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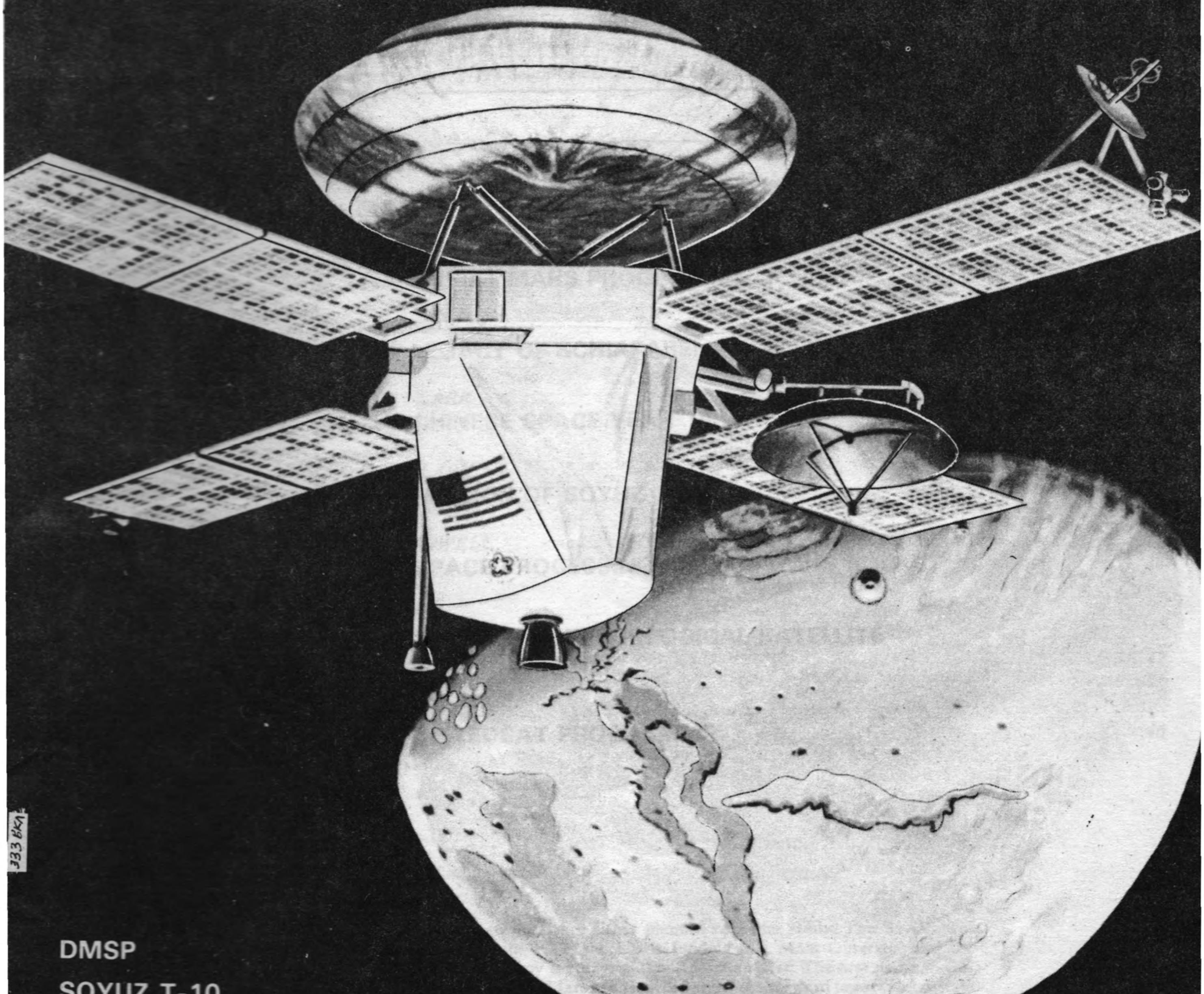
SPACE CHRONICLE



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SPACE CHRONICLE

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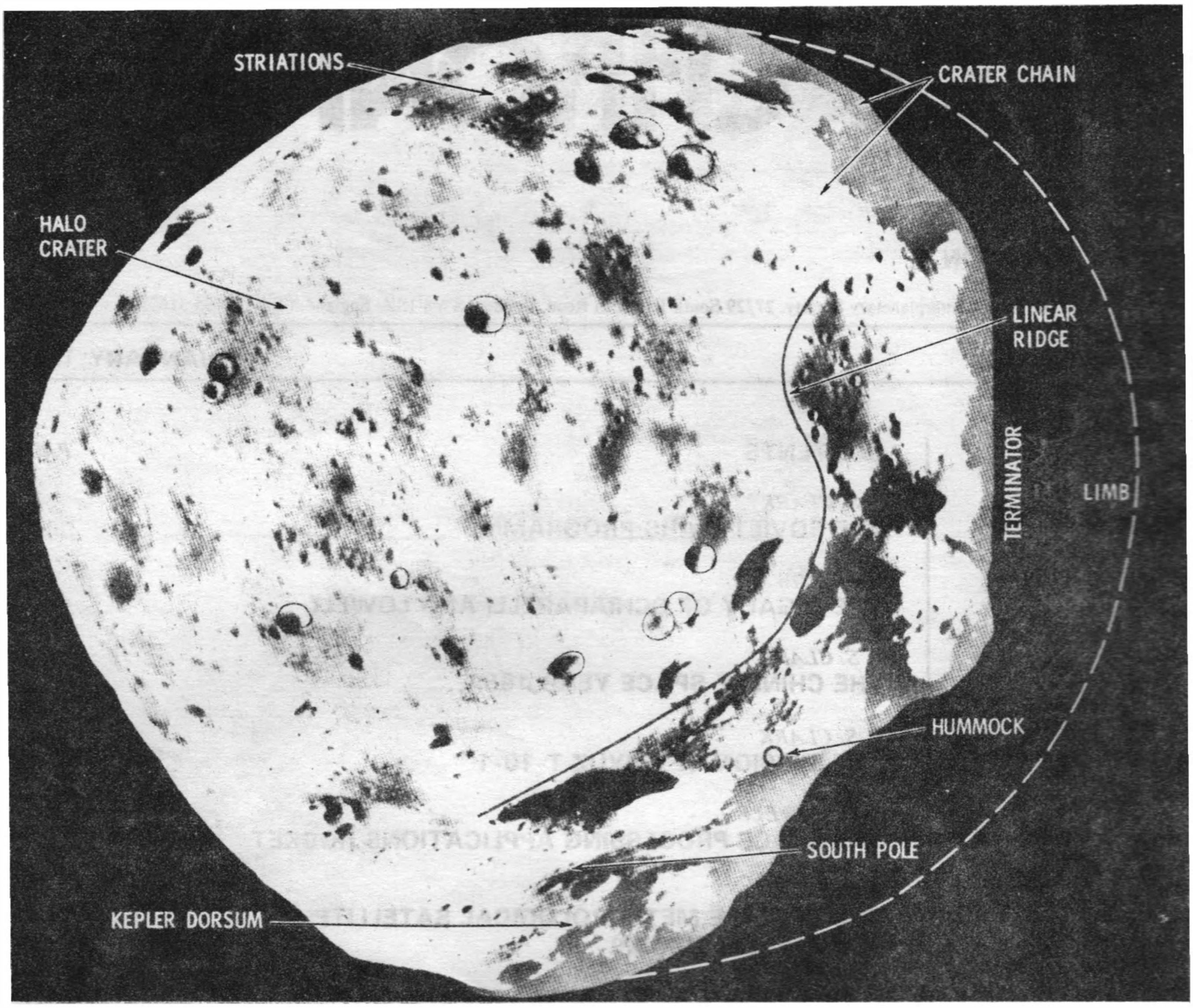
COVER

Several missions to Mars are either planned or under study. The Soviets will launch two probes in 1988, the US is funding the 'Mars Observer' and the European Space Agency is studying the 'Kepler' orbiter. The first paper in this issue discusses the Soviet Mars probe record and looks forward towards a possible sample return mission during the 1990's.

NASA



The Soviets have announced their intention of launching two Mars probes in 1988, part of which will land on Phobos (seen above). If the first attempt is successful, the second will land on Deimos.

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THE SOVIET MARS PROGRAMME

P. S. CLARK
Lee, London.

Beginning in 1960, the Soviet Union launched a number of probes to explore the planet Mars. While the contemporary Venus venture met with many successes, the Mars programme, using the same spacecraft technology, met with failure. Only one mission was a total success (Mars 5). This paper reviews the Mars programme, looking at the launch and arrival conditions that have applied and how the spacecraft have performed. Details will be given of future launch opportunities and a possible sample return mission will be examined. A companion paper [1] covers the Venus programme.

1. INTRODUCTION

The first attempts to launch a spacecraft towards Mars came in October 1960, but the two probes launched failed to attain orbit. The first Mars probe to leave parking orbit was Mars 1, launched in November 1962. A total of seven named "Mars" probes have been launched to the planet, with a single additional launch being given the "Zond" name. There were failures to reach orbit in 1960 and 1969, with additional failures to leave Earth parking orbit being given the "Cosmos" cover name or simply not being acknowledged by the Soviets.

The development of the Mars programme since the 1960 launch failures will be reviewed here, with the reasons for the abandonment of the programme after the multiple failures in February-March 1974 examined.

2. THE MARS LAUNCH WINDOWS

Since it is further from the Sun than the Earth, Mars can be seen at any point along the ecliptic. When it is on the far side of the Sun it is said to be in *conjuction* (the qualifier "superior" is not needed, since it cannot have an inferior conjunction). The planet then appears as it draws away from the western limb of the Sun. *Western quadrature* occurs when the Earth-Sun-Mars angle is 90°. Mars continues to draw away from the Sun although, since Earth moves more swiftly in its lower orbit, the relative velocities of the planets means that Mars can appear to move in a retrograde direction. When the three bodies are in a straight line, Mars is said to be at *opposition* (i.e. opposite the Sun in the sky) and it can be seen south at midnight local time. Mars then appears to draw closer to the Sun, passing through *eastern quadrature* and then conjuction again.

Taking the viewpoint of observers on both the Earth and Mars, the following equivalents are clear:

Mars at western quadrature = Earth at eastern elongation

Mars at opposition = Earth at inferior conjunction

Mars at eastern quadrature = Earth at western elongation

Mars at conjunction = Earth at superior conjunction

Compared with the orbits of Venus and the Earth, the orbit of Mars is very eccentric. Again taking a Martian observer's viewpoint, when Mars is at perihelion (1.3814 astronomical units) the maximum elongation of the Earth is 46.4° from the Sun, while at aphelion (1.6660 AU) the maximum elongation is only 36.9°. Launch windows to Mars occur at about the time of western quadrature, although the slower velocity of Mars means that the windows can last for 6-8 weeks. Arrival at Mars comes about 4-6 months after opposition.

Mars takes 686.98 Earth days to orbit the Sun. This means that eight Martian "years" are equal to approximately 15 Earth years. The figures are not as exact as in the relationship for Venus, the difference being 17 days (for Venus, the difference was only one day). Generally, the launch windows to Mars repeat after 15 years, although because of the orbital eccentricity the energy requirements vary greatly. The interval between successive windows is the synodic period, 779.9 days on the average. Again, the orbital eccentricity means that the synodic period can vary greatly, as the following examples based upon the Martian oppositions of 1963 to 1980 illustrate:

1963 February 4-1065 March 9 = 764 days
1965 March 9-1967 April 15 = 767 days
1967 April 15-1969 May 31 = 777 days
1969 May 31-1971 August 10 = 801 days
1971 August 10-1973 October 25 = 807 days

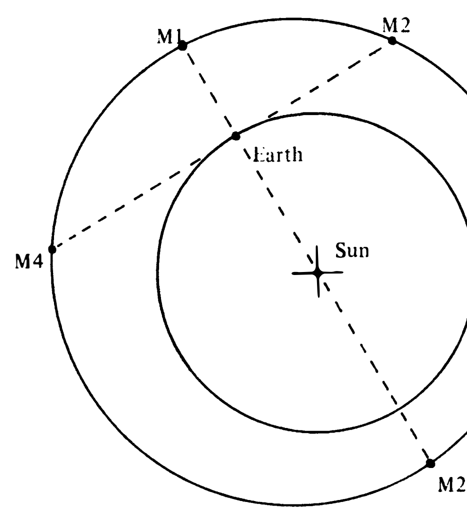

Fig. 1. The orbits of Earth and Mars drawn to scale. For convenience, the Earth is shown to be stationary. When at M1 relative to the Earth, Mars is at opposition, at M2 eastern quadrature, at M3 conjunction and at M4 western quadrature.

Table 1. Launch and Arrival Data for Mars Missions.

Mission	Launch Date	Earth at Launch Lon °	Earth at Launch Dist AU	Mars at Launch Lon °	Mars at Launch Dist AU	Encounter Date	Earth at Encounter Lon °	Earth at Encounter Dist AU	Mars at Encounter Lon °	Mars at Encounter Dist AU
Mars-1960A	1960 Oct 10	16.6	.998	57.2	1.491	(1961 May 13	231.9	1.010	158.7	1.666)
Mars-1960B	1960 Oct 14	20.6	.997	59.4	1.496	(1961 May 15	233.8	1.011	159.6	1.665)
Mars-1962A	1962 Oct 24	30.0	.995	86.8	1.564	(1963 Jun 17	265.0	1.016	193.3	1.630)
Mars 1	1962 Nov 1	38.0	.992	90.7	1.574	1963 Jun 19	266.9	1.016	194.2	1.629
Mars-1962C	1962 Nov 4	41.0	.992	92.2	1.577	(1963 Jun 21	268.8	1.016	195.1	1.627)
Zond 2	1964 Nov 30	67.7	.986	124.8	1.643	1965 Aug 6	313.2	1.014	238.8	1.526
Mars-1969A	1969 Mar 27	186.0	.998	216.3	1.582	(1969 Aug 11	318.0	1.013	290.6	1.416)
Kosmos 419	1971 May 10	228.5	1.010	261.5	1.472	(1971 Nov 22	58.8	.998	21.7	1.419)
Mars 2	1971 May 19	237.2	1.012	266.6	1.461	1971 Nov 27	63.8	.987	24.7	1.424
Mars 3	1971 May 28	245.8	1.013	271.7	1.450	1971 Dec 2	68.9	.986	27.7	1.429
Mars 4	1973 Jul 21	297.8	1.016	331.8	1.382	1974 Feb 10	140.6	.987	89.3	1.570
Mars 5	1973 Jul 25	301.7	1.016	334.3	1.381	1974 Feb 12	142.6	.987	90.3	1.573
Mars 6	1973 Aug 5	312.2	1.014	341.3	1.382	1974 Mar 12	170.8	.993	103.7	1.604
Mars 7	1973 Aug 9	316.0	1.014	343.8	1.383	1974 Mar 9	167.8	.993	102.3	1.601

Notes.
This Table lists all the known or rumoured launch failures in the Mars programme. Launch dates are generally known (that for Mars-1969A is the most widely reported) and encounter dates shown in parentheses are estimated from other missions and from considering the relative positions of the Earth and Mars. "Lon" is the ecliptic longitude of the planet as seen from the Sun, while "Dist" is the distance of the planet from the Sun in astronomical units.

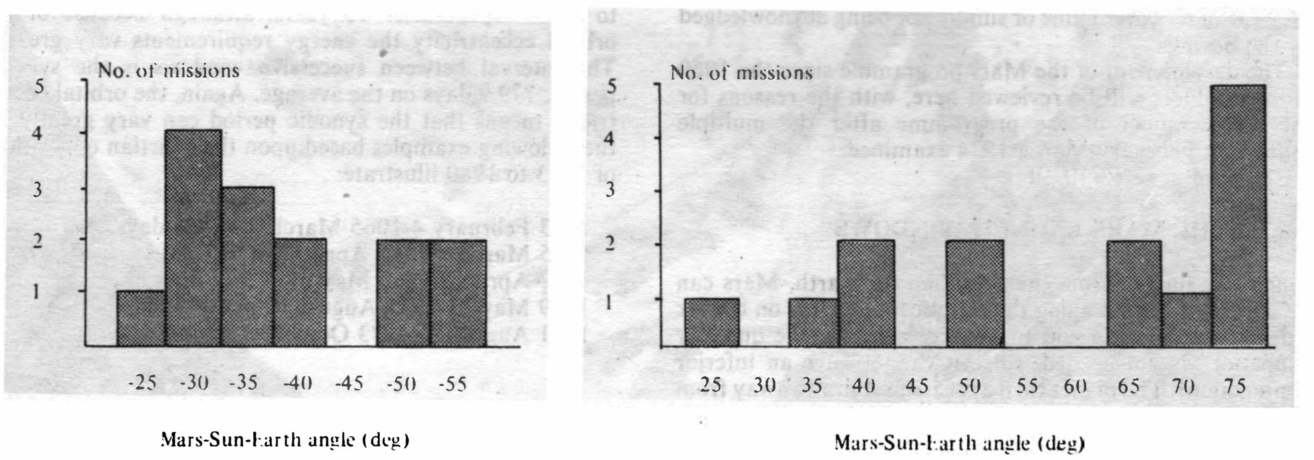

Fig. 2. Frequency plots of the angles Mars-Sun-Earth for (a) launches in the Soviet Mars probe programme and (b) at arrival at Mars. For Mars arrival, not only have the actual arrival dates been used, but also the estimated data presented in this paper.

1973 October 25-1975 December 15 = 781 days
1975 December 15-1978 January 22 = 769 days
1978 January 22-1980 February 25 = 764 days

The longer intervals between successive oppositions occur when the oppositions take place near Mars' perihelion point, and thus mark the years of favourable launch opportunities.

3. TRAJECTORIES TO MARS

When a spacecraft is launched towards Mars, it must depart in a direction so that its velocity vector is in the same general direction as that of the Earth's. As already noted, because of the orbital eccentricity of Mars, the launch windows vary, depending upon whether intercept is to be near Martian perihelion (favourable) or aphelion (unfavourable). Taking the minimum energy trajectory, with an intercept of Mars 180° away from the launch point, the minimum launch delta-V from a 200 km circular parking orbit is 3461 m/s for an intercept at Martian perihelion, while an aphelion intercept requires a launch delta-V of 3771 m/s, some 9% larger. Of course, this means a difference in payload mass: for Proton launch with a parking orbit mass of 25,000 kg and a stage with a dry mass of 1,700 kg and specific impulse of 314 seconds [2], a perihelion intercept would produce a payload of 6,425 kg, while an aphelion intercept would allow a payload of only 5,645 kg. On actual missions, the minimum energy orbits with intercepts 180° away from launch have not been used (these would lead to transit times of 237 days for a perihelion intercept and 281 days for an aphelion intercept), and thus the launch delta-Vs have been higher

TABLE 2. Details of the Mars-A, Mars-B and Zond-B Space Probes.

	Mars-A	Mars-B	Zond-B
Spacecraft mass, kg	1042.0	1037.0	996.0
Descent module mass, kg	310.0	-	-
Radio apparatus mass, kg	75.0	140.0	140.0
Power supply system mass, kg	103.0	103.0	103.0
Scientific apparatus mass, kg	18.5	44.5	34.0
Flight time, months	7-8	9-11	10
Maximum distance from Earth, 10^6 km	230	300	330
Area of solar cells, m^2	2.4	2.4	2.4
Power generated, volts	60.0	60.0	60.0
Number of course corrections	2	2	2
Mass of propulsion unit, kg	90.0	90.0	78.0
Thrust of engine, kg	200	200	200
Total impulse of the engine, kg-sec	10,600	10,600	8,000

The figures are reproduced from p. 502 of *The Creative Legacy of Sergei Pavolvich Korolyov.*

than the minima specified here, with a corresponding reduction in payload mass.

The Type 1 and Type 2 trajectories noted in Ref. 1 for Venus have counterparts in the case of Mars. No Soviet missions have used a Type 2 trajectory and none have been announced in advance that would require such a path.

It will be assumed as a first approximation that launches are made in a direction parallel to the Earth's velocity vector, and that the method described in Ref. 3 can be used to obtain the heliocentric orbits quoted here.

4. KOROYLOV'S EARLY MARS PROBE PLANS

Just as the collected works of Sergei Korolyov [4] describe the early plans for Venus missions, data are given for possible missions to Mars. Table 2 gives basic data for the planned Mars-A, Mars-B and Zond-B craft.

As with Zond-A in connection with the Venera programme, the role of Zond-B is uncertain, other than it is related to the Mars-B probe. The bodies of Mars-A and Mars-B would have been basically the same, but with different mission modules. When preparing his designs, Korolyov used the following data for the Martian environment:

temperature -70 to +20°C

composition: N_2 100%, some O_2

No successful Mars missions had then been completed and the studies could not have been updated until late 1965 at the earliest.

The craft's power unit would have allowed the encounter distance to be altered by ± 3,900 km. Mars-A would have carried a descent capsule, designed to land on Mars at a velocity of 12-14 m/s. Mars-B would have complemented the landing with a photographic mission, flying past at a distance of 1,000-30,000 km. As with the Venus missions, these probes would have used the "Molniya" booster.

Most probably, these studies of Korolyov would have seen application with the 1964 and early 1967 launch windows, since by 1969 the Proton booster was to be ready for mission using a different craft. Since there were many failures in the programme, it is difficult to equate the Mars-A and Mars-B concepts with the missions actually flown. These in 1960 and 1962 came before the Korolyov study, but they were probably allied to the Mars-B photographic concept. Pictures of Zond 3 (see Section 5.4), a left-over from the 1964 launch opportunity, suggest that a landing capsule was carried [5], and therefore this probe and Zond 2, actually launched to Mars, were probably of the Mars-A variety.

5. THE FIRST GENERATION FLIGHTS

The first generation probes were launched by the SL-6 booster, derived from the original Sputnik launcher. Although at least six attempts were made during 1960-1964, only two craft were successful in attaining a trans-Mars trajectory. Neither reached Mars in working order, but they did return some science data during the coast periods.

5.1 Spacecraft Description

Of the probes actually launched to Mars, only a mock-up of Mars 1 has been displayed, although the displayed Zond 3 was originally intended as a Mars probe. Mars 1 seems to have been the model from which the design evolved, later to be used on the Venus programme, while Zond 3 was almost identical to the Venera 3-8 series [6].

The first generation craft was basically a cylinder with an experiment module at the base. Two solar arrays were added for power generation, and a mid-course correction engine identical to that used on the first generation Venus probes was included. A description of the basic design is given in Ref. 1.

It would be logical for the three 1962 probes to have been identical, although Mars 1 was the only one to reach heliocentric orbit. Zond 2 was probably identical to Zond 3.

It will be assumed that the 1960 probes were like Mars 1, although the window constraints suggested slightly lighter payloads than in 1962.

5.2 Launches in 1960

The Soviet Union has never directly admitted to any Mars

TABLE 3. Heliocentric Orbit Data for First Generation Mars Missions.

Mission	Launch Angle °	Launch Delta-V m/s	Flight Path Angle °	a AU	e	Transit Time days	Arrival Angle
Mars-1960A	-40.6	3938	142.1	1.403	.289	215	73.2
Mars-1960B	-38.8	3975	139.0	1.417	.296	213	74.3
Mars-1962A	-56.8	3770	163.3	1.324	.249	236	71.7
Mars 1	-52.7	3802	156.2	1.334	.256	230	72.7
Mars-1962C	-51.2	3813	154.1	1.338	.259	229	73.7
Zond 2	-57.1	3649	171.2	1.259	.216	249	74.3

Notes
The launch dates of these missions are known; in the majority of cases the arrival (or intended arrival) dates are not known. These figures assume that the arrival dates noted in Table 1 are correct. The data given above are: launch angle – angle between the Earth-Sun and Mars-Sun lines at the time of launch; launch delta-V – velocity required to attain the heliocentric orbit from a 200 km Earth parking orbit; flight path angle – angle between the Earth-Sun line at launch and the Mars-Sun line at arrival; a – semi-major axis of the heliocentric orbit in astronomical units; e – eccentricity of the heliocentric orbit; transit time – interval between launch and arrival; arrival angle – between the Earth-Sun and Mars-Sun lines at planetary encounter.

launch failures in 1960; those noted here were announced by the Americans [7]. The US monitored the boosters as they rose above the horizon from Tyuratam, but they failed at the time of third stage ignition and nothing was placed in orbit. The American announcements indicated that two probes were lost, the first on 10 October 1960 and the second on 14 October.

Since neither reached orbit and the Soviets do not acknowledge them, little is known about the flights. The SL-6 booster would have been used, this vehicle having its first successful flight in February 1961 with Venera 1.

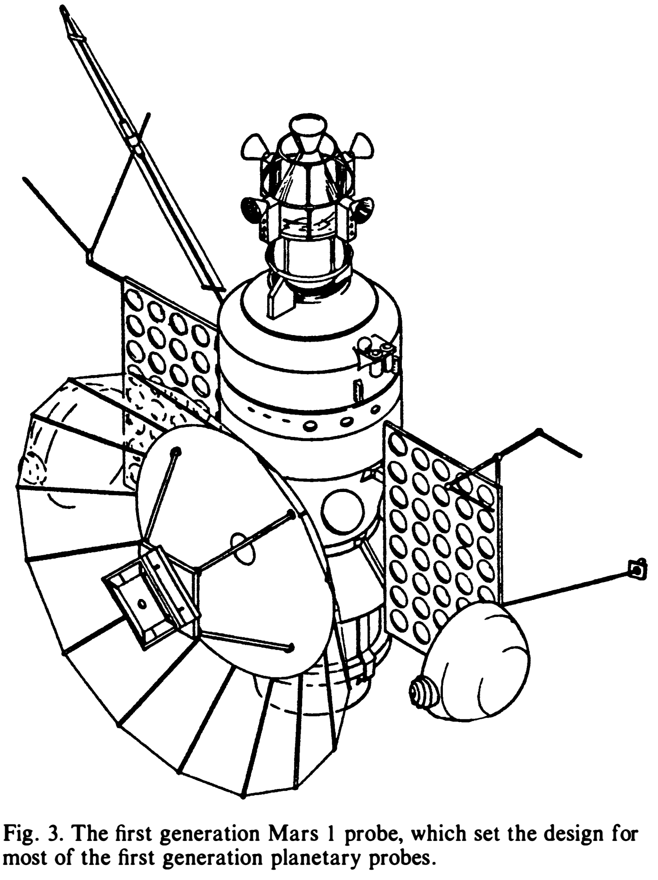

Fig. 3. The first generation Mars 1 probe, which set the design for most of the first generation planetary probes.

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From a consideration of later arrival conditions, the October 1960 craft should have arrived at Mars in May 1961; the arrival dates are taken here as 13 and 15 May. This is just before the arrival of the first planned Venus probes and if the flights had succeeded the Soviet Union would have had both a major return of scientific data and an event of propaganda value.

The two sets of craft approaching their targets might be thought to have imposed a strain on Soviet tracking systems. Since only the Yevpatoria site was operating in 1961. However two shifts of technicians could have covered the work.

By assuming the arrival dates indicated above and an initial mass of 6,450 kg (Venera 1 a few months later was 6,483 kg), a mission delta-V of 3,975 m/s implies a spacecraft mass of 850 kg (Table 4), taking the dry escape of the booster as 1,100 kg (Venera 1 was 1,098 kg) and a specific impulse of 340 seconds. This places the spacecraft in the same class as the 1962 probes, although general estimates have previously suggested masses similar to those found on the 1961 Venus missions (around 640 kg).

Two launch failures have been indicated above for the Mars 1960 opportunity, but a third attempt has been suggested [8].

Glushko lists an unidentified payload [9] for a 1960 launch and this might have been connected with a Mars flight.

5.3 Launches in 1962

The Soviet Union planned to launch three spacecraft to Mars in 1962. There must have been some doubts since, only a few months earlier, three Venus probes had failed to leave Earth orbit owing to problems with the final stages of the SL-6 booster.

The first attempt came on 24 October, when an unidentified craft was placed in Earth orbit. The Soviets made no comment and 24 objects were detected, suggesting an explosion.

A second attempt was made on 1 November: on success the mission was promptly named as Mars 1. The final attempt came on 4 November, when again the craft remained in Earth orbit, a total of five objects being tracked. In a period of four months, six planetary missions had been launched, of which only one succeeded in leaving Earth orbit.

The launch announcement said that Mars 1 had a mass of 893.5 kg, and that it would take about seven months to

reach Mars [10]. The basic objectives were said to be:

> to carry out prolonged investigations of space while flying to the planet Mars;
> to establish interplanetary radio communications;
> to photograph the planet Mars, with subsequent transmission of the photographs of the surface of Mars to Earth over radio channels.

Regular reports were carried by the Soviet press. On 2 November a photograph was taken and released three days later showing the motion of Mars 1 and its final rocket stage against the background of stars. Two days later, the accuracy of the initial orbital injection and the planned encounter distance were discussed [11]:

> The flight programme of the interplanetary station Mars 1 provided for putting it into an initial trajectory passing near Mars within a distance of 500,000 km. The design of the interplanetary station provides for corrections of its motion to be performed in flight from radio commands from Earth by means of a precise system of astro-orientation and a special engine to ensure that the automatic station flies over the surface of Mars at a height of between 1,000 km and 11,000 km. These heights will ensure that the whole programme of scientific investigations of the planet Mars is carried out. The refinements of the elements of the trajectory of motion of the interplanetary station Mars 1 which is being performed at the present time show that its trajectory, disregarding corrections, will pass at a distance of 261,000 km from the planet Mars. Correction of its trajectory should ensure that the station passes within the prescribed limits of between 1,000 km and 11,000 km from the surface of Mars.

A month into the flight the estimate of the miss-distance was refined to 193,000 km [12]. In March it was reported that communications with Mars 1 had exceeded the previous record distance set by the US Mariner 2 Venus probe – on 16 March the distance to Earth was 98,863,000 km [13]. The previous flight announcement had hinted at problems since it reported that "The strength of the radio signals from the station have slightly diminished" [14]. In May it was announced that contact had been lost [15]. The last communications session to be identified was on 21 March,. and it was presumably during this session that:

> ...analysis of the telemetry information has shown that in the Mars 1 station's system of orientation a fault has occurred, as a result of which the pointing of the on-board antennae towards the Earth has been disturbed: thus, it was not possible to make radio contact with it in subsequent sessions. At present, efforts to renew radio contact with the interplanetary station are continuing.

There was no announcement that a mid-course correction was completed, but it could have been attempted in March, destroying stability.

When it was launched, the Soviets released photographs of the spacecraft. It was very similar to the later Venera and Zond probes in the first generation series. The body was a cylinder with a total height of 3.2 m and a maximum of 1.0 m. The wings of solar cells were each 1.1 m high and 0.9 m across; each panel was attached to a radiator hemisphere with a diameter of 1.0 m. A parabolic dish antenna for communications was carried, with a diameter of 1.7 m. The experimental module at the base was cylindrical, 1.0 m in diameter and 0.6 m deep.

TABLE 4. Mass Breakdowns for First Generation Mars Probes.

	Mars-1960	Mars 1	Zond 2
Bus module, kg	565	608	825
Fuel load, kg	35	35	45
Experiment module, kg	250	250	275
Total mass, kg	850	893	1,145

Notes.
The estimated mass of the Mars-1960 probe is derived in the text. The launch mass of Mars 1 was announced; and the Zond 2 mass is from the source referenced in the text. The fuel load is calculated by assuming a 100 m/s mid-course correction capacity.

5.4 Launches in 1964-65

The launch of Zond 2 came on 30 November 1964, later in the window than expected. It is possible there were unexpected delays. Unlike Zond 1, which never had a specific planetary target announced (although it was generally accepted to be a Venus probe), the Soviets were open about the Zond 2 target [16]: "...a multi-stage carrier rocket with the automatic station Zond 2 was launched from the Soviet Union towards the planet Mars." The objectives were carefully cloaked with caution after the earlier failures:

> The object of this launch is to test the systems of the station in the real conditions of protracted space flight and to accumulate practical experience. At the same time, scientific investigations in interplanetary space are being performed.

Even with the launch announcement, however, there were hints of future problems:

> According to the telemetry data, which were obtained in the first transmissions, the power supply on board is approximately half that expected.

Possibly only one of the two solar panels had been deployed. Subsequent reports in December did not allude further to this problem. An innovation was revealed in the reports of communications sessions between 8 and 18 December [17]:

> During these sessions at commands given from the Earth, the automatic station was oriented in space relative to the Earth and to the Sun. For the first time in the actual conditions of space flight, the electro-jet plasma motors used as methods of control for the orientation system and carried on board the station were tested. Plasma electro-jet motors have a great future for use in space vehicles in prolonged flight.

It seems that contact was maintained until early May 1965, after which nothing further was announced. It was expected that Zond 2 could have passed 1,500 km from Mars on 6 August 1965, and that perhaps a parachute landing had been intended.

During the 1964 window there was only one Soviet flight announced, with no rumours of failures. However, a second launch had been planned, but the problems with Zond 2, coupled with the impending window closure, meant that the attempt had to be cancelled. The next opportunity was not

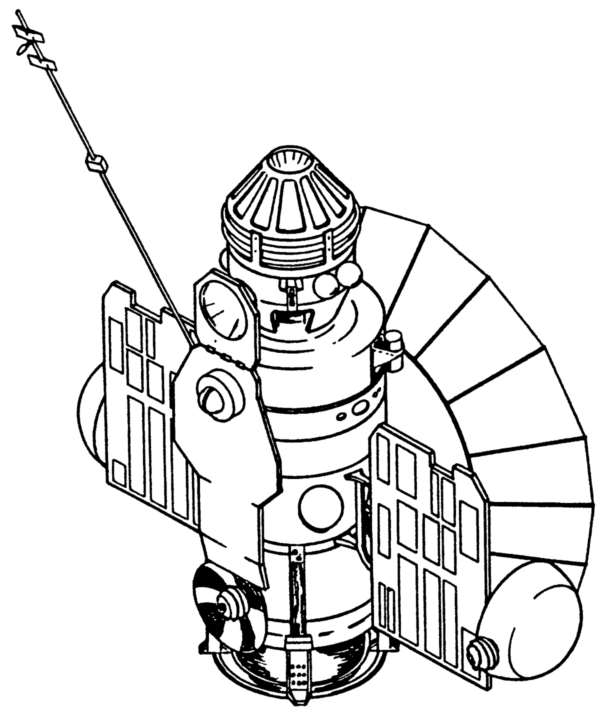

Fig. 4. The Zond 3 spacecraft, which completed a lunar fly-by. This craft should probably have been launched with Zond 2 on an impact mission to Mars.

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until early 1967, but before then there was the Venus launch window of November 1965. The Soviets wanted to ensure that the Venus probes would have better chances of success, so the second intended Zond Mars probe was launched towards a dummy planetary target to trouble-shoot the spacecraft systems.

Zond 3 was launched on 18 July 1965 with no planetary target, although the heliocentric orbit suggested a Mars mission was being simulated. The launch announcement gave no hint of the programme to be undertaken [18]:

> The purpose of this new launch is to test the station's systems in real conditions of extensive space flight and to perform scientific investigations in interplanetary space.

This should be compared with the stated objectives of Zond 2.

The main objective for Zond 3 was not an imaginary planet but the photography of part of the Moon that had been missed when Luna 3 took the first photographs of the hidden surface in 1959. The Soviets said [19]:

> ...the station carries equipment for photography in space and for transmitting pictures to Earth over long distances. For this purpose the station carries a photo-television and a transmitting radio system with a high gain parabolic antenna operating in the centimetre range. During the communications sessions this antenna is directed to Earth with high accuracy by means of the orientation system.
> In order to test the photo and television equipment in the radio channels for transmitting the image, the flight trajectory was selected so that is passed near the Moon, which made it possible to photograph the surface on the way. Photographing the Moon was begun on 20 July, 1.5 days after launch at 04.24 Moscow Time (= 01.24 GMT) when Zond 3 was at a distance of 11,600 km from the Moon's surface, and it was terminated at 05.32 MT (= 02.32 GMT) at a distance of approximately 10,000 km.

The images were sent to Earth:

> Transmission of the image began, in conformity with the programme on 29 July, from a distance of 2.2 million km, when the angular dimensions of the Earth became sufficiently small for the precise aiming of the parabolic antenna.

The initial frames covered part of the Moon as seen from Earth, but later ones covered the unknown portion of the hidden hemisphere. The photographs were to play an important role in testing of the communications system:

> For further tests of the radio link, transmission of photographs of the far side of the Moon will be continued during subsequent communications sessions, until Zond 3 is at an extreme distance from the Earth.

Over the next months, many tests were conducted with Zond 3. On 16 September, at a distance of over 12.5 million km from Earth, a mid-course correction was completed, the velocity change being 50 m/s [20]. Photographs of the Moon were re-transmitted on 23 October from a distance of about 31.5 million km [21]. The last communications session to be reported was on or just before 3 March 1966, when Zond was some 153,520,000 km distant [22].

Photographs of Zond 3 have been released, showing that it was almost identical to the Venera 3 probe landing mission. This adds to the suggestion that Zond 2 (presumably identical with Zond 3) should have tried to place a descent craft on Mars [23]. Using figures published by Glushko [24], a mass of 1,145 kg has been obtained for Zond 3, with Zond 2 being almost the same [25]. This is higher than the Venus probes launched in November (about 960 kg), but it would seem that Zonds 2 and 3 were each to perform a photographic mission as the spacecraft "buses" flew past Mars, as well as carrying the landing capsules.

5.5 Summary of the First Generation Programme

The Soviets made six attempts in the first generation Mars programme (excluding Zond 3), all of which failed to reach Mars in working order. Two did not reach orbit, two failed to leave Earth orbit and two failed during the trans-Mars coast. The most successful was Zond 3, left over from the 1964 launch window and flown on a test mission.

6. THE SECOND GENERATION FLIGHTS

In the late 1960's the large Proton booster was introduced for the lunar and planetary programmes. Its first use in the planetary programme was to launch spacecraft to Mars. Attempts were made in 1969, 1971 and 1973 using this booster, but the programme fell far short of success.

6.1 Spacecraft Description

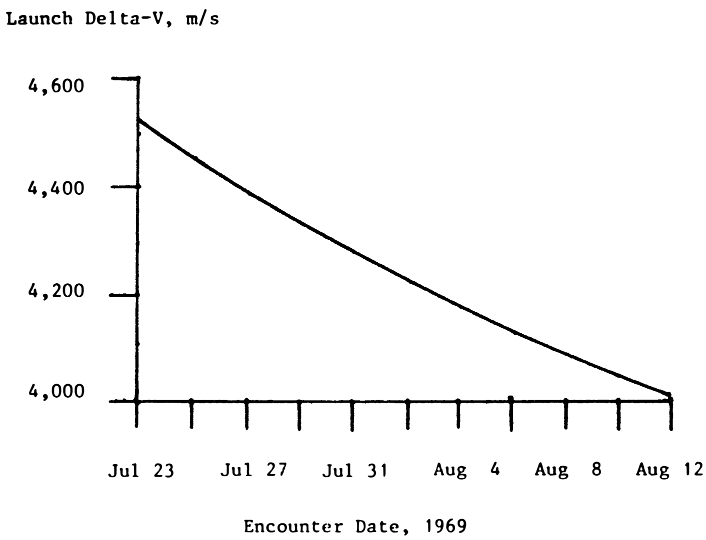
The second generation of Mars spacecraft were more than five times heavier than Mars 1 when launched fully fuelled, although on most of the flights either fuel or payload had to be sacrificed because of variations in the opportunities.

As with the first generation, the second, when carrying the landing vehicle, is in two sections: one is an orbiter or fly-by module ("bus") and the other is the combined landing

TABLE 5. Heliocentric Orbit Data for Second Generation Mars Missions.

Mission	Launch Angle °	Launch Delta-V m/s	Flight Path Angle °	a AU	e	Transit Time days	Arrival Angle °
Mars-1969A	-30.3	4030	104.7	1.443	.308	137	27.3
Kosmos 419	-33.1	3517	153.2	1.231	.180	196	37.1
Mars 2	-29.4	3537	147.5	1.243	.186	192	39.1
Mars 3	-25.9	3563	141.9	1.258	.194	188	41.2
Mars 4	-34.0	3691	151.5	1.322	.231	204	51.3
Mars 5	-32.7	3710	148.6	1.330	.236	202	52.3
Mars 6	-29.1	3737	151.6	1.340	.243	219	67.0
Mars 7	-27.8	3766	146.3	1.352	.250	212	65.4

Notes.
The same comments apply as in Table 3.



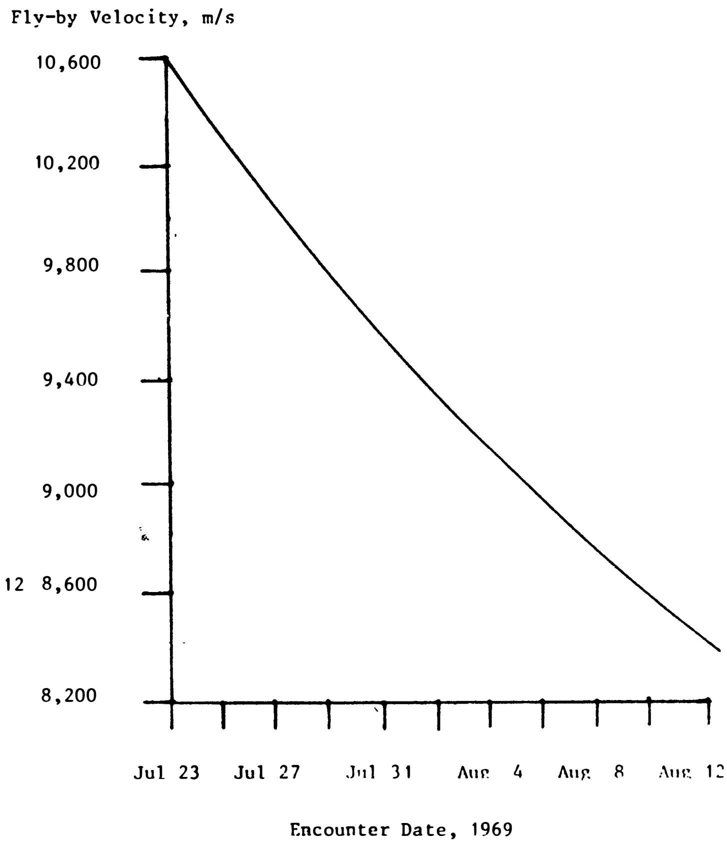


Fig. 5. The launch and arrival conditions for Mars-1969. A launch date of 27 March 1969 has been assumed. The trans-Mars launch delta-V is shown in (a) as a function of the arrival date, with the estimated arrival dates shown by an arrow. The fly-by velocity at a distance of 7,500 km is shown in (b), again as a function of arrival date.

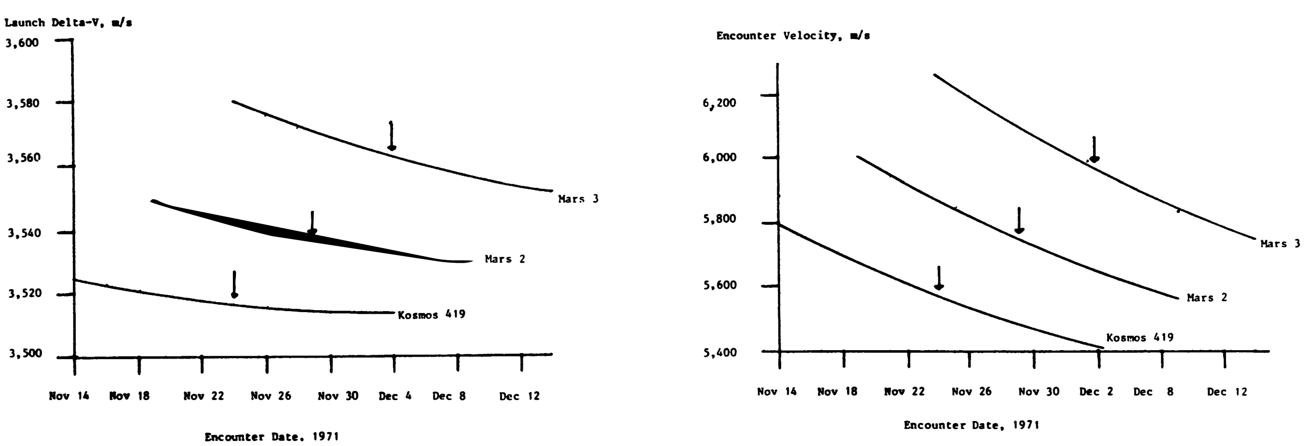


Fig. 6. The launch (a) and arrival (b) velocities for Mars-1971. The arrival velocities assume a common minimum distance of 1,450 km. The arrival date for Cosmos 419 is estimated.

TABLE 6. Second Generation Spacecraft Orbits Around Mars

Mission	Relative Velocity m/s	Encounter Velocity m/s	Delta-V m/s	Minimum Distance km	Maximum Distance km	Semi-Major Axis km	Eccentricity	Orbital Period min	Orbital Inclination °
Mars-1969A	7,996	8,473	-	7,500	-	-	>1	-	-
Kosmos 419	3,679	5,586	1,825	1,450	16,038	12,139	.601	677	-
			1,900	1,450	12,718	10,479	.538	543	-
Mars 2	3,936	5,759	1,863	1,380	24,938	16,554	.712	1,078	48.9
Mars 3	4,257	5,968	1,837	1,500	190,333	99,311	.951	15,840	60
Mars 4	3,665	5,361	1,825	2,200	21,592	15,291	.634	957	-
			1,900	2,200	16,764	12,877	.566	739	-
Mars 5	3,902	5,642	1,831	1,760	32,586	20,568	.749	1,493	35
Mars 6	3,686	5,543	-	1,600	-	-	>1	-	-
Mars 7	4,171	5,969	-	1,300	-	-	>1	-	-

Notes.
In calculating the above data, the Soviet-announced orbital periods and close approach distances have been used to obtain more refined maximum distances for closed orbits about Mars than the Soviets generally announce. The fly-by missions, the minimum distance in the hyperbolic trajectory is given. For failures to attain Mars orbit, the orbital data are based upon the delta-V capacity of the vehicle shown on the Mars 2, 3 and 5 missions. An American book referenced in the text gives the following Mars 3 orbital data: period – 12 days 16 hours, minimum distance – 1,530 km, maximum distance – 209,891 km (as implied by the orbital period).

capsule and conical heat shield. The total height is about 4.7 m, with a spread of 6.4 m across the opened solar panels.

The height of the bus is about 3.5 m and the maximum diameter is 2.3 m across the torus equipment tank at the base. A 2.8 m diameter antenna is carried for direct communications with Earth. Two solar panels are carried, each about 2.3 m high and 1.4 m wide. At the back of each panel is a conical antenna for communications with the landing capsule. The antenna has a base diameter of about 0.7 m, tapering to 0.4 m, and a length of 0.9 m. The diameter of the cylindrical body of the bus – which contains the fuel tanks – is about 1.8 m.

The actual landing craft is hidden at launch inside a conical heat shield with a diameter of about 3.1 m and a depth of 0.8 m. Pictures of the landing craft initially suggested that it was a sphere with a diameter of about 1 m, but other pictures suggest that when deployed on Mars it resembles Luna 9 (which rough-landed on the Moon in 1966).

In 1971 the lander complex entered the Martian atmosphere at about 6 km/s, and it was initially slowed aerodynamically. While the craft was still travelling at supersonic velocity, the first parachute was ejected by means of a small rocket, and this pulled out the main parachute. When the main parachute was deployed and the velocity was about that of sound, the heat shield was separated. A radio-altimeter was used during the final descent: at a height of 20-30 m solid propellant retrorockets were fired for the final landing, a separate rocket system firing to take the parachute to one side so that it would not foul the lander. The Soviets have published two paintings depicting stages in the landing, one showing the radio-altimeter dish hanging below the landing craft [26].

It was only in 1971 that the full Mars probes were launched, both carrying landing craft and the fuel to enter Martian orbit. In 1973 two orbiters were launched, with landing craft carried on separate missions with fly-by modules. Most probably, the missions in 1969 were of the fly-by module/lander variety.

6.2 Launches in 1969

After the problems of the 1962 and 1964 probes, the Soviet Union decided to miss the Mars window that opened in January 1967. Contributing factors might have been the failures of the Venera probes in early 1966.

The Americans flew two fly-by probes in the Mariner series in the 1969 window, both of which were fully successful. Mariner 6 was launched on 25 February and Mariner 7 on 27 March, the first as the window opened and the second as it closed. The Soviet Union was expected to launch more advanced probes since the use of a Proton booster was anticpated. The window closed with no attempts reaching Earth orbit. However, there were reports of failures [27], with the most probable being 27 March. At the time, the Proton booster was proving troublesome and had most probably delayed the launches. If the first booster failed to reach orbit, the Soviets could have cancelled the second mission.

Arrival at Mars would probably have been in the same general time period as the American Mariner probes (Mariner 6 flew past on 31 July and Mariner 7 on 5 August). Reasonable orbits result if an arrival near 11 August is taken, giving a mission delta-V similar to Mars 6/Mars 7 of 1973. These carried fly-by modules with landing craft, so a similar mission can be projected for Mars-1969. The fly-by module could have provided close-up photographs from about 1,000 to 2,000 km, while the landing capsule could have returned surface photographs and other data for about 24 hours.

6.3 Launches in 1971

The next window saw NASA establish the first artificial satellite of Mars. Mariner 8 was launched on 9 May, but failed to reach orbit, while Mariner 9 was launched on 30 May and went into orbit about Mars on 14 November.

Once more, Soviet probes were expected. The first launch came on 10 May, but the final stage of the Proton remained attached to the orbital stage, and the mission had to be abandoned. It was identified as Cosmos 419, representing the last failure of the Proton to launch a spacecraft out of Earth orbit (although there were later failures of the Proton to *reach* orbit).

On 19 May Mars 2 was launched at 16.23 and successfully

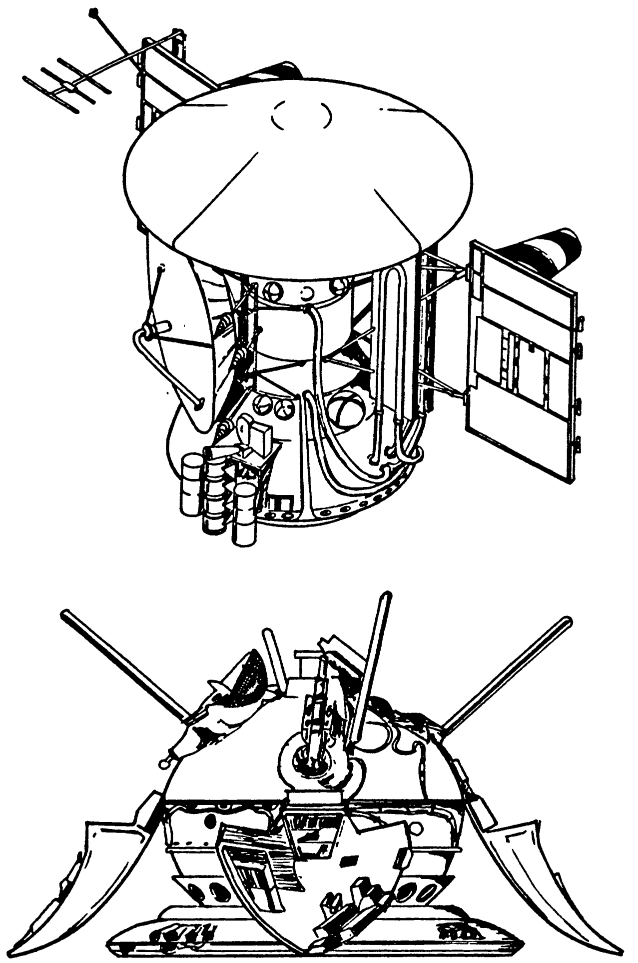


Fig. 7. The second generation Mars probe, as flown in 1971. The complete orbiter/lander craft is shown in (a), while the landing capsule as deployed on Mars is shown in (b). The Mars 6 and 7 craft, launched in 1973, were identical in appearance with the Mars-1971 spacecraft.

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left Earth parking orbit at 17.59. It was to carry "out a complex of scientific research about the planet Mars and the space surrounding it." The launch mass was 4,650 kg [28]. During the flight to Mars the probe was to study solar plasma, cosmic rays and the radiation environment. The third attempt came on 28 May at 15.26 when Mars 3 was successfully launched. During the coast phase it was to conduct measurements of the solar plasma and cosmic rays.

On 8 June at 01.20 Mars 3 underwent a mid-course correction, and on 17 June at 01.30 Mars 2 had a similar correction. On 27 November Mars 2 approached its target and the landing capsule separated. A third mid-course correction was made by the orbiter to ensure that it missed Mars (the second correction had been on 20 November) and at 20.19 the orbiter's engine ignited to place it in orbit about the planet. The initial orbit was 1,380-25,000 km, inclination 48.9° and period 18 hours [29]. The descent craft continued without any problems after a small solid propellant rocket engine had placed it on a descent trajectory.

Atmospheric entry was completed, but it crashed near 45°S, 302°W. A soft-landing had clearly been intended, but possibly the dust storm raging across the planet caused the failure.

The arrival of Mars 3 came on 2 December, with the descent craft separating at 09.14. Once more, a small solid

TABLE 7. Mass Breakdowns for Second Generation Mars Probes.

	Mars-1969	Mars 2/3	Mars 4/5	Mars 6/7
Bus module, kg	2,575	2,090	2,305	2,575
Fuel load, kg	285	1,925	2,080	285
Descent capsule, kg	450	450	-	450
Heat shield, kg	185	185	-	185
Total mass, kg	3,495	4,650	4,385	3,495

Notes:

The mass of the Mars-1969 probe is derived in the text, and is estimated: the launch masses for Mars 2 and Mars 3 were announced at the time of the launch; and the Mars 4/5 and Mars 6/7 masses are from the source referenced in the text. The Soviets have indicated that the Mars 6 capsule was 635 kg underneath its parachute, while a separate source lists the capsule itself as 450 kg. For all the probes, it is assumed that fuel is carried to allow mid-course corrections of 100 m/s during the trans-Mars coast: orbital "trim" manoeuvres after Mars orbit injection of 25-65 m/s have been allowed for Mars 2/3 and 50 m/s for Mars 4/5; and two manoeuvres, each of 100 m/s, have been allowed for Mars-1969 and Mars 6/7 "bus" modules after separation of the landing craft.

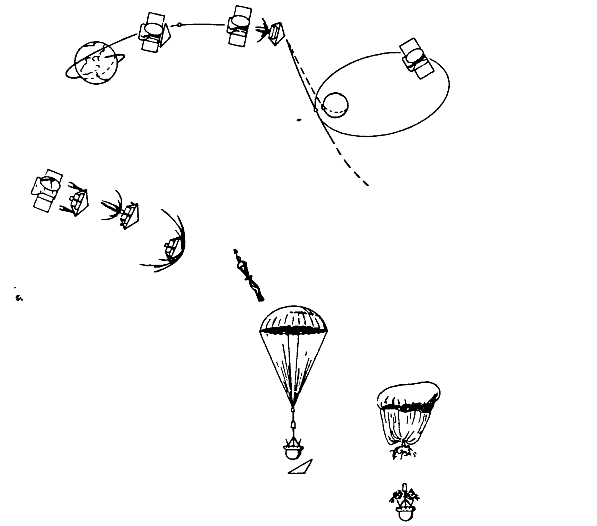

Fig. 8. The approach and landing profile of the Mars 2, 3, 6 and 7 craft. The lander separates from the main bus, deploys its parachute, separates its heat shield and uses a retro-rocket system to cushion the final landing. On Mars 2 and 3 the bus went into orbit around Mars, while on Mars 6 and 7 it flew past.

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propellant rocket was used to deflect the capsule to a landing on Mars, and atmospheric entry began at 13.44. The landing system seems to have worked perfectly, and at 13.49 the capsule landed near 45°S, 158°W. About a minute later the automatic sequencer instructed the transmission of a panorama, but after 20 seconds of signals contact was lost. Once more, it could have been a result of the dust storm, but some Soviet sources suggest that the fault lay with the orbiter, which failed to relay the data to Earth [30].

Although there were disappointments with the landing programme, the Mars 3 orbiter was successfully placed into a closed path about Mars: the Soviets announced only the close approach distance of 1,500 km and the orbital period of 11 days. These figures imply a maximum distance of about 190,300 km. An American book dealing with the

Mariner 9 programme gives more refined data [31]:

> Closest approach: 1,530 km
> Farthest approach: 190,000 km
> Orbital period: 12d 16h
> Inclination: 60°

However, the orbital altitudes do not equate with the orbital period. Taking the orbital period and closest approach distance as correct, the maximum distance from Mars should be about 209,900 km.

Although the orbits of Mars 2 and Mars 3 are very different, calculations show that the orbital injection manoeuvres were very similar. This allows an estimate to be made for the orbit intended on the Mars/Cosmos 419 mission. Taking the closest approach as 1,450 km (the average for Mars 2 and Mars 3), the maximum distance would have been 12,700 km to 16,000 km (see Table 6).

The orbiters continued successfully with their own programmes. Since the US Mariners had been concentrating on photography, the Soviets had decided not to give this a high priority. These main objectives had been [32]:

> measurements of the surface temperature of Mars by infra-red emission;
> exploration of the surface relief by the optical thickness of the atmosphere in the carbon dioxide absorption band;
> research into the photometric properties of the surface and the atmosphere;
> measurements of the water vapour content in the atmosphere;
> measurement of the temperature of the soil by the planet's radio emission;
> research into the ultra-violet emission of the atmosphere by the resonance lines of hydrogen, oxygen and argon.

The two orbiters continued working until August 1972.

6.4 Launches in 1973

After the mixed successes in 1971, it was expected that the window of July-August 1973 would see another group of spacecraft. However, the window was not as favourable (arrival in 1971 was soon after Mars' perihelion and therefore only a low delta-V was required) so it was expected that the probes would be less massive.

1973 represents the only time that the Soviets have successfully launched their full complement of spacecraft. The first to appear was Mars 4, launched on 21 July at 19.31. The launch announcement said that it would continue the programme of exploration begun by Mars 2 and Mars 3 [33]. On 25 July Mars 5 was announced: the launch had been at 18.56 and at 20.15 it had been placed in its heliocentric orbit [34]. The announcement said that Mars 5 was like Mars 4, and that "by means of scientific equipment installed on the station, Mars and its surrounding space are to be explored and the characteristics of the interplanetary medium are to be measured."

On 5 August at 17.46 Mars 6 was launched, the announcement stating [35]:

> Mars 6 differs somewhat in its design from the automatic stations launched towards Mars in July. It is envisaged that Mars 6 will carry out part of its scientific exploration with equipment on the Mars 4 station.

Finally, on 9 August, Mars 7 was launched at 17.00 with the statement [36]: "In design and mission, Mars 7 is analogous to Mars 6." Mars 4 and 5 would arrive in the first half of February 1974, while Mars 6 and 7 would arrive the following month.

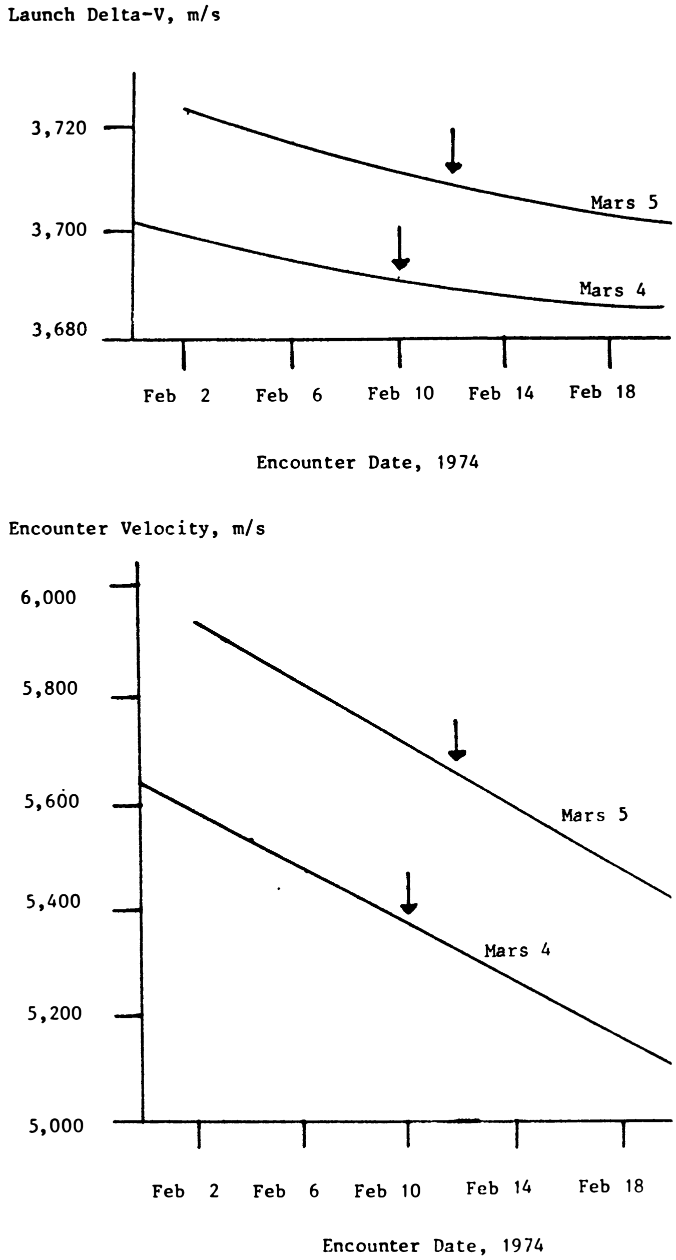

Fig. 9. The launch and arrival conditions for Mars 4 and 5, launched in 1973. In (b) a close approach distance of 2,200 km has been taken for Mars 4 and 1,760 km for Mars 5.

All four underwent course corrections within a month of launch: Mars 4 on 30 July, Mars 5 on 3 August, Mars 6 on 13 August and Mars 7 on 16 August. On 22 September it was said that although they were operating well during the journey to Mars, "at the present moment scientists are taking steps to eliminate disturbances in the operation of the telemtric system of one of the stations" [37]. Little else was said during the coast phase.

The next positive news came in mid-February 1974, when the arrivals of Mars 4 and 5 were announced simultaneously [38]. Mars 4 was the first to approach the planet (on 10 February) but "because of the faulty functioning of one of the on-board systems, the braking engine was not fired and

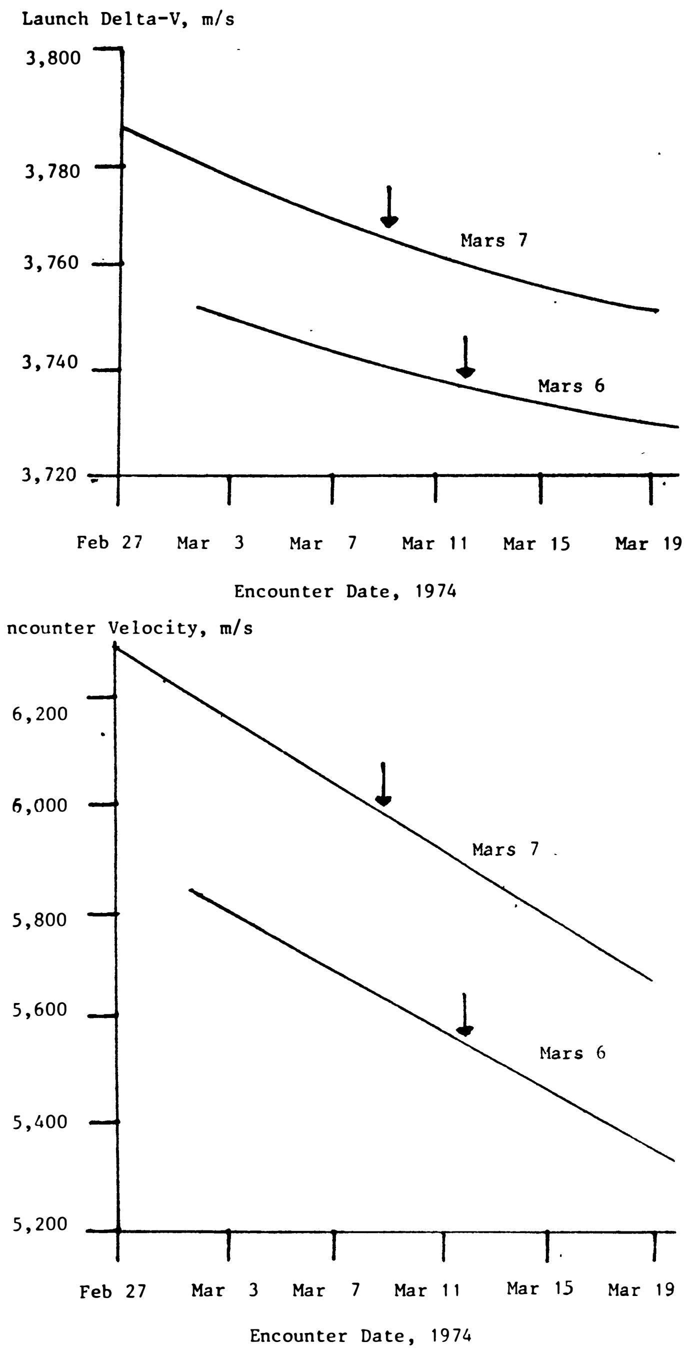

Fig. 10. The launch and arrival conditions for Mars 6 and 7, launched in 1973 on impact missions (with the buses flying past). In (b) a close approach distance of 1,600 km has been taken for Mars 6 and 1,300 km for Mars 7. It will be noted that Mars 7 arrived before Mars 6.

the station passed the planet at a distance of 2,200 km." During the unexpected fly-by photographs were taken and later transmitted to Earth.

Mars 5 fared more successfully. The approach was made on 12 February and at 15.45 the main engine fired to take it into orbit; initially the parameters were announced as 1,760-32,500 km, 35°, 25 hours, but these were later refined to 1,760-32,560 km, 35.33°, 24h 52m 50s [39]. One craft was at last in orbit around Mars, waiting for its companion craft a month later.

As with the orbiter missions, the arrivals of Mars 6 and 7 were simultaneously announced [40], but this time neither

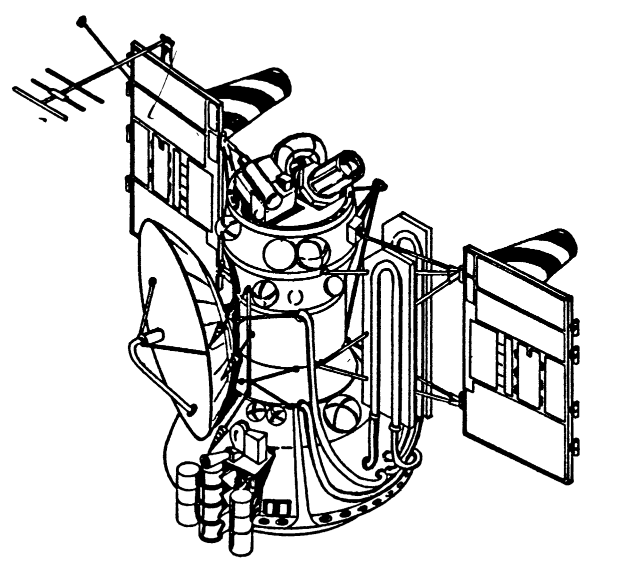

Fig. 11. The Mars-1973 orbiter spacecraft, as flown on the Mars 4 and 5 missions; an experimental platform replaces the landing capsule and its associated equipment. Mars 4 failed to attain Mars orbit.

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mission was a total success. Some time before, the Soviets had asked the Americans to supply Mariner 9 photographs of the areas 43°S, 42°W and 24°S, 25°W, and it was expected that these were the target landing areas. Owing to the failure of Mars 4, the Soviets ensured that Mars 5 would pass over the sites for communications purposes, although each lander would use its own fly-by craft as the primary link.

On 9 March the Mars 7 descent craft separated from the fly-by module, but "following a malfunction in one of the on-board systems it passed the planet at a distance of 1,300 km." Presumably, the on-board system mentioned was the solid propellant rocket used to deflect the descent craft away from its fly-by trajectory. This landing was to have been near 43°S, 42°W.

Mars 6 was more successful. On 12 March, after separating from the fly-by module, the lander entered a descent path but "in the immediate vicinty of the Martian surface radio communications with the descent module ceased." It landed near 24°S, 25°W at about 09.11. The signals were lost 148 seconds after the main parachute opened.

Therefore, out of four heavy craft launched to Mars, the Soviets obtained data from only one orbiter, two fly-by probes (plus Mars 4 on a fly-by trajectory) and one landing capsule during the initial part of its descent. The programme was an overall failure.

The masses of the craft were not released, but calculations based upon Glushko's data suggest that Mars 4/5 were about 4,385 kg and Mars 6/7 about 3,495 kg [2]. The Soviets have indicated that the landing capsule is about 450 kg on the surface and 635 kg underneath the main parachute (that is, including the heat shield).

6.5 Summary of the Second Generation Programme

The results of the second generation programme were disappointing. There were eight attempts during 1969-1973, one of which failed to reach orbit and one of which failed to leave Earth orbit. Of the six craft launched towards Mars, these can be divided into four orbit and four landing missions. Three of the four orbiters were successful, but none of the landers completed their missions.

TABLE 8. Summary of Launch Windows, 1960-2000.

Cycle 1	Cycle 2	Cycle 3	Arrival
1960 Oct 10	1975 Sep -	1990 Sep -	+1 May
Oct 14	Oct -	Oct -	+1 May
1962 Oct 24	1977 Oct -	1992 Oct -	+1 June
Nov 1	Nov -	Nov -	+1 June
Nov 4			+1 June
1964 Nov -	1979 Nov -	1994 Nov -	+1 July
Nov 30	Nov -	Nov -	+1 August
1967 Jan -	1982 Jan -	1997 Jan -	+0 August
Jan -	Jan -	Jan -	+0 August
1969 Feb -	1984 Feb -	1999 Feb -	+0 August
Mar 27	Mar -	Mar -	+0 August
1971 May 10	1986 May -		+0 November
May 19	May -		+0 November
May 28			+0 December
1973 Jul 21	1988 Jul -		+1 February
Jul 25			+1 February
Aug 5	Aug -		+1 March
Aug 9			+1 March

Notes.
The Mars launch opportunities repeat after about 15 years. Actual launch windows have the dates shown, while the launch opportunities are identified by the year, month and "–". The normal encounter months are shown, "+0" indicating that encounter is the same year as launch and "+1" indicating encounter the year after launch.

The greatest disadvantage of the spacecraft design is that the lander has to be separated and the landing made on the first fly-by. A better system is to take the lander into Mars orbit to examine the proposed site. The US Viking craft took this approach and the landings were delayed when the sites were found to be unsuitable; when better sites were found, both Vikings successfully soft-landed.

It is now more than a decade since the last Soviet mission to Mars, and as each lanch window has passed there have been no rumours of planned launches or failures. The Soviets seem to have abandoned Mars for the time being, especially since the original Mars 2 series of craft could not hope to match the success of the Vikings in 1976.

7. FUTURE LAUNCH OPPORTUNITIES

Table 8 lists future launch opportunities. The windows repeat after 15 years to within three weeks, and therefore the launch windows are shown in terms of 15 year cycles.

The data in Table 8 refer only to Type 1 trajectories and somewhat different limits apply for Type 2 (flight path in excess of 180°) paths. Launches will be 4-6 weeks earlier than quoted in Table 8, while arrival will be about 4-8 weeks after. As examples, the Vikings used Type 2 trajectories, resulting in launches on 20 August and 9 September 1975 and arrivals on 19 June and 7 August 1976.

The Soviets have talked in general terms about a number of future missions, the most common of which are:

1. Orbiter mapping mission
2. Atmospheric probe ("aeroplane")
3. Surface roving vehicle
4. Sample return mission

With the Soviet hiatus in the Mars programme, it is difficult to say which will actually be attempted this century,

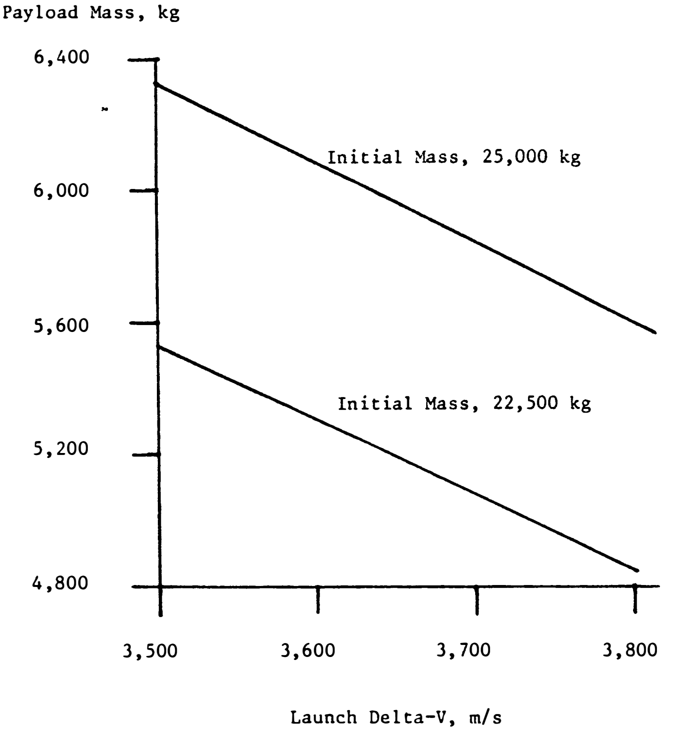

Fig. 12. The payload capacity of the Proton SL-12 booster to a trans-Mars orbit. Earth orbital masses of 22,500 kg and 25,000 kg have been assumed, and the escape stage is taken to have a mass of 1,700 kg, with the rocket engine having a specific impulse of 314 seconds.

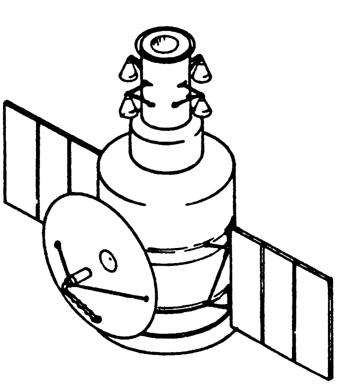

Fig. 13. Concept for the Mars Sample Return Mission orbiter spacecraft, showing the Earth return rocket stage. The main bus could be based upon the second generation Mars probe, but with a greater fuel capacity.

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if any. Technically, the orbiter mission would be the simplest to try, with the atmospheric "aeroplane" probe and surface roving vehicle ("Marsokhod") being of equal difficulty. By far the most difficult would be the recovery of a surface sample.

8. A POSSIBLE MARS SAMPLE RETURN MISSION

Based upon our present knowledge of the Soviet design philosophy, it is unlikely that they could complete a sample return mission using a single spacecraft. This could be overcome by the use of the giant launch vehicle, which is expected to be able to launch about 200 tonnes to a low

TABLE 9. Target Launch and Arrival Dates for the Mars Sample Return Mission Study.

Event	MSRM-1	MSRM-2	MSRM-3	MSRM-4
Earth launch	1994 Oct 18	1994 Oct 23	1994 Nov 2	1994 Nov 7
Mars orbit	1995 Aug 24	1994 Aug 30	-	-
Mars landin	-	-	1995 Sep 19	1995 Sep 25
Trans-Earth launch	1996 Sep 5	1996 Sep 11	-	-
Earth recovery	1997 Aug 22	1997 Aug 27	-	-
Earth launch	1996 Nov 13	1996 Nov 18	1996 Nov 28	1996 Dec 3
Mars orbit	1997 Sep 3	1997 Sep 9	-	-
Mars landing	-	-	1997 Sep 29	1997 Oct 5
Trans-Earth launch	1998 Nov 11	1998 Nov 17	-	-
Earth recovery	1999 Sep 29	1999 Oct 4	-	-

Notes.
The above dates have been chosen as representative of the launch windows in 1994 and 1996 for this study; launches in 1994 have an "A" designation in the subsequent Tables, and the launches in 1996 are designated "B."

TABLE 10. MSRM Orbiter Requirements.

Manoeuvre	MSRM-1A	MSRM-2A	MSRM-1B	MSRM-2B
Trans-Mars injection, m/s	3,700	3,685	3,635	3,625
Mid-course correction, m/s	100	100	100	100
Mars orbit injection, m/s	1,720	1,635	1,885	1,825
Orbital trim, m/s	50	50	50	50
First rendezvous manoeuvre, m/s	95	95	95	95
Second rendezvous manoeuvre, m/s	95	95	95	95
Trans-Earth injection, m/s	1,320	1,340	950	975
Mid-course correction, m/s	100	100	100	100
Mass Breakdowns				
Orbiter bus, kg	2,624	2,701	2,572	2,625
Fuel, kg	2,838	2,755	3,057	3,000
Total mass, kg	5,459	5,456	5,629	5,625
Return rocket, kg	200	200	200	200
Fuel, kg	166	169	121	125
Total mass, kg	366	369	321	325
Launch mass, kg	5,825	5,825	5,950	5,950

Notes
The velocities have been rounded to the nearest 5 m/s, and the mass requirements are the exact arithmetical results of these manoeuvres.

Earth orbit, but there are too many unknowns to prepare a meaningful study. The same comments apply to the large shuttle vehicle, said to have a payload capacity of about 60 tonnes to a low Earth orbit.

No other launch vehicles seem to be on the point of introduction capable of an advanced planetary mission, so the Proton booster has been assumed here. Figure 12 shows the payload capacities for the Proton for various mission delta-Vs, assuming the following:

1. Earth orbital masses of 22,500 kg and 25,000 kg
2. Escape stage dry mass of 1,700 kg and specific impulse of 314 seconds [2].

In support of a possible post-Viking sample return mission, NASA conducted a number of studies, looking at different mission profiles and spacecraft design [41]. Although it was to be used for the windows in 1979 and 1981, it can be used as a guide for 1994 and 1996 because of the repetition of windows after 15 years.

8.1 The Mission Profile

For each of the two windows to be considered, it will be assumed that four craft will be launched using different SL-12 boosters. The Soviets demonstrated in 1973 that they can successfully launch this number of Mars probes over a short period. Two pads can be used, with as little as a week between launches from the same pad. Two of the craft will be orbiters with an Earth return rocket and two will be the landing/ascent stage vehicles with a Mars fly-by bus.

For convenience, the missions to be launched will be

TABLE 11. MSRM Lander/Fly-by Spacecraft Requirements.

Manoeuvre	MSRM-3A/MSRM-4A		MSRM-3B/MSRM-4B	
Latitude	0°	30°	0°	30°
Trans Mars injection, m/s	3635	3625	3600	3590
Mid-course correction m/s	100	100	100	100
Deflection manoeuvre, m/s	100	100	100	100
Landing manoeuvre, m/s	500	500	500	500
Mars ascent manoeuvre, m/s	4,910	4,940	4,910	4,940
Mass Breadowns				
Fly-by module, kg	786	786	780	780
Fuel, kg	214	214	220	220
Total mass, kg	1,000	1,000	1,000	1,000
Descent shroud, kg	500	500	500	500
Heat shield, kg	635	635	692	692
Parachute system, kg	500	500	500	500
Total mass, kg	1,635	1,635	1,692	1,692
Descent stage, kg	1,000	1,000	1,000	1,000
Fuel, kg	488	488	506	506
Total mass, kg	1,488	1,488	1,506	1,506
Return capsule, kg	85	85	100	100
Ascent rocket stage, kg	277	274	283	279
Fuel, kg	1,415	1,418	1,494	1,498
Total mass, kg	1,777	1,777	1,877	1,877
Launch mass, kg	5,900	5,900	6,075	6,075

Notes.
Missions in 1994 and 1996 are scaled for landings either on the equator or at latitude 30° (N or S). As with Table 10, velocities are rounded to the nearest 5 m/s, but the masses are the exact arithmetical results of the velocities.

designated MSRM-1 to -4 (Mars Sample Return Mission), with the 1994 launches coded "A" and the 1996 launches "B." The MSRM-1 and -2 craft are planetary orbiters, and MSRM-3 and -4 are the landers.

It is assumed that the launches from Earth orbit are made over a period of two-three weeks. First the two orbiter craft are launched five days apart, and after a gap of ten days the first lander is launched, the second following after a further five days. The transit times are 290-320 days, with the 1994 launches having the longer transit times. It is assumed that Type 2 trajectories are used on all missions.

During the Mars encounter phase, the second of the orbiters arrives about three weeks before the first of the landers. An orbit with the following parameters has the same orbital period as the Martian "day," while the closest approach of 2,000 km guards against premature decay:

Orbital period: 1,477 min
Minimum distance: 2,000 km
Maximum distance: 32,052 km
Maximum velocity: 3,711 m/s
Minimum velocity: 565 m/s

The manoeuvres to enter and leave Mars orbit from heliocentric orbit are not too demanding if they can be made at about the closest approach distance.

Immediately after orbital injection, the orbiters begin checking the landing sites and – if the preliminary sites are unsuitable – looking for better nearby sites.

During the trans-Mars coast period, the lander has been hidden within a payload shroud with a small fly-by module attached. This module has only a limited experiment capacity, since it is required simply to provide manoeuvres and power during the coast phase. As Mars approaches, the lander complex (still within its shroud) separates and the fly-by module performs a manoeuvre to ensure that it does not hit the planet. As atmospheric entry proceeds, the upper payload shroud separates and the parachutes open. The heat shield separates and in the final descent the parachutes are cast off, retro-rockets firing to ensure a soft-landing.

After landing, the first priority is to search for the most interesting sample within reach of the telescopic arm (extendable to about 8 m). The mission allows for a sample totalling up to 10 kg to be taken and returned to Earth. Launch of the sample into Mars orbit would generally be within 2-3 weeks of landing to minimise the chance of failure caused by an extended stay on the Martian surface.

In the meantime, the orbiter has been far from inactive, with its own research programme in Mars orbit. In preparation for the launch of the sampler ascent stage, the orbiter path is lowered:

Orbital period: 1,380 min
Minimum distance: 200 km
Maximum distance: 32,052 km
Maximum velocity: 4,650 m/s
Minimum velocity: 472 m/s

It is into this orbit that the ascent stage launches itself for the rendezvous and docking manoeuvres under automatic control. Once it has been secured in the docking cone on the orbiter's Earth return stage, the ascent rocket separates

from the Earth return capsule. Immediately, the orbiter boosts itself and its cargo back into its original 1,477 minute orbit.

Since the craft have to wait for a suitable opportunity, trans-Earth injection does not come until about 13-14 months after the orbiters first arrive at Mars. The manoeuvre is made against the direction of Mars' velocity vector, and the Earth return stage and capsule begin the 320-350 day return journey.

A return from heliocentric orbit requires higher re-entry velocities than have been encountered on lunar missions to date. The re-entry velocity at 200 km is about 13 km/s for a 1994 launch (return in 1997), but "only" 12.6 km/s for a 1996 launch (return in 1999). The landing technique is similar to that used for the Luna sample-return missions: the capsule separates from the rocket stage and makes a parachute landing inside the Soviet Union. The rocket stage is allowed to decay naturally in the atmosphere.

8.2 The Orbiter Spacecraft

The orbiter spacecraft could be derived from those flown in the second generation programme, although a larger fuel load would be required. The return stage would be carried atop the orbiter, where the descent craft were carried during the 1971-1973 missions. Table 10 provides a summary of the mission requirements and the resulting mass breakdowns for the orbiters as projected here.

The mission objectives for the orbiter are:

1. Enter Mars orbit;
2. Act as a communications link between Earth and a lander;
3. Manoeuvre to dock with the ascent vehicle (the orbiter would be passive);
4. Return rocket to eject from Mars orbit and return capsule and sample for Earth recovery.

The failure to achieve objective 1 would immediately mean that a lander mission was doomed to failure. In addition to the engineering requirements noted above, there will be essential science requirements:

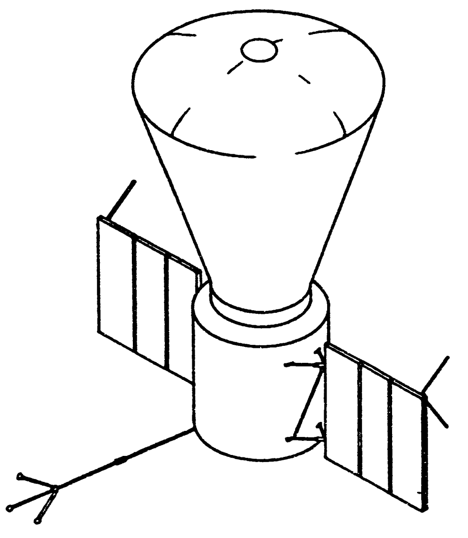
5. Studies in ultraviolet and infrared wavelengths, amongst others;
9. Magnetic field experiments, including the study of the interaction of the Martian field with the solar wind.

A specific impulse of 315 seconds has been assumed for both the main orbiter engine and the Earth return rocket: the former has a maximum thrust of 1.5 tonnes and the latter a thrust of 0.5 tonnes.

8.3 The Lander Spacecraft

The landing craft would be a new design to the planetary programme, although it would reflect some of the characteristics of the Luna sample-return craft. The fly-by module would be of a new design, with mission objectives:

1. Act as a communications module for the fly-by/lander complex, complete course corrections and supply power during the trans-Mars coast;
2. Place the descent complex on to a Mars impact trajectory and then manoeuvre to a Mars fly-by trajectory.



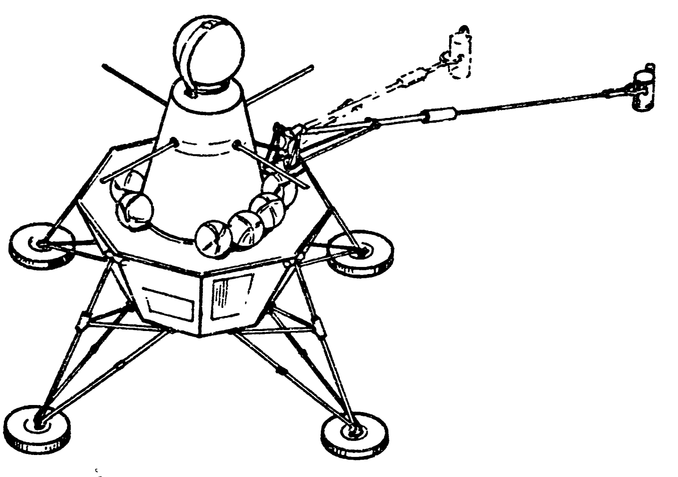


Fig. 14. Concept for the Mars Sample Return Mission landing spacecraft. At top is the complete craft; the lander is shown below. The lander has been designed with Luna 16 in mind.

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No science instruments would *need* to be carried on the fly-by module, but some experiments could be included:

1. Study of cosmic radiation during the pre- and post-Mars encounter phases;
2. Close-up photography of Mars during the fly-by at a distance of 1,000-2,000 km.

The landing craft would be in two basic parts: the descent and ascent stages, the latter including the Earth return capsule. The lander's descent stage would carry the main experiments and the sample arm. The experiments could be:

1. Photography on the Martian surface;
2. Measurements of wind velocities and temperatures;
3. Studies of the atmosphere.

The ascent stage could be designed to ensure that the experiments could continue once the surface sample has been launched. The sample arm would be telescopic to a maximum length of about 8 m and would rotate about its

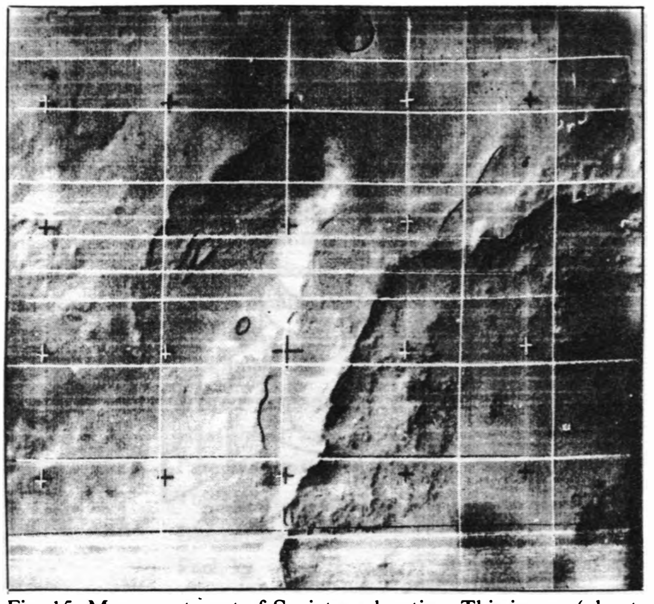

Fig. 15. Mars – a target of Soviet exploration. This image (about 100 km on a side) was returned by Mars 5.

Novosti

mount on the lander by ± 45°. A TV camera could be mounted on the sample head to allow monitoring of the sample collection, although the whole operation would have to be automatic once the sample had been chosen.

The ascent stage would be a single stage liquid propellant rocket having a single main engine and four verniers (the latter for pitch-over during the ascent and for the fine manoeuvres during docking). Multi-stage rockets were studied for the ascent stage, but the single stage concept was the simplest approach.

8.4 Comments on the MSRM Concept

The launch of a MSRM programme is within the Soviet Union's known booster power, and they have pioneered automatic space operations. The same mission could be flown by both pairs of orbiter/lander missions launched at any window considered. The Soviets have shown that they are improving the lifetimes of operating spacecraft, this being the main problem on earlier interplanetary missions, and therefore the mission outlined above does seem possible before the end of the century.

9. CLOSING COMMENTS

Some comments on the long-duration manned Salyut missions have suggested a possible manned flight to Mars. That would require unmanned pathfinders, so the re-introduction of the unmanned Mars programme can be expected.

The Soviets have indicated that they intend to launch a spacecraft to Mars in 1986 (the launch window is in May) which will enter an orbit identical with that of the satellite Phobos.

ACKNOWLEDGEMENTS

The writer would like to thank Bill Baker of Novosti, and Ralph Gibbons for the spacecraft illustrations.

Authors note: Soviet space programme analyst D. R. Woods, has supplied the following revised data:

Mars 3 orbit: closest approach: 1,530 km; farthest distance: 214,500 km; orbital period: 12d 16h 03m; inclination: 60°.

Mars 5 orbit: closest approach: 5,154 km; farthest distance: 35,980 km; orbital period: 24h 52m 30s; orbital inclination: 35° 19′ 17″. Orbital injection, about 1,200 m/s. This orbit is far higher closest approach distance than the orbit quoted in the text (which is most usually quoted).

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THE LEGACY OF SCHIAPARELLI AND LOWELL

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A retrospective is presented of Giovanni Virginio Schiaparelli of the Brera Observatory in Milan and his discovery of markings on Mars described as *canali*, and of Percival Lowell, founder of an observatory in Arizona dedicated to the study of those markings. A summary is given of events from the eruption of the Martian canal debate a century ago, to the establishment of the observatory in 1894 and beyond Lowell's death in 1916.

It is emphasised that, although his interpretation of Schiaparellian features as canals constructed by sentient beings would ultimately be proven erroneous, Lowell's direct and indirect contribution to the study of Mars and other planets was salutory. His energy, enthusiasm, and imagination inspired many individuals to view Mars (and other planets) as objects worthy of study and eventual exploration.

Despite his early death, Lowell's influence persisted long after the canal furore of the turn of the century had subsided. The reactions of the scientific community to Lowell's theories and that of the press are reviewed, followed by the literary response as revealed principally through the pages of imaginative fiction. The paper concludes with a summary of the "old" Lowellian Mars and the "new" Mars revealed by modern spacecraft.

1. GIOVANNI VIRGINIO SCHIAPARELLI

About 100 years ago, long-smoldering debates were heating up in Europe and the United States on the possible existence of intelligent life beyond Earth. These debates received their immediate impetus from reports beginning in 1877 released by the Italian astronomer Giovanni Virginio Schiaparelli.

When Mars approached Earth during the late summer opposition of that year, the respected observer, using a relatively small telescope some 22 cm in diameter at the Brera Observatory in Milan, detected a network of fine lines on the planet. He termed them *canali*, which to him meant channels or grooves.

In his now famous work, *Osservazioni Astronomiche e Fisiche Sull'asse di Rotazione e sulla Topografia del Pianeta Marte,* covering the Martian opposition of 1877, Schiaparelli advised his readers that he would be using such terrestrial terms as *isola, istmo, stretto, canale, penisola, promontorio,* etc., to describe features he had observed.

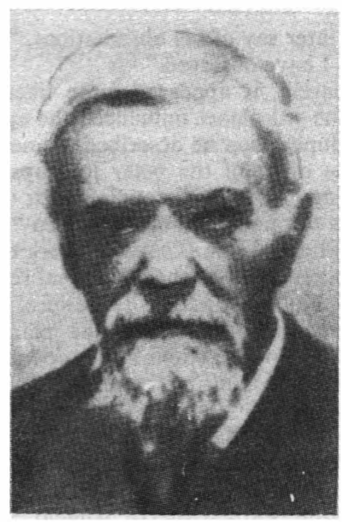
Canali were seen (and reported) during the subsequent oppositions of 1879-1880 and 1881-1882. A planet is in opposition when it is opposite to the Sun from the Earth. Mars moves in an elliptical orbit, which brings it to slightly more than 55 million km at most favourable opposition and to more than 95 million km at least favourable. Oppositions occur every 26 months. Closest approaches (most favourable oppositions) happen every 15 years or so.

Schiaparelli studiously avoided any suggestions that the canal-like markings were other than naturally-occurring geographical features. Thus, when reporting on his work in the journal *L'Astronomie* in 1881, he described them in the following terms:

"There are on this planet, traversing the continents, long dark lines which may be designated as *canals*, although we do not yet know what they are. These lines run from one to another of the sombre spots that are regarded as seas, and form, over the lighter, or continental, regions a well-defined network. Their arrangement appears to be invariable and permanent; at least, as far as I can judge from four and a half years of observation. Nevertheless, their aspect and their degree of visibility are not always the same, and depend upon circumstances which the present state of our knowledge does not yet permit us to explain with certainty... Sometimes these canals present themselves in the form of shadowy and vague lines, while on other occasions they are clear and precise, like a trace drawn with a pen... They cross one another obliquely, or at right angles. They have a breadth of two degrees, or 120 kilometres, and several extend over a length of eight degrees, or 4,800 kilometres... Every canal terminates in a sea, or in another canal; there is not a single example of one coming to an end in the midst of dry land.

"This is not all. In certain seasons these canals become double... On the 26th of December [1879] – a little before the spring equinox, which occurred on Mars on the 21st of January 1880 – I noticed the doubling of the Nile [a canal] between the Lakes of the Moon and the Ceraunic Gulf. These two regular, equal, and parallel lines caused me, I confess, a profound surprise, the more so because a few days earlier, on the 23rd and 24th of December, I had carefully observed that very region without discovering anything of the kind.

"I awaited with curiosity the return of the planet in



Giovanni Virginio Schiaparelli.

1881, to see if an analogous phenomenon would present itself in the same place, and I saw the same thing reappear on the 11th of January 1882, one month after the spring equinox – which occurred on the 8th of December 1881. The duplication was still more evident at the end of February...

"Yet greater was my astonishment when, on the 19th of January, I saw the canal Jamuna, which was then in the center of the disk, formed very rigidly of two parallel straight lines, crossing the space which separates the Niliac Lake from the Gulf of Aurora. At first sight I believed it was an illusion, caused by fatigue of the eye and some new kind of strabismus, but I had to yield to the evidence. After the 19th of January I simply passed from wonder to wonder; successively the Orontes, the Euphrates, the Phison, the Ganges, and the larger part of the other canals, displayed themselves very clearly and indisputably duplicated. There were not less than twenty examples of duplication, of which seventeen were observed in the space of a month...

"Their tint appears to be a quite deep reddish brown. The parallelism is sometimes rigorously exact. There is nothing analogous in terrestrial geography. Everything indicates that here there is an organization special to the planet Mars, probably connected with the course of its seasons."

He would later say of his observations, "I am absolutely sure of what I have observed."

To Schiaparelli, it appeared quite likely that seasonal changes on the red planet influenced the appearance of the canals. The duplication he described seemed to come about as one or the other of the polar ice caps commenced its annual melting cycle. This, coupled with the fact that the canals always terminated in areas termed "seas," inevitably led to speculation by some that a network existed for circulating polar melt water to the equatorial regions.

This was heady stuff indeed. To be sure, earlier observers had seen lines or markings on the planet. Seventeenth century telescopic observations by Francesco Fontana, Christiaan Huygens and Giovanni Domenico Cassini all included them.

The first map of Mars – as distinguished from simple sketches – was prepared from observations made of the 1830 opposition by Wilhelm Beer and J. H. von Maedler. Thirty-two years later, Father Pierre Angelo Secchi of Rome produced a map showing colourations on Mars. But these were introductory efforts, in no way comparable to the systematic observations of Schiaparelli who, in a map released in 1877, scattered names from ancient geography and mythology all across the planet. His nomenclature forms the basis for that still in vogue today.

The translation into English of the Italian word *canale* by *canal* (and not, for example, by *channel* or *groove*) led in time to the notion of artificiality. This, in turn, provided fertile soil for the emergence of one of the greatest debates in the history of astronomy. It continued with surprising intensity for at least two decades and its effects linger in some quarters to this day.

The controversy over the nature, even the very existence, of the Martian canals began in earnest about a century ago as the news of Schiaparelli's discoveries worked its way into the astronomical community and, soon after, into the public consciousness. For a while, no-one but the Italian astronomer himself was able to detect the canals. The reason seemed to be that, during successive oppositions, Mars was travelling through the far reaches of its orbital path around the Sun. Doubts thus began to build up: were the *canali* real?

As if to provide an answer to this widely expressed question, in 1886 first the American astronomer H. C. Wilson of the Cincinnati Observatory and then the French astronomer Henri J. A. Perrotin of Nice reported viewing Schiaparelli markings. So did others, as Mars began moving closer to Earth and thus once again became more favourable for observation. At the same time, some observers, try as they might, never could detect anything that resembled the network first reported by Schiaparelli.

Among those who quickly espoused the idea of artificial canals was Camille Flammarion, a well-known French observer and populariser of astronomical subjects. By 1882, the year that the canals were beginning to gain widespread publicity, his *La Pluralité des Mondes Habités* had appeared in its 33rd edition! Within a decade, Flammarion went on to publish *La Planète Mars et ses Conditions d'Habitabilité*. In it, he ventured some interesting opinions:

> "The considerable variations observed in the network of waterways testify that this planet is the seat of an energetic vitality. These movements seem to us to take place silently because of the great distances separating us; but while we quietly observe these continents and seas slowly carried across our vision by the planet's axial rotation and wonder on which of the shores life would be most pleasant to live, there might be at the same time thunderstorms, volcanoes, social upheavals and all kinds of struggle for life... Yet we may hope that, because the world of Mars is older than ours, mankind there will be more advanced and wiser. No doubt it is the work and noise of peace that for centuries have animated this neighbour."

2. PERCIVAL LOWELL

All of this attracted the attention of Percival Lowell, wealthy member of one of America's most famous families and a man well trained in science. Born in Boston on 13 March 1855, his earliest memory is astronomical. Years later (1910), he would reminisce that "Consciously, I came into the world with a comet, Donati's Comet of 1858 being my earliest recollection and I can see yet a small boy half way up a turning staircase gazing with all his soul into the evening sky where the stranger stood."

Percival was the son of Augustus Lowell, prominent Boston businessman, textile magnate, educator and a man keenly interested in science and the arts; and of Katharine Bigelow Lawrence of an equally prominent New England family. Percival's brother was Abbot Lawrence Lowell, president of Harvard from 1909 to 1933, and one of his sisters was Amy, the well-known poetess and biographer of John Keats. Abbot Lawrence was also the biographer of Percival.

The boy exhibited an early interest in astronomy and soon acquired a 6 cm telescope. His first telescopic observations of Mars date from 1870 when he was 15 years old. Percival's education at Harvard was first rate, with intense studies in mathematics, physics, history and the classics. He was elected Phi Beta Kappa and was invited to give a short commencement talk – it dealt with the nebular hypothesis on the origin of the Solar System earlier put forward by Kant and Laplace. After graduation, Lowell began what became rather regular overseas travels and was soon writing articles and books based on them. His best known and most popular was *The Soul of the Far East,* which appeared in 1888 and helped to set his lucid and entertaining literary style.

On what turned out to be his last trip to Japan (in 1892), he carried along a 15 cm telescope to make astronomical observations. It was then that he learned that because of failing eyesight, Schiaparelli was giving up his observations of Mars and the other planets. By the time he returned to

Boston towards the end of 1893, Lowell had resolved to carry on the work of the great Italian astronomer.

His first task was to build and outfit his own observatory. Lowell wanted it to be ready and in operation within a year, by October 1894 when Mars would come into favourable opposition for viewing. With the help of associates and equipment from Harvard and elsewhere, he began the task of first locating a site for his observatory (it turned out to be the 2,100 m high Coconino Plateau at Flagstaff in Arizona Territory) and then developing the site and access to it. Next came the construction of the observatory and installation of a 30 cm telescope obtained from the Harvard Observatory and a 46 cm one that had just been completed by John A. Brashear of the Alleghany Observatory in Pittsburgh.

Lowell began his grand project of studying the canals of Mars in the spring of 1894, several months before the October deadline. He made his first observations on 31 May with the 30 cm instrument and a day later with the Brashear refractor. Assisted by associates William H. Pickering and Andrew E. Douglass, his intensive observations of the red planet, coupled with an acute imagination, formed the basis of Lowell's belief in the artificial nature of the Martian canals. As he would one day confide to a group of college students during a lecture:

> "For all great work imagination is vital; just as necessary in science and business as it is in novels and art... The difference between everyday and scientific use of it is that in science every imagining must be tested to see whether it explains the facts. Imagination harnessed to reason is the force that pulls an idea through. Reason, too, of the most complete and uncompromising kind; imagination the guiding motive power, reason the guiding rein."

Percival Lowell in his Arizona observatory drawing the canals of Mars.

3. THE CASE FOR ARTIFICIALITY

Lowell carefully built his case for the artificial nature of the canals. His first task was to reject creation by natural events. Schiaparelli, for example, had suggested that his *canali* were caused by geologic processes. First, Lowell insisted, the lines crisscrossing Mars were all straight, unlike faults or fissures. Then, too, he believed them individually to be of uniform width, something unlikely in nature. Finally, they appeared to radiate systematically from what Lowell characterised as "special points,"

"On the first two counts," he wrote in 1895 in a book entitled simply *Mars*, "we observe that the lines exceed in regularity any ordinary regularity of purely natural contrivance." He felt that, insofar as is known, physical processes do not give rise to "perfectly regular results; that is, results in which irregularity is not also discernible." He added that "too great regularity is in itself the most suspicious of circumstances that some finite intelligence has been at work." Anticipating the voice of scepticism, he asserted that the more he observed Mars and its lines (the canals) the more regular they appeared.

Lowell was intrigued by the apparent fact that the lines formed "a system that, instead of turning anywhither, they join certain points to certain others, making thus, not a simple network, but one whose meshes connect centres directly with one another..." Only a moment's consideration, he ventured, would reveal "the intrinsic improbability of such a state of things arising from purely natural causes."

To his own satisfaction and that of his many converts, Lowell demolished the idea that the Martian lines could be cracks. The uniformity of breadth and their straightness appeared to negate that possibility. Nor could the lines be rivers, "for," he wrote, "rivers could not be so obligingly of the same size at source and mouth, nor would they run from preference on arcs of great circles" as the canals appeared to do. He also rejected the thought that the lines are really furrows that had been ploughed out by meteorites "since, in order to plough, invariably, a furrow straight from one centre to another, without either missing the mark or overshooting it, the visitant meteorite would have to be specially trained to the business." So much for the furrows!

Though obviously disturbed that Schiaparelli did not opt for artificiality, Lowell took some consolation in his admission that "I should carefully refrain from combating this proposition, which involves no impossibility." ("Io mi guardero bene dal combattere questa supposizione, la quale nulla include d'impossibile.") Thus, with great confidence, Lowell summed up his arguments favouring the construction of the Martian canals by intelligent beings:

> "Their very aspect is such as to defy natural explanation, and to hint that in them we are regarding something other than the outcome of purely natural causes. Indeed, such is the first impression upon getting a good view of them. How instant this interference is becomes patent from the way in which drawings of the canals are received by incredulously disposed persons. The straightness of the lines is unhesitatingly attributed to the draughtsman. Now this is a very telling point. For it is a case of the double-edge sword. Accusation of design, if it prove not to be due to the draughtsman, devolves *ipso facto* upon the canals."

Many astronomers and other interested persons in and out of science, remained unconvinced. To bolster his arguments, Lowell wrote in his 1906 work *Mars and its Canals* that "Not everybody can see these delicate features at first sight, even when pointed out to them; and to perceive their more minute details takes a trained as well as an acute eye, observing under the best conditions." Two years later, in

Mars as the Abode of Life, he would seek credibility in his interpretations of the markings on Mars thus: "I say this after having had twelve years' experience in the subject – almost entitling one to an opinion equal to that of critics who have had none at all."

A total of 183 canals were observed during the 1894 opposition at the Lowell Observatory, of which 116 had not been detected by Schiaparelli. But 67 were among the 79 canals mapped earlier by the Italian astronomer. Eventually, more than 700 canals would be observed and placed on charts by Lowell and his team.

First seen by Schiaparelli in 1879, double canals were confirmed by Lowell in 1899 and by 1907 over 50 had been mapped. Dark spots labelled "carets" by Lowell were observed too; they were checkmark-like features found along the inner edges of the Martian "seas." His studies led him to believe that physical conditions were such that life could exist on Mars and that the canals by their very presence provided the proof. He used every avenue open to him to diffuse his theories: public lectures, astronomical journals and magazines, popular literature, the *Annals* of his observatory, and five astronomical books.

Responding to arguments that the temperature was too low on Mars, Lowell suggested that it was not, that it was "astonishingly mild" there and, indeed, the "temperature is not incomparable with that of the Earth." Others pointed out the extreme thinness of the atmosphere; Lowell, agreed, but cautioned that:

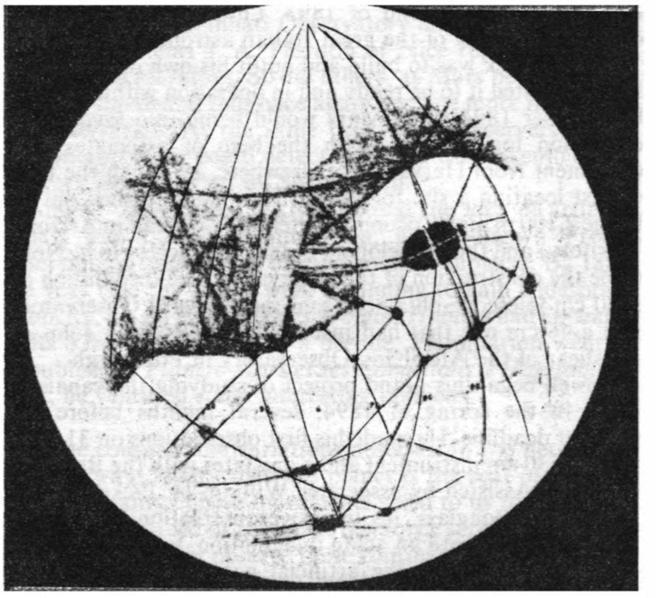
> "One deduction from this thin air we must be careful not to make – that because it is thin it is incapable of supporting intelligent life... That beings constituted physically as we are would find it a most uncomfortable habitat is pretty certain. But lungs are not wedded to logic, as public speeches show, and there is nothing in the world or beyond it to prevent, so far as we know, a being with gills, for example, from being a most superior person... To argue that life of an order as high as our own, or higher, is impossible because of less air to breathe than that to which we are locally accustomed, is, as Flammarion happily expresses it, to argue not as a philosopher, but as a fish."

The matter of water was also repeatedly raised. Many astronomers argued that the polar caps were made up of dry ice (solid carbon dioxide). Lowell felt otherwise, noting that "just as the fact of change in the polar caps proves the existence of air, so it implies the presence of water also." He interpreted the observed blue at the edge of the melting cap as water, saying that "Unless... we invoke some unknown substance for which we have absolutely no warrant in the physical premise, the band girdling the polar cap was a polar sea."

Blue-green markings had been observed on Mars by Lowell and other astronomers, but interpretations as to what they meant varied. To Lowell, these were surface reactions to seasonal changes, waves of darkening from the poles to the equator due to the transfer of water as the seasons changed.

What carried the water to cause the changes? The canals, of course. "If," he wrote, "the planet possesses inhabitants, there is but one course open to them in order to support life. Irrigation, and upon as vast a scale as possible, must be the all-engrossing Martian pursuit... What the physical phenomena assert is this: if there be inhabitants, then irrigation must be the chief material concern of their lives."

Lowell was quite aware that if there were water on Mars it would be available in very limited quantities. This implied narrow rather than wide canals. Thus, what appeared as canals were rather more than that: they were lines of



One of Lowell's hundreds of drawings of Mars: longitude 60° on the meridian.

"artificially irrigated country." "If therefore," he added, "we suppose what we call a canal to be, not the canal proper, but the vegetation along its banks, the observed phenomena stand accounted for."

Then there were the "oases" or "singularly correlated system of spots" associated with the network of canals. "The spots are oases in the midst of the desert," Lowell speculated,

> "and oases not innocent of design... For here in the oases we have an end and object for the existence of the canals, and the most natural one in the world, namely, that the canals are constructed for the express purpose of fertilising the oases... The canals rendezvous so entirely in defiance of the doctrine of chance because they were constructed to that end. They are not purely natural developments, but cases of assisted nature."

4. REACTIONS TO LOWELL'S THEORIES

Interest was understandably aroused as these ideas were disseminated by the press and by Lowell himself in popular lectures. Many people believed him, in part because of his family renown, in part because of his effectiveness as a communicator and in part because he was able to produce masses of data derived from thousands of hours of observations at his telescope.

Others, of course, did not believe him. One quote in the Lowell Observatory archives is particularly pointed: "Prof. Percival Lowell is certain that the canals on Mars are artificial. And nobody can contradict him." Perhaps even more cutting was Lick Observatory Director Edward S. Holden's sarcastic statement that "It is suggested that the conclusions reached by Mr. Lowell at the end of his work agree remarkably with the facts he set out to prove before his observatory was established at all." As the debate grew in intensity, Lowell and his associates replied in kind.

Lowell was not without supporters in the astronomical community. Prof. Charles A. Young of Princeton wrote that "The observations of 1894 have made it practically certain that the so-called 'canals' of Mars are real, whatever may be their explanation." Later, he would caution that "It is so easy to see what one expects and wishes to find, especially on a disc so small and delicately marked as that of Mars."

The astronomer Henry Norris Russell observed that "Perhaps the best of the existing theories, and certainly the most stimulating to the imagination, is that proposed by Mr. Lowell and his fellow workers at his observatory in Arizona." And W. W. Payne of Minnesota's Goodsell Observatory wrote, in a review of *Mars*, that Lowell's work was "crowded with an array of facts that are made to signify much that is new by the gifted and ready reasoning power which Mr. Lowell possesses, in a remarkable degree."

Percival Lowell was also encouraged by positive public response. The Reverand Edward Everett Hale (*The Man Without a Country*) was much impressed, writing that "You cannot resist the conviction which shows itself, not in the language, but in its intensity: not in his words but in the man."

So popular were Lowell's lectures that one one occasion, while talking on "Mars as the Abode of Life" at Boston's Huntington Hall, he found all thousand seats filled and could only satisfy demand by giving two lectures back to back. It would be difficult to surpass his performance today on a subject of scientific importance.

Many astronomers persisted in believing that the canals were illusory, so Lowell and his associates began to bring to bear the camera to support their contentions. During the opposition of 1905, claims were sent forth from Flagstaff that new canals had been discovered; and, moreover, that some canals, old and new, had been photographed. Drawings were one thing; photographs quite another.

That Lowell Observatory photographs did, in fact, prove the existence of canals was by no means established by the astronomical community. Thus, Oxford University Professor H. H. Turner stated that he did "not mean to deny the claim any more than I am prepared to admit it. Personally, I find it extremely difficult to say exactly what is on these prints and friends to whom I have shown them differ a good deal in their interpretation." But another British astronomer, A. C. D. Crommelin, in his presidential speech to the British Astronomical Association in October 1905, took a more positive view:

> "The results are a very notable advance in planetary photography; nearly every print shows one or more canals, while the best of them show six or eight. I had the pleasure of meeting Prof. Lowell a few weeks ago... when he showed me the pick of his prints, on many of which the canals were clear and unmistakable, appearing as continuous narrow, slightly curved lines. These photographs did a great deal to strengthen my faith in the objective reality of the canals which I had previously looked on as probable but not quite certain."

To obtain better photographs of the red planet, Lowell took advantage of the more favourable 1907 opposition by sending an expedition to a site near Alianza, Chile. There, using a 45 cm refractor over a three-month period, the Lowell Observatory team succeeded in taking some 13,000 photos.

Press and popular attention was at its height as the world breathlessly awaited news of the remote expedition. Meanwhile, in Flagstaff, some 3,000 images were obtained using a 60 cm telescope. Canals, Lowell triumphantly reported, appeared on prints from both sources.

Many agreed. Science writers in America and Britain began to fall in behind Lowell. One wrote that "A long disputed matter has finally been determined by the successful photography of some of the Martian canals," while another asserted that the photographs had suceeded in "forever disposing of their [the canals'] illusory character."

Part of the public fascination with the markings of Mars is explained by interest in canals in general. The Suez Canal had been completed a mere eight years before the Schiaparellian discovery of *canali*, and the building of the Panama Canal occurred during the 1904-1914 period, coinciding with the time when the Mars furore was rising to a peak and then levelling off.

That peak was 1907, the year of a favourable opposition and of fairly widespread support for Lowell's theories. In September, the *Scientific American* editorialised that "With the aid of photography, he [Lowell] has established beyond doubt the existence of a delicate tracery of lines on the sphere." And a *New York Times* writer noted that "While Lowell concentrates all his fine intellect and splendid energy on his investigations of the planet Mars, a large number of other astronomers and scientific writers seem to be devoting too much of their time to disproving his theories."

With the advent of the 1909 Mars opposition, telescopes larger than those of the Lowell Observatory were trained on Mars with, for Percival Lowell, keenly disappointing results. Leading astronomers of the calibre of George Ellery Hale at Mount Wilson in California and E. M. Antoniadi at Meudon in France found nothing suggesting canals. Sceptics of Martian canals rolled on the offensive, seeking to demolish one by one Lowell's arguments.

The next opposition was unfavourable and little new light was shed on the planet. Lowell became increasingly embittered as he desparately sought to defend his theories against mounting criticism from astronomers located at the larger observatories.

It was thus with particular relish that Lowell read praise of his work in the *New York Times* of 29 October 1916:

> "The world cannot afford to withhold from Professor Lowell the homage that is due to a tireless, expert, indomitable explorer of astronomical space. He has reached his conclusions as to the existence of the canals of Mars and their artificial origin and the purpose they serve after twenty-two years of persistent observations... He has answered in strictly scientific terms the objections of his critics. He has triumphantly exploded their theory that the white caps at the Martian poles are composed of carbon dioxide instead of snow and ice, that the lines he sees so clearly and photographs so plainly and draws so accurately are similar to those observed on other planets... They are not the same. He is convinced that his proof of the existence of intelligent life on Mars is as clear as the proof that there is sodium in the Sun."

A fortnight later, Percival Lowell died of a stroke.

5. THE LITERARY RESPONSE TO LOWELLIAN MARS

The reaction to the canal controversy had a lasting literary fallout. Indeed, Lowell's Mars persisted in the pages of fiction far longer than it did in the world of science; and, it is quite probable, that in the former the influence of Lowell was more profound.

The first literary reaction to the discovery of Martian *canali* in 1877 by Schiaparelli was Percy Greg's two-volume novel *Across the Zodiac*, published three years later. A mysterious substance called apergy negates terrestrial gravity, making possible the voyage to Mars. The spaceship resembles "the form of an antique Dutch East-Indiaman" whose deck and keel are "absolutely flat, and each one hundred feet in length and fifty in breadth, the height of the vessel being about twenty feet."

Greg, English poet, historian, novelist and son of William Rathbone Greg the essayist, offers a monarchical, scientifically advanced Mars with strong capitalist inclinations and

an unusual environment. "Masses of land reflected a light between yellow and orange indicating... that orange must be as much the predominant colour of vegetation as green is on Earth... The sky," he continued, "instead of the brilliant azure of a similar latitude on Earth, presented to my eye a vault of pale green... The lower slopes [of a mountain] were entirely clothed with yellow or reddish foliage."

In his 1891 novel *A Plunge into Space*, Robert Cromie has his Mars-bound spaceship *Steel Globe* secretly constructed in the Alaskan wilderness. It is powered by "... the law of gravitation" which "may be diverted, directed, or destroyed." The voyage to the red planet is uneventful, the natives are friendly and life there appears idyllic, made so, according to Cromie, by the judicious application of advanced science and technology.

Serialised in *Cosmopolitan* Magazine in 1897 and appearing in book form a year later, H. G. Wells' *War of the Worlds* dealt not with a terrestrial expedition to Mars but with malevolent Martian invaders of our planet. The alien monster from outer space made its debut.

Far more distinguished than earlier English-language works and extremely popular in terms of sheer numbers of readers, *War* received approving reviews when it appeared. "Mr. Wells has done good work before," offered *The Academy Review* of 29 January 1898, "but nothing quite so fine as this. He has two distinct gifts – of scientific imagination and of mundane observation – and he has succeeded in bringing them together and harmoniously into play." In addressing the science in the novel, the reviewer went straight to the leading authority of the time:

> "According to Mr. Percival Lowell, who made an exhaustive study of Mars in 1894, these canals are really belts of fertilised land, and are the only habitable tracts on Mars, the remainder of the land surface being desert. The view that the Martians – it is less unreasonable to think that Mars is inhabited than that it is not – would look towards our Earth with longing eyes is thus quite within the bounds of legitimate speculation... the reasons given for the invasion of the Earth by Mars are perfectly valid from a scientific point of view, and are supported by the latest observation of the nature of the planet's surface."

Right on the heels of the Wells classic came Garrett P. Serviss's "Edison's Conquest of Mars," published in the New York *Evening Journal*. It all has to do with Thomas A. Edison and a punitive expedition to the red planet. *Conquest* did not appear in book form until 1947, 18 years after its author's death.

Appearing at almost the same time as the serialised version of *War of the Worlds*, Kurt Lasswitz's *Auf zwei Planeten* offers a more peaceful panorama: the Martians come to us as explorers, scientists and teachers of a higher order of civilisation. A professor of mathematics at the Gymnasium Ernestinium in Gotha and author of a history of atomic theory down from the middle ages to Newton, Lasswitz reflected in *Two Planets* late 19th century German faith in the benefits of science and technology. He was also a strong believer in duty before pleasure, a characteristic Lasswitz finds in many of his visiting Martians.

Whereas Wells' Martians became prototypes for alien monsters in general, Lasswitz's denizens were quite like man though with somewhat higher body temperatures and larger eyes. Speaking of eyes, part of the story is seen through those of the Martians and there is even a love affair between a German and a beautiful Martian maiden.

The visitors from space establish a ring-shaped station above the North Pole which was, in the author's words, "nothing else but the Mars terminal of Earth. It... made it possible for the inhabitants of the planet Mars to establish regular connection between worlds." An "area without gravity" or "abaric field" created a kind of null zone that kept the space station aloft. Objects entering it were, according to Lasswitz, "no longer attracted by Earth."

In 1899 the oddly-titled book *Pharaoh's Broker* by Ellsworth Douglass was published. Once again, Earthmen travel to Mars, this time in a cigar-shaped spaceship propelled by some kind of gravitational mechanism. The travellers: a Jewish grain speculator from Chicago, Isidor Werner; and a German physics professor from Heidelberg, Dr. Hermann Anderwelt.

Almost nothing is known of the author of this exceptionally rare 300-odd-page book published in London by C. Arthur Pearson Limited. He was probably English, though he may have been an American. Whatever his nationality, he was remarkably prescient in some areas, naive in others.

Like other writers of speculative space fiction, Douglass called upon anti-gravity to solve the propulsion requirements of his space travellers. "There is no other planet or star nearer to us than Mars when in opposition," it is explained. "Therefore there will be nothing to attract us out of our correct course; and if we can manage to come anywhere near the true course, the gravitational attraction of Mars will draw us to him in a straight line," Douglass fared only somewhat better in describing conditions on Mars, with its "...fewer large bodies of water, and a very much greater proportion of land." " 'Behold again the infinite wisdom of the Creator!' cried the doctor. 'Although Mars is a much smaller planet than our own, it is fitted for almost as large a population. The land is nearly all grouped about the Equator, where it is warm enough to live comfortably.' "

Perhaps most extraordinary was the account of zero-gravity conditions in space experienced by the planetary voyagers and the importance of exercise in avoiding muscular deterioration and "Space Fever" or what today we refer to as space sickness:

> "It was a sort of rowing or pulling machine [Douglas has Isidor Werner explain], which I rigged up by running a bar through one end of the doctor's spring scales, and fastening the other end to the foot of my bed. I pulled vigorously against this spring for hours at a time, and was delighted to find that my strength had not left me, and that I could easily lift as much as these scales had been made to weigh. I remember my returned appetite... after the first hour of as vigorous exercise as our rarefied air would permit."

Edwin Lester Arnold, author of *Lieut. Gullivar Jones; His Vacation* published in London in 1905, was definitely an Englishman, the son of Sir Edwin Arnold, distinguished diplomat and author of a number of works concerning the Far and Near East.

The hero, a US Navy lieutenant, flies to Mars on a magic carpet after uttering, in a moment of despair, the words "I wish I were anywhere but here, anywhere out of this red-tape-ridden world of ours. *I wish I were in the planet Mars!*" Once there, he is accepted by the natives and undergoes all manner of adventures, including falling in love with a comely Martian girl whom he rescues from a tribe of semi-human barbarians.

Two years before Gullivar Jones, a curious American book was released by Brentano's in New York: *The Certainty of a Future Life in Mars: Being the posthumous papers of Bradford Torrey Dodd*. Dodd, we discover, has been reicarnated on a modified Lowellian Mars and transmits what he has found and learned there to his son back on Earth.

"The Martian world is one country," Dodd reports, "There are no nationalities... There is a circulating medium, banks

and business enterprises, but it is more veiled, more hidden, less, far less, insistent than with you... One prime element of difference is in the nourishment and the area of population. The Martian lives only on fruit, and he lives only a few degrees on either side of the equator....Also there are no railroads, but innumerable canals, which form a labyrinth of waterways, and are fed from the tides of the great northern and southern seas."

Fenton Ash, pseudonym for Frank Atkins (who also wrote under the name Frank Aubrey), was another English author inspired by the wave of interest stirred up by Schiaparelli-Lowell Mars publicity. A *Trip to Mars* appeared in London in 1909 and contained an author's preface in which he admits that "Amongst other difficulties the storywriter here meets with, by no means the least confronts him when he is called upon to decide which of various theories put forward by different scientists he shall adopt as a starting point."

Ash's spaceship *Ivenia* is, in fact, Martian; it has come to Earth and, as the story unfolds, takes two terrestrials back to Mars, travelling out through our atmosphere with wings extended. "But after a time, as she gained the upper air, these were folded away, the upper covering was replaced, and she became once more the great, egg-shaped mass [described earlier in the book]."

Still another British writer, Mark Wicks, describes in *To Mars via Moon* (1911), a utopian Mars strongly inspired by Percival Lowell, to whom the book is dedicated. Long passages on Schiaparelli, Lowell and the Martian canal controversy make it a sort of interplanetary travelogue and planetary primer. Wicks' spaceship *Aeronal* was "...shaped somewhat like a fish, being constructed of a special metal... It was ninety-five feet in length, and its diameter twenty feet in the broadest part, tapering off to a point at either end."

The book is full of illustrations, including many maps of Mars and a splendid frontispiece showing the spaceship, the Martian city of Sirapion and the several radiating canals, Wicks describes the latter:

> "What we actually saw was this: not a single wide canal but a series of comparatively narrow canals, running parallel to each other, with a very wide strip of vegetation between each. Usually the canals were linked together in pairs by smaller cross canals running diagonally from one canal to the other in alternate order. These were the irrigation trenches... it was exceptional for the canals to have a width of more than two hundred yards. Most of those we were looking at were only about sixty feet wide! and only the wider ones are used for navigation purposes."

With the exception of the Wells and Lasswitz works, none of the fiction inspired by Schiaparelli and Lowell could remotely be considered as best-selling. None, that is, until the appearance of a story by a most unlikely newcomer.

Two years before Schiaparelli announced his discovery of *canali* on Mars, a baby was born in Chicago (on 1 September 1875) who would, through these pages of fiction, build a magical Martian civilisation. His name: Edgar Rice Burroughs.

The boy received a mediocre education, failing in an attempt to pursue studies at the prestigious Phillips Andover Academy in Massachusetts, and military school training. At the age of 21, he enlisted in the US Cavalry. Upon discharge, Burroughs worked for a while in his father's battery business, then married and somewhat later headed west to try his hand at mining. Returning to Chicago, he worked in sales, accounting and mail-order, ending up peddling advertisements to such popular pulp magazines as *The Argosy* and *The All-Story Magazine.*

By the time he was 37, he was unemployed and with no discernible career pattern before him. However, he had taken one astute step: while selling advertisements to the 'pulps,' he had carefully analysed the kinds of fiction they published and the stories that seemed most popular with the readers. So he wrote a story himself.

Inspired by Schiaparelli's *canali* and Lowell's interpretation of them, he chose as his locale the planet Mars. The preliminary title was "Dejah Thoris, Martian Princess." On 4 August 1911, he posted the manuscript to *All-Story* and, after some correspondance with managing editor Thomas Newell Metcalf, added 20,000 words to the original 43,000. He also changed the title to "Under the Moons of Mars." The story was published in six installments from February to July 1912 under the pseudonym Norman Bean.

Success was immediate and stunning, catapulting the unknown Burroughs into an author who, before his career was over, would write more than 60 books and countless stories. His works would appear in more than 30 languages and he would be read in almost every corner of the world. His paperback sales in English alone would easily exceed 50 million copies.

The hero of "Under the Moons of Mars" is John Carter, a former Confederate Army officer. On a prospecting trip in the West he is set upon by hostile Indians but escapes and hides in a cave. There, miraculously, his spirit is separated from his body and, equally miraculously, body and spirit together appear on a Lowellian Martian desert.

Mars is depicted as a dying, warlike world inhabited by strange creatures, including a humanoid species of green giants and a society of copper-coloured humans. After a series of adventures, Carter meets, falls in love with and later marries Princess Dejah Thoris of Helium. But all does not go well. A giant air-supply plant malfunctions. As Carter inspects the damage in the huge structure, he loses consciousness only to regain it back on Earth. Devastated, he implores the gods to take him back to his adored princess and to the world he has learned to love.

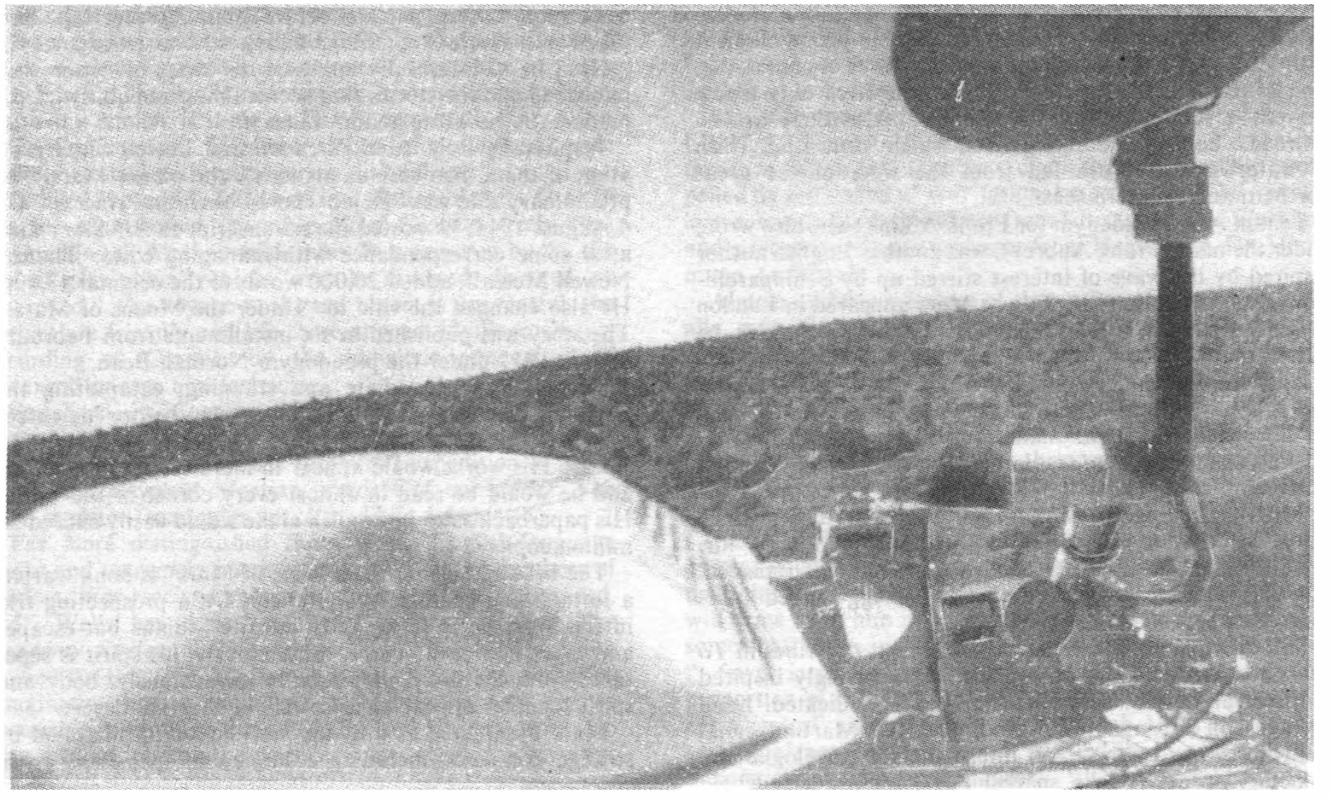
All-Story's editor pleaded for another story so, on 5 April 1912, Burroughs sketched out a plot that became "Tarzan of the Apes." On 11 June, the manuscript was completed and posted to the magazine, in which it was published as a complete novel in the October issue. Tarzan's success was if anything more astonishing than that of the earlier Mars tale. Nevertheless, instead of preparing an immediate sequel to it, Burroughs followed up "Under the Moons of Mars" with "The Gods of Mars," an 85,000-word manuscript for which he received $750. (In those days, *All-Story* cost 15 cents and had a circulation of about 500,000. Burroughs' novel-length magazine stories were later published as books.)

Tales of adventures on Mars continued to pour forth from the prolific mind of Edgar Rice Burroughs as dozens of other writers followed suit. Virtually all consciously or unconsciously accepted the Lowellian model of an aged, dying world, populated by intelligent beings. Only quite recently has the trend changed.

The thought of Mars as an inhabited, dying world saddened Lowell above all. He knew that despite their canals, the Martians would one day succumb to the inevitable. "The process that brought it [Mars] to its present pass," he wrote,

> "must go on until the bitter end, until the last spark of Martian life goes out. The drying up of the planet is certain to proceed until its surface can support no life at all... When the last ember is thus extinguished, the planet will roll a dead world in space, its evolutionary career forever ended."

What one can now term the "old" Lowellian Mars inevitably gave away to the "new" Mars revealed through the spacecraft eyes of a later generation – a more desolate



The new Mars. The two Viking landers showed the surface of the planet from ground level for the first time. *NASA/JPL*

world than imagined by Lowell, but in many ways just as intriguing.

6. THE "OLD" MARS AND THE "NEW" MARS

What today we think of as the "old" Mars, which was derived from late 19th and early 20th century concepts, remained popular in some quarters right up to the opening years of the Space Age. In many cases, simple nostalgia for a romantic yesteryear seems the only reason for clinging to what were rapidly becoming outmoded ideas.

Since Mars' rotation period is 24.66 days, about that of Earth's, and its axial inclination is 25.17 degrees, again close to ours, it was inevitable that these similarities would be conveniently extended to include other parallels. (The Martian seasons, incidentally, would be twice as long as ours, or nearly so, to reflect the almost twice as long year.) Also, it was widely believed in the 19th century that the planets were formed first in the outer Solar System and progressively came into being as the Sun was approached. Being further out, therefore, Mars must be older than Earth and hence more advanced.

Life, then, would have taken hold earlier on the red planet, so the argument went, and from it intelligence should likewise have arisen sooner. Thus, following the discovery of *canali* in 1877, Lowell had a certain platform of logic from which to advance his ideas – and so did the fiction writers who took their cue from him.

Yet Lowell remained on the defensive during much if not most of the period during which he defended his intelligent-life-on-Mars thesis. Though doubts about this thesis, and about the very existence of the putative canals, only increased as the years went by, there was a positive side to the whole affair, one well expressed by R. L. Waterfield in his *A Hundred Years of Astronomy* published in 1938:

> "Now the story of the 'canals' is a long and sad one, fraught with backbitings and slanders; and many would have preferred that the whole theory of them had never been invented. Yet whatever harm was done was more than outweighed by the tremendous stimulus the theory gave to the study of Mars, and indirectly to the planets in general. Whether in a positive way to champion it, or in a negative way to oppose it, it attracted many able observers who otherwise might have never taken an interest in the planets – so the pistol which Schiaparelli had so unwittingly let off, though it shocked the finer feelings of many, had undoubtedly been the starting signal of that race for discovery which the planetary astronomers are still successfully pursuing."

Writing nearly a quarter of a century later, Otto Struve and Velta Zebergs agreed ('Astronomy of the 20th Century,' Macmillan, 1962). "Up to the end of the 1900s," they pointed out, "planets were visually observed mainly by amateurs using relatively small instruments. At the present time [1962], most large observatories devote a considerable proportion of their observing time to planetary studies, and some of the best-known astrophysicists are attempting to interpret these observations. This change in attitude can to a large degree be attributed to the efforts of one man, Percival Lowell, and to his part in one of the greatest astronomical controversies of this century: the existence of life on Mars."

Science fiction writers persisted in their Lowellian attachment far longer than unfolding advances in planetary astronomy permitted. The public, too, remained credulous: witness the panic caused by the Orson Welles' radio adaptation of *War of the Worlds* on the evening of 30 October 1938. As Hadley Cantril wrote in his *The Invasion from Mars: A Study in the Psychology of Panic* published in 1940, "For

a few horrible hours people from Maine to California were destroying all armed resistance sent against them; that there was simply no escape from disaster; that the end of the world was near. Newspapers the following morning spoke of 'the tidal wave of terror that swept the nation...' " Cantril noted somewhat laconically that "The chairman of the Federal Communications Commission called the programme 'regrettable.' "

Though intelligent life on Mars had been discounted by the astronomical community long before World War II, the feeling that Mars might harbour at least a primitive biology persisted. It only began to dissipate following the mid-July 1964 flyby of Mars by the American space probe Mariner 4, which sent back 20 pictures of a bleak, lunar-like surface completely devoid of canals, oases or anything remotely hospitable.

The picture presented four years later by Mariners 6 and 7 was hardly brighter: plenty of craters but no evidence of Lowellian features. The atmosphere was confirmed to be extremely thin and water ice could not be detected in the polar caps. The "old" Mars of Percival Lowell was ready for final rites. And the "new" Mars was born.

Mariner 9 entered into Martian orbit in November 1971 after a six-month journey through interplanetary space. For an astonishing 349 days (four times its design lifetime) the probe observed the planet below, sending back to Earth more than 7,300 pictures.

Among the amazing features that revealed themselves were huge, 15-30 km-high volcanic constructs including Olympus Mons that possesses a caldera at its crest larger then the entire island of Hawaii. Just as impressive was Valle Marineris in the Tithonis Lacus-Coprates region that spans some 80 degrees of longitude. The Grand Canyon would be dwarfed by the 8,000 km-long system.

As if these discoveries were not enough, striking evidence of former fluvial action on Mars came to light: channels and tributaries ressembling dried river beds that presumably came into being during an epoch when Mars' atmosphere was denser and its climate warmer, thereby permitting liquid water to flow – at least seasonally – across the equatorial regions. Colour changes long observed from Earth are now believed to have been caused by the successive deposition and removal of dust by the wind. Indeed, when Mariner 9 reached Mars on 13 November 1971, a planet-wide dust storm was raging, obscuring surface detail. Great basins were also discovered, probably caused by meteoric or asteroidal impacts. One, Hellas, is about 1,600 km in diameter.

The older crater terrain that revealed itself so strikingly to the early Mariner spacecraft might be in the process of being replaced slowly by younger volcanic terrain. Perhaps, according to one interpretation, Mars started out much like the Moon and as a result of internal radioactive heating is slowly "boiling up" and, in the process, becoming more Earthlike. It is even possible that the present atmosphere was built up relatively recently by volatiles released by volcanic action.

In 1976, two more probes reached Mars: Viking 1 and Viking 2. They each divided in two, one part becoming orbiters and the other soft landing craft. The Viking 1 lander descended on Chryse Planetia at 11:53 GMT on 20 July, that of Viking 2 on 4 September at Utopia Planetia some 7,200 km to the east northeast. They confirmed that Mars is a very cold, dry, almost airless world and probably lifeless: experiments designed to detect micro-organisms in the soil that could metabolise simple compounds of carbon were negative, as were other tests. The biggest factor against Martian life came from an experiment that was not a life-detection experiment as such. Rather, it was designed to determine the composition of the Martian soil to see if there were organic compounds similar to those found in meteorites. The surprise: nothing organic was found at either of the two sites. Yet if there were micro-organisms on Mars, one would have expected to find an accumulation of their dead bodies and waste materials as we do on Earth. No such evidence came to light.

There the matter rests for now.

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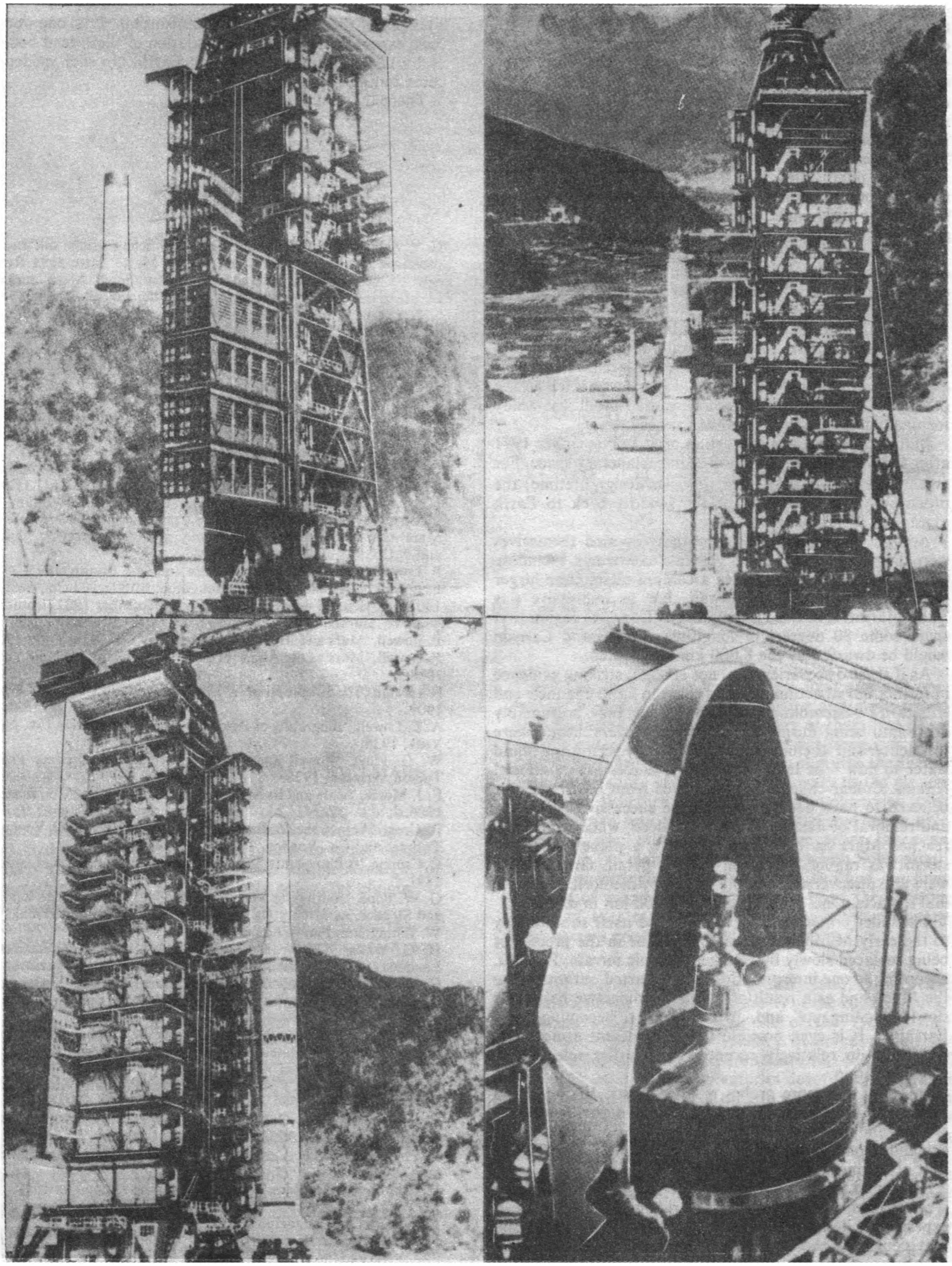

Preparation of the Chinese CZ-3 launch vehicle carrying an experimental communications satellite. The launch on 8 April 1984 was from the new Xichang (Sichuan province) site.

(Photograph courtesy of Theo Pirard)

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THE CHINESE SPACE YEAR OF 1984

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During 1984 there were three successful Chinese satellite launches to Earth orbit. This paper will review the developments of 1984 and look forward to possible future space activities.

1. INTRODUCTION

In recent years it has become the norm for there to be a single Chinese satellite launch each year, but in 1984 three boosters placed satellites into orbit successfully. During the year, the Chinese introduced a second launch site and flew the first two of the new advanced Long March 3 boosters, successfully orbiting the first Chinese geostationary satellite on the second flight.

The Chinese space programme to the end of 1983 was reviewed previously [1]. Different designations are sometimes used for the triple payload launch of September 1981; here, the payloads are referred to as PRC 9-1, 9-2 and 9-3, and not PRC 9, 10 and 11.

Table 1 is a list of the orbits attained by the various Chinese space objects in 1984, the initial orbits usually being quoted for each object.

2. PRC-12 IN JANUARY 1984

On 29 January the 12th orbital mission provided two 'firsts' in the Chinese space programme: the first launch from a new launch site and the first flight of the new Long March 3 booster (Long March 1 launched the first two Chinese satellites, while Long March 2 seems to have been a design study that was never used on a space mission).

The orbital inclination for the flight (31.05°) was new to the Chinese, the original Shuang-ch'eng-tzu launch site at 41.3° N not allowing such orbits without expensive manoeuvres. The new launch site is discussed in Section 5 and the launch vehicle is reviewed in Section 6.

During its mission, PRC-12 performed a number of orbital manoeuvres, the largest of which came on 30 January at about 08.12 GMT (all times quoted in GMT). At the time of the manoeuvre the satellite was over 28.61° N, 107.25° E, in the general area of the new launch site. The orbital plane was changed to 36° and the apogee raised to over 6,000 km (see Table 1).

The delta-V required for this manoeuvre was nearly 1,850 m/s. This is appropriate to transferring a satellite from a 31° 10-11 hour parking orbit to a near-geostationary orbit [2], and therefore the manoeuvre must have been a test of an apogee motor for such a mission. A series of smaller orbital adjustments were made during 1984 (noted in Table 2). These probably represent the testing of a small rocket system to keep the planned geostationary satellite at its correct orbital longitude.

As well as the satellite (designated 1984-008A) the launch also appeared to orbit three other objects: 1984-008B was the final stage of the booster and two fragments were designated 1984-008C and 1984-008D.

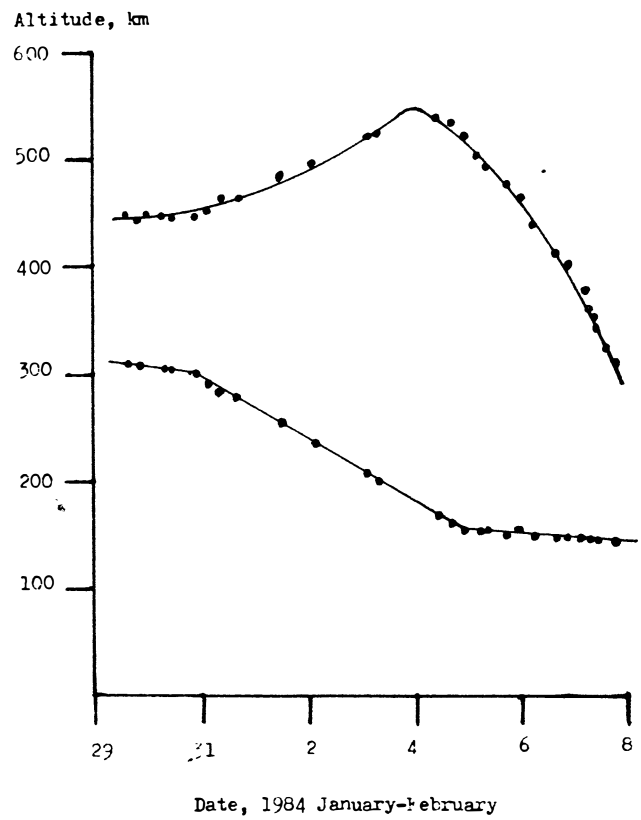

Fig. 1. The anomalous decay of 1984-008B, the PRC-12 rocket body. Unusual for a natural decay from this type of altitude, the apogee increased. While apogee was increasing, the perigee decreased almost linearly with time, while perigee remained almost constant when apogee was decreasing.

Figure 1 shows the orbital altitude of 1984-008B *versus* time. When an object is decaying from a low Earth orbit, both perigee and apogee should reduce. However, in the case of 1984-008B, the perigee is reducing while the apogee is increasing; the maximum apogee was about 538 km on 4 February.

The remaining two objects from the launch are not without some mystery. Some sparse data appeared in the Goddard Space Flight Center's *Two-Line Orbital Elements* for 1984-008C, the last data being Jan 30.14 with an orbit of 339-381 km, and a decay notice was issued for the same day. This orbit is far too high for a natural decay. Data for 1984-008D appeared until Feb 2.77 (orbit: 221-506 km) and a

TABLE 1. Chinese Launches in 1984.

Launch date	Object	Epoch	Incl deg	Period min	Perigee km	Apogee km
1984		1984				
Jan 29	PRC-12	Jan 31.23	36.03	160.80	359	6475
	Rocket	Jan 29.56	31.05	92.11	308	448
	Fragment C	Jan 29.82	31.12	92.37	353	428
	Fragment D	Jan 31.99	31.04	92.00	280	465
Apr 8	PRC 13	Apr 8.72	31.05	633.29	413	35688
		Apr 12.06	0.72	1444.55	35521	36383
		Apr 16.08	0.75	1435.95	35777	35790
	Rocket	Apr 11.77	31.08	630.09	437	35499
Sep 12	PRC-14	Sep 12.41	67.94	90.25	174	400
	Rocket	Sep 12.34	67.94	90.24	174	399
	Fragment C	Sep 12.97	67.91	90.16	174	390
	Fragment D		No Two-Line Data Available			

This Table lists all the objects that resulted from the three Chinese launches in 1984. Data are based upon the Goddard Two-Line Orbital Elements and assume a spherical Earth with a radius of 6378.1 km. No *Two-Lines* were issued for the fragment designated D from the PRC-14 launch. However, the Goddard Satellite Situation Report for 30 September 1984 gave the following data: 67.9°, 89.8 min, 168-362 km.

TABLE 2. Manoeuvres by PRC-12.

Epoch	Initial Orbit Perigee	Apogee	Epoch	Final Orbit Perigee	Apogee	Delta-V
Jan 29.56	308	448	Jan 31.23	359	6475	1846.2*
Feb 10.16	355	6475	Feb 11.72	378	6495	7.5
Feb 11.72	378	6495	Feb 11.94	379	6513	2.3
Feb 13.17	379	6512	Feb 14.41	394	6559	8.9
Feb 15.09	395	6559	Feb 15.76	402	6581	4.1
Mar 11.35	403	6580	Mar 12.14	447	6580	9.8
Mar 28.10	447	6582	Mar 30.36	481	6581	7.6
Apr 24.79	478	6580	Apr 26.26	475	6580	0.7
May 12.27	475	6580	May 12.95	469	6578	1.6
Jun 20.17	467	6580	Jun 20.28	467	6578	0.2
Jul 4.34	465	6579	Jul 5.24	461	6579	0.9
Sep 18.15	460	6579	Sep 19.73	462	6581	0.7
Oct 6.18	460	6582	Oct 8.22	459	6584	0.5

Notes.
This Table lists all the manoeuvres implied by the *Two Lines*. Since they are often small, some might have been missed, while others listed above might be the result of tracking errors. The first manoeuvre marked "*" involved an orbital plane change from 31.05° to 36.03°. Altitudes are in km and detla-Vs are in m/s.

decay notice appeared for 15 February. The orbital figures for 1984-008D were similar to those for 1984-008B.

In the past it has not been unknown for non-existent objects to be designated or for an object to have two international designations issued in error. In such cases, the way to clear the erroneous data from the satellite catalogue is to issue a decay notice. The launch of PRC-12 presented the American satellite trackers with something totally new, and it thus seems possible that 1984-008C and 1984-008D were designations issued in error, and these objects never existed.

3. PRC-13 IN APRIL 1984

While it was suggested that the strange behaviour of PRC-12 indicated a mission failure, the next launch proved such ideas to be incorrect. PRC-13 was the first experimental communications satellite, and the Chinese were able to place the satellite on station with its first flight – an impressive achievement.

PRC-13 was launched on 8 April at 11.20 [3]; again the Long March 3 booster was used from the new launch site. The satellite was placed into its eccentric transfer orbit on the first southbound pass over the equator. Ejection from this transfer orbit was attained on 10 April at 00.41 and a near-geostationary orbit was entered (the velocity change involved was 1,887 m/s). A subsequent orbital change on 16 April at 10.27 57s put the satellite into its correct geostationary location [4].

When initially placed in the near-geostationary orbit, the

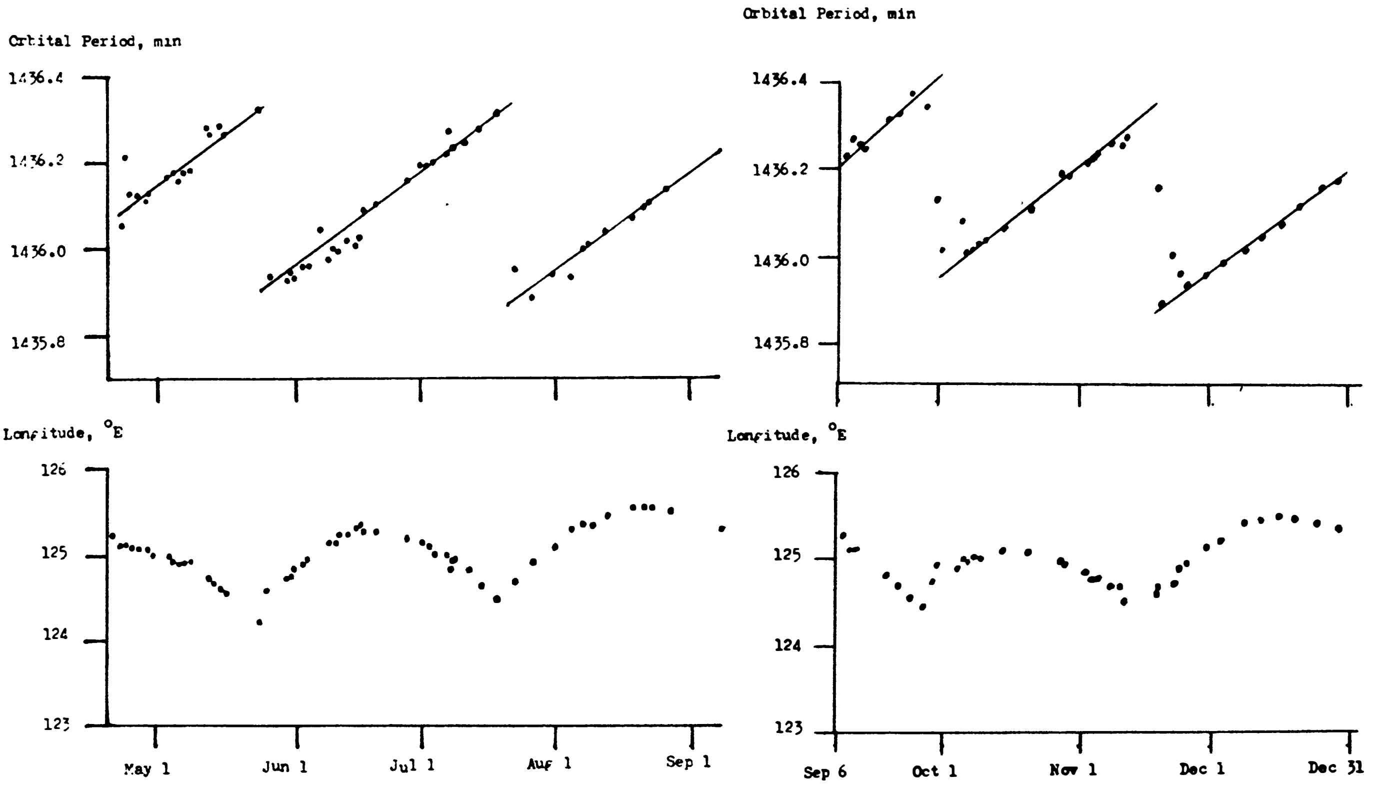

Fig. 2. The drift in location of the geostationary PRC-13 satellite. The upper part of each graph shows the orbital period, with the lower part showing the sub-satellite longitude at 12h GMT on the dates of orbital determination. The orbital adjustments are clearly shown. The straight lines are the "best fit" orbital periods for the various intervals.

TABLE 3. Station-Keeping Manoeuvres by PRC-13.

Pre-Manoeuvre Orbit Epoch	Perigee km	Apogee km	Post-Manoeuvre Orbit Epoch	Perigee km	Apogee km	Delta-V m/s
May 24.98	35785	35797	May 26.97	35779	35788	0.3
Jul 18.83	35788	35794	Jul 22.82	35772	35796	0.3
Sep 26.64	35699	35883	Oct 5.61	35782	35787	3.3
Nov 7.52	35783	35797	Nov 19.68	35780	35785	0.3

Notes
A summary of the station-keeping manoeuvres performed by PRC-13 after it entered its operational geostationary orbit. In some cases the *Two Lines* data suggested that the orbit was decreased in steps, but this summary excludes the intermediate orbits.

satellite was at 142.9° E and when the operational orbit was attained the location was 125.0° E, the position already registered for the STW-1 communications satellite ('STW' stands for Shiyan Tongxin Weixing). A sister satellite designated STW-2 has been registered for the location 70° E; to attain this one would expect the near-geostationary 'drift' orbit to have a period of significantly more than 1,436 minutes – perhaps closer to 1,460 minutes.

Although a satellite with an orbital period of 1,436 minutes would theoretically appear stationary when over the equator, in practice this does not happen because of perturbations by the Moon and Sun and the irregularities in the Earth's shape. Figure 2 shows both the orbital period and sub-satellite longitude of PRC-13 *versus* date of orbital determination (the positions are at 12.00 each day). This clearly shows the changes experienced by the satellite. After orbital injection the orbital period slowly increased owing to the perturbations to about 1,436.34 minutes, at which time the period was reduced to about 1,435.94 minutes. After this, the orbital period increased again, to be subjected to further corrections.

The longitude of the satellite went through a cycle of initially increasing and then decreasing while the orbital period increased. This is because when the orbital period is less than 1,436 minutes the satellite completes more than 360° in a day, while the period in excess of 1,436 minutes means that less than 360° are completed in a day. It is clear from Fig. 2 that the maximum longitude occurs when the period is 1,436 minutes.

Table 3 provides a summary of the station-keeping manoeuvres performed by the satellite during 1984. The delta-V values were obtained by assuming a two-impulse manoeuvre,

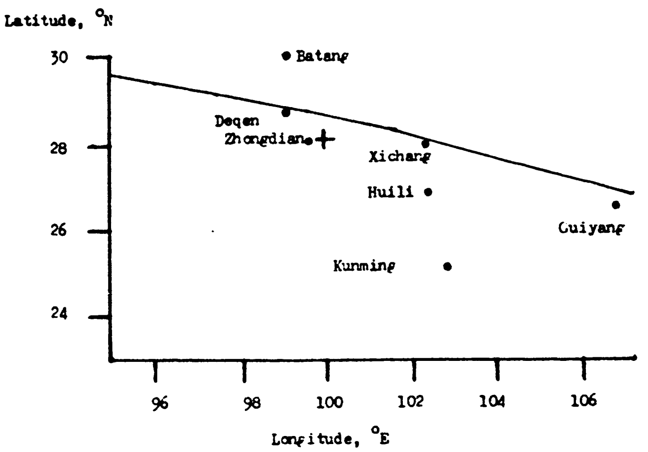

Fig. 3. The ground track of PRC-13 on rev 0 (orbit at launch), together with the major inhabited areas. The cross shows the position of the new launch site as estimated in Ref. 10.

Town	Lat. °N	Long. °E
Kunming	25.07	102.68
Huili	26.80	102.30
Zhongdian	28.00	99.50
Batang	30.03	99.02
Degen	28.75	98.97
Xichang	27.88	102.30
Guiyang	26.52	106.65

first manoeuvring at perigee and then at apogee. However, there is a simple relationship that can be derived analytically for the delta-V requirement in a near-geostationary orbit:

$$\text{delta-V} = 1025 \frac{dP}{P} \text{ m/s}$$

where dP is the change in orbital period and P is the initial orbital period. This approximation is correct to 0.1 m/s for $-10 < dP < +10$ minutes.

The delta-V required to manoeuvre PRC-13 from its original drift orbit to its original geostationary orbit was 15.4 m/s, and the station-keeping manoeuvres were an additional 4.2 m/s, giving a total delta-V for 1984 of 19.6 m/s.

PRC-13 was cylindrical, with a diameter of 2.1 m and a height of 3.1 m, including the antenna system. The mass of the satellite in its transfer orbit was 900 kg, while the geostationary orbit mass was 420 kg. The satellite used an up-link frequency of 6 GHz and a down-link frequency of 4 GHz [5].

The satellite was still operating at the end of 1984 and, considering that it was the first Chinese geostationary communications satellite attempt, it must be considered an outstanding success.

4. PRC-14 IN SEPTEMBER 1984

After the innovations with PRC-12 and -13, the third launch of 1984 was a return to the largest programme flown by the Chinese: the recoverable photoreconnaissance satellites. PRC-14 was launched from the original northern launch site, generally known as Shuang-ch'eng-tzu, by the FB-1 booster on 12 September at about 05.43. After five days in orbit a capsule was ejected and recovered on Earth. The final northbound equator crossing of the capsule was probably Sep 17.1660 over 307.98° E.

The operation of this satellite seems to have followed the pattern of the earlier launches in this series, in that no manoeuvres were completed and there was a payload bus left in orbit after recovery, the bus decaying from orbit after 17 days. It is notable, however, that the orbital inclination was 67.9°, the highest inclination used in the photoreconnaissance satellite programme.

TABLE 4. Summary of Estimates of the New Launch Site.

Lat. (°N)	Long. (°E)	Location
29.31	103-120	Westerly part of area speciafied [7]
-	-	Tibet? [2]
31	105	South of this location, in Szechwan Province [8]
26.8	102.3	Near Huili, in Szechwan Province [9]
28	100	- [10]

5. THE NEW LAUNCH SITE

Until 1984 all the Chinese orbital missions had come from a northern launch site, generally known as Shuang-ch'eng-tzu located at 41.3° N. In 1984 the Chinese identified this site as being Jiuquan, located in Gansu Province [6].

With PRC-12 it was clear that a new launch site was in use, because of the original orbital inclination for the mission. During 1984 a number of estimates were made for the location of the new site, and these are summarised in Table 4.

Figure 3 shows the ground-track of PRC-13 (which at this scale matches that of PRC-12). A working location of 28° N, 100° E will be used for the time being for the new launch site since the ground-tracks pass closest to the launch site given in Ref. 10.

The nearest place of any size to this location seems to be Zhongdian in Szechwan Province. The launch pictures released of PRC-13 show that the site is surrounded by mountainous terrain (PRC-12 was launched in local darkness).

No launch time was quoted for PRC-12 in Section 2, but now that the launch site has been pin-pointed with reasonable accuracy, the launch time can be calculated to be 12.24.

6. THE LONG MARCH 3 LAUNCHER

The pictures released for PRC-12 (for example, see Ref. 11) and PRC-13 [12, 13] confirm that the first two stages are those used on the FB-1 (Fengbao-1) booster with stabilising fins added to the first stage. A new third stage using liquid oxygen and liquid hydrogen has been added.

Since the injection delta-V for the geostationary orbit was about 1,890 m/s, the transfer orbit mass of the payload was 900 kg and the final payload mass was 420 kg, the specific impulse of the injection "kick" rocket comes to 253-sec, about what would be expected for solid propellants.

6.1 The Ascent Profile

The launch profile suggested here is derived from considering both PRC-12 and PRC-13. In the case of PRC-12, the initial perigee was about 180° away from the injection point. On

TABLE 5. The Long March 3 Booster.

	Stage 1	Stage 2	Stage 3
Length (m)	18.8	9.5	8.0
Diameter (m)	3.3	3.3	2.2
Dry Mass (kg)	13,500	3,175	2,000
Fuel Mass (kg)	135,500	36,800	7,000
Isp (sec)	285	290	370
Thrust (tonnes)	280	70	4.5

Notes
The masses and specific impulses (Isp) quoted above are estimated. Together with a payload shroud (1,000 kg) and the STW-1 payload (900 kg), the total mass of the Long March 3 at launch is 199,875 kg using the above figures; the Chinese suggest as mass of 200 tonnes. The first stage diameter is about 6 m over the stabilising fins. The length of the vehicle at launch is about 43 m, including the payload shroud with a length of about 5.4 m. The FB-1 booster, using the first two stages of the Long March 3, is about 31.5 m long, and with a 3,075 kg payload has a launch mass of about 193,000 kg.

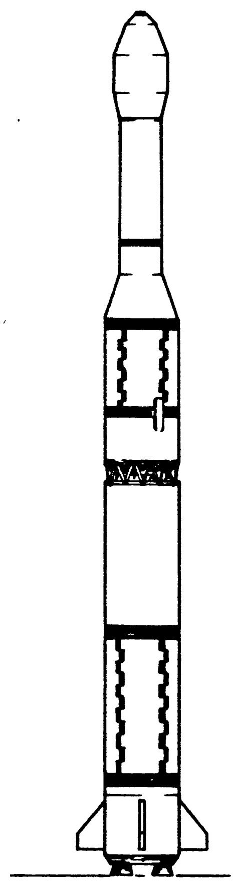

Fig. 4. The new Long March 3 booster, based upon the first two stages of the FB-1 launch vehicle. (Drawing by R. F. Gibbons, based upon Chinese photographs).

PRC-13 the initial perigee was located close to the descending node. Thus it would seem that PRC-13 entered its transfer orbit with a two impulse manoeuvre from the third stage. The satellite and rocket initially enter a 310-420 km orbit, the apogee being close to the descending node – the first crossing of the equator since the launch is made to the south-east. Injection is perhaps 2,000 km downrange from the launch site, and the combination coasts for a few minutes until the equator is approached. As the rocket stage and payload approach the equator the rocket stage re-ignites to place the payload into a 420-35,690 km orbit.

Since PRC-12 was a test flight, only the initial orbital injection was completed, and then the kick rocket on the payload was ignited to alter the orbit of the payload itself. Therefore, at launch the PRC-12 booster would be only partially fuelled.

6.2 The Booster

A drawing of the launcher appears in Fig. 4. The new upper stage has a diameter less than that of the first two stages and the payload shroud flares slightly to give a slight hammer-head appearance. The second stage is lengthened slightly over the version used for the FB-1 missions. Table 5 presents the estimated dimensions and other characteristics of the booster.

After the successes of the first two launches, the Chinese are now offering the booster for commercial users [14].

7. SPACE TRACKING SHIPS

Just as the Soviet Union developed a fleet of space tracking ships to fill in gaps in their land-based network, the Chinese have done similarly. To date, however, all the major Chinese space manoeuvres seem to have been initiated while spacecraft have been over China (most probably, recoveries are pre-programmed at the final pass over China), including the PRC-13 geostationary orbital injection, which came near a descending node.

The Chinese tracking ships as described [15] are called Yuanwang 1 and Yuanwang 2:

"The Yuanwangs are two ocean-going survey ships... engaged in tracking the communication satellite as it settled into orbit around the Earth. On top of each of the two 190 m long and 20 m wide vessels is an antenna network... The cabin contains some of China's most sophisticated technology – the ship's engines, navigation and tracking equipment, and its communications, meteorological, survey and control systems. They were installed to track the satellite, collect and process data and carry our remote control and retrieval.
Launched towards the end of the 1970s, the two ships have been involved in a number of rocket retrievals. In 1980, when China launched a carrier rocket into the South Pacific, the two Yuanwangs successfully completed their survey and recovery mission. They also carried out tracking from a designated area in 1982 when a submarine-based carrier rocket was launched."

The Soviet ships have been dedicated to space work, but probably the Yuanwangs are general research ships, performing space work as only one of many tasks at sea.

8. CHINESE TEST PROGRAMME MISHAP

Not much information has been released about the failures in the Chinese space programme, but following the second successful flight of the Long March 3 they gave details of a mishap that took place some years earlier [16]:

"When the experimenters at the number 5 pad of a rocket experiment centre was testing the fuel flow and its speed on 28th January 1978, a roaring explosion took place around the pad, followed by fire. Gigantic air waves

TABLE 6. Chinese Objects in Orbit.

Launch	Object	Epoch	Incl deg	Period min	Perigee km	Apogee km
PRC-1	Satellite	Dec 24.39	68.44	112.68	436	2263
	Rocket	Dec 24.65	68.40	107.08	425	1759
PRC-12	Satellite	Dec 30.84	36.15	163.36	459	6584
PRC-13	Satellite	Dec 29.57	1.08	1436.17	35784	35792
	Rocket	Dec 29.64	30.69	629.99	486	35445

Notes
This Table lists all the Chinese objects still in orbit as at 31 December 1984. The orbits are calculated from the last set of *Two Lines* to be issued for each object in 1984.

destroyed the windows and doors, shattered a roof and bent the steel beams. Even glass in buildings as far as 80 m away was shattered. A dozen or more people who participated in the test were thrown to the floor with their hair, eyebrows and faces burned. Some of them lost their hearing because of broken eardrums."

The report continues to comment on some scientists returning to work within a week of the explosion despite their injuries. It is possible that this accident came during the testing of the third stage of the Long March 3, since that booster was introduced some years later than originally intended.

9. INTO THE FUTURE

After the successful flight of the first geostationary communications satellite, a flight to the STW-2 location in the next year or so is possible. The Chinese have also mentioned the launch of a meteorological satellite in the not-too-distant future, although whether this will be the previously-reported retrograde orbit mission or a geostationary mission is unclear. If a retrograde mission is flown using the Long March 3, it will be interesting to see whether the launch is from the original Shuang-ch'eng-tzu launch site or the new site in Szechwan.

While the indigenous manned programme has been postponed for the time being, it seems probable that a Chinese citizen *will* orbit the Earth before the end of the decade. Chinese and American officials are discussing possible flight of a Chinese astronaut aboard a Shuttle mission as part of a co-operative space science programme [17].

Table 6 provides a summary of the Chinese objects still in orbit at the end of 1984.

ACKNOWLEDGEMENT

The author would like to acknowledge the Goddard Space Flight Center for their supply of *Two-Line Orbital Elements*, without which this paper could not have been produced.

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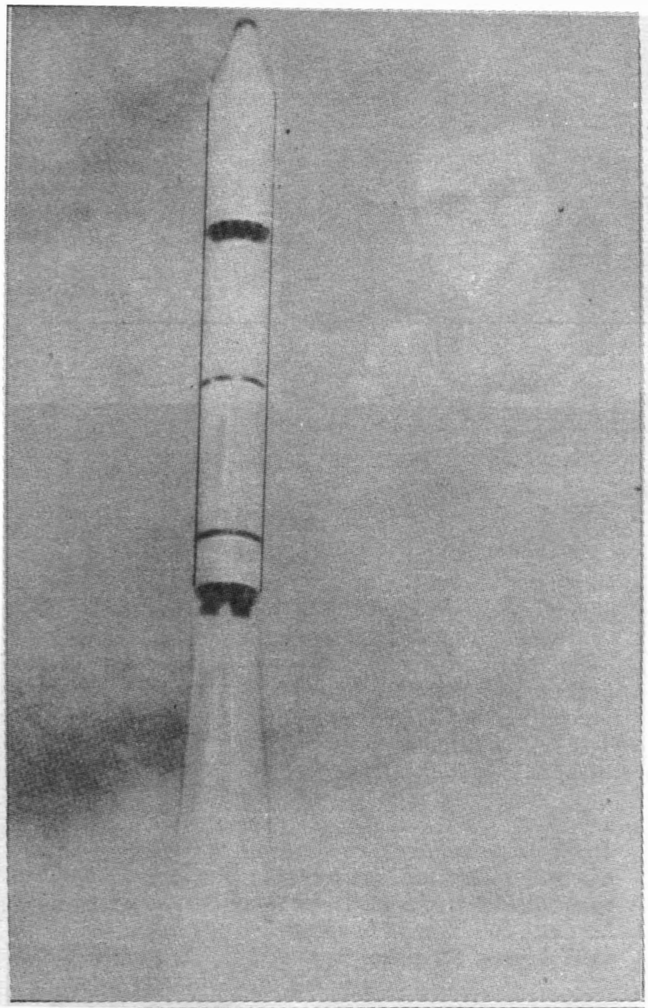

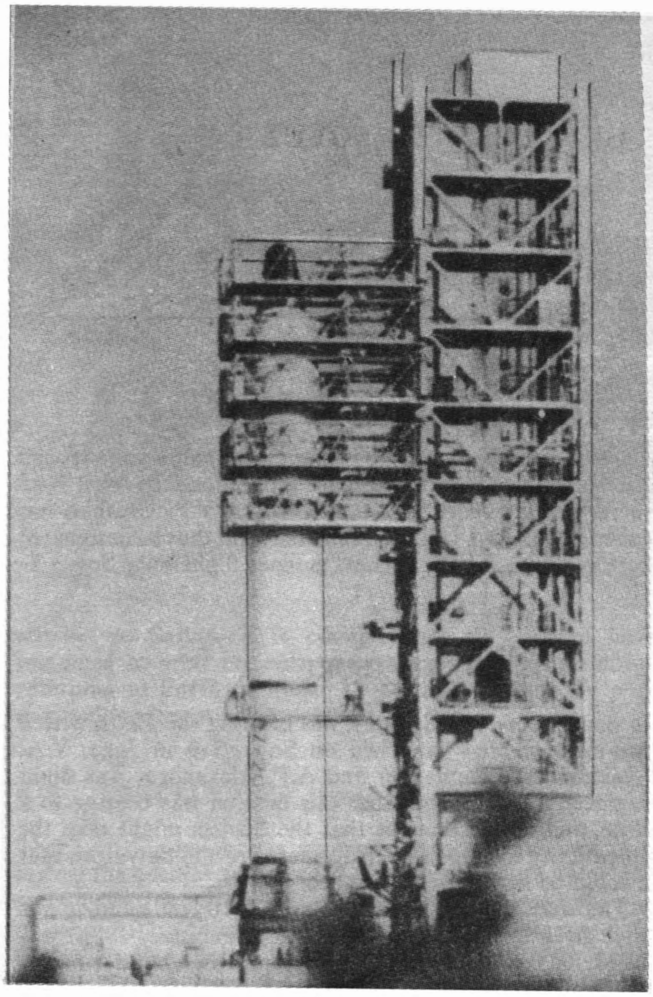

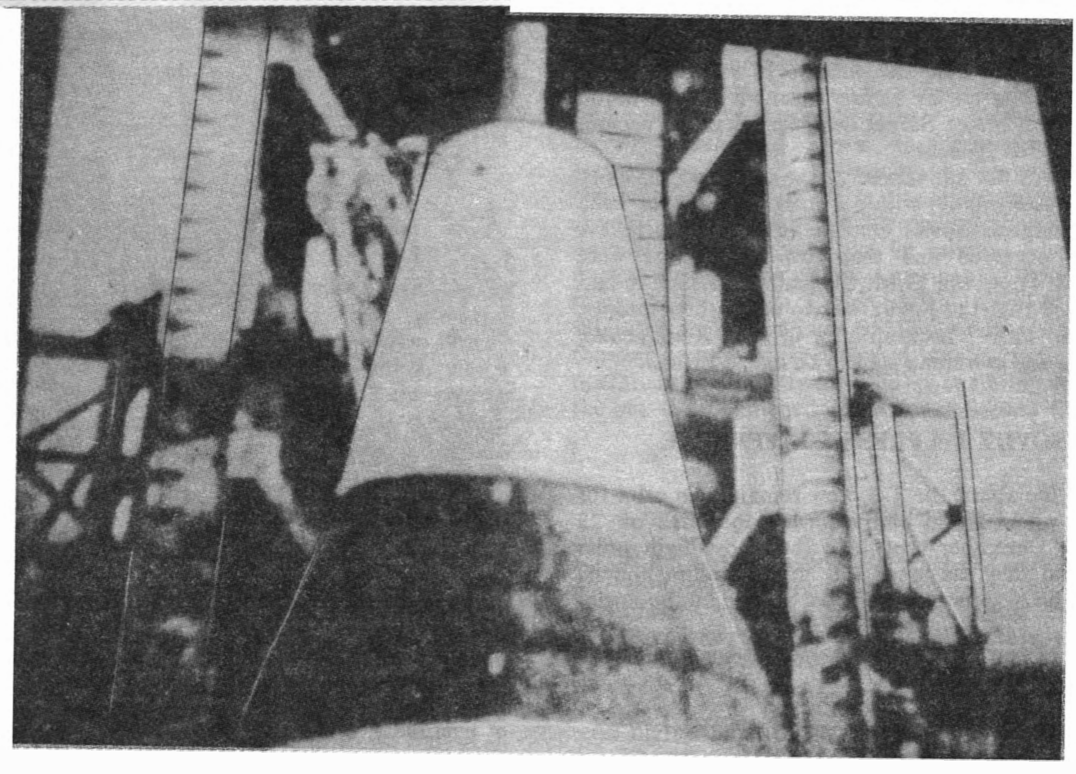

Preparation and launch of a CZ-2 vehicle carrying a recoverable reconnaissance package.

(Photograph courtesy of Theo Pirard)

THE MISSION OF SOYUZ T-10-1

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1. INTRODUCTION

On 26 September 1983 the Soviet Union suffered its second manned launch abort in its space programme. In April 1975 there was an abort at altitude, which V.P. Glushko has called Soyuz 18-1 [1]; the 1983 abort will thus be designated here as Soyuz T-10-1, the next manned flight being Soyuz T-10.

2. THE LAUNCH ABORT

In September 1983 Salyut 7 was orbiting the Earth with a two-manned crew launched on Soyuz T-9 in June: V.A. Lyakhov was commander and A.P. Alexandrov was flight engineer. In mid-September this mission was coming to a close, and it was thought that the Soviets might take the opportunity to launch a replacement crew to Salyut, so that it could be permanently manned.

The launch of the intended Soyuz T-10 (the number was later given to the successful launch in February 1984) was scheduled fror 19.38 GMT on 26 September, but during the final stages of the countdown a fire broke out in the base of the SL-4 booster. After some delay, the mission was aborted and the shroud tower ignited to carry the Soyuz descent craft and crew away from the inferno. It was revealed at the 1983 IAF Congress by former cosmonaut Konstantin Feoktistov (now a major Salyut designer) that the booster remains burned for 20 hours.

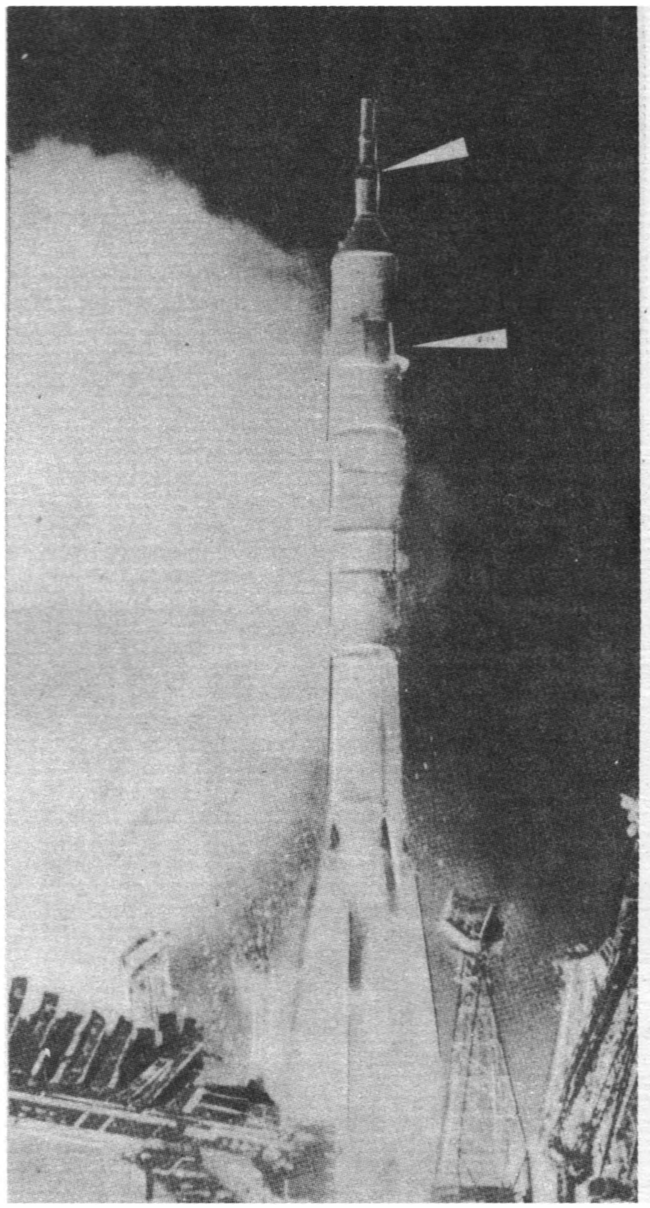
The launch was not announced at the time, but the story broke in the western press within a week. In October 1983 at the IAF Congress Soviet officials acknowledges that a launch abort occurred and that two cosmonauts were involved: V.G. Titov and G.M. Strekalov. Earlier, it had been speculated that the Soyuz was to carry three people, possibly the Soyuz T-7 back-up crew of V.V. Romanenko, V.P. Savinykh and a woman said to be called "Irena."

3. THE SOYUZ T-9 PRESS CONFERENCE

As a result of the abort, the T-9 crew remained in orbit for an extra six weeks or so and returned to Earth on 23 November. In December they held their post-flight press conference, and they discussed the launch failure and its implications; these comments were not carried by the Soviet media.

Two pieces of new information came out concerning the aborted mission:

1. The T-9 crew were intended to hand Salyut 7 over to the intended T-10 crew.
2. The EVA work conducted by the T-9 crew on 1 and 3 November was intended for completion by the T-10 crew. This would have been done before the T-9 crew returned to Earth.



A Soyuz A-2 launch with two vital elements of the T-10 abort indicated. The upper arrow shows the rockets of the escape system; the lower points to the 'petals' that were deployed to slow down the escaped craft. (This picture is from the French/Soviet mission of June 1982).

Novosti

Additionally, the crew of the aborted mission was confirmed as that given above.

The Soyuz T-8 crew, from left: Serebrov, Titov and Strekalov, the latter two of whom formed the crew for the failed T-10.

4. ADDITIONAL INFORMATION

There are some anomalies with the illustrations released to represent the Salyut 7/Cosmos 1443/Soyuz T-9 complex which operated during the summer months of 1983. Two points should be noted, both of which relate to pictures carried by the publication *Soviet Union* [2]:

1. The cover picture shows the three spacecraft complex with no cut-away, but Salyut has the solar panels added which were carried into space as part of the Cosmos 1443 cargo and deployed only in early November - some 2½ months after Cosmos 1443 was undocked.
2. The cut-away drawing inside the magazine shows a three-man crew operating on the complex. Soyuz T-9 carried only two men.

Therefore, whatever they relate to, the illustrations do not seem to represent the T-9 mission as actually flown.

5. POSSIBLE SOLUTIONS

The discrepancies noted above and the rationale for the T-10-1 mission can be resolved by noting that Titov and Strekalov on the aborted mission were the two-man "core" crew who flew with A.A. Serebrov on Soyuz T-8, which failed to dock with the Salyut 7/Cosmos 1443 complex in April 1983.

Considering the pictures in *Soviet Union,* it would seem that they relate to the intended T-8 mission (three men), and on that flight there would have been EVA work to add the solar cell panels to Salyut by Titov and Strekalov. We can assume that they had been trained specifically for this work.

After the T-8 failure, Titov and Strekalov could not be launched on the next mission, which was already scheduled for their back-ups, Lyakhov and Alexandrov. Soyuz T-9 was launched with the intention of testing the Salyut 7/Cosmos 1443 systems in joint mode. Titov and Strekalov were recycled as back-ups for T-9 and were to fly to Salyut in September to perform their EVA work. The launch abort cancelled these plans.

While the Soviets said that Salyut 7 should have been handed over to the T-10-1 crew, this would only be a "bonus" for an unplanned mission. Rather than fly a full 4-6 month mission to Salyut, it is possible that they would have remained in orbit for only one cycle of landing windows, returning to Earth on about 17 December when the next nominal landing window opened.

6. CONCLUSIONS

The T-10-1 mission was planned as an afterthought, following the docking failure of T-8, and the T-8 crew (trained specifically for Salyut EVA work) were recycled for the mission. Although a crew handover would have taken place on Salyut in October 1983, the replacement crew would have remained in orbit for only about 80-85 days rather than attempting a new duration record or waiting for the next resident crew to arrive.

Originally the Soviets said that the two docking ports on Salyut 6 and - by implication - Salyut 7 meant that replacement crews could be launched and the station permanently manned. However, until September 1983 no such attempt was made. Additionally, the Soviets have indicated that at present they need to give the ground crew (both on the mainland and onboard the tracking ships) a rest between missions. This problem will be relieved when the Soviets deploy their version of the American TDRSS communications satellite system. Called SDRN, it will consists of three satellites positioned over 95°E, 200°E and 344°E. Once these new satellites are deployed, we can expect the Soviets to operate a permanently-manned space station - most probably the one to be launched on the giant booster in 1986-87.

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THE SPACE PROCESSING APPLICATIONS ROCKET

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In the early 1970's the US began research into materials processing in space. After preliminary experiments aboard Apollo, Skylab and Apollo-Soyuz, NASA was faced with a half decade hiatus in manned space flight activity until the Shuttle became operational. The space agency filled the gap by using sounding rockets to continue the important materials processing research. Between 1975 and 1981 a total of 49 materials experiments were conducted on nine suborbital rocket flights.

1. EARLY RESEARCH

The idea of materials processing experiments in space is credited to Hans Wuenscher, a NASA employee [1], who conceived the idea in early 1966 while serving as the Assistant Director for Advanced Projects of the Process Engineering Laboratory at the Marshall Space Flight Center (MSFC) in Alabama. He proposed that simple materials experiments should be flown on Apollo lunar flights and, following a favourable response from NASA headquarters, his project was approved in December 1969 for flights on Apollos 14-17.

The first, relatively simple, experiments were conducted on Apollo 14 as it returned from the Moon in February 1971. In the Composite Casting Demonstrations, 11 metal samples were melted and solidified in a furnace to demonstrate that alloy casting could be performed in space. The Heat Flow and Convection Demonstration used a two-chambered apparatus to study field convection and heat flow in the absence of gravity; a repeat demonstration was performed during Apollo 17.

The third experiment on Apollo 14 was the Fluid Electrophoresis Flight Demonstration. Three sample materials were photographed as they were electrically separated from the fluid medium while flowing between negative and positive electrodes; an improved version was flown on Apollo 16 [2].

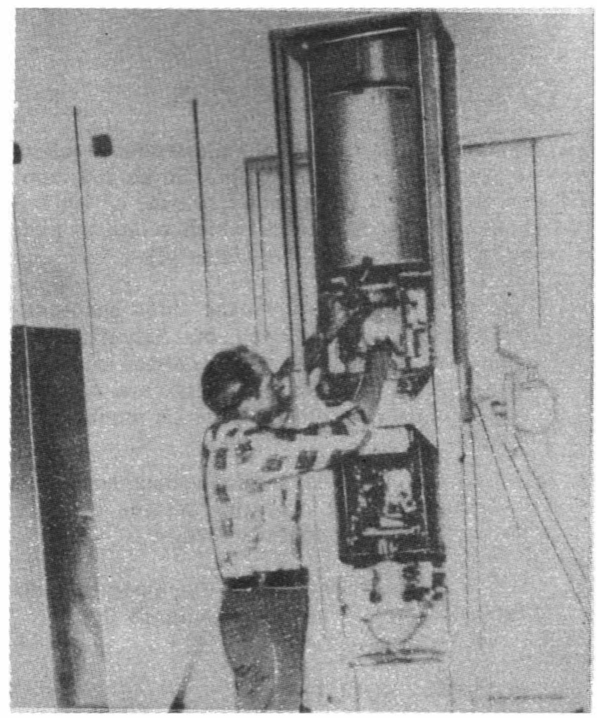
2. SKYLAB AND ASTP

The foundations of the present materials processing programme were laid in the Skylab and Apollo-Soyuz projects from 1973 to 1975. Four separate processing apparatus were incorporated in the Skylab M512 Materials Processing Facility (Table 1) to perform crystal growth, alloy smelting, brazing and welding experiments.

Two similar apparatus were aboard the American Apollo-Soyuz spacecraft, with the addition of two sophisticated electrophoresis investigations. A requirement for long running times prevented electrophoresis experiments from being conducted on sounding rocket flights.

3. SOUNDING ROCKETS

Hans Wuenscher of MSFC is again credited with the idea of using sounding rockets to perform materials research in space. While attending an engineering conference at the NASA Goddard Space Flight Center in 1970, Wuenscher inquired at the Sounding Rocket Division about the availability of space on the rockets for extra experiments. He was informed that lead ballast carried on certain firings could be removed for the installation of additional apparatus.



The 155 kg payload for the first SPAR materials processing research rocket is checked out at the NASA Marshall Space Flight Center.

NASA

MSFC prepared a simple processing experiment for two sounding rocket flights designated Research Rocket (RR) 1 and 2. The stability of bubbles in plain and fibre-reinforced indium-bismuth alloy [3] was investigated in a furnace based upon the Apollo 14 casting installation, using sample cartridges originally intended for use on Apollo 15.

The first experiment (RR-2) was flown on NASA rocket 13.113 GT, an Aerobee 170A test round fired from the White Sands Missile Range in New Mexico on 19 October 1971. The payload was recovered, but the metal sample was found to have been only partially melted.

RR-1 repeated the metal melting experiment during an evaluation test flight of the Canadian-built Black Brant VC vehicle. NASA rocket 21.006 NT was launched on 27 January 1972 from Wallops Island, Virginia but unfortunately the recovery system malfunctioned and the payload

TABLE 1. Skylab and ASTP Processing Aparatus.

Skylab
Multi-purpose Electric Furnace (M518)
Exothermic Brazing Experiment (M552)
Sphere Forming Experiment (M553)
Metals Melting Experiment (M551)
ASTP
Multi-purpose Electric Furnace (MA 010)
Crystal Growth Reactors (MA 028)
Electrophoresis Experiment (MA 011)
Electrophoresis Demonstration (West Germany) (MA 014)

TABLE 2. SPAR Flight Chronology.

Payload	Date	Rocket Number*	Altitude (km)	Result
SPAR I	11 December 1975	21.032 NP	206	Success
SPAR II	17 May 1976	21.033 NP	188	Success
SPAR III	14 December 1976	21.034 NP	174	Success
SPAR IV	21 June 1977	21.045 NP	179	Partial Success
SPAR V	11 September 1978	21.046 NP	165	Success
SPAR VI	17 October 1979	21.047 NP	170	Hard landing
SPAR VII	14 May 1980	27.018 NP	204	Success
SPAR VIII	19 November 1980	27.019 NP	233	Crash landing
SPAR IX	2i January 1981	27.017 NP	209	Success

* 21 denotes Black Brant VC rocket, 27 is Black Brant VIII (Nike-boosted VC).

was lost at sea. Although inconclusive, the RR results served to demonstrate to NASA the feasibility of conducting materials processing experiments on sounding rockets.

4. GROUND-BASED EXPERIMENTS

While the Skylab and Apollo-Soyuz materials experiments were being conducted, NASA researchers worked on ground-based experiments to gather background data. KC-135 and F-104 jet aircraft were used to perform simple materials tests while the aircraft flew ballistic arcs, experiencing up to a minute of microgravity on each arc.

The Saturn 5/Shuttle dynamic test stand at MSFC was used as a drop tower to simulate weightless conditions. Experimental packages were dropped inside from a height of 90 m, providing about four seconds of simulated microgravity. The simulations and laboratory bench work provided information on the basic principles underlying each materials process before any experiments were conducted in space.

5. SPAR PROJECT

The Apollo-Soyuz mission in July 1975 was the last NASA manned space flight until the reusable Shuttle was scheduled to fly in 1979. NASA decided in 1974 to use sounding rockets to conduct further materials research in a space-like environment. Plans were made to fly up to 15 SPAR (Space Processing Applications Rocket) payloads on single stage Black Brant VC rockets to be launched from the White Sands Missile Range in New Mexico.

The 200 kg payload compartment of SPAR, which measured 3 m in length and 41 cm in diameter, was divided into three sections: experiments, support equipment and ogive recovery system. Approximately five minutes of microgravity conditions were obtainable on each 15 minute flight, with residual accelerations limited to only 3 x 10^{-5} g.

SPAR was managed for NASA by Roger Chassay of MSFC, receiving a modest amount of funding: $1.75 million was allocated in Fiscal Year 1976 and a peak of $3 million was reached in 1978 [4]. NASA funded each experiment and accepted flight proposals from industrial, foreign and NASA in-house experimenters.

6. FURNACES AND CONTAINERLESS PROCESSING

The General Purpose Rocket Furnace, one of several standard apparatus supplied by NASA for SPAR experiments, contained three separate sample chambers with individual temperature control. Each was capable of reaching temperatures of 1,150°C and was equipped with gas bottles or water reservoirs to cool the samples after processing.

A special furnace was developed for samples requiring directional solidification (melting and refreezing a narrow zone of a sample using a continuously moving heating element). The four individual furnace units, mounted on rails, operated at temperatures of up to 1,600°C. A water-cooled chill block was attached to each furnace to resolidify the sample [5].

A device to suspend samples in mid-air during processing was developed to prevent contamination caused by contact with the walls of the container. The samples were suspended in the 'acoustic levitator' by means of ultrasonic sound waves; single-axis levitators employed a solitary sound source, while three-axis levitators used three sound generators in order to manipulate specimens more efficiently. Furnaces capable of reaching a maximum temperature of 1,575°C were optional with acoustic levitator experiments.

An 'electromagnetic levitator' is a device that suspends samples magnetically with a radiofrequency coil, while heating the sample with radio energy (somewhat like a microwave oven); its use is limited to ferromagnetic metals.

7. SPAR FLIGHTS

The first SPAR payload was successfully fired from White Sands on 11 December 1975. The nine experiments of SPAR I (Table 3) were designed to investigate physical metallurgy, alloy casting, fluid physics and crystal formation.

In the Dendritic Remelting and Macrosegregation investigation, conducted by Mary-Helen Johnston and Carolyn Griner of MSFC, a significant absence of fluid flow related to surface tension was discovered in a molten sample of ammonium chloride. Without fluid flow present it is possible to produce alloys in space that would be more uniform than could be made on Earth.

Another experiment, Particle Interface Interactions, revealed that the process of sedimentation was largely absent in microgravity. Sedimentation, the separation of solid material from a liquid solution, is a key element of many manufacturing processes on Earth. The experiment indicated that compensation would have to be devised when producing materials in space that usually involved sedimentation.

When SPAR II was launched on 17 May 1976, four of the ten experiments aboard were duplicated in order to obtain the maximum amount of data. Included in the experiment complement was the production of metal foams (lighter and stronger than an equivalent volume of solid metal), the casting of four different metal alloys and a repeat

TABLE 3. SPAR Experiments (total: 49).

Experiment name and sponsoring agency	SPAR flight no.
Thoria-dispersed magnesium casting (Aerospace Corp.)	1
Dispersion strengthened lead-silver alloys (DFVLR/West Germany)	1
Lead-antimony eutectic (alloy) (Marvalaud, Inc.)	1
Dendritic remelting and macrosegregation – I (MSFC/NASA)	1, 2*
Contained polycrystalline solidification (Grumman Aerospace)	1, 4, 5
Liquid mixing (MSFC/NASA)	1
Foams from sputter deposited aluminium (Battelle Northwest Laboratories)	1
Particle interface interactions (MIT)	1
Bubble behaviour in metal melts (Grumman Aerospace)	1, 5
Solidification of lead-antimony eutectic in space (Marvalaud, Inc.)	1, 2*
Closed-cell metal foams (Battelle Northwest Laboratories)	2*
Agglomeration of immiscible liquids (aluminium-indium) (Battelle Memorial Institute)	2
Aluminium alloy solidification (University of Hamburg/West Germany)	2
Thoria-dispersion strengthened composites (alloys) (Aerospace Corp.)	2*
Liquid mixing in rocket flight environment (MSFC/NASA)	3
Containerless processing of beryllium (General Electric)	3
Thermal migration of bubbles (Grumman Aerospace)	3
Epitaxial growth of single crystal films (Rockwell Science Center)	3, 5
Contact and coalescence of viscous/visoelastic bodies (acoustic levitator) (MIT)	3
Crystallisation materials (MIT)	4
Containerless processing of ferromagnetics (General Electric)	4
Containerless processing technology (levitators) (JPL/NASA)	4
Foam Copper (Marvalaud, Inc. - Johns Hopkins University)	4, 9
Dendritic remelting and macrosegregation - II (MSFC/NASA)	5
Solidification of magnetic composites (Grumman Aerospace)	5, 9
Directional solidification of immiscible Al-In alloys (CNEG/Grenoble, France)	5, 9
Directional solidification of Bi/Mn-Bi composite (Grumman Aerospace)	6
Tin-lead metal casting (MSFC/NASA)	7
Epitaxial growth of gallium arsenide single crystal films (Rockwell Science Center)	6
Acoustic levitator technology (JPL/NASA)	7
Bubbles in floating liquid drops (acoustic levitator) (JPL/NASA)	7
Movement of bubbles in molten glass (MSFC/NASA)	8
High temperature glass production (acoustic levitator) (Rockwell International)	8
Liquid drop samples in acoustic levitator (JPL/NASA)	6, 8
Tin-bismuth alloy solidification (MSFC/NASA)	9

* experiment carried in duplicate (counts as two).

of the dendritic remelting experiment from SPAR I to verify the earlier results.

Two of the investigations were designed to study immiscible materials – molten metals that will not mix on Earth but that will combine in microgravity to form alloys with enhanced strength and other desirable characteristics. Gold and aluminium were fused to form an alloy with improved electrical conductivity at cryogenic temperatures (superconductivity), and immiscible aluminium and indium were also processed.

The first demonstration of acoustic and electromagnetic sample levitation in space occurred on SPAR III. Successfully launched on 14 December 1976, the payload contained five experiments: the growth of thin films from single crystals, an investigation of liquid mixing and two containerless processing evaluations. The thin film experiment experienced anomalies and was granted a reflight on SPAR V.

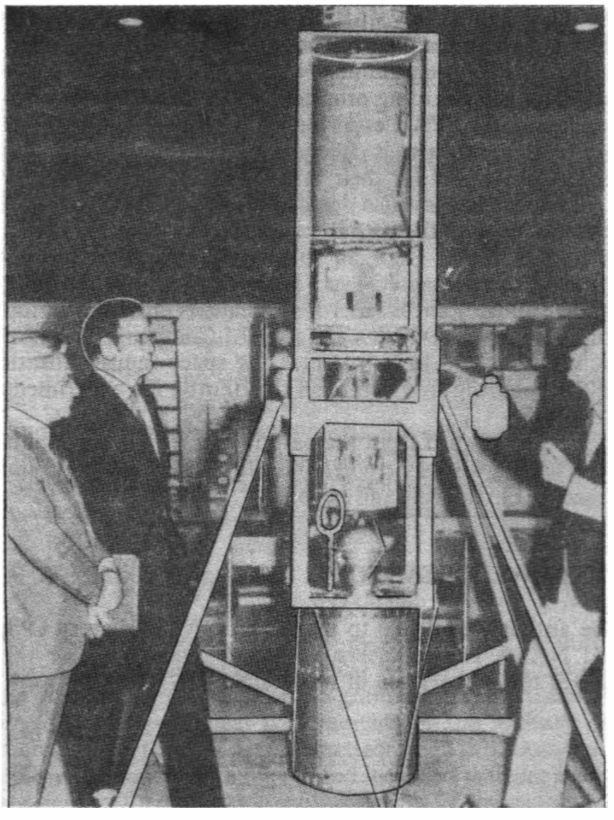
An acoustic levitator developed by Don Uhlmann of the Massachusetts Institute of Technology (MIT) was used to investigate the feasibility of containing two blobs of water while they contacted and merged together in microgravity. The space processing simulation was not accomplished because the mechanism failed to levitate the water drops.

A berryllium sample was successfully processed by an electromagnetic levitator built by General Electric. The beryllium melted completely without touching the radiofrequency coil, but the grain structure of the sample was not as fine as anticipated. General Electric electromagnetic levitators are scheduled to make regular trips into orbit aboard the Space Shuttle beginning in 1985.

Highlighting the five experiments conducted by SPAR IV on 21 June 1977 [6] was the first test of a three-axis acoustic levitator in space. Developed by Taylor Wang of the Jet Propulsion Laboratory (Payload Specialist on the Spacelab 3 mission), the device levitated a 2.5 cm globe of water but broke down before the specimen could be rotated or oscillated. An electromagnetic levitator was also used to process samples of magnetic materials and the polycrystalline solidification experiment from SPAR I was repeated. At least one other experiment suffered a malfunction and the flight was only partially successful.

After a year delay to correct the malfunctions experienced on the previous flight [7], SPAR V lifted off on 11 September 1978. Three of the six experiments in the payload were reflights from previous missions, including polycrystalline solidification from SPAR I and IV and the thin film experiment from SPAR III. The thermal migration of bubbles investigation (SPAR I) was also being reflown because the initial results were inconclusive.

An experiment sponsored by the Grumman Corporation sought to determine if manganese-bismuth alloy acquired enhanced magnetic characteristics when processed in microgravity, and a new version of Mary-Helen Johnston's macrosegregation experiment was also flown. Aluminium and



The SPAR III payload is inspected at the Marshall Space Flight Center before shipment to the launch site.

NASA

indium (Al-In) were processed by directional solidification, but the two metals remained mixed for only a short time before permanently separating. A reflight for the experiment was arranged on SPAR IX.

The flight of SPAR VI on 17 October 1979 was marred by a landing accident [8]. The payload touched down in mountainous terrain about 80 km downrange, and a hole was punched in the side of the payload compartment as it tumbled and came to rest against a rock. The single-axis acoustic levitator also sustained shock damage.

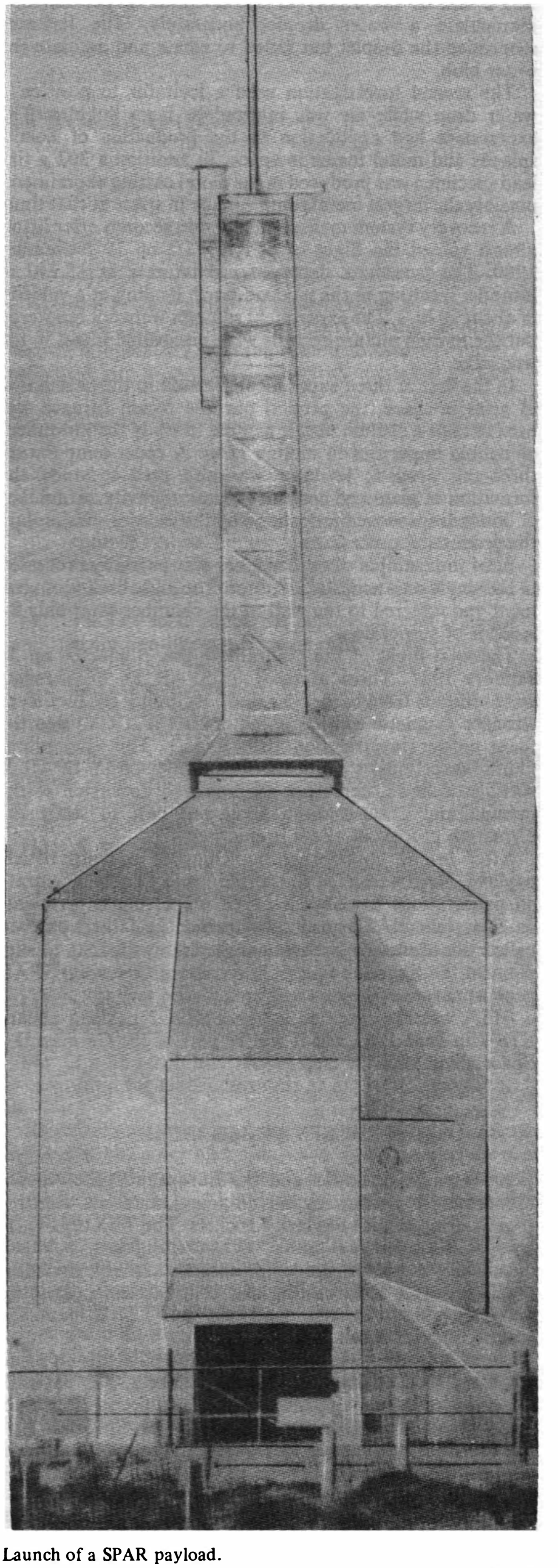
A small bead of gallia-calcia glass was processed in the levitator, but the sample did not completely resolidify because it was suspended for only 27 of the planned 240 seconds. A three-axis levitator was employed in the second experiment to study the dynamic behaviour of liquid drops by varying the intensity of the sound sources suspending the water.

The third experiment on the flight was an attempt to grow thin films of gallium arsenide by a convection-free process known as liquid phase epitaxy. The recovered semi-conductor films were of good quality and demonstrated the benefits of processing thin films in microgravity for such applications as solar cell manufacturing in space.

Finally, three samples of bismuth/bismuth-maganese alloy were processed by directional solidification to investigate their magnetic properties. The samples, each solidified under slightly different conditions, were later compared with identical examples produced on the ground.

A more powerful rocket was substituted on SPAR VII to provide an extra minute of microgravity for the payload. The new 14 m Black Brant VIII vehicle was a Nike-boosted version of the VC model.

Taylor Wang of JPL was the principal investigator of two acoustic levitator demonstrations conducted on SPAR VII when it was launched on 14 May 1980. The first experiment



Launch of a SPAR payload.

NASA

was a test of the ability of the levitator to position and manipulate a water droplet accurately. The levitator suspended the droplet but failed to rotate and oscillate the water blob.

The second investigation used a levitator to position a water drop while air was injected to form bubbles. The experiment had application to the production of hollow spheres and metal foams in space. In addition a 302 g tin-lead specimen was produced in the metal casting experiment, possibly the largest metal sample made in space at that time.

A recovery system malfunction at 466 seconds after liftoff almost ruined the flight of SPAR VIII on 19 November 1980. The parachute deployed prematurely at 15,240 m altitude, resulting in the payload crash landing at a velocity of about 90 m/s. The experiment samples were not recovered but the motion picture records were discovered intact in the wreckage.

In the first of three experiments related to the production of glass in space, the general purpose rocket furnace was used to melt a sodium borate sample to study the movement of bubble impurities in molten glass. A room temperature three-axis acoustic levitator was also used to study the formation of glass and ceramics in microgravity. A number of liquid drops were manipulated by the levitator to simulate the production process.

A 64 mm sample of optical glass was partially processed in the single-axis acoustic levitator. The glass broke containment and adhered to the wall of the chamber after only 82 seconds of suspension.

The final flight of the programme was conducted on 21 January 1981. Three of the four SPAR IX experiments were reflights from earlier missions, including production of stronger magnetic composite materials (SPAR V) and the foam copper investigation (SPAR IV). The aluminium-indium directional solidification experiment from SPAR V was also reflown, achieving an improved dispersion of the indium, and a tin-bismuth alloy was cast to study the formation process of alloys in microgravity.

After briefly considering launching of a tenth SPAR payload, NASA decided to end the project and concentrate on preparations for Shuttle-borne processing experiments on Spacelab. NASA also developed a specialised payload called the Materials Experiment Assembly (MEA) to supplement the Spacelab research, consisting of several SPAR general purpose furnaces and an acoustic levitator.

MEA was incorporated in the OSTA-2 payload aboard STS-7 in June 1983 and it will be part of the German D-1 Spacelab mission in late 1985.

8. OTHER ROCKET PROGRAMMES

West Germany, Sweden and the European Space Agency are presently conducting an on-going materials research project using British Skylark 7 rockets. The TEXUS (Technologie Experimente unter Schwerelosigkiet) payloads encompass a wide range of processing activity, including crystal growth, alloy casting and containerless processing. As of the end of 1983 there had been nine TEXUS launches from Kiruna, Sweden.

Japan is flying a number of processing payloads on a new two stage rocket designated TT-500A. The 330 kg payloads are intended to help Japanese researchers prepare the elaborate processing experiments planned for Spacelab J in 1988. The Soviets have also flown a limited number of processing payloads on MR-12 rockets.

9. THE REWARDS

Although SPAR was terminated after only nine flights, the project provided NASA with invaluable experience in planning and managing the present Materials Processing in Space (MPS) programme. NASA formulated its current policy for safeguarding proprietary experimental data while developing the SPAR experiments. Unlike scientific investigators (whose data is freely available), industrial firms require protection for their valuable data.

The space agency also decided to adopt a service-oriented relationship with the SPAR experimenters, treating them as customers rather than as sub-contractors [9]. Customer status for experimenters was a large step in the establishment of the Shuttle Joint Endeavor agreements currently in force with McDonnell Douglas and the 3M Company. The agreement encourages firms to enter the space industrialisation field by offering free flights on the Shuttle for experimental hardware.

The real reward from the pathfinding SPAR and Shuttle experiments will come when industry is permanently established in Earth orbit and beyond.

ACKNOWLEDGEMENT

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THE DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP)

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Since 1966, the USAF has operated a Defense Meteorological Satellite Program (DMSP), also known as Program 417, designed to provide high-quality three-dimensional visual and infrared (IR) cloud-cover imagery, as well as other meteorologically and environmentally significant data (including vertical temperature and atmospheric moisture profiles) on a timely and global basis. In 1973, this programme was transformed into a joint service activity managed by the USAF on behalf of the Department of Defense [1].

1. INTRODUCTION

The USAF developed its own meteorological satellites, rather than utilising meteorological imagery from the civilian meteorological satellite programme, for two reasons. First, the meteorological requirements of the military are different from those of civilian meteorologists in that high-resolution cloud-cover imagery and localised meteorological data were required whereas civilian need is for low-resolution but wider coverage [2].

Second, the USAF required that a high level of confidentiality be maintained with respect to some of the capabilities and applications of the Program. Indeed, it was only in March 1973, after 13 DMSP satellites had already been successfully launched, that it acknowledged for the first time that it had been operating its own meteorological satellite system.

The USAF began experimenting with its own meteorological satellites in 1962. A prototype DMSP was launched from Vandenberg Air Force Base on 19 January 1965 [3]. The first operational DMSP was launched on 15 September 1966 by a McDonnell Douglas/Boeing Thor-Burner 2 vehicle. It was a 12-sided frustum in shape, measured 1.64 m in length, 1.1 m in diameter and weighed 195 kg. A further 17 DMSP satellites of this basic configuration were launched through February 1976 [4].

On 11 September 1976, the USAF launched the first of four much more advanced Block 5D DMSP satellites followed, on 21 December 1982, by the first of the current series of Block 5D-2 satellites. All were launched from the Western Test Range at Vandenberg Air Force Base and all, except the Block 5D-2 satellite, by Thor-Burner 2 launch vehicles. The relevant details of these launches are given in Table 1. The Program is a continuing one, with projected satellites being larger and heavier and having increasingly enhanced capabilities.

2. THE SATELLITES

The Block 5D satellites were 6.4 m long, 1.68 m wide, and weighed about 500 kg, of which about 135 kg was the weight of the sensor payload. The spacecraft consists of four major sections:

(1) a precision mounting platform for the sensors and other equipment that require precise alignment;

(2) an equipment support module which contains the electronics, reaction wheels and some meteorological sensors;

(3) the reaction control equipment support structure, which has a third stage motor, hydrazine reaction control system for use during the ascent of the satellite, and a nitrogen unit for coasting and initial stabilisation of the satellite in orbit; and

(4) a 9.3 m^2 solar panel that deploys in orbit from an accordian-like structure on the latter section. The solar panel rotates on an axis to track the Sun, and can support electrical loads of 290 W average direct current (DC) power [5].

The primary sensor located on the precision mounting platform is the Operational Linescan System (OLS), which has four sub-systems:

(1) A very high resolution visible scanner with a resolution of 0.64 km, used for collecting information during daylight;

(2) a very high resolution infrared (IR scanner), with 0.67 km resolution, used for gathering information during darkness;

(3) a high resolution visible scanner with 3.7 km resolution for global coverage; and

(4) a high resolution IR scanner with 4.4 km resolution for global coverage at night.

The visible scanners respond in the 0.4 to 1.1 micron region, thereby covering not only the visual but also the near infrared portions of the spectrum, while the two IR scanners respond in the 8 to 13 micron long-wavelength spectral region [6].

The Vertical Temperature/Moisture sounding device is an eight-channel IR radiometer that measures vertical temperatures globally in the 15 micron range. The supplementary sensors include an auroral electron detector, a lightning detector and an ionospheric sounder system [7].

The antennae suite on the spacecraft consists of an S-band turnstile antenna which protrudes from the single side of the satellite not covered by solar cells and which uses a 6 W solid state transmitter to relay cloud cover data to the ground terminals; a VHF array beneath the satellite which accepts ground commands that are either executed in real-time or stored in three-core memory units for subsequent action; and a UHF transmitter which sends real-time telemetry to the ground stations [8].

The DMSP satellites orbit at an average altitude of about 850 km, in near polar (98.7° inclination) Sun-synchronous orbits. The OLS is able to cover a swath of about 2960 km

TABLE 1. USAF Defense Meteorological Satellite Program (DMSP).

Satellite Designation	Launch Date	Launch Site	Launch Vehicle	Weight kg	Period mins	Orbital Inclination	Perigee km	Apogee km	Comment
1966-82A	16 Sep 1966	WTR	Thor-Burner 2	195	100.86	98.46	705	891	First operational DMSP. Purpose not disclosed until 1973. 12-sided frustum. 1.64 m long, 1.10 m diameter
1967-10A	8 Feb 1967	'	'	'	101.55	98.84	796	868	
1967-80A	22 Aug 1967	'	'	'	102.20	98.97	834	892	
1967-96A	11 Oct 1967	'	'	'	100.18	99.16	667	866	
1968-42A	23 May 1968	'	'	'	102.10	98.94	817	904	
1968-92A	23 Oct 1968	'	'	'	101.45	99.00	797	855	
1969-62A	23 Jul 1969	'	'	'	101.36	98.80	788	856	
1970-12A	11 Feb 1970	'	'	'	101.39	98.71	773	874	
1970-70A	3 Sep 1970	'	'	'	101.30	98.73	764	874	Decayed 21 Sep 1970
1971-12A	17 Feb 1971	'	'	'	100.86	98.83	763	833	Carried 2 small (0.73 kg) aluminium spheres piggyback for radar calibration
1971-87A	14 Oct 1971	'	'	'	101.68	98.96	796	877	
1972-18A	24 Mar 1972	'	'	'	101.83	98.80	803	805	
1972-89A	9 Nov 1972	'	'	'	101.80	98.65	813	872	
1973-54A	17 Aug 1973	'	'	'	191.58	98.86	811	852	
1974-15A	16 Mar 1974	'	Thor-Burner 2A	'	101.54	98.94	782	877	
1974-63A	9 Aug 1974	'	'	'	101.76	98.86	806	875	
1975-43A	24 May 1975	'	Thor-Burner 2	'	102.00	98.93	813	892	
1976-16A	19 Feb 1976	'	Thor-	-	88.97	98.87	90	355	Decayed immediately
DMSP-5D-F1 (1976-91A)	11 Sep 1976	'	'	450	101.60	98.70	818	848	First DMSP Block 5D Satellite, also known as USAF Advanced Meteorlogic Satellite (AMS). 6.40 m long and 0.94 m diameter
DMSP 5D-F2 (1977-44A)	5 Jun 1976	'	'	'	101.74	99.20	811	869	Second DMSP Block 5D satellite, also known as AMS-2
DMSP 5D-F3 (1978-42A)	1 May 1978	'	'	513	101.47	98.71	820	835	Third DMSP Block 5D satellite
DMSP 5D-F4	6 Jun 1979	'	Thor-	513	101.50	98.77	819	838	Fourth DMSP Block 5D satellite
DMSP 5D-2-F1 (1982-118A)	21 Dec 1982		Atlas-Burner 2	751	101.36	98.72	816	827	First advanced series of Block 5D satellites. Same length as previous 5D satellites (6.4 m but 1.68 m diameter)

(1600 nm) at right angles to the satellite's flight direction; this equates to a coverage of about 26° at the equator. The satellites have an orbital period of about 101 minutes. Each satellite therefore scans every point on the Earth every 12 hours – or twice a day, once ascending (traversing from south to north) and once descending (traversing from north to south). The operational DMSP system consists of two satellites, with one satellite passing over any given point at noon and midnight and the other in the early morning and early evening [9].

The satellites have both stored and direct modes of data transmission. Data are recorded worldwide in the stored mode and then dumped to three readout stations (CRSs) at Fairchild Air Force Base, Washington, Loring Air Force Base, Maine and Kaena Point Remote Tracking Station (RTS) in Hawaii. Each of these CRSs has a 12 m parabolic antenna inside a radome, together with an operations building containing radio frequency, ground communications and computerised command and control sub-systems. The data dumped to the CRSs is then transmitted through the Hughes geosynchronous satellite system to the USAF Global Weather Central (AFGWC) at Offutt Air Force Base, Nebraska, and the USN's Fleet Numerical Oceanographic Central (FNOC) at Monterey, California [10].

(The Hughes WESTAR system consists of two equatorial geosynchronous satellites, located at 90°W and 123°W; a Control Center at Glenwood, New Jersey; and Tracking, Telemetry and Command Support ground facilities at Dallas, Texas, and Atlanta, Georgia).

If the direct transmission mode, data are transmitted directly from the DMSP satellite to USAF and USN mobile terminals and to USN carriers. Data readout terminals (designated AN/SMQ-10) are operated on the *Constellation*, the *John F. Kennedy*, the *Forrestal*, the *Independence*, the *Nimitz* (CV-68), and the *Kitty Hawk* (CV-63), one of which is always in the Pacific area and another in the Atlantic area. Each carrier is equipped with two S-band antennae, located on each side of the flight deck: one receives

signals as the satellite comes over the horizon and the second follows it to the opposite horizon [11].

Mobile terminals consist of 9.8 m long, two-man operated vans with 3 m diameter antennae mounted on pedestals at the rear, transportable to any point on the Earth in C-130 and C-5 transports and made operational within 72 hours [12]. The USAF plans to deploy 16 of these mobile terminals [13].

The 4000th Aerospace Applications Group (AAG) at the USAF Global Weather Central (AFGWC) at Offutt Air Force Base, Nebraska, is responsible for the command and control of the DMSP satellites and for processing the data and distributing it to the various users. It is one of the largest real-time electronic data processing (EDP) centres in the United States. In 1976, it operated six large Univac computers.

3. DMSP APPLICATIONS

Meteorological satellites have been described as "probably the most underrated" of the whole range of military satellites [14]. Data produced by the DMSP satellites are used for a wide variety of purposes. When NRO Director McLucas disclosed the existence of the Program in March 1973, he went on to state, the DSMP system "furnishes the best data possible to decision-makers anywhere in the world whose operations are affected by weather" [15].

Mobile DMSP terminals have now been extensively deployed around the world. A mobile DMSP terminal deployed in the Egyptian desert as part of an exercise operated continuously for nine weeks and was rated 95% efficient in supplying reliable weather information [16].

DSMP satellites provide data on barometric pressures, air densities, atmospheric moisture profiles and other meteorological factors and are also used to support the NROs photographic reconnaissance satellite programme. The provision of high-resolution cloud cover imagery in almost real-time allows the managers of the photographic satellites to programme orbits so as to avoid passes over areas covered by clouds as well as to activate the cameras only when the skies are clear so as to avoid wastage of film [17, 18].

Information provided by the ionospheric sounder (SSI/P) on the DMSP satellites has a wide range of applications. Disturbances in the ionosphere affect satellite navigation, ground-space UHF/SHF communications, HF communications, over-the-horizon (OTH) radar, high frequency direction finding (HF-DF), single frequency position measurements, precision tracking and signature radars etc. [19].

Finally, the DMSP satellites carry communications systems unrelated to their meteorological functions. One of these is a small single channel transponder (SCT) built by Hughes Aircraft, weighs about 30 kg, and operates in the UHF range [20]. This SCT is part of the Air Force Satellite Communications (AFSATCOM) system, the primary purpose of which is the dissemination of Emergency Action Messages (EAMs).

The second communications system that operates under the Defense Meteorological Satellite Program is a system to serve as a back-up for communications with US Embassies and US installations outside the continental US. The actual communications antennae are evidently deployed not on the DMSP satellites themselves but on the Boeing Burner 2 upper-stage booster vehicles used to inject the satellites into their final orbits. The Burner 2 vehicles are 1.32 m in length and 0.94 m in diameter and weigh 66 kg, and are carefully maintained in circular orbits with altitudes of about 800-850 km, inclinations of about 98-99°, and nodal periods of some 101 minutes [21]. The relatively low altitude of these vehicles means that the antennae used need to emit relatively little power and can be quite small.

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THE METEOSAT PROGRAMME

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1. INTRODUCTION

In 1972, eight Member States of the European Space Research Organisation decided to embark upon a programme for the development of pre-operational meteorological satellites - Meteosat - and entrusted its execution to the organisation that later became the European Space Agency. ESA was subsequently charged with the in-orbit operation of the spacecraft, of which two models, F1 and F2, were successfully launched in 1977 and 1981. The intention remained, nevertheless, to establish a meteorological community which would be responsible for setting up a system of operational spacecraft derived from the original Meteosat. That aim was achieved with the signature in Geneva on 24 May 1983 of a Convention for the creation of an international organisation known as Eumetsat whose main purpose is to establish, maintain and operate systems of operational meteorological satellites, the initial one being the continuation of the Meteosat pre-operational programme. The Convention was signed by 12 countries on that date; three others signed later and more are expected. Eumetsat will rely on ESA for carrying out the programme. The Meteosat Operational Programme foresees the launch of three satellites, in August 1987, mid-1988 and 1990, and their subsequent exploitation until 1995. It fulfils the five missions described below.

Earth image from Meteosat 2 in July 1981.

ESA

2. THE EARTH IMAGING MISSION

The radiance of the Earth's surface and of its cloud cover are detected simultaneously in three spectral bands:

1. the visible (VIS) image in the 0.5 to 0.9 μm region of the spectrum is made up of 5,000 lines, each containing 5,000 picture elements. The resolution at the sub-satellite point is 2.5 km. The signal-to-noise ratio will be greater than 200 for 80% albedo;
2. the thermal infrared (IR) image covers the 10.5 to 12.5 μm region of the spectrum. It comprises 2,500 lines each containing 2,500 picture elements. The resolution at the sub-satellite point is 5 km. The discrimination will be better than 0.65 K for a black body at 290 K;
3. the water vapour (WV) absorption band image is in the 5.7 to 7.1 μm region. It consists of 2,500 lines, each containing 2,500 picture elements. The resolution at the sub-satellite point is 5 km. The discrimination will be better than 1 K for a black body at 260 K.

For each spectral channel, the radiometric information is encoded into 256 grey levels.

* *This is a modified version of the author's paper presented at Space '84, Brighton, 16-18 November 1984.*

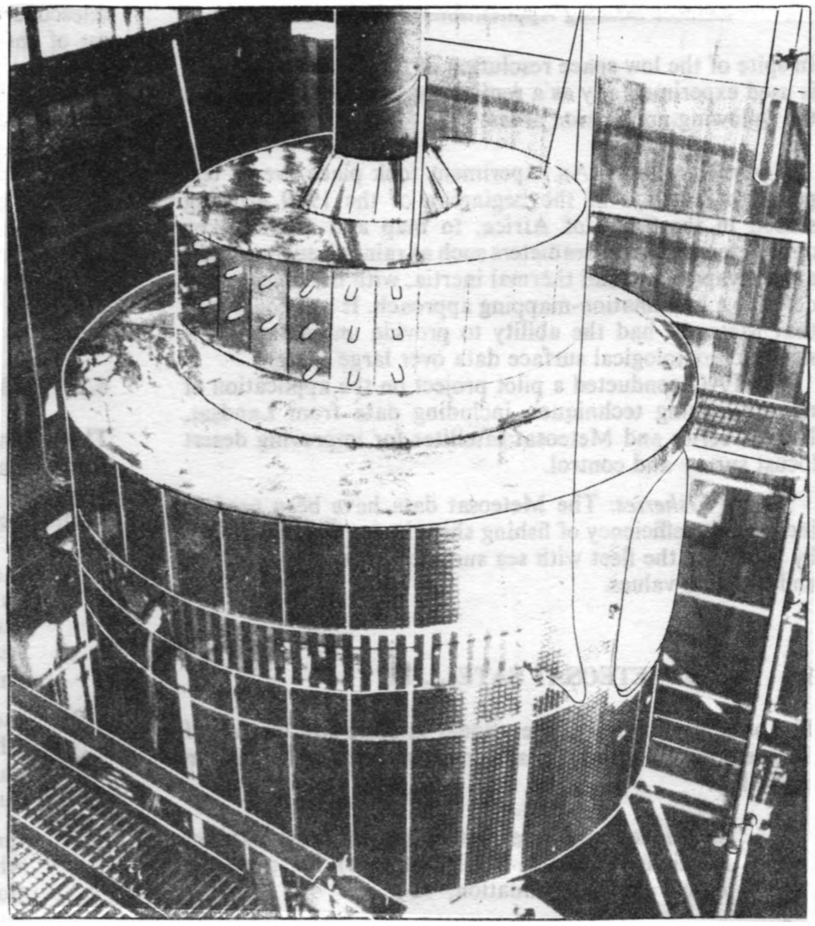
3. THE DISSEMINATION MISSION

Pre-processed images and other meteorological data are relayed to user stations. The transmissions are made in both digital and analog formats (Wefax pictures).

The processing of images is performed in two stages: pre-processing and image processing proper. Pre-processing consists of demultiplexing the data stream and compensation for radiometer and imaging chain imperfections, including amplitude equalisation of both visible channels. The processing provides:

1. the computation of a deformation model to specify the difference between actual location of points in the images and the location they would have if the satellite position and orientation were absolutely fixed and ideal;
2. the conversion (rectification) of the raw image to one of standard aspect, i.e. as if it were taken from the fixed and ideal position with an absolute accuracy of better than 2 infrared pixels RMS error and a consecutive image accuracy of better than 0.5 infrared pixel error;
3. absolute radiometric calibration information for the infrared and water vapour channels provided for every image.

Two Meteosat satellites have been launched.
ESA



3.1 The Collection of Environmental Data

Environmental data gathered by various types of fixed and mobile data collection platforms (DCPs) are collected by up to 66 channels provided for this purpose. This mission supports platforms that transmit messages according to an agreed schedule (self-timed platforms), as well as platforms that transmit only in response to specific environmental criteria (alert platforms).

4. THE EXTRACTION OF METEOROLOGICAL PRODUCTS

The actual extraction of products is performed automatically for the region within at least a 50° great circle arc (up to 55°) from the subsatellite point. Before data are distributed, they are quality controlled by experienced meteorologists. Products have a 32 x 32 IR pixel resolution, except for Cloud Top Height charts which have a 4 x 4 IR pixel resolution.

1. Cloud Motion Vectors (CMV): extracted twice per day at 0000 UT and 1200 UT and distributed by 0230 UT and 1430 UT. Around 600 vectors per run are produced with a target accuracy ranging from 5 m/s RMS for low level to 10 m/s for high level CMVs.
2. Sea Surface Temperatures (SST): extracted daily at 1200 UT and based on a 3-hourly composite, distributed by 1430 UT. 800 data per day with a target accuracy of $\Delta T < 1.5°C$ RMS.
3. Cloud Analysis (CA): provides cloud cover in up to three layers together with cloud top temperature. Extraction at 0000 UT and 1200 UT and distributed by 0230 UT and 1430 UT.
4. Upper Tropospheric Humidity (UTH): provides average relative humidity between 700 and 300 mb in line with the WV channel contribution function. Extraction at 1000 UT and 1200 UT and distributed by 0230 UT and 1430 UT. Target accuracy $\Delta R < 20\%$ RMS relative humidity.
5. Cloud Top Height (CTH): provides in image form a Wefax map of cloud tops in 1500 m intervals between 4.5 and 12 km. Extraction will be done at 0300, 0900, 1500, 1200 UT and disseminated within 1 hour *via* Meteosat.

CMV, SST, CA and UTH encoded into WMO SATOB Bulletins are injected into the GTS (Global Telecommunications System) *via* the Offenbach Regional Telecommunications Hub (DWD). CTH maps are broadcast as Wefax pictures *via* the satellite.

5. THE ARCHIVING OF DIGITIAL DATA AND IMAGE NEGATIVES

All available images are regularly archived in digital form with the extracted meteorological products (except the CTH maps). Two slots of images per day are archived on photographic film. A comprehensive catalogue will be maintained to cover all archived data.

5.1 Remote Sensing Applications of Meteosat

In spite of the low space resolution of the images, Meteosat is used experimentally as a remote sensing tool *inter alia* in the following application areas:

Agrometeorology: An experiment took place over a test period of 18 days at the beginning of the 1979 growing season in the Sahel of Africa, to map and monitor key agrometeorological parameters such as rainfall, surface radiation, evaporation and thermal inertia, with the objective of defining a germination-mapping approach. It was concluded that Meteosat had the ability to provide unique and consistent climatological surface data over large areas.

The FAO conducted a pilot project on the application of remote sensing techniques, including data from Landsat, NOAA series and Meteosat satellites for improving desert locust survey and control.

Aid to Fisheries: The Meteosat data have been used to increase the efficiency of fishing ships in the Gulf of Guinea by providing the fleet with sea surface temperature relative and absolute values.

6. THE METEOSAT SATELLITE

The basic design of the operational satellite will be that of the Meteosat F2 with two major improvements to the mission capability:

1. the mission performance transponder provides eight additional channels (2400 bits/sec) for meteorological data dissemination;
2. the water vapour absorption channel (5.7 to 7.1 microns) is available in parallel with visible and infrared channels.

A number of minor modifications based on Fl and F2 experience and on technology improvement are incorporated, leading, *inter alia,* to an increased reliability.

Meteosat is composed of two cylindrical bodies concentrically stacked. The initial weight of the satellite in orbit is approximately 300 kg, including 39 kg of propellant (hydrazine).

The main body is covered with solar cells to supply electrical energy. Most Meteosat subsystems, including the radiometer, are located in this cylinder. The second cylinder carries:

1. an array of radiating dipoles electronically fed in such a way that they simulate an S-band antenna which is artificially and permanently oriented towards the Earth (Electronically Despun Antenna) EDA;
2. most of the telecommunications equipment;
3. additional antennae.

The two cylinders mounted on top of the drum are toroidal pattern antennae (S and UHF frequency bands).

The payload consists of a high-resolution radiometer and a data transmission system. The radiometer is an electro-optical instrument that includes a large telescope with a focal length of 3650 mm; a set of detectors located in the focal plane of the telescope measure the radiance of the Earth and its cloud cover in the visible, thermal-infrared and water vapour absorption spectral bands. By virtue of the spin motion of the satellite, at 100 rpm, the radiometer scans the Earth along the East-West axis; the scan along the North-South axis is achieved by tilting the optical telescope axis slightly at the end of each East-West scan. A set of three images, one in each of the spectral bands, is produced once every 30 minutes.

The communication package consists of a transponder and an associated antenna system. The transponder operates in the S-(1675-2105 MHz) and UHF-(402 MHz) bands and ensures the dissemination of satellite images (Wefax, and high resolution) and data collection platform messages towards user stations on two channels, the collection of data transmitted from platforms on up to 66 channels and the exchange of meteorological data between users on eight channels.

6.1 The Meteosat Ground Segment

The ground segment is divided into two parts: the ground facilities needed to carry out the Meteosat missions on the one hand and the user stations on the other. The ground facilities consist of four elements:

1. the Meteosat Operations Control Centre, which is entrusted with the operational management of the satellite and the tracking facilities. It controls the performance and operation of the satellite and ensures that the missions are carried out correctly;
2. the Data Referencing and Conditioning Centre, which is mainly responsible for processing the image data and for the formatting needed for their subsequent exploitation;
3. the Meteorological Information Extraction Centre, which extracts specifically meteorologial information such as wind fields, sea surface temperature charts, cloud system analyses and radiation balances, from the processed images;

(These first three elements are located in ESOC, Darmstadt, West Germany).

4. the Data Acquisition Telecommand and Tracking Station, located at Michelstadt, near ESOC, is responsible for the acquisition of the satellite's radiometric and housekeeping data and of messages from the data-collection platforms. It transmits to the satellite telecommands and meteorological data or images for dissemination to user stations. Finally, in association with a land-based transponder at Kourou (in French Guiana) it carries out the ranging measurements needed to locate the satellite precisely.

The different user stations are:

1. the Primary Data User Stations, which receive the rectified Earth images disseminated in digital form through the satellite;
2. the Secondary Data User Stations, which are conceptually simpler and thus cheaper and which receive the image data in a standardised (Wefax) format and messages from the Data Collection Platforms, all of which are disseminated through the satellite;
3. the Data Collection Platforms, which take measurements of the local environment and transmit them to the satellite. They can be installed in extremely varied locations: on the ground, on buoys, ships and aircraft;
4. the Meteorological Data Distribution Stations, which include receiving and transmission facilities and which can disseminate meteorological information to and from national meteorological services.