PSLV-C19/RISAT-1 mission: the launcher aspects

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India's Polar Satellite Launch Vehicle (PSLV) precisely placed the indigenous Radar Imaging Satellite (RISAT-1) in the intended orbit successfully on 26 April 2012. This marked the 20th successive success of the launcher. This article gives the special aspects of the 'PSLV-C19/RISAT-1 mission' from the techno-managerial perspective of launch vehicle project. Also given is a summary of the performance of the launch vehicle in this flight.

Keywords: Launch vehicle, orbit planning, satellite, techno-managerial challenges.

Introduction

THE Polar Satellite Launch Vehicle (PSLV) is a four-stage launch vehicle designed and developed with the primary objective of placing spacecraft in the Sun-Synchronous Polar Orbits (SSPO). After three valuable developmental flights, PSLV was operationalized in 1997 with the launch of PSLV-C1 carrying the 1205 kg Indian Remote Sensing satellite, IRS-1D.

During the operational phase, the payload capacity of PSLV was enhanced by increasing the propellant loading of the first stage from 125 tonnes to 139 tonnes, induction of augmented second stage (liquid PL40), high performance third stage solid motor (HPS3) and carbon fibre reinforced polymer (CFRP)-based structures. Provisions were added for accommodating multiple spacecraft either using Dual Launch Adaptor (DLA) or auxiliary payload decks on the Equipment Bay (EB) of the vehicle.

PSLV has three variants, namely, PSLV – the generic version with six regular strap-on motors (S9), PSLV–CA – the core alone version without strap-on motors and the more powerful PSLV-XL with S12 strap-on motors (S12 is the extended version of the regular S9 strap-ons in terms of length and propellant loading). The upper stage has three versions based on propellant loading required for a particular mission. The vehicle configuration for a mission is selected based on spacecraft characteristics and the mission requirements. The current payload capability of the PSLV-XL vehicle is 1750 kg in 600 km SSPO and 1425 kg for the Sub Geosynchronous Transfer Orbit (Sub-GTO) of 284 × 21,000 km.

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All the three variants of PSLV have been successfully employed to place spacecraft in different destinations like SSPOs, planar orbits with specific inclination and also the Sub-GTOs. Today, PSLV is a universal and versatile launch vehicle. Each of its missions is unique with respect to the orbit, spacecraft, trajectory parameters and other requirements, posing fresh techno-managerial challenges to the planning and execution teams. The recent PSLV-C19/RISAT-1 mission is an apt example in this regard.

New aspects of PSLV-C19

The PSLV-C19/RISAT-1 mission employed PSLV-XL configuration of the launch vehicle (Figure 1) with its upper stage (PS4) loaded with 2.5 tonnes of liquid propellant to carry the heaviest satellite (1858 kg) ever entrusted to PSLV. There are several unique features and requirements specific to PSLV-C19 vehicle, the following being the salient ones.

Figure 1. PSLV-C19 lifting off with RISAT-1 on 26 April 2012 at 05.47 h IST.

Orbit planning

The initial mass budget for RISAT-1 was 1725 kg aiming a SSPO, 627 km above the Earth. Later, the satellite mass was respecified to 1858 kg. Corresponding capability of PSLV-XL was assessed for various feasible orbits and it was decided to inject the satellite in 480 km circular orbit with an inclination corresponding to 536 km SSPO mission, so that the orbit could be raised to 536 km using spacecraft propulsion system.

Accommodation of RISAT-1 within the payload fairing of the launcher

RISAT-1 was the biggest satellite to occupy the envelope of payload fairings of PSLV. Initially, it was proposed to use a larger heat shield which demanded exhaustive study on the aerodynamics of the altered configuration of the launcher. Later, the RISAT-1 configuration was optimized (Figure 2) by swapping the locations of its payload (the specific instruments/equipment housed in the satellite) and the satellite bus (the standard structure of the satellite), enabling accommodation of RISAT-1 well within the existing proven payload fairings (Figure 3). This was a major preparatory step towards launching RISAT-1 on-board PSLV (Figure 4).

Assessment on launch pad

PSLV-C19 was the first PSLV-XL to be launched from the First Launch Pad (FLP) of Satish Dhawan Space Centre, Sriharikota. At FLP, the rocket is built up on a stationary launch pedestal near the umbilical tower using a Mobile Service Tower (MST) which houses the entire launch vehicle during preparation and moves away on rails at the time of launch. Both the previous launches of PSLV-XL variant took place from the Second Launch Pad (SLP), where the launch vehicle gets integrated on a mobile launch pedestal inside a conveniently large stationary building. Once the integration is complete, the mobile pedestal carries the launch vehicle to the umbilical tower of SLP. It was important to verify that MST at FLP could handle the S12 strap-on motors with adequate

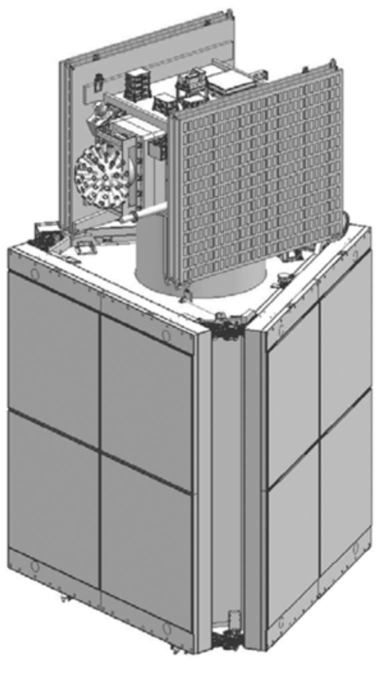

Figure 2. Final configuration of RISAT-1.

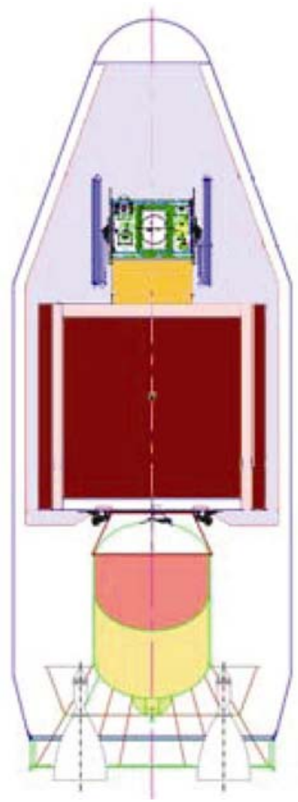

Figure 3. Accommodation of RISAT-1 within PSLV heat shield.

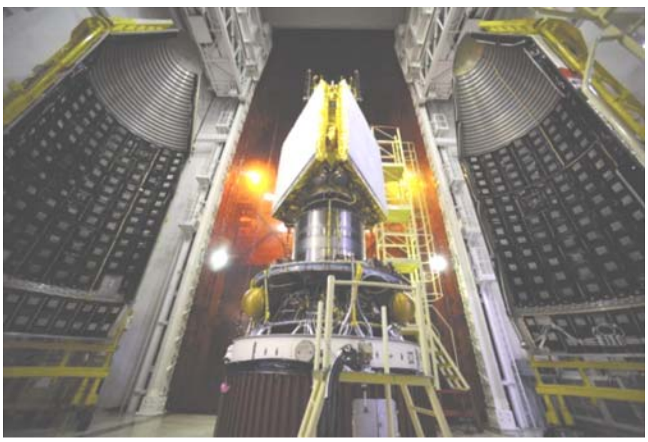

Figure 4. RISAT-1 before closure of heat shield.

assembly access. A trial of S12 strap-on motor assembly was carried out at FLP, demonstrating the total feasibility. Figure 5 shows the S12 assembly in PSLV-C19.

Another aspect examined in detail was the vehicle lift-off dynamics with respect to the physical gap between the PSLV-XL and the nearby ground structures (namely the launch pedestal and the umbilical tower) at FLP. Analysis was carried out on the launch pad acoustics and thermal aspects as well. All parameters were confirmed to be benign and acceptable.

First polar mission of XL variant

Though PSLV-C19 was the third launch of PSLV-XL version, after the PSLV-C11/Chandrayaan-1 and the PSLV-C17/GSAT-12 missions, this was the first polar orbit venture of the variant. The trajectory of the vehicle was designed such that all the constraints such as down-range safety and environmental parameters (dynamic pressure, angle of attack, tail-off thrust of separating bodies, etc. during lower stage separation events) were met.

With respect to acquiring the telemetry signal from the launch vehicle, analysis showed a visibility gap between the down-range tracking stations at Thiruvananthapuram and Mauritius, due to the low injection altitude of 480 km. An additional tracking station was provided at Rodrigues Island (using transportation terminal) so that complete telemetry signal could be received in real time without any data loss.

Upper stage structural characteristics and its impact on autopilot design

The upper stage of the vehicle (PS4) was meticulously looked into with respect to the way in which its structural behaviour was influenced by the heaviest satellite attached atop. Its impact on control capability of the vehicle had to be well understood. Extensive vibration tests were carried out with a stacked configuration of a flight-identical PS4 stage with simulated satellite mass of about 2000 kg for validation of the structural dynamics characteristics (Figure 6).

It was observed that due to the heavy spacecraft the base-fixed lateral frequencies were lower than the vehicle requirements. In the vehicle stack level, the second and third bending mode frequencies were lower from the control–structure–interaction point of view. Also, there was a local bending in the yaw plane at inertial sensor area which could prompt unnecessary control action. Based on exhaustive analysis of the test results and a series of reviews, the Digital Auto Pilot (DAP) design was fine-tuned. In the new design of DAP, compensators were tuned to provide extra attenuation to second bending modes during first stage flight regime in the yaw plane by reducing the rigid-body band width by a small margin compared to earlier missions. The changes were made for initial flight regimes up to the burn out of strap-on motors (named zone-1 and zone-2). A comparison of the

Figure 5. Assembly of S12 strap-on motors in PSLV-C19 at first launch pad.

Figure 6. Vibration test of PS4 stage with simulated RISAT-1 mass for dynamic characterization.

Table 1. Mission simulation: various levels

Simulation test bed	Purpose
6D simulations	To validate trajectory, Closed Loop Guidance (CLG) and Digital Auto Pilot (DAP) designs in autonomous mode using the mathematical models for vehicle, control, navigation and environmental parameters.
OILS (On-board computers-In-Loop Simulations)	To validate the on-board software design. Stress tests are devised and carried out to ensure error-free on-board software by perturbing all the parameters well beyond 3σ dispersions.
HLS (Hardware-in-Loop Simulations). Actual inertial sensors in the loop	To validate flight computers and Inertial Navigation Systems (INS) in closed loop by mounting INS on Angular Motion Simulator (AMS).
ALS (Actuator-in-Loop Simulations)	In these simulations, the response and performance of the flight control actuators are assessed in the closed loop mode.

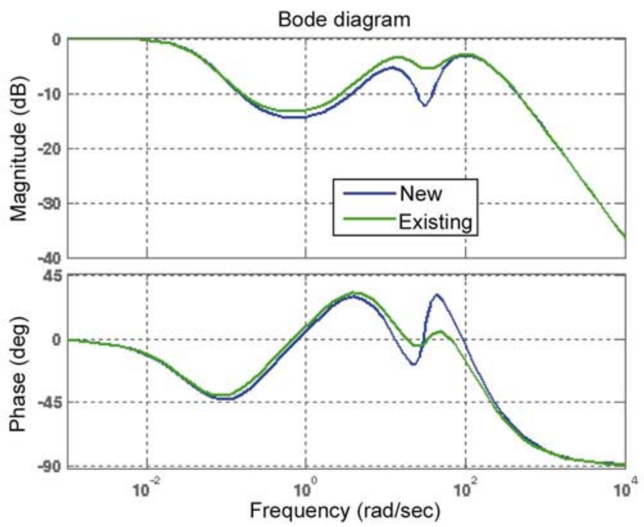

Figure 7. Comparison of compensator characteristics before and after digital auto pilot modifications during zone-2 in yaw plane (first stage regime).

Figure 8. PSLV-C19 with RISAT-1 on the launch rehearsal day.

compensator characteristics before and after the modifications for zone-2 regime (from 25 to 70 sec after ignition of first stage) is shown in Figure 7.

The process towards success

All the regular and the new aspects of PSLV-C19 were thoroughly assessed by the launch vehicle design review teams concerned. All the mandatory mission simulations were carried out with mission hardware such as on-board computers, control electronics, actuators and also the associated software on-board. Table 1 shows the various levels of mission simulations. Nearly 100 such simulation cases were exercised for PSLV-C19.

The realized propulsion, mechanical, electrical, avionics and software systems were all critically verified by the mandatory mechanisms of Flight Readiness Review (FRR) in the system level and the launch vehicle level. Quality assessment and audit teams, again in system as well as launch vehicle levels, confirmed the acceptability of all the flight elements.

The elaborate testing of the launcher was carried out during different phases of vehicle integration, supervized by the Mission Readiness Review (MRR) team. On successful launch rehearsal (Figure 8) and confirmation of all the health parameters, the final clearance for going ahead with the mission was issued by the Launch Authorization Board (LAB). PSLV-C19 lifted off with RISAT-1 on 26 April 2012 at 05.47 h IST.

Post-flight analysis

PSLV-C19 injected RISAT-1 into a polar orbit with 470 km perigee (distance from the Earth to the nearest point on the orbit) and 479 km apogee (distance from the Earth to the farthest point on the orbit) with an inclination of nearly 97.6°. The orbit was well within the dispersions specified. The vehicle body rates at satellite separation were less than 0.5°/sec as planned.

RISAT-1 was later raised to 536 km SSPO using its thrusters on-board. After the orbit raising, about 62 kg of propellant (out of 100 kg initially loaded) remained in the

Table 2. PSLV-C19 flight profile

	Time (sec)	Local altitude (km)		Inertial velocity (m/sec)	
Event	Flight	Prediction	Flight	Prediction	Flight
Stage-I ignition	0.00	0.02381	0.02381	451.89	451.89
Stage-I separation	114.20	70.093	72.130	2147.31	2160.86
Stage-II ignition	114.40	70.326	72.712	2146.45	2159.04
Heat shield separation	155.20	116.235	117.938	2388.70	2387.36
Stage-II separation	265.86	226.021	227.202	4098.79	4115.84
Stage-III ignition	267.06	227.223	228.212	4096.11	4113.33
Stage-III separation	512.72	434.574	446.450	5871.01	5881.90
Stage-IV ignition	522.72	440.729	452.630	5862.01	5873.10
Stage-IV cut-off	1027.74	485.340	485.390	7618.74	7616.00
RISAT-1 separation	1064.74	486.143	486.200	7623.20	7622.83

Table 3. Comparison of the first two global lateral modes with the predicted values

First mode (Hz)		Second mode (Hz)	
Analysis	Flight	Analysis	Flight
2.11	2.25	4.72	5.01

satellite because of the precise orbital placement by PSLV and the performance of the satellite thrusters, extending the satellite life further.

Uninterrupted telemetry data was available as a result of deployment of additional station at Rodrigues Island. The Post Flight Analysis (PFA) teams have gone through the telemetry data on various vehicle components such as the propulsion systems, structural systems, avionics systems, control systems, separation systems, etc. and confirmed satisfactory performance (Table 2).

All the propulsion systems performed almost in the nominal range. The estimated specific impulse values of the stages, derived from trajectory matching, are within the dispersion bounds specified. No control–structure interaction was seen during the first stage regime (with respect to the effect of the heaviest satellite). All the separation events were clean and imparted only negligible disturbance to the ongoing stage.

Benign vehicle loads and control force requirements were seen from PFA. The aerodynamics parameters, viz. Mach number, dynamic pressure, relative velocity, altitude, angle of attack and Q-alpha during the first-stage regime were reconstructed from position, velocity and vehicle orientation angles in Earth centred inertial frame and also from wind profiles measured at $T + 15$ min (T denotes the lift-off time).

The peak dynamic pressure observed in PSLV-C19 flight was 69.77 kPa (upper limit 90 kPa) and the maximum angle of attack was around 0.84° (upper limit 3°) during the maximum dynamic pressure regime. The maximum Q-alpha was 649.89 Pascal-radians (upper limit 4000 Pascal-radians) at 60 sec into the flight.

The effectiveness of DAP compensator tuning based on stage-level vibration test was assessed during PFA by comparing the first two global lateral modes with the predicted values and good matching was observed (Table 3). Body rates showed no control–structure interaction during the entire flight regime.

Conclusion

PSLV-C19/RISAT-1 mission was the 20th consecutive success of the workhorse launcher of Indian Space Research Organisation. The satellite was the heaviest and biggest among the various spacecraft carried till date by PSLV. Typical aspects that called for closer attention and analysis have been pointed out in this article. Also mentioned is the way in which each specific requirement was catered to. The major findings from PFA have been summarized. The professionalism and adequacy of launch vehicle management in terms of planning, preparation and pursuit are brought out.

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