Concept design and planning of India's first interplanetary mission

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In the quest for planetary exploration, Mars holds a special position in view of the many similarities it has with Earth. This article highlights the significant aspects of the concept design and planning which paved the way for the successful Indian Mars Orbiter Mission (MOM). Lessons learnt from historical failures of Mars missions are summarized. The main driving factors of the MOM design are reliability, optimal utilization of existing launch systems, and minimum energy orbit placement around Mars with an innovative, highly elliptic orbit. An exposition of the mission strategy, trajectory design, technological features and science goals is also presented. The article concludes with a glimpse into the possible future Mars mission challenges to humanity.

Keywords: Design and planning, elliptic orbits, interplanetary trajectory optimization, Mars Orbiter Mission.

Introduction

OVER millennia, human beings are fascinated and inspired by what happens across the universe. Space technology developments over the last six decades have provided us the opportunity of probing a little beyond our own planet. The initial discoveries, which are the results of these scientific endeavours, point to the vast potential that exists for boundless knowledge and immense resource around our own solar system and beyond. After successfully designing and implementing India's first Moon mission[1–4] with Chandrayaan-1, it was but natural for India to think about planetary exploration beyond the Moon.

In the quest for planetary exploration, Mars holds a special position in view of the many similarities it has with Earth and because it holds the secrets of our past and the possibilities of our future. Mars was formed around the same time, yet with only half the diameter of Earth. The levels of mean surface temperature that exist on Mars are also present on Earth in some extreme places where man has successfully ventured into. The corresponding lengths of a day for these two planets are also almost the same. Much like on Earth, the Martian environment is governed by interactions of atmosphere, hydrosphere, cryosphere and lithosphere. The red planet has captured the imagination and attention of scientists for this reason, and many unmanned missions to Mars have taken place. Several of the initial missions to Mars met with many difficulties in view of the innate complexity and length of these missions.

The Advisory Committee for Space Science (ADCOS) at the Indian Space Research Organisation (ISRO) has taken up the formulation of a vision document for planetary exploration programmes and identified missions to Mars as one important component of this vision. In order to concretize these concepts into an integrated and viable blueprint for undertaking systematic and planned missions to Mars, a Mars Mission Study Team was formed with experts from all major Centres and Units of ISRO.

Launch scenarios and capabilities for Mars mission, detailed mission options for the future launch opportunities to Mars, spacecraft design and configuration challenges, possible scientific experiments to augment the current understanding of Martian science, and deep space network challenges are all addressed by the ISRO Study Team. There are several new technological challenges, all of which required focused attention. These are extensively analysed by the Study Team taking inputs from relevant experts across all the Centres of ISRO. The findings were also presented to a galaxy of senior systems engineering and science experts in the country to get their feedback.

It is an intrinsic and deep understanding of the issues involved that gives us the perspectives and right directions for the appropriate solutions for this complex mission design. During the intense deliberations of the Mars Orbiter Mission (MOM) Study Team, various kinds of Mars missions were considered: fly-by, orbiter and more complex options. It is clear that a fly-by, which gives only a short time for scientific study, is not an attractive challenge. Initially it appeared that an orbiter or lander would require larger transportation capability than the established PSLV launch system. However, detailed analysis confirmed that, if one can have a highly elliptic orbital mission around Mars, the proven and highly reliable PSLV-XL launch system can be utilized. Scientifically also it was found that, what initially appeared to be a limitation, can be turned into a unique opportunity by configuring experiments that exploit the highly elliptic orbit. It is this critical analysis and overall system understanding, at the preliminary design stage itself, that gave ISRO the initial confidence to successfully undertake this complex mission.

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ISRO launched MOM on 5 November 2013; the spacecraft was inserted into Mars orbit on 24 September 2014. India also became the first country to successfully get a spacecraft into the Martian orbit on its maiden attempt. This article highlights the significant and important aspects of the concept design and mission planning, which eventually paved the way for the successful mission to Mars.

Lessons learnt from historical failures of Mars missions

The first task of the Mars Mission Study Team constituted by the Chairman, ISRO in August 2010 was to study the Mars missions undertaken so far by the international community and consolidate the lessons learnt.

Of the 55 Mars mission attempts[5], only 26 had succeeded; a success rate struggling to reach the 50% level. Few of them had achieved partial success. Thus, historically Mars has been a tough target for space exploration.

The first attempts by Soviet Union to reach Mars in a fly-by mission were named Korabl4 and Korabl5, also called Marsnik1 and Marsnik2. Both were launched in October 1960. The third stage of both launch vehicles failed and neither reached Earth's orbit.

The first mission of USA to Mars, Mariner3, failed in its fly-by attempt in November 1964. A shield that was designed to protect the instruments on-board the spacecraft during launch failed to release once it had reached Earth's orbit. Due to this additional mass, the spacecraft was unable to enter the necessary trajectory to reach Mars. The spacecraft is now in a solar orbit.

Nozomi was launched by Japan in July 1998, and failed to reach the intended Mars orbit. In various Earth fly-by orbital operations, propulsion-related problems plagued this complex mission. The spacecraft flew by Mars in December 2003 and went into a roughly two-year heliocentric orbit.

The Phobos-Grunt mission of Russia with the Chinese Mars orbiter Yinghuo-1 as a piggyback, was launched in January 2012. It reached an Earth orbit, but the upper stage failed to ignite and take it onto the Mars transfer trajectory. The spacecraft eventually decayed and crashed into the Pacific Ocean along with the orbiter. The failure analysis report attributes the loss of the probe to memory chips that became fatally damaged by cosmic rays[6].

The European Space Agency launched Mars Express with Beagle 2 in June 2003. This mission was a partial success. The Mars orbiter worked well, but the landing spacecraft Beagle 2 (from the United Kingdom) failed. It was initially thought to have crashed on landing. However, in January 2015, using images taken by NASA's MRO, Beagle 2 was found intact on the surface of Mars. Images suggest that solar panels of the lander had failed to fully open.

Overall, the failure scenario of Mars missions can be grouped into three categories: launch failures, en route failures and landing failures. There were nine launch failures of which as many as six occurred in 1960s, two in early 1970s, one in 1996 (Mars 8 of the Soviet Union, because of the failure of the second burn of the fourth stage). Of the total nine en route failures, three occurred in 1960s, three in 1970s/1980s and two in 1990s. There was one recent failure of Phobos Grunt launched in November 2011. The number of landing failures also was nine, of which five occurred in 1990s, one in 1980s, two in 1990s and one in 2000s.

This analysis shows that in the initial decades there were many failures, but now there are relatively more successes. However, it is true that the complexity and length of the missions make them difficult; and the issues have to be properly factored in the mission and system design. Adequate testing for verifying and validating critical subsystems holds the key to success. This is particularly relevant to the propulsion system functioning for Mars orbit capture, power management, thermal design and communication systems. All these were carefully addressed during the preparation for MOM and are described in detail in the various articles in this special section. With the collective and intense efforts at ISRO in meeting these demands, we did not encounter any serious problem that we could not address and satisfactorily resolve as MOM progressed.

Methods of reaching Mars

Minimum energy orbit placement around Mars and optimal utilization of the existing launch vehicle systems were the main driving factors for the MOM design. The dates for Mars expedition were chosen through assessment of the mission opportunities across the Earth–Mars synodic cycles. Opportunities occur approximately every 2.1 years in a cycle that repeats roughly between every 15 and 17 years (the synodic cycle). Within the span of this 15–17 year cycle, mission opportunity characteristics are similar but not the same. These orbits have essentially three components: (i) Earth orbital phase, including phasing orbits, (ii) Trans-Mars phase, and (iii) Mars orbit-capture phase. The Tran-Mars phase has to be precisely designed to capture the minimum-energy opportunity. Among the two minimum-energy Earth departure opportunities of November 2013 and January 2016, the first one was better requiring about 380 m/s less velocity. This is significant with respect to the utilization of PSLV as the launch system, as one could do a reasonably good MOM with PSLV in 2013, but not in 2016.

The travel from Earth to Mars takes about 300 days. Mission planning, executing various manoeuvres and operations, and controlling any small deviations in its course through mid-course corrections are the challenges one will encounter. Specific challenges in, reaching the Mars orbit relate to power, communication and propulsion systems. Because of lower solar irradiance due the large distances, one has to provide much larger solar panel area. When on the far side from Earth, the Mars orbiter can be typically 400 million km away; and it will take around 20 min for a signal to travel from the ground station to the orbiter. Hence, on-board autonomy has to be provided for all critical operations, as the Earth–Mars distance does not allow real-time interventions. Restart of the propulsion system, after nearly a year of travel in space, for Mars orbit capture manoeuvre is a major technical challenge. To meet the challenging task of managing distance up to 400 million km, S-band systems are kept for both TTC and data transmission. Delta differential one-way ranging (Δ-DOR) transmitter is provided for ranging to improve orbit determination accuracy required for the mission operations.

Detailed mission studies were conducted to identify the size of initial parking orbit around the Earth as also the final orbit size around Mars. Table 1 gives the typical velocity impulses for a parking orbit around Earth of 250 × 23500 km and for a parking orbit around Mars of 500 × 80000 km. The required values of the argument of perigee (AOP) are also given. It should be emphasized that the Mars mission in 2013 is important for two reasons: (i) if we miss this opportunity, we have to wait for another 26 months for the next one; (ii) additionally, the velocity impulse requirement for the next opportunity in January 2016 is more by 380 m/s and will require a heavier launch vehicle.

Mission strategy

In an interplanetary mission design, the Earth parking orbit characteristics are so chosen to minimize the energy requirement for Trans-Mars injection and for Mars orbit insertion operations. Apart from selecting the minimum energy opportunity, optimal utilization of the existing launch vehicle system is a main driving factor for the MOM design. With 23 consecutive successes since 1993 till October 2013, PSLV a four-stage vehicle is a reliable and proven work horse of ISRO. It was developed primarily for launching remote sensing satellites of 1200 kg class in sun-synchronous polar orbit. It had also carried out geosynchronous transfer orbit (GTO) missions. With its excellent track record, PSLV was found to be a suitable and viable option for placing the MOM spacecraft in an initial orbit around the Earth.

In its regular GTO missions, PSLV achieves about 178 degrees of AOP for suitable maximum payload. But the MOM demands an AOP of 299 degrees at the time of Trans-Mars injection, which is executed after several phasing orbits. Due to the perturbing forces from non-uniform gravity field, the Moon and the Sun, the initial Earth parking orbit characteristics keep changing. Accounting for these changes in the AOP, the initial Earth parking orbit AOP is fixed. These phasing orbits are determined depending on a chosen lift-off date. This implies that the launch vehicle is expected to achieve different AOPs for different lift-off dates. Values of required launch AOP, for one typical phasing orbit sequence, range from 275 to 288 degrees for lift-off dates between 28 October 2013 and 14 November 2013. Such a large AOP, which is different from those of the usual PSLV launches, is achieved by introducing a long coasting between the third stage (PS3) separation and the fourth stage (PS4) ignition that shifts the perigee location to the desired slot.

Figure 1 depicts the PSLV trajectories for a regular GTO-type elliptic parking orbit mission and for MOM. Both are optimal trajectories for the respective mission constraints and are designed based on proven trajectory and mission optimization methodologies established in ISRO[7–9]. As is obvious from the figure, the characteristics of the two trajectories are entirely different. A coasting of 1600 sec between PS3 separation and PS4 ignition is introduced for the Mars mission. Two ship-borne terminals are required to ensure visibility during PS4 ignition and satellite separation events.

Another parameter that must be ensured by the launch vehicle at the time MOM injection is right ascension of ascending node (RAAN). This parameter fixes the launch

Table 1. Mars mission launch opportunities

Departure date	Flight duration (days)	Arrival date	Argument of perigee (degree)	Total velocity impulse (m/s)
30–11–2013	298	24–11–2013	299	2590
10–01–2016	275	11–10–2016	246	2970
17–05–2018	239	11–01–2019	121	2570

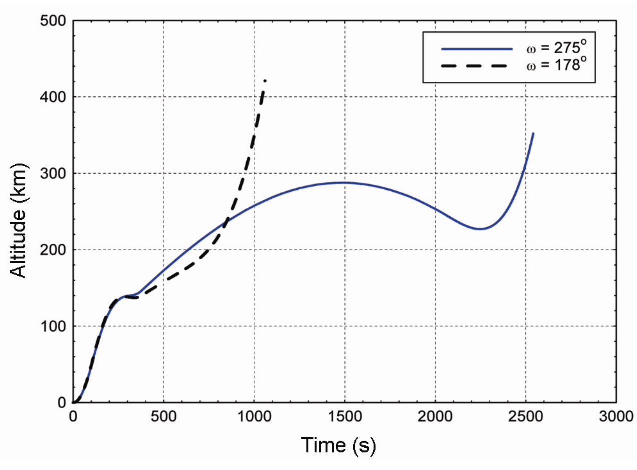

Figure 1. New trajectory design to achieve the required argument of perigee.

vehicle trajectory/parking orbit crossing point on the equator with reference to an inertial axis (vernal equinox). RAAN also undergoes changes due to perturbing forces during phasing orbit evolution. It is because of the requirement of RAAN that the lift-off time of the launch vehicle has to be precise and the launch window available on the day of launch is narrow (1–5 min) compared to normal launches (30–60 min or more).

From the parking orbit, a velocity impulse of about 1470 m/s must be added to the existing orbital velocity at perigee to put the spacecraft in Trans-Mars phase/cruise phase. This addition is split into several burns: (i) to reduce the finite burn loss, (ii) to provide flexibility for lift-off day of the launch vehicle, (iii) to validate the spacecraft systems before Trans-Mars phase, and (iv) to ensure visibility of the burn events. Details of how the spacecraft reached Mars orbit on 24 September 2014 are described in a separate article in this special section.

The spacecraft approaches Mars in a hyperbolic trajectory, typically with a velocity of 6.5 km/s with respect to the planet. The last major manoeuvre was to retard the spacecraft typically by about 1.1 km/s. This reduction would enable it to enter an elliptical orbit around Mars (typically with a height of 80,000 km at apoapsis and 500 km at periapsis), endorsed for its uniqueness for observing the planet comprehensively during its mission life. Minor deviations from this target could have caused the spacecraft to either evade capture by Mars, or crash onto its surface.

Scientific objectives of MOM

As far as the scientific experiments on MOM are concerned, several proposals were initially considered, which can be classified into four categories: (1) Martian atmospheric studies, (2) solar and X-ray spectroscopy, (3) imaging Mars, its moons and possibly asteroids and (4) radio experiments. These specifically are required to address the gaps in the existing knowledge; so the outcome of these efforts will be interesting to the world science community.

From a large list of about 20 proposals from the Indian scientific community, and after a rigorous review process, five experiments are selected for MOM. While these are described in detail in separate article in this special section, a brief summary is given here.

The first experiment is the high accuracy measurement of methane content in the Martian atmosphere the information about its origin, whether it is biogenic or volcanic. This is crucial in understanding the possible life processes on the planet.

The next experiment is the investigation of the Martian upper atmosphere escape process, especially the loss process of water. Understanding this process for non-magnetic planets such as Mars is important to infer the evolutionary history of the planetary atmospheres.

In another experiment, the Mars Exospheric Neutral Composition Analyzer measures *in situ* the neutral composition and density of Martian upper atmosphere–exosphere at altitudes 500 km and beyond. As an additional science goal, this experiment will also provide first ever limits to neutral particle distribution around the Mars satellite, Phobos.

The spacecraft also carries a camera to capture the topographic features. The highly elliptical orbit of MOM provides a unique opportunity to capture repeatedly a number of full-disc pictures of Mars, which was not possible in the other Mars missions.

Finally, a thermal infrared multispectral imager will map the surface composition and mineralogy of Mars and will detect hot spots which indicate underground hydrothermal systems.

The challenge of precise insertion into Mars orbit

It is interesting to get a flavour of the perfection and precision demanded by this mission. In the initial five-phase orbital manoeuvres around Earth, the planned total velocity increment was 875.5 m/s, whereas the actual value realized was 873.43 m/s. This close match was achieved due to the accuracy of the ISRO-designed and built ceramic servo accelerometer. This sensor is sensitive to changes in acceleration at the level of one millionth of the gravity force we experience on Earth. This accelerometer was also used in several subsequent trajectory manoeuvres, thereby enabling accurate velocity computation and position. As the spacecraft leaves Earth, the accuracy needed in terms of the overall attitude (orientation) targeting requirement to reach Mars is of the order of 0.01 arcsec. In simpler terms, this is equivalent to shooting a 1 cm diameter coin placed at a distance of 200 km. Further, a propulsive error of a mere 1 m/s in the velocity given to the spacecraft by the propulsion system leaving for Mars can generate as much as 200,000 km error in the position when the spacecraft approaches Mars. Closer to Mars, a delay of 30 sec in initiating the retarding burn would have resulted in a periapsis of 363,083 km.

The roundtrip light time at the distances involved in the MOM operations can be as much as 24–43 min. This drives the need for spacecraft autonomy for nominal as well as non-nominal operating conditions, as it is impossible to micromanage such operations from Earth in real time. The thoroughly ground-tested, inbuilt method of autonomy on MOM is based on continuous watch, fault detection, isolation and reconfiguration, without disturbing the Earth-pointing attitude. The Mars orbit insertion is the most complex and critical operation in the mission. Because of the Mars–Sun–Earth geometry, the orbit insertion take place when MOM is in eclipse. The radio link between MOM and ground station also gets blocked as the spacecraft is on the other side of Mars at this critical juncture, and MOM must execute all functions autonomously.

Considering the robustness and optimality of the mission design, intrinsic redundancies built into the system and undergoing a thorough test protocol before launch, we have successfully reached our final orbit around Mars, creating history not only for ISRO and India, but also for the world, having become the first country to successfully get a spacecraft into the Mars orbit on its maiden attempt.

The future challenges to humanity in Mars exploration

As the orbiter, lander, rover and sample-return missions by space-faring nations take shape in the coming decades, at a far end of the spectrum of possible missions to Mars is the human expedition to the red planet. During the last few years, this theme has attracted enormous interest of a large number of space-faring nations, astrobiologists, economists, explorers and innovators.

The expedition to Mars for human settlement is a complex undertaking. This enterprise allows the potential for humans to leave Earth and to make way deep outward into the cosmos. In the context of human settlement on Mars, it is estimated that a population of 150–180 would allow normal reproduction for 60–80 generations, which is equivalent to 2000 years. To promote the diversity in gene pool, it is advantageous to choose the crew from diverse ethnic backgrounds and with different skill sets.

At the same time, a single expedition to Mars with a crew of six for planetary settlement involves at least nine launch vehicles with Low Earth Orbit (LEO) payload capacity of 150 metric tonnes[10]. It is conceivable that demands on logistics for this kind of operation can only be met with multinational cooperative effort.

Radiation in space is a major issue to contend with. From the standpoint of humans in interplanetary space, the two important sources of radiation for the Mars expedition are the heavy ions of galactic cosmic ray and sporadic production of energetic protons from large solar particle events. Another important factor for the expedition is the absence of gravity during Mars transfer trajectory. One of the major effects of prolonged weightlessness seen in long-duration space flights has been an extended loss of bone mass.

The most important technology needed to enable human mission to Mars is efficient aero-assist technology for descent. Mars entry, descent and landing are fraught with many engineering challenges. One of the important challenges emanates from an atmosphere which is thick enough for substantial heating, but not sufficiently dense for low terminal descent velocity. The supersonic use of parachutes has been limited due to performance, stability and structural concerns. A known instability, referred to as area oscillations, exists for operation above Mach 1.5, as a result of the fluid structure interaction between the flow-field and canopy fabric[11]. New technological developments like inflatable aerodynamic decelerators and supersonic retro-propulsion have a great potential in addressing such issues[12–14].

The landing site is often chosen on the basis of the need to perform entry, descent and landing operations in relative safety. In future scenario, the landing site must be suitable to allow for *in situ* resource utilization. All these possibilities pose many interesting challenges for the coming generations of scientists and technologists.

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