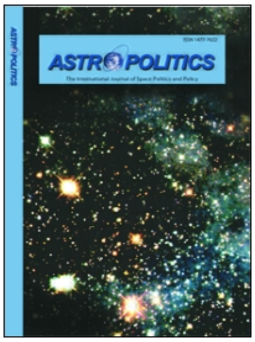

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ABSTRACT

The Indian space program is a spacefaring success story with demonstrated capability in the design and building of application and scientific satellites, and the means to launch them into desired orbits. The end-to-end mission planning and execution capability comes with a high emphasis on self-reliance. Sounding rockets and small satellite launch vehicles provided the initial experience base for India. This experience was consolidated and applied to realize larger satellite launch vehicles. While many of the launch vehicle technologies were indigenously developed, the foreign acquisition of liquid propulsion technologies did help in catalyzing the development efforts. In this case, launch vehicle concept studies showed the inevitability of using a cryogenic upper stage for geosynchronous Earth orbit missions, which proved to be difficult technically and encountered substantial delays, given the geopolitical situation. However, launch capability matured from development to operational phases, and today, India's Polar Satellite Launch Vehicle and Geosynchronous Satellite Launch Vehicle are in a position to meet both domestic and international market demands.

The Indian space program is over 50 years old and has grown in capability and capacity for both domestic and international needs. From its inception, it has been a civilian program, not spun off from the military missile program as in some spacefaring countries. In fact, the Indian missile program—Integrated Guided Missile Development Program (IGMDP)—came into being in 1985, which is much later than the civilian program. When IGMDP was announced, India had already flown its first satellite launch vehicle (SLV-3), and initiated the SLV continuation (SLV-C) program and the Augmented Satellite Launch Vehicle (ASLV).

Sounding rockets and the SLV-3 provided the initial learning ground for vehicle technologies; lessons from vehicle flight failures helped in consolidation of design practices; and a strong and committed leadership provided pathways for the development and realization of launch vehicles. Today, the Polar Satellite Launch Vehicle (PSLV) is a success with more than 30 consecutive flights; the Geosynchronous Launch Vehicle (GSLV) is nearing

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completion of development trials and the flight test of a heavier version of GSLV is also planned in 2016. The Indian space program caters to international clientele on commercial terms. This article describes the successes and travails of the Indian launch vehicle program.

The space program in India commenced with the launch of a Nike-Apache sounding rocket on 21 November 1963 from the coastal village of Thumba, near the city of Trivandrum (now Thiruvananthapuram), the capital of the state of Kerala. Thumba's location, close to the magnetic equator, provided a unique opportunity for studying an equatorial electrojet, leading to the establishment of the Thumba Equatorial Rocket Launching Station (TERLS) with international cooperation. Besides the U.S.-supplied Nike-Apache, the Judi-Dart from the United States and the Centaure provided by France were flown from Thumba in the early years. These sounding rockets were all solid propellant-based, fin-stabilized systems. The sounding rockets flown in later years, like Dragon (France), ARCAS (United States), and Skua and Petrel (United Kingdom), were also solid propellant-based. This experience with different sounding rockets provided India some familiarity with aspects of handling, integration, payload preparation, instrumentation, launch operation, data collection, and analysis.

Launch vehicle concept studies

Vikram Sarabhai, the founder of the Indian space program, had ideas and thoughts on the role space can play in India's development. The experience to be gained with the sounding rockets would provide the initial steps to the overall aims and objectives of the space program. The development of satellites and launching them into orbit formed part of his vision. He established the Space Science and Technology Center (SSTC) and co-located it with TERLS. Sarabhai's main objective of establishing SSTC was to develop all rocket and SLV-related technologies. SSTC came into being in 1965–1966. A core group of engineers, some of whom had just finished their doctorates from U.S. universities and some who had done their engineering studies in India, were recruited for this purpose and trained for short periods at the Institute of Space and Aeronautical Sciences (ISAS) in Japan. This core group was to lead the indigenous rocket development at SSTC.

By 1967, the sounding rocket flight activity had picked up at TERLS; the facility for processing propellant and manufacture of hardware for the Centaure[1] sounding rocket was close to commissioning; the SSTC team had started development work in makeshift laboratories; and, at the same time, plans had been drawn up for the basic infrastructure required for design, development, and testing. Sarabhai felt that it was also time to challenge the SSTC team to think innovatively and come up with a conceptual design for a small satellite launch vehicle. Sarabhai's thought process was ahead of its time. While communication satellites in the United States were in the initial phase of operationalization, Sarabhai was foreseeing the potential of harnessing space for a variety of societal applications. By 1968, he had asked his senior colleague to look for a launch site on India's east coast[2] from where communication satellites could be launched.

The aerodynamics team at SSTC began working on this and, towards the end of 1967, they made a presentation to the Rohini Consultative Committee.[3] A group of young engineers, including the author, had also independently made an assessment essentially based on empirical charts provided in a design handbook.[4] The design produced by the aerodynamics team appeared too optimistic with regard to payload and performance in comparison with the empirical approach, and the issue came in for intense discussion. The outcome of the meeting was to reexamine the design and rework it in more rigorous detail. The design objective given was that the vehicle should be capable of placing 30–40 kg of payload in a 400 km circular orbit. The satellite life specified was 100 days and a time period of five years was suggested for the realization of the vehicle. A team of engineers, led by Y. Janardana Rao, after studying a few options suggested that the development be centered on a four-stage vehicle labeled SLV-3. All four stages of the vehicle employed solid propellants.

The reason for the choice of solid propellant stages was apparent. The Indian trainees were given an exposure to solid propellant rockets; further, all of the sounding rockets flown from Thumba used solid propellants and this also provided a level of design and operations familiarity; and both Japan and the United States had operational launch vehicles based on solid propellant rockets. In the late 1960s, ISAS had configured Lambda 4S (L4S) and Mu satellite launch vehicles using solid propellant stages. L4S was a small launcher and the Osumi satellite it had placed in orbit was only 12 kg. The Mu[5] rocket and its variants provided higher payload capability, but it was a five-stage vehicle and employed strap-on boosters. To fashion the Indian launch vehicle on this concept, was not feasible for a first attempt for reasons of design simplicity and reliability. The other all-solid propelled launch vehicle in operation was the Solid Controlled Orbital Utility Test system (SCOUT),[6] designed by NASA Langley and built by Chance Vought Aircraft. The SCOUT presented a better model for India to emulate.[7]

Evolution of the satellite launch vehicle project

The stages of a launch vehicle provide the required burnout velocity in increments, with the final stage providing the final increment to inject the satellite into orbit. To perform this function, the SLV has many subsystems and parts, each of which must carry out the assigned tasks as per a required schedule. The experience at that time in SSTC was in aerodynamically fin-stabilized rockets with no active control. Development of new technology was called for to realize the SLV. Some existing technologies, like the solid propellant rocket motor, could be scaled up, but most of the technology requirements were essentially new and involved learning on the job. Hence, learning the technology, scaling, establishing facilities, and developing vendors capable of supplying materials, products, and services with low quantity demand but high on quality all had to be concurrently accomplished in a timely manner with little or no room for error. Under these circumstances, the SLV development demonstrated a significant achievement for India.

The SLV-3 compared with SCOUT in terms of the number of stages and some features, but with a more modest capability. The overall length and diameter of SCOUT were 23 m and 1.14 m, respectively. The vehicle weighed 22 t at lift-off. The corresponding numbers for SLV-3 were 22 m, 1.0 m, and 17 t. The SCOUT at the design stage in 1960 was capable of lofting a 59 kg satellite into low Earth orbit (LEO) and, over time, this capability was increased to 208 kg. SLV-3 was designed to loft a satellite of 40 kg into LEO. There were also differences in the type of propellants, structures, and control systems.

The technical and schedule requirements were demanding, but the development teams were more than willing to take up the challenge. The SLV-3 project, in particular, was a preparatory and learning process for the future. Sarabhai was a student of management[8] and believed that individual subsystem teams, set in a competitive environment, were likely to be more successful in achieving the required outcomes. The principal subsystems of SLV-3 were made into projects with a designated project director tasked to develop that subsystem. Consequently, nine project directors were designated to develop the launch vehicle systems.[9] In addition, there were separate project directors for the overall vehicle coordination and for the satellite integration.

There were both advantages and disadvantages of dividing up the responsibilities among a number of independent project managers. It fostered competition and each manager strived to bring out the best design for the subsystem he was responsible for. The disadvantage was the absence of standard design approaches, pursuit of more than one development option without clarity on closure of options in favor of the best one, and the absence of interface management mechanisms. This last point is important, as a design shortfall or change in one stage can have impact on the performance and on other subsystems, and needs to be studied in real time—the coordinating team had to evolve a mechanism towards this, a task rendered more difficult as designs, product development, processes, fabrication, testing requirements, and facility establishment were all happening simultaneously.

Credit must be given to the design teams as they had to initiate the design of a subsystem based on specifications yet to be realized, and keep flexibility in design to accommodate for shortfalls in the realized properties and specifications. For example, the grain design and internal ballistics of the rocket motor had to be carried out when the propellant system was itself under development, and there were uncertainties in the final realized properties. With mutual discussion, arguments, and compromises, initial properties were assumed for starting the design. These properties became the specifications for the propellant team to evolve an appropriate composition. The schedule did not allow sequential operation and the downstream operations with long lead times were taken up concurrently. These operations included building up the facility (civil works, electrical works, and installation of equipment), and fabrication of fixtures required for handling, propellant casting, curing, and inspection operations. This was the case with all of the major subsystems with iteration involved between requirement and achieved development result. The pioneering design technologies that were developed with the SLV program are highlighted in Table 1.

Sarabhai passed away in December 1971, and after an interim arrangement, the responsibility for the space program was vested with Satish Dhawan. Dhawan, a respected aeronautical engineer, was the director of the prestigious and foremost science and engineering academic institution —the Indian Institute of Science. While maintaining continuity of the Sarabhai space vision, Dhawan introduced organizational and managerial changes, which were conducive to meeting the objectives of the space program in a more accountable and objective fashion. The various stage and subsystem projects were replaced as an integrated vehicle development project and placed under a single leadership. A.P.J. Abdul Kalam, who in later years led the country's missile development program and the Defense

Table 1. Design Technologies Developed in the Satellite Launch Vehicle Program.

Motor case	Low alloy steel for the lower stages to be fabricated by industry; glass fiber-reinforced plastic for the upper stages using filament winding machine developed indigenously.
Propellant	Composite propellant using imported binder for the lower stages; composite propellant using indigenously developed binder for the upper stages.
Airframe	Light alloy structure fabricated by industry.
Control system	Secondary injection thrust vector control (SITVC) and fin tip control system for the booster stage; bipropellant reaction control system (RCS) for the second stage; monopropellant reaction control system for the third stage; spin-up motors for the fourth stage and satellite.[10]
Navigation & Guidance system	Inertial navigation system and the necessary sensors. *Due to weight and volume constraints, an open loop guidance system was incorporated. The result was that a precise orbit would not be attained, but an orbit guaranteeing the specified life of 100 days could be managed.*
Thermal protection system	Thermal protection against aerodynamic heating for the payload fairing, parts of the airframe; thermal protection against combustion gases in the motor chamber and nozzle.
Ordnance systems	Devices for stage ignition, separation, fairing separation, and other staging events. In addition, pyro-actuated devices were also developed. The tele-command destruct system was another feature.
Avionics	Onboard computer, telemetry, tele-command.

Research and Development Organization (DRDO) and also became the president of India, was chosen to lead the SLV-3 development.

SLV-3 was an experience in both technology development and project management. Technology development initially took place in an unorganized fashion and in many instances there was more than one agency involved in a particular system development. One of the first exercises by SLV management was to ensure that everyone contributed to the project positively. Towards this end, compromises were struck and development tasks were distributed among the players.[11] At the culmination of the SLV-3 project, valuable experiences with launch vehicle technologies, support requirements, laboratories, facilities and infrastructure, and development of the launch complex on the east coast of India were all realized. The positive and major fallouts of SLV-3 development included a cadre of competent designers and subsystem developers; mission planning and implementation capability; practice of design reviews involving external experts at critical project milestones; infrastructure, process facilities, test facilities, integration facilities; safety requirements for handling and processing of hazardous materials; and the development of an industry support system.

The first flight of SLV-3 on 10 August 1979 ended in a failure. The cause was a stuck valve in the second-stage Reaction Control System (RCS), resulting in the draining out of the RCS propellant and loss of control of the vehicle. Even though the flight was a failure, it gave valuable insights into the performance of the other vehicle subsystems. The problem was identified and rectified and the subsequent flight in July 1980 performed well. After the development flights, a SLV continuation (SLV-C) project was envisaged.

Augmented satellite launch vehicle

Although SLV-3 served as a crucial learning experience in technology development, technological know-how, and project management, its payload capability at 40 kg was inadequate. Meaningful scientific satellites at the time were in the order of 130 to 150 kg. Studies showed that the addition of two motors on the SLV booster stage as strap-ons could achieve this class of payload. Thus, ASLV came into being. ASLV used technology modules developed for the SLV, incorporated improvements in some of the subsystems, and essentially converted SLV-3 from a four-stage to a five-stage system by using the strap-ons as an additional stage. The addition of the two strap-ons increased the mass at lift-off to 40 t and allowed the incorporation of closed-loop guidance. Other key modifications entailed the incorporation of canted nozzles for the strap-ons so that the thrust vector passed through close to the vehicle center of gravity; increasing the energetics in the lower-stage propellants; process improvements to obtain close performance tolerance of the strap-ons; improved fourth-stage motor[12] with increased propellant mass and reduced inert mass; and heat shield to accommodate a larger payload.

Though ASLV borrowed technologies from SLV-3, its mission was complicated—the five stages of the vehicle demanded the management of more events and the dynamic pressure at the end of the booster stage burn was rather high. In this high dynamic pressure regime, events like burnout of the strap-ons, ignition of the core first stage, separation of the strap-ons, and transfer of control to the first stage had to happen sequentially and within close intervals of each other. The first flight in March 1987 ended in failure, as the first stage ignition did not take place. The reason could not be exactly identified, but it was attributed to the failure of the ignition chain in the flight environment. After incorporating changes adding to the reliability of the ignition chain, a second flight test took place in July 1988. This flight also ended in failure due to structural break-up of the vehicle. The failure investigation discovered major design shortcomings, such as inadequate control during transition from the strap-ons to the first-stage control and in the design of the autopilot, which added to the problem.

A number of corrective steps were introduced to overcome the design inadequacies involving modifications for a less demanding flight regime, and more intensive simulation studies. Specific design changes included modification to the strap-on motor propulsion design to reduce the maximum thrust at burnout and reduce the dynamic pressure; introduction of fins on the core vehicle to aid stability and bring down the demand on control force; and software changes to aid real-time decision (relating to strap-on burnout time detection). With these changes, the third flight of ASLV on 20 May 1992 was successful. The vehicle carried the 106 kg Stretched Rohini Satellite Series-C (SROSS-C) satellite with payloads for scientific experiments. Due to an anomaly in the imparted spin rate, the satellite was placed in a lower orbit of 267 km by 391 km and had a short lifespan of two months. The subsequent flight of ASLV in September 1994 met all of the flight and orbital criteria and was a complete success.

Polar satellite launch vehicle

By the 1980s, ISRO successfully built and launched experimental communication and remote sensing satellites, and put in place mechanisms to design and develop such application satellites. Consequently, ISRO started to seriously consider development of launch vehicles capable of orbiting application satellites. The capabilities of both SLV and ASLV were inadequate. Additionally, it was realized that development of liquid propulsion systems based on storable and cryogenic propellants would be essential for realizing higher-capability launch vehicles. The SLV and ASLV employed liquid propulsion systems for control purposes in the second and third stages. These were low-thrust, pressure-fed bipropellant and monopropellant systems. Obviously, more advanced systems were needed.

The European Space Agency (ESA) had embarked on the development of the Ariane 4 launch vehicle in the 1970s. The French Company Société Européenne de Propulsion (SEP) was tasked with the development of the Viking engine, which powered the booster and the second stage of Ariane 4. In 1974, ISRO and SEP signed an agreement[13] for the transfer of technology of the Viking engine and pressure transducers. The agreement was unique in the sense that no transfer of funds was involved. ISRO, in turn, had to fabricate and supply 7000 transducers to SEP and also provide the services of ISRO engineers equivalent to 100 man-years. This technology acquisition helped ISRO leapfrog in realization of liquid engine development.

SEP at that time was also developing HM-7, a cryogenic engine for the third stage of Ariane 4. SEP did indicate its willingness to share the technology with ISRO at a nominal price. The offer was not accepted due to ISRO's constraints in simultaneously managing multiple vehicle technology development, and on manpower and finance limitations. In hindsight, this was a major opportunity missed, as technology denial and consequent necessity to initiate indigenous development on cryogenic engines proved to be expensive in terms of time lost at nearly two decades.

Of note is that, just prior to the signing of the agreement with SEP, a study team had been formed to study possible future launch vehicle scenarios for India. The guideline set for the study team was the capability to place an 800 kg satellite in geosynchronous orbit (GEO).[14] The study team recommendation was for a vehicle employing liquid propulsion systems using storable propellants for the lower stages and cryogenic propellant for the upper stage.

Another study team was formed in the late 1970s to study launch vehicle configurations suitable for placing indigenously built remote sensing satellites.[15] This committee studied various configurations and the emphasis was on solid propellant stages based on the experience thus far, but all configurations featured one liquid-propelled stage. The vehicle sizing was initially done for placing a 600 kg remote sensing satellite in 550 km orbit. However, the satellite team felt that 600 kg posed a major development constraint and the reference specifications were revised to 1000 kg satellite in 900 km polar orbit[16] and the vehicle (booster mainly) had to be resized. The configuration suggested by the committee was a four-stage vehicle with the second stage employing liquid propulsion and the remaining stages based on solid propulsion. The configurations employed solid propellant strap-ons also, but there was divergence in the committee on the size of the strap-ons to be used. An Office Order of Chairman ISRO stipulating the major features of the configuration decided the matter.[17] The Polar Satellite Launch Vehicle (PSLV), as the vehicle was christened, was 2.8 m in diameter at the base and consisted of four stages; the second stage was liquid based on the Vikas (Indian name for the indigenously built Viking engine), and there were two more solid upper stages, and six strap-ons of one m diameter derived from the SLV-3 first stage. Subsequently, from considerations of mission requirements of precise velocity cut-off, the top solid-propellant stage was replaced with a liquid-propellant stage.

If SLV and ASLV brought home the core technologies and mission management of launch vehicles, the development of PSLV witnessed the nucleation of a number of technologies of a higher order of magnitude. PSLV was to fly operational satellite systems, which required accurate orbital injection. There was more attention to simulation, modeling, analysis, and reliability. Single point failures had to be identified and associated systems appropriately designed to minimize the risk of failure. New facilities and infrastructure had to be put in place, new industries identified, and project management had to take into account progress and readiness of these at the appropriate times to keep the project schedules under control. In a development project like PSLV, where a number of technologies are being conceived and brought to fruition for the first time, design, process, and performance anomalies are bound to arise from time to time. The management of these in order to contain the schedule slippage becomes quite an issue. Added to these are issues brought about by geopolitics, especially the Missile Technology Control Regime (MTCR) of 1987.

As a result of the coming into being of the MTCR, procurement of critical materials, components, devices, and equipment became difficult even for the civilian space program. ISRO had to either look for alternate sources or take steps to produce the technologies indigenously. Satish Dhawan took over the chairmanship of ISRO in 1972 and one of the guidelines given by him was to involve Indian industry in the space system development work. Industries were treated as partners in development and referred to as work centers. Vikram Sarabhai Space Center, the launch vehicle development center, had an active policy of developing products and processes at the lab level, scaling them up to pilot plant level, and then locating an industry and transferring the technology to them. Most hardware materials were available in the country or could be sourced from non-U.S. sources. Fabrication capability was available in the country as well, and as such, the MTCR did not seriously impact the development of the PSLV.[18]

A number of important technological milestones were realized with the PSLV. Some of these are highlighted in the following:

- The first stage motor with 125 t of solid propellant was among the largest in the world. When it was tested in 1989, it was the third largest.
- The third stage motor at two m diameter was one of the largest composite case upper-stage motors.

- Through material selection and screening as well as process control, the performance of the six strap-on motors could be consistently obtained within narrow tolerance bands.[19]
- From SEP, the technology of the Viking engine was procured. Realizing the stage including the propellant tanks, the engine gimballing mechanism, the water tank, integration, and testing were major achievements. Indigenous development of the silica-phenolic throat insert was an important breakthrough as well.
- The fourth stage employed titanium tanks and a radiative cooled nozzle extension made of columbium alloy.
- Guidance algorithms.
- Diversity of control systems, like secondary injection thrust vector control for the first stage, gimbaled engine for the second and fourth stages, gimbaled nozzle for the third stage, and separate roll control systems.
- Strap-down inertial navigation system.
- Redundant on-board computer system to cater to large computation requirements.
- Avionics system.
- Ordnance and staging systems.
- Mission management.

The maiden mission of PSLV took place on 20 September 1993. The performance of the vehicle was normal until the second stage and initiation of the third stage, after which things started going wrong. Failure analysis showed that unduly large disturbances were created in the second and third stages[20]: early gimbal nulling, as programmed during the second stage tail-off, created disturbances, which were uncorrected; and non-ignition of two of the four retro rockets during the second-stage separation resulted in collision between the separated second and third stages, thus aggravating the disturbance on the third stage before ignition. The third-stage control system should have corrected the disturbance, but an implementation error in the pitch control loop of the digital autopilot software in the guidance and control processor prevented this. This problem occurs when the control command exceeds the specified maximum value, resulting in what is called "overflow error."

After corrections, the PSLV was successfully test flown in October 1994. Since then, PSLV has had a string of continuous successful launches and the launch of June 2016 was the thirty-fifth in the series. Also, continuous improvements in the stage propulsion system and reduction in structural mass boosted the PSLV capability of 1000 kg in the D2 flight to 1750 kg with extended length strap-on motors. For lighter payloads, PSLV can be flown without any strap-ons, a core alone version, with a payload of 1350 kg.[21]

PSLV has also been used for missions other than polar orbital injection. Notable among these are the GEO transfer orbit missions for the meteorological satellite *Kalpana* and the GEO communication satellite GSAT-12; space capsule recovery experiment (SRE); LEO missions involving commercial and scientific missions; lunar (*Chandrayaan*) and Mars (*Mangalyaan*) orbiter missions; navigation satellite missions (Indian Regional Navigation Satellite System); and scientific satellites, like Astrosat. With its proven reliability and versatility, PSLV rightly is referred to as ISRO's workhorse launcher.

Geosynchronous satellite launch vehicle

The Indian space program, from its early days, has been aware of the potential of communication satellites for the benefit of the Indian population. As early as 1975, Satellite Instructional Experiment (SITE) was conceived. In a fruitful partnership of India's need with U.S. technology, NASA's first direct broadcasting satellite was used to beam television programs relating to health, agriculture, and development to 2400 remote villages in India. The societal needs of education, hygiene, agriculture, and development outreach to rural India and the success of SITE catalyzed the need for a domestic communication satellite program. The Indian National Satellite (INSAT) system was created in the early 1980s and Loral Space and Communications built the INSAT-1 series. Subsequent INSAT series—the bulk of them are in the 2500 kg class—were designed and built in India.

The capability to launch the INSAT class of satellites was an evident need and ISRO had initiated vehicle configuration studies quite early. A follow-up study in the 1980s took into account the technology progress achieved in the realization of launch vehicles in India, and the conclusion was that a cryogenic stage was essential to achieve the stated GEO objectives. Cryogenic engine technology is challenging and expensive, and requires a facility to produce liquid hydrogen and oxygen.

It became meaningful to address the GSLV configuration when the PSLV systems had gained a level of design and qualification maturity. The qualified PSLV stages and combinations could form the lower stages of such a vehicle. In fact, the configuration studies examined combinations of a PSLV solid booster and variants for core and strap-on functions, PSLV liquid second stage as a single or twin-engine cluster, and a suitable cryogenic top-stage. The committee had studied options involving a liquid stage with cluster of two engines referred to as L-110[22] as the core with two solid strap-ons forming the first stage, the PSLV liquid stage L37.5 as the second stage, and cryogenic third stage. It was felt that the indigenous development of a cryogenic engine and stage would be a long affair and import possibility should be seriously explored.

After a series of reviews of all factors (development time, design confidence, reliability, and other related issues), a three-stage configuration was finalized. The first stage employed the PSLV solid booster stage (S125[23]) as core with four liquid stages (L40) containing 40 t storable propellants in each as strap-ons. The strap-ons were 2.1 m diameter and stretched version of L37.5, the second stage of PSLV. The L 37.5 formed the second stage. The third stage was the cryogenic upper stage whose thrust and mass options were firmed up based on available import options. Performance studies had been carried out based on a cryogenic stage with 12 t propellants, as well as the French HM-7 stage. The vehicle employed a 3.4 m payload fairing to accommodate the 2.5 t class of satellite.

While this configuration met the performance objectives, it was not an elegant way of staging. The solid core stage burnt out nearly 50 seconds earlier than the L40 strap-ons. The strap-ons were attached to the solid stage, and hence, the empty mass of the solid stage had to be carried for the burn duration of L-40. The preferred staging practice is to employ liquid stage as the core with solid strap-ons to augment the thrust. A configuration with L110 as core with two S125 strap-ons would have allowed the jettisoning of the strap-ons at the end of their burn, providing a more efficient and elegant alternative.[24]

The candidate power plants considered for GSLV were the Rocketdyne RL-10 of the United States, SEP HM-7 of France, and LE-5 of Japan. Both the U.S. and French companies indicated the possibility of selling a cryogenic stage, but the technology was not on offer. The sale from the United States hinged on clearance from the State and Commerce Departments, and therefore was not certain given the geopolitics; the French option was priced too high for India, with a further condition that the power plant be used only for Indian satellite launches and not commercial launches; and Japan showed no interest in responding to the Indian request for proposal (RFP).

However, the former Soviet Union responded to the Indian RFP positively with an offer of delivery of two flight-worthy cryogenic stages, as well as transfer of technology. The cryogenic engine, KVD-1 M, was developed for the Soviet Moon program. The engine never flew, but was tested extensively on the ground. Financially, the deal was comfortable for India at the cost of $90 million U.S. dollars at the 1991 exchange rate in Indian currency. Despite the deal, it was ultimately annulled. At the time of the deal, the Soviet Union was breaking up and the deal violated MTCR[25] guidelines. Given these violations, the United States imposed sanctions on ISRO and prevailed upon Russia to annul the cryogenic technology transfer. Though India and Russia renegotiated the contract and Russia agreed, as compensation for the technology transfer, to supply two additional flight-worthy stages. Russia also agreed to supply further stages, and a supply detail of seven stages was agreed to. Another feature of the contract was the electronic system required for the control and operation of the engine, which would be the responsibility of India with tests in Russia, by integration of the Indian electronics with the Russian hardware.

Six flights of GSLV using the Russian supplied cryogenic stage were carried out between 2001 and 2010. The first three missions were successful, but of the remaining three, two were failures and one was partially successful. In this latter case, the F04 mission of September 2007, the satellite was injected in a lower perigee and wrong inclination requiring the use of spacecraft propulsion to push the satellite into a useful orbit. The failure of the F02 mission in July 2006 and the F04 mission issue were due to a malfunction in one of the L40 strap-ons. The failure of the F06 mission of December 2010 was due to the snapping of connectors and disabling of the control of the vehicle at 47.6 seconds into flight.

Concurrent with the Russian deal, the indigenous development of a C-12 cryogenic stage identical to the Russian system was taken up by India. There was a short time interval when the technology transfer was active, and this period was used to assimilate as much of the Russian cryogenic technology as possible. ISRO ensured that industry teams from India also participated in the discussions with the Russian team—this enabled industry involvement in the stage realization in India right from the beginning. With the formal closure of the technology transfer, design, and development activities, industry involvement, creation of facilities, and procurement of special materials were all attended to for indigenous development. In the development, a number of technology issues did arise, but they were all resolved and the indigenous cryogenic stage was ready by 2010. It was integrated with the vehicle and the launch-designated GSLV D3 mission took place on 15 April 2010. In this mission, the lower stages performed to expectations, the cryogenic stage start-up also occurred as per designated sequence, and the ignition of the vernier and main engines also happened, though engine operations could not be sustained, resulting in overall failure of the mission.

Detailed failure analysis was unable to pinpoint the cause of failure, but the committee made recommendations to render the design more robust. With all of the improvements in place, two successful flights of what was now called the GSLV Mark II[26] took place incorporating the indigenous cryogenic stage. The GSLV D5 mission was launched in January 2014 and the D6 mission in August 2015. The successful missions added to confidence in the design and development approach, and paved the way for operationalization of the GSLV.

The international trend in communication satellites is towards heavier satellites capable of carrying more numbers of transponders. Chandrashekar[27] estimated that only 12% of the communication satellites fall in the medium weight category of the 2500 kg class. The balance, 88%, are nearly equally divided among intermediate (2500–4200 kg), heavy (4200–5400 kg), and extra-heavy (greater than 5400 kg). This trend is seen in ISRO communication satellites as well, with 44% of the communication satellites launched since May 2011 falling in the 3000 or more kg[28] weight category. This type of payload is beyond the capability of GSLV Mark II and the present GSLV configuration does not provide much scope for growth.

The limitations of GSLV Mark II prompted ISRO to examine other options. As early as 2000, ISRO started examining the requirements for GSLV Mark III to launch 4 to 4.5 t to GEO. The vehicle was configured as a three-stage system drawing from the proven technologies of PSLV and GSLV Mark II. The change of guard at the Liquid Propulsion System Center was willing to develop clustering technology of liquid engines. Unlike the earlier GSLV, an elegant stage comprising a cluster of two Vikas engines, designated L110, formed the core booster. Two large, solid propellant motors, designated S200, formed the strap-ons. Both the core and the strap-ons did draw upon the technologies qualified in the PSLV and GSLV programs with improvements in design and process.

The range safety constraints for equatorial launches from Satish Dhawan Space Center (SDSC), the Indian spaceport at Sriharikota, required that the second-stage impact be contained in the South Andaman Sea. This constraint requires the top cryogenic stage to be able to provide nearly half of the injection velocity for GEO transfer orbit insertion. From this consideration, the design team decided on a 25 t cryogenic stage named C-25. This stage is not a scale-up of the C-12, but takes advantage of the learning curve and incorporates improvements. The payload fairing was fixed at 5 m to accommodate the larger satellites and the vehicle weighed 640 t at lift-off. The vehicle is also referred to as LVM-3, the acronym for Launch Vehicle Mark III.

To date, both the core liquid stage and the solid strap-ons are realized. The cryogenic stage is undergoing ground qualification tests. A suborbital flight test[29] of the vehicle, employing the liquid core, two solid strap-ons, and a passive cryogenic stage, was successfully carried out from SDSC in December 2014. The flight validated the vehicle lower-stage flight performance, controllability, and other features. With the benefit of learning curve of the cryogenic stage of GSLV Mark II, the realization of cryogenic stage for LVM-3 is progressing well. The C-25 engine has been ground tested for extended duration in July 2015 and is expected to be qualified for flight in 2016. The LVM-3 has good growth potential. Improvements in the cryogenic stage—reduction in inert mass, increase in tank length and propellant loading, and replacement of L110 core engine with semi-cryogenic engine—can potentially enhance the GEO transfer orbit payload capability of the GSLV to 6 t.

ISRO is also working on reusable launch vehicle (RLV) technologies. A RLV prototype was tested in a suborbital flight in 2016. Thermal protection materials were earlier qualified in the space capsule recovery experiment. Air-breathing propulsion technology development is also underway, for which a supersonic combustion ramjet (scramjet) engine was qualified in ground tests and was recently flight tested. These technologies are being developed with human spaceflight in mind. LVM-3, with appropriate modifications for human rating, is the planned carrier vehicle.

Commercial launch prospects

PSLV is an extremely reliable and cost-effective vehicle and, as previously stated, is applicable for diverse missions. The payload bay was modified early on in the operational phase of the rocket to accommodate the piggyback of small satellites (smallsats). For example, KITSAT from South Korea, TUBSAT and BIRD from Germany, and PROBA from Belgium were launched on PSLV. In its last flight of June 2016, PSLV carried 19 smallsats, 17 of which were for international customers. PSLV was also used to launch the Italian astronomical satellite AGILE with a mass of 352 kg.

The prospects for commercial launch in India are influenced most directly by U.S. export rules and regulations. In this regard, the International Traffic in Arms Regulations (ITAR) acted as a damper for launching foreign satellites from India. Over time, these regulations eased. The first breakthrough was the Technology Safeguards Agreement (TSA) signed between the United States and India in July 2009. This agreement changed U.S. policy to permit the launch of civil and non-commercial satellites containing U.S.-ITAR components on Indian launchers. The positive fallout was seen in the carriage of ALSAT-2A on board PSLV C-15 in August 2010; the satellite was built by a French company for the Algerian Space Agency and contained U.S. parts.[30] The next positive change was the removal of commercial satellites from the U.S. munitions list, effective in November 2014. Additionally, many satellite components are also delisted and do not figure as part of any blanket ban. This change permits U.S. satellite-related exports to India, which figures among the non-embargoed countries.

These positive changes do not necessarily mean an automatic increase in the launch of U.S. satellites from India. In fact, currently there is a ban on U.S. satellites to use PSLV as a launcher. The U.S. government ensures that minimum prices offered by foreign launch providers are not below the U.S. commercial launch prices by having a Commercial Space Launch Agreement with the launch service providing country. India has not signed this agreement; consequently, U.S. satellites cannot fly on the PSLV, though the United States does provide clearance for U.S. satellites to launch on the PSLV on a case-by-case basis. In the June 2016 flight of the PSLV, for example, besides the main Cartosat 2 satellite, 19 smallsats were placed in orbit; 13 of these were from the United States, including a 110 kg Earth observation satellite for Terra Bella, a Google-owned company.

With GSLV moving closer to operational status, India will be in a position to offer diverse launch options and there is scope for increased commercial flights at competitive prices. The government of India does not subsidize launch costs, but overall development costs are low and the total development, which takes place within ISRO as of now, is evolving to include industry participation to supply integrated stages and support services.

Conclusions

A high level of maturity characterizes launch vehicle development in India. The PSLV proved to be a reliable launcher, primarily for lofting Earth observation satellites into 600 to 800 km sun synchronous polar orbits. The PSLV also has capability to carry co-passenger smallsats and release them in orbit. Further, the PSLV allows easy configuration changes from the basic version to suit mission needs, and can also be used for GEO transfer orbit and deep space missions.

The development of GSLV posited challenges for ISRO. The outlook of the engineers developing liquid propulsion systems was not as forward looking as those involved in the solid rocket propulsion systems. In the solid rocket case, a self-reliant indigenous development route was pursued, while, in the liquid case, there was a reliance, at least initially, on foreign technology. The GSLV configuration was also a reflection of lack of confidence in the development of L110 forcing management to opt for four individual liquid-engine strap-ons. Despite the complexity of a liquid pump-fed system, it was well within the design capability of Indian mechanical and propulsion engineers, as was subsequently proven in the development of L110 for the LVM-3. Moreover, the fourth-stage pressure-fed engine on the GSLV was an indigenous design with a successful and reliable track record.

Of note as well is that the development of the cryogenic engine reflects missed opportunities. The offer from France to participate in the development of HM-7 was not taken up by India. This was an error of judgment by the ISRO leadership at that time. Also, earlier indigenous development starts did not receive encouragement and were not pursued. Finally, the prevailing geopolitical situation curtailed the technology acquisition process from Russia. It became essentially an indigenous effort in the end. On the positive side, the final qualification and flight tests of the cryogenic stage reflect highly on the capability and commitment of the liquid propulsion engineers of ISRO. In hindsight, the cryogenic stage was possible many years earlier, if the initial indigenous effort had been encouraged and funded.

The successes notwithstanding, there is the problem of inadequate capacity. ISRO has averaged three to four launches of PSLV in a year and there is a need to increase the number and the frequency of launch to have a stake in launch markets. There is a concerted effort to increase this and, in 2016, four flights were accomplished in the first half of the year. In a discussion with reporters following the launch of PSLV C-34 on 22 June 2016, ISRO

Chairman Kiran Kumar indicated plans to achieve a launch capacity of 12 to 18 per year. Indian industry will need to play a major role to achieve and sustain this type of capacity.

The potential and promise of Indian launch vehicles is on a progressive growth trajectory, and expected to play a significant role in the commercial satellite launch market. It must be noted that satellite manufacturers want, and will pursue, the lowest cost of service for delivery to their customers. This is to ISRO's advantage. At the same time, other launch services providers will want to increase their market share in a regulated market that is circumscribed by geopolitics, domestic lobbying, and explicit or hidden state subsidies. These are barriers to ISRO's global market penetration. The entire industry of commercial launch is going through an evolution with the state-assisted entry of national private providers of launch services. ISRO is not immune from these impacts, but the result remains to be seen.

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Notes

1. The Department of Atomic Energy concluded an agreement with Sud Aviation of France for the licensed manufacture of two-stage Centaure rocket in India. The know-how transfer included drawings, equipment specifications, and training of some engineers in the Sud Aviation plant in France.
2. E. V. Chitnis gives a first-hand account of "selecting site for satellite launching" in the chapter titled "Early ISRO: 1961–1971," edited by P.V. Manoranjan Rao, *From Fishing Hamlet to Red Planet: India's Space Journey* (New Delhi, India: Harper Collins India, 2015), 20–21.
3. The series of indigenously developed sounding rockets were named Rohini Sounding Rockets and the team of engineers at SSTC was called Rohini engineers. The complete group of engineers constituted the Rohini Consultative Committee, which was used by Sarabhai for nucleating and brainstorming ideas.
4. K. D. Wood, *Aerospace Vehicle Design Volume II: Spacecraft Design* (Chicago, IL: Johnson Publishing, 1964).
5. For details of L4S and Mu launch vehicles, see *Encyclopedia Astronautica*, http://www.astronautix.com/ (accessed August 2016).

6. The Federation of American Scientists describes the SCOUT launch vehicle in some detail, http://fas.org/spp/military/program/launch/scout.htm (accessed August 2016).
7. There is evidence of Indian interest in SCOUT in the early years of the Indian space program. Also, there is a mention of Homi Bhabha having tried for the technology transfer of SCOUT from the United States in February 1965. See P. V. Manoranjan Rao and P. Radhakrishnan (eds.), *A Brief History of Rocketry in ISRO* (New Delhi, India: University Press, 2012).
8. Vikram Sarabhai founded the first management institution in India—the Indian Institute of Management at Ahmedabad, India.
9. The launch vehicle systems consisted of the four propulsive stages, heat shield, guidance package, telemetry, and tele-command. The launcher and tracking system development were also included in the subsystem development projects.
10. A totally different type of control, using jet vanes mounted at the exit of the first-stage nozzle, was used in SCOUT.
11. The multiple development agencies in solid propellant rocket systems and distribution of tasks among them by the SLV project management are described in Rajaram Nagappa, "Evolution of Solid Propellant Rockets in India," Defense Research and Development Organization (DRDO) Monographs, Special Publication Series, Defense Scientific Information and Documentation Center (DESIDOC), New Delhi, 2014, 79–81.
12. This motor development was completed and the motor was flight qualified in the SLV-C flight.
13. A. E. Muthunayagam, "Liquid Propulsion in ISRO," Chapter 2.10, in *From Fishing Hamlet to Red Planet: India's Space Journey*, edited by P.V. Manoranjan Rao (New Delhi, India: Harper Collins India, 2015), 228–229.
14. Annual Report, Department of Space, 1972–1973. The extract quote: "a team has been constituted to analyze, study, and report on an optimum approach to the development of a multistage launch vehicle, capable of placing a satellite of about 800 kg weight in synchronous equatorial orbit."
15. Gopal Raj, *Reach for the Stars* (New Delhi, India: Viking, 2000), 169–172.
16. Ibid., 172.
17. Annual Report Department of Space, 1981–1982.
18. Almost coincident with the launch of ASLV in March 1987 came the formation of MTCR. ISRO had started experiencing difficulty in procurement of materials and components from the United States ahead of MTCR. In respect to solid propulsion systems, difficulty was experienced in the procurement of PBAN resin, carbon fabric, and graphite, among other items. Indigenization efforts were underway in some of these systems and were accelerated. In fact, in the third flight of ASLV, the solid motor strap-ons propellant had to be changed, as PBAN was not available. Indigenously produced hydroxyl terminated polybutadiene (HTPB)-based propellant was used in its place. HTPB had superior energetic and aging characteristics over PBAN, and the resin was produced by an industry in Mumbai, India, based on ISRO know-how. Alternate European sources were available for procurement of the equivalent of DuPont Chemical's Kevlar™49 fiber. ISRO had synthesized the polymer, but could not attract industry interest as the off-take was low. A similar situation existed in respect to other subsystems.
19. The motors were processed in different work centers. Employing a material selection and screening process, the standard deviation in key performance parameters could be contained within narrow bands. For a more detailed description of the performance of the motor, see *Supra* note 11, 96–97.

20. The failure of the PSLV maiden flight is reproduced from the chapter, “The Workhorse: Polar Satellite Launch Vehicle,” *A Brief History of Rocketry in ISRO*, 160–161.
21. Ibid., 164.
22. The stage nomenclature followed in ISRO used prefix S for solid, L for liquid, and C for cryogenic stages. The number following represented the mass of the propellant in the stage. Thus, L-110 meant a liquid stage with 110 t of propellant.
23. The propellant loading in S125 was subsequently increased to 139 t for use in PSLV. This improved motor designated S139 also is used for GSLV flights.
24. Liquid systems are more complex than solid propellant systems. However, it was not beyond the scope of Indian mechanical and propulsion engineers to take up the design of L110. This was doable as India assimilated the Viking engine technology and realized the L37.5 stage. The liquid propulsion development team, however, was not confident and the ISRO management preferred to take the proven route of employing L-40, a stage derived from the qualified L37.5 stage.
25. The MTCR of the export control items list includes components, subsystems, materials, and technology, which come under the purview of the ban. While it could be argued that a cryogenic stage can hardly be conceived and used for missile application, post-Soviet Russia, under its late president Boris Yeltsin, was beholden to the United States and not strong enough to resist the U.S. pressure.
26. GSLV using the indigenous cryogenic stage was labeled as Mark II to differentiate it from the flights involving Russia-procured cryogenic stages.
27. See article in this issue of *Astropolitics*: S. Chandrashekar, “Space, War, and Security: A Strategy for India,” *Astropolitics* 14, no. 2–3 (2016).
28. The satellites falling in the 3000+ kg category are: GSAT-8 (3093 kg), GSAT-10 (3400 kg), GSAT-16 (3181.6 kg), and GSAT-15 (3164 kg).
29. Details of LVM-3 can be garnered from ISRO, http://www.isro.gov.in/launchers/lvm3 (accessed August 2016).
30. “U.S., India Find Way around ITAR Export Laws with Bilateral Space Launch Agreement,” Parabolic Arc, Spaceflight, 13 July 2010, http://www.parabolicarc.com/2010/07/13/india-find-itar-export-laws-bilateral-space-launch-agreement/ (accessed August 2016).