First developmental flight of geosynchronous satellite launch vehicle (GSLV-D1)

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The maiden developmental flight of GSLV-D1 on 18 April 2001 which successfully injected the GSAT-1 satellite in geosynchronous transfer orbit, is a historic milestone for the Indian space programme. This is the culmination of developmental efforts for this vehicle in the last decade. Geosynchronous Satellite Launch Vehicle (GSLV) is a three-stage vehicle employing a solid core with 129 t propellant, 4 liquid strap-ons, each with 40 t of propellant, liquid second stage with 37.5 t of propellant and a cryogenic stage with 12.5 t of propellant. The flight has validated the complex vehicle and mission design aspects, soundness of a number of new vehicle systems such as cryo stage, liquid strap-ons, hot separation of first stage, larger diameter payload fairing, launch hold release mechanism, launch pad facilities for handling and filling-earth storable and cryogenic propellants. This has also enabled the Indian Space Research Organization to demonstrate the level of professionalism attained to meet emergencies and take corrective actions to accomplish the flight objectives successfully within three weeks of its first attempt.

THE Geosynchronous Satellite Launch Vehicle (GSLV) is the fourth generation launch vehicle developed by the Indian Space Research Organization (ISRO). The first generation SLV-3 (all-solid four-stage vehicle) and the second generation ASLV (all solid five-stage vehicle with strap-ons and closed loop guidance technologies) were experimental vehicles. Polar Satellite Launch Vehicle (PSLV), employing both solid and liquid technologies has come to stay as the operational vehicle for launching national remote-sensing satellites. The four-stage PSLV has a payload capability of 1250 kg in sun synchronous polar orbit, 3800 kg in LEO and 900 kg in geosynchronous transfer orbit (GTO). Five flights of PSLV have been accomplished so far. PSLV has enabled a modest entry into commercial launch services also. The GSLV project has made the best use of the technologies developed in the launch vehicle area so far, while evolving this new configuration with many critical technologies, systems and modules. This paper gives an account of the challenges and achievements during the development of GSLV.

Configuration consideration

Even as the earlier three generations of launch vehicles were being developed, conceptual studies for a GSLV were in progress. These studies gained momentum in the late 80s and after a study of a large number of configurations, the present configuration of GSLV was selected. The factors that were considered for GSLV configuration, at that point of time, included the spacecraft requirements, maximum use of the available modules and the utilization of infrastructure already developed for PSLV, safety considerations and the efforts needed for development of new technologies. The GSLV project was approved in November 1990.

Configuration description

GSLV is basically designed to carry out GTO missions. It adopts the flight-proven solid and liquid stages of ISRO's PSLV and a procured cryogenic upper stage from Glavkosmos (GK), Russia. The first development flight GSLV-D1 launched on 18 April 2001 carried a communication test satellite GSAT-1 weighing 1540 kg in GTO. GSLV can also be used to launch a variety of spacecrafts capable of performing communication, navigation, earth resource survey and LEO missions.

GSLV is a three-stage vehicle, about 49 m long and weighing about 401 t at lift-off (Figure 1). The first stage (GS1) comprises a solid propellant motor (S125) and four liquid strap-ons (L40). The second stage (GS2) is powered by a single liquid engine (L37.5). The third stage (GS3) is a cryogenic stage (C12), powered by an engine having re-startable capability also.

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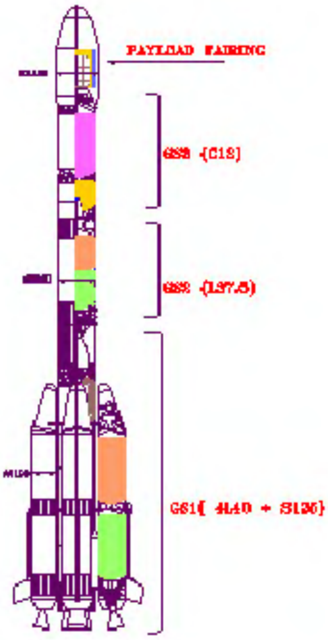

Figure 1. Vehicle configuration.

Need for a cryogenic stage

The cryogenic stage was chosen in view of its higher propulsive efficiency compared to solid and storable liquid stages. Typically, specific impulse of cryogenic stage is about 460 s compared to 260–300 s for solid and earth-storable stages. For GSLV configuration, 1 s improvement in specific impulse of the upper stage results in 15 kg of improvement in payload. Considering the complexity in technology and time taken elsewhere for such development, it was decided to get this stage with technology from Russia. However, subsequently, due to the geopolitical situation, technology transfer did not materialize and the contract with Russia was limited to supply of seven units of flight cryogenic stages and two mock-ups. While the cryogenic stage was being procured from Russia, it was decided that the total on-board avionics during the cryogenic stage phase flight would be developed by ISRO.

Propulsive stages

First stage

The first stage, GS1, comprises a solid core booster (S125) and four liquid strap-ons (L40). S125 is 2.8 m in diameter, made of M250 grade maraging steel and it has a nominal propellant loading of 129 t of hydroxyl terminated poly butadine (HTPB)-based solid propellant. Each L40 is loaded with 40 t of hypergolic propellants, unsymmetrical dimethyl hydrazine and nitrogen tetroxide as fuel and oxidizer respectively (UDMH and N_2O_4), stored in two independent aluminium tanks of 2.1 m diameter in tandem and has a pump-fed engine producing a thrust of 686 kN.

Second stage

The second stage, GS2, is 2.8 m in diameter and is loaded with 37.5 t of liquid propellants (UDMH and N_2O_4) in two compartments of an aluminium alloy stage tankage separated by a common bulkhead. This has a pump-fed engine of 721 kN thrust.

Third stage

The third stage, GS3, is the cryogenic stage and is 2.8 m in diameter and uses liquid hydrogen (LH_2) and liquid oxygen (LOX) as fuel and oxidizer in two separate tanks of aluminium alloy interconnected by an inter stage structure. Total propellant loading is 12.5 t. The stage details at a glance are depicted in Table 1.

Payload fairing

The payload fairing protects the spacecraft from hostile flight environment during ascent phase. The payload fairing is ejected at an altitude of about 115 km during the second stage flight, well above the atmosphere, where the heat flux density is less than 1135 W/m^2.

GSLV payload fairing is made of aluminium alloy and is 3.4 m in diameter and 7.8 m long and in two halves. Unlike in PSLV where the payload fairing is integrated with the launch vehicle after the integration of the spacecraft with the payload adapter, in GSLV the spacecraft is encapsulated within the payload fairing before integrating with the vehicle, as is done for most of the international launchers.

Stage separation systems

The vehicle is provided with various separation systems such as flexible linear-shaped charge (FLSC) for first stage (GS1), pyro-actuated collet release mechanism for second stage (GS2) and merman band bolt-cutter separation mechanism for third stage (GS3).

GS1 is separated after the ignition of the second stage. The separation is assisted by the GS2 exhaust gases impinging on the S125 dome and the accelerating GS2 (ongoing stage). During GS2–GS3 separation, retro rockets mounted on GS2 provide the separation velocity. GS3-spacecraft (GSAT-1) separation velocity is provided by spring thrusters mounted at the separation interface. After the separation of the spacecraft, a collision avoidance manoeuvre is carried out on the cryo stage.

Table 1. Stage details at a glance.

Parameter	GS1 (First stage) S125 booster	GS1 (First stage) L40 strap-on	GS2 (Second stage)	GS3 (Third stage)
Length (m)	20.3	19.7	11.6	8.7
Diameter (m)	2.8	2.1	2.8	2.8
Propellant mass (t)	129	40	38	12.5
Case/tank material	M250 steel	Aluminium alloy	Aluminium alloy	Aluminium alloy
Propellant	HTPB	UDMH and N_2O_4	UDMH and N_2O_4	LH2 and LOX
Burn time (s)	100	160	150	720
Maximum vacuum thrust (kN)	4699	686	721	Uprated phase: 80.2 Nominal phase: 73.6
Specific impulse (Ns/kg)	2613	2754	2893	Uprated phase: 4523 Nominal phase: 4514
Control system	Multi-port SITVC for pitch and yaw	EGC single-plane gimballing,. for pitch, yaw and roll	EGC two plane gimballing for pitch and yaw control. Hot gas RCS for roll control.	Two steering engines for thrust phase control and cold gas RCS for coast phase control.

Inertial navigation and guidance

The three-axes attitude stabilization of the vehicle is achieved by autonomous control systems provided in each stage. Single-plane engine gimbal control (EGC) of the four strap-ons is used for pitch, yaw and roll control. S125 stage is provided with secondary injection thrust vector control (SITVC) to augment the pitch and yaw control. The second stage has EGC for pitch and yaw and hot gas reaction control system (RCS) for roll. For the third stage, two swivelable auxiliary engines using LH_2 and LOX with two-plane control provide pitch, yaw and roll control during thrusting phase and cold gas system during coast phase.

Navigation, guidance and control system (NGC) in the equipment bay (EB) located above the third stage guides the vehicle from lift-off till spacecraft injection. A redundant strap down inertial navigation system (RESINS) generates the state vector information. Digital autopilot (DAP), guidance and control processors (GCP) carry out guidance and sequencing functions. While DAP resident in the computer on-board computes the control commands, the closed loop guidance scheme ensures optimum steering of the vehicle to obtain the required accuracy at satellite injection.

For performance monitoring, tracking, range safety/flight safety and preliminary orbit determination (POD), the vehicle is provided with instrumentation using pulse code modulation (PCM) transmitting in S-band frequency and transponders operating in C-band. During flight, the launch base tracking system tracks the vehicle. The telemetry acquisition is done by the ground telemetry system at the launch base and down range stations located at Port Blair, Brunei and at Biak, Indonesia till the separation of the satellite from the launcher.

Design challenges

Though GSLV uses propulsion and avionic modules from PSLV, as a vehicle, GSLV is different with its own aero and structural dynamic characteristics. The vehicle had to be characterized aerodynamically and the near neutral stability is ensured by appropriate design. The structural characteristics are to be carefully evaluated by ground resonance tests. Dynamic characterizations of pogo and slosh phenomena associated with liquid rockets are carried out using detailed experiments. With the liquid stages as strap-ons, the propulsion, control and structural interaction during the atmospheric phase of flight are to be analysed, taking into account pogo, slosh and structural dynamic aspects. The combined analysis, which is very complex, is to be carried out and suitable solutions are to be arrived at to avoid undesirable interactions. Unlike in PSLV, the GSLV flight sequence during the transition from first stage to second stage is done by first igniting the second stage and then separating the first stage. This results in elimination of retro and ullage rockets. A vented inter stage is introduced to expel the exhaust from the second stage. This also enhances the reliability of the system.

Complexity of the cryogenic stage

The cryogenic stage has a specification of 75 kN thrust and is loaded with 12.5 t of propellant containing LH_2 and LOX. The cryogenic stage uses two vernier engines for controlling the stage. The engine qualification involved 29 engines, each engine going through several hundred seconds of tests and multiple starts. One of the major challenges during the development phase of the cryogenic stage was defining the mechanical, electrical, thermal interfaces with ISRO subsystems and qualifying them through a series of joint hardware tests and software checks.

Total avionics system for cryogenic stage was realized by ISRO. Algorithms developed by GK were implemented in ISRO electronics. A number of interface checks were done at the level of the engine and through a series of cold and hot tests of stage using ISRO electronics. A technological mock-up was used to study the handling, transportation and assembly at the launch pad. The realization of the cryogenic umbilical arms for feeding the propellants and the safe retraction of these, just prior to take-off was a critical development.

Mission design

Modelling the vehicle dynamics during the lift-off phase of GSLV posed a major design challenge. Clearances with launch pad and umbilical tower for worst-case conditions of wind and other disturbances were analysed in detail. The safety aspects during normal and abort conditions were closely studied and thoroughly analysed using scale model cold flow and hot tests.

The vehicle is guided in open loop mode from lift-off till 10 s after the burnout of the GS1 stage. Subsequent to this, till satellite injection, it follows a closed loop guidance path. During the GS2 phase of flight, the guidance ensures that the stage, after its cut-off, does not impact beyond the safe zone specified with respect to land mass. Also, there was a requirement for authorization flag for the cryogenic stage to be issued at a pre-specified time before the GS2 phase cut-off, for attaining the proper ignition conditions for the cryogenic stage. To take care of all these requirements and to achieve an optimal solution, explicit E-guidance scheme is followed during the GS2 phase of flight. Further to this, to achieve pillbox conditions for the ignition of cryogenic stage, a guidance margin is provided in the GS2 stage. During the cryogenic stage flight, a more simplified flat earth guidance scheme is employed. Based on extensive studies and simulations, it was found that this scheme meets the necessary target conditions like perigee and apogee, in addition to the constraint of argument of perigee in a more optimal way.

The on-board software has been developed to meet the mission requirements considering all constraints during the flight. Hardware and software are validated exhaustively through hundreds of simulations using digital, processors-in-loop, actuators-in-loop and hardware-in-loop simulations. All subsystems are characterized either by theoretical studies or by experiments and these parametric values are used in the simulations. These simulations include normal flight performance with 3 sigma dispersions, stress cases to verify the software for extremes of vehicle performance and also failure cases. One noteworthy point in GSLV design is that altitude-based wind bias steering design has been introduced. Wind biasing has been done on the basis of similarity of wind conditions to provide 95% launch probability throughout the year ensuring minimal aerodynamic loads.

It was planned to ignite the liquid strap-ons during the final moments of countdown in order to check their performance and then ignite the solid core. This necessitated the development of a launch hold-and-release mechanism with stringent specifications, which was successfully developed and used in GSLV-D1 mission. The vehicle checkout system was also developed with decentralized set-up for checking different elements and with provision of synthesis and surveillance till the last minute.

Critical technologies for GSLV

The vehicle development was carried out in Vikram Sarabhai Space Centre (VSSC), Liquid Propulsion Systems Centre (LPSC), ISRO Inertial Systems Unit (IISU) and Sriharikota Range (SHAR). More than 150 industries were involved in the realization of various components and sub-systems. Several academic institutions/ national laboratories have contributed significantly in their specific areas. Some of the critical technology challenges during development included:

- Welding technology for aluminium alloy tankage for L40 strap-ons.
- Characterization of shut down transients of L40 and implementation of staging process.
- Design and development of separation systems for the stages.
- Complex mission studies during the atmospheric phase flight.
- Provision of increased margins, wherever possible, to enhance the system robustness.
- Characterization of vented inter stage and separation.
- Qualifying the interface between ISRO electronics and the cryostage through a series of tests, including hot tests.
- Establishment of the automatic filling system for simultaneously loading the L40 stages at launch complex.
- Establishment of the cryostage-filling system at the launch complex and demonstration through propellant-filling mock-up.

Cryogenic contract management

Management of the contract for cryogenic stages in view of the technical complexities and differing work cultures between the two participating countries was a major task. It required enormous efforts to interface suitably during the development of the engine and stage, to qualify the interfaces effectively, including a stage-level hot test, to accept and carry out interface checks of the cryogenic stage with equipment bay in a specially created technical complex at SHAR and to carry out cryogenic stage operations as part of the vehicle during the launch campaign. The qualification of the filling procedures at SHAR using a filling mock-up was a major effort. Mechanisms were also developed to certify the stage for flight assembly and launch operations and post-flight analysis.

GSAT-1 satellite

GSAT-1 weighing around 1540 kg was an experimental communication satellite. The spacecraft has three solar panels on south and a solar sail on north. This spacecraft is meant to be a test platform to flight-prove the new technologies like 10 N RCS thrusters, fast recovery star sensors, pyro electric earth sensor, heat pipe radiator panels, antenna-pointing mechanism, etc., in addition to communication experiments.

GSLV-D1 launch

Launch campaign for GSLV commenced at SHAR on 20 November 2000. After independent checks and filling up of fuel, GSAT-1 was encapsulated inside the payload fairing at assembly hall, a procedure different from that for PSLV. The countdown for the flight commenced on 26 March 2001. The countdown activities included:

- Filling up of earth-storable propellant for strap-on stages and second stage.
- Completion of pyro arming.
- Movement of mobile service tower and filling up of the cryogenic propellant.
- Automatic countdown by the computer commencing at T-12 min.

First launch attempt

The first launch attempt was made on 28 March 2001. However, the launch countdown was held at T-1 s and the launch was aborted by the automatic launch processing system (ALS) after detecting that one of the strap-on boosters did not develop the required thrust. During the abort of the L40 firing, the foam insulation pads on one of the strap-ons caught fire and were immediately quenched with water. Following the mission abort, the safety systems came into action to protect the launch vehicle. The vehicle was safely disarmed. Subsequently, all the propellants were removed from the vehicle.

Based on a detailed analysis of the data obtained during the 5 s operation of the strap-on motors during the countdown sequence, examination of the records of engine and tear-down-analysis of the disassembled engine, it was established that the reason for one of the strap-on boosters not developing the required thrust was due to a defective plumbing in the oxidizer flow line to the regulator of the engine, which had escaped detection during testing. This resulted in reduced flow of oxidizer to the engine and hence lower thrust.

Based on physical examination, analysis of the recorded data and subsequent tests, it was concluded that the fire spreading over one of strap-on boosters was limited to the burning of foam insulation pads and was incidental and did not cause any damage to the vehicle. It was decided to provide additional flame protection for these insulation pads.

The anomalous engine was replaced with a standby engine. All the other systems of the vehicle were examined in detail and were found to be healthy.

Launch of GSLV-D1/GSAT-1 mission

Subsequently, taking into account the preparedness of all the vehicle systems, the launch was rescheduled for 18 April 2001. Accordingly, the countdown was picked up on 16 April, with the start of fuel-filling operations. The mobile service tower (MST) was removed at T-16 h to enable further operations like the second-stage filling, cryofilling operations and global electrical checks. The ALS system took over the control of the vehicle checkout at 12 min prior to lift-off. The final countdown went very smoothly, without any 'hold'. The liquid strap-ons were ignited at T-4.6 s. After confirming that all the engines attained the required thrust, the launch hold-and-release mechanism was withdrawn on command. The ignition of the core solid-stage took place exactly at the opening of the launch window as planned. The vehicle took-off majestically from the SHAR launch base and after 1026 s of flight, injected the satellite into a GTO of 182.4×32140.6 km at 19.3 deg inclination, thus making India one of the select countries to possess the capability for launching communication satellites into GTO. The vehicle closely followed the predicted flight path as demonstrated in the altitude and velocity profiles shown in Figures 2 *a* and *b*.

GSLV-D1 performance

From lift-off till injection of spacecraft, all the vehicle systems functioned normally as seen from the telemetry and tracking data.

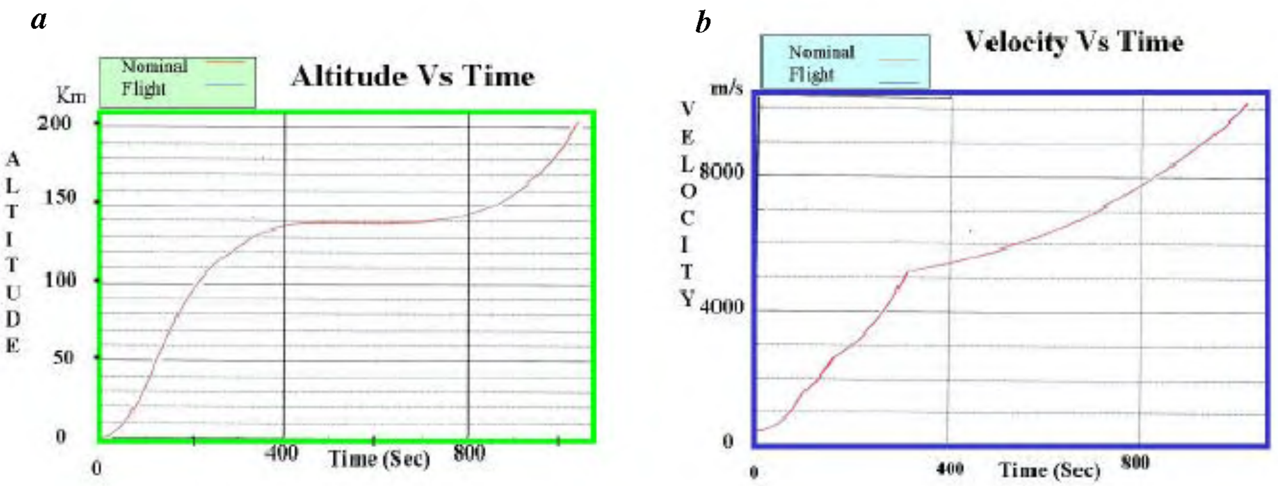

Figure 2. ***a***, Altitude profile; and ***b***, velocity profile.

Table 2. Solid core motor performance

Parameter	Predicted	Achieved
Action time (s)	100.7	100.32
Average pressure (MPa)	3.5	3.5
Maximum pressure (MPa)	5.1	5.1

Table 3. Liquid strap-ons' motor performance

Strap-ons	L1	L2	L3	L4
Average pressure (bar)	51.99	51.96	52.79	51.96
Burn time (s)	161.4	161.5	159.4	161.5

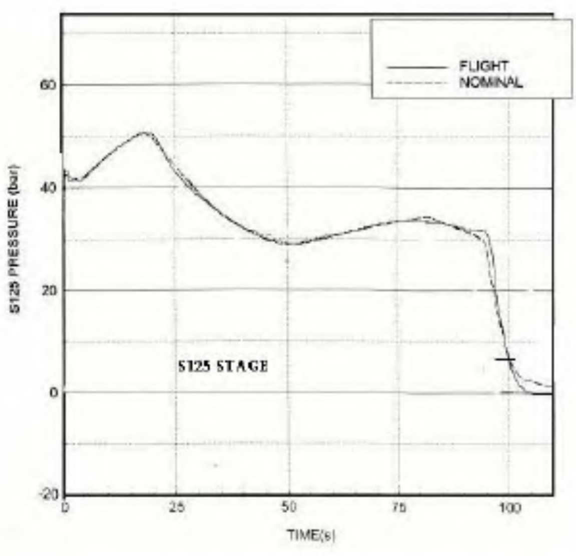

Figure 3. Solid-core motor performance.

GS1 stage performance

Solid core (S125) motor performance

The solid motor performance is well within the predicted performance as depicted in Table 2 and Figure 3.

Liquid strap-on (L40) motor performance

For the 4 liquid strap-ons labelled as L1, L2, L3 and L4, the motor performance was well within the predicted performance as depicted in Table 3 and Figure 4.

GS2 stage motor performance

The second stage, GS2, performed as per prediction and provided the required velocity till guidance issued the command to cut-off the stage on reaching the specified target. The performance of this stage is presented in Table 4 and Figure 5.

The GS2 stage placed the cryogenic upper stage along with the spacecraft into the targeted pillbox as presented in Table 5.

Cryogenic upper stage (CS) motor performance

The cryogenic stage burned for a duration of about 700 s and added an impulsive velocity of about another 5.2 km/s, taking the spacecraft into GTO. The cryo stage performance is presented in Table 6 and Figure 6.

The specification and the flight-achieved parameters in the injection conditions are given in Table 7.

The lower apogee in the flight was due to a shortfall in the total mission velocity by about 60 m/s (about 0.6% of orbital velocity requirement 10.2 km/s). This

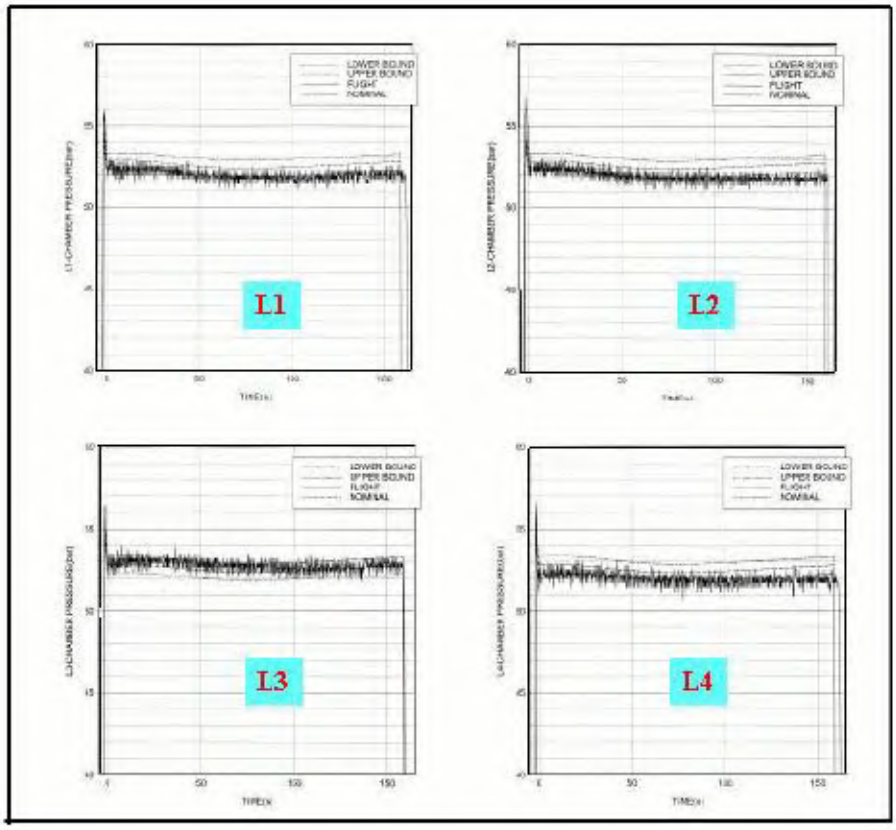

Figure 4. Liquid strap-ons' motor performance.

Table 4. GS2 stage motor performance

Parameter	Predicted	Achieved
Average Pc (bar)	52.6	52.6
Burn time (s)	150.08	148.10

Table 5. Cryogenic stage pillbox conditions

Parameter	Predicted	Achieved
Altitude (km)	127.1	127.0
Velocity (m/s)	5195.6	5194.7

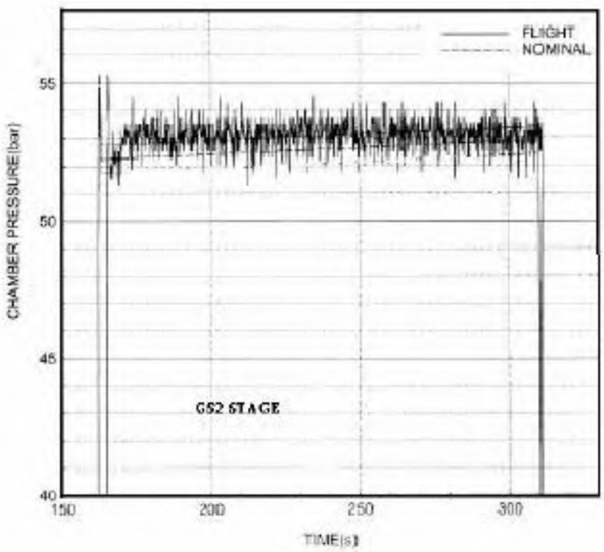

Figure 5. GS2 stage motor performance.

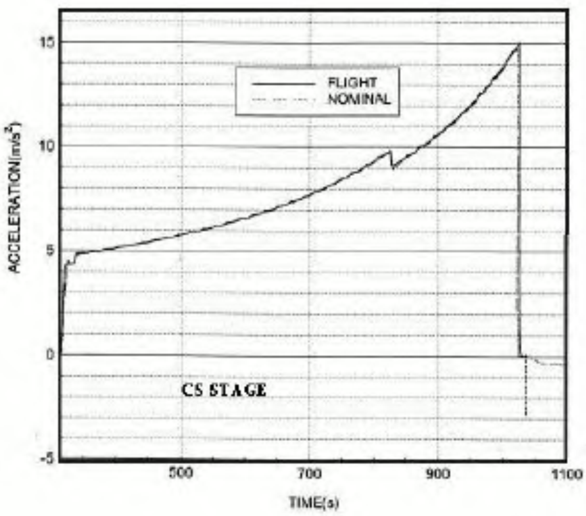

Figure 6. Cryogenic stage motor performance.

Table 6. Cryogenic stage motor performance

Parameter	Predicted	Achieved
Burn time (s)	709.96	705.86

Table 7. GTO injection parameters

Parameter	Specification	Achieved
Perigee (km)	180 ± 5	182. 4
Apogee (km)	35975 ± 675	32140.6
Inclination (deg)	19.3 ± 0.1	19.3

shortfall of 0.6% in the mission was corrected by the satellite propulsion system while raising the orbit.

GSAT-1 satellite performance

GSAT-1 was successfully injected into the GTO. Through a series of orbit-raising manoeuvres, the satellite was raised to near geo-synchronous altitude. Deployment of all systems, including the antenna reflector, solar array and the solar sail were successfully completed. Several new aspects of communication satellite technologies have been evaluated.

During the orbit-raising manoeuvre however, the differential flow rates from its two propellant tanks (known *a priori*) resulted in more than expected disturbance and the use of control thrusters of lower specific impulse for further orbit raising resulted in complete usage of propellant available on-board. This situation led the satellite to be in a drift orbit with an orbital period of 23 h 2 min.

GSLV project cost

The total GSLV project cost is Rs 1405 crores. This includes, cost of 3 GSLV vehicles on an average of Rs 150 crores, the cryogenic contract, development cost of vehicle systems and cost of establishment of facilities like launch complex cryo/earth storable facilities.

GSLV upgrades

Having demonstrated the validity of design in the first development flight, it is proposed to introduce graded improvements in the subsequent developmental flights. The candidate improvements for the next flight, scheduled in a year from now are: use of 138 t of propellant loading in core solid motor and higher pressure engines in strap-ons and second stage. The GSLV-MKII will use the indigenous cryogenic stage. This is proposed by the year 2003–2004. GSLV-MKII aims at 2000 kg payload in GTO.

Conclusions

In conclusion, GSLV-D1 launch mission has fulfilled all its intended objectives and injected the GSAT-1 spacecraft into the GTO. In the process, ISRO has attained a higher level of maturity to handle more complex missions under difficult environments.

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