Evolution of Indian launch vehicle technologies

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A multitude of inter-disciplinary technologies have been mastered indigenously for realizing a series of operational space launch vehicles. The vehicles range from relatively tiny Rohini sounding rockets to gigantic satellite launch vehicles, PSLV and GSLV. These vehicles now launch on demand, the entire IRS range of remote sensing satellites and communication satellites up to 2.5 tonnes, providing precise orbital injection. This article presents the evolution of the technologies, various major subsystems and their validation methodologies for these satellite launch vehicles of ISRO. An attempt has been made to present the conceptual foundations of the entire range of the accomplishments. The paper also includes a brief description of the facilities at the launch complex of ISRO. It delineates briefly the plans for developments in the near future in respect of reusable launch vehicles, and advanced facilities.

Keywords: Evolution, infrastructure, launch vehicle, multidisciplinary, rockets.

LAUNCH vehicle is a critical element in the self-reliant programme of space endeavour, because of vicissitudes of geopolitics and non-availability of the know-how from those who possess this technology, because of the various dual use based control regimes, particularly, Missile Technology Control Regime. Considering that access to technologies, components, materials, etc. is under stringent technology control regimes of the developed countries, all-round indigenous effort by ISRO, in association with national R&D institutions, academia and industry to develop the complete range of technologies was called for the development of launch vehicles. It started with the development of basic technologies in various disciplines of rocketry through sounding rockets, a learning phase during 1960–1970s. Subsequently, ISRO acquired further expertise through an experimental phase in 1980s, by developing Satellite Launch Vehicle-3 (SLV-3) and Augmented Satellite Launch Vehicle (ASLV) and creating the associated design and manufacturing infrastructure as well as the integrated facilities for providing smooth launch and post-launch services. Based on these experiences, ISRO undertook successful development of Polar Satellite Launch Vehicle (PSLV) and Geosynchronous Satellite Launch Vehicle (GSLV) (Figure 1) to meet the national needs of launching of IRS and INSAT class of satellites. These satellites are providing diverse space services to the country, namely, remote sensing, weather monitoring, telecommunication and TV broadcasting. Up till now, the PSLV has launched 10 remote sensing satellites, having the highest payload mass of 1600 kg in Sun Synchronous Polar Orbit (SSPO). Further, the GSLV has launched three satellites of Geostationary Satellite (GSAT) type, the heaviest mass of payload being 1950 kg in Geo-stationary Transfer Orbit (GTO). PSLV has also demonstrated its versatility to launch a satellite into GTO. In each of these launches, the orbit injection accuracies have met the stringent specifications laid down as per mission specification.

Further, technologies have been developed for imparting PSLV, a multiple satellite launch capability in a single mission. So far, PSLV has also launched six foreign satellites as co-passenger payloads, along with our own satellites. In many cases, mass of Indian geo-stationary satellites exceed 2.5 t which is beyond the present capability of GSLV and is expected to grow to 4 t, in the near future. Noting this demand, ISRO has commenced the development of GSLV Mk-III, which will have capability to place payloads of 4 t in GTO and 10 t class in Low Earth Orbit (LEO). This vehicle is targeted to make its first launch in a couple of years.

Currently, developments in launch vehicle technology all over the globe are directed towards the reduction in the cost of launch by an order of magnitude. Towards this, ISRO has initiated the development of Reusable Launch Vehicles (RLVs), including the possible use of air-breathing engines. In addition, detailed feasibility studies have been carried out on manned mission to explore new scientific and technological frontiers, which call for man rating of the launch vehicle, for improved safety and reliability.

This article attempts to explain the step-by-step evolution of the launch vehicle technologies, from the beginning and the technological challenges faced during development phases. The indigenous launch vehicle technology developments carried out so far and the developmental plans for future launch vehicle technologies are also included.

Satellites for various applications and their requirements on launch vehicles

In order to perform its defined functions in space, a satellite houses a variety of payloads related to space-based applications and observations. The envisaged utilization of a satellite determines its preferred orbit, which in turn defines the performance characteristics of its launch vehicle. The cost effective utilization of spacecraft demands

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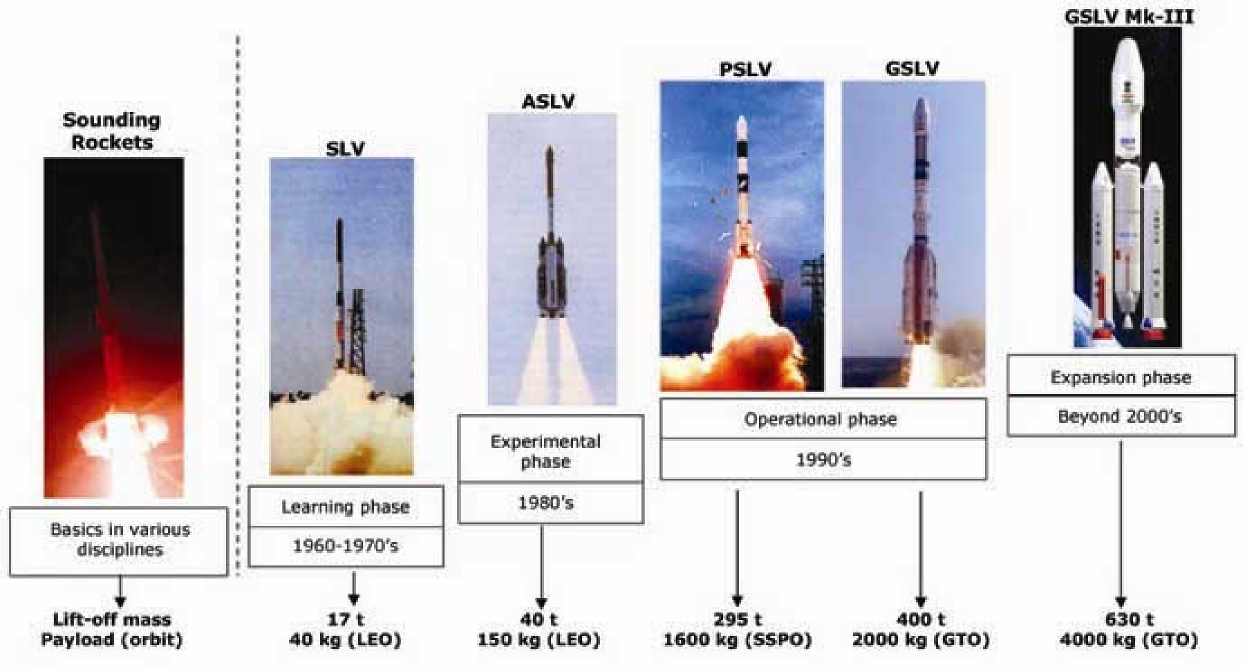


Figure 1. Evolution of Indian launch vehicles.

Table 1. Typical satellites, their applications and preferred orbits

Applications	Typical mass (kg)	Typical orbit	Orbital injection requirements Altitude (km)	Orbital injection requirements Velocity (km/s)
Scientific applications	500	400 km circular, Inclination = 50°	400	7.67
Remote sensing	100	800 km circular, Inclination = 98°	800	7.54
Telecommunication	200	36,000 km circular*, Inclination = 0°	200	10.24

*Launch vehicle injects the satellite into GTO with perigee of 200 km and apogee of 36,000 km; onboard satellite fuel is used to circularize the orbit to the required altitude.

large duration of operations in space, typically for a period ranging from 5 to 15 years. Typical application satellites, their mass, preferred orbits and orbital injection requirements are given in Table 1.

A satellite launch vehicle pilots the satellite along a predetermined path to the required altitude, and imparts the requisite orbiting velocity to inject it into the desired orbit. Towards this, an integrated launch vehicle system is to be realized addressing, essentially: (1) Design and development of a vehicle meeting stringent performance specifications, (2) Setting up of associated test facilities, (3) Vehicle mission management, and (4) Launch complex and post-launch support facilities. Each of these elements has been elaborated later in the paper.

Launch vehicle systems design and the required technology evolutions

Figure 2 shows the areas of activities involved in the design of a satellite launch vehicle. The main areas are: (1) Propulsion, (2) Aerodynamics and Thermal, (3) Structures and Materials, (4) Navigation, Guidance, Control and Vehicle Avionics, (5) Separation Mechanisms, identified here as Stage Auxiliary Systems, (6) Integration, Checkout and Launch, and (7) Mission Management. Figure 2 depicts important subsystems of a typical multi-stage vehicle, GSLV. The first stage is made up of a core booster motor and four strap-on motors. The second stage is a liquid stage, whereas the third stage is cryogenics. The equipment bay and a payload fairing for housing the payload(s) are housed on top of the third stage.

The design cycle starts with the identification of the mass of the payload and the specification of its orbit, defined in terms of apogee and perigee altitudes and the angle of inclination of the plane of the orbit with respect to the equatorial plane. Acceptable tolerances in the two altitudes and the inclination angle complete the set of specifications.

As depicted in Figure 2, the design and development of a satellite launch vehicle should address a number of im-

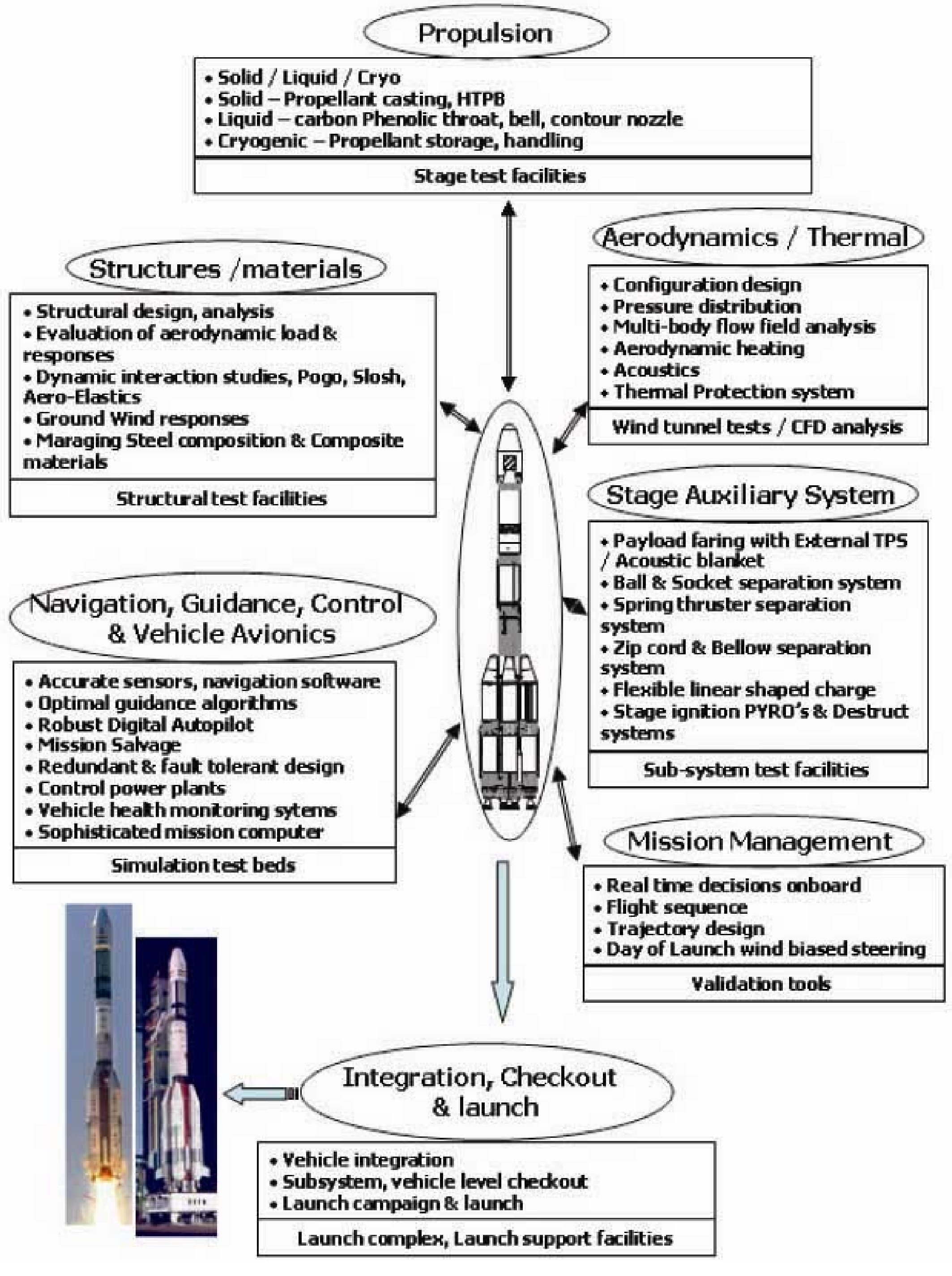


Figure 2. Main subsystems of a satellite launch vehicle.

portant factors like: (i) providing sufficient propulsive energy to inject the satellite precisely into the required orbit, (ii) stabilization and steering of the vehicle along the designed flight trajectory, (iii) navigation and guidance of the trajectory to achieve precise terminal conditions, (iv) reliability of in-flight operation of all its mission critical subsystems and their redundancy management to assure fail-safe operation, (v) auxiliary systems to provide structural integrity, enact separation of spent components and protection of vehicle and payload in the hostile flight en-

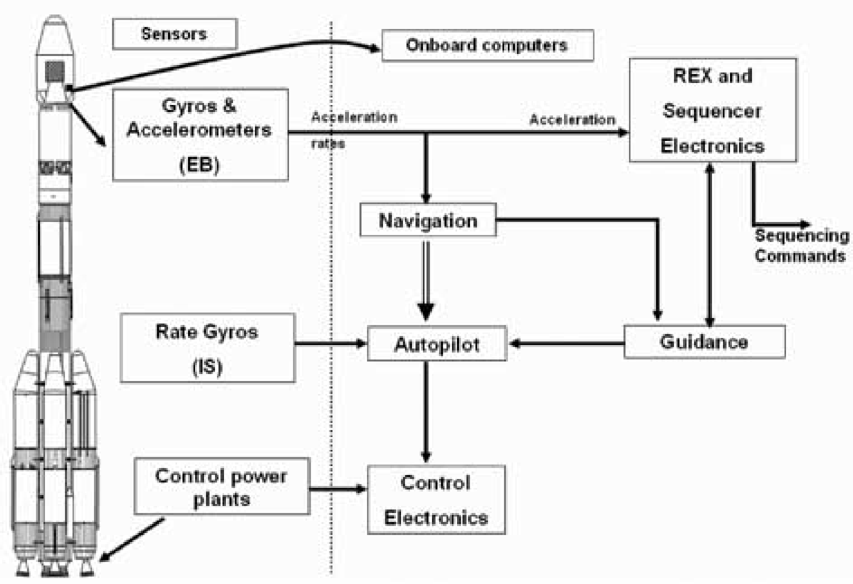


Figure 3. Navigation, guidance and control system scheme.

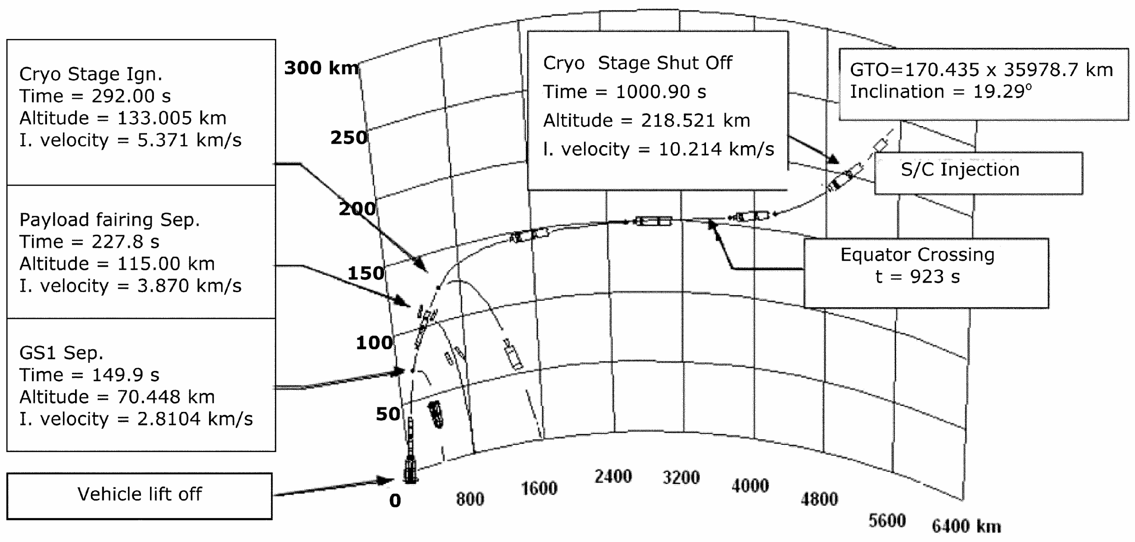


Figure 4. Mission profile.

vironment, and (vi) in-flight monitoring of the performance of subsystems. Exhaustive design validation and flight readiness tests need to be carried out during the different phases of development and at various stages of aggregation, involving, automated test beds, data acquisition and processing facilities. Judicious management of the flight trajectory is required, in terms of restricting the aerodynamic loads on the structure of the vehicle and destabilizing loads on the autopilot, smooth separation of spent stages and the payload faring, impact areas of separated hardware, in order to achieve the best realizable performance of the vehicle without jeopardizing the mission and range safety.

Initially, vehicle sizing in terms of number of stages, size of each stage, propulsion system in each stage, design of nominal flight sequence as well as optimal trajectory design, considering aerodynamic and propulsion parameters and atmospheric conditions are carried out. These provide inputs to the detailed design of individual stages and equipments. The overall mission design is obviously multi-disciplinary and interactive, between the design of propulsion, aerodynamics, structure, thermal as well as navigation, guidance, control. Some of the salient developments required in each of the above-mentioned areas are explained in the following sections.

Propulsion systems

Propulsion system provides the thrust profile required for achieving the target terminal altitude and velocity for the payload. With the present day launch vehicles, the payload capability of a multi-stage vehicle is about 0.5% of its lift-off mass, wherein the propellant mass is about 85.5% and non-propulsion system mass (inert mass) is about 14% of the total vehicle mass.

Commonly, launch vehicles employ three types of propulsion systems, viz. solid, liquid and cryo-propellants. Specific impulse, which is the integral of the thrust produced per unit mass of the propellant, is a prominent measure of the velocity addition performance of a propulsion system. The specific impulses of liquid and cryo-propulsion systems are 20% and 80% higher than that of solid propulsion systems, respectively. However, liquid and cryo systems, having to employ relatively larger number of flow control components, are more complex and expensive than the solid propulsion system. As such, due to the requirements of high thrust and large energy in the initial phase of flight, solid supplemented by earth storable liquid-propulsion systems are used as boosters for lower stages, whereas higher performance, smaller and lower thrust liquid and cryo systems are used for upper stages. Velocity addition by a stage is given by

$$\Delta V = gI_{\text{sp}} \ln((m_{\text{p}} + m_{\text{s}} + m_{\text{pl}})/(m_{\text{s}} + m_{\text{pl}})) ,$$

where g is acceleration due to gravity, I_{sp} is specific impulse, m_{p} is propellant mass of the stage, m_{s} inert mass of the stage and m_{pl} is payload for the stage (for lower stages, corresponding upper stages are the payload whereas for the final stage, satellite is the payload). Thus for the given propellant loading, lower the inert mass of the stage, higher the velocity addition. Accordingly, composite and other high strength-to-weight ratio materials are the choice materials of construction for motor cases and other load-bearing structures in a stage. The masses of the avionics packages, inter-stages, payload fairing and other non-propulsion elements of the vehicle are kept to the minimum to maintain lower inert mass.

Aerodynamics and thermal protection

Aerodynamic characterization of the vehicle is extremely important and it is estimated by employing a combination of wind tunnel tests, available aerodynamic data banks, and analytical and empirical methods including tools of Computational Fluid Dynamics (CFD). The aerodynamic characteristics comprise detailed pressure and load distribution along the length of the vehicle to do design of load-bearing structural elements. The analysis of vehicle flexibility using load distribution is needed for the design of the autopilot. Characterization of vehicle is needed for wide ranges of angles of attack and speeds of the vehicle. Additionally estimation of aero acoustic characteristics, multi-jet interactions and consequent base heating during simultaneous operation of engines are also needed. Estimates of aerodynamic noise due to shock oscillations in the transonic region and boundary layer are based predominantly on experimental and flight measurements. The vehicle needs to be thermally protected to counter the aerodynamic heating and this requires accurate design inputs on the aerodynamic heating pattern. Other important thermal considerations are for the protection of protrusions, components exposed directly to exhaust jet plumes.

Structures and materials of construction

Structural elements are important ‘passive’ subsystems in a launch vehicle, which provide shape, structural integrity, and space for housing various subsystems and to protect them from the hostile thermal, vibration, noise and acceleration flight environment. The payload fairings house the spacecraft, give aerodynamic shape to the vehicle and protect the final stage and satellite from aerodynamic heating and harsh acoustic environment from aerodynamic noise and jet noise. The payload adapter structure provides interface between launch vehicle and satellite, whereas the base shroud provides the interface between launch vehicle and the launcher. The equipment bay interface structure houses onboard avionics elements. Between two propulsion stages, there is a load-bearing structure called inter-stage. The inter-stage houses all needed subsystems specific to the stage. The thermal and acoustic protection paints and blankets protect the vehicle and avionics packages from the aerodynamic heating, aerodynamic noise, jet noise and heating. As these systems contribute significantly to the inert mass of the vehicle, the mass reductions in these systems are essential without sacrificing the structural integrity to increase the vehicle payload capability. Development of light alloy and fibre-based composite structures with high strength-to-weight ratio, ‘optimum’ aerodynamic shape, ‘optimum’ construction of inter-stages, thermal protection paints, acoustic blankets, relevant design tools and competent test facilities are needed to meet the demands.

Stage auxiliary systems

Any satellite launch requires ignition of the propulsive stages, separation and jettisoning of objects such as the spent stages of the vehicle, the payload fairing and finally injection of payload(s) into orbit. The termination of the flight is also needed in case of abnormalities in the vehicle system. These functions are achieved by the stage auxiliary systems, viz. pyro, separation and destruct systems.

Pyro system in a launch vehicle initiates stage ignition, stage separation and stage destruction actions on being commanded by the vehicle onboard sequencing and telecommand system. The separation systems employ different mechanisms to separate and jettison various structures with different size, shape and inertial properties from the continuing stages. The function of the onboard destruct system is to terminate the flight either by destruction or by deactivation of the stages on command from ground, in case of abnormalities in the vehicle system or deviation in the flight path, which can result in destruction of life and properties. On destruction command, thrust is terminated along with minimum fragmentation for solid motors, whereas liquid engines are shut-off, combined with propellant tank puncturing and propellant draining.

Avionics and navigation, guidance and control systems

It is essential to achieve precisely the mission-defined orbit, as it influences the duration of the precious service life of the satellite. The calibre of the avionics system determines this performance. The Navigation, Guidance and Control (NGC) system is the brain of the launch vehicle, which implements the predetermined flight plans, utilizing the optimum propulsive energy. This system realizes the preset optimum trajectory in real time, steers the vehicle along the desired path during its entire mission and injects the payload precisely in the intended orbit. The dispersions in propulsion system performance, estimated aerodynamic characteristics, expected structure of the wind, a variety of internal and external disturbances cause deviations in the launch vehicle trajectory from the preset path. The navigation system measures the instantaneous state of the vehicle, and using this information the guidance system generates the vehicle steering commands to achieve the specified orbit. The vehicle control systems, comprising an autopilot and the control power plants, stabilize and steer the vehicle along the desired trajectory in the presence of destabilizing internal and external disturbances. A typical hardware and software elements of NGC system is given in Figure 3.

The accuracy of the navigation sensors, the versatility of the navigation software, and the effectiveness of the guidance scheme determine the accuracy of orbital injection. The robust autopilot design, considering the most probable control–structure–slosh interaction and the performance of control power plants, determine the disturbance-rejection, stabilization and steering capability. All these functions are carried out through a set of fault-tolerant and reconfigurable real time onboard computers. Redundancy has been built into each of the components, and a well-defined mission salvage plan is introduced to take over, in the case of irrecoverable failure of any of the elements of the avionics system in flight. Further, all the computational software systems need to meet the requirements, without compromising on the accuracy, reliability and robustness. For an efficient function of onboard avionics, the tasks are distributed over the multi-processor configurations with proper synchronization of the functions, and signal flow without any delay.

The Telemetry Tracking Command (TTC) system in the vehicle enables the monitoring of health and performance of the entire range of subsystems during the flight. The state-of-the-art NGC and TTC systems are realized using indigenous inertial sensors, onboard computers, optimal fault-tolerant software, the control electronics, and the control power plants.

The validation of NGC system under the flight environments is another significant task, which involves the realization of simulation test beds with multiple computers and real-time operating software.

Mission management

Figure 4 shows a typical flight trajectory, along with the sequence of events. In order to achieve the desired orbit with highest possible payload, the launch vehicle needs to fly along a trajectory optimized under the constraints imposed by the launch site, launch azimuth, range safety and parameters of the vehicle. Management of the stage transition, involving shut down and switching off of control and separation of lower stage, followed by ignition of upper stage and smooth transfer of control to the upper stage involving conflicting requirements at times, is crucial for the success of any launch vehicle mission. This requires designing of a complex sequencing of events, based on real time detection of critical events and corresponding decision-making. The atmospheric flight is the most disturbed phase of flight, wherein the atmospheric wind plays a major role. Controllability and structural integrity of the vehicle depend on structure of winds prevailing over the launch site. In order to achieve all weather launches and all day launch without over-design of the subsystems, the steering required for the atmospheric flight needs to be designed with winds very close to the time of launch.

ISRO has met successfully all these requirements of developing complex software design packages, versatile simulation tools and a well established, tested and automated measurement, design, simulation and validation tools.

Launch complex and launch support facilities

The sequence of events at launch complex is to integrate the vehicle, mount it on launch pedestal, mate the satellite with the vehicle, checkout whether the parameters of the integrated vehicle and satellite are within the allowable bands and then launch the vehicle. The seamless integration of vehicle subsystems into an integrated vehicle involves delicate handling, and filling of gases and fluids. Detailed checks have to be carried out at each phase of aggregation. In order to protect the integrated vehicle and subsystems from the environmental conditions, the gas and fluid filling and checkout operations are carried out through remote control. The computerized checkout system checks all vital parameters of various subsystems. Alignment, calibration and initialization of inertial systems just before launch, loading of flight critical input data at the last minute are the other critical tasks. During the flight, the vehicle is tracked closely, till the injection of the satellite into orbit. Also, the telemetry transmits data, with adequate bandwidth and magnitude resolution, on the performance and health of the subsystems of the vehicle. In addition, a tele-command link also exists to be able to destruct the vehicle, in the case of a malfunction in the vehicles that threatens life and property. ISRO has well-established facilities at its launch complex to carry out all these operations.

Progression of development of launch vehicles and their versatility

The following approaches have guided the path towards self-reliance in launch vehicle technologies:

1. Step-by-step development of increasingly more versatile technologies required to launch heavier satellites with higher injection accuracies
2. Taking advantages of lessons learnt from failures
3. Retaining the pedigree of already developed stages and technologies, in order to reduce the overall development cost and time
4. Increasing the versatility and cost effectiveness of vehicles by incorporating multiple satellites launch capabilities and deriving their variants to cater to a wider range of autonomous payloads.

Sounding rockets

The development of the Rohini sounding rockets had two major objectives namely (a) to meet the requirements of conducting *in situ* observations on upper atmosphere, ionosphere and near space, and (b) to develop competence in the basic aspects of rocketry that serve as stepping stones to develop satellite launch vehicles.

Starting with the launch of a Nike-Apache sounding rocket from the Thumba Equatorial Rocket Launching Station (TERLS), Thiruvananthapuram on November 21, 1963, a wide range of rocket-based studies in the geomagnetic equatorial region, using a variety of sounding rockets have been carried out.

Towards the development of technologies, a series of different sizes of sounding rockets were designed and flight-tested. Figure 5 gives a summary of the main features of the operational Rohini sounding rockets. These sounding rockets enable meteorology studies, such as those related to the onset of monsoon, studies of the equatorial electrojet, the D-region of the ionosphere, studies of the upper F-region of ionosphere, chemical and mass composition of gases above normal atmosphere and radiation such as the X-rays from space, which can be detected only above about 350 km.

SLV-3

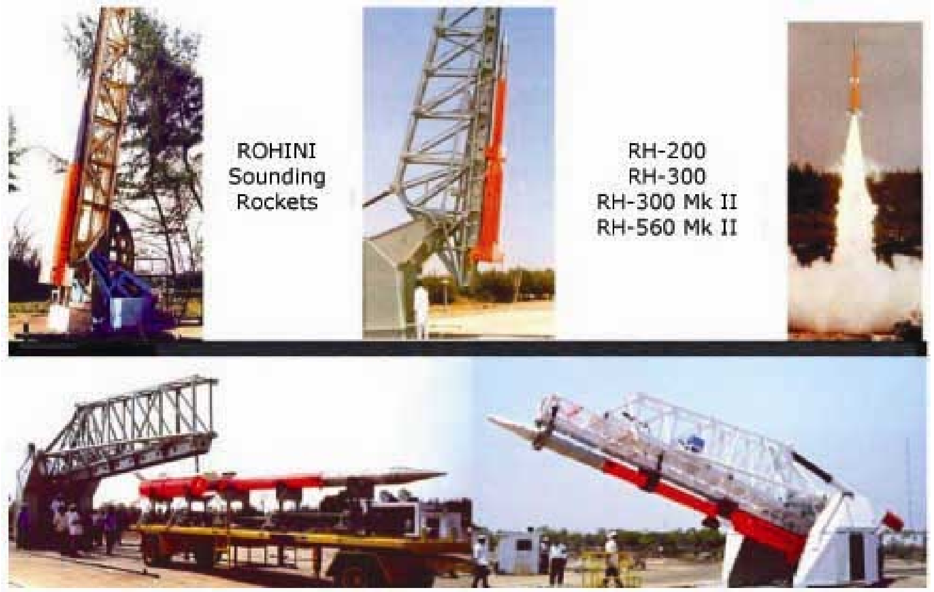
Applying the technologies developed in sounding rockets to multi-stage rocket systems led to the development of India’s first satellite launch vehicle SLV-3, having the capability of placing a 40 kg payload in LEO. SLV-3 was a four-stage vehicle, all using solid propellants. It used fins to have built-in aerodynamic stability. A heat shield protected the satellite from aerodynamic heating. It also had an analog autopilot, on-board event programmer, inertial attitude measurement system and telemetry, tracking and tele-command avionics. The SLV-3 program resulted in far-reaching developments in diverse disciplines of rocketry and gave confidence to take up projects of greater complexities. One such development was the comprehensive modelling and computer simulation of the trajectory of the vehicle from lift-off till the injection of the satellite into orbit. A number of simulations with off-nominal conditions for various vehicle parameters led to the mapping of sensitivity functions, fixing the tolerances to the large number of variables of the vehicle and subsequently Monte Carlo simulations. All these procedures have become a standard procedure in ISRO for designing a vehicle, clearing it for flight and for resolving a large variety of design and acceptance issues.

Though the first flight test conducted in 1979 was not successful, it provided invaluable insight into design and development of multi-disciplinary aspects of launch vehicle systems, various interfaces like launcher to satellite, launcher and launch complex operations, international tracking, telemetry and command networks, among others, paving the way for the smooth operation of the subsequent three successful flights.

Intricacies related to a host of critical areas of satellite launch vehicles, such as, solid propulsion, segmented structures for solid propellant motors, aero and flight-dynamics related to aerodynamic stability and staging, autopilot, open loop guidance, control power plants, injection of satellite into orbit and overall mission management were learnt through three successful launches of SLV-3 during 1980–83.

ASLV

Considering the need to achieve higher payload capability for scientific experiments and space applications, ASLV configuration was conceived to augment the SLV-3 by adding two strap-on motors to the first stage, giving a payload of 150 kg in LEO. The new developments carried



Features	RH-200	RH-300	RH-300 Mk II	RH-560 Mk II
No. of stages	2	1	1	2
Length (m)	3.6	4.8	4.9	7.7
Lift-off weight (kg)	108	370	510	1350
Payload wt. (kg)	10	60	70	100
Altitude (km)	85	100	150	550
Application	Meteorology	Middle atmosphere	Middle atmosphere	Ionosphere

Figure 5. Sounding rockets of ISRO.

out during this phase included strap-on boosters, bulbous payload fairing, canted nozzles, closed loop guidance, inertial navigation system based on stabilized platform, new digital avionics based on M6800 processor and development of the launch complex facilities required for vertical integration. Despite two failures, detailed failure analysis enabled better understanding of the relatively more difficult atmospheric regime of flight in respect of peak aerodynamic pressure, autopilot design, uninterrupted controllability, control–structure interaction, influence of prevailing wind structures, and demands to be met for clean stage separation, event management by in-flight decision making based on onboard observations, and providing closed loop guidance, while using solid propellant stage for achieving lower dispersions in satellite injection conditions. With two consecutive successful launches of ASLV, many of the critical mission management aspects were mastered.

PSLV

Development of PSLV was initiated for inserting 1 t class of operational remote sensing satellites into SSPO and it constituted a quantum jump in developments, in terms of size and complexity. Figure 6 gives the basic configuration of PSLV. It consists of four stages: (a) large solid motor with 139 t propellant loading, (b) earth storable liquid propellant main engine with 37 t propellant loading, (c) high performance solid propellant motor with composite motor case in upper stage, (d) final stage twin engines with 2.5 t liquid propellant loading. Some of the new technologies introduced in PSLV are engine gimbal control system for liquid propellant engines, flex-nozzle control system for solid propellant rocket motors, digital autopilot, closed loop guidance with three-axis guided injection employing a Redundant Strap down Inertial Navigation System (RESINS), and all digital avionics. A large and heavy mobile service tower facilitated launch pad assembly and check out.

All the PSLV systems functioned well in the first flight conducted in 1993, but the mission could not succeed in injecting the satellite into orbit, due to a software implementation error. This led to further strengthening of the ground simulations, additional testing of vehicle hardware and software systems to its widest probable range of variables, prior to launch.

Ten consecutive successful launches of PSLV have taken place between 1993 and 2007 with different types of

Figure 6. PSLV configuration.

missions and payloads. Starting with a payload of 800 kg in its first developmental flight, the capability of PSLV has been systematically and significantly improved to 1600 kg, in its eighth SSPO mission. These improvements have been made by incorporating improved propellant loading for solid as well as liquid stages, improved efficiency of the upper stage, and overall inert mass reduction by adopting composite structure, wherever feasible, optimization in strap-on firing sequence, miniaturization of avionics packages, etc. The capability of PSLV to carry 1000 kg to GTO has also been established with the launch of KALPANA-1. During its operational phase, additional technologies were developed to improve the payload capability of PSLV, its capability for multiple satellite missions, achieving different orbital missions in a single launch and making the vehicle a versatile platform for a host of missions such as LEO, SSPO and GTO.

The vehicle has provision to carry up to two microsatellites in the vehicle equipment bay or a possible mix of micro and minisatellites. The fifth mission of PSLV carried two microsatellites in a piggyback mode – KITSAT-3 of Korea and TUBSAT of Germany. Till date six such small spacecrafts have been launched successfully.

A dual launch adapter was developed to carry two satellites of around 500–600 kg. The PSLV-C7 successfully launched two such satellites Cartosat-2 and Space Capsule Recovery Experiment (SRE).

Figure 7 shows the mission profile of SRE. The objective of this experiment was to develop a spacecraft recoverable from orbit, as well as to gain experience in re-entry and recovery procedures required for the design of future reusable launch vehicles. Some of the important technologies developed include: (1) light weight and reusable thermal protection system, (2) aero-thermal structure design/analysis, (3) hypersonic aerothermodynamics, (4) navigation, guidance and control of reentry vehicle, (5) deceleration systems, (6) floating systems and recovery systems/operation, and (7) management of communication block out. All these technologies were validated in the recent successful recovery operation of SRE, precisely at the identified location, near the east coast of SHAR in Bay of Bengal.

ISRO has envisaged a number of variants of PSLV (Figure 8) to cater to different mission requirements. These configurations provide wide variations in payload capabilities ranging from 600 kg in LEO to 1900 kg in SSPO. Core-alone configuration without strap-on motors is designed to launch two satellites of 400 kg each into LEO. A three-stage configuration without strap-on motors and liquid stage will offer lower launch cost of 500 kg class of satellites into LEO.

GSLV

Concurrent with the development of PSLV, ISRO initiated the development of the GSLV for launching 2 t class of communication satellites into GTO. In order to improve the reliability and maximizing the payload capability, the GSLV is configured with only three stages, employing solid, liquid and cryogenic propulsion modules for its

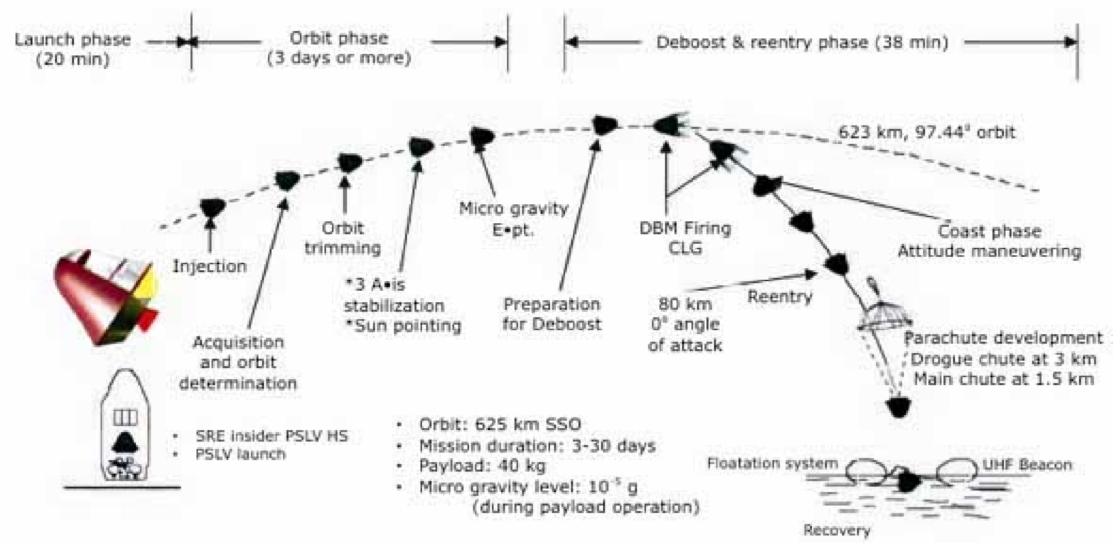


Figure 7. Space capsule recovery experiment mission profile.

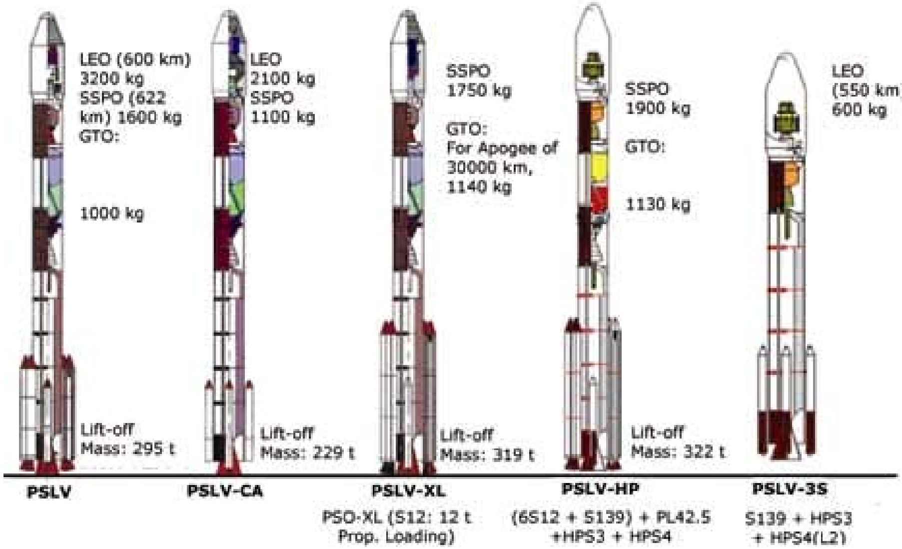


Figure 8. PSLV variants and payload capability.

stages, as shown in Figure 9. GSLV retains the pedigree of many subsystems used in PSLV, to get advantage of higher reliability, reduced development cost and time. The third stage of GSLV is cryo as it delivers higher specific impulse. Initial launches employed procured cryogenic stage from Russia. The appropriate technology developments have taken place to build the cryogenic stage indigenously with participation of Indian industry and the engine has been fully qualified and stage is expected to be ready within next one year.

The total avionics system for cryo stage for stage and propulsion control, such as mixture ratio and thrust regulation has been developed by ISRO and successfully tested in all three flights.

GSLV has successfully completed two developmental flights and two operational flight with communication satellites. Starting from the payload of 1540 kg for the first developmental flight, the payload is systematically improved to 2000 kg. The payload improvements were due to increase in propellant loading, high pressure engine for liquid stages, up-rating the cryogenic engine thrust, inert mass reduction, trajectory shaping, equipment mass optimization. Introduction of vehicle steering, utilizing the wind structure measured on the day of launch, quite close

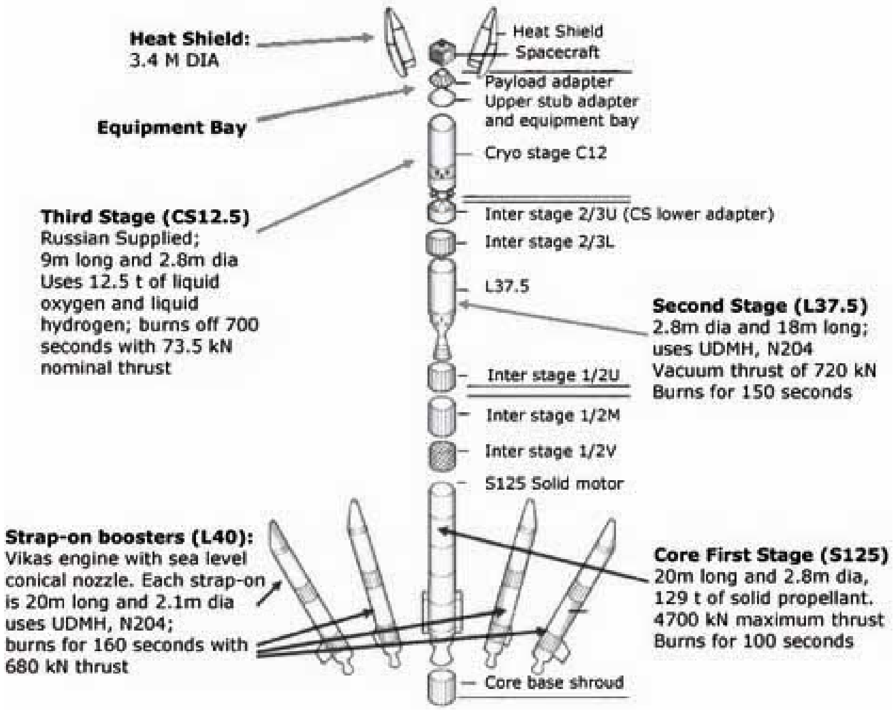


Figure 9. GSLV configuration.

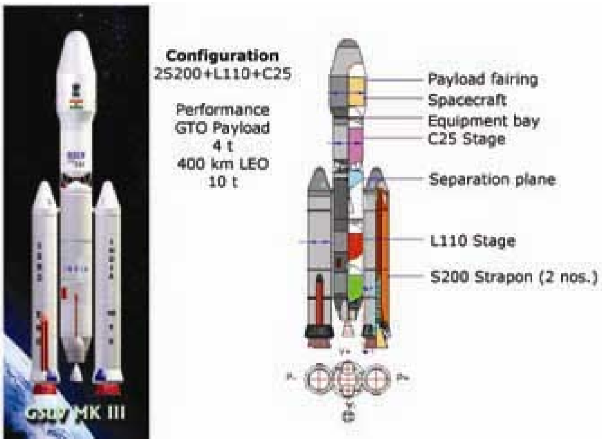


Figure 10. GSLV Mk-III configuration.

to the time of launch, has resulted in significant reduction of aerodynamic loads on the vehicle. This procedure and the measures to protect the vehicle from rain have made the vehicle an all-weather and all season launch vehicle.

GSLV is also being configured for launching navigation satellites into a 19,000 km circular orbit directly. The development of a Payload Assist Module (PAM-G) derived from the fourth stage of PSLV has been initiated. GSLV will launch the PAM-G along with the payload into an elliptic orbit. Subsequently, PAM-G will be used to circularize the orbit as part of launch vehicle mission.

GSLV Mk-III development

Development of GSLV Mk-III is initiated to meet the demands of launching of 4 t class of spacecraft, as well as to offer cost effective launch services. Figure 10 shows the configuration of GSLV Mk-III. It is a three-stage vehicle with two solid strap-on motors of 200 t propellant loading and liquid core of 110 t propellant loading with the clustering of two engines. The upper stage with a cryo engine has a propellant loading of 25 t. The overall characteristics of the stages are given in Table 2. Important technology developments among these are: (a) one of the large solid propellant boosters in the world, (b) a flex nozzle control system for the large solid booster, (c) liquid stage with clustered engines, (d) a high thrust cryo engine operating in gas generator cycle, (e) composite structures, (f) improved Failure Detection and Isolation (FDI) schemes in avionics and control systems, and (g) miniaturized avionics and Telemetry, Tracking and Command (TTC) packages with improved band-width. The first developmental flight of GSLV Mk-III is expected within a couple of years.

Highlights of technology developments for ISRO's launch vehicles

This section highlights the technology development aspects for each of the complex technologies used in launch vehicles.

Table 2. GSLV Mk-III: Propulsion modules

S-200	L-110	C-25
200 T HTPB propellant system Flex nozzle control Contoured nozzle M250 motor case High mass ratio	2 Vikas clustered HP engines UH25, N_2O_4 propellants 196 s burn duration	18 T engine in GG cycle 25 ton LOX/LH_2 2 burn capability 4 DEG gimballing Crown cone LOX tank

Solid propellant motors

Propulsion started with a tiny motor of 75 mm diameter with 2 s burn duration and 4 kg propellant mass, in 1967. The sounding rockets required solid motors with diameter ranging from 125 mm to 560 mm and propellant loading ranging from 14 kg to 700 kg. The booster stage of SLV-3 required motor of 1 m diameter with 9 t propellant loading. ASLV and PSLV required canted nozzle version as strap-on motor. RLV has demanded booster motor, having reduced burning rate. The core stage of PSLV and GSLV is a world-class solid motor of 2.8 m diameter with 139 t propellant loading and yielding 4700 kN peak thrust. Based on these experiences, a much bigger motor of 3.2 m diameter with 200 t propellant loading is under development for the GSLV Mk-III.

Advanced indigenous technologies have been incorporated in these input motors, namely, (i) Hydroxyl Terminated Poly Butadiene (HTPB), which yields solid propellant with high specific impulse and stable visco-elastic properties, (ii) Maraging steel, with very high strength-to-weight ratio for motor cases, (iii) Segmented motor case, with a number of sections, requiring for their fabrication advanced welding technologies and high precision machining, (iv) Joint-to-joint leak proof seals, and (v) Flex seal nozzles.

Earth storable liquid propellant engines

The liquid (at earth ambient temperatures) propellant engines of ISRO are of three categories: (1) Reaction Control System (RCS), for on-off type of operation, (2) pressure fed engines for main propulsion in upper stages, and (3) large turbo-pump fed engines for booster stages.

RCS thrusters are mainly used for control with fast on and off capability using mixed oxide of nitrogen (MON-3) and mono methyl hydrazine (MMH) as propellants. Both, bipropellant and monopropellant thrusters with different thrust ratings have been used in launch vehicles.

ISRO has also developed a 7.5 kN pressure-fed engine and PSLV fourth stage uses two of these engines, with common bulkhead tank and 2 t loading of propellants. This is a high performance propulsion stage, with specific impulse of 305 s used in the last stage of PSLV for guided injection. Similar motor is used for roll control of PSLV during the first stage flight. The PAM-G stage planned for GSLV is built around the same modules. Efforts are on to increase the specific impulse to 320 s by changing mixture ratio, increasing chamber pressure and increased nozzle area ratio.

The second stage of PSLV/GSLV and strap-on motors of GSLV used large turbo pump fed engines with N_2O_4 and unsymmetrical di-methyl hydrazine (UDMH) as propellants. It employs indigenous aluminum alloys and heavy-duty nozzle throat insert. The chamber pressure level has been increased to 58.5 bar with the increased propellant loading of 42 t. This stage provides specific impulse of 295 s.

The GSLV Mk-III is configured with L110 as core liquid stage with 110 t as propellant loading, 4 m diameter and overall length of 16 m. The stage is configured with two clustered engines equipped with contoured nozzles of area ratio 31, which gives specific impulse of 294 s. Two cylindrical monocoque tanks are made of aluminum alloy.

Cryogenic propulsion

The cryogenic stage used in GSLV is having a 7.5 t thrust with propellant loading of 12 t. The propellants are liquid oxygen (LOX), which boils at –182°C, and liquid hydrogen (LH2), which boils at –253°C. The system demands a number of metallic and non-metallic materials and ignitor compatible to cryo conditions. The cryogenic propulsion system requires many challenging and critical technologies relating to materials, material insulation and propellant feed system. The design and development of multilayer insulation system for the liquid hydrogen and liquid oxygen tankage has been successfully developed and used in GSLV cryogenic stage. Similarly high speed turbo pumps with special seals which prevent the accidental mixing of LH2 and LOH have been developed over the feed system.

Using the experience gained from the development of cryo stage for GSLV, a larger cryogenic upper stage is under development for the GSLV Mk-III. The stage has propellant tanks for storing a total of 27 t of LOX and LH2 and is powered by a single cryogenic engine, working on gas generator cycle developing a nominal thrust of 200 kN with an estimated vacuum specific impulse of 445 s.

Avionics systems

Navigation systems: After going through a series of steps involving realization of (1) stabilized platform inertial attitude reference system, using single degree of freedom Rate Integrating Gyroscope (RIG), (2) Stabilized Platform Inertial Navigation System (SPINS), using RIGs and navigation grade Servo Accelerometers (SA), ISRO has developed a RESINS using Dynamically Tuned Gyros (DTG). The DTGs and SAs are indigenous. Redundancy in gyros and accelerometers, and a failure detection and isolation methodology result in a highly reliable and accurate INS. The achieved orbital injection accuracies of PSLV and GSLV have been excellent. This has been achieved due to continuous improvement in the performance of RESINS.

Efforts are on to realize an INS using optical gyros and high performance accelerometers, and the system is being qualified for the GSLV Mk-III. An aided navigation system using miniature DTG-based INS, satellite navigation receiver and a Kalman filter has been successfully used for the recently completed first reentry mission (SRE) of ISRO.

Guidance systems: Open loop guidance was adopted for SLV-3, wherein no in-flight correction is made to overcome inherent deviations in the trajectory, due to a variety of dispersions in the actual performance of the vehicle. In order to achieve precise injection of the satellite in the desired orbit, a closed loop guidance scheme was introduced from ASLV onwards. In order to reduce loads on the vehicle structure during the atmospheric phase, the open loop steering program is followed in all the launch vehicles, whereas to achieve the mission accuracy, the closed loop guidance schemes are implemented in the exo-atmospheric phase of mission.

In PSLV, the velocity to be gained, Vg, guidance was improved to take care of large yaw manoeuvre during PS2 and PS3 phases. As PS4 is three-axis stabilized and guided through closed loop, a novel and robust, explicit guidance scheme was designed and implemented during its regime. To meet the improved accuracy requirements for GSLV missions and to handle range safety constraints and to achieve the GTO mission requirements, explicit scheme used for PSLV mission has been improved and implemented in GS2, whereas a totally new approach, based on flat earth guidance scheme was developed and implemented in cryo flight phase to achieve accuracy requirements of GTO. In GSLV Mk-III, a robust unified flat earth guidance scheme will be implemented. In another novel approach, the flat earth scheme of GSLV is suitably modified and implemented in reentry guidance of SRE mission.

Autopilot: In SLV-3, lower stages were controlled with analog autopilot, whereas the final stage was spin stabilized. Digital autopilot was used for the first time in ASLV. Active attitude stabilization and steering for the lower stages was carried out with the digital autopilot. But the last stage was spin stabilized. A number of techniques for taking the flexibility of the vehicle into account, such as the blending of signals from gyros located in different stages and using digital filters for shaping the loop response were introduced in ASLV.

The PSLV is three-axis stabilized from lift-off, till satellite injection. Destabilization through liquid sloshing was also considered in the design of the autopilot. With the increasing confidence on the wind statistics from the accumulated data, passive load relief was introduced through wind biasing. The important considerations in PSLV are dynamics of engine gimball control for the liquid second stage, in terms of modelling, slosh and engine dynamics and ensuring vehicle stability under complex control–structure–slosh interactions. The pogo phenomenon, leading to structure-propulsion interaction, was also modelled for the first time in PSLV and stability analysis of the structure–propulsion loop carried out to ensure pogo-free launch vehicle system. The smooth control transition requirements from lower stage to the next demanded the introduction of novel rate control scheme. The desired attitude and rate at various satellite injection instants were achieved through suitable autopilot designs, using Reaction Control Systems. The additional challenge in GSLV has been due to the control systems placed on the liquid strap on stages in the atmospheric phase, leading to the possibility of pitch-yaw-roll-slosh coupling.

To increase the robustness in the control loop, the control law design is improved to handle instantaneous vehicle attitude errors up to 360°. To avoid mathematical singularity, state-of-the-art control laws are designed based on quaternion approach, which is valid for all attitude angle manoeuvres. The reusable launch vehicle of future presents a totally new set of challenges, due to the dynamically changing atmospheric flight environment, the high degree of pitch-yaw-roll coupling and the multidisciplinary-input multidisciplinary-output nature of the system. The appropriate designs to solve these problems have been initiated through case studies.

Great strides have been made in streamlining the design and analysis procedures. A large number of programmes have been developed and integrated in-house into a user-friendly package for addressing specific design and analysis issues, which has helped to cut down the cycle time for design.

Control power plants: During the atmospheric phase of the flight, continuous control systems are preferred to prevent wide swings in attitude, inherent in the usage of on-off type. Thrust vector control or movable fins provide such control forces and moments. ISRO has achieved total self-reliance by developing (i) variable fluid flow actuators, for Secondary Injection Thrust Vector Control (SITVC), (ii) electro hydraulic actuators for fin tip control and gimballed engines, (iii) electromechanical actuators for deflecting the flex seal nozzles or gimballed engines. These actuators characterized by stall force, stroke length or range of angular deflection cover a wide range and are used in solid, liquid and cryo stages of all the satellite launch vehicles of ISRO.

Onboard computers: Starting from ASLV, Onboard digital Computers (OBCs) have been integral parts of avionics of the satellite launch vehicles of ISRO. OBC carried out, autopilot-related computations, stored programme and real time decision-based sequencing, navigation and closed loop guidance-related computation and pre-processing of telemetry data in real time and multi-task mode. Dual configuration of OBC provided redundancy in PSLV and GSLV and has higher memory capacity and is of distributed type with cross-strapped redundancy.

The present generation of OBC is having fixed point arithmetic and assembly language programing. In order to improve the limitations, the next generation of OBC is selected with a 32-bit processor with floating point arithmetic and Ada will be used as the language for flight software development. All software tools like Ada compiler, assembler and linker are developed and thus can support flight software development in Ada for processors.

Simulation test facility

ISRO has placed great reliance on hardware-in-loop simulation for validating and verifying the performance of onboard systems in general and those carrying out the NGC functions in particular.

The integrated simulation facility creates realistic environments to the onboard systems. Simulation test beds with multiple computers and real time operating software permit (i) onboard computers-in-loop simulations, (ii) aggregated hardware-in-loop simulations, and (iii) actuator-in-loop simulations. A typical facility established for this purpose is given in Figure 11. A major component is an Angular Motion Simulator (AMS) for onboard inertial navigation sensors and systems, which simulates the 3-axis angular motion of the vehicle during flight. ISRO has designed and built indigenously a high performance AMS to meet the simulation demands which is shown in Figure 12.

In autonomous simulation, thousands of runs are taken using digital computers to validate the algorithms design and overall system design. Once the system design is validated, the next phase starts with the testing of onboard software and hardware with actual processing elements and associated software. Extensive simulations are carried out under various environments and onboard systems, and with nominal and failure conditions to evaluate the system performance.

Software design tools

ISRO has developed a number of versatile software design tools such as design of trajectory, design and analysis of structures, analysis of orbital missions, thermal design, simulation of integrated 6-degrees-of-freedom trajectory, vehicle flexibility, slosh motion and nonlinear actuator dynamics, design and analysis of solid, liquid and cryo propulsion systems and so on.

Computational fluid dynamics

ISRO has been using two phase flows for internal flow problems in finite volume, finite element and element-free framework, space marching three-dimensional boundary layer code for solving heat flux and boundary layer profiles. Unsteady Navier–Stokes code in a body fitted framework (UNS3D) and Parallel Aerodynamic Simulator (PARAS-3D) are some of the major codes used for characterizing the aerodynamics of vehicle. The UNS3D code has finite rate chemistry capability and was used for atmospheric reentry flow field calculation. The PARAS-3D is a CFD

Figure 11. Actuator-in-loop simulation facility.

Figure 12. Angular motion simulator.

code, which can handle extremely complex geometries like complete aircraft with stores and the grid generation is interfaced with CAD output files. Various flow problems solved using this code are, lift off flow field of GSLV with all the strap-on firing, aerodynamic coefficients of PSLV, GSLV, GSLV Mk-III, RLV-TD, scramjet FTD and very good match with experiments is noticed.

Wind tunnel facilities

The wind tunnel facilities available in the country have been extensively used to generate data in all Mach number ranges including supersonic and hypersonic Mach numbers regime to finalize the configurations, aerodynamic characterization, structural and thermal designs, performance evaluation and control design for sounding rockets, SLV-3, ASLV, PSLV, GSLV, GSLV Mk-III as well as for the advanced R&D activities related to air-breathing propulsion, RLV and launch pad related studies. In addition to the conventional force and pressure measurement tests for the design of launch vehicles, special tests such as stage separation tests, aero-elastic tests, are also carried out for ensuring the clear stage separation and structural dynamic design of launch vehicles.

In order to meet the aerothermodynamics design data generation requirements of future reusable launch vehicles of ISRO, the limited test facilities in the country will be used to generate data in the hypersonic Mach number range of 6 to 12.

Launch complex facilities

ISRO has established launch complex at the Satish Dhawan Space Center (SDSC) to cater to the launching of a variety of launch vehicles at increasing frequency.

Mobile Service Tower (MST) and umbilical tower of the First Launch Pad (FLP) permit vertical assembly of a vehicle at launch pad. The FLP shown in Figure 13 can handle both PSLV and GSLV. Facility at FLP comprises launch pedestal, MST and an Umbilical Tower (UT). The tower houses all the fluid lines for propulsion stage servicing. MST is a 85 m tall building fabricated out of structural steel weighing 2500 t provides environmental protection and access to launch vehicle during integration, checks and servicing. A cryo arm is provided for servicing the cryo stage of GSLV. After completion of vehicle build-up, checks, propellant filling and count down activities, the MST is moved back during launch.

In order to service increased frequency of launches and to accommodate larger launch vehicle, like GSLV Mk-III, ISRO has built a larger Second Launch Pad (SLP). It comprises a Vehicle Assembly Building (VAB) for vehicle build up on a Mobile Launch Pedestal (MLP) and a fixed UT for servicing and checkouts. After stacking at VAB, the vehicle is moved to UT about a km away (Figure 14), where the servicing of the stages, such as, pyro arming and checks are carried out. VAB can withstand cyclonic winds and seismic disturbances. The SLP facility can cater to the requirement of PSLV, GSLV and GSLV Mk-III type vehicles.

Checkout evaluation for launch vehicles

A computerized checkout system for servicing of all launch vehicles during the prelaunch operations and count down are generally distributed systems, located at the launch control center, a safe distance away from the launch pad. All the command/data lines to and from the vehicle are interfaced with the vehicle. It checks hundreds of voltages, temperatures and pressures, in scores of subsystems of the vehicle, basically to check and record that they are within the preset limits, signifying readiness of the vehicle to carry out the mission. It also participates in the initializing of the INS.

The Automatic Launch Processing System is based on distributed concept, with a remote check out terminal room. Safety features are incorporated to ensure protect-

Figure 13. PSLV on first launch pad.

ion of onboard systems, even in the case of ground system malfunction. The Automatic Launch Sequence (ALS) is executed from the host computer in synchronization with the countdown time from T-10 min onwards to validate entire vehicle parameters and generates a hold, in case of malfunction of any of the vital parameters.

Technologies for advanced launch vehicles

The Indian launch vehicle programme constantly strives to improve technologies to meet the long-term needs. Currently identified technologies are realization of: (1) large cryogenic and semi-cryogenic boosters, (2) air breathing propulsion, and (3) building blocks for RLV. High specific impulse propellants, high strength materials like Al–Li alloy, metal matrix composites, supersonic and hypersonic wind tunnel facilities, CFD tools for internal and external flow field analysis, smart actuator system, robotics, fault-tolerant onboard computers and advanced navigation sensors are some of the elements of advanced technologies. Further, in order to explore new frontiers in science and technology, studies for manned mission are also on the agenda.

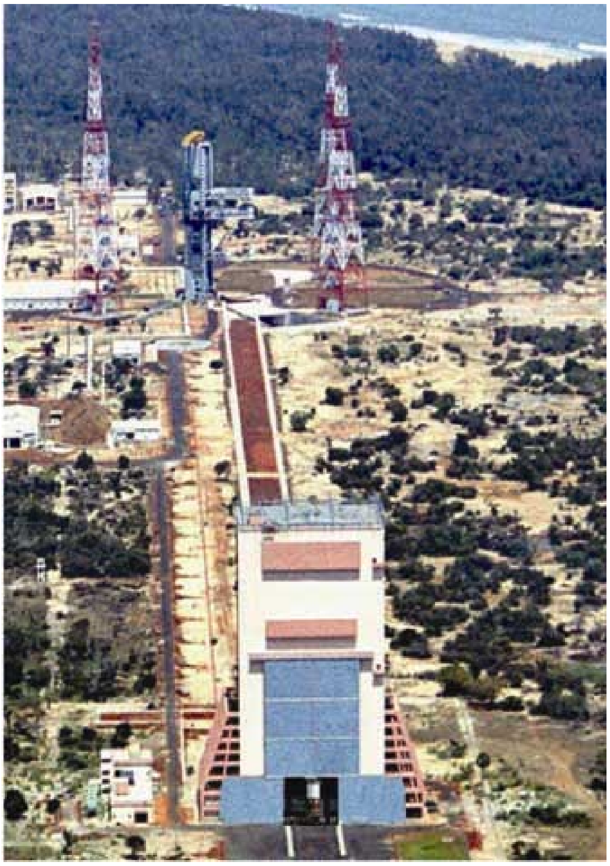


Figure 14. Second launch pad, vehicle assembly building and umbilical tower.

Air breathing propulsion

Reducing requirement of propellant is fundamental to low cost access to space, as propellant forms about 85% of launch vehicle mass out of which bulk of the propellant is oxidizer. In air breathing propulsion, the entire requirement of oxidizer need not be carried, along with the vehicle.

ISRO has initiated the development of Dual Mode Ram Jet (DMRJ) based on the detailed studies of the options available. VSSC has since demonstrated successfully a stable supersonic combustion through a series of ground tests for an equivalent flight Mach number of two to ten. Fuel injection, mixing, ignition and flame holding as air travels at speeds greater than one kilometer per second within combustion chamber is often equated to 'lighting a candle in hurricane'. Theoretical studies including extensive use of CFD tools have supported design and analysis.

DMRJ-FTD is conceived as a simple and cost effective flight demonstrator vehicle, as it uses an existing sounding rocket as a carrier. It is planned to flight test a scramjet engine in flight Mach number range of 6–7. Realization of the vehicle and engine is making rapid progress. Also, a major test facility capable of up to four times the flow rates of the current scramjet test programme is coming up. This scramjet propulsion test facility can test and evaluate scramjet combustors up to flight Mach number eight.

Reusable launch vehicle

The RLV aims to bring down the cost of placing a kg of payload into orbit by an order, through reuse of the vehicle systems. For an Expendable Launch Vehicle (ELV), the cost of launching one kg to LEO is approximately $10,000–15,000. This is due to the fact that 67% of the ELV cost is that of its hardware, which is expended. Also, for an ELV the payload fraction is approximately 1–2%. In an RLV, attempts will be made to reuse all systems. With an air-breathing engine as first stage the payload fraction can be improved to as high as 4%. Application of these technologies would bring down the launch cost by an order of magnitude.

Extensive studies on configuration options for Single Stage to Orbit (SSTO)/Two Stage to Orbit (TSTO) have concluded that with the current levels of technologies of propulsion and materials only a TSTO is feasible. Towards realizing the TSTO and associated new technologies, ISRO has undertaken the development of a Reusable Launch Vehicle Technology Demonstrator.

It has a wing-body configuration and will be capable of flying in a corridor similar to that of the first stage of a TSTO-RLV. Actually, it is a scaled down version of the first stage of TSTO-RLV. Its return flight will have high angles of attack in the upper atmosphere, in order to reduce

Figure 15. Reusable launch vehicle – new technologies.

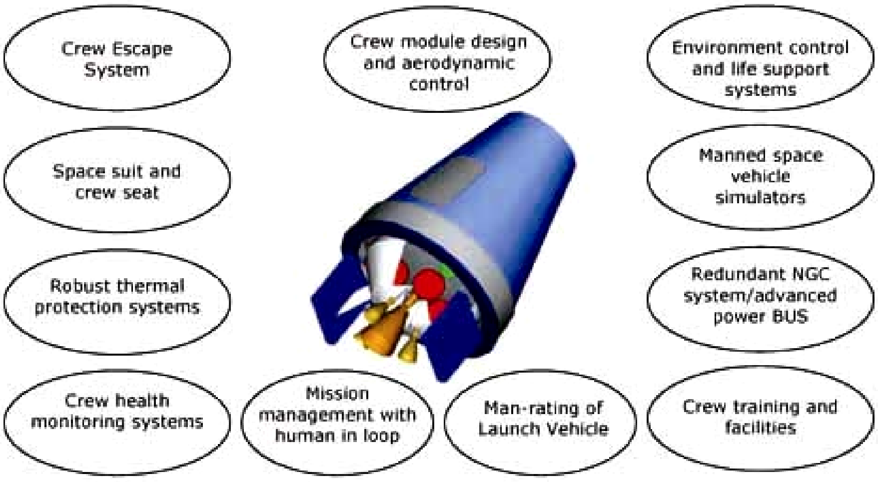


Figure 16. Manned mission – new technologies.

the kinetic energy, before reaching lower altitudes. It will use aerodynamic controls during the atmospheric flight. The entire flight will be autonomous, similar to that of the first stage of the TSTO-RLV. This RLV-TD will be designed using available technologies to start with, and progressively will adopt and test new technologies. In a brief period of about 3–6 years, RLV-TD will prove, in a cost effective way, advanced technologies that are required for taking decisions regarding the route to be followed for design and development of the full scale TSTO-RLV.

Some of the technologies to be perfected through these trials are related to hypersonic aerothermodynamics, reusable thermal protection systems, design of reusable structures including control surfaces, autonomous flight management, and NGC for re-entry and controlled descent, in-flight health monitoring system, and abort systems are depicted in Figure 15.

Indian manned space programme

The Indian space programme after crossing several major milestones, including development and operationalization of launch vehicles, satellites for scientific research and applications as well as exploiting the vantage point of space for a variety of uses of relevance to national development is now poised to explore newer dimensions, as a part of long term goal. Such goals are not only meant to retain the pre-eminence of India in space, but also will ensure India's rightful role in other emerging areas of space, such as planetary exploration and human presence in space. Besides carrying forward the policy of a level of self-reliance, these initiatives will also facilitate India's ability to participate on equal partnership basis, in many international programmes. It is against this backdrop that ISRO has embarked in the recent past, on studying different options for a manned space mission.

In the first instance, the Indian manned space Programme is envisaged as a national effort to develop a fully autonomous orbital vehicle, using existing GSLV vehicle with necessary modifications for man rating. The studies were presented in different technical forums and finally presented to a National Technical Committee of about 80 scientists from all over India. There was a general consensus to undertake this mission at the earliest.

Compared to an unmanned space vehicle, a host of new technologies will be required to accomplish such a complex programme. Various key technologies required for the manned mission have been identified in the preliminary studies. In this context, a host of new systems needs to be designed and developed. These include crew module, service module, launch escape systems, environmental control and life support systems and avionics system. Figure 16 shows the different elements of a manned mission envisaged by ISRO.

Conclusions

From a modest entry to space arena, India has made significant progress in launch vehicle technologies with end-to-end visualization of the entire system, and sequence of activities. These include multi-disciplinary technology development, setting up of appropriate research and development laboratories, establishing critical manufacturing facilities at industry, developing elaborate quality assurance protocol and test and evaluation procedure, and launch operations. Presently, India has PSLV and GSLV, as operational satellite launch vehicles, capable of launching on demand, both remote sensing and communication satellites into prescribed orbits, with high precision. They provide diverse space services to the country, as visualized by the founding fathers of the Indian space programme. This paper has attempted to present the launch vehicle requirements, vehicle systems, required technologies, subsystem design aspects and launch process. The launch vehicle technologies have gone through an evolution phase to reach the present state of maturity. The Rohini sounding rockets, the SLV-3 and the ASLV development programmes provided the learning and experimental stage of the technology leading to total self-reliance in the design development and realization of materials, components and sub systems. This has helped in a major way in the realization of operational launch vehicle PSLV and GSLV which have proved to be reliable and robust platforms for launching remote sensing, communication and commercial satellites. The technology developments being carried out for enhanced payload capabilities as well as future technology demonstration studies for advanced space transportation systems are also included.

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1. Gupta, S. C., *Growing Rocket Systems and the Team*, Prism Books, Bangalore, 2006.
2. Gupta, S. C., Growth of capabilities of India's launch vehicles. *Curr. Sci.*, 1995, **68**, 687–691.
3. Madhavan Nair, G., Four decades of Indian launch vehicle technology. *J. Aerospace Sci. Technol.*, 2004, **56**, 85–92.
4. Narayana Moorthi, D., Indian launch vehicle programme. *Space Forum*, 2005, **5**, 3.
5. Gupta, S. C. and Suresh, B. N., *Development of Navigation Guidance and Control Technology for Indian Launch Vehicles in Developments in Fluid Mechanics and Space Technology.* Dedicated to Satish Dhawan (eds Narasimha, R. and Abdul Kalam, A. P. J.), Indian Academy of Sciences, Bangalore, 1988.
6. Rao, U. R., Gupta, S. C., Madhavan Nair, G. and Narayana Moorthi, D., PSLV-D1 mission. *Curr. Sci.*, 1993, **65**, 522–528.