PSLV-D1 mission

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The first developmental flight of the four stage Polar Satellite Launch Vehicle (PSLV D1) carried out from SHAR Centre, Sriharikota on 20 September 1993 is a major milestone in the country's march towards self reliance in the highly complex launch vehicle technology. The flight has demonstrated the performance of practically all the subsystems of PSLV and has validated the design aspects of the vehicle as well as the infrastructure needed for such an elaborate mission, even though the spacecraft could not be orbited due to unexpected disturbance to the vehicle around the separation of second stage from the third stage. This paper brings out the preliminary quick look results of the mission.

THE first developmental flight of the indigenously developed Polar Satellite Launch Vehicle (PSLV), PSLV-D1 took place on 20 September 1993 from the Sriharikota Launch Complex, 80 km north of Madras. PSLV is designed to place one tonne class Indian Remote Sensing Satellites (IRS) in Polar Sun Synchronous Orbit. PSLV-D1 carried a 846 kg IRS-1E (refurbished engineering model) satellite. Though the mission resulted in a suborbital flight with a height of about 350 km and a range of about 1700 km along the polar flight path due to the launch vehicle not being able to attain the required injection altitude and velocity conditions to place the satellite in 817 km polar orbit, the launch has demonstrated the design and successful functioning of almost all the subsystems of the vehicle encompassing technologies in multifarious fields such as propulsion, structures, aerodynamics, control, navigation, guidance and electronics.

The integration, checkout and launch of PSLV-D1 is the culmination of the developmental efforts of nearly ten years in the three major launch vehicle centres of ISRO, viz. Vikram Sarabhai Space Centre (VSSC), Liquid Propulsion System Centre (LPSC) and SHAR Centre in association with other centres of ISRO, national laboratories, academic institutions and industries. During this period many new technologies were perfected, new infrastructure were created and the lessons learnt from ASLV flights were fully incorporated.

Description of PSLV

The 44 metre tall, four stage PSLV, using solid and liquid propulsion systems alternately for its stages has a take-off weight of about 283 tonnes. The first stage (PS1) consists of 2.8 m diameter core motor made of maraging steel M 250 casing and uses Hydroxyl Terminated Poly Butadiene (HTPB) based solid propellant weighing 129 tonnes cast in 5 segments. The stage provides a maximum thrust of about 460 tonnes with a specific impulse of 264 seconds. The first stage has six solid strapon motors (PSOM) of 1.0 m diameter made of 15 CDV6 steel casing with a propellant loading of about 9 tonnes each. Each of the strapons, similar to the strapon motor of ASLV, provides a maximum thrust of 66 tonnes with a specific impulse of about 260 seconds. Thus the first stage of PSLV alone is equivalent to 14 times the ASLV core. The liquid second stage (PS2) is of 2.8 m diameter and carries 37.5 tonnes of UDMH (unsymmetrical dimethyl hydrazine) and N2O4 (nitrogen tetroxide) propellants stored in aluminium alloy, Al 7020 tank with the UDMH and N2O4 compartments separated by a common bulkhead. The stage uses a turbopump fed liquid engine. The stage provides a maximum thrust of 72 tonnes with a specific impulse of about 295 seconds. The third stage (PS3) is of 2.0 m diameter with a Kevlar–Epoxy motor case having 7 tonnes of HTPB solid propellant and provides a maximum thrust of 35 tonnes and has a specific impulse of 291 seconds. The liquid fourth stage (PS4) has a twin engine configuration with a total propellant loading of two tonnes. It uses MMH (mono methyl hydrazine) and MON (mixed oxides of nitrogen) as propellants stored in titanium alloy tank. These liquid engines are regeneratively cooled and pressure fed and each of them provide a thrust of 735 kg at a specific impulse of 307 seconds.

Each stage has its own control power plants for three axis control. The first stage uses a Secondary Injection Thrust Vector Control (SITVC) system having strontium perchlorate as injectant which is injected through a set of 24 valves located around the nozzle divergent. This provides control of the vehicle in pitch and yaw planes. The first stage also uses two Reaction Control Thrusters (RCT) to provide roll control during the thrust phase and an Auxiliary Control System (ACS) during the PS1–PS2 separation regime. Both the reaction control systems have bipropellant liquid thrusters using MMH and MON as propellants. In addition to these, one ground lit strapon and one air lit strapon are provided with independent SITVC systems to augment roll control in their respective flight regimes, if required. The second stage is provided

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with Engine Gimbal Control (EGC) system to provide pitch and yaw control during flight. The gimbal control is provided by electro hydraulic actuators which gimbals the engine about the required axis for a maximum of 4 degrees. The roll control is provided by the Hot Gas Reaction Control System (HRCM) which uses the hot gases bled from the gas generator of the engine. The control in pitch and yaw planes during the PS3 thrust phase is achieved using a Flex Nozzle Control (FNC) using two electro mechanical actuators. The roll control during thrust phase of third stage and control in all axes during the long coast of third stage, as well as after burn out of fourth stage till spacecraft separation, are provided by the fourth stage bipropellant reaction control system (RCS) employing MMH and MON. During the thrust phase of PS4, the control in all the three axes is achieved by the two axis Engine Gimbal system actuated by two electro mechanical actuators for each engine.

The vehicle electronics contained in the Equipment Bay (EB) and the Satellite mounted over the PS4 stage are protected from the hostile atmospheric environment by the heatshield. The bulbous heatshield of 3.2 m diameter and 8.3 m length is made of aluminium alloy isogrid construction and has acoustic blankets to protect the spacecraft from excessive acoustic loading.

Different kinds of separation devices are employed such as ball and socket type with spring thrusters for separation of strapons from core vehicle; Flexible Linear Shaped Charge (FLSC) system for first stage; merman band type for second stage and for fourth stage; ball type for third stage and zip cord linear bellow system and merman band type for heat shield. Retro solid motors mounted on PS1 and PS2 impart separation velocities to the spent stages and Ullage motors in PS2 provide positive acceleration to the stage before ignition.

The equipment bay housed around the PS4 stage contains the Navigation, Guidance and Control system (NGC) processors, Redundant Strap down Inertial Navigation System (RESINS), Tracking, Telemetry and Telecommand (TTC) packages, power supplies, sequencer electronics, etc. The Inertial Guidance system (IGS) performs the functions of navigation, guidance, attitude control and flight sequencing. Navigation function is accomplished by RESINS. Guidance and Control Processor (GCP) generates guidance, control and sequencing commands. The guidance system has digital autopilot software to provide the necessary attitude control error functions and commands. All the onboard telemetry parameters are transmitted through three different telemetry carriers to the ground using S-band transmitters. C-Band transponders are provided for tracking the vehicle during the entire flight regime. Tracking is also provided by the use of S-Band range and range rate transponders. The telecommand onboard the vehicle is used to terminate the flight by destroying the individual stages using destruct pyro devices in case vehicle deviates from the defined flight trajectory. During the atmospheric flight of 160 seconds, an open loop guidance scheme is used, after which the closed loop guidance system guides the vehicle till spacecraft injection.

Prelaunch preparations for PSLV-D1 mission

The subassemblies for PSLV-D1 from various work centres at VSSC, LPSC and SHAR were transported to SHAR launch complex for the final integration of the vehicle inside the huge Mobile Service Tower (MST), a 76 m tall, three thousand tonne steel structure moving on wheels. MST has all the facilities to handle the rocket assembly including an overhead crane of 60 tonne capacity and a clean room for spacecraft preparation and heat shield assembly. The launch campaign commenced with the stacking of the 25 tonne nozzle end segment of the first stage in May 1993. The assembly of all the four stages, the pyro devices and checkout of the electrical and mechanical interfaces went off smoothly. Finally the integrated vehicle was checked out using an automatic check out system with four mini computers and forty micro computers from the remotely located Launch Control Centre (LCC) six kilometers away.

The IRS-1E spacecraft, carrying one LISS camera built at SAC, Ahmedabad and a Monocular Electro-Optical Stereo Scanner (MEOSS) developed by DLR, Germany, was realized at ISRO Satellite Centre (ISAC), Bangalore. After completion of detailed checkout of all vehicle systems, the spacecraft was mated with the launch vehicle at T – 10 days. This was followed by detailed compatibility checks of the vehicle and spacecraft with participation of ground stations before and after heatshield assembly.

The exploded view of the PSLV with all its major subsystems is depicted in Figure 1. Figure 2 shows the sequence of the various flight phases of the vehicle.

The countdown

The countdown for the launch commenced on 16 September 1993, at T – 72 hours (T being the launch time). It started with filling of non-hazardous fluids such as strontium perchlorate for the SITVC, helium and nitrogen gas. Later, the propellant (MON, MMH, N_2O_4 and UDMH) filling operations for the second and fourth stages were carried out using the automated checkout system. Arming operations for nearly 160 onboard pyro elements formed a major part of the countdown. Different phases of pressurization of all high pressure systems were also carried out. From T – 8 hours onwards the warming up of inertial sensors, their calibration and alignment as well as detailed checks on flight computers, instrumentation and power supply were carried out. During the last 10 minutes, nearly 50 commands were issued by the

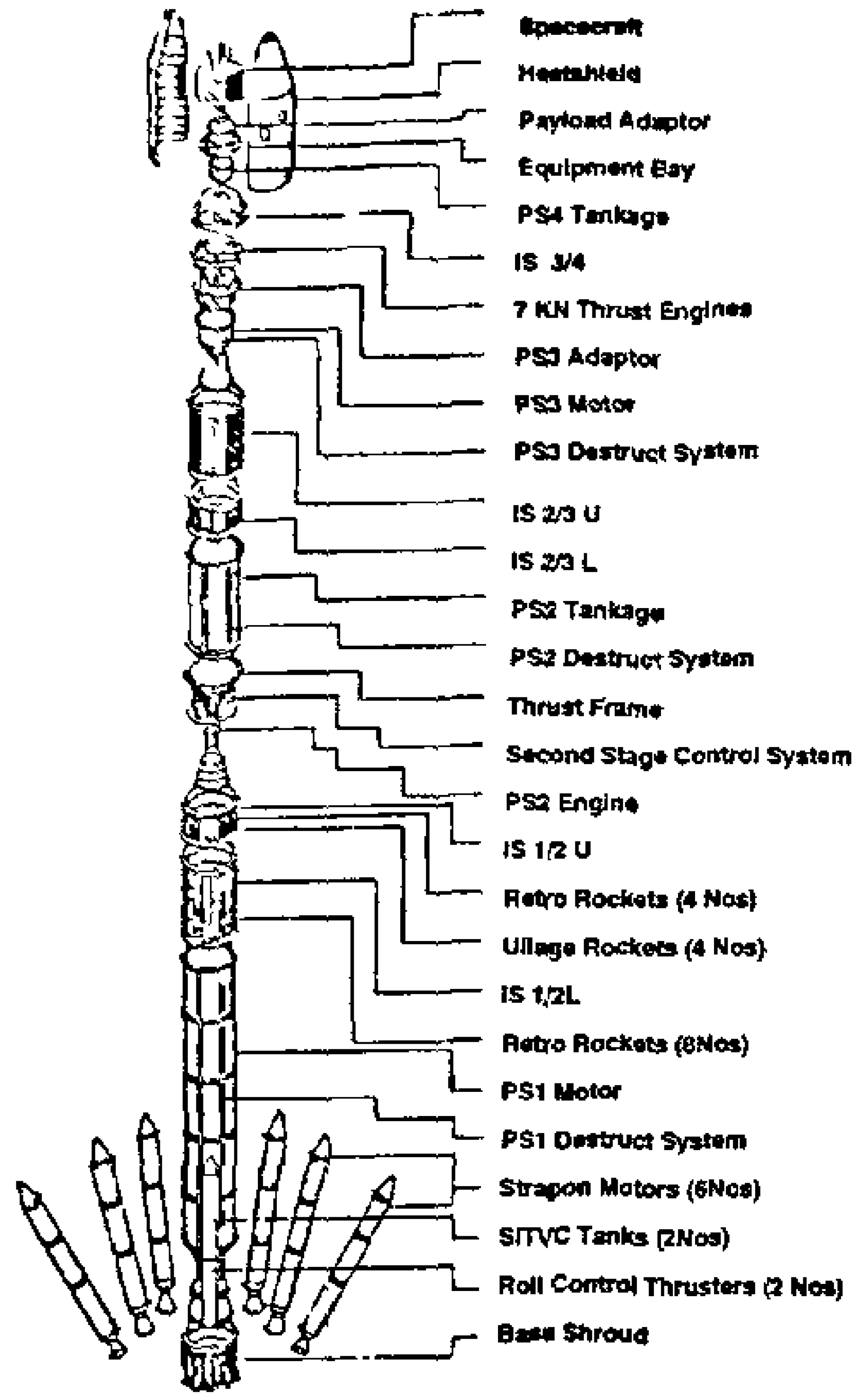


Figure 1. PSLV exploded view.

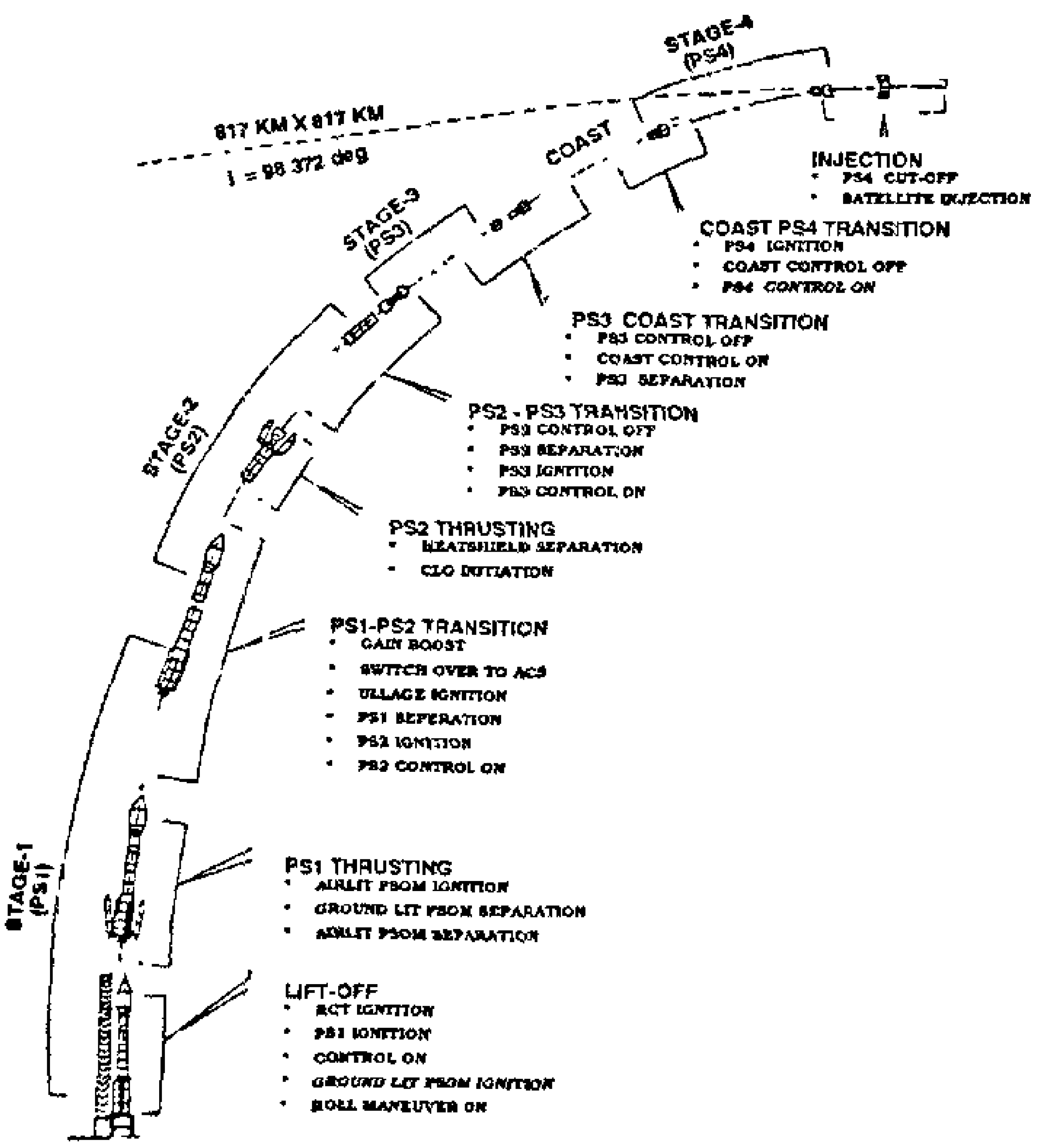


Figure 2. PSLV flight phases.

Automated Launch Processing System (ALPS). The ALPS also monitors nearly 500 parameters on the health of the onboard subsystems and would hold the countdown automatically in case of any deviation beyond specified limits.

The countdown which was proceeding smoothly was held at T – 3 hours on 19 September 1993 at which time an anomaly was detected by the checkout computer. Further analysis indicated that the onboard systems were functioning normally and that the snag was due to an error in decoding of data by the checkout computer. This was corrected and the launch was rescheduled for the next day, i.e, 20 September 1993 between 1014 and 1054 hours. After a thorough check, the countdown was resumed at T – 10 hours on 19 September 1993 and it proceeded smoothly. There were three minor holds during the final phase of countdown and these were cleared after ensuring that the health of vehicle was normal. The holds are part of any launch vehicle countdown to ensure that the health of the vehicle is normal till launch.

Lift-off

Three seconds before lift-off, the two reaction control thrusters of the first stage were ignited and their normal functioning was confirmed by the redundant monitoring parameters by ALPS prior to issue of ignition command to the first stage. From then onwards nearly sixty events were automatically commanded in flight by the onboard computer.

The first stage thrust built up in about 600 milli seconds after ignition command and lift-off of the vehicle was detected by the snap of the last minute plug at T + 860 milli seconds. This detection of event by computer set in motion the flight events, some of which were preprogrammed and others were based on real time detection of specified parameters on board. The first two strapons were ignited at 1.3 seconds after lift-off and the vehicle rose vertically for 5 seconds by which time it cleared the umbilical mast.

The lift off, one of the critical phases of flight for any launch vehicle was thus absolutely normal. Later inspection of the launch pad indicated that the launch pedestal and umbilical mast which got the full blast of the first stage exhaust requires negligible maintenance to get ready for the next flight. A host of new techniques involving vehicle-launch pad interface such as the launch pedestal, jet deflector, thermal protection, lift-off dynamics have hence been validated.

First stage flight regime

The roll command was given at T+5.9 seconds to roll the vehicle by 5 degrees and to align it to 140 degree azimuth. The pitch programme was also initiated. The flight regime through atmosphere for the first stage is the most difficult one posing a number of aerodynamic, structural and control problems. In order to reduce the severity, the stage was put on gravity turn flight path until burn out. The main motor reached its peak performance at 17 seconds delivering a maximum thrust of 460 tonnes. The remaining four strapons were ignited at T+30.3 seconds. The transonic regime occurred around 35 seconds at an altitude of 4 to 5 km. Maximum disturbance to the vehicle was noticed around 62 seconds at about 16 km where the dynamic pressure was high and atmospheric winds also reached their maximum. The phase where PS1 and all the six strapons burnt simultaneously was smooth and as predicted. The two numbers of ground lit strapons were separated at about 73.3 seconds and the air lit four strapons were separated at 90.3 seconds as planned. The first stage burn out was detected by onboard computer at 103.6 seconds. The most difficult part of controlling the attitude of the vehicle during transonic, high dynamic pressure and heavy wind conditions was managed perfectly by the digital auto pilot using SITVC and gimbal reaction control thrusters. Figures 3, 4 and 5 show the actual performance of the PS1 motor, two ground lit strapons and that of the four air lit strapons respectively. The performances of all these seven motors were well within the limits of prediction. The errors in pitch, yaw and roll are shown in Figures 6, 7 and 8 respectively and they were all within the designed specifications in this flight regime.

PS1–PS2 transition

After burn out of the first stage, the vehicle was coasted for a period of 5 seconds to bring down the tail off thrust to within manageable limits for PS1 separation. The auxiliary control system for management during the transition between first and second stage came on as desired. This is required since the first stage control system SITVC depends on main propulsion and its effectiveness will come down during the tail off of the first stage. The ullage rockets were fired at 105.2 seconds to ensure that positive acceleration was available for the liquids in the second stage to stay in place. The command for PS1 separation at 108.6 seconds was followed by ignition of second stage in 200 milli seconds. The separation was effected using FLSC system initiated through a remote mounted safe arm unit. The pull out of the second stage nozzle from the 4.7 m long interstage was effected

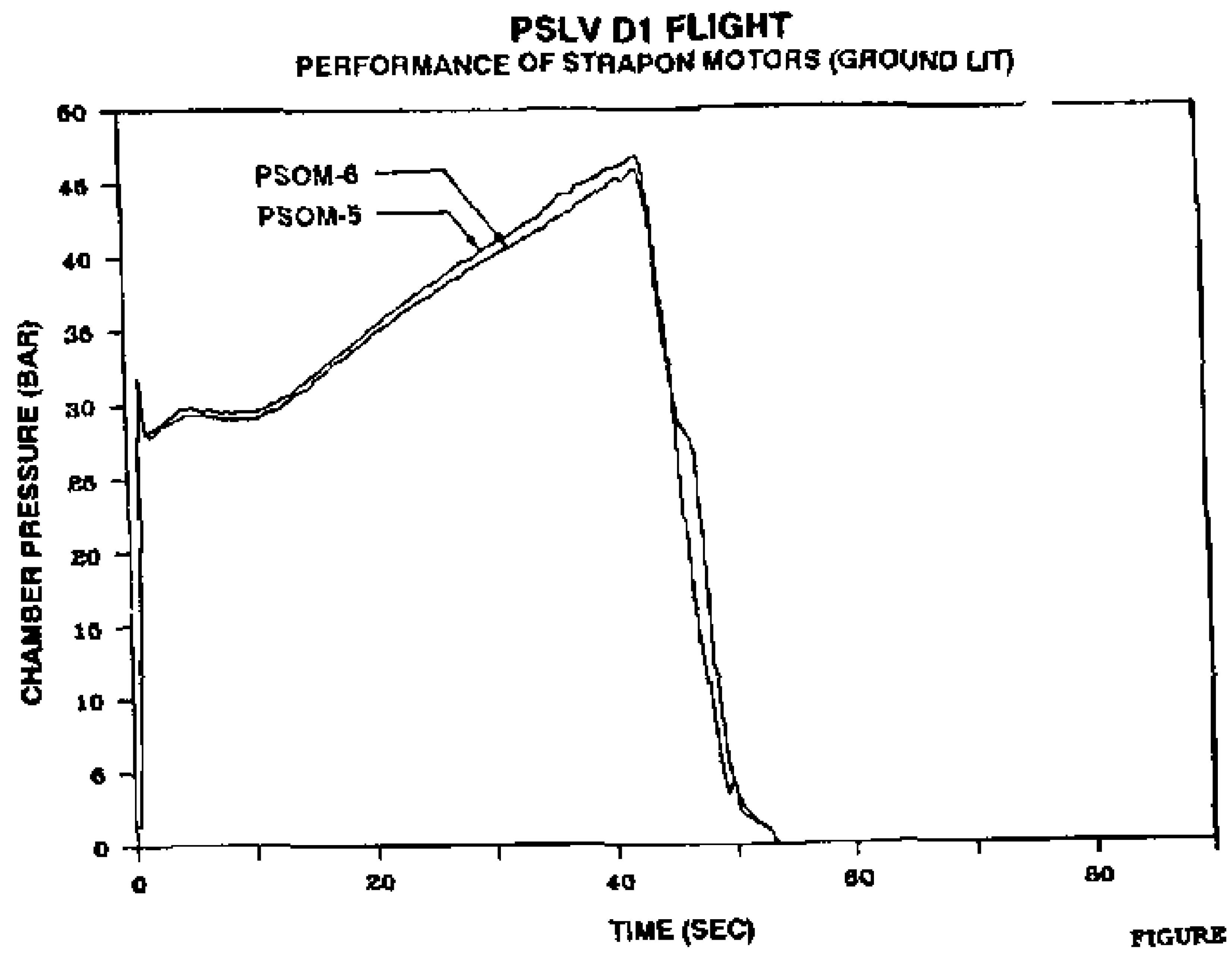
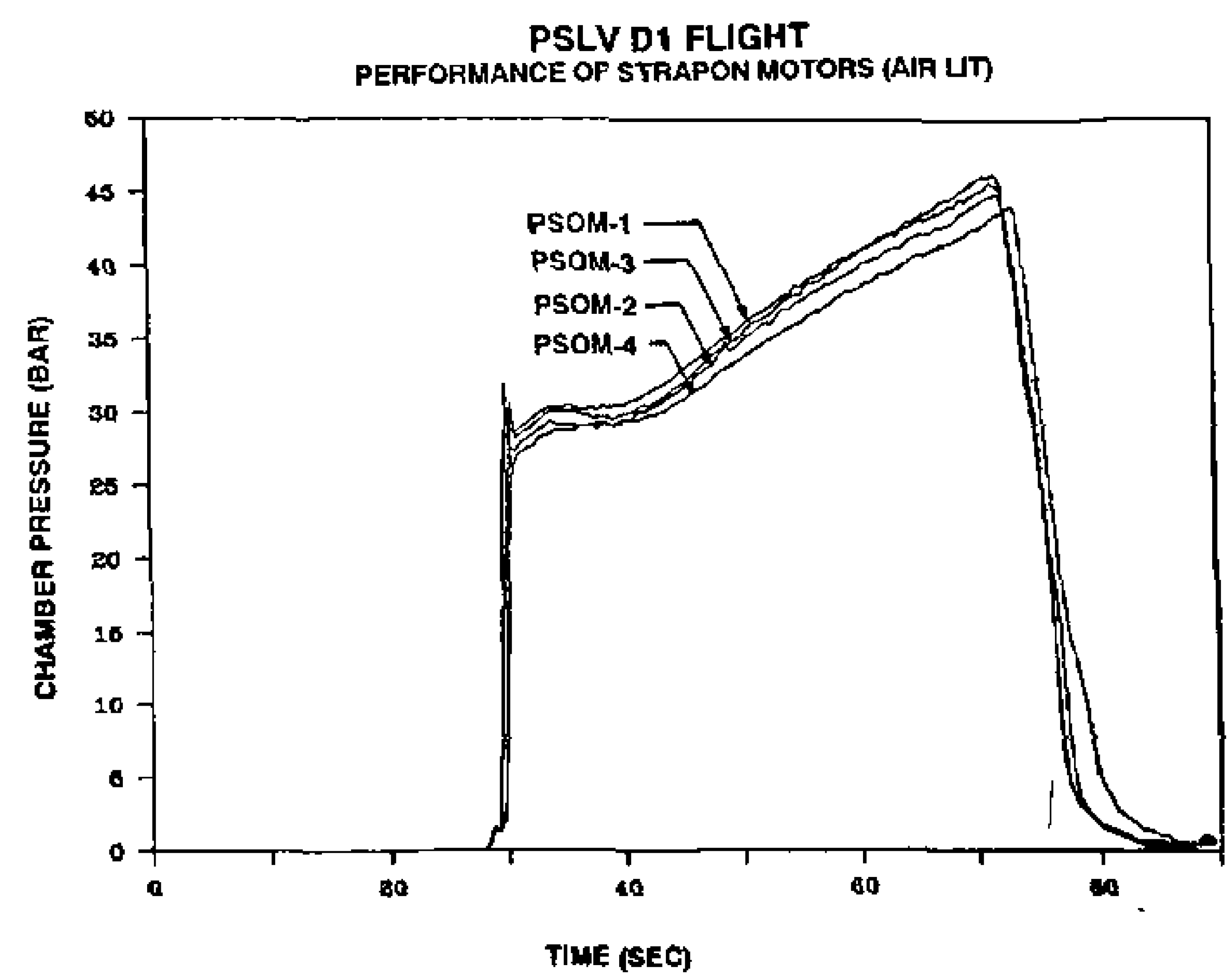


Figure 4.



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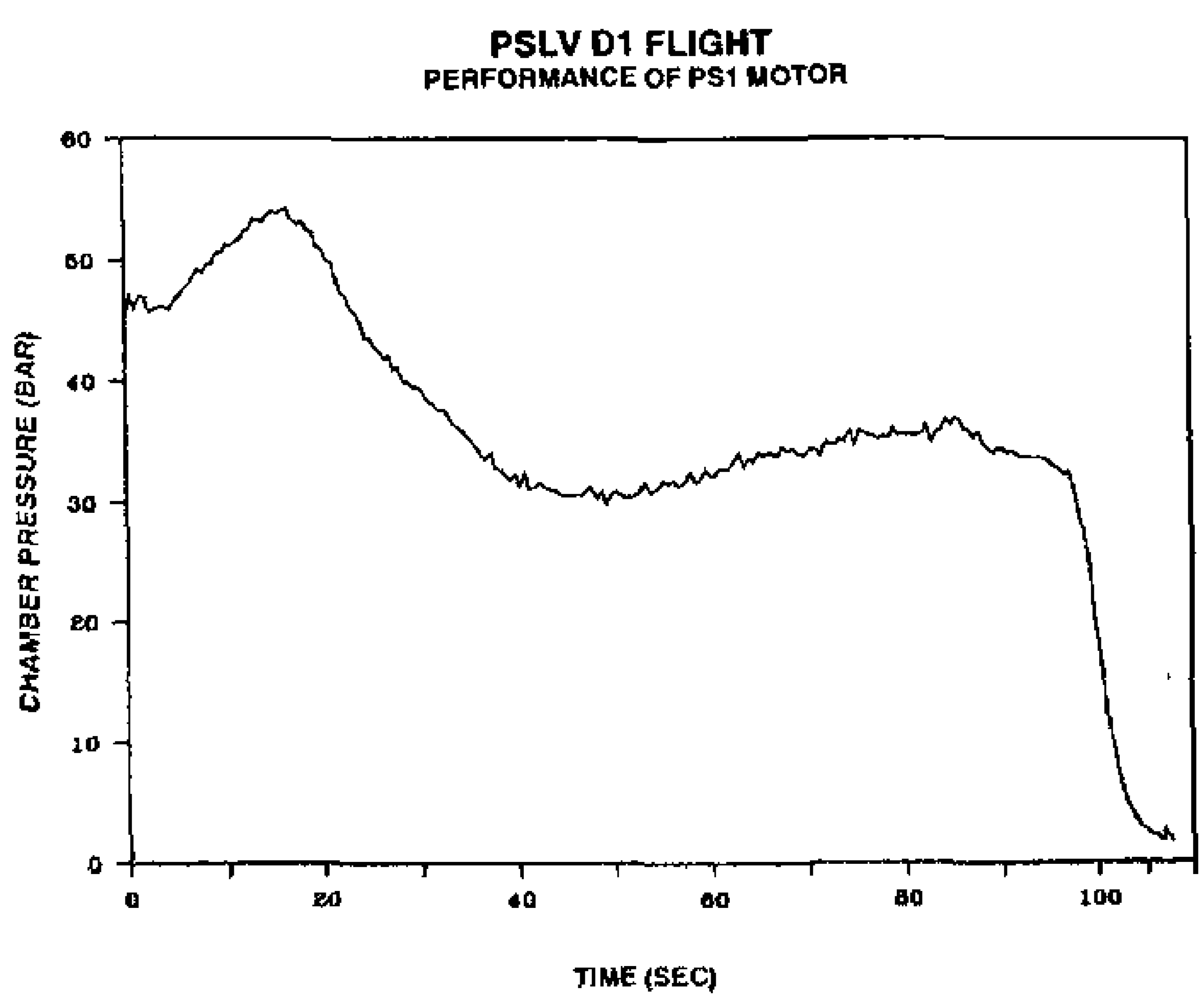

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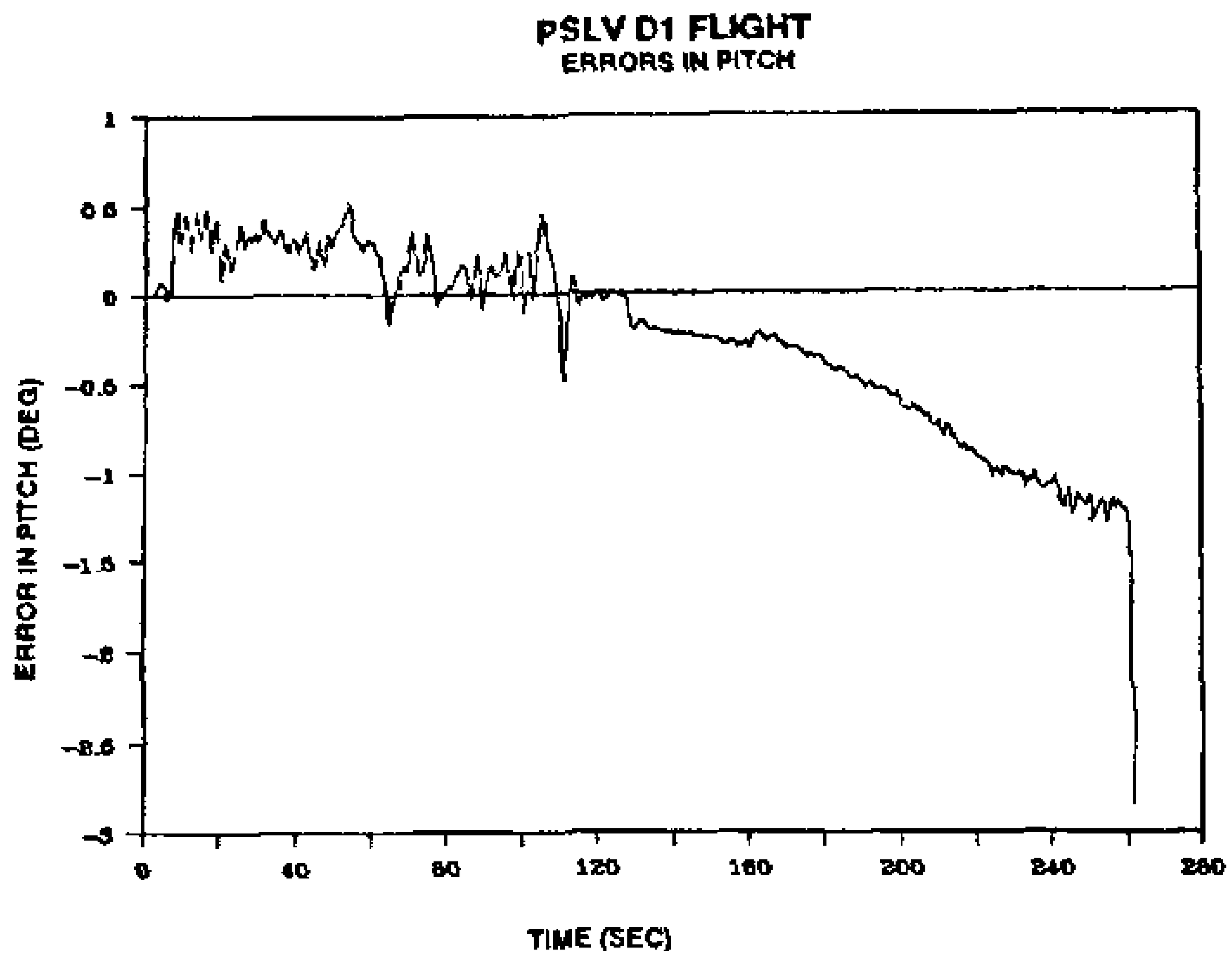

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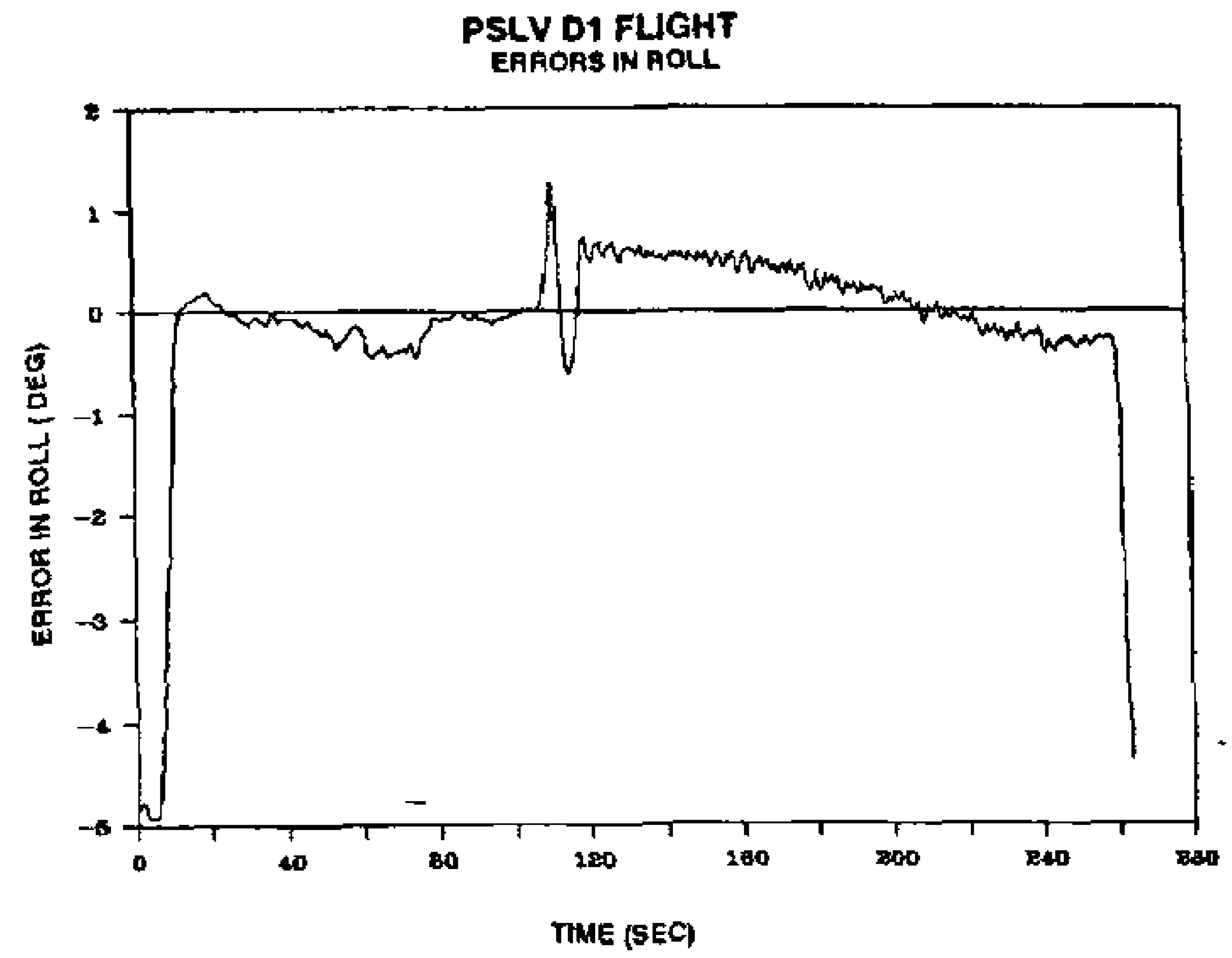

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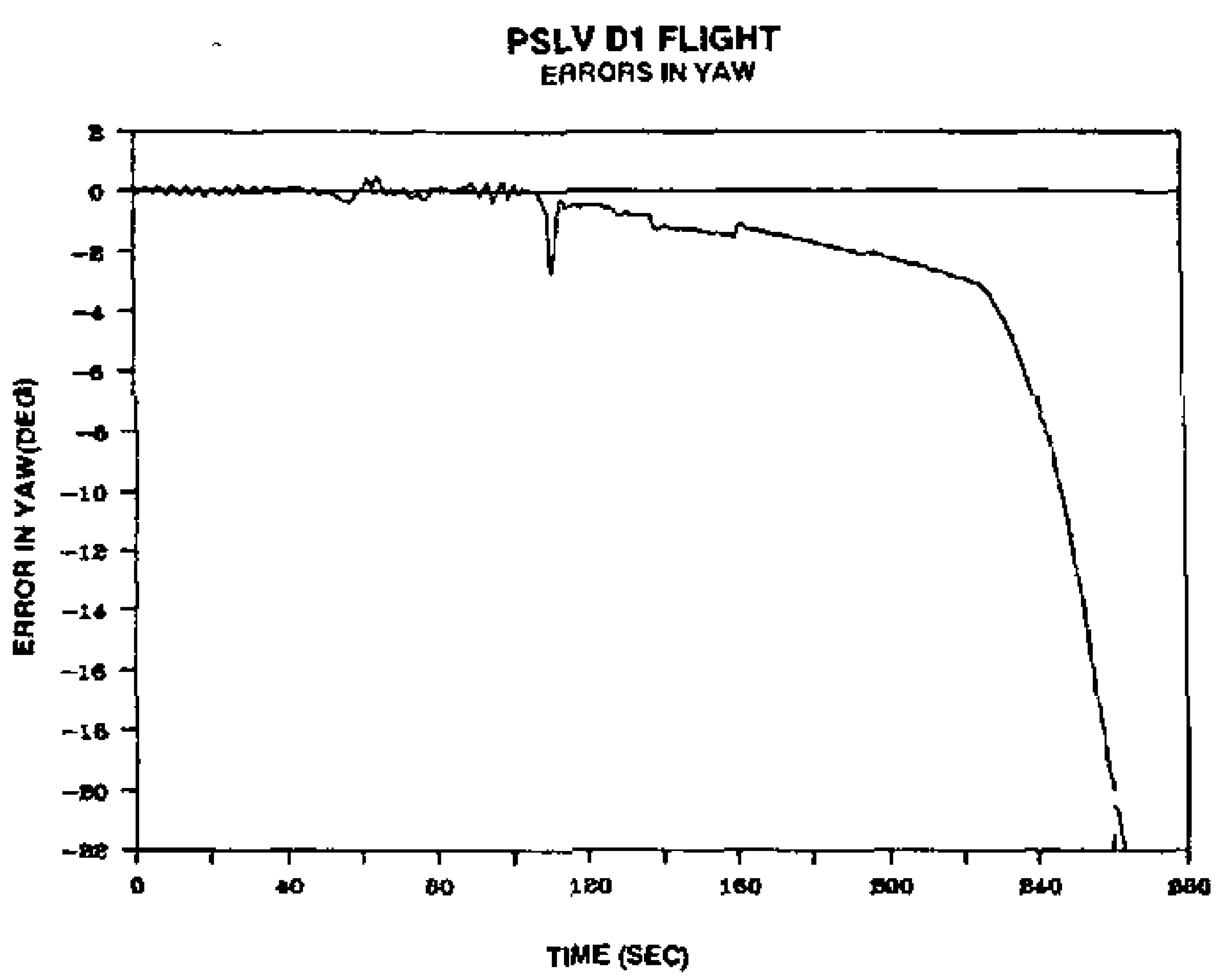

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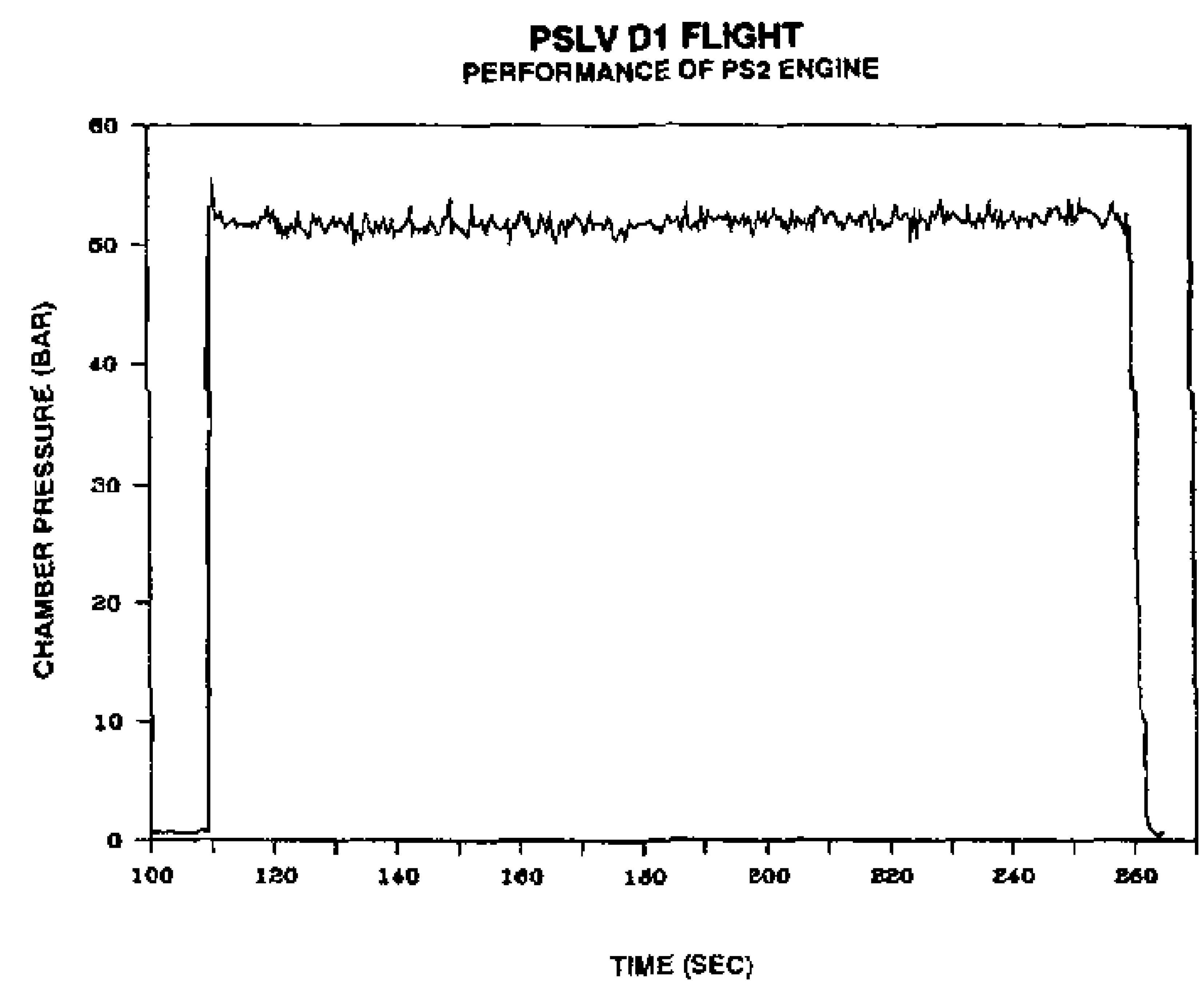

Figure 9.

using 8 nos. of retro rockets. The staging event between PS1 and PS2 is the most critical one in the entire flight regime.

Second stage flight regime

The PS2 engine developed the full thrust of 72 tonnes within 2.8 seconds as expected and its performance was steady throughout the burn duration of 152 seconds as seen in Figure 9. The initial disturbance to the stage was captured by the attitude control systems as predicted with the use of engine gimbal control actuators. At the beginning of the second stage regime, the yaw maneouver was started so as to put the vehicle along its polar path from 140 degrees azimuth which meant that its ground trace was along the Indian and Sri Lankan coast in the international waters as desired. The large heatshield of 3.2 m dia and 8.3 m long was separated into two halves and jettisoned at 155.6 seconds while the vehicle was thrusting. The merman band and zip cord system for this event performed normally without causing any disturbance to the vehicle or to the spacecraft. Just after heatshield jettisoning, closed loop guidance was initiated for position and velocity correction to the vehicle to achieve the injection of the spacecraft into a precise orbit.

PS2–PS3 transition

The tail off of the second stage was detected by the computer at 261.5 seconds which initiated subsequent sequence of events. The separation commands were issued three seconds later and the ignition command for the third stage 1.2 seconds thereafter, as planned. When the third stage was ignited at 265.7 seconds, the vehicle was at an altitude of 249.5 km with a velocity of 3.83 km per second. The trajectory up to this moment as measured by RESINS and telemetry matched almost exactly with that observed by the high precision tracking radars at SHAR and Thiruvananthapuram and was as expected.

The telemetered chamber pressure history of the third stage shown in Figure 10 confirmed normal performance of this motor for a total duration of about 81 seconds. However, in spite of full actuation of the flex nozzle control system, the unexpected large disturbance around the second stage separation could not be overcome and the vehicle went into an abnormal angular motion. This resulted in the vehicle reaching only 340 km altitude as against the planned altitude of 414 km during third stage separation at 383.8 seconds and the velocity was 3.54 km per second instead of 5.98 km per second expected. This loss of velocity and altitude resulted in a suborbital flight of the vehicle.

Flight regime beyond third stage separation

The fourth stage was ignited at 565.2 seconds as planned. Both the engines of the fourth stage developed full thrust and the engine gimbal system functioned normally. From the steady performance shown by the engines for more than 80 seconds as shown in Figure 11, it is clear that the fourth stage would have continued to do so, if the flight had been normal.

The telemetry data confirmed normal performance of

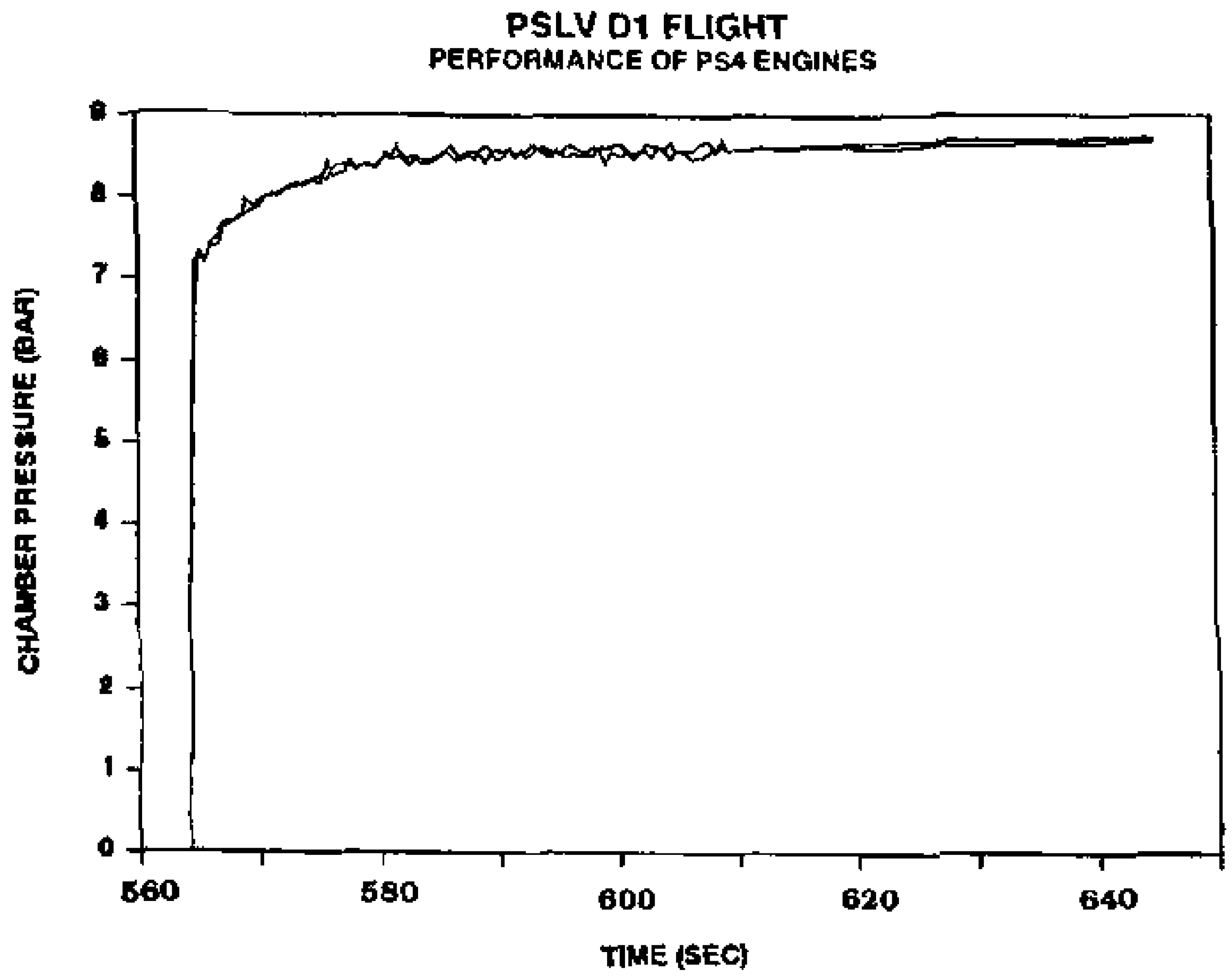

Figure 11.

all the subsystems during the entire regime of flight data recorded for 693 seconds.

Figure 12 gives the chronological history of various flight events compared with expected.

Telemetry and tracking

The ground stations at SHAR and Thiruvananthapuram recorded excellent quality of telemetry data. The vehicle was tracked by high precision C-Band Radar and S-Band Range and Range Rate System. The Down Range Station at Mauritius was standing by to receive the data. However, the vehicle did not attain sufficient altitude and velocity to be within its visibility. The spacecraft was switched on right from take-off and signals received confirmed normal performance.

The telemetry data received from lift-off till 693 seconds

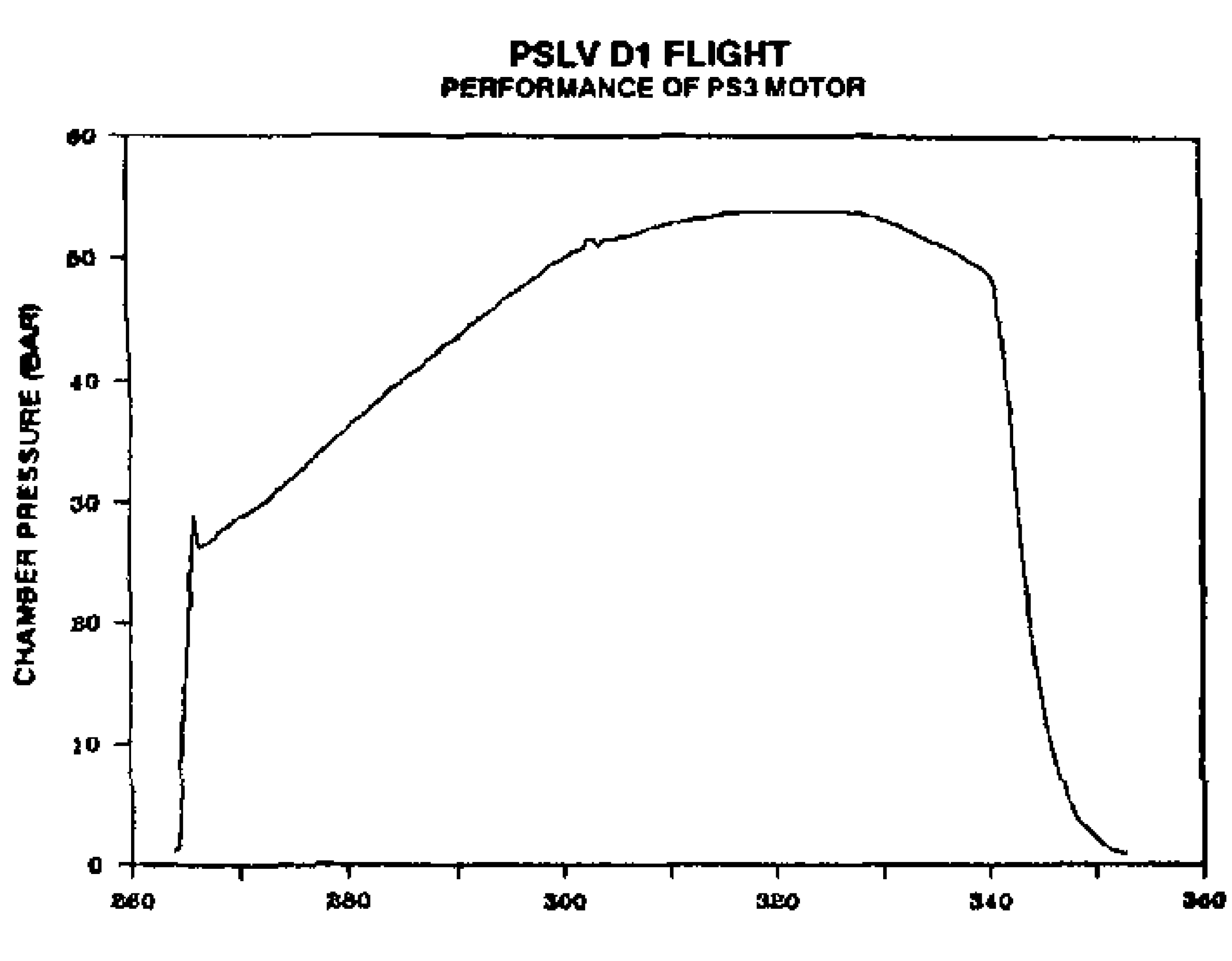

Figure 10.

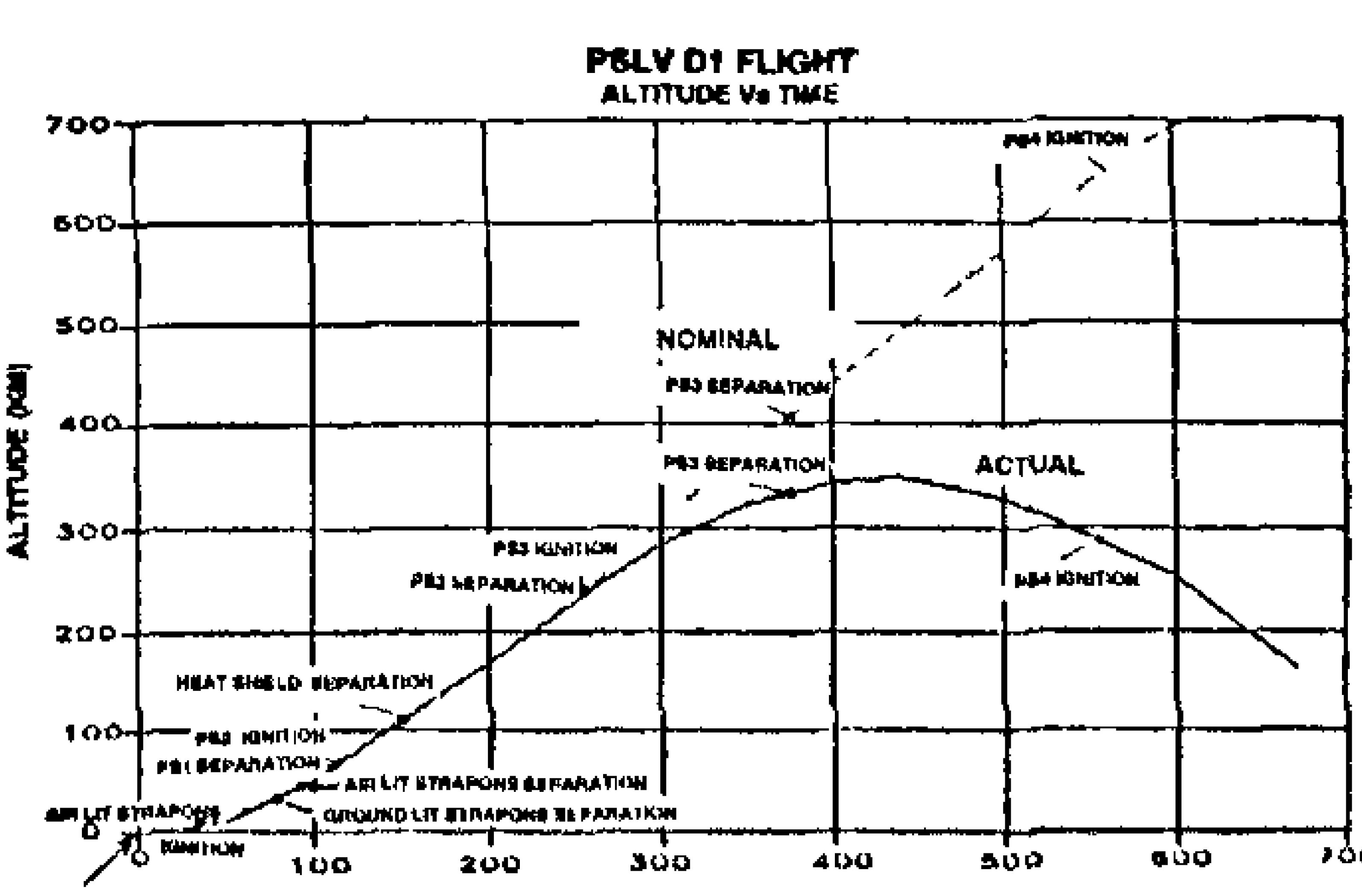

Figure 12.

were of excellent quality. Nearly one billion bytes of data were recorded. They are being converted into engineering units and are being analysed to confirm performance of various subsystems and to pin point the reason(s) for the anomaly during the second and third stage transition.

PSLV-D1 Mission accomplishments

The satisfactory performance of practically all the vehicle subsystems has given confidence in the design and development of large rocket motors, their control systems, guidance, navigation and auto pilot, structural hardware, software for implementing various onboard functions, mission design and launch campaign management encompassing vehicle integration, propellant servicing, checkout operations as well as real time computer system and TTC networks. The data collected through telemetry and tracking confirm satisfactory performance of almost all the 79 subsystems. The PSLV-D1 mission has proved many technologies which were successfully developed afresh. The following are just a few of the major developments accomplished and validated through the mission:

- Proving the giant solid booster along with six strapon motors in the most difficult zone of flight in atmosphere.
- Flight testing two liquid stages for the first time.
- Evaluation of high performance third solid stage motor.
- Altogether, 10 major rocket motors were flight proven and 30 other small motors were tested under various environments in flight.
- Flight evaluation of RESINS with a performance matching with the tracking data from precision radars.
- Linking of six onboard computers in redundant configuration to carry out the flight management functions of navigation, guidance, digital auto pilot and sequencing.
- Evaluation in flight of new control systems using engine gimbal and flex nozzle.
- Qualification of giant light alloy structures.
- The large bulbous heat shield employing isogrid technology.
- Development of a variety of control components and control systems.
- Reliable pyrotechnic systems.
- Variety of stage separation devices and heatshield jettisoning system.
- The mission integration and management involving host of complex technologies.

The major facilities created include:

- Sea level as well as high altitude test facilities at Mahendragiri for qualifying both second and fourth stage liquid engines;
- Large fabrication facilities to deal with 2.8–3.0 m rocket hardware, titanium machining and welding;
- Production facilities for propellants;
- Propellant casting and curing facilities and static testing facilities for 125 tonne solid boosters ;
- Facilities for qualifying massive light alloy structures and heatshield;
- Assembly, integration, checkout and ground resonance testing facilities at Valiamala near Trivandrum;
- Facilities for testing inertial sensors and simulation of entire mission;
- Facilities for testing stage separation and heatshield jettisoning;
- Massive mobile service tower;
- Sophisticated mission/ launch control centres at SHAR;
- High precision radars in C-Band positioned at SHAR and Mauritius;
- Beryllium machining facility.

While detailed failure analysis is being carried out, actions for the realization of flight systems for the next flight are being taken up parallelly to realize the next flight of PSLV as soon as possible. The cost of each PSLV is only about Rs 45 crores. The total cost of PSLV project is about Rs 415 crores which includes two rocket flights and all the infrastructure created as well as the cost of development and tests. The cost of two PSLV rocket flights and essential standbys is about Rs 100 crores. The rest is towards the cost of various infrastructure created at SHAR, Valiamala and Mahendragiri. All these will be available not only for PSLV programme, but also for the GSLV programme.

In summary, the flight has validated practically all the PSLV subsystems in flight and the facilities and techniques for such a complex mission. In particular, the critical modules to be used in GSLV, viz. the solid first stage motor system and the liquid second stage have been flight validated.

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