PSLV-C25: the vehicle that launched the Indian Mars Orbiter

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Polar Satellite Launch Vehicle (PSLV) of the Indian Space Research Organisation (ISRO) successfully executed the launch of the Indian Mars Orbiter by precisely placing the spacecraft in the initial Earth-bound orbit on 5 November 2013. This was the critical first step of the three-phase Mars Orbiter Mission (MOM). The focus of this article is on the major challenges tackled by the launch vehicle project team in designing, planning and executing MOM.

Keywords: Argument of perigee, coasting, launch vehicle, Mars mission flexibility.

Introduction

THE recent historic mission of the Indian Mars Orbiter and its success heavily and critically depended on the Polar Satellite Launch Vehicle (PSLV), the work-horse launch vehicle of the Indian Space Research Organisation (ISRO).

Operationalized in 1997, PSLV's primary objective was to enable India to launch 1000 kg-class national remote sensing satellites to sun-synchronous polar orbits (SSPOs). Later, the payload capacity of the vehicle was enhanced to 1600 kg through the augmented liquid-propelled second stage (PL40), high performance third-stage solid motor (HPS3) and structures made of carbon fibre reinforced plastic (CFRP). PSLV in its variant configurations (with and without the strap-on motors around its first stage and with suitable tanks in the fourth stage for optimum fuel loading) has been successfully utilized not only for SSPOs but also for sub-geosynchronous transfer orbits (Sub-GTOs) and low inclination orbits. In 2008, the regular six S9 solid strap-on motors of PSLV were replaced by the stretched S12 version resulting in the powerful configuration called PSLV-XL that offers a payload capability of 1750 kg for 600 km SSPO and 1425 kg for sub-GTO of $284 \times 21{,}000$ km.

While taking up the assignment of the Mars Orbiter, PSLV had to its credit 23 consecutive successes in various types of national and commercial missions proving its versatility, reliability and precision. PSLV-C25 (Figure 1), the vehicle designated for the Mars Orbiter, employed the PSLV-XL configuration which was already proven in four previous missions. PSLV-C25 is a masterpiece mission till date, both technically and managerially. Given the caliber of payload capability, the vehicle offered an excellent mission flexibility that played unique and pivotal role in this mission, enabling an optimal scheme to reach Mars. The mission managers had almost a new vehicle at hand in terms of the nature and quantum of the specific activities ranging from planning to execution of this unique mission.

Unique mission assignment

The journey of Mars Orbiter involved three phases, namely the Earth-centred phase, the heliocentric phase and the Martian phase. The crucial first step in this journey was the precise launch of the 1337 kg orbiter by PSLV-C25 into an Earth-centred elliptical orbit of $248 \times 23{,}550$ km.

The specifications of this initial Earth-bound parking orbit, especially the inclination of 19.2° (angle between equatorial plane and orbital plane) and a unique constraint on the perigee (the orbital point closest to the Earth) were to be met meticulously. The specified angle of 283° between the point of northward equator-crossing and the perigee location (called the 'argument of perigee'

Figure 1. PSLV-C25 lifting off with Mars Orbiter on 5 November 2013 at 14:38:26 h (IST).

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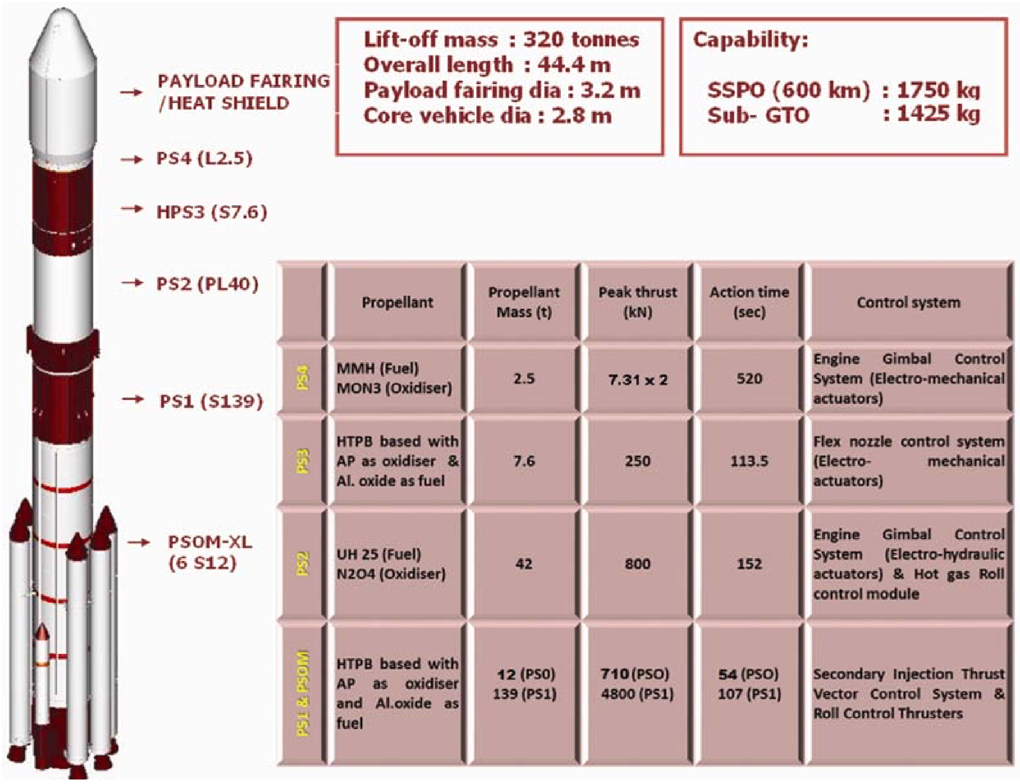

	Propellant	Propellant Mass (t)	Peak thrust (kN)	Action time (sec)	Control system
PS4	MMH (Fuel) MON3 (Oxidiser)	2.5	7.31 x 2	520	Engine Gimbal Control System (Electro-mechanical actuators)
PS3	HTPB based with AP as oxidiser & Al. oxide as fuel	7.6	250	113.5	Flex nozzle control system (Electro- mechanical actuators)
PS2	UH 25 (Fuel) N2O4 (Oxidiser)	42	800	152	Engine Gimbal Control System (Electro-hydraulic actuators) & Hot gas Roll control module
PS1 & PSOM	HTPB based with AP as oxidiser and Al.oxide as fuel	12 (PS0) 139 (PS1)	710 (PSO) 4800 (PS1)	54 (PSO) 107 (PS1)	Secondary Injection Thrust Vector Control System & Roll Control Thrusters

Figure 2. Configuration of propulsion stages in PSLV-XL.

Figure 3. Mars Orbiter integrated to PSLV-C25.

or AOP, measured along the orbital plane) was unusually large for this mission when compared to the typical values of the order of 178° for Sub-GTOs. Another orbital constraint was the specified RAAN of 127°. (RAAN the Right ascension of the ascending node is the angle measured eastward along Earth's equatorial planes between the direction of Pisces and the orbit's ascending node, where it crosses the equator northwards.) These constraints were essential to have optimal departure condition for the Trans-Mars injection of the Mars Orbiter with minimum fuel requirement.

The aforementioned AOP constraint demanded the injection of the spacecraft to take place in the southern hemisphere of Earth (after crossing descending node), since the injection altitude was near to the perigee altitude. This, in turn, meant a longer flight duration between the lift-off of the launcher (lat. 13.2°N) and the spacecraft injection (lat. 19°S). This is where the mission flexibility offered by PSLV's four-stage propulsive configuration (Figure 2) proved handy: the longer flight could well be achieved by a long coasting between the burn-out of the third stage (PS3) and the ignition of the fourth stage (PS4).

In fact, PSLV is the only launch vehicle of ISRO having this feature of coasting feasibility in the upper-stage regime. Hence, the Mars Orbiter was sized and configured to suit the PSLV platform. Figure 3 shows Mars Orbiter mounted over the payload adaptor of PSLV-C25.

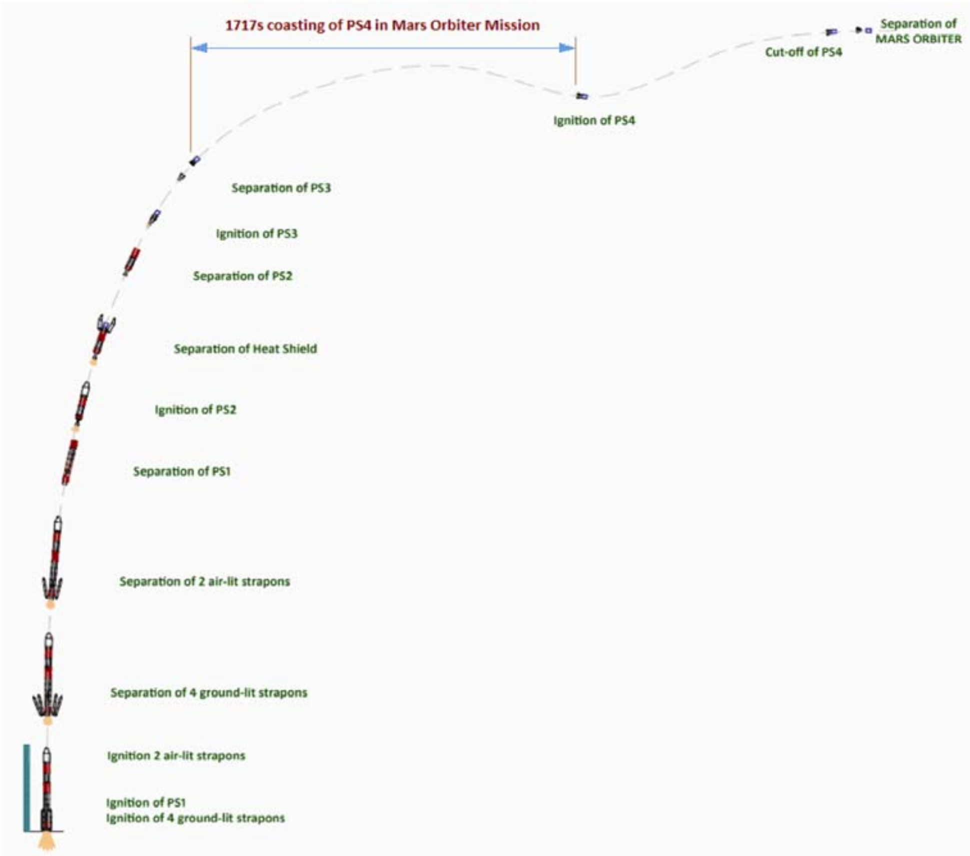

Figure 4. Mission profile of PSLV-C25.

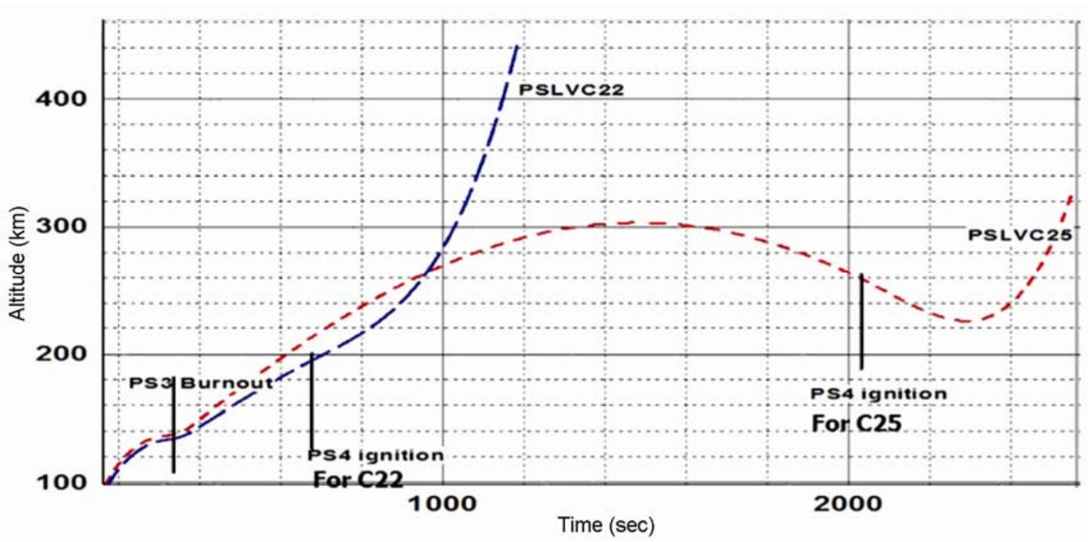

Figure 5. Comparison of altitude plots for argument of perigee of 283° and 178°.

Long coasting and implications

The mission profile for the PSLV-C25/Mars Orbiter mission was finalized with a long coasting of 1717 sec between the burn-out of PS3 and the ignition of PS4 (Figure 4).

The long coasting necessitated specific assessments, modifications and validation of the following:

- Coast phase guidance algorithm.
- Thermal management of PS4 stage during the extended exposure to extreme cold space.
- On-board battery capacity.
- PS4 control fuel consumption.
- Availability of telemetry data during the non-visible zone of the flight.

Coast phase guidance algorithm

Figure 5 compares the altitude plot of PSLV-C25 (AOP 283°) with that of a typical sub-GTO mission of AOP 178°, like PSLV-C22. In a regular GTO or SSPO mission of PSLV, the PS4 stage is ignited well before the coast-apogee altitude and the algorithm for computing the internal guidance parameters is designed with corresponding limits. For PSLV-C25, the PS4 ignition had to be in the descending leg of coast ellipse due to long coasting and hence the coast phase guidance algorithm had to be tailored accordingly. This was an essential change to ensure that PS4 would meet the specified injection conditions in the orbit, even under worst combinations of propulsion parameters and inert mass, with no compromise on the guidance margin (amount of propellant reserved to take care of performance dispersions) in the stage. Without the modification in algorithm, PS4 could deplete all its propellants before reaching the target conditions.

Computation of the true anomaly (angle between the directions of perigee and the current position of the orbiting body as seen from the point around which the body orbits) was modified to take care of 0–360° variations. Also, the sign of predicted vertical velocity was corrected for the descending ellipse. Computation of angles between the desired and current acceleration vectors was altered to cater to larger angles.

Thermal management of PS4 stage

During the long coasting after PS3 burn-out, the vehicle would enter the Earth's shadow and experience space-cooling effect. Thermal analysis was carried out considering solar load and Earth albedo based on the flight trajectory, vehicle orientation and the heat loss from the vehicle due to surface emission to space during the coasting. Solar loads corresponding to various launch dates were considered in the analysis.

No additional thermal protection system (TPS) was found necessary for the propellant feed lines, PS4 actuators, pyro valves, carbon gas bottles and the propellant tank. However, PS4 pressure regulator modules and the spring thrusters in the satellite separation system were provided with additional TPS to ensure safe margins. Enhanced pre-launch phase cooling was provided for the S-band telemetry transmitters and the inertial navigation system (both located on PS4) to lower the temperature at lift-off so that the in-flight temperature rise was within the acceptable limits.

On-board battery capacity

While sufficient margin existed for on-board battery capacity for the total mission duration of about 3100 sec, the capacity of the heater battery of inertial navigation system was enhanced from 5 to 10 Ah for better margin.

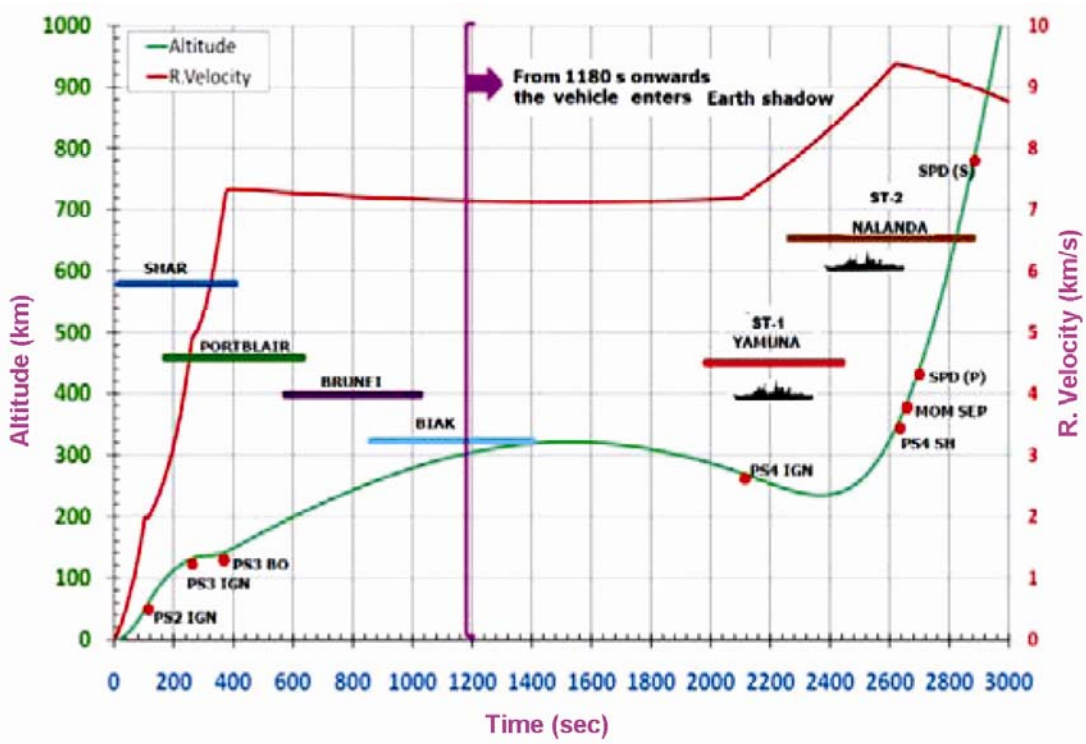

Figure 6. Telemetry visibility in PSLV-C25.

PS4 control fuel consumption

During the coasting, the vehicle would be controlled through the PS4 reaction control system (RCS) in on-off mode. The total control fuel consumption considering the longer coasting of PSLV-C25 was estimated to be 4–5 kg against the regular requirement of 2–3 kg in earlier missions. Here adequate margin was already available and no change was necessary.

Availability of telemetry data during the non-visible zone of the flight

Two ship-borne terminals (ST-1 and ST-2 on ships *Yamuna* and *Nalanda* respectively) were planned to be deployed in the Pacific Ocean to capture the critical events of PS4 ignition and Mars Orbiter separation. Acquisition of telemetry signals from ST-1 with antenna diameter of 1.8 m was ensured from 50 sec prior to PS4 ignition. Signals from ST-2 (4.6 m diameter antenna) were ensured up to 50 sec after the separation of the Mars Orbiter. Thus the availability of valuable flight data was positively ensured (Figure 6).

Stringent schedule for meeting the unique opportunity

Mars is slower than the Earth in orbiting the Sun. Hence, to have a minimum energy transfer from Earth to Mars, departure of the spacecraft from Earth should be planned when Mars is ahead of it and the orbits of the two planets are close. This occurs only once in two years and the opportunity in 2013 was during the end of November. The date for Trans-Mars injection of the Mars Orbiter was thus fixed and correspondingly the lift-off of PSLV-C25 had to be scheduled within a short time span between the last week of October and the second week of November 2013.

Sensitivity to Earth's movement around the Sun made it necessary to plan for specific AOPs corresponding to each particular day of the proposed launch window (October–November 2013). This in turn called for the generation and configuration control of multiple initialization files on-board PSLV-C25. Twenty-six sets of trajectories and close-loop guidance designs were prepared in this regard. They were validated through extensive simulations and made available well before the start of count-down. The RAAN constraint for a given day of launch was to be met by adjusting the lift-off time. Table 1 shows five out of the 26 typical specification sets.

The lift-off window for PSLV-C25 for a particular day was just 5 min and any slip would result in postponement of the launch to the next date. This implied that there should not be any glitch during the count-down. The achieved readiness of PSLV-C25 in all respects and fitting into this stringent time-frame was by itself a professional and techno-managerial success.

Table 1. Typical target conditions for the launch window in 2013

Launch date	Optimum injection time (UT)	RAAN (degree)	AOP (degree)
21 October 2013	11:21:25	135.01	273.70
28 October 2013	10:44:45	132.72	276.40
5 November 2013	09:50:43	127.06	282.55
12 November 2013	09:05:04	122.51	287.20
15 November 2013	08:59:00	123.95	285.90

Precision pays

The orbit (248 × 23,550 km), its inclination (19.2°) and AOP (283°) achieved by PSLV-C25 were all precise. This precision spared 6 kg of the fuel on-board the Mars Orbiter, a precious saving in such interplanetary missions. Table 2 summarizes the flight of PSLV-C25.

The full telemetry data were flawlessly acquired by all receiving stations, including the two ship-borne terminals at their respective optimal locations in the Pacific Ocean. From the post flight analyses, it was confirmed that all

Table 2. PSLV-C25 flight profile

	Time (sec)	Local altitude (km)		Inertial velocity (m/s)	
Event	Flight	Prediction	Flight	Prediction	Flight
Stage-1 ignition	0.00	0.0238	0.0238	451.89	451.89
Stage-1 separation	112.14	57.687	58.0	2387.64	2413.66
Stage-2 ignition	112.34	57.854	58.17	2387.14	2413.48
Heat shield separation	201.14	113.173	114.081	3624.90	3664.602
Stage-2 separation	263.00	132.311	132.271	5379.33	5380.776
Stage-3 ignition	264.20	132.531	132.456	5378.95	5380.835
Stage-3 separation	582.76	194.869	195.163	7730.88	7740.523
Stage-4 ignition	2099.52	271.317	297.587	7642.04	7620.510
Stage-4 cut-off	2616.30	342.515	336.237	9833.49	9840.126
Mars Orbiter separation	2653.30	383.388	375.869	9803.62	9808.942

the propulsion systems of PSLV-C25 had nominal performance and all the separation events were clean. The vehicle loads and control force requirements were benign as expected. The thermal margins were not perturbed at any point of the flight, including the long-coast regime. The ignition and performance of PS4 after the long coasting were normal. The temperatures of the propellants in PS4 were near to their usual operating conditions.

Conclusion

PSLV-C25/Mars Orbiter mission marked the first interplanetary venture of India. The mission flexibility offered by PSLV enabled successful achievement of the unique orbital conditions for the critical Trans-Mars injection of the Mars Orbiter. This outstanding success of PSLV highlights the expertise and maturity gained by the country in the field of reliable and sustained launch vehicle programmes.

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