THE SPACE TRANSPORTATION SYSTEM IN INDIA : PRESENT SCENARIO AND FUTURE DIRECTIONS
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Introduction

It was the vision of Dr. Vikram A. Sarabhai in 1962 to utilize the potential of Space Technology and its applications for National development. Dr. Sarabhai the founding father of space programme in India had enunciated: "we must be second to none in the Application of Advanced Technologies for the real problems of man and society". This vision of Dr. Sarabhai has been the guiding spirit for all developmental activities of Indian Space Transportation System in India. The Indian space endeavor had its modest beginning with the launch of sounding rocket from Thumba on November 21, 1963. Since then in the last four and half decades, India has attained total self reliance by successfully developing and operationalising the Polar Satellite Launch Vehicle (PSLV) and Geosynchronous Launch Vehicle (GSLV). Launch Vehicle is a critical element in the self-reliant space programme because of (1) vicissitudes of geopolitics, (2) non-availability of the know-how from those who possess this technology due to various dual use based control regimes, particularly Mission Technology Control Regime (MTCR). Considering that access to technologies, components, materials, etc. are under stringent technology control regimes, all-round indigenous efforts by ISRO, in association with national R&D institutions, academies and industry to develop the complete range of technologies were needed for the development of space transportation systems. This demanded indigenous efforts to develop technologies in various disciplines of propulsion, aerodynamic, avionics, control and guidance, inertial systems, sensors, flight dynamics, structures and materials, chemical systems, advanced composite materials, fabrication technology, etc. This paper attempts to explain the evolution of Space Transportation Systems and Technologies from the beginning to the present operational phase. Attempt has been made to present the developmental efforts in space transportation systems and the accomplishments. The future directions for technologies and systems needed for reducing the cost of access to space are described. The study efforts on human space programme are also included.

Evolution of Space Transportation in India

The development of basic technologies in various disciplines of space transportation was initiated through sounding rockets, a learning phase during 1960,1970s. The indigenous development of rockets demanded mastery over a broad range of multidisciplinary technologies. The Rohini sounding rockets were developed with two major objectives of meeting the requirements of conducting experiments on upper atmosphere, ionosphere and near space and acquiring the competence in the basic aspects of rocketry, as stepping stones to develop the more powerful and complex space transportation systems. Started from 75mm diameter rocket motor of 2 s burn duration and 4 kg propellant mass configured for the initial solid propulsion technology demonstration in 1967, step-by-step developments have been made to meet the requirements for sounding rockets. As a result, a series of rockets of different sizes were designed and flight tested. Fig.1 gives a summary of the four sounding rockets, their diameters, mass, payload carrying capability and maximum altitude achieved by these rockets.

Sounding rockets provided the necessary technological capability in solid propellants. Applying these to the larger and multi-stage rocket systems, in early 1970s, efforts were initiated for the development of Indias first Satellite Launch Vehicle SLV-3[1] having capability of placing 40 kg payload in Low Earth Orbit (LEO). SLV-3 was a four-stage vehicle using solid propulsion with a lift off mass of 17 t having a diameter of about 1m. It was a fully indigenous effort. During this phase significant developments have taken place in the areas of solid propulsion, materials, chemical systems, segmented booster, motor structures, aerodynamics, open loop guidance, staging technology, secondary injection thrust vector control, fin tip deflection for boost phase control, reaction control systems for upper stage control, avionics, composite payload fairing, inertial systems, experience on orbital mission management etc. To assemble and test long size solid propulsion systems, integration and launch of the vehicle,

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a large geographic area free from human habitation was required and for this purpose a launch station at Sriharikota, 75 km north of Chennai in Nellore district was developed as a major facility with associated infrastructure. The first attempt to launch SLV-3 in 1979 was not successful due to minor malfunction of control thruster. However, in the second flight of SLV-3 during 1980, the Rohini Satellite was placed in orbit, making India one of the six nations in the world to develop this technology. SLV-3 programme resulted in significant developments in multiple disciplines of rocketry and gave confidence to take up projects of greater complexities. The intricacies of launch vehicle technology and mission management were learnt through three successful launches of SLV-3 during 19801983. It provided the required insight into design and development of multi-disciplinary space transportation systems, various interfaces like launcher to satellite, launcher and launch complex operations, establishing tracking, telemetry and command networks.

Considering the need for higher payload capability for scientific experiments and to achieve such a space mission within a shortest possible time, a configuration of ASLV with payload capability of 150 kg was evolved. ASLV was five-stage vehicle derived out of four-stage of SLV-3 by the addition of two strap-on boosters called zero stage. It served as the low cost flying test bed for new technologies. The technology developments carried out during this experimental phase include strap-on booster technology, bulbous payload fairing, canted nozzles, closed loop guidance, inertial systems based on stabilized platform, and new digital avionics based on M6800 processor. In addition, the launch complex development technologies required for vertical integration also happened during this period. The first flight was a failure on account of non-ignition of the first-stage motor due to suspected failure in the ignition chain. The second flight also failed due to certain lacunae in the control during the transition from zeroth stage to first-stage regime. Despite two failures during 19871988, the extensive analysis brought out improvements in the better characterization of vehicle, new technologies and simulations. The major contribution of the ASLV experience was that it enabled a better understanding of the complex atmospheric regime of flight considering control structure interaction, implementation of onboard real-time based decision for mission management, closed loop guidance for better tolerance in satellite injection conditions. With two consecutive successful launches of ASLV during 19921994, all the objectives of this program were achieved.

Operational Phase of Space Transportation System
PSLV and GSLV

Even when the development of ASLV was going on, ISRO took the challenging task of developing PSLV [2, 3] for launching 1 t class of operational remote sensing satellites into Sun Synchronous Polar Orbit (SSPO). The basic configuration of PSLV is given in Fig. 2. PSLV provides a quantum jump in developments in terms of size and technology. The various technological developments during this programme were: world class large solid motor with 139 t propellant loading, technology related to large liquid engines with 40 t propellant loading as well as smaller liquid engines up to 2.5 t loading, high performance solid motor with 7 t propellant loading in composite motor case, strapdown navigation system development, digital autopilot, closed loop guidance with three-axis guided injection, all digital avionics, stressed skin construction for inter-stages, isogrid structures for payload fairing, development of super alloys like Maraging steel and Titanium for motor cases and tankages, and state-of-the-art control systems such as Engine Gimbal Control (EGC) and Flex Nozzle Control (FNC)[4]. This also lead to the development of much bigger vehicle integration and launch facilities such as mobile tower, launch control centre along with the significant expansion on the tracking, telemetry and telecommand. Also the gigantic PSLV developmental efforts generated facilities and industrial support of bigger proportion. Large number of infrastructure was required for motor fabrication and testing which were realized with the participation of industries. An aerospace division was also created at HAL to support large-scale light alloy structure fabrication. The requirement of large-scale liquid engine development, testing and integration called for creating a liquid propulsion testing complex at Mahendragiri during 19821988 time frame. All the PSLV systems functioned well in the first flight conducted in 1993, but still the mission could not succeed in injecting the satellite into orbit due to a software implementation error. This led to strengthening further the ground simulations, additional testing of the vehicle hardware and software systems to its fullest capabilities prior to launch. A world-class state-of-the-art simulation facility with fully indigenous infrastructure was established for this purpose. From then onwards all the PSLV flights are successful. 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 single launch and making the vehicle a versatile platform for host of missions such as LEO, SSPO and GTO. Starting with a
payload capability of 800 kg in its first developmental flight, the capability of PSLV has been systematically and significantly improved to 1800 kg in its latest SSPO mission. These improvements have been made possible by incorporating improved propellant loading for solid as well as liquid stages, improved efficiency of the upper stage, 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 1300 kg to GTO has also been established with the launch of Chandrayana-1 recently. This vehicle has provision to carry multiple microsatellites in the vehicle equipment bay or a possible mix of micro and mini satellites. The first one has been accomplished in the fifth mission of PSLV wherein it carried two microsatellites in a piggyback mode - KITSAT-3 of Korea and TUBSAT of Germany. In the subsequent missions, several micro/mini satellites of different countries have been launched and C10 carried 10 satellites comprising of both major and mini spacecraft from different countries.

Concurrent to development of PSLV, ISRO initiated the challenging task of developing the GSLV for launching 2 t class of operational communication satellites into GTO [5]. In order to improve the reliability and maximizing the payload capability, the GSLV is configured with three stages, employing solid, liquid and cryogenic propulsion modules for its stages as shown in Fig. 3. Keeping the pedigree of already developed stages and in order to reduce the overall development cost and schedule, the PSLV modules were maximally utilized for the first two stages of GSLV. As cryogenic propulsion delivers more energy in terms of specific impulse, the configuration is designed with cryogenic engine for its third stage. Initially a procured cryogenic stage from Russia was used for the upper stage. The major technology developments during this project phase are technologies related to cryo engine and stage systems. Though the cryogenic stage was procured from Russia, total avionics system for propulsion control for thrust regulation and propellant management was developed, validated and implemented by ISRO. Definition of the mechanical, electrical, thermal interfaces with ISRO systems and qualifying them through a series of joint hardware tests and software checks posed a major challenge. Even though the first three launches have taken place from first launch pad developed during PSLV time frame, in order to efficiently carry out the integration and cryo propellant servicing, a state-of-the-art second launch pad also was developed and established for GSLV and future heavy lift launches. GSLV has capability to launch 2200 kg to GTO and is expected to reach 2.5t with the introduction of indigenous Cryo stage. The indigenous cryo stage development is a major challenging development task but the engine and stage have been qualified through a series of ground tests, short and long duration stage level tests. It is expected to fly the indigenous cryo in the next launch of GSLV before end 2009.

**GSLV MK-III Development**

Development of GSLV Mk-III is initiated to meet the demands of launching 4t class of spacecraft [5] as well as to offer cost effective launch services. Fig. 4 shows the configuration of GSLV Mk-III. It is a three stage vehicle with two solid strap-on motors of 200t propellant loading and liquid core of 110t propellant loading with the clustering of two engines. The upper stage with a cryo engine has a propellant loading of 25t. Important technology developments in this vehicle are:

- One of the large solid propellant boosters in the globe
- A flex nozzle control system for the large solid booster
- Liquid stage with clustered engines
- A high thrust cryo engine operating in gas generator cycle
- Composite structures
- Improved Failure Detection and Isolation (FDI) schemes in avionics and control systems and
- Miniaturized avionics and TTC packages with improved band-width

With this configuration the launch cost per kg of payload is expected to reduce by 50%. The developmental flight of GSLV Mk-III is expected within next two years.

**Space Capsule Recovery Experiment**

The objective of the space capsule experiment was to develop a spacecraft recoverable from orbit, master the reentry technologies and to gain experience in reentry and recovery procedures required for the design of future reusable launch vehicles [6].

Some of the important technologies developed include:

- Light weight and reusable thermal protection system
- Aero-thermal structure design/analysis
- Hypersonic aero-thermodynamics
- Navigation, guidance and control of reentry vehicle
Deceleration systems
Floating systems and recovery systems/operation, and
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. Fig.5 shows the mission profile of SRE.

Mission to Moon

In order to expand the scientific knowledge about the Moon and master the technologies needed for interplanetary mission this project was conceived about 9 years back. The mission is to achieve $100 \times 100$ km lunar polar orbit with the satellite mass of 590 kg with 2 years life time. The main objective of this mission is to carry out the integrated studies of chemical, mineralogical and topographic mapping of the whole moons surface. The ten instruments provided on board the spacecraft allow high resolution remote sensing of the moon in visible, near infrared, low energy and high energy X-ray regions. The space craft was launched successfully on October 22, 2008 and it was injected into the lunar orbit on 8th November after several successful operations. Subsequently the moon impact probe weighing 34 kg was deorbited and touched the moons surface at the predetermined location precisely after 20 minutes. The mission profile is given in Fig. 6.

The payload contains lunar terrain mapping camera, x-ray spectrometer, stereo imager, imaging spectrometer etc. The technologies that are successfully demonstrated are interplanetary trajectory, the mission strategy, power management, thermal control, onboard autonomy, deep space spacecraft control and communication link and special mechanisms. All onboard instruments are functioning normally and enormous amount of data is being collected which will be used for detailed analysis by all scientists.

Future Directions for Space Transportation System

Indian Space Transportation System constantly strives to improve technologies to meet the long-term needs. Currently identified technologies are realization of, (1) large cryogenic upto 500 kN thrust and semi-cryogenic boosters, (2) air breathing propulsion, and (3) building block 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 actuation 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 human mission have also been carried out.

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. Extensive theoretical [7] and experimental [8] studies have been carried out on various aspects of air breathing propulsion. While the earlier studies focused on rocket based combined cycle, the current focus is on the scramjet engine cycle where the critical technologies and high temperature materials are crucial and are being addressed. ISRO has 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 candle in hurricane. Theoretical studies, including extensive use of CFD tools, have supported design and analysis.

DMRJ-Flight test demonstrator 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 program is coming up. This scramjet propulsion test facility can test and evaluate scramjet combustors up to flight Mach number eight. Development of air breathing propulsion technology for TSTO-RLV is envisaged in a progressive manner. Starting with DMRJ-FTD flights for 0.1t class ram-scramjet engine, RLV-TD is planned to use one-ton class of turbojet, ramjet and scramjet engines. These technology developments would pave way for the subsequent design and development of bigger air breathing engines (of 10 t class and above) for use in advanced RLV. Fig.7 illustrates the advanced reusable launch vehicle using the air breathing propulsion.
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 expandable Launch Vehicle (ELV), the cost of launching one kg to LEO is approximately $10,000 to 15,000. This is due to the fact that 67% of the ELV cost is that of hardware, which is expended. Also, for an ELV the payload fraction is approximately 15 to 20%. 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 low as 4%. With these, the cost per kg for LEO orbits can be brought down substantially to around $1000 to 2000. Extensive studies on configuration options Single Stage to Orbit (SSTO)/Two Stage to Orbit (TSTO) have shown that with the current levels of technologies of propulsion and materials TSTO is feasible in the immediate future. 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 its return flight will have high angles of attack in the upper atmosphere, in order to reduce the kinetic energy before reaching lower altitudes. It will use aerodynamic controls during the atmospheric flight. The entire flight will be autonomous. This RLV-TD will be designed using available technologies to start with, and will progressively adopt and test new technologies. In a brief period of about 3 to 5 years, RLV-TD will prove, in a cost effective way the advanced technologies that are required for taking decisions regarding the route to be followed for design and development of the full scale TSTO-RLV. Presently the priority is assigned to understand and master the technologies related to hypersonic flight of a winged body configuration and will have fully autonomous operation through the intended mission.

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, NGC for re-entry and controlled descent, in-flight health monitoring system, and abort systems, as shown in Fig. 8. Subsequently RLV-TD will be used as a test-bed for evaluating new propulsion systems like the air-breathing SCRAMJET/RAMJET modules.

Studies on Indian Human Space Program

The Indian Space Programme after crossing several major milestones including development and operation-


Fig. 5 Mission profile of SRE

Fig. 6 Mission to Moon

Fig. 7 Advanced Reusable Launch Vehicle using Air Breathing Propulsion

Fig. 8 Reusable Launch Vehicle - New Technologies

Fig. 9 Manned mission - New Technologies