambda/\Delta\lambda \), is 100 at the blue end and 200 at the red end of the spectrum.

The input optics used to collect the light from the upward and downward directions are quite different. In the upward-looking case, the design is driven by the desire to measure the downward-streaming flux. Thus, a horizontal diffusing plate is viewed by the input optical fibers using a small lens. The diffuser makes the angular response function similar to the ideal response function (proportional to the cosine of the zenith angle). Because the instrument protrudes only a small distance from the body of the probe, a baffle is used to limit the range of azimuth angles to 170°. This baffle is blackened to minimize reflection of skylight from the baffle to the diffuser. The range of zenith angles accepted by the baffle is from 5° (to avoid seeing the parachute overhead) to 88°. Measurements made with the sun behind the shadow bar and again with the sun out from behind the bar permit separation of the direct and diffuse downward solar fluxes in the half of the upper hemisphere centered on the sun. An additional measurement is also made with the optical axis of the instrument directed 180° away from azimuth of the sun to give the portion of the downward diffuse flux coming from this half of the upper hemisphere.

For the measurements in the downward direction, other considerations become important. Because we want to study the reflection spectrum of distinct regions on the ground, spatial resolution is as important as the determination of the upward flux. We therefore chose to image the slit of the spectrometer on the ground and to
spread the light along the slit over 20 CCD pixels. Thus, we can spatially resolve 10 regions along the slit on the surface. The slit is bore sighted along the vertical axis of the field of the imagers to provide the morphological context of the spectrally measured regions. The slit is 4° wide and extends from 10° to 50° nadir angle. The 40° nadir angle range covering 20 CCD pixels gives 10 resolution elements each 4° square on the ground. The spectral intensities measured can be weighted with the cosines of the known nadir angles and integrated in nadir angle. At least 8 different evenly spaced azimuths are measured to permit an integration in azimuth for the upward flux. Thus, the optics and the sampling scheme permit integration of the spectral radiation field for the upward flux and also provide spatially resolved measurements of the spectral reflectivity of the surface.

Upward and downward spectra are obtained roughly every two km during the descent from 160 km to the surface. In the upward direction, the integration times for the measurements under the shadow bar are limited to insure that the measurements are completed while the diffuser is completely shaded. For downward-looking measurements, the integration times are limited so that the probe does not rotate more than 1.5 times the angular width of the spectrometer slit at a nadir angle of 30° (the center of the slit) during the integrations. The f/2 system permits S/N > 100 in a single spectral and spatial pixel for the downward-looking spectrometer. For the upward-looking measurements, 8 CCD detector pixels are combined along the length of the slit (which has no spatial resolution for the ULVS) to give similar S/N for the ULVS and DLVS.

3.3.3. IR Spectrometer

The IR spectrometer has two entrance paths, one viewing upward, and one viewing downward, in order to measure both the upward and downward fluxes. The ULIS has a diffuser as the entrance window (as for the ULVS), viewing about half the upward hemisphere. This allows the measurement of flux directly. The downward-looking input has a fused silica window and input lenses that define the field of view (FOV) at the entrance slit of the spectrometer. The input optics of these instruments transfer IR radiation through fiber optics to two aligned entrance slits placed one above the other perpendicular to the plane of dispersion of the grating. A shutter is installed just inside the input slits. An f/2 collimator lens assembly focuses the beams onto the transmission grating, and a camera lens assembly focuses the dispersed light onto the IR focal plane array. The IR spectrometer uses transmission gratings working in first order with achromatic lenses. A polarization compensator, consisting of a coated tilted plate, is included in the collimated beam in front of the grating to reduce sensitivity to the state of polarization of the incoming beam. Both the upward and downward-looking spectra are imaged directly on the two linear arrays of InGaAs detectors through a sapphire window with antireflection coating.

The optical field of view of ULIS is defined by the diffuser and external baffles and is 170 degrees in azimuth by 83 degrees in zenith angle (from 5 to 88 degrees
zenith). The spectrometer slit of DLIS maps into a 3° by 9° field of view (pixel footprint) with the center of the field of view 20° from the nadir.

In the case of the ULVS, the exposure time is sufficiently short that an adequate exposure is possible under the narrow shadow bar even when the probe is rotating at its maximum rate of 15 rpm. In the case of the ULIS, the total integration time is of the order of 60 s. Thus, no shadow bar is used to separate the direct and diffuse downward flux. Instead, measurements are accumulated in four azimuthal quadrants relative to the sun, and the shade provided by the probe itself is used to separate the direct and diffuse downward flux in the ULIS. For the DLIS, measurements are accumulated in 8 separate azimuthal regions relative to the sun.

In the normal mode of operation, the total time for data collection is an integral number of probe rotations, but is always constrained to be between one and three minutes. The time for data collection is estimated at the beginning of each cycle, and is updated during the cycle based on the data from the sun sensor after each rotation.

Within each azimuthal region, data are collected alternately with the shutter closed and with the shutter open. The process is symmetrical in time so that linear drifts in temperature (and hence dark current) are accounted for when the shutter-closed data are subtracted from the shutter-open data. The total shutter-open time is equal to the shutter-closed time. Within each azimuth region, the process begins and ends with the shutter closed for half the time used for the other open and closed intervals. Within each shutter-open or shutter-closed interval, the IR array can be read more than one time (depending on rotation period and temperature) to avoid saturation by the dark current. In addition, the shutter rate is kept at about 5 Hz so that temperature variations beyond linear drifts and their changes in dark current are adequately compensated.

3.3.4. Solar Aureole Camera

The solar aureole camera will measure the intensity of scattered sunlight over a range of scattering angles sensitive to particle size. Scattering at small angles (less than 40°, depending on particle size) is a good diagnostic of particle projected area. The forward scattering lobe becomes more strongly peaked at small scattering angles as the particle radius increases. The width of the forward scattering lobe does not depend strongly on particle shape for equal projected area particles, and it is insensitive to the particle refractive index.

Particle shape effects are much more pronounced at intermediate and large scattering angles, especially in polarization. The solar aureole camera will measure the vertical and horizontal polarization in the sunward and anti-sunward directions as the probe spins. These measurements will be performed at two wavelengths (500 and 935 nm) to provide sensitivity over a wide range of altitudes and particle size.

The angular sampling characteristics of the solar aureole camera are listed in Table 1. Measurements at small angular distance from the sun are made when the sun is behind the shadow bar, as viewed from the solar aureole camera window. The
solar zenith angle during descent is near 50°. In the sunward direction the camera covers scattering angles of 5°–25°. During the measurement in the anti-sun direction the scattering angle coverage is 75°–125°, on a 1° grid (see Figure 10). Each measurement samples the total column above the probe. The aureole contribution from a 2-km layer of the atmosphere is found by taking the difference between two measurements.

When measurements are collected near the sun, the shadow bar prevents direct sunlight from striking the Solar Aureole window assembly. A beam splitter is used to provide input from a calibration lamp. Calibrations are performed every six months during the cruise to Titan and four times during the descent. They are made in such a way that the signal from the atmosphere can be subtracted from the total signal.

A telecentric micro-lens design provides wide angular coverage at f/2 for the solar aureole system. The polarizers used for the visible and near IR channels are quite pure; the polarization they impart to unpolarized light is within a few percent of 100%. The degree of polarization can be obtained from the measurements if the direction of the polarization vector is assumed to be known. For the small particles expected in the atmosphere of Titan, the polarization is expected to be perpendicular to the scattering plane near 90° scattering angle, so the degree of polarization in the scan made at scattering angles between about 75° and 125° will be known. Optical fiber ribbons are located at the foci of the camera lenses. They merge with fiber ribbons from the other visible optical elements to feed the focal plane as shown in Figure 8.

The use of solar aureole measurements to retrieve particle size distributions is well known, and several retrieval algorithms have been described in the literature (see, e.g. Dave, 1971; Nakajima et al., 1983). Accurate retrievals require a high signal/noise ratio. The solar aureole camera was designed to achieve $S/N > 100$.

The $6° \times 50°$ solar aureole field-of-view maps onto a $6 \times 50$ pixel area of the CCD. Calculations show that $S/N$ will be $>100$ provided that 6 pixels are summed. Pixel summing will be performed during data analysis by summing pixels along arcs with constant angular distance from the sun. In this way no angular resolution will be lost to pixel summing. The expected $S/N$ varies from $\sim100$ to $\sim900$ depending on wavelength, altitude, solar zenith angle and azimuth during the measurement interval between 160 km altitude and the surface.

3.3.5. Violet Photometers
The purpose of the violet photometers is to extend the spectral range of the measurements to 350 nm from the short wavelength limit of 480 nm of the visible spectrometers. Because no sharp spectral features are expected in this spectrum, a single spectral channel is used. In this spectral region, the spectrum of the incident sunlight is modified by the absorbing properties of the small photochemical aerosols in Titan’s stratosphere. These particles absorb more and more of the short wavelength end of the spectrum with increasing depth into the atmosphere. Hence,
Figure 10. The solar aureole camera samples the scattering angle ranges shown by the shaded regions, for a solar zenith angle of 50 degrees. Also shown are phase function curves for spheres having a log-normal size distribution with mode radii ranging from 0.0625 to 2 microns doubling each time, at a wavelength of 0.5 microns. The smallest particles have the smallest forward-scattering peak.

in order to measure the energy deposition, it is important to filter the response of the detectors to make them relatively spectrally flat so that the violet measurements can be converted to absorbed energy independent of assumptions regarding the spectrum of the light measured. The product of the spectral response of the violet
detectors and the transmission of the violet filters is spectrally flat to about ±15% from 350 to 480 nm for these measurements.

The Upward-Looking Violet (ULV) photometer shares the diffuser of the ULVS system, and the field of view of the ULV is identical to that of the ULVS. The shadow bar permits separation of the direct and diffuse downward flux in the violet in the same way as for the ULVS, and the sampling in azimuth is the same for the ULV and the ULVS systems. The DLV uses exactly the same baffle and diffuser design mounted on the bottom of the sensor head to measure the upward violet flux, but without the shadow bar. The sampling in azimuth of the DLV is limited to two regions, near the azimuth of the sun and near 180° from the sun. These two measurements sum to give the total upward violet flux.

For the sake of simplicity, the electronics for the ULV/DLV systems use the same 12-bit A/D converter used for several other housekeeping functions including voltage and temperature monitoring. The light level in the upward-looking violet channel at the top of the atmosphere is known from the solar spectrum. A single gain with a fixed time constant is used in the ULV system with no provision for gain change or change in integration time in flight. The gain is adjusted when the instrument is built so that the sum of the signal from the in-flight calibration signal and the downward solar flux at Titan occupy between half and three quarters of the 4096 available digital steps. The signal from the in-flight calibration system is adjusted to be roughly equal to the signal expected from the sun at the start of the descent. This gives about 1000 digital steps for the violet signal at the start of the descent. The random noise in the ULV channel is comparable to the size of a digital step. The gain of the DLV system is larger by about a factor of ten than that of the ULV system to account for the lower expected signal looking down on Titan. We can measure the absorption of the violet energy in the bandpass of the violet photometers during the descent to a few tenths of a percent of the downward flux at entry.

3.3.6. Sun Sensor

The timing of all of the upward-looking DISR measurements requires precise knowledge of the solar azimuth angle. To satisfy this need a sun sensor is located beside the shadow bar. The field of view of the sensor is a 64° cone centered 47° from the zenith. The sun sensor consists of a window, a lens system, a filter, a reticule containing three slits, a pair of lenses to focus the light on a silicon photodiode detector, and its associated readout electronics. As the sun crosses the field of view, three large pulses are seen as the sun’s image passes through the three slits of the reticule. The time of the maximum signal in the center slit defines the azimuth of the sun. The first and third slits are not parallel to the center slit, but converge to permit determination of the zenith angle of the sun. The times of all three slit crossings are transmitted in housekeeping. The time between the first and third slit crossing compared to the times between successive crossings of the center slit (the
rotation period) gives the angle between the spin axis of the probe and the vector
toward the sun.

In addition, the brightness of the central pulse in each rotation past the sun is in­
cluded in the telemetry to give a measure of the direct solar beam at the wavelength
of the sun sensor system (939 nm) as a function of altitude. The sun sensor is
designed to track the direct solar beam down to 1/1000 of its brightness outside
Titan’s atmosphere. At the nominal solar zenith angle of 50°, the sun signal would
be lost at a vertical extinction optical depth of 4.4. This compares to a vertical
optical depth of less than about 1 in some current models of Titan at the wavelength
of the sun sensor.

The sun sensor uses several logic tests on the relative timing of the series of
three pulses on successive rotations to distinguish pulses due to the sun from vari­
atations in intensity that might be due to diffuse clouds above the probe. If the probe
falls beneath a thick cloud and loses lock, the internal rotation rate transmitted by
the probe spin sensor is used to time DISR data collection. The DISR sun sensor
continues to look for the sun after losing lock, and will find the sun if it reappears
from behind a passing cloud.

3.3.7. Surface Science Lamp

The purpose of the surface science lamp (SSL) is to illuminate the surface of Titan
in spectral regions where strong atmospheric absorption bands prevent sunlight
from penetrating to Titan’s surface. The SSL permits continuous measurements of
the spectral reflectivity of the surface to be made throughout the entire spectral
range. The SSL is a 20 Watt lamp with a parabolic reflector which illuminates the
surface and fills the narrow 3 × 9 degrees FOV of the IR spectrometer with enough
light to give a S/N of 50 at 60 m altitude within the strong methane bands even if
the surface reflectivity is as low as 0.05.

The lamp system is activated when an altitude of 700 meters is reached (given
by the radar altimeter) and is operated during the last several minutes of the descent
where a continuous sampling of the reflection spectrum of the surface is obtained
using both the DLVS and DLIS.

3.4. Internal Calibration System

Almost all of the science goals of the DISR experiment require measurements to
be made on an absolute photometric scale. This is difficult enough for a single
optical system and detector, let alone for a system as complex as DISR. The meas­
urements of the apparent brightness of the sun at high altitude near the start of the
descent at continuum infrared wavelengths is expected to be relatively unaffected
by atmospheric scattering and absorption, and so can provide an important check
on the absolute calibration of this one DISR optical system. The ability to tie all
the various DISR systems together on a single photometric scale is provided by the
internal calibration system built into the DISR sensor head.
Figure 11. The assembly that collects light from the three redundant 1-watt lamps and illuminates the bundle of fibers that carry the light to the input end of each of the DISR sub-instruments.

The internal calibration system consists of a set of three redundant 1-watt lamps which illuminate one end of a bundle of thick quartz fibers (see Figure 11). Each of these fibers carries some light from the calibration lamps to the first optical element in each of the other DISR optical systems. This light is reflected from either the inside of the window for that system or from a small reflector mounted on the back of the window and passes through the rest of that optical system to the detector. The fraction of the light from the calibration lamps carried to the input of each DISR measuring sub-instrument is carefully measured before launch, and is expected to remain constant through the mission. We should be able to track changes in the sensitivity of detector pixels, in the transmission of the imaging fiber optic conduit, or in other optical elements during the cruise by monitoring the relative outputs of each DISR system to the light provided by the internal calibration system.

It is important to emphasize that we are not relying on the stability of the absolute output of the lamps of the internal calibration system, only on the stability of the relative fraction of the light carried to each DISR subsystem by the thick quartz fibers of the calibration system. These quartz fibers are not expected to be susceptible to darkening by energetic particle bombardment. Thus, the changes in the relative output of the different DISR optical pixels can be tracked with time after launch and even measured at several times during the Titan entry.

There are no moving parts in the internal calibration system, so the light from this system is added to the light from the ambient Titan atmosphere during the descent. The light from the calibration system is designed to exceed by a large
factor the light from the ambient atmosphere. In addition, we have designed the internal calibration procedures to collect light with the calibration lamps on, then off, and then on again at the same azimuth to permit accurate subtraction of the ambient signal from the signal provided by the calibration system. The calibration light levels are adequate to make measurements with S/N better than the target value of 100 even after subtraction of the portion of the signal due to the ambient atmosphere.

3.5. MECHANICAL DESIGN

The DISR instrument consists of two packages, the sensor head (SH) and the electronics assembly (EA) mounted to the top of the instrument shelf in the Huygens Probe. The sensor head is mounted on a metal bracket above the top surface of the instrument shelf and sufficiently far outboard so that the front of the SH protrudes out through the back side of the probe. This permits clear views from the zenith to the nadir and in directions to ±85° in azimuth from the radial direction. (See Figure 12.)

The EA (see Figure 13) is a box containing six boards mounted horizontally above the power supply which is built into the chassis base. The six boards include the CCD drive board provided by MPAE, the data compression board provided by TUB, the IR detector system drive board provided by the PO, and the digital board, the CPU board, and the auxiliary board provided by LMA. The mass of the EA is
4.4 kg including radiation shielding on particular electronic parts. The six boards are an integral part of the structure and are bolted to the chassis side and back walls.

The mechanical design of the sensor head is shown in Figure 14. The SH assembly holds the detectors, fiber optics, foreoptics for the visible and infrared spectrometers, the three imaging cameras, the solar aureole camera, the internal calibration system, and the surface science lamp all in precise alignment over a temperature range of some 150°C, for ten years, and throughout the vibration and shock environment of the mission. In addition, the thermal environment of the detectors is controlled during the descent and the detectors are protected from the energetic particle environment during the mission.

The sensor head has a CCD detector side and an IR side. The face of the CCD is held 20 μm away from the end of the fiber optic conduit that delivers light from the three imagers, the solar aureole input assembly, and the visible spectrometers. This conduit and its face that mates to the CCD are shown in Figure 15. The CCD half of the sensor head including the detector, fiber optic conduit, imager lens assemblies, solar aureole assembly, and the visible spectrometer is shown in Figure 16.
Figure 14. The Sensor Head as seen from above and from below.
Figure 15. The fiber optic conduit including the end view that mates with the CCD detector.

Figure 16. The CCD mated to the fiber optic conduit, the three imager lens assemblies, the solar aureole input lens assembly, and the visible spectrometer.
The IR half of the sensor head begins with the pair of IR array detectors and their preamp board. This detector is mounted to the IR spectrometer, the shutter, and the fiber input assembly as shown in Figure 17.

The two detector assemblies are surrounded by a tungsten radiation shield 4 mm thick, sufficient to prevent protons with energies <64 MeV from reaching the detectors and significantly reducing the radiation dose experienced by the detectors. The mass of this radiation shield is 1 kg out of the total mass of the SH of about 3 kg.

The optical systems are securely mounted to a titanium optical bench which is secured to the base of the sensor head housing using a ball joint and two slip joints. This optical bench provides the means of tying all the optical systems together to the detectors. Figure 18 shows how the optical bench assembly fits into the sensor head box. Figures 19 and 20 show the optics assemblies after insertion into the main sensor head box. These views show the Surface Science Lamp, the Sun Sensor, the three imager lenses, the visible spectrometer, and the input optics assemblies for the Solar Aureole system and for the visible and IR spectrometers. Several calibration fibers used to bring light to the input optics are also visible.
Figure 18. The optical bench assembly and how it fits into the sensor head package.

Figure 19. The optics after insertion into the main sensor head box.
Figure 20. The sensor head before the front housing is installed. The Sun Sensor, Surface Science Lamp, imager lenses, and inputs to the DLIS and DLVS are visible along with some of the calibration fibers bringing light to the input optics.

The DISR thermal design must maintain interface constraints, cool and maintain the detectors’ temperature within limits, maintain all other components within their temperature limits and minimize mass and power. In particular, it is important that the detectors are cooled as rapidly as possible from their temperatures near 260 K at Titan entry to temperatures below some 220 K to minimize the influence of dark current and to ameliorate the defects in CCD pixels that may have been damaged by energetic particle impact during cruise.

The detector cooling system includes a thermal strap to provide a heat sink to the atmosphere via an attachment to the probe. A heater ensures that the detectors will remain above their minimum temperature limit. The heater is thermostatically controlled to maintain the temperature of the detectors above 160 K. The coupling to the housing and masses of the detector components are minimized to allow a rapid cooldown. The temperatures of the PC boards in the sensor head are maintained with a second electronic thermostatically controlled heater.

The sensor head housing is constructed of aluminum to provide thermal coupling between the interior and the exterior. This will maintain the exposed windows well above the ambient atmospheric temperature. The exposed portion of the hous-
ing is covered with a low density insulation and is coated with a conductive paint. The interior housing is conductively isolated from the probe but radiatively and convectively coupled to the probe. This method allows the probe to provide some heating of the sensor head ‘warm’ components. The sensor head front housing is thermally isolated from the rear housing.

3.6. COMPRESSION OF IMAGING DATA

Imaging data are compressed on board before transmission in order to achieve a balance between the number and the quality of images received. The images (digitized at 12 bits/pixel) are first divided by an onboard flat field to eliminate artifacts introduced by variations in the transmission of the fiber optic conduit. The data are then reduced from 12 to 8 bits/pixel using a square root software algorithm. The data are then passed to a lossy hardware data system for further compression.

For most test scenes, the image distortions are relatively small for an additional compression by a factor up to 8 using a standardized JPEG compression scheme. An implementation of such a compression by software running on the main processor would limit the image cycle time to more than 1 minute. Therefore, a dedicated hardware coprocessor has been developed which performs a complete compression of a 256 x 256 pixel image within less than 130 msec at low power and for light weight. The coprocessor is designed around an STV3200 DCT chip, an 80C86 microprocessor and 8 ACTEL FPGAs. The compression algorithm running on this dedicated coprocessor deviates in some aspects from the JPEG scheme in order to decrease power and mass and enhance the robustness against transmission errors. The SNR (in the image intensities) of the modified hardware implementation is <1 dB below the values achievable with standard JPEG. On simulated low contrast images as expected for Titan, the noise is increased above shot noise by factors of only some 1.7 and 2.5 for compression ratios of 3:1 and 6:1. For well exposed images, features with a contrast as low as 1% are seen in images compressed by as much as 6:1 by the lossy compressor.

3.7. ELECTRONICS

The electrical block diagram of the entire DISR instrument is shown in Figure 21. The left-hand portion of the diagram shows electronics which are in the sensor head, while the right-hand section indicates the electronics housed in the electronics assembly package. The SH contains three small boards: one provided by MPAE contains the preamps for the CCD; one provided by PO contains the preamp for the IR detector; and the third, provided by LMA, provides preamps for the Sun Sensor and its test Light Emitting Diode as well as the violet detectors of the ULV and DLV instruments. The European Co-Is also provide the three shaded boards as shown in the EA: the driver provided by MPAE for the CCD; the driver for the IR detector provided by PO; and the hardware Data Compression System (DCS) provided by TUB.
Figure 21. Block diagram of the electronics on the six boards in the Electronics Assembly. The three cards provided by the European Co-Is are shown shaded, and the functions contained on the CPU Board, the Digital Board, and the Auxiliary Board provided by LMA are shown.

The CPU board provides radiation-hard critical Random Access Memory (RAM) in 128 k bytes of program RAM and an additional 64 k bytes of data RAM. It also holds 128 k bytes of Programmable Read Only Memory (PROM) and a separate block of 64 k bytes of EEPROM which can be changed by commanded uploads. The microprocessor is a MA31750 running at a clock speed of 12 MHz capable of some 1.6 million instructions per second (MIPS). Some 1.2 MIPS are required for operation of the DISR as planned. A watchdog timer is provided with a 100 Hz clock at 16-bit resolution.

The Digital Board contains a large (1.5 Mbyte) frame buffer of static RAM accessible by the CPU or by any of three Data Management Assembly (DMA) channels. Every 10 seconds the entire frame buffer will be refreshed by CPU block read/write routine using a full Error Detection And Correction (EDAC) function provided by a single Harris Semiconductor chip.

Three programmable DMA channels are provided using Actel 1020 Field Programmable Gate Arrays (FPGA). The mode, word count, source, and destination addresses are all programmable.

The Probe interface provides dual telemetry packet channels for transmission of the science data. It provides dual Memory Load Command channels to receive
the data and/or commands from the Probe. Dual serial status channels are also provided to transmit a 16-bit housekeeping status word to the probe upon request. Redundant channels are also provided to receive the Probe Data Broadcast data such as spin rate, time, and altitude. This interface provides a means of receiving an indication of which telemetry channel is to be used for commanding the DISR.

The Auxiliary Board contains the digital interface to the IR detector system. It also contains several analog circuits to condition signals from the ULV, DLV, Sun Sensor, the Inflight Calibration System; to control the focal plane and SH electronics card heaters; and to monitor temperatures, lamp currents, and other housekeeping data in the instrument. A multiplexer and 12-bit A/D converter is used on the Auxiliary Board for this purpose.

3.8. SOFTWARE AND DATA COLLECTION MODES

The DISR flight software was developed using an object-oriented design in the Ada language. The software uses a re-entrant event dispatcher to control execution based on the priorities of events occurring in both the hardware and software. Multi-tasking is not used. Hardware interrupts are used to provide services for the probe interface, the sun sensor, a general purpose event timer, the telemetry channels, the direct memory access controllers, the CCD, the IR detector, and the hardware data compressor.

The software controls the calibration and surface science lamps. The calibration lamps are turned on during appropriate parts of calibration cycles.

All commands to the DISR are processed by the software. Only six commands exist, although some have a variety of parameters.

1. A receipt-enable telecommand must begin a commanding session. This command is used to protect against spurious commands.
2. A change-mode telecommand may be used to change the operating mode of the DISR into descent mode (the default mode), into calibration mode, into single telecommand mode, or into memory access mode.
3. Single measurement telecommands direct the instrument to perform one or more repetitions of a particular measurement. These commands are useful during instrument calibration and test.
4. Single test telecommands are similar to single measurement telecommands, except they initiate preprogrammed test sequences on the specific portions of the hardware including the IR shutter, hardware data compressor, heaters, and lamps.
5. Memory upload commands are used in memory access mode to store new tables which are read by the software. These table entries include bad pixel maps, square root compression tables, and parameters that control measurement scheduling and processing.
6. Memory dump telecommands can transfer any portion of DISR memory into telemetry for verification.
The software also coordinates and controls all data collection. Optimum exposure times are computed for each subinstrument using the CCD and IR detectors. These times are based on the data number population histograms of the most recent previous exposure of the same type. The exposure time can also be limited by the amount of smear caused by the spin of the probe.

On-board data processing functions also include several miscellaneous functions. Adjacent columns of pixels may be summed within the same instrument field of view. Data for the hardware data compressor must be reformatted before it is fed to the compressor. Lossless compression is done entirely in software. Bad pixels are eliminated according to a bad pixel map which is stored in EEPROM. Data from the imagers are also reduced from 12 bits to 8 bits before being fed to the hardware data compressor. This reduction is done using a table lookup which performs a pseudo-square root transformation of the raw data. A watchdog timer can reset the microprocessor if it times out. The software that builds telemetry packets periodically resets the watchdog timer. If telemetry is not being produced, the processor will be reset and execution will be restarted.

Calibration and instrument health data are collected at six-month intervals during the cruise. At each opportunity one of five possible activities may be performed. The Health Check sequence exercises each software controlled function to test for normal operation. The In-Flight Calibration sequence is used to obtain relative response and measure the noise level of the detectors. The Simulated Descent uses parameters loaded into special tables to test descent sequencing. Two types of activities are available for contingencies. Single Measurement and Single Test commands can be used to diagnose problems with specific instrument subsystems. Finally, memory dumps and uploads can be used to verify the contents or memory and to upload new table values to correct for instrument subsystem malfunctions.

One of the more interesting aspects of the software is the way it schedules collection of related data from various subinstruments in an optimized way. During descent, data collection is divided into cycles which form a coordinated set of measurements within a limited time span. Several different types of cycles are used to meet the differing needs of data collection during different parts of the descent. The software uses information from the probe, including the altitude, time, and spin rate, to decide which type of cycle to start next. The cycle choice also depends on the amount of buffer space available within the DISR and on the current probe telemetry rate. The software chooses a cycle type which will gather sufficient data to keep the instrument from running out of telemetry packets, yet it must also choose a cycle type which will not provide so much data that it overfills the available buffer space.

Differing requirements are placed on the data buffering scheme depending on how close the probe is to the surface. Normally data can be gathered much faster than they can be telemetered. If the probe is still high enough to allow sufficient time for telemetry before impact, data may be profitably buffered, allowing the buffer to fill further as each cycle passes. On the other hand, if the probe is near the
surface, each data set should be telemetered as soon as it is complete to prevent the probe from hitting the surface with substantial amounts of data still in the buffer.

Early in the descent the probe is falling rapidly. It is important to measure quantities such as the solar flux deposition and solar aureole profile within vertical intervals which are small compared to the atmospheric scale height. Cycles high in the atmosphere are driven by a cycle duration constraint, even if many cycles are in the buffer a long time before they are telemetered. However, at some altitude it is important to start each new cycle with almost nothing in the buffer. The most recent, lowest altitude data will be transmitted immediately if the buffer is in this state.

We use both of these scheduling algorithms during the descent. Above 20 km altitude, we use duration-constrained scheduling. At 20 km, we pause to permit all previously buffered data to be telemetered. After this, new cycles are only begun when the telemetry buffer is nearly empty.

Within data cycles, it is usually important to schedule measurements at particular azimuths. Images, for example, must be scheduled to occur at 12 equally spaced azimuths to provide data for a mosaic. The software determines the azimuth at the beginning of each cycle and predicts its change with time during the cycle using a quadratic extrapolation. As new information about the spin rate becomes available from the sun sensor, these predictions are updated during the cycle and the following measurements are scheduled using the revised predictions.

4. Measured Quantities

The altitudes and times during the descent where various types of cycles are gathered are shown in Figure 22. The instrument is turned on near 170 km altitude. In order to fill the initially empty telemetry buffer as rapidly as possible, the instrument begins with a data collection cycle which contains an image panorama. The data collected in cycles which contain image panoramas are shown in Table 2. Note that on alternate cycles of this type, the azimuths of the images are offset by 15°, half the width of the images. These cycles contain a full set of spectral data (with downward looking visible spectra in the center of each of the images) and solar aureole data as well. Above 20 km, these cycles are constrained to collect all their data in between 1.5 and 4.5 minutes.

Above 20 km altitude, a non-imaging cycle is chosen as the next cycle if the DISR telemetry buffer contains data that will take more than four additional minutes to transmit. Non-imaging cycles are interleaved between imaging cycles to produce spectral measurements at higher vertical resolution than would be possible if all cycles contained image panoramas. The time for data collection in non-imaging cycles is limited to between 1.5 and 3 minutes. The maximum cycle duration prevents long gaps between observations which might occur at very slow probe rotation rates where a cycle might take a very long time to complete. The minimum
cycle time forces the scheduler to wait before the beginning of the next cycle and is used to tune the relative numbers of imaging and non-imaging cycles. Increasing the minimum cycle duration allows the telemetry buffer to be emptied further during the cycle, and increases the likelihood that an imaging cycle will be chosen next.

The standard non-imaging cycle differs from the imaging cycle in three respects: (1) 6 (rather than 12) DLVS spectra are obtained evenly distributed in
azimuth beginning 20° from the sun; (2) no HRI or MRI images are obtained; and (3) six SLI images are obtained evenly distributed in azimuth beginning 15° from the azimuth of the sun. The SLI data in 2 13-column wide regions are summed to two columns of brightness as a function of zenith angle, losslessly compressed, and included in the telemetry stream. The location of the horizon can be determined in each of these six azimuths relative to the sun on non-imaging cycles. These data, together with the full SLI images on imaging cycles, constrain the attitude of the probe during every measurement cycle.

Special calibration cycles are performed four times above 20 km at roughly equally spaced detector temperatures. These data use the on-board calibration lamps to provide signals which dominate those from Titan. These cycles provide relative calibrations of the upward and downward looking subinstruments as well as corroboration of the flat field properties of the CCD and IR detectors. A special long exposure measurement is also made with the IR subinstrument while the shutter is closed to accurately determine the dark current generation rate for each pixel.

At 20 km altitude a special ‘pause’ cycle occurs in order to empty the telemetry buffer. Imaging cycles are then gathered between 20 km and 3 km, with each new cycle beginning only when the telemetry buffer drains to a preset low level. This sequence is interrupted twice (near 9 and 4 km altitude) for the Spectrophotometric Cycles when downward-looking spectra are obtained as rapidly as possible for one probe rotation. These data map the spectral reflectance of the surface at high spatial resolution.

If normal image cycles were continued below 3 km altitude, telemetry of the data would not be completed before impact with the surface. Therefore, between about 3 km and 500 m special cycles are used in which a set of HRI, MRI, SLI images, spectra, and solar aureole measurements are obtained as rapidly as the telemetry rate permits regardless of the azimuth. (See Figure 22b).

Between 500 m and 250 m, single HRI images are obtained as rapidly as the telemetry rate permits (about every eight seconds). Single HRI images and dark current measurements are the only data collected in this altitude interval. In the last image near 250 m the scale will be about 25 cm/pixel.

The surface science lamp is turned on at an altitude of 700 m. For the final 250 m of the descent we obtain only DLV, DLVS, and DLIS measurements. Some 19 spectra are obtained with the Surface Science Lamp turned on. These yield continuous reflection spectra of the surface over the spectral range of the DLIS for constraining the composition of the surface. As the probe continues to rotate slowly while these exposures are collected, each will view a different region on the surface. Two of the 20 pixels along the DLVS slit will be illuminated by the SSL, and these will permit the DLIS spectra to be extended to shorter wavelengths. The S/N of these spectra increase as 1/(altitude)^2 reaching more than several hundred before impact for surface reflectivities exceeding a few percent.

If the instrument survives impact, it will collect data according to a special sequence. One purpose of these cycles is to measure transient phenomena such
as reflection from any cloud of dust or spray which may occur due to probe impact. A set of 10 upward- and downward-looking spectra are collected first using the ULV, ULVS, ULIS, DLV, DLVS, and DLIS subinstruments. Following these spectral measurements, images are taken with the three cameras. The SLI should give images from the foreground to 6° above the horizon. If the probe survives long enough, it may be possible to see cloud features blown by the wind. Spectra and image measurement sets are then gathered alternately for the remainder of the mission. Approximately two minutes after impact, the surface science lamp is switched off. After that it is alternately switched on and off every two minutes. All measurements after impact are taken as rapidly as possible until the buffer fills up. After the buffer is full, new measurements are gathered as buffer space allows.

A summary of the data collected in various parts of the descent is given in Table 3. The coverage of the region of the surface seen in the HRI and MRI frames in each panoramic mosaic is given in Figure 23. A nominal wind model was used to generate the drift in probe with time. Figure 23 shows that a significant amount of overlap is expected in various mosaics from which the wind profile can be derived.

Figure 24 shows the areal coverage as a function of spatial resolution for the images from the three frame imagers of DISR. Notice that the resolution at the highest altitudes matches typical resolutions available from the Cassini orbiter camera when the frame covers one tenth of the disk. DISR images begin at this resolution and extend to some three orders of magnitude higher resolution.

4.1. LABORATORY CALIBRATION

During the course of the hardware phase of this work, a total of three complete DISR instruments were produced. The calibration of these units constituted a considerable effort. For each instrument, the relative spectral response, absolute response, field of view, spectral resolution, and spatial resolution were measured over
Figure 24. Areal coverage on Titan’s surface Vs. Spatial resolution. The coverage and resolution of mosaics made using the SLI (circles), MRI (squares) and the HRI (diamonds). Every other panoramic mosaic is shown as a point. Every other frame of the 3-image sets are shown also using the same symbols. The coverage and resolution of each of the five single HRI frames at the lowest altitudes is shown by a triangle. For comparison, the coverage and resolution of the ISS camera on the Cassini orbiter is shown by solid diamonds when Titan fills the frame, and when the frame covers 1/10 the diameter of Titan.

a temperature range from 180 K to 300 K for the 13 optical systems (subinstruments) which include the three frame imagers, the solar aureole camera (with four channels), the upward and downward looking visible spectrometer, the upward and downward looking infrared spectrometer, the upward and downward looking violet photometers, the sun sensor photometer, the surface science lamp, and the inflight calibration system. Because of the pressure to deliver the instrument in time for integration into the probe, the time available for such tests on the flight instrument was limited to about two months. A total of 5.1 Gbytes of calibration data was collected for the flight instrument during August and September of 1996 before delivery.

These calibration measurements were made using a custom facility designed at the University of Arizona. A key element was the design of a cold box which could be purged with dry nitrogen to prevent condensation on the sensor head. The inside
### TABLE 3
Summary of descent data

<table>
<thead>
<tr>
<th>Altitude Range (km)</th>
<th>36-Image Cycles</th>
<th>Non-Image Cycles</th>
<th>3-Image Sets + Spectra Images Using Sets</th>
<th>High-Res. Spectra Only Sets</th>
<th>Spectra Only Sets</th>
<th>Spectral Sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>160–20</td>
<td>10</td>
<td>33</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>20–3</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3–0.5</td>
<td>–</td>
<td>–</td>
<td>20</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.5–0.25</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.25–0.0</td>
<td>–</td>
<td>–</td>
<td>18</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>After Impact (first 10 min.)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>83</td>
<td>93</td>
<td></td>
</tr>
</tbody>
</table>

Total number of images: >500.

Total Direct, Diffuse, Upward, Downward sets of flux measurements: 68.

Solar Aureole Measurements: 48 in each of two colors and two polarization states

Surface Spectra: 642 in IR, >3100 in Vis.

of the box was cooled by cold nitrogen gas. In addition, the copper strap attached to the detectors in the sensor head was attached to a clamp cooled by liquid nitrogen and fitted with a heater. The front of the sensor head was mounted through a 3 by 6 inch hole in a 20 inch diameter integrating sphere. Light injected through a small hole in the sphere produced a diffuse illumination that could fill the field of view of all the DISR instruments simultaneously with a uniformity of 2% or better. The brightness and color of the wall of the sphere could be measured through a second small hole in the sphere.

The wavelength scales of the visible and infrared spectrometers could be determined by illuminating the inside of the sphere with light from neon-mercury and krypton emission line lamps. Driving the temperature of the sensor head while making exposures with all the DISR spectrometers established the wavelength scales of the spectrometers over temperature.

The relative spectral response of the solar aureole cameras and the imagers were measured over temperature by illuminating the integrating sphere with an Optronics OL-750 dual pass monochrometer that was scanned over wavelength at each temperature. The relative output of the monochrometer was monitored with a calibrated silicon and germanium detectors viewing the wall of the integrating sphere through one of the small holes in the sphere.

The absolute response of the each optical system was measured over temperature by illuminating the integrating sphere using a high intensity Optronics 740 tungsten lamp. The brightness and color of the wall of the sphere illuminated with this lamp was measured by using the laboratory spectrometer which was calibrated using an Optronics 455 standard lamp traceable to the bureau of standards.
By using the integrating sphere in this way, all the windows of the DISR instrument could be stimulated simultaneously with light of a known brightness and color while the temperature of the detectors were driven by the cold box.

A separate optical system was used to measure the spatial resolution and field of view of each of the DISR subinstruments at room temperature. A ten inch diameter spherical mirror was used to produce a collimated beam of light. A small reference detector in the beam monitored any changes in the intensity of the lamp. A computer controlled altitude-azimuth mount was built to turn the sensor head through a wide range of angles while each window was centered in the collimated beam. The relative measurements of each DISR optical system over angle were recorded as a function of orientation. More than 1000 points were used to define the relative spatial response of the ULV, DLV, ULIS, and ULIS systems which used bear’s ear baffles to limit the field of view to roughly half the upward or downward hemisphere. For the instruments with smaller fields of view, we used several cuts across the field in orthogonal directions. The collimator was fitted with a linear polarizer to measure the orientation of the polarizers in the solar aureole channels, and to confirm the low sensitivity to the orientation of linearly polarized input light in the spectrometers.

In addition, special calibration targets consisting of vertical and horizontal stripes were imaged by the HRI, MRI, and SLI to measure the geometric distortion across the fields of view of these imagers.

The collimator and the computer driven altitude-azimuth mount were used to produce measures of the point spread function of the imagers and solar aureole camera at many locations in each field of view. In these tests, successive images of the collimated beam were made after steps of a fraction of a pixel in vertical and horizontal directions at several locations in each field of view.

For most of the tests, the detector temperature was above the cold values expected at the end of the Titan descent. For all the calibration tests, data were collected with the illumination source turned on and then off so that any dark signal produced by the detectors could be subtracted from the bright measurements before analysis. This simple need effectively doubled the amount of data that had to be collected for all but the measurements from the infrared spectrometer system, for which the shutter operated at 5 Hz throughout, and both shutter open and closed data was automatically recorded. The dark current produced by each pixel of each of the DISR detectors produced as a function of integration time and temperature was recorded and fitted to a model for comparison with the experience during the mission.

The response of the flight system to the inflight calibration lamps was also recorded over a wide range of temperatures with each of the three redundant calibration lamps.

The calibration of the sun sensor system posed special problems. Normally, sunsensor data are recorded only when the system is locked onto a series of pulses that satisfies the criteria loaded in software for being valid pulses due to fairly
regular rotation of the instrument. In this case, a breakout box was used to isolate the analog signals from the detector of the sun sensor system in order to measure the relative spectral response of the system. To test the dynamic behavior of the system, and to obtain a full absolute calibration, a special device was constructed of a flat mirror that could be rotated under computer control in the output beam of the collimator. This reflected collimated beam was swept past the input of the sun sensor system at a variety of spin rates and elevation angles to calibrate this system. The times of the first and third pulse relative to the time of the center pulse as the system was illuminated at various elevation angles served to map the locations of the slits in the sensor system.

Finally, measurements of the crosstalk from each DISR system into each of the other systems was measured at room temperature was measured in a series of tests in which only a single window at a time was left unmasked on the DISR sensor head. Further, cross talk as a function of temperature was measured by making a series of measurements in the integrating sphere while the temperature of the detectors and optics were driven to simulate the temperature profiles expected during the Titan entry. The actual brightness and color of the wall of the integrating sphere was measured by separate laboratory instrumentation to provide a ‘ground truth’ in these tests.

The results of the calibration are sufficiently extensive and important to warrant separate publication. We include here only a few samples to give a feeling for the quality of the measurements. Figure 25 shows the relative spectral response of the SLI over a wide range of detector temperatures, while Figure 26 shows the absolute response of the three imagers as a function of detector temperature. Figure 27 shows the relative spectral response of the two solar aureole channels and one of the imagers at a temperature of 200 K. Figure 28 shows the relative spatial response of the ULVS. The relative spectral response of the violet photometer, visible spectrometer, and infrared spectrometer are shown in Figure 29.

5. Results from Test Observations

5.1. TEST PROGRAM

In all, three flight-type DISR sensor heads were built. The intention was to build first a prototype instrument (DISR01) in time to make optical tests which could be used to refine the design if that were to prove necessary. However, delays in development and fabrication resulted in the first instrument being produced at about the time the flight unit was needed for integration into the flight probe. The fabrication of the second unit, DISR02, (to serve as the flight spare) was begun immediately upon the completion of the first unit. Hence, optical tests on the first unit were completed too late to influence the fabrication of the second. The first unit was calibrated, delivered, and integrated into the flight probe as rapidly as possible while the second unit was being completed.
Figure 25. The relative spectral response of the SLI as a function of wavelength at several different detector temperatures, as labeled. The relative spectral response is available for each pixel in the imager. The relative response varies very little over the imager; the curves shown are for the average over the SLI array. The relative spectral response of the MRI and HRI are very similar.

During the testing of the first unit, a problem involving cross talk in the fiber image conduit feeding the CCD was discovered. Imperfections in the conduit permitted a few tenths of a percent of the light traveling down the conduit to scatter across the conduit and then scatter down a portion of the conduit far from the first scattering. In this way, a small fraction of the light can travel laterally a considerable distance across the detector. The amount of light is sufficiently small that it does not affect the performance of any single sub instrument (imager, solar aureole or visible spectrometer). However, because the imagers are broad-band instruments while the visible spectrometer divides the light into 200 spectral bins, the absolute sensitivity of the imagers is some two orders of magnitude greater than that of the spectrometers. Thus, the imagers are saturated by a large factor during the long (1 second) integration necessary for the visible spectrometer measurements. In this way, the light scattered from the imager portion of the conduit can amount to an appreciable fraction of the spectrometer signal when spectra are collected.

The need for rapid delivery of the first unit permitted only small changes to the first unit to partially overcome this effect before integration into the probe. The
Figure 26. The average absolute response of the three DISR frame imagers as a function of detector temperature, as labeled. The response varies slightly from pixel to pixel, and the ratios of the responsivity of each pixel to the average are available from the calibration measurements.

crosstalk could be partially compensated by decreasing the transmission of the imager window nearest to the spectrometer portion of the fiber conduit. By decreasing the transmission of the MRI window to 25%, the cross talk from the imagers to the spectrometers was reduced to about 20% or less of the spectrometer signal. In addition, software was added to read additional columns of the detector on each side of the spectrometer columns to measure the scattered light from the imagers during spectral readings. These data could be used to compensate for the light scattered from the imagers and correct the spectral measurements to a few percent. The price paid for this improvement to the visible spectrometer measurements was a decrease in the S/N of the MRI by about a factor 2.

After completion of the second DISR unit, we decided to proceed with the production of a third unit (DISR03) that could largely correct the crosstalk in the fiber optic conduit between the imager and spectrometer portions of the bundle. This was done by using a then-recently space-qualified optically opaque epoxy to bond the separate sections of the fiber optic conduit together. This decreased the cross talk between the imagers and the spectrometers by about an order of magnitude, and permitted the transmission of the MRI window in DISR03 to be doubled relative to that in DISR01. The third unit was tested, calibrated, and exchanged with the first
Figure 27. The relative spectral response of two of the solar aureole channels and of one of the frame imagers at a detector temperature of 200 K, as labeled.

Once a good flight model and flight spare model were safely available, DISR02 was available to serve as a field test unit. In view of the complexity of the instrument, we feel it is essential to obtain high fidelity data in the earth’s atmosphere that can be used to develop reduction, analysis, and inversion algorithms well in advance of the Titan entry. Thus, we have instituted a modest program to collect a realistic data set using the DISR02 model. This program includes images of natural terrain from a helicopter at several altitudes up to 10,000 feet above the surface, as well as upward and downward solar spectra and solar aureole observations from the ground. In order to obtain these data at realistic integration times for the instrument, we have fastened 1% neutral density filters over the windows of the three imagers and the four solar aureole channels. Some data have been collected with no additional attenuation over the upward or downward looking spectrometers or the violet photometers to avoid any modification of the spatial response functions produced by the external baffles around the diffusers of these instruments. The use of neutral
density filters over the imagers and not over the spectrometers has the advantage of decreasing the cross talk from the imagers to the spectrometers to a negligible level in the DISR02 unit, somewhat as we believe we have achieved with the modified fiber optic conduit in the DISR03 flight unit. In addition, a special absorbing film attenuator was developed which can be fastened over the ULVS, ULV, and DLV diffusers without significantly modifying the spatial response function of these instruments. This has permitted us to obtain unsaturated data from the ULV and DLV systems in the Earth’s atmosphere despite the fixed time constant of these systems. Also, we can obtain data from the ULVS system which includes strong crosstalk from the imagers to test our ability to correct for crosstalk using the extra column readings surrounding the visible spectrometer portion of the CCD.

We began our test program by fixing the instrument on a horizontal plate that could be rotated about a vertical axis mounted on the roof of our building. Data from tests using this device were obtained in ‘single-measurement mode.’ This was followed by tests using a rotating plate driven by a stepper motor to simulate the rotation of the instrument during descent through Titan’s atmosphere. In this case, the data were collected in ‘descent mode,’ and used the sun sensor to determine the azimuth of the observations exactly as planned during Titan entry. Finally, we have begun using a system that can produce a controlled wobble of the spin axis in two dimensions to test our ability to measure and correct for any swinging motion under the parachute during Titan descent. In addition, we have obtained some data during

Figure 28. The relative spatial response of the ULVS as a function of azimuth and zenith angle. The gap in response due to the ten degree wide shadow bar is clearly visible.
Figure 29. The relative spectral response of the DLV, DLVS, and DLIS at a temperature of 200 K as a function of wavelength. The spectral response of the ULV, ULVS, and ULIS are similar. Together, these channels permit measurement of the upward and downward solar flux from 350 to 1700 nm.

helicopter flights to illustrate the type of imaging data produced by the DISR. We describe some of the data obtained in this program in the following sections to give an impression of the type of data we expect from Titan.

5.2. TOTAL DOWNWARD SOLAR FLUX FROM UPWARD LOOKING SPECTROMETERS

We have used the DISR02 unit to obtain data both in ‘single measurement mode’ by manually pointing the instrument at the azimuth angles relative to the sun where data are planned for the Titan entry, and with the instrument mounted on a rotating platform and using the sun sensor to control acquisition in ‘descent mode’ exactly as programmed for Titan entry. The first test was made in ‘single measurement mode’ on the morning of September 3, 1997 at nine solar zenith angles between about 25° and 50°. We manually aligned the instrument to obtain data at each of the azimuths planned for non-imaging cycles. For the ULVS observations, measurements were made with the instrument pointed at 5.5°, 140°, 180°, 320° and 338° from the azimuth of the sun. For the ULIS, observations were made with the
instrument stationary at 0°, 58°, 112°, 180°, 248°, and 302° from the azimuth of the sun.

For both the ULVS and ULIS observations, the count rate when the sun was not directly illuminating the diffuser was fit to a cosine curve in azimuth, and the count rate due to the diffuse sky was predicted at the azimuths where the direct solar beam together with the diffuse skylight illuminated the diffuser. This predicted count rate for the diffuse sky was subtracted from the total count rate from measurements that included the direct beam plus diffuse light. The remaining count rate was divided by the absolute responsivity of the instrument at the location of the sun in the field of view to give the spectrum of the direct beam from the sun. The diffuse measurements alone were reduced to give the average diffuse intensity in the field of view with the approximately cosine zenith angle weighting provided by the diffuser and uniform weighting in azimuth. This value multiplied by $\pi$ gives the downward diffuse flux. With this processing, the spectrum for the downward diffuse flux and the flux in the reduced direct solar beam is shown in Figure 30 when the sun was at 35° solar zenith angle. When the direct solar beam flux is multiplied by the cosine of the solar zenith angle and added to the downward diffuse flux the resulting total downward solar flux is given in Figure 31. Also shown in this Figure 31 is the downward total solar flux at 35° solar zenith angle outside the atmosphere of the Earth.

Measurements of the type shown in Figure 31 will be available for some 80 different altitudes on Titan below 160 km. They will be combined with the results of the ULV measurements to give the total downward solar flux as a function of altitude. Because no neutral density filter was added over the ULV photometer for the September 3, 1997 test, the ULV data for that day are saturated. The vertical lines in Figure 31 show the portion of the spectrum covered by the violet photometer measurements planned for Titan. The total integrated solar flux from 350 to 1700 nm will be used with the upward flux to give the net flux and the solar heating rate as a function of altitude.

5.3. Extinction Optical Depth vs. Wavelength from Upward Looking Spectrometers

Figure 32 shows the set of nine ULVS spectra of the direct solar beam at solar zenith angles from 25.7° to 50°. Also shown is the solar flux from Neckel and Labs (1984) convolved to the spectral resolution of the ULVS instrument. Figure 33 shows the log of the direct beam flux vs. the secant of the solar zenith angle (the airmass) at a few continuum wavelengths across the ULVS spectra of Figure 32. The natural log of the ratio of spectra at any airmass to the spectrum outside the atmosphere gives the total extinction optical depth for molecular Rayleigh scattering, aerosol particle scattering, and molecular gaseous absorption for that slant path through the atmosphere of the Earth. Figure 34 shows the total vertical extinction optical depth as a function of wavelength from the ULVS and ULIS observations.
Figure 30. ULVS and ULIS spectra obtained at solar zenith angle 35° for different azimuths from the sun as labeled. The solar flux outside the Earth’s atmosphere is shown, along with the spectrum of the direct solar beam at 35° solar zenith angle. The average intensities observed when the instrument was pointed at azimuths of 5.5°, 140° and 180° from the sun for the ULVS and at 112° and 180° for the ULIS have been multiplied by $\pi/2$ to give the diffuse downward flux in the half of the diffuse beam centered at those locations. The total diffuse downward flux is obtained by fitting the diffuse flux as a function of azimuth by a function that is linear in the cosine of the azimuth. The average of this value multiplied by $\pi$ is the entire downward diffuse flux.

near 35° solar zenith angle for wavelengths between 460 and 1600 nm. Note the good agreement in the region of overlap between the two spectrometers. Also note from Figure 33 that straight line exponential fits (Beer’s law) to the observations at these continuum wavelengths at the nine values of airmass intercept the vertical axis for zero airmass at a flux ratio quite near 1.0, and thus are in good agreement with the Neckel and Labs (1984) solar flux at 1 A.U. outside the Earth’s atmosphere.

A more precise confirmation of the absolute calibration of the DISR visible spectrometer is available from the ULVS data covering a wider range of airmass (1.8 to 3.3) obtained in descent mode on the rotating platform during a test on November 23, 1998. Assuming that the direct beam flux follows Beer’s law permits extrapolation to zero airmass from these observations. Figure 35 shows this extra-
Figure 31. Total direct plus diffuse downward solar flux measured by the ULVS and ULIS for 35° solar zenith angle. The solar flux outside the Earth’s atmosphere multiplied by the cosine of 35° is also shown. The observed flux is reduced below that outside the atmosphere by Rayleigh molecular scattering, by aerosol extinction, and by molecular absorption bands of water, oxygen, and ozone. The vertical lines at 350 and 480 nm indicate the passband of our Violet Photometer channels.

At wavelengths where molecular absorptions occur in the Earth’s atmosphere, the Beer’s law extrapolation to zero airmass falls well below the Neckel and Labs spectrum. This is not due to errors in calibration but is due to the nonlinear absorption in the terrestrial molecular bands as shown in Figure 36. Figure 36 shows the observations of November 23, 1998 for 6 wavelengths (all boosted by 3% to adjust for the small calibration shift). At the continuum wavelengths (560, 601, and 701 nm), the data extrapolate linearly to unity (the Neckel and Labs solar flux) at zero airmass. Attempting to extrapolate the data in the three wavelengths which include significant molecular absorption results in an intercept at zero airmass that is significantly below the solar flux outside the atmosphere. Extrapolating the data...
Figure 32. The flux in the direct solar beam measured by the ULVS at 9 solar zenith angles as shown compared to the solar flux outside the atmosphere of the Earth.

assuming that the total extinction optical depth is proportional to the vertical optical depth (kappa) times the airmass to a power, alpha, results in the dashed curves of Figure 36 at these wavelengths. When either the contribution due to particles and Rayleigh scattering (which both have an alpha of unity) dominate the total extinction or the contribution due to the molecular absorption (for which alpha is < unity) clearly dominates the total extinction, kappa and alpha can be found as functions of wavelength from these observations as shown in Figure 37. Notice that the derived value of alpha is >0.95 in the continuum regions (i.e., except in the strong oxygen band near 760 nm and the strong water bands near 680 nm, 720 nm, and longward of 780 nm).

In the data obtained in single measurement mode on September 3, 1997, the optical depth for aerosol scattering was much larger than on November 23, 1998, and so the particle and Rayleigh scattering extinction were subtracted from the total extinction observed in the September test before the nonlinear molecular parameters alpha and kappa were found. The results of the partitioning of Rayleigh scattering, aerosol extinction, and molecular absorption as functions of wavelength for both days are shown in Figure 38. Note that the aerosol extinction was much less on November 23, 1998 than on September 3, 1997. The opposite was true for
Figure 33. The flux in the direct solar beam at six continuum wavelengths plotted as a function of airmass (secant solar zenith angle). The slopes are the extinction optical depths at each wavelength due to molecular Rayleigh scattering and aerosol particle extinction.

The water absorption. This was larger by roughly a factor of 2 in the September observations compared to the November observations. It is quite reassuring to note that the extinction in the oxygen band at 760 nm remained the same on the two days. While we could not determine the values of alpha from the September observations in the continuum regions after the extinction due to Rayleigh scattering plus aerosols was subtracted (no absorption remained to be fit), the values of alpha derived on both days are in good agreement in the water and oxygen bands since the molecular absorption dominated the small amount of aerosol extinction on November 23 (when the total extinction was fit) and the aerosols and Rayleigh scattering were correctly subtracted before fitting the bands in the September observations.

A final check on the spectral observations of the direct solar beam was made by computing a model spectrum using the Modtran program developed by the U. S. Air Force (Bark et al., 1989). Here the number of free parameters included: (1) the altitude at which the observations were made (to permit computation of Rayleigh molecular scattering and oxygen absorption); (2) the total vertical column abundance of water vapor (taken to be 3.34 precipitable cm in the model shown in Figure 39); and (3) the number density and size of the atmospheric aerosols. The
Figure 34. The total extinction optical depth due to Rayleigh scattering, aerosol extinction, and molecular absorption from the ratio of the direct beam fluxes near 35° solar zenith angle and the solar flux outside the Earth’s atmosphere from Neckel and Labs (1984). Note the good agreement in the region where the ULVS and ULIS spectrometers overlap between 850 and 960 nm.

During the Titan descent, methane will play a role similar to that of water in the Earth observations. Knowledge of the absorption coefficients for methane as
functions of wavelength will permit the extinction optical depth due to methane at each altitude to be used to determine the methane abundance as a function of altitude. The wavelength dependence of aerosol extinction will be found at each altitude, and will be compared with the aerosol size found from the solar aureole observations.

5.4. PARTICLE SIZE AND NUMBER DENSITY FROM SOLAR AUREOLE MEASUREMENTS

The solar aureole measurements are made through polarization analyzers that are oriented vertically and horizontally in filters centered near 500 nm and 935 nm. The data are collected in a section of the detector covering 6 columns by 50 rows at a scale of approximately 1°/pixel. The rows extend from approximately 28° to 78° solar zenith angle. The region of the sky covered is about 6° by 50°. The direction
ULVS Transmission Vs. Airmass

Figure 36. ULVS transmission (Direct beam flux/incident flux from Neckel and Labs (1984) versus airmass at 3 continuum wavelengths and 3 wavelengths in molecular absorption bands. In the continuum wavelengths near 560 nm, 601 nm, and 701 nm linear absorption (Beer's law) holds, as shown by the solid lines. Where molecular absorption is important, the absorption is decidedly nonlinear. The dashed lines show nonlinear absorption proportional to airmass raised to a power less than 1.0. Note that all the DISR measurements have been boosted by 3% based on the results shown in Figure 35.

of view of the solar aureole channels is tipped about 6° in azimuth to the left (as seen looking out from the sensor head) from the 0° reference meridian of azimuth defined by the sun sensor slit system. Measurements are planned between azimuths of about 5° and 11° and near 180° from the sun. Figure 40 shows the region near the sun observed through the blue channels on September 3, 1997. Here the total intensity is shown obtained by adding the components measured through the vertical and horizontal polarization analyzers. If the direction of polarization is assumed to be known, the measurements can also give the degree of linear polarization. Measurements made near 180° azimuth are polarized perpendicular to the scattering plane (maximum electric vector horizontal) for Rayleigh molecular scattering and for scattering by the small aerosol particles expected in the atmosphere of Titan. Observations made near 180° azimuth are summed for the six columns of the solar
Kappa and Alpha Vs. Wavelength

Data from Rooftop Test of 11/23/98

Figure 37. Nonlinear absorption parameters kappa (the extinction optical depth for unit airmass) and alpha where the extinction optical depth = kappa * airmass^α. Note that alpha is near unity in continuum regions (near 700 nm and shortward of 680 nm) and significantly less than unity in regions where molecular absorption is important.

aureole system in each of the four color and analyzer channels and returned for each of the 50 rows.

Solar Aureole measurements were collected in single measurement mode on September 3, 1997 at nine different solar zenith angles. Figure 40 shows the contours of blue channel intensity (given by I/F where πF is the incident solar flux though the filter bandpass) near the sun. The intensity and the degree of polarization observed for the Earth when the solar zenith angle was 36° are shown in Figure 41. Similar observations are collected in the two red solar aureole channels.

The solar aureole observations are sensitive to the projected-area size of the particles, to the ground reflectivity, to the shape of the single scattering phase function at scattering angles up to some 140°, and to the single scattering polarizing properties of the particles in addition to the total extinction optical depth (determined from the ULVS measurements). Some simple models are shown in Figure 42 compared to the blue observations. It appears that spherical particles with a relatively narrow size distribution characterized by a single effective size are not able to fit the observations well. When the particles are large enough to have about the right shape near the sun, the phase function produces too little
Figure 38. Vertical optical depths due to Rayleigh scattering, aerosol particles, and molecular absorption versus wavelength in two observing sessions as labeled. Note that the vertical optical depth of the oxygen band at 760 nm is unchanged on the two dates, while the aerosol optical depths and the amount of water is rather different.

light 90° from the sun. A baseline model consisting of a layer of small particles (geometric cross section weighted) mean radius of 0.1 μm above (or even mixed with) a layer of particles with a geometric cross section weighted mean radius of 6 μm comes close to fitting the observations. The observations are compared to the baseline model and one model with a narrow size distribution in panel (a) of Figure 42. Panels (b) though (e) show the baseline model with one parameter at a time changed away from the best-fitting value. Panel (b) shows that the height of the peak near the sun constrains the radius of the large particles to be near 6 μm. Panel (c) shows that the shape of the observations some 10 to 20° from the sun constrains the radius of the small particles to be near 0.10 μm. Panel (d) shows that the observed brightness near 90° scattering angle (azimuth = 180° and zenith = 50°) constrains the vertical optical depth of the small particles to a value near 0.10 when the total aerosol optical depth is fixed at 0.25 from the ULVS observations at 500 nm. Panel (e) shows that the ground reflectivity is constrained to be near
Figure 39. Solar flux measured at 35° solar zenith angle divided by solar flux outside the Earth’s atmosphere as a function of wavelength from the ULVS (dots) and the ULIS (triangles). The heavy solid curve is a model computation using the Modtran program developed by the Air Force. The absorption bands of oxygen (near 640 and 760 nm) of water vapor (most other significant features) and continuum extinction due to atmospheric aerosols plus Rayleigh scattering are shown. The free parameters of the fit include the altitude of the observation (for molecular scattering and oxygen absorption), the amount of water vapor in the atmosphere (3.34 precipitable cm), and the number density and size of atmospheric aerosols (derived from our solar aureole observations below.)

0.05 μm by the observations near the horizon both in the direction toward and away from the sun.

Figure 43 shows the predicted extinction optical depth for the solar aureole baseline model as a function of wavelength compared to the extinction optical depth measured from the upward-looking visible spectrometer at several continuum wavelengths on the same day. Note that the large particles alone have nearly a constant extinction optical depth with wavelength, unlike the spectral observations. When a component of small particles is added in the baseline model, the predicted extinction optical depth is in reasonable agreement with the spectral observations. The models shown in panels (b) through (e) give some idea of the uncertainty in each of the parameters in the baseline model.
For these observations in the atmosphere of the Earth, the 6 \( \mu \)m radius particles may be associated with water droplets in a thin haze. The population of particles with radius near 0.1 \( \mu \)m may be associated with sulfate pollution products. Other observers (see Remer et al., 1997) have often noted bimodal and even trimodal populations of aerosols in urban areas.

On Titan, the situation will be different, but a similar interaction of the solar aureole and upward-looking spectrometer observations is expected. On Titan the process will be easier in that we will have observations at a large number of altitudes, and can follow the changes of particle size with depth one layer at a time with the properties of the particles at all higher altitudes already determined. The
situation will be more difficult in that single scattering calculations will have to be available for non-spherical fractal particle aggregates. Also, calculations for the spherical atmosphere rather than for plane parallel layers will be needed. Finally, however, the addition of the red solar aureole observations will give enhanced sensitivity at low altitudes while the blue channel will give good sensitivity at high altitudes because of the much larger optical depth of the expected small particles at blue compared with red wavelengths on Titan.

5.5. PANORAMIC IMAGES

On December 17, 1997, near the winter solstice, we flew DISR02 in a helicopter over Picacho Peak, Arizona. Images were recorded at 4 different altitudes above ground level (150, 1280, 2500, 3260 m) at local times between 11:00 to 15:30. Solar zenith angles ranged from 57 to 72°, similar to those anticipated during the descent to Titan’s surface in November, 2004. At each altitude we acquired 24 sets of simultaneous exposures of the HRI, MRI and SLI for a total of 72 images. The
Figure 42. The intensity I/F (where $\pi F$ is the incident solar flux) as a function of zenith angle at 15° azimuth from the sun (as negative zenith angles) and opposite the azimuth of the sun. In (a), a model with a single layer of particles is compared with the observations. When the particle size is adjusted to fit near the sun, the brightness opposite the sun is much too low. The baseline model consisting of a layer of particles with $\langle r \rangle = 0.1 \mu m$ above a layer with $\langle r \rangle = 6 \mu m$ is also shown. In panels (b) through (e) one parameter at a time is adjusted away from the baseline model. The regions of the data that are sensitive to the size of the large and small particles, the optical thickness of the small particles (with fixed total optical depth), and the ground reflectivity are shown.
exposures were staggered by about 30° in azimuth. The three highest-altitude sets contained sufficient overlap to allow the construction of panoramic mosaics.

Assembling each set of two-dozen image triplets into a mosaic requires determining the roll, pitch and yaw angles and the vertical and horizontal displacements of the DISR Sensor Head relative to some absolute origin at the time each triplet is recorded. During the descent, the values of the altitude, the yaw and a combination of the roll and pitch will be available from DISR housekeeping information, but the other attitudinal and positional variables must be fixed using the recorded scene information. Anticipating this need, an image-driven registration algorithm has been developed. It acquires the fiducials necessary for constructing a properly rectified and registered mosaic from the images themselves. The Picacho Peak test flight serves as a rigorous test of this strategy.

The registration procedure requires knowing the approximate altitude and the radius of the planet’s surface. It is based on the geometry map generated by the calibration of each imager’s optical distortion field. This mapping assigned each pixel, in each of the three DISR imagers, two dihedral field angles relative to the center of each imager’s field of view. These relative maps were combined with the results of an additional calibration: one that determined the absolute pointing of several tens of individual pixels in each imager’s field. Joining the two calibration data sets resulted in the assignment of an absolute nadir and an absolute azimuth angle to each of the imager pixels.

Possessed of this pointing information, and using a graphical interface which allows images to be magnified, contrast-stretched and individual pixels to be iden-
Figure 43. The extinction optical depth of the particles determined from the upward-looking visible spectrometer (points) compared with the extinction optical depth as a function of wavelength of the particles in the baseline model. The extinction optical depths of the small particle component, the large particle component, and the total extinction optical depth of the particles in the baseline model are shown. Note that the baseline model determined from the total extinction optical depth and solar aureole measurements at 500 nm are in reasonable agreement with the extinction optical depth determined throughout the wavelength region from 500 nm to 1000 nm.
or contracted in size (Z) as needed to achieve a faithful relative alignment. Given the incomplete decoupling between motions and the obscuration of control points, significant iteration between these orthogonal projection planes is required. Two additional projections, stereographic and conic, also help to minimize distortion and reveal additional detail. After achieving geometric registration, a Hapke (1981) model of the average surface reflectance is derived from the pointing information and solar position and divided into the observed intensities at each location to photometrically balance the individual images of the mosaic observed at different scattering geometries.

The resulting panoramic mosaics are shown in Figures 44, 45, and 46. In Figure 44, a mosaic of the (72) images recorded near 3260 m altitude is shown in a stereographic projection. This projection emphasizes the SLI frames and the 50°-wide vertical field of view they provide, a view that includes the horizon and cloud features above the horizon. It shows the success of the photometric model in equalizing the stretch of the various individual frames, especially those near the anti-sunward direction around Picacho Peak itself, which had been washed out by a considerable backscatter. A solar glory has been revealed in one of the frames opposite to the sun’s position and the shadow cast by the mountain is also evident.

In Figures 45 and 46, the data are shown projected onto a plane tangent to the Earth’s surface (gnomonic). Figure 45 displays only the images of the two downward-pointing higher-resolution imagers, the HRI and MRI. Its outer boundary is near 55° nadir angle. Figure 46 shows a magnified view of the central part of Figure 45 to illustrate the full resolution of the HRI images.

In all three versions of the mosaic, the many squares of farmed land act as a grid pattern that rigorously tests the ability of the algorithm to align the images. The procedure is successful, demonstrating an alignment with a typical error of about one pixel in a test where the unknowns are less determined than they will be when constructing the actual Titan panoramic mosaics. The mission mosaics should be easier to produce in two respects: The descent module is not likely to gyrate as sporadically as did the helicopter during the Picacho flight and, as mentioned above, several of the parameters describing the attitude of the instrument will be available from housekeeping data.

5.6. DOWNWARD LOOKING VISIBLE REFLECTION SPECTRA (SPECTROPHOTOMETRIC MODE)

Images of the campus of the University of Arizona were obtained using DISR02 from a rotating platform fastened to one corner of the roof of the Lunar and Planetary Laboratory building. When these data were taken, DLVS spectra were also taken every 3.75° in azimuth. These spectra were obtained to simulate the data we expect to collect at two altitudes in the ‘Spectrophotometric Map’ cycles during the Titan descent. The imaging data are displayed as a panoramic image in Figure 47. Here the DLVS spectra were binned into ‘blue’, ‘green’ and ‘red’ channels as well
as in an ‘IR’ channel extending from 660 nm to 1000 nm. The ratio of blue/IR, green/IR, and red/IR were interpolated in the spectral map and the ratios multiplied by the intensity observed in the IR image mosaic generated from the imaging data. The result is an image that contains high spatial resolution intensity information and lower resolution color information. The same method can be used to obtain color information from the spectrophotometric maps planned for Titan. At other altitudes, correlations of reflection spectra with different morphological types of terrain may permit other color image displays.
Notice that four blocks in the color image are marked in the image of Figure 47. The upward intensity spectra of these four regions are shown in Figure 48. Figure 49 shows the four spectra divided by a model of the total downward solar spectrum at the zenith angle of the sun when the DLVS spectra were obtained. In this way the atmospheric features in the reflected light can be corrected, and spectra of surface spectral reflectivity (I/F) can be produced. Notice the relatively smooth spectrum of the concrete sidewalk, the spectrum of the green grass (with its high
Figure 46. Enlargement of the central portion of Figure 45 to show the full resolution of the HRI imager near the nadir.

reflectivity at wavelengths longer than 720 nm, and the bumps in the red portion of the spectrum from the two samples where dirt was visible among the grass. Similar techniques are planned for the Titan observations.
5.7. DOWNWARD LOOKING IR SPECTRA USING THE SURFACE SCIENCE LAMP

We also were able to observe using the DLVS and DLIS after sunset using the surface science lamp to illuminate a portion of a dusty asphalt street behind the Lunar and Planetary Laboratory building on the campus of the University of Arizona. The instrument was some 20 m above the street when the observations were made. The spectral reflection of the dry street from these measurements is shown in Figure 50. The dips in the apparent reflectivity near 950, 1130, and 1380 nm are due to the strong absorption due to water vapor in the 40 m path from the instrument to the street and back to the instrument. After these data were obtained, we soaked the street with water and observed the reflection spectrum a second
5.8. SUN SENSOR MEASUREMENTS

We made the first test using an apparatus that spins the instrument at a controlled spin rate as a function of time on August 3, 1998. On that day we rotated the instrument at a variable rate with time similar to the rotation rate profile we expect during entry into Titan’s atmosphere. The measurements of the rotation rate from the times of the center slit crossings of the DISR sun sensor are shown for another test on October 2, 1998 in Figure 51. Notice that the measurements are well
Figure 49. The intensity spectra in Figure 48 divided by a model of the total downward solar flux through the Earth’s atmosphere based on the measurements of the ULVS. Note that most atmospheric absorption features have been eliminated. The small remaining feature at 760 nm is due to the slightly different spectral resolution in the ULVS and DLVS.

behaved. Near some 2300 seconds into the test the solar zenith angle was about 67°. During several of our tests using DISR02 we noticed a tendency to lose lock for a few rotations and then reacquire lock a few times near this zenith angle. We suspect that the narrow slits in the sun sensor of our field test unit, DISR02, may be partially obstructed by debris at this zenith angle. In any case, the sun sensor was able to control the azimuth of the data collection during all but a few minutes of the descent, and very nominal data sets have been acquired during our tests.

Figure 52 shows the measurements of the angle from the instrument vertical (perpendicular to the instrument baseplate) and the direction to the sun during the October 2 test as a function of time as well as the true solar zenith angle as a function of mission time on that day. The measured zenith angle agrees with the computed zenith angle to about 0.2°, about the accuracy with which we are able to level the instrument on our rotating apparatus. The rms deviations from the slow trend in the error are 0.12°. This is about what we expect from the ability of our rotating table to spin the instrument smoothly. Thus, the accuracy with which we can determine the tip angle of the spin axis to the direction of the sun can be
Figure 50. The reflection spectrum of a dirty paved street behind the Lunar and Planetary Laboratory of the University of Arizona measured after dark using the Surface Science Lamp of DISR02 mounted some 20 m above the street. The upper curve is the dry street, while the lower curve is for the street after wetting the street with a garden hose. The emission feature near 580 nm is from emission line street lamps in the area. The absorptions near 950, 1130, and 1380 nm in the ‘dry street’ reflectivity curve are due to the water vapor in the path between the instrument and the street. Note that the shape of the water absorptions are broader for the liquid water in the ‘wet street’ spectrum.

determined to an accuracy comparable to the angular resolution of our best imaging data (0.12°).

Figure 53 shows the values of the direct solar beam at the wavelength of the sun sensor (near 940 nm) as a function of airmass for several tests between August 1998 and April 1999. During the July and August tests, clouds built up during the afternoon, and the measured flux from the direct solar beam decreased suddenly several times at the larger airmasses as clouds blocked the direct solar beam. The smooth curves through the points in Figure 53 are models constructed by adjusting two constants: the vertical optical depth of aerosols and the vertical optical depth of water vapor in the 940 nm band. The extinction due to aerosols is linear with airmass, while the extinction due to water vapor varies as the airmass to 0.6 power in this band. On days when the observations spanned a large range of airmass, the vertical optical depths of both the aerosols and the water vapor could be uniquely
Figure 51. The rotation rate as a function of time determined from the sun sensor during the rooftop test of October 2, 1998. The rotation rate was designed to simulate the rate expected during Titan entry. The sun sensor lost and then reacquired lock a few times near a mission time of 2400 s.

determined from the sun sensor observations alone. Figure 54 shows the vertical column water vapor abundance (in precipitable cm) derived from the vertical water vapor opacity in the 940 nm band of the sun sensor passband as a function of time through the second half of 1998 and the first half of 1999. (One observation in September 1997 was plotted in September 1998.) Also shown are the measurements of dew point recorded on the campus of the University of Arizona. Note that the total vertical water abundance derived from the sun sensor measurements is well correlated with the dew point measurements. Also shown is the first water abundance measurement made on Mt. Bigelow outside of Tucson compared with the dew point measured in the city on that day. The observation on Mt. Bigelow near 9000 ft elevation corresponds to less water than indicated by the dew point measurement in the city of Tucson (2400 ft). Both the dew point measurements and the DISR water vertical abundance show the expected increase in atmospheric water in the summer monsoon season followed by a decrease in the cooler and dryer winter months.
Figure 52. The angle from the instrument vertical (perpendicular to the instrument baseplate) as a function of time compared to the solar zenith angle as a function of time computed from the Astronomical Almanac during the test on October 2, 1998. The error was less than ±0.2°, corresponding to our ability to hold the baseplate horizontal in our test apparatus. The standard deviation of the error is about 0.12° from the mean trend of the error. This is dominated by the ability of our apparatus to rotate the instrument smoothly during each rotation.

The sun sensor wavelength was chosen to fall in a continuum region for the Titan atmosphere, and will be used to provide high time resolution (between 4 and 30 seconds) of the aerosol optical depth. These data will be an important addition to the measurement of the direct solar beam from the ULVS and ULIS at lower time and vertical resolution.

The results of our first test made on the rotating platform with a tipping motion added are shown in Figure 55. Many clouds were present on this day, and the sun sensor kept losing and reacquiring the sun. Nevertheless, the apparent zenith angles of the sun in the tipping frame of reference of the instrument are shown by the points in the figure. The smooth curve is the expected variation of the apparent zenith angle with time which is the sum of a 2° amplitude sine wave with a period of six minutes on the slow setting of the sun with time. The plot demonstrates that we can measure the component of the tip of the instrument baseplate in the direction toward the sun from the sun sensor to an accuracy of some 0.2°, about the size of a SLI pixel. The relatively slow six minute period was chosen for this test.
Figure 53. The flux derived from the sun sensor in its passband near 940 nm as a function of airmass during several rooftop tests between August, 1998 and April, 1999, as labeled. The smooth curves are models obtained by adjusting the vertical optical depths of aerosols and water vapor for each day. The aerosol optical depth varies linearly with airmass, while nonlinear the water vapor absorption varies as the airmass to 0.6 power. All the models reach the same value outside the atmosphere (at airmass = 0.0). Thick clouds blocked the solar beam occasionally during the observations in summer monsoon season in July an August.

to be sure that the sine wave would be adequately sampled even in the presence of gaps in the observations due to clouds. On Titan, the oscillation due to wind gusts may be much faster than in this test, but our time resolution will be between several seconds and a few tens of seconds. The sun sensor observations will be able to provide important constraints on the orientation of the probe on each rotation of the spacecraft (some 500 times) during the descent.

The sun sensor attitude information gives the angle between the normal to the instrument platform and the vector to the sun. This is equivalent to the component of the tip of the instrument platform toward the sun. The orthogonal component of the instrument tip (i.e., the component in a direction perpendicular to the azimuth of the sun) can be constrained by images of the horizon from the SLI. While complete SLI images are only obtained on image cycles, a condensed form of SLI data is obtained during all nonimage cycles. These data include the sum of the
Figure 54. Measurements of dew point (open squares, right scale) measured on the campus of the University of Arizona Vs. time compared with vertical abundance of water vapor (left scale) derived from the vertical water opacity in the 940 nm band of the DISR sun sensor measured on the roof of the Lunar and Planetary Laboratory in Tucson (open circles) and on Mt. Bigelow at an elevation of some 9000 feet (solid point) outside the city of Tucson. The dew point and water abundance plotted in September 1998 were actually observed in September of 1997. The error bar on the July observation is particularly great because the afternoon clouds shortened the range of airmass sampled, and the total vertical opacity in the sun sensor passband could less reliably separated into linear aerosol opacity and nonlinear water vapor opacity. The correlation of the dew point measurements (which varied by a few degrees during the DISR observations) and the vertical column water abundance observed by DISR for the measurements in Tucson is evident. As expected, the water abundance above the Mt. Bigelow site is less than would be expected from the dew point measured at the lower elevation (2400 ft) in the city of Tucson.

intensity in two vertical regions each 13 CCD columns wide (2.6°) and 50° high at six different azimuths relative to the sun. Thus, the SLI image and SLI strip data will be able to constrain the other component of the tip of the instrument platform some 50 times during the descent. Data on platform orientation at still higher time resolution will have to come from other housekeeping observations or from fitting together mosaics from our individual imaging frames which are obtained several times per rotation low in Titan’s atmosphere.
5.9. VIOLET PHOTOMETER MEASUREMENTS

Ideally, one would like to have a perfectly flat spectral response with sharp cuton and cutoff wavelengths in the violet photometer system in order to eliminate any sensitivity to the shape of the violet spectrum when the ULV and DLV data are reduced to give the energy in the upward and downward flux between the wavelength limits of the filter. While the filters of the ULV and DLV systems are not absolutely flat, they are flat to about 15 percent. Further, it is possible to choose the three parameters of an equivalent rectangular filter (cuton wavelength, cutoff wavelength, and effective mean response) that give exactly the correct flux in an arbitrary spectrum that can be described by up to a second order polynomial in wavelength (Tomasko et al., 1980). For our ULV and DLV photometers the cuton and cutoff wavelengths defined this way are 350 nm and 475 nm, respectively. While the solar spectrum is far from quadratic in the violet region of the spectrum, most of the structure is due to sharp absorption lines that have a structure much finer than the variation
in response with wavelength of our violet filter. Test calculations show that we
can give a model-independent flux between the cuton and cutoff wavelengths that
is uncertain by <1% (aside from absolute calibration uncertainties) instead of the
15% or so that one might guess from the departure from flatness of our violet filter.
Of course, the constraint on the integral of the violet spectrum times the relative
spectral response of the ULV and DLV instruments is well determined, and can be
used to constrain any model of the spectrum and level of violet radiation in Titan’s
atmosphere.

The violet photometers have a fixed gain and time constant appropriate for Ti­
tan, and give saturated readings on Earth without the addition of an external filter.
In general, simply adding a glass neutral density filter on the top of the diffusers
will change significantly the relative spatial response of the violet optical system
consisting of the external bear’s ear baffle and the diffuser. However, we have been
able to add a thin sheet of absorbing material to the top of the external diffuser
in the ULV, ULVS, and DLV systems which has changed the spatial distribution
function rather little from the values measured in our laboratory calibration to per­mit
unsaturated measurements of violet flux in our rooftop measurement program.
This filter consists of a small piece of high contrast black and white 35 mm film
that was exposed to image a target consisting of evenly distributed black circles
on a white background. In the negative image, the film consists of absorbing black
grains surrounding a pattern of clear circles. The spacing and size of the circles
are arranged so that the area of the circles is approximately 1% of the total area.
The circles are arranged so that the 4 by 5 mm diffuser is covered by a grid of
some 40 rows of 50 holes each, thus sampling the total area of the diffuser. Little
light is reflected from the black emulsion to the external baffles and then back to
the diffuser, so the spatial response pattern is largely unchanged from the pattern
measured before the film filter was added.

The relative spatial response in not entirely unchanged, however. The substrate
of the film also attenuates the light that is not blocked by the darkened silver grains.
Tests show that the film itself has a vertical optical depth of about 0.07 at the
wavelengths of the violet photometers. When the transmission of the filter and its
modification of spatial response function due to the film are included, however,
measurements with the ULV and DLV systems are possible on Earth.

The results of one set of measurements with this sysem are shown in Figures 56
and 57. The values of the direct solar beam in the violet fall exponentially with
increasing airmass over the region from about 2.2 to 4.6 airmasses, as would be
expected. The data indicate that the optical depth for unit vertical airmass was
about 0.48 in the violet passband on this day. The cosine of the zenith angle times
the direct solar beam gives the downward direct flux in the violet channel. The
mean diffuse intensity is measured using the 170° wide field of view in azimuth
looking 180° from the sun and within 5° of the sun under the shadow bar. The
diffuse intensity convolved with the wide azimuthal field of view varies to a good
approximation as the cosine of the azimuth from the sun. The spatial response of
the ULV and DLV diffusers in zenith angle approximates a cosine response, so \( \pi \) times the measured mean intensity is a good approximation to the downward diffuse flux. The total of the downward diffuse flux and the downward direct flux gives the total downward flux is shown in Figure 55. The upward diffuse flux is obtained from the average of the DLV mean intensities measured with the 170° wide field of view in azimuth measured at 0° and 180° azimuth with the approximately cosine weighting in nadir angle. The total upward flux versus airmass, as well as the total downward minus upward flux, (the net flux) are shown as functions of airmass. Figure 56 shows the total downward, upward, and net fluxes on a linear scale versus airmass. The derivative of such net flux measurements on Titan will give the solar heating rate as a function of altitude due to sunlight between 350 and 475 nm.
5.10. Future plans

We have recently added a programmable wobble to the spinning platform to test and simulate the operation of the instrument under a swinging parachute. During this phase of our tests we have begun to make panoramic mosaic images of the Tucson valley from a U.S. Forest Service tower on the top of one of the surrounding mountains. This will give us valuable information on the ability of our housekeeping data from the sun sensor and from the SLI strip data obtained in each data cycle at 6 different azimuths to yield the attitude of the platform during the descent to permit more automatic assembly of image mosaics from our Titan entry observations. The attitude of the instrument is also needed for reduction of our flux and solar aureole observations as well as our goal of measuring winds from the drift of features in images obtained at different times.

In addition, we are currently planning a series of test images made from various heights between 5 and 15 meters of specially constructed targets. The data will be used to develop and test algorithms for finding the heights of features in the images from data acquired at various altitudes above the surface. Ultimately, we hope to
develop a capability to produce stereoscopic maps of the heights of the terrain in our Titan images.

5.11. SUMMARY

We have included brief samples of data from each portion of the field test unit including ULVS, DLVS, ULIS, DLIS, ULV, DLV, SA, Imagers, Sun Sensor, and Surface Science Lamp. This ground test program has proven very valuable for developing reduction, display, and analysis algorithms that will be necessary to reduce the complex data from the DISR instrument rapidly after entry into the atmosphere of Titan. Already, the brief samples of data shown provide convincing evidence of the value of the data anticipated from the experiment to support the goals for studies of energy balance, aerosol properties, gaseous composition, and the nature of the surface of Titan.

Acknowledgements

The planning, design, development, fabrication, and test of the DISR instrument would not be possible without the collaboration of a large number of dedicated and highly talented individuals. We wish to especially thank the many dedicated contributors at Lockheed Martin Aerospace, Denver and their suppliers, for their work on the design and development of the mechanical, optical, electrical and software of the DISR instrument; the engineers and technicians of the Paris Observatory for their work on the infrared detectors, their support electronics, and the shutter; the people of the Max Planck Institute for Aeronomy for their work on the design of the CCD detector and its read electronics; and the engineers of the Technical University of Braunschweig for their design and development of the data compression hardware. Without the dedicated efforts of all these people the DISR would not be possible.

References


THE GAS CHROMATOGRAPH MASS SPECTROMETER FOR THE HUYGENS PROBE

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Abstract. The Gas Chromatograph Mass Spectrometer (GCMS) on the Huygens Probe will measure the chemical composition of Titan’s atmosphere from 170 km altitude (~1 hPa) to the surface (~1500 bPa) and determine the isotope ratios of the major gaseous constituents. The GCMS will also analyze gas samples from the Aerosol Collector Pyrolyser (ACP) and may be able to investigate the composition (including isotope ratios) of several candidate surface materials.

The GCMS is a quadrupole mass filter with a secondary electron multiplier detection system and a gas sampling system providing continuous direct atmospheric composition measurements and batch sampling through three gas chromatographic (GC) columns. The mass spectrometer employs five ion sources sequentially feeding the mass analyzer. Three ion sources serve as detectors for the GC columns and two are dedicated to direct atmosphere sampling and ACP gas sampling respectively. The instrument is also equipped with a chemical scrubber cell for noble gas analysis and a sample enrichment cell for selective measurement of high boiling point carbon containing constituents. The mass range is 2 to 141 Dalton and the nominal detection threshold is at a mixing ratio of 10^-8. The data rate available from the Probe system is 885 bit/s. The weight of the instrument is 17.3 kg and the energy required for warm up and 150 minutes of operation is 110 Watt-hours.
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Acknowledgements 

References
1. **Scientific Objectives**

1.1. **INTRODUCTION**

Titan is unique in the solar system in several respects. The dense atmosphere is still chemically reducing, even though Titan is small enough to allow hydrogen to escape readily from its gravitational field. The major constituents of the atmosphere, nitrogen and methane, are continuously broken apart by a combination of solar UV, impinging electrons from Saturn’s magnetosphere, and a steady flux of cosmic rays. The resulting molecular fragments recombine to form a variety of new species, many of which were detected for the first time by Voyager 1 (Broadfoot et al., 1981; Hanel et al., 1981; Kunde et al., 1981; Samuelson et al., 1981, 1983; Lutz et al., 1983; Bézard et al., 1993). The existence of still more complex compounds is manifested by the ubiquitous, surface-hiding aerosol blanket. In addition to hydrocarbons and nitriles, the atmosphere is known to contain CO, CO₂ and externally delivered H₂O (see reviews by Hunten et al., 1984; Morrison et al., 1986; Lunine et al., 1989). The origin of this atmosphere, the processes involved in its evolution, the end products and their subsequent fate as they interact with the surface remain to be elucidated. A particularly interesting aspect of this investigation is the possible relevance of the chemical evolution currently occurring on Titan to some of the prebiotic syntheses that took place on the early Earth (Raulin et al., 1992a; Owen et al., 1997). It is the purpose of the GCMS to provide an accurate analysis (see Table 1) of Titan’s atmospheric composition along the descent trajectory of the Huygens Probe. The instrument is a follow-on to others used in making measurements of the atmosphere of Venus (Niemann et al., 1980) and Jupiter (Niemann et al., 1992).

1.2. **ATMOSPHERIC COMPOSITION: ARGON, ISOTOPES AND ORGANIC COMPOUNDS**

Despite the great success of Voyager 1, the composition of Titan’s atmosphere is still poorly known (Table 2). The present uncertainty in the methane mixing ratio and its variation with altitude can be resolved from the continuous recording of mass spectra by the GCMS during the Probe’s descent. The Voyager observations left open the possibility that several percent of some heavy, spectroscopically undetectable gas might be present (Samuelson et al., 1981). Non-radiogenic argon (³⁶Ar + ³⁸Ar) is the most likely candidate (Owen 1982); the mass spectrometer can detect it down to mixing ratios of 10–100 ppb. The mole fraction of argon that could remain undetectable in presently available observations has been steadily decreasing with improved treatment of the data, first to ≤10% (Strobel et al., 1993), then to ≤6% (Courtin et al., 1995), the same upper limit originally reported for the heterosphere by Broadfoot et al., (1981), and most recently to 2.6% with an uncertainty of ±4.5% (Samuelson et al., 1997). In fact, several percent of argon
would be difficult to explain based on current models for the origin of Titan’s atmosphere (Owen and Bar-Nun, 1995).

The full range of abundance and isotope data provided by the GCMS will be employed to study atmospheric origin and evolution. For example, the ratio $^{14}$N/$^{15}$N has been found to be 4.5 times the terrestrial value in Titan’s HCN (Marten et al., 1997; Owen et al., 1998). Yet the value of $^{12}$C/$^{13}$C in HCN is normal (Hidayat et al., 1997). This situation is reminiscent of Mars, where $^{14}$N/$^{15}$N is 1.6 times normal and $^{12}$C/$^{13}$C is again normal. It suggests that as much as 45 times the current amount of nitrogen on Titan has escaped from the satellite, while there must be a correspondingly large reservoir of carbon somewhere on Titan, presumably in the form of hydrocarbons. Such a reservoir is required in any case to replenish the CH$_4$ that is continually being dissociated (Strobel, 1982; Yung et al., 1984). The GCMS is ideally suited to attack this problem, as it can measure the relevant isotope ratios in a variety of compounds in Titan’s atmosphere, including N$_2$, which is inaccessible to other instruments. It will even measure $^{36}$Ar/$^{38}$Ar to see if this ratio has also been affected by the same escape process that fractionated the nitrogen.

Once the relative importance of atmospheric escape and chemical exchange have been determined for nitrogen, it will be possible to establish the original value of D/H in Titan’s methane. For example, if D/H $\sim$ 2 $\times$ 10$^{-5}$, the value in Saturn’s hydrogen (Griffin et al., 1996), it might favor a sub-nebula origin for most of Titan’s atmosphere. The current best estimate of Titan’s D/H is based on CH$_3$D measured in the $n_6$ band by Infrared Space Observatory/Short Wavelength Spectrometer (ISO/SWS, Coustenis et al., 1998a). The result, D/H = 7.5 $\times$ 10$^{-5}$, is in agreement with the earlier ground-based infrared observations which gave D/H = 7.75 $\pm$ 2.25 $\times$ 10$^{-5}$ (Orton, 1982). The central value thus appears to be approximately a factor of 3 greater than the Saturn D/H or the protosolar D/H as derived from the Galileo Probe Mass Spectrometer at Jupiter (Mahaffy et al., 1998). On the other hand, it is about a factor of 4 lower than that on comets Halley

### TABLE 1

<table>
<thead>
<tr>
<th>Science objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric composition</td>
</tr>
<tr>
<td>Abundances of all constituents within the mass range of the instrument with mixing ratios $&gt; 10^{-8}$, selected species to $10^{-10}$.</td>
</tr>
<tr>
<td>Atmospheric origin</td>
</tr>
<tr>
<td>Discrimination between primordial and radiogenic argon. Surface composition. Other noble gas abundances. Value of D/H.</td>
</tr>
<tr>
<td>Atmospheric and interior evolution</td>
</tr>
<tr>
<td>Chemical evolution</td>
</tr>
</tbody>
</table>
(Balsiger et al., 1995; Eberhardt et al., 1995), Hyakutake (Bockelee-Morvan et al., 1998) and Hale-Bopp (Meier et al., 1998) which all have a D/H $\sim 30 \times 10^{-5}$. The available evidence therefore suggests that comets could not have been the main source of Titan's atmosphere, contrary to the hypothesis of Griffith and Zahnle (1995). Instead, degassing of the icy planetesimals that accreted within Saturn's subnebula to form Titan seems implicated. Investigations of noble gas abundances and isotopes can shed further light on the origin of the atmosphere. For example, most of the neon on Titan may have come from the rocky fraction of the satellite, while krypton and xenon could have been contributed primarily by the ice, as on Earth (Owen and Bar-Nun, 1995). The dissociation of NH$_3$ by the solar ultraviolet radiation (Atreya et al., 1978) or by impact induced shock chemistry (McKay et al., 1988) could have produced all of the N$_2$ in Titan's present day atmosphere early in its accretionary history. A satisfactory resolution of the complex question of the origin and evolution of Titan's atmosphere requires, however, accurate in situ measurements of D/H as well as the abundance and isotopic ratios of argon, particularly $^{40}$Ar/$^{36}$Ar, as the current data are poorly constrained and model dependent.

The oxidized compounds offer other opportunities and challenges. The production of CO$_2$ requires hydroxyl (OH) that may come either from the outside atmosphere (e.g., by bombarding ice particles or micrometeorites) or from internal sources (e.g., the reaction of CH$_4$ with CO). The external source seems likely to be more efficient, but we don’t know the flux of incoming particles. The recent detection of water vapor in Titan's upper atmosphere by ISO/SWS (Coustenis et al., 1998a) is encouraging. The spectra can be fitted with a uniform H$_2$O mixing ratio of 0.4 ppb. The OH produced from the photolysis of H$_2$O would react with CO to produce CO$_2$. If some fraction of the nitrogen we now see in Titan's atmosphere was originally incorporated as N$_2$, one would expect a comparable amount of primordial CO. In that case, a significant amount of CO$_2$ would have been produced and a corresponding deposit of ‘dry ice’ could now be present on the surface, intimately mixed with accumulated organic aerosols (Samuelson et al., 1983; Owen and Gautier, 1989). Note, however, that the observed amount of H$_2$O seems insufficient for producing the observed CO$_2$ by the conventional mechanism (i.e., CO + OH $\rightarrow$ CO2). It may be necessary to invoke an additional path, such as a reaction between the externally delivered H$_2$O and Titan’s own methane (actually between OH, the photoproduct of H$_2$O, and the dissociation products of CH$_4$). On the other hand, the situation regarding CO itself is in a less than satisfactory state. The first detection of CO was in the near infrared, i.e., the data yielded the CO abundance in Titan’s troposphere (Lutz et al., 1983). Their CO mixing ratio of $\sim$50 ppm was later confirmed by Muhleman et al., (1984) and again by Gurwell and Muhleman (1995) who observed the J(1-0) transition of CO at 115 GHz. The microwave data pertain to the stratosphere, so a uniform mixing ratio with altitude is indicated by the above authors. Courtin et al., (1998) have performed a more sophisticated analysis of the near infrared absorptions but obtained the same result.
TABLE 2
Atmospheric composition of Titan*

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mixing Ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major Species (global values)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>0.85–0.98</td>
<td>Hanel et al., 1981</td>
</tr>
<tr>
<td>Ar</td>
<td>0.026 ± 0.045</td>
<td>Samuelson et al., 1997</td>
</tr>
<tr>
<td>CH₄</td>
<td>≤0.06</td>
<td>Broadfoot et al., 1981</td>
</tr>
<tr>
<td>CH₄</td>
<td>≤0.15 at surface</td>
<td>Courtin et al., 1995</td>
</tr>
<tr>
<td><strong>Minor Species</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>2–6 × 10⁻³</td>
<td>de Bergh et al., 1988</td>
</tr>
<tr>
<td>D/H</td>
<td>7.8 ± 2.3 × 10⁻⁵</td>
<td>Orton, 1992; Coustenus et al., 1998b</td>
</tr>
<tr>
<td><strong>CN Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂N₂</td>
<td>~2 × 10⁻⁸</td>
<td>Coustenus and Bézard, 1995; Bézard et al., 1993</td>
</tr>
<tr>
<td>C₄N₂</td>
<td>condensed phase</td>
<td></td>
</tr>
<tr>
<td><strong>C-N-H Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCN</td>
<td>~2 × 10⁻⁷ (global)</td>
<td>Coustenis and Bézard, 1995; Bézard et al., 1993</td>
</tr>
<tr>
<td>HC₃N</td>
<td>~3 × 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>CH₃CH</td>
<td>1–5 × 10⁻⁹ (global)</td>
<td></td>
</tr>
<tr>
<td><strong>Oxygen Group (global values)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>0.4–6 × 10⁻⁵</td>
<td>Lutz et al., 1983; Muhleman et al., 1984; Gurwell and Muhleman, 1995; Marten et al., 1988; Hidayat et al., 1998</td>
</tr>
<tr>
<td>CO₂</td>
<td>~1 × 10⁻⁸</td>
<td>Samuelson et al., 1983</td>
</tr>
<tr>
<td>H₂O</td>
<td>4 × 10⁻¹⁰ (global)</td>
<td>Coustenis et al., 1998a</td>
</tr>
<tr>
<td><strong>C-H Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₆</td>
<td>1–2 × 10⁻⁵</td>
<td>Coustenis and Bézard, 1995; Bézard et al., 1993; Coustenis et al., 1998b</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>~10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>C₂H₂</td>
<td>2–6 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>C₂H₄</td>
<td>10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>CH₃C₂H</td>
<td>~3 × 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>C₄H₂</td>
<td>~2 × 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 ± 0.2 × 10⁻⁹ (global)</td>
<td></td>
</tr>
</tbody>
</table>

*Values at other latitudes and seasons likely to be different.
However, Marten et al., (1988) and Hidayat et al., (1998) using microwave observations of transitions from higher rotational levels derived a lower value for the CO abundance and found evidence for a decrease of CO with altitude. Noll et al., (1996), studying the 5 micron spectrum, derived a value of only 10 ppm for CO. Considering the importance of CO in the models of the origin and evolution of Titan’s atmosphere, the GCMS will investigate the chemistry of CO on Titan by measuring the abundance of this gas at the four altitudes at which atmospheric GC samples are taken.

The drivers for the chemistry on Titan are solar ultraviolet radiation, the charged particle induced chemistry when Titan is immersed in Saturn’s magnetosphere, and galactic cosmic rays, especially for lower atmospheric chemistry. The chemistry of CH$_4$ on Titan proceeds, to some extent, in a manner similar to that proposed for Jupiter, with the exception that H$_2$ is replaced by N$_2$ as the major gas. The stable hydrocarbons resulting from the CH$_4$ photochemistry are C$_2$H$_6$, C$_2$H$_2$, and C$_2$H$_4$. Subsequent reactions involving C$_2$H$_2$ result in the formation of methylacetylene or allene (C$_3$H$_4$), and polyynes (C$_{2n}$H$_{2n}$, n = 2, 3, 4 ...). Propane C$_3$H$_8$, butane C$_4$H$_{10}$ and other heavier hydrocarbons are expected to be formed following the reaction of the radical CH$_3$ with C$_2$H$_5$, C$_3$H$_7$, etc.

Lower mixing ratios are expected with an increasing number of C atoms, but available observations paint a more complex picture. Careful reanalysis of the Voyager data by Coustenis and colleagues has revealed striking variations in abundances of minor constituents with latitude on Titan (Coustenis and Bézard, 1995 and references therein). At 50°N, they find the following in order of increasing abundance: C$_4$H$_2$, C$_2$N$_2$, HC$_3$N, C$_3$H$_4$, C$_3$H$_8$, C$_2$H$_8$, HCN, C$_2$H$_2$, C$_2$H$_6$. Abundances measured at this latitude can be over 17 times the values at southern latitudes. The abundances measured by the GCMS along the Probe trajectory can be used to calibrate the remote measurements by the Composite Infrared Spectrometer (CIRS) on the Cassini Orbiter, allowing analysis of these variations over the globe during a season different from the one sampled by Voyager 1.

Unlike Jupiter, the CH$_4$ chemistry on Titan is not isolated, as the above list of constituents shows (cf. Table 2). Atomic nitrogen produced on dissociation of N$_2$ reacts with CH$_4$ and products of its photochemistry, CH$_3$ and CH$_2$, to produce HCN. Photolysis of HCN produces CN. The reactions of CN with CH$_4$, CN (or HCN) C$_2$H$_2$ and C$_2$H$_4$ yield, respectively, HCN, C$_2$N$_2$, HC$_3$N, and C$_2$H$_3$CN (not yet detected). Reactions of CN with the other hydrocarbons result in the formation of additional nitriles such as CH$_3$CN. Other possible nitriles with mixing ratios in the range 10$^{-8}$ to 10$^{-9}$ are: C$_3$H$_5$ – N, CH$_2$ = CH – CN, CH$_3$C ≡ C – CN and HC$_4$ – CN. Lower mole fractions are expected for nitriles at higher molecular weight. For comprehensive discussions of the models of chemical pathways in Titan’s atmosphere, the reader is referred to Yung et al., 1984; Atreya, 1986; Lunine et al., 1989; Toublanc et al., 1995; Lara et al., 1996.

The GCMS will approach this analysis problem in four ways: by taking mass spectra continuously, thereby measuring every m/e peak from 2 to 141 Dalton; and
by making discrete GC analyses at various altitudes, including sample enrichment, thereby permitting both greater sensitivity and specificity in identification at those points. A third approach is possible in collaboration with the ACP experiment (see Israel et al., this volume), and a fourth possibility exists (as described below) if the Probe survives the landing.

1.3. DESCENT SEQUENCE

The mass spectrometer will make direct measurements continuously from initiation of experiments until landing at a sampling rate of 5 ms. A minimum of five GC samples will be taken, one immediately after the opening of the inlet valve, another one in the lower stratosphere, a third near 60 km (where concentrations of most complex trace gases are thought to be the highest) and two more below 60 km altitude. One of the latter will be devoted to analysis of the output from the aerosol pyrolysis experiment and the other taken near the atmospheric temperature minimum to provide the best CO/N₂ separation. A sixth sample can be taken close to the surface if the nominal descent time is maintained. Its purpose is to characterize conditions near the ground, especially to search for evidence of the vapor phases of possible surface condensates. The timing will be adjusted to ensure read out of the GCMS prior to impact for the nominal descent scenario.

1.4. SURFACE SCIENCE

Titan has the largest unexplored surface in the solar system. This surface is currently being studied at a very low spatial resolution (~300 km) by ground-based and Hubble Space Telescope observations through near-IR windows (Smith et al., 1996 and references therein, Combes et al., 1997; Gibbard et al., 2001) and by means of radar (Muhleman et al., 1995). Owing to the presence of Titan’s thick, chemically active atmosphere, the surface of this satellite must be one of the most unusual we are ever likely to see. This surface must contain or conceal a reservoir for atmospheric methane, since the present atmospheric abundance of this gas will be destroyed by photochemistry in just 10⁷ years. Unless we just happen to be living at the time when Titan’s original methane comes to an end, the surface (or sub-surface) must provide a means for replenishing this gas. The products of atmospheric chemistry will accumulate on Titan’s surface over geologic time, with the potential of producing deposits with depths on the order of a kilometer or more. If liquids are present, one can imagine their influence on the landscape through erosion, and the possibility that further chemical processing also occurs in them (Raulin et al., 1995).

Three extreme models for Titan’s surface have been proposed:

- a global ocean of hydrocarbons dominated by ethane but containing methane, nitrogen, carbon monoxide and many other dissolved species;
- a global covering of precipitated aerosols;
- an icy landscape dominated by impact craters, perhaps including rocky debris.
It is now clear that the first of these models cannot be correct. A solid surface with lakes or seas of liquid hydrocarbons and some areas dominated by aerosol deposits is more consistent with existing data (Lunine, 1993, 1994; Lorenz, 1993; Smith et al., 1996).

If Huygens lands in a liquid, a compositional analysis with the GCMS is straightforward. Mass spectra of evaporating liquid showing the relative abundances of nitrogen, ethane, methane, argon and other noble gases, simple hydrocarbons, nitriles and oxides would be an outstanding contribution to understanding the origin and evolution of the atmosphere. If the Probe settles into a deposit of aerosols, one needs to extrapolate the accumulated information from the descent measurements to interpret the data. This would offer an opportunity to determine the level of chemical complexity achieved by chemical synthesis in the atmosphere, as even rare aerosols may accumulate in measurable concentrations on the surface. Here the GCMS heated inlet will ensure that the more volatile components of such aerosols reach the instrument. Landing on exposed ice could still permit a measurement of H2O ice ‘bedrock’ and a search for condensed CO2, measurements of fundamental importance to an understanding of atmospheric evolution. A determination of D/H in H2O on the surface would be of great interest for comparison with atmospheric values in CH4 and other species. It is recognized, however, that this is the most challenging landing scenario, both for Probe survival and for a good interface between the gas inlet and the surface.

2. Instrument Description

2.1. General

Mass spectrometry as the principal chemical identification technique is ideally suited for an exploratory mission like the Huygens Probe and was successfully demonstrated by the Galileo Probe Mass Spectrometer (Niemann, et al., 1996). All atoms and molecules within the mass and sensitivity range of the mass spectrometer will be detected. No a priori knowledge of the composition is required. The simultaneous occurrence of species of similar composition can sometimes lead to ambiguities in species identification. Two electron beam energies in electron impact ionization usually remove the difficulties by generating energy dependent fractionation patterns. Further improvement of species separation and more accurate species identification is achieved with a gas chromatographic system coupled with the mass spectrometer. Gas chromatograph mass spectrometer systems are among the most powerful analytical tools for chemical analysis of many types of compounds, and especially of gas mixtures. The added complexity, compared to stand-alone gas chromatographs or mass spectrometers, is recognized but the benefits resulting from a combined instrument outweigh the possible disadvantage of increased instrument complexity. The advantage offered by combining gas
Figure 1. Illustration of the Gas Chromatograph Mass Spectrometer operational principle. Signal intensities are shown in the ordinate vs. time in the abscissa. Column sample injection time is shown in the first trace. The 3D plot shows signal intensities of column elutents for a 4-component sample on the abscissa and the corresponding mass spectra of the elutents in the third coordinate. The simultaneous mass spectra of all four components i.e. without chromatographic separation is shown at the origin and illustrates the significant signal overlap in the mass spectra.

chromatography and mass spectrometry is best illustrated in Figure 1. In this three-dimensional display the detector signal obtained from a gas mixture using only a mass spectrometer vs. mass is plotted at the origin of the time axis, and the detector signal using only a gas chromatograph vs. time is plotted at the origin of the mass axis. The mass spectrum shows a mass overlap at many mass values for the mixture and the gas chromatograph shows distinct peaks without species identification. The advantage of this combination is illustrated in the display allowing time dependent separation of the components by the gas chromatograph and molecular identification of the mass spectrometer.

A functional block diagram showing the main elements of the GCMS/ACP system is shown in Figure 2. The Instrument Operating Characteristics and Huygens Probe Resources Required are summarized below in Table 3 and Table 4.

The main elements of the instrument are:

A mass spectrometer system consisting of ion sources, mass analyzer and ion detector.
A gas sampling system consisting of a direct atmospheric sampling system to introduce atmospheric gas into the ion source and to enrich trace species and noble gases.

A gas chromatograph for batch sampling at specific altitudes in the atmosphere and subsequent time separation of species for identification by the mass spectrometer.

A sample transfer system for gas mixtures, generated by the aerosol pyrolyzer, to the mass spectrometer sample inlet systems. A detailed schematic for the GCMS systems is shown in Figure 3.

The mass spectrometer has five ion sources feeding a common mass analyzer, one ion source at a time. The first source, IS1, samples the atmosphere continuously. The second ion source, IS2, samples the ACP output, and the IS3, IS4 and IS5 ion sources are detectors for three gas chromatographic columns (GC columns). The choice is prescribed for the Probe descent by a preprogrammed sequence.

The ion source connected to the direct atmospheric sample, IS1, is selected during the descent’s first 30 min and at any time thereafter when no peaks are present at the output of any of the GC columns. For the analysis of the gas mixture from the ACP, the ion source IS2 will be selected and, during the GC analysis of these mixtures, the sequence will be identical to that associated with the atmospheric GC samples.
TABLE 3
Instrument operating characteristics

| Gas sampling: | 1) Continuous direct atmospheric gas sampling. |
|              | 2) Batch sampling for GCMS analysis, distributed over descent altitude. |
|              | 3) Sample enrichment for MS (100 to 1000× enrichment). |
| Ambient pressure range: | 1 hPa to 1500 hPa. |
| Altitude above surface: | 176 km to 0 km. |
| GC System: | 3 parallel columns with H₂ carrier gas. Independent MS ion source detection. |
| Ion source: | Five sources, electron impact ionization. Maximum operating pressure 1 × 10⁻³ hPa. |
| Ion detector: | Dual Secondary Electron Multipliers, pulse counting and analog current mode. |
| Background noise: | 1 count/min. |
| Mass range: | 2 Dalton to 141 Dalton. |
| Sensitivity: | 1 × 10¹⁴ counts/s/hPa source pressure. |
| Dynamic range: | ≥ 1 × 10⁻⁸. |
| Resolution/crosstalk: | 1 × 10⁻⁶ for adjacent half mass up to 60 Dalton, less for higher mass. |

TABLE 4
Probe resources required

| Data Rate | 15 packets per cycle |
| Viewing requirements: | 1) Sample inlet near stagnation point. |
| | 2) Sample outlet near minimum pressure point (e.g. inside of Probe body). |
| Deployment mechanisms: | 1) Metal ceramic breakoff caps, pyrotechnically operated. |
| | 2) Valves, solenoid operated. |
| Altitude information: | Obtained from altimeter data provided by Probe or ambient pressure desired near surface. |
| Temperature range: | −20 °C to +50 °C operating, −20 °C to +60 storage. |
| Power: | 41 Watts average, 71 Watts peak. |
| Energy: | 110 Wh. |
| I (Max): | 1.68 A (Main), 1.32 A (Protected). |
| Weight: | 17.3 kg. |
| Size: | Cylindrical, 198 mm diameter, 470 mm high. Mounting flange bolt circle 248 mm. |
Figure 3. Schematic of the Gas Chromatograph Mass Spectrometer. Details of the Aerosol Collector Pyrolyser are shown in an accompanying paper in this volume.

2.2. GAS SAMPLING SYSTEM

The gas sampling system has three subsystems: direct atmospheric sampling, the gas chromatograph and the ACP sample line. The direct atmospheric sampling and the gas chromatograph are self-contained units sharing only the mass spectrometer. The ACP sample line is connected from outside the instrument and interfaces with both the gas chromatograph and the mass spectrometer. The direct atmospheric sampling and gas chromatograph share gas flow lines with a gas inlet port in the Huygens Probe Fore Dome at the Probe apex near the stagnation point and an outlet port at the minimum pressure point at the rear of the Probe. Metal ceramic devices seal inlet and outlet ports. All inlet and outlet lines are evacuated after instrument calibration prior to shipment. They will be opened in sequence by redundant pyrotechnic actuators after Probe entry and ejection of the Probe Front Shield.
2.2.1. Direct Atmospheric Sampling

Most of the composition measurements will be obtained from direct atmospheric sampling during descent. Ambient atmospheric gas is conducted through pressure-reducing devices (i.e., leaks) into the ion source, and a sample enrichment and scrubber cell will enhance trace constituent detection and rare gas analysis.

At an altitude of approximately 170 km when the Probe is ready for instrument deployment, i.e. all protective devices are jettisoned, the Atmospheric Inlet and Outlet will be opened to the atmosphere. The inlet port geometry is designed to allow ambient gas to enter from outside of the gas boundary layer. A dynamic pressure of about 70 Pa before parachute jettison and 10 Pa after will force atmospheric gas to flow close to the ion source through the sample system tubulation and manifolds. Small quantities of atmospheric gas will be introduced from the sample system into the ion source IS1 through fixed size leaks and removed at a constant rate by chemical getters and a sputter ion pump. Noble gases will be pumped only by the sputter ion pump and at a slower rate than the reactive gases, increasing the noble gas mixing ratio in the ion source relative to the atmosphere. Laboratory calibration will establish exactly the relationship between ambient and ion source partial pressures.

The gas leaks are arrays of glass capillaries located in the ion source. Typically, seven capillaries per leak are used with inside diameters ranging from 2 μm for the lowest conductance leak to 20 μm for the largest. Capillary arrays instead of single capillaries were chosen in order to reduce the chance of blockage by small aerosol particles. The gas conductances are selected so that the pressure in the ion source does not exceed $10^{-4}$ hPa in a nominal descent.

The full dynamic range of the mass spectrometer is best used when the ion source pressure is kept at the maximum operating value. Fixed-size leaks do not allow this to occur at all times because the ambient pressure increases during descent. The direct sampling is divided into two sections. This will prevent a large pressure change in the ion source and accommodate a purified noble gas and enrichment cell measurement. A pressure-time profile and measurement sequence are shown in Figure 4. In Figure 4a the change in ambient pressure is shown and predicted cloud or haze levels are also indicated. Nominal values from the Lellouch-Hunten model (Lellouch et al., 1997) of the atmosphere of Titan were used. The pressure variation in ion source IS1 is shown in Figure 4b. From time $t_0$ to time $t_1$ leak L1 will be opened by switching the microvalves VL1 and VZ (see schematic Figure 3). While the ambient atmosphere is sampled through leak L1, the enrichment cell EC will be charged. The enrichment cell adsorbs trace gases e.g. high boiling point hydrocarbons and nitriles but no nitrogen or noble gases. By opening valves VS7, VE and VV, gas flows through the cell until the evacuated volume ECV is filled. All remaining reactive gases except methane will then be removed by getter G3 after closing of valves VS7 and VV and opening VG.

The gas flow through leak L1 is discontinued after 30 minutes, at time $t_1$, by closing valves VL1 and VZ. The remaining gas in the ion source is pumped out
Figure 4. Pressure vs. time profiles of the ambient atmosphere and in the mass spectrometer ion sources during the Probe descent through the Titan’s atmosphere. (a) Ambient atmospheric pressure, possible cloud locations and sample enrichment cell and gas chromatograph sample collection times are also indicated. (b) Pressure in the direct sampling ion source. Noble gas and sample enrichment gas analyzer times are: Time t₀–t₁ 0–30 mins. Direct atmospheric sampling; Time t₁–t₂ 30–31:29 mins. Background; Time t₂–t₃ 31:29–33:00 Rare gas cell; Time t₃–t₄ 33:00–34:50 Rare gas and enrichment cells; Time t₄–t₅ 34:50–36:00 Instrument background. (c) ACP ion source dedicated sampling time. (d) Operating times of the three ion sources dedicated to the gas chromatographic columns.

leaving only background pressure which will be measured by the mass spectrometer. At time t₂ the enrichment cell will be isolated by closing valve VE and heated to desorb the collected trace gases. Simultaneously, the gas mixture residing between the valves VV, VE, VG and VL₃ will be introduced into the ion source IS₁ through L₃ for noble gas analysis. At time t₃ the gas content of the enrichment cell will be added to the gas mixture for analysis by opening valve VE. When the enrichment cell and noble gas analysis are complete at time t₄, the subsystem will be isolated from the ion source by closing valve VL₃ and background pressure is observed again. At time t₅, 36 minutes, direct leak L₂ will be activated by opening VL₂ until the end of the mission. Sampling for the first 30 minutes through leak L₁ will be continuous and at a high rate. The direct atmospheric sampling through leak L₂ will be interrupted repeatedly by sampling sequences for the analysis of elutents from the gas chromatographic columns and ACP products.
2.2.2. Gas Chromatographic Analysis

Gas chromatography allows, under suitable conditions, the gas phase separation of complex mixtures of hydrocarbons, nitriles and permanent gases including carbon monoxide. This technique has already been used successfully in planetary exploration (Raulin et al., 1992b).

A small amount of an unknown mixture of gases is introduced into a carrier gas stream which flows continuously into a specially prepared gas chromatograph column. Each component in the mixture, in the ideal case, elutes from the column outlet at a different time. A detector at the outlet gives a signal related to the quantity or concentration of the components of the gas mixture.

Difficulties in data interpretation result when universal detectors are used because the exact chemical composition of the elutent is not known. A mass spectrometer eliminates most of the difficulties (see illustration in Figure 1). Advantages and disadvantages of combined GCMS instrument techniques have been discussed in great detail in the technical literature (Watson, 1997; Kitson et al., 1996; McFadden, 1973); and the arguments apply to this application as well. One disadvantage is the increased complexity of the instrument which must be of particular concern here because of the specific mission environment. The short time available for sampling and analysis, long time reliability and severe limits placed on weight and power require special considerations.

The use of open capillary columns (Do and Raulin, 1989, 1990, 1992; de Vanssay et al., 1993; Aflalaye et al., 1995) and of packed columns (de Vanssay et al., 1994) were considered. Best instrument performance and moderate instrument complexity have to be balanced in this design. Three chromatographic columns with different properties are used and operated in parallel to cover the range of expected atmospheric species (Navale et al., 1998). One column will separate CO and N₂ and other stable gases. A second column will separate nitriles and other organics with up to three carbon atoms. A third column will provide the separation of C₃ through C₈ saturated and unsaturated hydrocarbons and nitriles of up to C₄. A silica steel micropacked GC column 2 m in length with 0.75 mm internal diameter (for column 1) and silica steel wall coated open tubular (WCOT) GC capillary columns 10 m and 14 m in length with 0.18 mm internal diameter, (for columns 2 and 3) were found to be most suitable. The columns are wound in a 178 mm diameter coil on high temperature foil heaters. A thermally isolated oven encloses each column to allow efficient heating. The columns will be operated at 0.18 MPa inlet pressure and the outlet is vented through a flow restrictor to the ambient atmosphere.

Hydrogen was selected as carrier gas because of efficient storage and pumping. It is stored in 100 g of hydride metal alloy enclosed in a stainless steel housing. The amount of hydrogen required for the GC operation, assuming 180 minutes descent time and a 50% reserve, is approximately 3 standard liters. The hydrogen carrier gas reservoir (CGR) will be equipped with an injection valve IV shown schematically in Figure 3. The valve is solenoid operated and similar in design to
the microvalves. The valve plunger punctures a diaphragm and initiates carrier gas flow. A miniaturized silicon diaphragm pressure sensor, PSH, is used to monitor the pressure in the CGR. A pressure regulator, PR, controls the flow through the flow restrictors and columns. For safety a burst diaphragm, BP, installed in the CGR is set to burst at 3 MPa.

The Probe does not spend sufficient time for repeated gas chromatographic analysis in the altitude region between 176 km and 60 km. To overcome this difficulty samples will be collected at specified times during the descent through this region of the atmosphere in sample volumes SV1 through SV3 for later analysis. In the lower atmosphere and near the surface, samples will be injected directly from the atmosphere into the carrier gas flow path of the GC.

At system initiation hydrogen carrier gas flows from the hydrogen reservoir CGR (see Figure 3), through the injection valve IV, pressure regulator PR, restrictor FR2 and valve VD4. After passing through sample injection valves VS5, VG1, 2, 3, the gas flow splits into the three GC columns. A fraction of the flow exiting the columns will be split off and conducted through capillary leak arrays, RL1, 2 and 3, into the ion sources. The remaining gas will be vented through valve VX and column restrictor CR.

The atmospheric samples collected in the sample volumes will be analyzed one at a time by first flushing the inlet manifold between valves VD1 and VD2 with carrier gas and then operating valve pairs VS1, VG1, etc. several milliseconds to allow the sample volume to be discharged into the carrier gas stream. The GC analysis time allowed per sample is about 10 minutes. Direct sample injection will be accomplished in a similar fashion by first closing VD1 and VD2 and injecting part of the trapped sample gas through valve VS5 by redirecting the carrier gas flow through VD3 for a short time interval. Injection of the ACP sample from the sample transfer manifold into the GC column will be accomplished through valve VS6 in a similar manner. A time profile of the complete GC sampling sequence is shown in Figure 4d.

2.3. AEROSOL COLLECTOR PYROLYSER ANALYSIS

The operation of the Aerosol Collector Pyrolyser (ACP) and details of the sample transfer are described in a separate paper (see Israel et al., this volume). The pyrolysis products will be provided through a sample transfer line made of 0.5 mm internal diameter nickel tube connected to an injection valve IVA (ACP Inlet in Figure 3) at the center of the instrument housing. Internally a feed tube connects to the GC inlet valve VS6, the direct inlet valve VL4 and to the outlet via valves VAA, VAB, and flow restrictor FRA.

The ACP line will be opened just prior to the first sample transfer. When gas flow has been established, sample gas analysis begins using the dedicated ion source IS2. After analysis is completed, sample gas in the ACP line is vented through the outlet and the line is refilled with the next sample. The sample for
the gas chromatograph is injected by opening valve VS6 for a short time interval to superimpose the sample on the carrier gas stream as described in the previous section. The time line for the ACP sampling is shown in Figure 4c.

2.4. POST SURFACE IMPACT ANALYSIS

It is likely that the Probe will continue to operate for a short time after surface impact. As the nature of the surface is not known, it is hard to predict the specific contact the Probe will make. The most probable landing position is expected to be upright, which is also optimum for the instrument. In case of a landing on a liquid surface, the heated inlet tube will be submerged in the liquid, which will rapidly evaporate in the inlet tube and the vapors will flow through the inlet lines. Rapid direct sampling through leak L2 will provide composition measurements of the vapor. In case of a landing on a solid surface, the surface will be heated locally by the inlet tube and volatized gases will flow through the inlet lines and be available for analysis.

GC analysis will be initiated through valve VS5, as described above, if the Probe survives for more than two minutes.

The surface sampling mode will be initiated by an altimeter signal shortly before surface impact.

2.5. ION SOURCES

Electron impact ionization is used in the miniaturized ion sources. A well collimated electron beam is directed through the ionization region into which the gas stream is conducted by the capillary leaks. The flow paths are short because the valves and capillary leaks are mounted directly on the ion sources. The electron guns have heated filaments of 0.075 mm diameter (97% tungsten, 3% rhenium) wire and require approximately 1 watt of power. The electron beam energies can be chosen from two pre-selected values (i.e., 25 eV or 70 eV) to permit species identification and discrimination by observing energy dependent fractionation. A typical electron beam current is 80 $\mu$A. Ions are focused and transmitted into a quadrupole switching lens assembly by multi-element ion lenses of small aperture. Quadrupole switching lenses are operated as ion beam deflectors. Any one of the five ion beams can be deflected by the switching lens into the quadrupole mass analyzer at any time. Switching is accomplished in microseconds by changing the bias voltages to the appropriate values for the ion source of choice. The ion source arrangement and the switching lens system are shown schematically in Figure 5a.

Sample gas decoupling of the ionization regions is achieved by differential pumping. The principle of sample decoupling is shown in a schematic diagram in Figure 5b. By designing the gas conductances $C$ such that their ratios $C_1/C_2$ and $C_1/C_3$ are approximately $10^3$ and $10^2$ respectively, the separation in partial pressures between ionization regions is $10^6$. For example, gas in ion source IS1 with a partial pressure of $10^{-6}$ hPa will be seen by the other ion sources as a partial
Figure 5. Illustrations of ion source configuration and schematic of differential vacuum pumping system.

Figure 6. An ion source showing the electron and ion focusing lenses. The overall height is 63 mm.

pressure of $10^{-12}$ hPa. The pressure in the quadrupole mass filter and detector region is below $10^{-6}$ hPa to eliminate ion scattering. The size of conductances $C_2$ is determined by the ion lens apertures which are designed to be long and narrow. The pumping speed of the getters and the sputter ion pumps determine the size of conductances $C_1$ and $C_4$. An ion source, showing the electron and ion lens arrangement and an ion source system showing the individual ion source and the switching lenses in the partially assembled ion source housing are seen in the photograph in Figure 6 and Figure 7, respectively.
2.6. QUADRUPOLE MASS FILTER AND ION DETECTOR

The quadrupole mass filter accepts the ion beam generated by the ion sources transmitting only ions of a chosen charge to mass ratio. Detailed descriptions of the operating principle of quadrupole mass filters can be found in the technical literature (e.g., Dawson, 1976). The selected ion beams are focused on two secondary electron multiplier ion detectors. The quadrupole rods are excited by radio frequency ($V_{AC}$) and direct current ($V_{DC}$) potentials which together create a dynamic electric field within the quadrupole region that controls the transmitted mass (m/e value) and the resolution. A mass scan is executed by varying the radio frequency potential $V_{AC}$ to satisfy the relationship $M = 0.55 \frac{V_{AC}}{f^2}$ where $V_{AC}$ is in volts, $f$ in MHz, and $M$ in Dalton. The resolution will be controlled over the mass range (2–141 Dalton) by programming the ratio of $V_{DC}$ to $V_{AC}$ to maintain the resolving power defined by a crosstalk criterion appropriate for that mass range. The ion transmission efficiency will be 100% resulting in flat top mass peaks over the mass range of interest. This allows a mass scan mode in which each mass is monitored by a single step.

In another operating mode, the DC voltage will be reduced to zero which creates a high pass filter giving the sum of all masses greater than, for example, 2 Dalton. This feature allows the use of the mass spectrometer as a nonspecific GC-detector.
Figure 8. The ion detector assembly, showing the entrance lenses, the support structure, and the location of the continuous channel secondary electron multipliers. The overall length is 110 mm.

excluding the detection of the abundant hydrogen ions produced by the GC carrier gas.

The ions passing the mass filter will be detected by a pair of continuous dynode secondary electron multipliers with effective entrance aperture sizes differing by a factor of $3 \times 10^3$. Charge pulses at the anodes of the secondary electron multipliers are amplified and counted. The background noise of the secondary electron multipliers is approximately one count per minute. The upper count rate is limited to approximately $3 \times 10^7$ counts/s by the pulse width of the anode pulses of the secondary electron multipliers. The instrument sensitivity for 100% ion transmission is approximately $1 \times 10^{14}$ counts per sec per hPa. Secondary electron multiplier background count rates of one count per minute or less yields a detection threshold of $1.7 \times 10^{-16}$ hPa partial pressure in the ion source region for a signal to background count ratio of unity. The maximum pressure level in the ionization region is limited by mean free path conditions to about $10^{-3}$ hPa. In the low mass range (<46 Dalton) the lower detection limit is often not realizable because of background gases emitted from the surrounding surfaces or because of interference at some mass numbers from other gases present in high concentrations. Typical background gases in the ion source are H$_2$, CH$_4$, H$_2$O, CO, and CO$_2$. The exact sensitivity is established by calibration and varies with species because of differing ionization efficiencies for neutrals and the conversion efficiency at the secondary electron multiplier. The detector assembly, consisting of the entrance
Lenses, support structure and the continuous channel secondary electron multiplier, is shown in Figure 8.

2.7. PUMPING SYSTEMS

The pumps establish a flow of sample gas through the ion sources when a sampling device is opened. They remove the gas from the ion source regions after analysis and closure. Non-evaporable getters and sputter ion pumps are used because they are easily adapted to space flight systems. The sputter ion pumps depend only on electrical power for operation and work without moving parts. Hydrogen is sorbed reversibly at a very high rate and in very large quantities by the getter material, while nitrogen is efficiently pumped by irreversible bonding. The getter material is sintered titanium and molybdenum powder. The sorption capacity for hydrogen is \( \sim 20 \text{ hPa liter/g} \) for an equilibrium pressure of \( 10^{-4} \text{ hPa} \) at a worst case temperature of 200 °C. More favorable conditions exist at the expected operating temperature of \(<100^\circ\text{C}\). The getters, after activation in a vacuum, will remain activated indefinitely at room temperature. The components of a getter pump assembly consisting of the getter wafers, heat shields and the housing are shown in Figure 9.

Uncertainties exist about the concentration of argon and methane in Titan’s atmosphere. These gases will be pumped by sputter ion pumps. Synthesis of hydrocarbons in the sputter ion pumps is minimized by special processing of the cathodes. A partially assembled sputter ion pump, the anode, cathode and housing without magnet assembly, is shown in Figure 10.

2.8. ELECTRONIC SYSTEM

The electronics system block diagram is shown in Figure 11. The various subsystems required to control the sample flow, to power the sensor and ion detectors and process the output signal are under control of a microcomputer. Instrument potentials are produced by a number of programmable, floating-secondary DC-DC converters that are configured for each measurement. Telemetry and command streams connect to the spacecraft through redundant serial interfaces. The electronics system provides the flexibility to accommodate the diverse measurement and testing requirements.

The pyrotechnic devices used to break the ceramic seal in the sample inlet and outlet systems are fired by the Probe pyro bus. The sample-sequencing microvalves are powered by switching circuits under microcomputer control. Each of the five ion source supplies contains a filament emission regulator and electrode supply to provide the required voltages and currents. Fast switching of the ion beam deflectors is accomplished by high-speed bipolar electronic switches.

The quadrupole \( V_{AC} \) and \( V_{DC} \) potentials are generated in a dedicated supply. Prior to each measurement the microcomputer calculates the proper amplitudes and frequency step for the \( V_{AC} \) potential. An auto-tune algorithm is incorporated
Figure 9. Components of a getter pump assembly consisting of getter wafers, heat shields and housing. The wafer diameter is 25 mm.

into the control software to assure that changes such as component aging in the supply do not affect mass tuning and resolution.

Current pulses from the secondary electron multiplier are amplified by a low-noise trans-resistance amplifier and counted. The counts are held in a 32-bit register, which is then read by the microcomputer. A parallel electrometer channel measures multiplier current when the maximum count rate is approached allowing an inflight gain check.

A 1750A microprocessor controls and sequences the instrument in accordance with software instructions contained in programmable read-only memory (PROM). Control of the many subsystems is accomplished by writing to a separate, high-speed sensor data bus. The instrument software was written in a high-level language (i.e., Ada) whenever possible and in assembly language when speed is crucial. Code has been developed in a modular, top-down manner to increase test-
Figure 10. A partially assembled sputter ion pump, showing the anode grid structure, the cathode and the housing. (Indicated dimensions are in inches).

Figure 11. Electronics block diagram showing major digital and analog circuit subsystems.
ability and improve maintainability. The instrument will receive commands and transmit science and housekeeping data through the Probe Command and Data Management System (CDMS) interfaces.

Power to the instrument is derived from the common +28 V spacecraft bus. Inrush current limiting and overload protection is provided in the main power converter. The spacecraft bus voltage is transformed by a DC-DC converter to a number of standard secondary potentials that power the subsystems. To minimize size and weight of the electronics system approximately 80% of the electronic circuits are packaged in hybrids. A typical hybrid circuit, the micro-sequencer, is shown in Figure 12.

2.9. MECHANICAL CONFIGURATION

The mechanical layout of the instrument is shown in Figures 13 and 14. The ion source and mass analyzer assembly constitute the main body of the sensor system. Getter pumps and sputter ion pumps are directly mounted to the ion sources at the upper part of the assembly for compactness. The GC columns and the gas sampling system are concentrically arranged around the ion source assembly. The gas inlet tube, shown in Figure 13, extends forward to penetrate through the fore dome. The electronics system is located below the gas sampling system. The electronics support structure and the electronic circuit boards are shown in Figure 14. The electronics support structure is made of aluminum alloy and is attached to the center section of the instrument housing.

The instrument housing is also made of aluminum alloy and consists of three sections as shown in Figure 15. The lower housing encloses the sampling system and the ion sources. It also provides the inlet port interface with the fore dome of
the Probe. The upper housing covers the electronics system. The center housing provides the mounting support for all instrument components and most external interfaces. The housing is hermetically sealed by metal seals. The overall helium leak rates of $<10^{-8} \text{ hPa l s}^{-1}$ is sufficient to maintain the housing pressurized for more than ten years. The housing is designed to withstand 0.15 MPa internal pressurization and an external pressure of 0.15 MPa above the internal pressure. For flight, the housing is filled with dry nitrogen to 0.12 MPa.

The instrument is mounted on the Experiment Platform of the Probe (see Lebreton et al., Figure 10, this issue) via a flange at the center housing. The sample inlet line penetrates the Probe fore dome (see Lebreton et al., Figure 11, this issue) near the stagnation point outside of the boundary layer of the gas flow around the Probe body. The sample outlet port is at the rear section of the housing. The mounting position of the Aerosol Collector Pyrolyser on the Experiment Platform is adjacent to the GCMS for efficient sample transfer.
Figure 14. The assembled electronics package and support structure. Shown in front is the Programmable Read-Only Memory (PROM) board.

Figure 15. The assembled GCMS. The lower housing encloses the sampling system and the ion sources, while the upper housing covers the electronics system. The gas inlet port is at the dome of the lower housing. The sample gas is vented through a fiberglass tube toward the rear of the Probe. The housing is hermetically sealed and pressurized to 0.12 MPa during flight. (Indicated dimensions are in cm).
2.10. SAMPLING STRATEGY

Throughout the entire descent of the Huygens Probe through the atmosphere of Titan, the GCMS will perform a single charge to mass ratio measurement each 5 ms. A full scan will be performed each 936.5 ms selected from one of the five ion sources. The mass range measured with each ion source is determined by a stored sequence. The sequence also determines which ion sources are enabled for sampling during various stages of the descent. The sequence of measurements is shown in Figure 4. During the first 36 minutes of the descent, the direct inlet into a mass spectrometer ion source is analyzed, and atmospheric samples are collected for subsequent analysis by the GCMS. During the same interval, an atmospheric sample is processed to enrich the noble gas content to extend the sensitivity of the noble gas ratio analysis. During the descent interval between 40 and 95 minutes, the collected samples are analyzed sequentially by the GCMS as indicated in Figure 4, panel d. The output of the ACP is analyzed both directly by the MS and by the GCMS during intervening periods. In each of these analyses, the characteristics of the mass scan can be programmed.

Each integral mass number from 2 to 141 Dalton is sampled sequentially. During all mass scans, the total output from each ion source (with carrier gas rejected) will be measured. The purpose is to provide a continuous record of the total density in each ion source and to select the ion source to be sampled when an unknown gas mixture is flowing through the gas chromatographic columns. An illustration of the Full Scan is shown in Figure 16.

For the direct mass spectrometer measurements, 936.5 ms are required to complete a Full Scan. This resolution is more than adequate to define the atmospheric profile defined by the descent rate and will be used. The operation of the instrument when three GC columns are simultaneously on range is shown in Figure 17.

A diagnostic scan of the full mass range in 1/8 Dalton increments will be made at times during the descent when the rate of change of the atmospheric samples is lowest. This diagnostic scan and others will be interleaved with the atmospheric measurements.

The output of the Aerosol Collector Pyrolyser (ACP) will be sampled both directly and through the GC columns at the appropriate time in the descent as outlined...
in the accompanying paper describing the ACP and its operation. The same mass scan capabilities available for the GCMS measurements are available to the ACP instrument.

2.11. DATA FORMAT

The GCMS is intrinsically capable of generating much more data than can be transmitted within the bandwidth allocated to the instrument. Counter data are produced as two 16-bit words each integration period, one from the high sensitivity and one from the low sensitivity secondary electron multiplier. Only data from one counter are selected for telemetry. The data are compressed by taking the square root of the counter contents when the pulse count rate is $\geq 2.56 \times 10^4$ per second to yield 8 bits of counter data per integration period with one bit added for counter identification.

Even with data compression, science and housekeeping data are produced at approximately twice the available rate of a single telemetry channel assigned to the instrument. For this reason, the data will be sent alternately to the two (redundant) channels. If both telemetry channels function, all data will be recovered. If one channel fails, the effect will be to reduce the temporal resolution of the science data.

The science and housekeeping data are configured as subpackets within the standard Huygens Probe telemetry packet. The GCMS is allotted 15 telemetry packets per 16-second cycle; each packet is 126 octets in length, but seven of those...
are reserved for packet header and error correction. This results in an actual data rate available to the GCMS of 885 bits per second per channel. 

Science Data Subpacket: Data from one mass scan are packetized along with time tag information and are sent to telemetry once every 936.5 msec. These subpackets contain 1488 bits, for a data rate of 1589 bits per second.

Housekeeping Data Subpackets: Three different subpackets are used for low, medium, and high-speed housekeeping data. The total of the three types is approximately 100 bits per second.

Acknowledge Subpackets: These are used to send confirmation of external events such as ACP sync pulses and telecommands. Each subpacket consists of 32 bits.

Subpacket synchronization and descent sequence monitoring data consume an additional 52 bits per second (for both channels). This results in a total GCMS data production rate of approximately 1741 bits per second, versus the available telemetry of 1770 bits per second for two channels used alternately. If the Probe retrieves data faster than science data are being produced, the GCMS will insert idle subpackets which contain housekeeping data.

3. Instrument Calibration

In order to determine the overall system transfer characteristics, the instrument was calibrated on a dynamic flow system where the time, pressure and temperature profile to be encountered during the Probe descent was simulated. Gas mixtures containing known mixing ratios of gases were introduced into the high pressure flow system of the sample inlet system of the flight instrument. The design of the sample inlet system allows instrument calibration as it is used in flight. Components with limited operational lifetime i.e. getter materials and the sputter ion pumps were replaced after calibration. All pumps are designed to operate in a conductance limited mode so that small changes in pump performance will have a negligible effect on the instrument transfer function.

The calibration system consists of two parts: the high pressure gas flow and sample mixing system and the ultra high vacuum pumping stand. The high pressure gas flow and sample mixing system allow for the preparation and introduction into the unit of known gas mixtures at representative pressures and temperatures.

The ultra-high vacuum pumping stand is used to evacuate the ion sources, analyzer, detector, sample inlet system and the gas chromatograph subsystems. It is needed for the calibration (i.e., bakeout, getter activation) and tests of the instrument and also for final processing before pinch off. To assure isolation of each subsystem from the others, each subsystem requires its own pumping system, i.e., each ion source, the analyzer and detector subsystem, the direct sampling GC and enrichment cells were connected to separate pumping stations. During calibration the pumping station could be isolated from the instrument by bakable, miniature, ultra high vacuum valves.
A complete MS spectrum from 1–144 Daltons recorded during characterization is shown (Figure 18). A noble gas mixture listed in Table 5 was used for this sample.

A schematic diagram of the calibration system is shown in Figure 19. The flight instrument inlet and outlet ports are connected directly with vacuum flanges to the appropriate terminals of the high pressure gas flow system. The flow lines were thermally isolated and the gas temperature was controlled by heaters and heat exchangers. Absolute system pressure and the differential pressure across the inlet were monitored with precision pressure gauges. The gas flow was adjusted so that the differential pressure was equal to the Probe stagnation pressure expected in flight. Trace gas mixtures were added through the calibration gas line or they were introduced from prepared gas tanks with certified mixing ratios. The exact quantity of added calibration gas was determined by measuring the gas flow with flow meters and the pressure at the injection port.

Following the instrument measurement sequence, gas mixtures were introduced into the respective ion source and the GC subsystem at the appropriate times and pressure level consistent with the expected descent pressure and time profile. The separate ACP-GCMS compatibility test was performed to assure proper timing and sample transfer.
3.1. GAS MIXTURES USED IN GCMS SENSOR CHARACTERIZATION

In addition to the pure gases used for initial characterization, i.e., N₂, CH₄, H₂, Table 5 gives the certified gas mixtures that were utilized during the final calibration of the GCMS.

3.2. POST-LAUNCH CALIBRATION

The GCMS Flight Spare model together with the ACP Flight Spare model will be calibrated prior to Titan encounter following the same process as was used for the Flight Units. Since more time will be available, additional calibration gas mixtures will also be considered. Finally, the spare instruments and the calibration facility will be maintained and prepared for post encounter calibration and laboratory reproduction of the flight data in order to aid in the interpretation of the flight data.

4. Post Launch Performance and Testing

A full post-launch checkout of the GCMS was performed on 23 October 1997. Subsequent checkouts were performed approximately every six months. The operation was completely nominal in all cases. All housekeeping data and science data
TABLE 5
Calibration gas mixtures

a. Nitrogen (N$_2$) mixture with trace amounts of various light hydrocarbons and other components:

~100 ppm each of

- methane (CH$_4$)
- ethyne (C$_2$H$_2$)
- nbutane (C$_4$H$_{10}$)
- trans2butene (C$_4$H$_8$)
- carbon dioxide (CO$_2$)

~100 ppm each of

- ethane (C$_2$H$_6$)
- propane (C$_3$H$_8$)
- cis2butene (C$_4$H$_8$)
- 1,3butadiene (C$_4$H$_6$)
- carbon monoxide (CO)

- ethene (C$_2$H$_4$)
- propene (C$_3$H$_6$)
- 1butene (C$_4$H$_8$)
- 1,3butadiene (C$_4$H$_6$)
- pentene (C$_5$H$_{10}$)

b. Nitrogen (N$_2$) mixture with trace amounts of various heavy hydrocarbons:

~100 ppm each of

- 2methylpropane (C$_4$H$_{10}$)
- benzene (C$_6$H$_6$)
- 3methyl,lbutene

~100 ppm each of

- 2methylbutane (C$_5$H$_{12}$)
- toluene (C$_7$H$_8$)
- 2,2dimethyl propane (C$_5$H$_{12}$)

- isohexane (C$_6$H$_{14}$)
- oxylene (C$_8$H$_{10}$)

~50 ppm each of xenon, krypton, argon

~250 ppm neon

~575 ppm helium

c. Nitrogen (N$_2$) mixture with trace amounts of various noble gases:

~50 ppm each of xenon, krypton, argon

~250 ppm neon

~575 ppm helium

d. Nitrogen (N$_2$) with 10% argon

e. Helium with ~1000 ppm CO

f. Helium mixture with trace amounts of various hydrocarbons:

~150 ppm each of

- methane (CH$_4$)
- 2methylpropane (C$_4$H$_{10}$)
- propene (C$_3$H$_6$)

~150 ppm each of

- ethane (C$_2$H$_6$)
- 1hexene (C$_6$H$_{12}$)
- propane (C$_3$H$_8$)

- ethene (C$_2$H$_4$)
- ethyne (C$_2$H$_2$)

~5% each of xenon and krypton

~8% argon

~25% neon

g. Helium mixture with large amounts of various noble gases:

~5% each of xenon and krypton

~8% argon

~25% neon

h. Pure nitrogen (N$_2$)

i. Pure hydrogen (H$_2$)
were unchanged compared to pre-launch values. The synchronizing pulses from the ACP were received correctly.

Future instrument test during the cruise time will be conducted approximately every six months until entry into Titan’s atmosphere in 2005. Tuning of the mass spectrometer and vacuum integrity are two of the critical items to be checked. Periodic turn on of the sputter ion pumps is a cautionary step to remove small amounts of residual noble gases, primarily $^{40}$Ar, that are desorbed slowly from surfaces or microscopic cracks where they were trapped during the fabrication of the instrument.

5. Expected Results and Measurement Accuracy

The objective of this experiment, as stated above, is the measurement of the chemical composition of the atmosphere of Titan, i.e., the mixing ratio of the major and minor constituents and isotopic ratios when accessible during the Probe descent. The basic accuracy of the measurements and the detection limits of trace gases are determined by the sensitivity of the instrument, the maximum operating pressure of the ion source and the dynamic range of the mass spectrometer. The ion source sensitivity varies with species depending on the ionization cross sections, for example, the sensitivity is about $1 \times 10^{14}$ counts/s/hPa for molecular nitrogen. Since mixing ratios with respect to nitrogen will be determined, the relative sensitivity to nitrogen has to be obtained by calibration with the relevant gas mixtures.

The background count rate of the secondary electron multiplier ion detectors is less than 0.1 counts per second. An ion source pressure of $5 \times 10^{-4}$ hPa will be reached at the end of the direct leak 1 and leak 2 measurement phases and during the enrichment cell analysis periods. The exact ion source pressure cannot, of course, be predicted for Ion Source 1 since assumptions had to be made about the descent pressure-time profiles. A maximum ion source pressure of $1 \times 10^{-3}$ hPa is acceptable.

In the spectral regions where the maximum dynamic range of the instrument can be used, the accuracy will be limited by pulse counting statistics at low mixing ratios. At large mixing ratios where counting statistics become negligible, the measurement accuracy will be $\pm 2\%$ for peak height ratio measurements of adjacent mass peaks and $\pm 10\%$ for peak height ratios with wide mass separation. This is because of the error accumulation resulting from calibration uncertainties, small temperature drifts in the supply electronics and change in the gain of the secondary electron multipliers.

In the analysis of gas mixtures, ambiguities in species identification can occur and additional accuracy limitations are expected for species with overlapping mass spectra. Some ambiguities will be resolved by using different energies for the ionizing electron beam. This will only be effective for species with strongly
differing ionization potentials and energy dependent ionization and dissociation cross sections.

The isotopic ratios of hydrogen, carbon and nitrogen will be obtained from the direct methane and nitrogen measurements. The noble gas isotopic ratios will be determined most accurately from the noble gas cell data.

Enrichment factors of 100 in the enrichment cells are expected for ethane and propane and of 500 for higher order hydrocarbons. Krypton and xenon will be enriched approximately 10 times and 100 times, respectively. The actual accuracy can only be established after the data are received and analyzed, because the spectral interference depends on the actual data and background gas uncertainties resulting from the long storage and cruise time.

Mixtures of most low molecular weight hydrocarbons (\(<C_4\)) and nitriles will be separated by the GC columns and subsequent identification will not be ambiguous if full separation can be achieved. Overlapping eluted peaks will require more careful analysis including simulation on the laboratory calibration system using the Flight Spare instrument.

The basic sensitivity and detector thresholds for the ACP and GC measurements are the same as for the direct measurement. However, since both ACP and GC subsystems are sampling only at several specific times during the Probe descent, a continuous altitude profile of the constituents will not be obtained.

Space flight constraints of low weight, power, and volume put restrictions on the size of the vacuum pumps and thus limit the admissible sample size and the achievable background pressure. The available power for the RF generator for the quadrupole puts limits on the achievable mass resolution. The short descent time also restricts the chance for extensive signal averaging. This is particularly important for traces of reactive gases which may initially be absorbed or decomposed on the surfaces of the sample inlet system before they reach the ionization region. Reactions of hydrogen with loosely bound carbon or oxygen on the vacuum surfaces in the ion source regions cause the formation of methane and water vapor. This effect was significantly suppressed by surface processing, e.g., carbon depletion and formation of stable surface oxides. Methane and water vapor buildup in a hydrogen atmosphere are, however, still limiting the measurement accuracy for these gases in the GC system. IS1 and IS2 will not be affected, of course, by \(H_2\).

Water vapor measurements are not expected given mixing ratios of \(<10^{-9}\) and the inherent water vapor background in the instrument. Other gases causing chemical noise are carbon monoxide, carbon dioxide and ethane. Carbon monoxide and carbon dioxide form a constant background of several hundred counts per second which does not appear to change significantly when hydrogen enters the ion source. Ethane, on the other hand, does not occur in the background spectrum prior to exposure to hydrogen but it appears in small quantities of 1 ppmv levels when hydrogen enters the ion source. This background level can conceivably change in flight depending on its origin. If ethane is formed in a similar method as methane the background is expected to be the same as during the laboratory tests. Should
ethane slowly accumulate on the vacuum surfaces and be desorbed when hydrogen is introduced, the ethane background could become larger or smaller depending on which process, outgassing or pumping, dominates over the long time period of the cruise phase of the mission. The background level of ethane will ultimately determine the detection threshold of gases with similar fragmentation patterns e.g., ethylene and acetylene.

No background gases or chemical noise are expected above mass 44 at high ion source pressures. Hence constituent measurement accuracy in this region is expected to be determined by the statistical uncertainties associated with the respective sampling times at low concentrations or by the uncertainties caused by temperature drift, etc., to ±10% as stated above at large concentration levels. Examples of gases which will be detected in this higher, chemically cleaner mass range are krypton, xenon and the higher molecular weight hydrocarbons.

Evaporating cloud droplets of methane or other volatile compounds are expected to be detectable, although quantitative calibration was not possible because facilities to produce droplets in known quantities and size were not available during the calibration period.

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Galileo Electro Optics, Sturbridge, MA (secondary electron multipliers); Kulite Semiconductor Products, Leonia, NJ, (pressure sensor); Restek Corp., Bellefonte, PA (gas columns); SAES Getters, Colorado Springs, CO (getter material); Supelco, Bellefonte, PA (enrichment cell material); and Teledyne Electronic Technologies, Marina del Rey, CA (hybrids).

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HUYGENS’ SURFACE SCIENCE PACKAGE

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Abstract. The design and performance of the Surface Science Package (SSP) on the Huygens probe are discussed. This instrument consists of nine separate sensors that are designed to measure a wide range of physical properties of Titan’s lower atmosphere, surface, and sub-surface. By measuring a number of physical properties of the surface it is expected that the SSP will be able to constrain the inferred composition and structure of the moon’s near-surface environment. Although the SSP is primarily designed to sense properties of the surface, some of its sensors will also make measurements of the atmosphere along the probe’s entry path and will complement the data gathered by other experiments on the Huygens probe.

1. The Surface of Titan

Titan’s surface presents us with the largest single unexplored area in the entire Solar System. Due to the ubiquitous haze layers between 200 and 700 km altitudes, traditional imaging in the visible part of the spectrum has not allowed any direct observation of this surface. Voyager 1, for example, flew past Titan at a minimum distance of 4000 km, in 1980. None of the images that were taken by the craft revealed anything other than a slight asymmetry between the northern and southern hemispheres, and a faint north polar ‘hood’ (B.A. Smith et al. 1981). More recently, however, observations made by P.H. Smith et al. (1996) with the Hubble Space Telescope (HST) and work by Combes et al. (1997) using the European Southern Observatory (ESO) at infra-red wavelengths have suggested that the surface can be detected with low spatial resolution (hundreds of kilometres). These observations show that regions of enhanced brightness can be repeatably detected in particular regions. The implications of these data for the surface of Titan are not clear, but they strongly suggest that Titan’s surface, and in particular the region around the predicted landing site of the Huygens probe, is not homogenous.

Despite the lack of direct information from Voyager about the surface, a wealth of data was gathered about the atmosphere, including density and temperature profiles down to the surface. Analysis of these observations implied that the atmospheric methane would be lost, on a relatively short timescale, by photolysis and subsequent exospheric escape (Yung et al. 1984). If the atmosphere is a long-
lived phenomenon, and as suggested by Lorenz et al. (1997), this is not yet clear, then the satellite ought to hold a reservoir of methane to replenish that which is lost due to photochemical conversion. Methane could exist as a liquid at the prevailing surface conditions. This has led to the suggestion that the surface of Titan may contain significant quantities of mixtures of liquid methane and ethane, which is one of the first products of methane’s photolysis, plus less significant proportions of higher order hydrocarbons (Lunine et al. 1983). The form that such a store of liquid might take is not easily determined; the models have ranged from global oceans to subsurface aquifers and it appears that no single simple model can satisfy all of the constraints. A comprehensive review by Lunine (1994) compares the dominant models and he argues that a partially buried or disconnected ‘ocean’ presents the least inconsistencies.

The original Titan probe studies did not include a significant surface science capability. However, as the studies progressed, it was realised that surface survival was possible and thus the Phase A study included a small experiment package comprising impact deceleration and refractive index measurements (‘Huygens phase A study’, 1988). The Surface Science Package (SSP) proposed in response to the original announcement of opportunity, included an X-ray fluorescence spectrometer (XFS) design so that the surface’s elemental composition could be measured. However, when the SSP was selected in 1990 the XFS was excluded, primarily for budgetary reasons. However, many more properties are detectable by the present SSP, which has a wider complement of sensors, than originally envisaged in the Phase A design.

The SSP was proposed at a time (1990) when models involving significant bodies of surface liquid were perhaps more prevalent than at present, so the suite of sensors was biased towards a liquid landing scenario. However, the philosophy behind the SSP has always been that the sensors would be able to give useful data in the event of either a solid or liquid landing. This is achieved by making as many different measurements of the surface as possible within the mass and power constraints of the experiment’s allocated budget. In the phase A design, surface composition would have been inferred, in the case of a solid landing, by XFS and for a liquid impact the various properties measured, such as refractive index and thermal conductivity, would have constrained the composition (Lorenz 1994, Zarnecki et al. 1997).

It must be stressed that SSP will not operate in isolation, indeed other instruments on the Huygens probe and on the Cassini orbiter will provide measurements of properties that coarsely overlap those made by the SSP. For example, although the SSP performs its function over a very small region of the surface in the probe’s landing footprint, the Descent Imager and Spectral Radiometer (DISR) will probably image the SSP’s working area several times in the final seconds of the descent (Tomasko et al. 1997). A visual comparison of the region sensed by the SSP with the wider landscape observed by the DISR would enable an estimate to be made of how common the SSP’s measurements are in the wider surface. In addition,
DISR will switch to a mode taking near-IR spectra of the impact area during the terminal part of the descent, which will provide an important correlative data set for the SSP studies. By combining the results from the SSP with those gathered from other sensors, which operate at different spatial scales and different altitudes, a coherent model could be constructed for the make-up and structure of Titan’s atmosphere and surface within the compass of the probe’s descent path.

2. The SSP and its Sensors

Titan provides a challenging set of environmental conditions to the spacecraft engineer. During its descent the Huygens probe will encounter temperatures as low as 75 K and, uniquely for planetary probes, it will have to cope with the possibility of impact with a liquid surface. The latter possibility meant that the SSP was designed such that all of the sensing heads have relatively free access to a cavity that would be flooded by the surface liquid. Considerable care has been taken in the calibration of the SSP’s sensors. A cryogenic calibration system has been built so that the devices can be operated in liquid and gaseous hydrocarbon media at temperatures identical to those that the Huygens probe is expected to encounter in its flight mission (Garry and Zarnecki, 1996a). The flight model calibration programme has concentrated on the use of methane and ethane for the ‘ocean’ simulations, and gaseous nitrogen, methane, ethane, and argon for modelling the descent phase. More complicated mixtures of liquids and gases will be produced in future in order to test the flight spare sensors.
TABLE I

SSP operating modes and allocated data rate during the Huygens’ descent; the bandwidth allocated to the SSP may be increased in the event of the failure of another experiment.

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Time from entry ( (t_0) ) (min)</th>
<th>SSP Mode</th>
<th>SSP science data allocation ( \text{bit s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>1</td>
<td>Mode 1: Upper atmosphere</td>
<td>189</td>
</tr>
<tr>
<td>130</td>
<td>10</td>
<td>Mode 2: Mid atmosphere</td>
<td>504</td>
</tr>
<tr>
<td>18</td>
<td>85</td>
<td>Mode 3: Lower atmosphere</td>
<td>693</td>
</tr>
<tr>
<td>7</td>
<td>116</td>
<td>Mode 4: Proximity</td>
<td>693</td>
</tr>
<tr>
<td>0</td>
<td>147</td>
<td>Mode 5: Surface</td>
<td>693</td>
</tr>
<tr>
<td>0</td>
<td>150</td>
<td>Mode 6: Extended surface</td>
<td>693</td>
</tr>
</tbody>
</table>

The SSP is exposed to the medium surrounding Huygens by way of an aperture in the fore-dome. The leading rim of the experiment is sealed to the fore-dome with a flexible metal and Kapton bellows to prevent the interior of the probe from being excessively cooled by Titan’s atmosphere. Layers of foam insulation around the SSP structure prevent too much heat from being lost from the probe via the SSP walls. The fluid that passes into the mouth of the SSP cavity is vented through a thin tube that opens out on the topside of the probe; this allows Titan’s atmosphere or liquid surface to enter the cavity and provides a representative sample medium during the descent. The electronic support equipment for the SSP, in common with the other experiments on Huygens, is carried on a dedicated electronics platform within the probe.

The triggering of a pre-set deceleration g-switch during the probe’s entry trajectory activates the Huygens probe payload. A backup timer is provided to ensure that the equipment is awoken in the event of a failure of the deceleration sensor. It is expected that in the nominal flight mission the probe will begin its atmospheric operation at an altitude of around 160 km, and a chart of the SSP’s operating modes is shown in table I.

A brief description of the design and of each of the SSP’s sensors is given below. To illustrate the attitude of each sensor with respect to the probe a directional cone is shown towards the bottom of each figure pointing along the probe’s upward axis.

2.1. ACCELEROMETER EXTERNAL (ACC-E)

The accelerometer subsystem is designed to characterise the immediate surface of the landing site by recording the dynamic response of two devices mounted in different positions on the probe. One of the sensors, discussed by Lorenz et al. (1994), is designed to sense the force exerted on a pylon that protrudes from the
foredome aperture. The force is sensed by a piezoelectric ceramic element that is mounted between a hemispherical titanium alloy head and the pylon shaft. If Huygens lands on a relatively uniform surface the ACC-E penetrometer will be smoothly driven into the surface material until the probe’s fore-dome strikes the surface, bringing it to a halt. During the impact process the ACC-E is sampled at a rate of 10 kHz, giving it an effective depth resolution of 1 mm for a nominal mission impact speed of 5 m s\(^{-1}\).

The low mass of ACC-E’s titanium head means that the sensor has an excellent high frequency response to relatively low amplitude impulses. This responsivity allows the granular structure of an aggregated solid to be detected. Laboratory calibration tests of the ACC-E have shown that the device can distinguish between materials such as fine sands, grits, and coarse gravel (Lorenz et al., 1994). Although the ACC-E measures aspects of the surface’s mechanical properties at effectively a single point location, this information can be combined with images of the impact site gained by the Descent Imager and Spectral Radiometer (DISR) to provide a holistic interpretation for the ACC-E’s measurement of the surface’s mechanical properties.

2.2. ACCELEROMETER INTERNAL (ACC-I)

A single commercially available accelerometer forms the second part of the ACC sensor. This device is mounted on a foot of the SSP electronics box, which is fixed to the upper experiment platform. The ACC-I provides information about the vertical non-static accelerations experienced by the entire probe.

If the probe strikes a solid surface the prime role of the ACC-I is that of determining the compressive properties of the surface at the probe’s impact site. Two extreme cases, normal impact with a perfectly stiff solid, and an oblique landing in a fluid body of both low density and low viscosity bound the range of decelerations that the probe may experience. Although neither of these scenarios is likely, indeed
the first example would cause significant damage to the probe’s structure, the ACC-I has a dynamic range of $-100\, \text{g}$ to $+100\, \text{g}$ and a sampling precision of 12 bits, which means that the sensor has minimum resolution of $0.5\, \text{m s}^{-2}$.

2.3. ACOUSTIC PROPERTIES INSTRUMENT – SONAR (API-S)

Like the ACC subsystem, the API has two separate parts. The first of these is an active sonar system (API-Sonar) mounted on the front of the Top Hat cavity pointing downwards. This sensor will measure the effective acoustic cross-section of the medium within its field of view at a wavelength of around 13 mm. Each echo is sampled at a rate of 1 kHz, and during the final section of the probe’s descent this sensor may be able to provide information about the topography of the landing site with a vertical precision of around 0.1 m. In the case of a liquid touchdown the API-S may also be able to provide lower bounds to the depth of the liquid in which it has landed. During the probe’s descent the API-S is not expected to detect aerosols of condensed hydrocarbons, since the global average number density and size of such bodies, as calculated by Toon et al. (1992), is believed to be too small to present a detectable cross-section to the sensor at any altitude. This does not preclude the possibility of there being local enhancements of both the population and size of air-borne bodies such as raindrops, which may be detected (Lorenz 1993).
In the final few hundred metres of Huygens’ trajectory the API-S will be sufficiently close to the surface for it to detect the back-scattered echo from the surface beneath it. Software simulations of the API-S approaching various surfaces suggest that it is possible to discriminate between surface morphologies on the basis of the total range of their relief within the sounder’s footprint with a precision of around 10 m (Garry and Zarnecki, 1996b).

Following the impact of the probe with a liquid body the API-S will act as a depth sounder, using information gathered from the Acoustic Properties Instrument-Velocimeter (API-V) on the speed of sound in the medium. In comparison to its atmospheric operation the API-S operates with an increased efficiency when immersed simply as a result of the medium’s higher density and its better acoustic coupling to the API-S. Whilst afloat the API-S should be able to record the depth of the liquid beneath the probe (up to a maximum depth of 1000 m). More speculatively, it will detect any variation in the echo profile as a result of changes in the presence of suspended bodies (bubbles, sediments, etc.) in the sensor field of view. Note that in atmosphere the API-S has a beamwidth of around 20° (to half intensity), and when submerged the sensor is effectively a monopolar source.

2.4. ACOUSTIC PROPERTIES INSTRUMENT – VELOCIMETER (API-V)

The second portion of the API consists of a pair of piezoelectric transducers mounted at the front surface of the Top Hat on either side of the cavity. These sensors measure the speed of sound by transmitting, and subsequently receiving, a brief 1 MHz acoustic signal. The time interval between transmission and reception is
measured with a precision of 250 ns and the separation of 0.125 m gives a speed resolution of 8 cm s\(^{-1}\) when operating in gas at Titan's surface. Throughout the descent these sensors will be driven and subsequently sampled once a second, giving a detailed profile of the speed of sound along the probe's trajectory. At least three other sensors in the probe's payload can sense the atmospheric temperature, and thus the speed of sound will yield the ratio of \(\gamma\) (the ratio of specific heats) to \(m\) (mean molecular mass). For an ideal gas this results in knowledge of the mean molecular mass \(m\) (although, the lower atmosphere of Titan deviates from the ideal gas equation of state for nitrogen because of the high density, see Lindal et al., 1983). This data set will be an important crosscheck for the more detailed, but less frequent, measurements made by Huygens' Gas Chromatograph and Mass Spectrometer (GCMS) of the composition of Titan's atmosphere (Niemann et al., 1997). Whilst crossing the tropopause, and towards the surface, the API-V may detect the change in sound speed caused by populations of liquid or solid aerosols. The next important contribution made by the API-V is at Titan's surface in the event of the probe landing in a liquid body. The speed of sound is measured to a precision of 8 m s\(^{-1}\), a fidelity that corresponds to a mixing ratio of 1.6% for a methane/ethane ocean.

2.5. DENSITY SENSOR (DEN)

Upon landing in a liquid the density of any fluid that makes its way into the cavity of the SSP will be estimated by the DEN sensor. This instrument measures the upthrust applied by a liquid to a small buoyant float which is attached to the SSP by a pair of epoxy beams that are equipped with strain gauges (English, 1995). This sensor was admitted to the SSP complement of instruments by virtue of its small volume, mass, and power requirements and although the design of this device displays considerable ingenuity some difficulty was experienced in forming robust and light closed-cell foams. As a result the sensitivity of the DEN is somewhat less than the original design specification. However, in addition considerable scope remains for the detection of phenomena that are secondary to the main role of the SSP. For example, immediately following the probe’s impact with a liquid the DEN may detect the periodic inflow and outflow of fluid from the SSP cavity. Measurements of the rate at which this bobbing motion decays will place constraints on the viscosity of the impacted liquid, a property that is not directly measured by any sensor.

2.6. PERMITTIVITY SENSOR (PER)

In the event of a liquid landing the SSP will also be able to determine a number of electrical properties of the fluid. The PER device consists of 22 stacked parallel plates, the capacitance of which is measured at a number of different frequencies. By briefly pulsing the sensor with DC voltages the conductivity of the surrounding liquid may also be ascertained, placing constraints on the population of dissolved
Figure 7. Permittivity Sensor (PER)

Figure 8. Refractive Index Sensor (REF)
ions (if any) in the medium. The PER also carries a thermometer in the form of a silicon diode, which has a precision of better than 0.5 K.

Although any probable Titan atmosphere has a relative permittivity that is almost identical to 1, and therefore cannot be detected by PER, at the tropopause (altitude 40 km) significant quantities of methane/nitrogen may condense temporarily on the PER sensor. If sufficient material collects on the PER some or all of the sensing plates may be bridged and the condensate may thus be detected.

2.7. REFRACTIVE INDEX SENSOR (REF)

The REF sensor measures the refractive index of a liquid by using a linear critical angle refractometer, the method and design of which is discussed by Geake et al. (1994). This device consists of a section of a cylindrical prism that can be illuminated by collimated sources (light guides fed by light emitting diodes, LEDs, operating at 635 nm) that are both internal and external to the prism. When the REF is immersed in a medium of given refractive index light striking the interface between the prism and the liquid will experience a critical angle effect, in which case the light is refracted or reflected. For both the internal and external illumination only part of the beam is reflected or refracted onto the detector, the remainder escaping or being reflected from the prism. A 512 element linear photodiode array is attached to one face of the prism and this array is used to measure the resulting transition from light to dark, the position of this transition, or cut-off, being linearly related to the refractive index of the liquid. The sensor covers the refractive index range 1.250 to 1.450 with a discrimination of 0.001. The external light source is provided so that an estimate can be made of the opacity of the ambient liquid, from a comparison of the illumination profile received from the internal and external sources.

Along with the permittivity (PER) and density (DEN) sensors, the REF is not expected to provide significant information prior to the probe landing on Titan’s surface, but the presence of heavy local condensation at Titan’s tropopause remains a possibility. In this case the exterior face of REF’s prism may become partially coated with a solid or liquid condensate, the thickness and refractive index of which could be sensed by the REF.

2.8. THERMAL PROPERTIES SENSOR (THP)

The main role of the THP is to measure the thermal conductivity and diffusivity of the ambient medium in the SSP cavity. Along with the Acoustic Properties Instrument (API), the THP is designed to sense properties of both liquid and gaseous media, using two separate sets of redundant hot wire sensors enclosed in cylindrical shields. By applying a known current for a fixed duration to the THP’s sense wires in each of the four cylindrical canisters the wires are made to act as regulated heat sources. This method is covered in detail by Healy et al. (1976). In the close confines of the wires’ shields the transient heat pulse thus generated is lost by
conduction to the medium surrounding the wires at a rate that is determined by
the thermal properties of the material. Measurements of the wires' resistance as a
function of time before and after the heating pulse reveal the initial temperature of
the medium and its thermal properties. Two diameters of platinum wire are used
in the THP, the thinner wires (10 μm diameter) are sized for the relatively low
thermal conductivity of the atmosphere, and the thicker 25 μm diameter wires are
only driven when the Huygens probe has reached the surface.

A THP measurement is made every minute throughout the atmospheric phase of
the descent and will therefore provide a relatively fine record of the thermal prop­
erties of the atmosphere along Huygens’ trajectory. This data set will complement
the more frequent temperature measurements made by the Huygens Atmospheric
Structure Instrument (Fulchignoni et al., 1997) which also operates during the
probe’s descent.

2.9. TILTMETER (TIL)

One of the important analyses to be carried out after arrival at Titan is the re-
construction of the probe’s motion, i.e. its trajectory, attitude, swing and spin,
as it falls through the atmosphere and then subsequently during any post-impact dynamics. Throughout Huygens’ descent particular aspects of the probe’s motion will be measured with varying precision by three separate experiments, Doppler Wind Experiment (Bird et al., 1997), Huygens Atmospheric Structure Instrument (HASI), and SSP. Of these, TIL is the only device that provides unambiguous information about the Huygens probe’s attitude with respect to the local vertical rather than its acceleration. Two inclinometers are arranged to form an orthogonal x-y pair inside the sensor housing which is attached to the SSP electronics box. During the probe’s descent the TIL is sampled at a rate of 1 Hz.

Knowledge of the time-varying orientation of the probe is vital in the analysis of instrument data and it is also expected to give useful insights into the dynamics of the atmosphere along the descent path. The probe’s attitude history is also important in determining the probe’s aerodynamic properties which in turn can be used to solve iteratively equations of motion to reconstruct Huygens’ trajectory profile.

Once the probe has struck the surface the TIL outputs are measured twice a second, which sets a lower bound on the wave period that can be measured by the TIL data alone. Current estimates of surface liquid waves on Titan suggest that this sampling rate will give good temporal characterisation of waves arising in all but the gentlest of breezes; a surface wind speed of 1 m s$^{-1}$ is expected to generate waves with a dominant period of several seconds (Ghafoor et al., 2000). Characterisation of wave motion at the surface of a liquid enables important constraints to be placed on various parameters of scientific interest, such as the depth and spatial extent of the liquid body.
TABLE II
Descriptions of the measurements made by the SSP sensors are shown along with the sensitivities of two devices, Permittivity sensor (PER) and Acoustic Properties Instrument - Velocimeter (API-V), to the composition of their surroundings.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Sensor</th>
<th>Measured property and device sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC-E</td>
<td>No expected scientific return</td>
<td></td>
</tr>
<tr>
<td>ACC-I</td>
<td>Probe motion sensed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertical non-static acceleration from 2 Hz to 500 Hz</td>
<td></td>
</tr>
<tr>
<td>API-S</td>
<td>Back-scatter from dense particulate suspensions / rainfall.</td>
<td></td>
</tr>
<tr>
<td>API-V</td>
<td>Speed of sound and crude estimate of acoustic attenuation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For predominantly nitrogen atmosphere ( c = 200 \text{ m s}^{-1} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SBE = 0.1 m s(^{-1}) and PCS = 0.13% molar mixing for CH(_4):N(_2)</td>
<td></td>
</tr>
<tr>
<td>Descent</td>
<td>DEN</td>
<td>No expected scientific return</td>
</tr>
<tr>
<td></td>
<td>REF</td>
<td>Heavy condensation at tropopause may be detectable</td>
</tr>
<tr>
<td></td>
<td>PER</td>
<td>Heavy condensation at tropopause may be detectable</td>
</tr>
<tr>
<td></td>
<td>THP</td>
<td>Temperature, thermal conductivity and (perhaps) diffusivity</td>
</tr>
<tr>
<td></td>
<td>TIL</td>
<td>Attitude of probe during descent Sampled at 1 Hz with SBE = 0.03°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC-E</td>
<td>Mechanical surface properties at specific impact point</td>
<td></td>
</tr>
<tr>
<td>ACC-I</td>
<td>Mechanical surface properties in landing footprint of probe</td>
<td></td>
</tr>
<tr>
<td>API-S</td>
<td>Topographic and backscatter properties of surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relief discernible at 10 m level. Precision of 0.1 m vertical resolution</td>
<td></td>
</tr>
<tr>
<td>Dry impact</td>
<td>API-V</td>
<td>Speed of sound near surface, possibly detecting surface fog, see 'descent' entry</td>
</tr>
<tr>
<td></td>
<td>DEN</td>
<td>No expected scientific return</td>
</tr>
<tr>
<td></td>
<td>REF</td>
<td>No expected scientific return</td>
</tr>
<tr>
<td></td>
<td>PER</td>
<td>No expected scientific return</td>
</tr>
<tr>
<td></td>
<td>THP</td>
<td>No expected scientific return</td>
</tr>
<tr>
<td></td>
<td>TIL</td>
<td>Resting attitude of probe on surface ± 60° Sampled at 2 Hz with SBE = 0.03°</td>
</tr>
<tr>
<td>Phase</td>
<td>Sensor</td>
<td>Measured property and device sensitivity</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>ACC-E</td>
<td>No expected scientific return (force below trigger threshold)</td>
<td></td>
</tr>
<tr>
<td>ACC-I</td>
<td>Deceleration load at splashdown</td>
<td></td>
</tr>
<tr>
<td>API-S</td>
<td>Depth of liquid, possible suspended sediment echoes</td>
<td></td>
</tr>
<tr>
<td>API-V</td>
<td>Precision of 1 m vertical resolution</td>
<td></td>
</tr>
<tr>
<td>Liquid impact</td>
<td>Speed of sound (c) in near-surface liquid</td>
<td></td>
</tr>
<tr>
<td>DEN</td>
<td>Density of liquid and fluid motion during and after impact</td>
<td></td>
</tr>
<tr>
<td>REF</td>
<td>Refractive index and turbidity of liquid</td>
<td></td>
</tr>
<tr>
<td>PER</td>
<td>Temperature, permittivity ($\varepsilon_r$), and conductivity of liquid</td>
<td></td>
</tr>
<tr>
<td>THP</td>
<td>Temperature, thermal conductivity and (perhaps) diffusivity</td>
<td></td>
</tr>
<tr>
<td>TIL</td>
<td>Motion of probe on surface</td>
<td></td>
</tr>
</tbody>
</table>

**SBE** = Single Bit Equivalent, the minimum change in a material’s property which gives rise to a change of a single bit in a sensor’s output.

**PCS** = Primary Component Sensitivity – the precision with which the composition of a medium can be determined by a sensor. For example, a change of one bit in the received output from the API-V can be caused by a change of 0.13% in the molar concentration of methane relative to nitrogen.

3. **Sensor Performances**

The performance expected from each sensor in three scenarios: the probe’s descent, and landing at a dry or wet site is illustrated in Table II.

4. **Post Launch Checkout**

The Cassini Huygens mission was successfully launched from Kennedy Space Centre at 4.43 EDT on 15th October 1997 by a Titan IVB/Centaur launch vehicle. The first opportunity to checkout the Huygens probe came 8 days after launch. Further checkouts will occur at approximately 6-monthly intervals in order to verify the health of the probe’s systems and experiments during the interplanetary cruise phase.
<table>
<thead>
<tr>
<th>Sensor Subsystem</th>
<th>Status</th>
<th>Degree of checkout</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC-E Penetrometer</td>
<td>Fully functional.</td>
<td>The ACC-E sensor undergoes a self-stimulus test at the start of modes 1, 2 and 3. The sensor response was as expected indicating both aliveness and the correct system gain.</td>
</tr>
<tr>
<td>ACC-I Accelerometer Internal</td>
<td>Response to self-stimulus test was as expected.</td>
<td>ACC-I only measures changes in acceleration, hence in the cruise environment only an offset voltage was seen. The offset voltage changed with temperature as expected during the checkout period.</td>
</tr>
<tr>
<td>API-S Acoustic Properties Instrument - Sonar</td>
<td>Output as expected for zero g.</td>
<td>In vacuum there was no acoustic return signal but the sensor mechanical structure produced a resonance which was detected. This demonstrated functionality. The post launch resonance duration was slightly increased compared to previous vacuum tests. This effect is under investigation.</td>
</tr>
<tr>
<td>API-V Acoustic Properties Instrument – Velocimeter</td>
<td>Sensor functional.</td>
<td>In zero g and with no fluid medium only the sensor offset value was measured.</td>
</tr>
<tr>
<td>DEN Density Sensor</td>
<td>Output as expected for zero g and vacuum.</td>
<td>All 3 readouts (Internal, External and Dark scan) of Linear Photodiode Array were as expected. These demonstrated that the readout electronics were functioning, that dark current was nominal, there were no missing or noisy pixels and that the internal LED was functioning.</td>
</tr>
<tr>
<td>PER Permittivity Sensor REF Refractive Index sensor</td>
<td>Electronics operating nominally.</td>
<td>Free space permittivity measured.</td>
</tr>
</tbody>
</table>
The Huygens cruise checkout scenarios each consist of a nominal descent timeline in order to simulate the Titan entry and descent (e.g. probe wakeup sequence, experiment switch on, polling and mode changes) and to verify that the probe and experiments are functioning normally. There are two checkout scenarios (CO1 and CO2) each lasting approximately 3 hours. These have minor differences in the experiment operation profiles, due to power limitations during cruise, and slightly different simulated probe parameters (e.g. spin rate). The CO1 and CO2 scenarios will be used at alternate 6 monthly checkouts. For the SSP there are no significant differences between the two.

The checkout at Launch + 8 days (F1 checkout), in general confirmed that both the probe and the payload of 6 experiments are functioning normally. There were a few minor anomalies in probe or experiment behaviour, which required investigation; these are reported elsewhere in this issue (Lebreton and Matson, 1998).

At the F1 checkout the SSP experiment was found to be in good health; the switch on procedure was nominal, as were power consumption and data rate in all modes, status words, mode changes and housekeeping voltages. The housekeeping temperature sensors within the SSP were well within the operating range and were comparable with the probe’s reference temperatures. The SSP temperatures are plotted over the full checkout duration in figure 11. This demonstrates a small temperature increase within the probe as expected, and an increase of up to 25 K within the SSP electronics box.

<table>
<thead>
<tr>
<th>Sensor Subsystem</th>
<th>Status</th>
<th>Degree of checkout</th>
</tr>
</thead>
<tbody>
<tr>
<td>THP Thermal Properties Sensor</td>
<td>All four platinum wire sensors are intact and working nominally.</td>
<td>The high current pulse was not applied in vacuum (and during cruise). However, low current measurements indicated temperatures between 259 K and 262 K for the wires. This was compatible with the housekeeping temperatures.</td>
</tr>
<tr>
<td>TIL Tiltmeter</td>
<td>Not exercised during cruise.</td>
<td>In zero g the tilt sensors could be damaged by incorrect excitation voltages due to uncertain electrolyte contact with the terminals. To avoid this risk the sensor was not powered during cruise checkout.</td>
</tr>
</tbody>
</table>
### TABLE IV

Institutional members of the Surface Science Package consortium

<table>
<thead>
<tr>
<th>Co-Investigator</th>
<th>Institution</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.F. Green,</td>
<td>The Open University, Milton Keynes, U.K.</td>
<td>Project management, sensor development, calibration, and electrical ground support equipment.</td>
</tr>
<tr>
<td>J.A.M. McDonnell</td>
<td></td>
<td>Structural, thermal and electrical design and manufacture, sensor development, software development, integration and test facilities.</td>
</tr>
<tr>
<td>J. Delderfield</td>
<td>Rutherford Appleton Laboratory, U.K.</td>
<td>Sensor development Refractive Index sensor (REF).</td>
</tr>
<tr>
<td>J.E. Geake</td>
<td>University of Manchester</td>
<td>Sensor development Acoustic Properties Instrument (API).</td>
</tr>
<tr>
<td>C. Mill</td>
<td>Institute of Science and Technology, U.K.</td>
<td>Index sensor (REF).</td>
</tr>
<tr>
<td>R. Grard</td>
<td></td>
<td>Properties Instrument (API).</td>
</tr>
<tr>
<td>M. Banaszkiewicz</td>
<td>Space Research Centre, Academy of Sciences, Poland.</td>
<td>Electrical design, sensor development Thermal Properties sensor (THP).</td>
</tr>
<tr>
<td>P. Challenor</td>
<td>Southampton Oceanography Centre, U.K.</td>
<td>Titan ocean modelling.</td>
</tr>
<tr>
<td>R. Lorenz</td>
<td>University of Arizona, U.S.A.</td>
<td>Data analysis.</td>
</tr>
<tr>
<td>W.V. Boynton</td>
<td>University of Arizona, U.S.A.</td>
<td>Data analysis.</td>
</tr>
<tr>
<td>B. Clark</td>
<td>Lockheed Martin Astronautics Group, U.S.A.</td>
<td>Data analysis.</td>
</tr>
</tbody>
</table>

All nine of the sensor sub-systems within SSP were found to have survived launch and were operating as expected in a microgravity and vacuum environment. The sensor status and the degree of checkout possible during cruise are summarised in Table III.
5. SSP Consortium

The SSP consortium and Co-Investigator institutes are described in Table IV.

6. Acknowledgements

The work at the Open University (and previously at the University of Kent at Canterbury), the Rutherford Appleton Laboratory, and the University of Manchester Institute of Science and Technology (UMIST) is supported by the UK’s Particle Physics and Astronomy Research Council. The work performed at the Space Research Centre, Warsaw, is supported by the Polish Academy of Sciences. The work at the University of Arizona and Lockheed Martin Astronautics Group is supported by NASA.

Since the launch of Cassini Huygens, one of the SSP Co-Investigator team, John Geake of UMIST, has sadly died. He was responsible for the Refractometer sub-system, and the data from that sub-system will serve as a testimony to his invaluable contribution.

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Mission, ESA SP 1177, 177.
THE HUYGENS DOPPLER WIND EXPERIMENT
Titan Winds Derived from Probe Radio Frequency Measurements

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Abstract. A Doppler Wind Experiment (DWE) will be performed during the Titan atmospheric descent of the ESA Huygens Probe. The direction and strength of Titan’s zonal winds will be determined with an accuracy better than 1 m s⁻¹ from the start of mission at an altitude of ~160 km down to the surface. The Probe’s wind-induced horizontal motion will be derived from the residual Doppler shift of its S-band radio link to the Cassini Orbiter, corrected for all known orbit and propagation effects. It is also planned to record the frequency of the Probe signal using large ground-based antennas, thereby providing an additional component of the horizontal drift. In addition to the winds, DWE will obtain valuable information on the rotation, parachute swing and atmospheric buffeting of the Huygens Probe, as well as its position and attitude after Titan touchdown. The DWE measurement strategy relies on experimenter-supplied Ultra-Stable Oscillators to generate the transmitted signal from the Probe and to extract the frequency of the received signal on the Orbiter. Results of the first in-flight checkout, as well as the DWE Doppler calibrations conducted with simulated Huygens signals uplinked from ground (Probe Relay Tests), are described. Ongoing efforts to measure and model Titan’s winds using various Earth-based techniques are briefly reviewed.

1. Introduction

The primary objective of the Doppler Wind Experiment (DWE), one of the six scientific investigations comprising the payload of the ESA Huygens Probe (Lebreton and Matson, 1997; Jaffe and Herrell, 1997), is a determination of the wind velocity in Titan’s atmosphere (Atkinson et al., 1990; Bird et al., 1997a,b). Measurements of the Doppler shift of the S-band (2040 MHz) carrier signal to the Cassini Orbiter and to Earth will be recorded during the Probe descent in order to deduce wind-induced motion of the Probe to an accuracy better than 1 m s⁻¹. An experiment with the same scientific goal was performed with the Galileo Probe at Jupiter (Pollack et al., 1992; Atkinson et al., 1996, 1997, 1998). Analogous to the Galileo experience (Folkner et al., 1997), it is anticipated that the frequency

of the Huygens radio signal can be measured on Earth to obtain an additional component of the horizontal winds in spite of the roughly 4-fold decrease in signal level due to the longer free-space propagation distance. Specific secondary science objectives of DWE include measurements of: (a) Doppler fluctuations to determine the turbulence spectrum and possible wave activity in the Titan atmosphere; (b) Doppler and signal level modulation to monitor Probe descent dynamics (e.g., spinrate/spinphase, parachute swing); (c) Probe coordinates and orientation during descent and after impact on Titan.

DWE will complement remote-sensing observations of temperatures and winds from the Cassini Orbiter, providing 'ground truth' for the zonal wind retrievals from the Composite Infrared Spectrometer (CIRS) experiment (Kunde et al., 2002). It is anticipated that the Cassini Radio Science Subsystem (RSS) will provide additional clues about Titan's atmospheric dynamics from their series of radio occultation observations at a variety of latitudes (Kliore et al., 2002). If the Probe descends through regions of turbulence or vertical wave propagation, the Doppler fluctuations will provide information on the associated eddy momentum mixing or planetary waves, respectively. In contrast to the strong radio attenuation in the Jupiter atmosphere inferred from the Galileo Probe signal level measurements (Follmer et al., 1998), propagation effects at S-band for the Huygens DWE on Titan are expected to be negligible (Bird, 1997).

The largest uncertainties in the DWE wind measurement arise from trajectory errors and the stability of the oscillators used to generate the signal on the Probe and receive it on the Orbiter. The desired accuracy can be achieved only with a sufficiently stable radio signal over the duration of the descent. The specified frequency stability of $\delta f/f \lesssim 2 \cdot 10^{-10} \Rightarrow \delta f \lesssim 0.4$ Hz at S-band) was met by using rubidium-based Ultra-Stable Oscillators in both the transmitter (TUSO) and receiver (RUSO), rather than the standard Temperature Compensated Crystal Oscillators (TCXO).

This paper represents an update to the comprehensive pre-launch instrument descriptions by Bird et al. (1997a,b). Some comments on our present knowledge of Titan winds are presented in the next section. An overview of the experimental concept, results from simulated DWE frequency measurements, and a short comparison with the namesake experiment on the Galileo mission are presented in the third section. This is followed by a description of the DWE hardware, the TUSO/RUSO Ultra-Stable Oscillators, and selected DWE results from the cruise phase to Saturn. Included in this latter category are the first in-flight checkout 8 days after the Cassini/Huygens launch in October 1997 and a series of Probe Relay Tests (PRTs). It was the first such test (PRT#1) in February 2000 which uncovered anomalous demodulation characteristics of the receiver, eventually leading to a fundamental redesign of the Huygens mission (Lebreton and Matson, 2002). The associated changes in the geometrical conditions, and their obvious consequences for DWE, are incorporated into the present version of the paper.
2. Zonal Winds on Titan

An observational basis for understanding Titan’s atmospheric dynamics and meteorology was virtually nonexistent prior to the Voyager 1 flyby on 12 November 1980. Especially valuable information was obtained from infrared (Hanel et al., 1981) and radio science (Tyler et al., 1981) observations. A current review of the dynamic meteorology on Titan, assembled from subsequent studies of the unique Voyager 1 reconnaissance, has been written by Flasar (1998). Coustenis and Taylor (1999) also devote a chapter of their recent book to Titan’s atmospheric dynamics and meteorology.

The Doppler tracking data collected during the Voyager 1 occultation were used to derive Titan’s vertical temperature-pressure curve (Lindal et al., 1983). Assuming a pure N2 atmosphere, the temperature was found to decrease with altitude from a surface value of 94 ± 0.7 K to a minimum of ~70 K at the tropopause near 40 km (weak greenhouse effect). A later analysis, including consideration of the uncertainties in mean molecular weight, yielded a surface temperature in the range between 92.5 and 101 K (Lellouch et al., 1989). The temperature profile indicated a nearly adiabatic lapse rate below 3–4 km (implying efficient vertical mixing), but a statically stable region at higher altitudes. Vertically propagating gravity waves may exist at heights between 25 and 90 km (Hinson and Tyler, 1983).

Strong zonal winds on Titan (~100 m s⁻¹) are implied by the latitudinal temperature gradient deduced from the Voyager 1 infrared observations (Flasar et al., 1981; Flasar et al., 1997). Assuming hydrostatic, gradient-balanced flow, the zonal wind velocity \( u \) is related to the latitudinal temperature gradient by the ‘thermal wind equation’:

\[
\frac{\partial}{\partial \hat{z}} \left[ u^2 \tan \lambda + 2u \Omega a \sin \lambda \right] = -R \frac{\partial}{\partial \lambda} \left[ \frac{T}{\mu} \right]
\]

where \( \hat{z} = \ln \left( \frac{P_s}{P} \right) \) is the vertical log-pressure coordinate with \( P_s \) the surface pressure, \( T \) the temperature, \( \lambda \) the latitude, \( a \) the planetary radius, \( \Omega \) the planetary rotation velocity, \( \mu \) the mean molecular weight (mass per mole) of the atmospheric gas, and \( R \) the gas constant. The second term in Equation (1) can be neglected if \( u \gg \Omega a \simeq 11.7 \text{ m s}^{-1} \) (for an assumed Titan rotation period of 16 days), which probably holds until one approaches the surface. In this case the resulting circulation is said to be in cyclostrophic balance. General Circulation Model (GCM) simulations of the Titan regime (Del Genio et al., 1993; Hourdin et al., 1995; Tokano et al., 1999) confirm the likely validity of dynamical scaling assessments (Hunten et al., 1984), and imply that gradient thermal wind balance is an accurate diagnostic of the zonal-mean flow speed.

If the winds are negligible near ground level (e.g., Allison, 1992), Equation (1) may be solved for the zonal wind height profile provided one has knowledge of the temperature with height and latitude. Under these conditions, however, Equa-
tion (1) does not allow one to determine whether the winds are prograde or retrograde.

Integrating Equation (1) upwards, Flasar et al. (1997) have derived a model for the zonal wind that increases monotonically to \( \sim 100 \) m s\(^{-1}\) in the upper stratosphere at a latitude of \( \lambda = 45^\circ \). This model assumes the following equator-to-pole temperature gradients observed at three levels by Voyager 1: \( \Delta T \approx 16 \) K at the 0.5 mbar pressure level (\( \sim 230 \) km) from the observations in the 1304 cm\(^{-1}\) channel (Flasar et al., 1981; Coustenis, 1990); \( \Delta T \approx 1 \) K at \( p = 100 \) mbar (\( \sim 40 \) km) from observations at 200 cm\(^{-1}\), and \( \Delta T \approx 2 \) K at the surface from the thermal channel at 530 cm\(^{-1}\). Toon et al. (1988) have cautioned, however, that these observations may include a significant contribution from stratospheric aerosols. If the IR-observations are stretched to the maximum possible equator-to-pole gradients, corresponding to double the best-fit values (Lunine et al., 1991; Flasar et al., 1997), a zonal wind height profile can be derived with zonal velocities a factor of the order of \( \sqrt{2} \) larger than the best estimate. With the additional assumption that the temperature gradient increases roughly linearly with height (i.e., with \( \ln P \)), Lunine et al. (1991) integrated Equation (1) to obtain the following scaled formula for this ‘maximum envelope’:

\[
| u(z) - u_s | \lessapprox u_0 \left[ 1 + \frac{1}{8} \ln \left( \frac{P_0}{P(z)} \right) \right] \cos \lambda
\]

(2)

where \( u_s \approx 0 \) is the wind at the surface, \( P(z) \) is the pressure and the wind and pressure at a fiducial height were taken as \( u_0 = 200 \) m s\(^{-1}\) at the \( P_0 = 0.5 \) mbar level by Lunine et al. (1991). The latitudinal dependence in Equation (2) corresponds to superrotation at constant angular velocity (‘solid body’).

The hypothesized zonal flow on Titan is still a poorly understood regime in the theory of atmospheric dynamics. The meridional and vertical winds, although probably much weaker than zonal motion, are also largely unknown. Only recently have GCMs been adapted to the study of atmospheric superrotation on Titan (Del Genio et al., 1993; Hourdin et al., 1995; Tokano et al., 1999). While these have plausibly simulated an upper atmospheric superrotation qualitatively consistent with the observed temperature gradient on Titan, the detailed wind structure may well depend upon the specific (but as yet undetermined) contributions of the planetary boundary layer and upper level wave propagation, both depending upon the surface characteristics and topography.

Figure 1 shows a summary of what the observations and models imply about Titan’s zonal winds. The zonal wind height profile is plotted at \( \lambda = 19^\circ \)N, which is the latitude corresponding to the originally designated Huygens target on Titan. Subtle differences in the theoretical profiles occur for the new target latitude of \( \lambda = 10.7^\circ \)S, but the general trend, a roughly linear increase with height, is maintained. The latitude-adjusted profile derived from the Voyager 1 observations by Flasar et al. (1997) is shown by the short-dashed curve in Figure 1. The solid line is the corresponding ‘maximum envelope’ at this latitude given by Equation (2). The
Figure 1. Models of zonal wind height profiles on Titan at a latitude of 19°N. The curve given by the short-dashed line is the integral of the thermal wind equation, using equator-to-pole temperature contrast at various heights inferred from Voyager 1 infrared observations (Flasar et al., 1997). The solid curve is a ‘maximum envelope’ (Lunine et al., 1991) assuming upper bounds on the Voyager temperature gradients. The dash-dotted curve is a prediction from a specifically developed Titan circulation model (Hourdin et al., 1995). The long-dashed curves labeled ‘T1-T4’ are linear fits to four atmospheric simulations for a planet rotating at the Titan period (16 days) performed by Del Genio et al. (1993) over a more limited range of altitudes. T1: model with a global absorbing cloud at altitudes from 20–40 km; T2: same atmospheric simulation, but without an absorbing cloud; T3: T1 without stratospheric drag; T4: T1 with greatly weakened surface drag.

dash-dotted curve is a mean of the northern winter solstice and northern spring equinox models of Hourdin et al. (1995), which is valid for the Huygens epoch in January 2005. Also plotted in Figure 1 are linear fits to the results of a Titan dynamical process study using a terrestrial atmospheric GCM incorporating various idealizations of the stratification and drag likely to be relevant to the planet’s specific circulation regime (Del Genio et al., 1993; long-dashed lines T1–T4). The baseline Titan-like scenario (T1) features an optically thick (τ ≈ 5), statically stable cloud layer in the upper troposphere, slowed down to a 16-day planetary rotation period. The assumed thick cloud merely serves the purpose of imposing a strong upper atmospheric static stability in the adapted Earth model, as apparently required for an equatorial convergence of eddy momentum flux by barotropic eddies. Running the GCM code to equilibrium, one obtains zonal-mean flows of several tens of meters per second up to the maximum simulated altitude level near 100 mbar. The flow regime is supported by the horizontal mixing of quasi-barotropic eddies. The other curves in Figure 1 are the baseline Titan model of
Del Genio et al. (1993), but with the following modifications: (T2) without the absorbing global cloud, (T3) without stratospheric drag, and (T4) with negligible surface drag. The implication is that T1 agrees best with the winds inferred from the Voyager 1 observations (Flasar et al., 1981) as well as with the model prediction of Hourdin et al. (1995). The more recent calculations by Tokano et al. (1999) predict a very weak prograde zonal wind at the designated Huygens target latitude of only a few m s\(^{-1}\) in the troposphere and probably less than 20 m s\(^{-1}\) near the start of the descent at \(h \sim 170\) km. Evidently, the absorbing global cloud, stratospheric drag and surface drag are all essential ingredients of superrotational circulation on Titan.

Evidence for winds on Titan was also derived from ground-based photometric measurements recorded during the occultation of the relatively bright star 28 Sgr (Hubbard et al., 1993). A latitudinal profile, presumed symmetric about the equator, was inferred from the shape of isopycnic surfaces in the stratosphere (0.25 mbar level). The zonal flow varied from \(\sim 80\) m s\(^{-1}\) near the equator to more than 170 m s\(^{-1}\) at 60\(^\circ\) latitude.

Infrared heterodyne observations of Titan’s ethane emission in the 12 \(\mu\)m band, which originates near the 1 mbar level (\(\sim 200\) km altitude), have been used to estimate Titan zonal wind speeds (Kostiuk et al., 2001). The Doppler shift of a given \(\text{C}_2\text{H}_6\) line is measured when the telescope’s field-of-view is centered on the east and west limbs of the Titan disk, respectively. The frequency difference between the line centers of these two spectra should be twice the Doppler shift expected from the mean zonal flow velocity. The results provide strong evidence that Titan’s zonal winds are moving in the direction of planetary rotation (prograde). Using data from three separate observation opportunities at the NASA/IRFT at Mauna Kea (1993, 1995–1996), the combined statistical probability that the winds are prograde is 94\%. The wind speeds derived from simple models for the hemispheric mean measurements are high, but with an almost equally high uncertainty. Assuming solid body rotation, a mean equatorial zonal wind speed of 250 ± 150 m s\(^{-1}\) is retrieved, which implies an atmospheric rotation period of \(\sim 19\) h.

The traditional cloud-tracking technique to derive winds has been frustrated in the case of Titan by the virtual absence of contrast in the Voyager 1 images. Using a large amount of image processing, one attempt to measure winds from atmospheric features was performed (Wenkert and Garneau, 1987). Many near-infrared images of Titan have been obtained with the refurbished planetary camera (WF/PC2) of the Hubble Space Telescope (HST) during the 1994–1995 oppositions. Careful processing of the 14 images from 1994 revealed a large bright surface feature in the leading hemisphere (Smith et al., 1996). Although some structure in the WF/PC2 images is suggestive of atmospheric condensations (Lorenz et al., 1995; 1999; Caldwell et al., 1996), a confident cloud-tracking determination of wind vectors has not yet emerged.

Subsequent observations of Titan using adaptic optics at the ESO 3.6-m telescope in LaSilla (Combes et al., 1997) and the near-infrared camera (NICMOS)
on HST (Meier et al., 2000), failed to detect short-term changes in albedo that might be attributed to cloud activity. In spite of the general lack of contrast in the Titan atmosphere from imaging observations, anomalous infrared spectra have been recorded (Griffith et al., 1998) that are best explained by transient low-level clouds (~15 km altitude) occupying about 10% of the observed disk. More recent observations (Griffith et al., 2000) now reveal variations on shorter time scales (hours to days) in the 2.11–2.17 μm spectral region sensitive to CH₄ cloud reflection. These new measurements are best simulated by clouds at higher altitudes (~25 km) that cover typically 0.5% of the moon’s disk.

The GCM experiments and the few available observations suggest that planetary atmospheric circulation such as Titan’s may be maintained by ‘potential vorticity’ mixing (Allison et al., 1994). To the extent that this approaches the zero potential vorticity (ZPV) limit for a stable symmetric circulation about the equator, a maximum envelope can be derived for the latitudinal wind profile:

\[ u_{\text{max}}(\lambda) = (u_e + \Omega a)(\cos \lambda) \frac{2}{R_i - 1} - \Omega a \cos \lambda \]  

(3)

with \( u_e \) the equatorial zonal velocity and \( R_i \) the Richardson number. Equation (3) implies that \( u_{\text{max}} \) increases with latitude for the large values of \( R_i \) appropriate for a statically stable stratosphere, consistent with the Titan zonal wind profile derived by Hubbard et al. (1993), at least for latitudes from the equator to the maximum jet at 60°. A vertical profile for \( R_i(z) \) could be determined from a combination of DWE wind and HASI (Huygens Atmospheric Structure Instrument: Fulchignoni et al., 1997) temperature/pressure measurements at one latitude. Global remote sensing observations from the Cassini Orbiter would then provide an elegant test of the applicability of the ZPV constraint.

3. DWE Experimental Strategies

3.1. Titan Targeting

Successful execution of the DWE depends critically on the experiment geometry and sequence of events during Titan descent. In order to measure the presumably dominant zonal wind component, it is essential that the respective positions of Probe and Orbiter provide a favorable projection of the East-West wind drift motion onto the Probe/Orbiter line-of-sight. As mentioned earlier, telemetry demodulation problems discovered in the Huygens receivers on the Cassini Orbiter have resulted, after an in-depth analysis of the link performance, in a major redesign of the Huygens mission (Lebreton and Matson, 2002). Of particular concern to DWE was the rearrangement of the Huygens mission geometry required to reduce the Doppler shift of the Probe-Orbiter radio link.

According to the current planning, the Huygens Probe mission will no longer occur on the first, but rather the third targeted Titan flyby. The new mission date
has been moved back to 14 January 2005, about 6 months after arrival at Saturn. A backup opportunity with very similar geometrical conditions, but with increased fuel expenditure and extended delay for returning to the Cassini Saturn Tour, could be arranged for the subsequent Titan flyby 32 days later. The Probe will now be separated from the Orbiter on Christmas Day 2004, only 20 days prior to entry into Titan’s atmosphere. Two days later, a deflection maneuver will bring the Orbiter into a retrograde flyby trajectory that passes ‘left’ of Titan at a minimum altitude near 65 000 km, rather than the originally planned flyby at 1200 km on Titan’s ‘right’ side. The Orbiter Delay Time (ODT), previously set at 4 h, will now be 2.1 h after Probe entry.

Probe and Orbiter targeting at Titan can be visualized on the Titan disk from a direction defined by their asymptotic approach velocities, the so-called B-plane (see also Bird et al., 1997b; Sollazzo et al., 1997). Figure 2 shows a B-plane projection with the Probe and Orbiter targets at Titan at the time of Probe entry. The asymptotic velocity vector defines the direction of the S-axis, passing through the center of Titan perpendicular to the B-plane, and its unit vector $\hat{S}$. The B-plane passes through the center of Titan and is spanned by the T- and R-axes. The T-axis is defined by the intersection of the B-plane with the Titan equatorial plane. In other words, the direction of the unit vector $T$ along the T-axis is defined by the cross product $\hat{S} \times \hat{P}$, where $\hat{P}$ is a unit vector in the direction of Titan’s rotational axis, positive northward. The R-axis and associated unit vector complete the orthogonal system: $\hat{R} = \hat{S} \times \hat{T}$.

The concentric circles centered on the origin denote values of constant Probe entry angles in the Titan atmosphere. Maintaining a balance between peak and integrated heat flux on the front shield, an optimum entry angle of $\gamma = -64^\circ$ was derived from atmospheric entry simulation studies. The B-plane azimuth angle was originally selected as $\theta_p = -60^\circ$, which mapped on Titan to latitude 19°N, longitude 152°W at the start of the descent. The target delivery accuracy, defined by the 3σ targeting error ellipse, was formerly ±480 km × ±150 km, corresponding to ±3.3° in latitude and ±11.2° in longitude. The targeting ellipse corresponding to the revised mission, utilizing navigation data from two previous Titan flybys, is smaller (±306 km × ±35 km). Utilizing additional optical navigation data, the Orbiter would have been more accurately targeted to a point that yielded an altitude of closest approach at 1200 km at the azimuth angle $\theta_o = -22.6^\circ$ (Sollazzo et al., 1997). The semi-axes of the Orbiter targeting ellipse were 174 km × 39 km.

An essential component of the Huygens mission recovery was to reduce the Doppler shift of the radio link. Because the velocity magnitude could not be significantly changed, the only feasible way to accomplish this was to greatly increase the Orbiter flyby distance. Without reiterating the intermediate steps in the redesign process, it suffices here to note that the optimum Orbiter B-plane azimuth for a high-altitude flyby was determined to be $\theta_o = -180^\circ$, i.e. passing through the negative T-axis of the B-plane. The Orbiter B-plane target, however, is well out of the picture shown in Figure 2 (flyby altitude ~65 000 km). In order to maintain
Figure 2. Huygens Probe and Cassini Orbiter targets in the Titan B-plane. The concentric circles denote loci of constant Probe entry angles in the Titan atmosphere from center disk \((\gamma = -90^\circ)\) to \((\gamma = -40^\circ)\). Probe entry is optimized at \(\gamma = -64^\circ\). In the original mission plan, the Probe target was in the upper right quadrant and had a relatively large error. The Orbiter was formerly targeted for a flyby altitude at 1200 km, in the same quadrant. Retaining \(\gamma = -64^\circ\), the new Probe target was moved around to the left in order to optimize the radio link performance for the new Orbiter flyby trajectory at azimuth angle \(-180^\circ\).

If satisfactory link performance with the Orbiter now on the left side of Titan, it was necessary to retarget the Probe to a point in the same hemisphere. The optimum entry angle of \(\gamma = -64^\circ\), governed by the entry thermal budget, was not changed. An optimum B-plane azimuth was determined to be \(\theta_p = -190^\circ\), yielding an atmospheric entry point on Titan at latitude 10.7°S, longitude 199°W. The Titan rotation axis will now be tilted away from the incoming Probe by 6.0° (angle between \(\hat{P}\) and \(-\hat{R}\)). The trace of the Titan equator on the disk is shown in projection onto the B-plane in Figure 2.
3.2. PROBE MOTION DURING DESCENT

The nominal Huygens entry/descent trajectory for various zonal wind models is depicted in Figure 3. As the Probe enters the Titan atmosphere, it is subjected to a deceleration of the order of 13 $g$ at an altitude $h \approx 228$ km. A first parachute is deployed at a speed near Mach 1.5 ($h \approx 162$ km), marking the beginning of the descent phase (time $= t_0$). Slowing to subsonic velocity, the heat shield is jettisoned and transmission of data is initiated (at $t = t_0 + 150$ s). The radio signal will be recorded both on the Orbiter and on Earth in the directions indicated. The Probe then falls at the terminal velocity governed primarily by the ballistic coefficient of the Probe parachute system. It is assumed that the Probe also drifts in longitude with the east/west winds, remaining at a roughly constant latitude for negligible north/south winds. The large initial parachute is released at $t = t_0 + 15$ min ($h \approx 114$ km) and replaced by a smaller drogue parachute in order to decrease the descent time. The time constant for the Probe velocity to adjust for changes in the winds will decrease toward lower altitudes due to the increasing atmospheric density (Bird et al., 1997b). In the case of the maximum envelope profile (s. Figure 1), the Probe touchdown on Titan will be about 360 km east of the atmospheric entry point. The zonal drift will produce a small shift in the apparent direction
to Earth as shown in Figure 3. This drift also affects the apparent position to the Orbiter. The larger shift in direction shown in Figure 3 (clockwise ~50°), however, is caused by its apparent motion toward the horizon along the high-altitude flyby trajectory.

The (first order) Doppler shift measured on the Orbiter is given by:

\[
\Delta f = -\frac{f}{c} \Delta V
\]

\[
\Delta V = \left( \vec{V}_p - \vec{V}_o \right) \cdot \vec{R}_{op}
\]

where \( \vec{V}_p \), and \( \vec{V}_o \) are the Probe and Orbiter velocities, respectively, and \( \vec{R}_{op} \) is a unit vector from Orbiter to Probe (radio ray path):

\[
\vec{R}_{op} = \frac{\vec{R}_p - \vec{R}_o}{|\vec{R}_p - \vec{R}_o|}
\]

Higher order Doppler, special relativistic, and gravitational red shift terms can be neglected (Atkinson et al., 1998).

The sign of \( \Delta V \) is negative at the beginning of the Titan descent, so that the received frequency is increased (blue shifted) from Equation (4). In the Titan-centered frame, the ray path projection of the Probe velocity consists of 4 contributions:

\[
\vec{R}_{op} \cdot \vec{V}_p = V_1 + V_2 + V_3 + V_4
\]

where the four terms are sensitive to Probe motion as follows:

\( V_1 \sim \) zonal wind \( u \) (positive toward East)
\( V_2 \sim \) Titan rotation \( \Omega a \cos \lambda \) (co-aligned with \( V_1 \))
\( V_3 \sim \) meridional wind \( v \) (positive toward North)
\( V_4 \sim \) descent velocity \( v_T + v \) (positive upwards)

and the Orbiter's velocity projection onto the radio ray path is:

\[
\vec{R}_{op} \cdot \vec{V}_o = V_5
\]

The term \( V_1 \), the drift velocity due to zonal winds, is the measurement of interest to DWE. This will be either parallel or antiparallel to the velocity \( V_2 \) from Titan rotation, the magnitude of which is assumed to be \( \Omega a \cos \lambda \simeq 11.6 \text{ m s}^{-1} \) at \( \lambda = -10.7^\circ \). The meridional drift term \( V_3 \) would be indeterminate without the additional Doppler measurement from Earth. It is expected to be small (\( v \ll u \)) except perhaps in the last few kilometers above the surface. The vertical velocity \( V_4 \) must be determined independently using measurements of height from the Probe’s proximity sensor and/or HASI temperature/pressure data.
The eventual uncertainty in the zonal wind velocity will be sensitive to any measurement error in the descent velocity $V_4$. This was an especially serious problem for the Galileo Probe, for which the line-of-sight to the Orbiter was very nearly vertical (Pollack et al., 1992; Atkinson et al., 1998). Assuming that the Huygens descent velocity can be determined to the estimated accuracy of 1% (Bird et al., 1997b; Fulchignoni et al., 1997), the associated uncertainty in the zonal wind speed will be about 2 m s$^{-1}$ (20 cm s$^{-1}$) near the beginning (end) of the descent.

Figure 4 presents the expected time profiles of the five line-of-sight Doppler contributions in Equations (7) and (8) for the nominal Huygens descent (duration: 135 min). The upper panel shows the total Doppler shift between Probe and Orbiter (solid line). It is clear that most of the Doppler shift comes from the motion of the Orbiter projected along the line-of-sight to the Probe (dashed line). The Doppler shift from other individual motions of the Probe in the Titan atmosphere are plotted at higher resolution in the lower panel. The curves are for eastward zonal drift (dotted line), planetary rotation (dashed line), southward meridional drift (dot-dashed line), and vertical descent (triple-dot-dashed line). All of these are expected to produce a frequency decrease (red shift) from their motion away from the Orbiter.
from the Orbiter. The discontinuity at \( t = 15 \) min, most prominent in the descent velocity, marks the exchange of parachutes. The 100% nominal zonal wind model \( u(z) \) (Flasar et al., 1997; see also Figures 1 and 3) was used for computing the zonal wind contribution \( V_1 \). The minor contribution from Titan rotation \( (V_2) \) slowly increases during the descent as the radial projection of the zonal motion becomes more favorable. The new geometry for the Huygens DWE at Titan yields an almost negligible Probe/Orbiter line-of-sight projection for the meridional component \( V_3 \). A nominal velocity of \( v = -1 \) m s\(^{-1}\) was used in Figure 4, but even substantially higher velocities would not be measurable because of the small projection onto the line-of-sight.

Independent determinations of Probe horizontal drift may be available near the surface from either (a) proximity sensor measurements utilizing pendulum swing motion, or (b) successive images from the Descent Imager & Spectral Radiometer (DISR: Tomasko et al., 1997). These would provide a helpful comparison with the DWE height profile just prior to touchdown where the horizontal winds may well be weak. It is hoped that DWE measurements will continue after impact on Titan to provide a reliable absolute frequency reference for zero wind.

3.3. PARALLELS WITH THE GALILEO DOPPLER WIND EXPERIMENT

The main scientific goal of the namesake experiment performed during the Galileo Probe mission at Jupiter on 7 December 1995 (Atkinson et al., 1996; 1997; 1998) was very comparable to that of the Huygens DWE. It is remarkable that this is one of the few obvious similarities between the two investigations. As demonstrated in Table I, there are distinct differences in the instrumentation and experimental geometry. Whereas the Galileo DWE observed an L-band signal from a rapidly-changing vantage point with only a small Doppler component for the zonal motions, the Huygens DWE will be recording an S-band signal with a significant and constantly increasing component in the zonal direction. The Galileo Probe’s carrier signal was also successfully recorded at radio telescopes on Earth (Folkner et al., 1997), which was located in a direction nearly orthogonal to the Probe-Orbiter line. Although this viewing geometry was ideal for measuring zonal winds, it was also far away from the axis of the Probe’s antenna, which, of course, was pointed at the Orbiter. The resulting extremely low signal levels meant that these frequency measurements could be retrieved only upon implementing a sophisticated signal extraction process to deconvolve the phase modulation from the raw spectral recordings.

Zonal winds at Jupiter were observed to be prograde, strong and surprisingly uniform \(~160–180\) m s\(^{-1}\) at levels between 4 and 20 bars, thereby suggesting an absence of strong meridional temperature gradients at the deep, weakly stratified levels sounded by the Galileo Probe (Atkinson et al., 1997; 1998). There was evidence for slowing down at higher levels, where the zonal flow should merge with the velocities measured for the visible clouds. Independent accelerometer
## TABLE I
DWE Comparison: Huygens/Cassini and Galileo Probe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Galileo Probe</th>
<th>Huygens/Cassini</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Relay Link:</td>
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<td></td>
</tr>
<tr>
<td>frequency band</td>
<td>L</td>
<td>S</td>
</tr>
<tr>
<td>chain A/B frequency (MHz)</td>
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<td>2040.0/2097.1</td>
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<tr>
<td>RF power (W)</td>
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<td>10</td>
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<td>polarization A/B</td>
<td>LCP/RCP</td>
<td>LCP/RCP</td>
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<td>signal source A/B</td>
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<td>TUSO/TCXO</td>
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<td>data rate (bits/s)</td>
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<td>8192</td>
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<tr>
<td>USO</td>
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<td></td>
</tr>
<tr>
<td>output frequency (MHz)</td>
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<td>10.000</td>
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<tr>
<td>warm-up time (hours)</td>
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<td>&lt;0.5</td>
</tr>
<tr>
<td>drift stability $\Delta f/f$ (30 min)</td>
<td>$1.73 \pm 0.09 \times 10^{-9}$</td>
<td>$2 \times 10^{-10}$</td>
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<tr>
<td>Probe Antenna</td>
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<tr>
<td>type/size</td>
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<td>helix/0.17 m</td>
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<tr>
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<td>5</td>
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<tr>
<td>3 dB-beam $\Theta$ (°)</td>
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<td>120</td>
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<td>Orbiter Antenna</td>
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<tr>
<td>parabolic antenna $\Theta$(m)</td>
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<td>4.3</td>
</tr>
<tr>
<td>gain(dBi)</td>
<td>21.0</td>
<td>34</td>
</tr>
<tr>
<td>3 dB-beam $\Theta$ (°)</td>
<td>12.6</td>
<td>2.6</td>
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<tr>
<td>PRL Receiver</td>
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<tr>
<td>local oscillator A/B</td>
<td>USO/USO</td>
<td>RUSO/TCXO</td>
</tr>
<tr>
<td>Doppler recording rate (Hz)</td>
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<td>8</td>
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<tr>
<td>signal power recording rate (Hz)</td>
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<td>Doppler resolution (mHz) [mm s$^{-1}$]</td>
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<td>48 [7]</td>
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<td>signal power resolution (dBm)</td>
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<td>±0.05</td>
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<td>DWE Geometry</td>
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<td>entry angle (°)</td>
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<td>entry velocity (km s$^{-1}$)</td>
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<td>maximum entry deceleration (g)</td>
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<td>13</td>
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<td>entry latitude (°)</td>
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<tr>
<td>entry longitude (°)</td>
<td>4.46 W</td>
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<tr>
<td>mission duration (min)</td>
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<td>135±15</td>
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<tr>
<td>Probe aspect angle (°)</td>
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<td>25–70</td>
</tr>
<tr>
<td>planet rotation velocity</td>
<td>12.6 km s$^{-1}$</td>
<td>11.6 m s$^{-1}$</td>
</tr>
</tbody>
</table>
measurements from the Galileo Probe Atmospheric Structure Instrument agreed with the DWE results (Seiff et al., 1997). On Titan, however, strong vertical shears are likely to be an important feature of a statically stable and differentially heated atmosphere. In situ verification of these thermal winds by the Huygens DWE could be extrapolated to a global scale from Orbiter observations of the horizontal temperature contrast using the techniques established by the Voyager IRIS experiment (Flasar et al., 1981).

3.4. GROUND-BASED MEASUREMENTS OF TITAN WINDS

Ground-based observations of the Huygens Probe to support the DWE will be made at one or two large radio antennas. With the current nominal trajectory, the Probe mission on Friday, 14 January 2005, will occur in the ground received three-hour time interval starting at about 09:11 UT. This will be shortly after culmination, for example, at the Very Large Array in New Mexico or the Deep Space Network (DSN) complex in California (the DSN 70m antennas are presently not equipped to track the Probe signal, because their standard S-band receivers do not cover the Probe’s transmission frequency). Another available ground-based station would be the new NRAO 100-m antenna at Green Bank, WV/USA, which would have visibility of the Huygens Probe at least at the start of descent. The expected signal strength is even somewhat better than for the Earth-based observation of the Galileo Probe. Key parameters in the link budget for the Galileo and Huygens Earth-based Doppler measurements are compared in Table II. Saturn’s mean distance from Earth is roughly twice that of Jupiter, but the additional free-space loss for the experiment at Titan is only 2.3 dB rather than the expected 6 dB. This is because the Huygens DWE will be performed at opposition, in contrast to the Galileo Probe

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**TABLE II**

Earth Reception of Galileo Probe and Huygens

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Galileo Probe</th>
<th>Huygens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>L</td>
<td>S</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>1387.0</td>
<td>2040.0</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>Probe antenna gain to Earth (dBi)</td>
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<td>4</td>
</tr>
<tr>
<td>Distance to Earth (AU)</td>
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<td>8.1</td>
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<tr>
<td>Receiving antenna</td>
<td>VLA</td>
<td>NRAO 100-m</td>
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<tr>
<td>Receiving diameter (m)</td>
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<td>100</td>
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<tr>
<td>Receiving efficiency</td>
<td>0.5</td>
<td>0.7</td>
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<tr>
<td>Receiving noise temperature (K)</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>Received voltage SNR in 1-second</td>
<td>4.9</td>
<td>5.5</td>
</tr>
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</table>
Figure 5. Geometry for DWE wind measurements Probe-to-Orbiter and Probe-to-Earth in a Titan-fixed coordinate frame. The projected positions of Probe, Orbiter, and Earth are plotted on the Titan surface for the time of the nominal mission on 14 January 2005. The Probe position remains constant for the no wind case assumed here. The sub-Earth and sub-Sun points, indistinguishable at this scale on this date of solar opposition, drift westward due to Titan's rotation. The Probe–Orbiter projection is aligned essentially along the zonal (E-W) direction. The Probe-Earth projection is slightly inclined to the Probe-Orbiter projection, thereby making it more sensitive to possible meridional motion.

experiment conducted at almost maximum Earth range near solar conjunction. An important factor is the comparative transmitter antenna gain in the direction to Earth, which is within the 3 dB beam and thus distinctly more favorable for the Huygens geometry at Titan than for the Galileo Probe at Jupiter. Probe motion due to rapid planetary rotation, which carried the Galileo Probe beyond the planetary limb and further degraded the effective radiated power toward Earth, will not be a problem for the Huygens DWE.

The relevant geometry for the Titan wind measurements is shown in Figure 5 for the nominal Huygens mission. Titan, orbiting Saturn at a constant distance of 20.4 Saturn radii, is located fairly close to Saturn's noon meridian on this date.
The sub-Earth and sub-Sun points are virtually identical because Saturn is exactly at opposition. The ground tracks of the Cassini Orbiter, Huygens Probe and sub-Earth points are shown in a Titan body-fixed coordinate system from a viewpoint above the intersection of Titan’s equatorial plane with the Titan anti-Saturn meridian (180°). It is assumed in this plot that the Probe descends straight down in the body-fixed frame (no winds). The trajectory of the Orbiter projects to a point northwest of the Probe and moves during the mission in northwesterly direction. The Probe-Orbiter Doppler shift measures primarily the Probe zonal velocity (after removing the vertical motion). The Probe-Earth Doppler basically detects the same Probe motion in reverse, but with a slightly larger admixture of meridional velocity. Although angular separation of the two Doppler measurement directions is not near the optimal 90°, the two measurement sets could still allow for separation of the zonal and meridional winds.

In spite of the improvement over the Galileo Probe experiment, the strength of the Huygens signal will still be too weak to detect directly at the Earth antennas because the signal is strongly modulated by the (then) unknown telemetry. Instead, wide-band recordings of the Probe signal will be made during the three-hour Probe descent. After the Probe telemetry is relayed to Earth by the Cassini Orbiter, the recorded signal would be processed against a model of the telemetry, enabling signal integration over several seconds for the Probe carrier frequency measurements.

4. DWE Instrumentation

4.1. END-TO-END CONCEPT

DWE is the only Huygens investigation with instrumentation on both Probe and Orbiter (part of the Probe Support Equipment – PSE). Figure 6 shows a block diagram of the DWE measurement from start to finish. The DWE-TUSO drives the signal generated by the Transmitter A, one of the two redundant radio links. The carrier signals of the radio links are separated in frequency (A: 2040 MHz; B: 2097.1 MHz) and polarization (A: LCP = left circularly polarized; B: RCP = right circularly polarized). An internal TCXO oscillator drives link B and another TCXO serves as back-up on link A in case of TUSO failure during cruise. The final selection of oscillators on link A will be made a few days prior to Probe-Orbiter separation. The TUSO output signal at 10 MHz is upconverted to 2040 MHz and transmitted to the dedicated Probe Support Avionics (PSA) Receiver A on the Orbiter via the Cassini High Gain Antenna (HGA). Cruise checkouts, which are conducted approximately every six months, enable continuous monitoring of the DWE components and radio subsystem. At Titan the signal is amplified for free-space transmission via the Probe transmitter antenna. Receiver A is tuned to the nominal Transmitter A output frequency at 2040 MHz in checkout mode ($f_{\text{ref}} = 0$) and is shifted by $f_{\text{ref}} = +38.5$ kHz for descent mode.
Timing and signal generation in PSA-A are controlled by the DWE-RUSO. Switching to a back-up TCXO is possible in case the RUSO fails. Phase-lock loop control in the receivers is governed by a numerically controlled oscillator (NCO), the output of which provides the DWE frequency measurement at 8 samples per second. The signal level is monitored in parallel at the same sample rate. The TUSO will be powered well before the initial transmission from the Probe (as much as four hours head start), in order to warm up and achieve the required frequency stability. The RUSO has a much more favorable thermal environment and will be switched on about one hour before the start of data reception.

4.2. TRANSMITTER AND RECEIVER USO PROGRAMS

The DWE ultrastable oscillators, the first rubidium oscillators used in a deep space mission, were developed and constructed by Daimler-Benz Aerospace – DASA, Satellite Systems Division (now: Astrium Telecommunications), Ottobrunn, Germany. The DASA design concept was built around a Rb-resonator in a ‘physics package’ supplied by Efratom Elektronik GmbH.

The required fast warm-up time and insensitivity to the mechanical loads expected during the Huygens entry phase were the major drivers in the selection of a rubidium ultrastable oscillator. The DWE instrument specification imposed a requirement for a frequency stability over the duration of the mission of \( \delta f_0/f_0 < 2 \cdot 10^{-10} \) (\( f_0 \): nominal output frequency) within a 30-minute warm-up time. This could not be guaranteed with a state-of-the-art quartz oscillator.
Each USO consists of the physics package (rubidium resonance cell and lamp plus an SC-cut crystal) and six printed circuit boards integrated into an aluminum box (Faraday cage). The temperatures at three points in the physics package are monitored by analogue sensors. A lock indicator is provided to telemetry when the output is phase-locked to the Rb resonance frequency.

The mass of each unit is 1.9 kg, packed into a rectangular volume of approximately $17 \times 12 \times 12$ cm. The peak power consumption is less than 18.4 W during a warm-up time of $\sim$20 min, after which the power drops to a steady-state value $\sim$7.8 W (nominal values for the expected ambient temperature of 5 °C during Titan descent).

The actual drift stability determined during the DWE-USO qualification test program over an expanded range of temperatures ($-30^\circ < T < 60^\circ$) in vacuum (0.1 mbar) and ambient pressure was $\delta f_t/f_0 \leq 1.4 \times 10^{-9}$. This frequency stability exceeds the specified value, however, only for high temperatures ($T > 40^\circ$), or when the USO needs more than the required 30 min to warm up ($T < -20^\circ$). Under the expected environmental conditions at Titan, the error in the measurement of the line-of-sight velocity due to intrinsic oscillator instability should not exceed the originally specified goal of $\pm 6$ cm s$^{-1}$. More detailed information about the mechanical, electrical and frequency characteristics of the DWE-USO are presented elsewhere (Bird et al., 1997a,b).

5. Results of First In-flight Tests

The first in-flight checkout (F1) of the Huygens Probe payload occurred as planned on 23 October 1997, 8 days after the launch of the Cassini spacecraft. Only very minor problems were found in the quick-look data and a back-up checkout scheduled as contingency at launch +12 days was declared unnecessary.

An overview of the DWE data recorded during F1 is shown in Figure 7. The top two panels of Figure 7 show the recorded frequency $f_R$ in the two redundant radio chains at the same scale, starting 40 min after the start of the checkout. The received signal level ($AGC = \text{automatic gain control}$) is shown for chains A and B in the bottom two panels. Both $f_R$ and $AGC$ are recorded at a sample time of 125 ms.

The initial 20 min are used for warming up the receivers and other Probe Support Equipment, including the DWE-RUSO. Measurements of frequency relevant to the nominal mission at Titan are possible only after an additional 20 min, which are allocated to the same warm-up process for the DWE-TUSO. This procedure is necessary only for the cruise checkouts. The nominal sequence of events during the actual mission at Titan are such that both DWE-USOs will be warmed up and stable at the moment the Huygens signal is acquired.

Whereas the TUSO/RUSO combination governs the recorded frequency in chain A, the standard oscillator frequency measurements in chain B are highly irregular.
Figure 7. Huygens-DWE recorded frequency and signal level during the first in-flight checkout. Doppler data for radio chains A and B (upper 2 panels) are shown at the same scale (left ordinate: frequency in Hz; right ordinate: radial velocity in m s⁻¹). Chain A, driven by USOs, is frequency-stable. In contrast, chain B (no USOs) displays random oscillator drifts and discontinuities. The signal level (AGC) traces are virtually identical in the two chains (lower two panels). The first 40 min of the test (USO warm-up period) are not displayed.
The jumps in frequency, which arise from a thermal feedback loop driving a standard radio oscillator, are apparently random. Upon closer inspection of the intervals between jumps, it is found that the recorded frequency exhibits an unpredictable drift of instrumental origin. The frequency trace in chain A remains at its nominal value near 0 Hz during the entire checkout (Huygens is obviously not moving with respect to the receivers on the Orbiter). The large deviation from $f_R = 0$ in chain B is due to the imprecise output frequencies of the standard oscillators, which are constrained only to one part in $10^6$. Unusual time profiles are seen in the signal level recordings (AGC), whereby both chains display the same irregular decrease by about 1 dB over the duration of the test. It was determined that this anomalous behavior, as subsequently verified by a special AGC-test after the first Venus flyby, was caused by solar radio noise entering the receivers through the sunward-pointed Cassini HGA. This interference essentially vanished after the Cassini spacecraft reached a solar distance of 2.7 AU, at which point the HGA was no longer needed as a sunshade and could be pointed at Earth for the remainder of the cruise phase.

It was determined rather late in the Probe pre-launch test program that a small, but annoying, spurious oscillation was present in the chain A frequency data. The amplitude of this oscillation was enhanced significantly after the Probe was mated to the Orbiter for launch configuration and was also seen to increase over the duration of the pre-launch checkout tests.

A high-resolution plot of the recorded frequency in radio chain A over a one-minute interval during F1, shown in the upper panel of Figure 8, reveals this spurious oscillation at a time when it had almost reached its maximum amplitude of 25 Hz peak-to-peak (p-p). The frequency of the spurious oscillation, as marked by the dominant peak in the power spectrum (Figure 8, second panel), is very constant at $f_s = 0.366$ Hz. This spectrum is the Fourier transform of the frequency time series in the test elapsed time interval from 50–200 min (Figure 7, upper panel). Harmonics of this frequency are also evident in the spectrum, albeit with considerably less power.

It was recognized soon after the discovery of the spurious oscillation that the unwanted modulation in the data could be eliminated by a Fourier filtering technique. The filtering procedure consists of re-assigning all spectral amplitudes above a given threshold to values at the noise level, selected randomly from the spectrum baseline. The third panel of Figure 8 shows such a ‘filtered spectrum’. Although the two spectra look quite different, only 191 points of the original spectrum (from a total of 72 000) with amplitudes above the (arbitrary) cutoff at 10 Hz$^2$/Hz were reduced to noise levels by this process. The spectral power amplitudes at frequencies below 1 mHz, which are basically responsible for long-term drifting, were left unfiltered.

Finally, applying an inverse transform to the filtered spectrum, one obtains the filtered frequency trace in the time domain shown in the bottom panel of Figure 8. The spurious oscillation has virtually vanished. The filtered frequency measurements are centered at $\langle f_R \rangle \simeq -2.8$ Hz and the standard deviation is $\sigma_f \simeq 1.5$ Hz.
Figure 8. High-resolution frequency data from chain A during a one-minute interval beginning at 125 min. after start of test (upper panel). A power spectrum of the F1 frequency data from Figure 7 is shown in the second panel. The spurious oscillation, with amplitude \( \sim 20 \text{ Hz} \) (p-p) and constant frequency \( f_s = 0.366 \text{ Hz} \), is evident in both data and spectrum. The spectral amplitudes of the original spectrum are reduced to the noise level at frequencies near \( f_s \) and its harmonics to produce a 'filtered spectrum' (third panel). The inverse transform of the filtered spectrum yields a frequency time series without the spurious oscillation (last panel).
for the data sampling rate rate of $f_d = 8$ Hz. The accuracy of the frequency measurement can be improved by increasing the integration time up to values near the natural time constant of the Probe system. This will be of the order of a few tens of seconds near the start of descent, decreasing to a few seconds just prior to impact (Bird et al., 1997b). Assuming the data of Figure 8 are representative of the actual descent on Titan, we can expect to obtain a radial velocity measurement accuracy of the order of $\sigma_{\Delta v} \simeq \pm 6$ cm s$^{-1}$ for a typical integration time of 2 s.

After considerable study, it has become known that the probable cause of the spurious oscillation is an internal USO signal used in a feedback loop to apply a small AC magnetic field to the rubidium cell. The oscillation frequency of this signal ($f_m = 135.63$ Hz) is derived from the 10 MHz USO output signal. When sampled by the receiver at the sampling rate $f_d$, an apparent spurious oscillation appears at the frequency $f_s = n \cdot f_d - f_m = 0.3663194$ Hz, where $n = 17$. Although the internal USO signal has the correct frequency to produce the spurious oscillation, it is still unclear why the amplitude grows from 8 to 25 Hz (p-p) over the duration of the checkout. Having monitored this disturbance for a total of 8 semiannual flight checkouts through September 2001, certain patterns in the amplitude of the spurious oscillation have emerged. Among these is a weak correlation between the received frequency offset and the oscillation amplitude that may be useful for final calibration of the DWE data from Titan. Still unknown, however, is the reason why the effect increased so dramatically when the Probe configuration was closed and then mated to the Orbiter for launch. Viewing the situation optimistically, this historical development implies that the oscillation amplitude may well be smaller after the Probe separates from the Orbiter and transmits remotely while descending through the atmosphere of Titan.

6. Probe Relay Test: Doppler Calibration

The DWE frequency measurement $f_R$ used to determine the zonal winds on Titan is the difference between the Doppler shift of the received signal $\Delta f$ and an offset frequency $f_{\text{off}}$. This offset frequency is comprised of an internal receiver reference frequency $f_{\text{ref}}$ and the intrinsic offset frequencies of RUSO $f_{\text{off,R}}$ and TUSO $f_{\text{off,T}}$, converted to S-band.

$$f_R = \Delta f - f_{\text{off}} \quad (9)$$

with

$$f_{\text{off}} = f_{\text{ref}} + f_{\text{off,R}} - f_{\text{off,T}} \quad (10)$$

In order to determine the absolute value of $\Delta f$, it is necessary to know the value of $f_{\text{off}}$ to reasonably high precision. Atkinson (1990) demonstrated that it is possible, in principle, to conduct a Doppler wind measurement by tracking only the changes of $f_R$ between successive samples, i.e. without knowledge of the absolute
value of the measured frequency. This approach, however, may not be feasible because of constraints on the geometry between Huygens and Cassini during the Titan descent.

According to the original mission plan, which was valid until July 2001, Cassini was to approach Titan at a velocity of $-5.7 \text{ km s}^{-1}$ during nearly the entire Huygens descent (negative velocity for decreasing distance). The carrier frequency measurement (DWE science data) would have consequently been blue-shifted by about $38.5 \text{ kHz}$ with respect to the nominal $2040 \text{ MHz}$ on chain A. Because this value is higher than the maximum trackable carrier frequency deviation in the receiver ($\pm 30 \text{ kHz}$), the band pass can be tuned to either checkout mode ($f_{\text{ref}} = 0 \text{ Hz}$) used for the regular in-flight checkouts or mission mode ($f_{\text{ref}} = 38.5 \text{ kHz}$) for the mission.

This strategy was changed, however, after the above mentioned redesign of the Huygens mission with a high altitude Orbiter flyby. The new geometry greatly reduces the Cassini/Huygens range rate from the roughly constant $-5.7 \text{ km s}^{-1}$ to a nearly linear increase from $-2.5$ to $+1.6 \text{ km s}^{-1}$. The resulting Doppler shift thus varies from about $+17$ to $-11 \text{ kHz}$. Under this scenario the Huygens transmission from Titan would best be received in checkout mode. A switch to mission mode is undesired and, because of built-in precautions to default to mission mode if the signal is momentarily lost, must be inhibited by continually commanding the receiver to checkout mode.

The regular in-flight checkouts performed thus far ($f_{\text{ref}} = 0 \text{ Hz}$) have revealed a nearly constant offset between TUSO and RUSO of $f_{\text{off}_T} - f_{\text{off}_R} \approx -2.8 \text{ Hz}$. It is unlikely that the RUSO and TUSO offsets would maintain their constant difference by drifting at exactly the same rate. A far more plausible conclusion is that both RUSO and TUSO output frequencies have not changed significantly since launch. On the other hand, it cannot be taken for granted that the value for the Doppler compensation in mission mode $f_{\text{ref}}$ (never used in checkout mode) is set exactly to $38500.0 \text{ Hz}$.

An opportunity to calibrate the receiver frequency in mission mode and test the DWE instrumentation for the first time with a time-dependent Doppler shift occurred during the initial Probe Relay Test (PRT#1) conducted on 3/4 February 2000. The prime objective of PRT#1 was a flight calibration of the signal-to-noise measurement by the Automatic Gain Control (AGC), but the test also demonstrated that carrier lock on the dynamic signal could be maintained even for very low AGC levels and was declared a success from the DWE standpoint. Unfortunately, the test also demonstrated that the receivers were unable to demodulate the synthetic telemetry data. A more detailed analysis revealed a serious design flaw in the receiver that could only be circumvented with an extensive complete overhaul of the Huygens mission. A follow-up test (PRT#2) was performed approximately one year later to better characterize the link performance as a function of the various signal parameters.
As illustrated in Figure 9, a direct measurement of $f_{ref}$ could be obtained during the third Probe Relay Test (PRT#3) on 18 June 2001, scheduled primarily to verify the tracking capabilities of the carrier tracking loop.

Similar to the two previous PRTs, a simulated Huygens signal was uplinked to Cassini at various power levels from the Goldstone DSN station DSS 24. The Huygens Probe itself, including the TUSO, remained dormant. Correspondingly, the frequency offset for the PRT was $f_{off} = f_{ref} + f_{off,R}$. The signal was received with the Cassini HGA and routed to the Huygens dedicated PSA.

The uplink frequencies were generated by a Hydrogen maser, the stability of which is superior to that of the DWE-USOs by about two orders of magnitude. For the tests on chain A with RUSO, the frequency was programmed to sweep over a range from +78 to −40 kHz around the nominal value of 2040 MHz. It was confirmed that the carrier loop bandwidth is ±31 kHz. During these frequency sweeps, the band pass was switched instantaneously from mission to checkout mode.

The determination of $f_{ref}$ was performed by comparing the frequency measurements before and after the mode switch (see lower panels of Figure 9). The switch itself led to a link interruption (Carrier Lock Status = ‘no’) of about 10 s. The frequencies measured before the switch were extrapolated using a linear regression
and the result compared with the post-switch frequency. The slopes of the pre- and post-switch Doppler traces (about 100 Hz \( s^{-1} \)) differed by less than \( 10^{-4} \). A best fit was obtained for an internal reference frequency \( f_{\text{ref}} = 38\,504.2 \text{ Hz} \). The same procedure was applied to a second switch to checkout mode from the same test sequence. A mean value from these two measurements was \( f_{\text{ref}} = 38\,504.1 \pm 0.2 \text{ Hz} \). As mentioned earlier, the actual Huygens mission will now most probably be conducted with the receiver in checkout mode, rather than the Doppler-shifted mission mode. Nevertheless, the good agreement with the pre-launch calibration for \( f_{\text{ref}} \) and the excellent carrier lock performance during the series of PRTs do provide their small measure of encouragement for a successful DWE at Titan.

7. Conclusions

The Huygens Doppler Wind Experiment is designed to determine the direction and strength of Titan’s zonal winds. The wind is measured over a height range from 0–160 km from its Doppler signature on the Probe’s radio relay signal to the Cassini Orbiter. Similar Earth-based observations will be recorded in order to separate meridional from zonal drift motion. The necessary frequency stability of the Probe carrier signal and its measurement on the Orbiter is realized by using rubidium ultrastable oscillators. In spite of a slight imperfection due to a spurious oscillation of the frequency measurement, the DWE instrumentation is fully functional and capable of meeting the originally defined scientific goals. Final trajectory reconstruction and analysis of Probe dynamics will benefit from the DWE data, enhancing the overall scientific yield of the Huygens mission.

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