Growth of capabilities of India's launch vehicles

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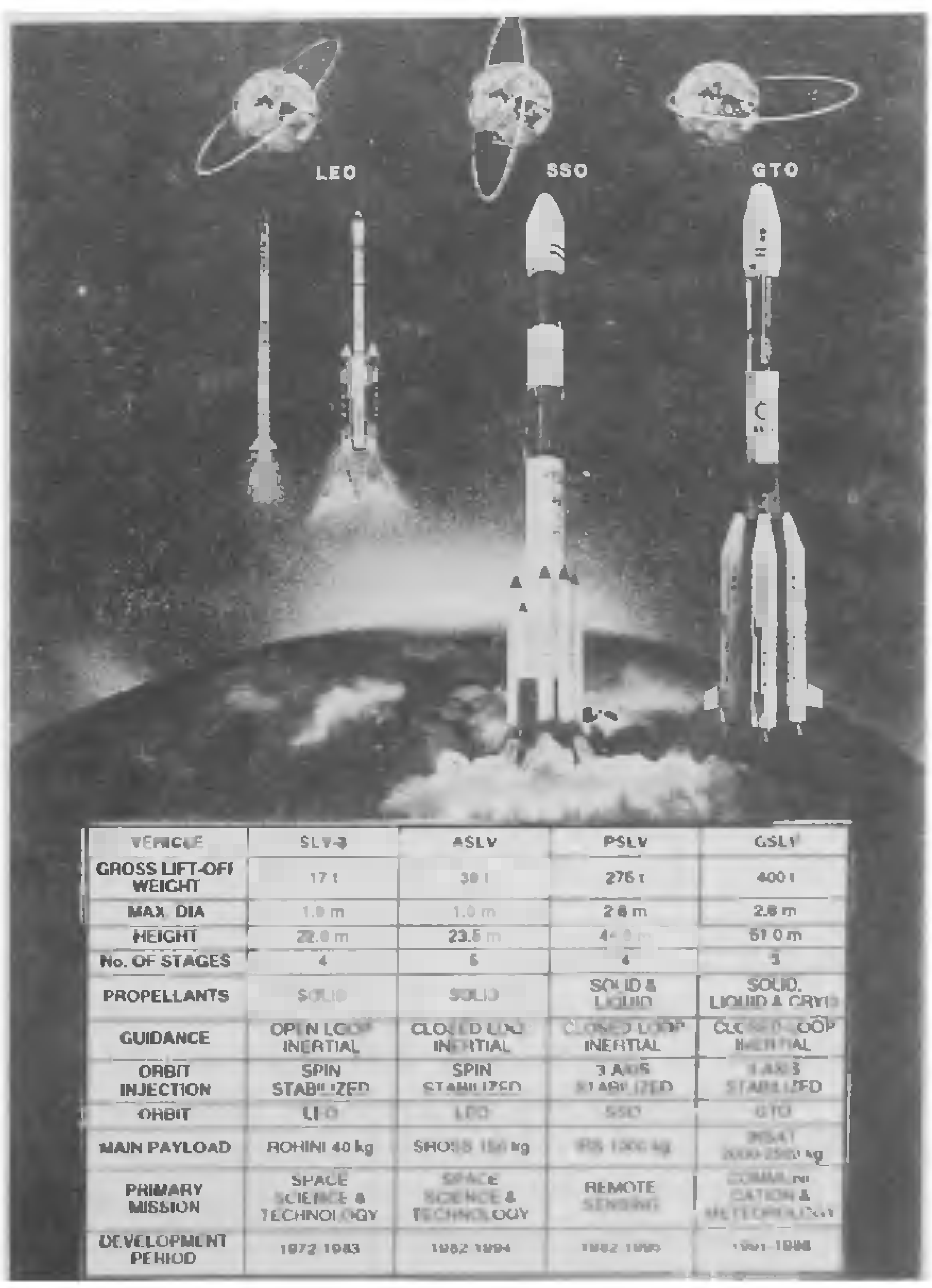
Need of different types of launch vehicles in the space programme of India is discussed. In the context of the successful missions of ASLV-D4/SROSS-C2 and PSLV-D2/IRS-P2, the growth of the capabilities of the launch vehicles is examined in terms of the accuracy of injection of satellites in orbits and the mass of satellites.

BRILLIANTLY successful missions of ASLV-D4/SROSS-C2 and PSLV-2/IRS-P2[1], in a short span of six months in 1994 are amongst the most important milestones in India's space programme and constitute gigantic achievements for a wide spectrum of science, technology and industry community in the country. These systems were conceived, configured, developed, designed and built in India with extensive participation of the Indian industry and a high degree of self-reliance. The countdown preceding the launches, which comprises loading the liquid fuels and pressurant gases, arming the pyro-devices and computerized checking of the health of hundreds of on-board and ground support modules, proceeded smoothly and permitted the launches to take place within extremely narrow launch windows. The satellites, specially IRS-P2, were injected into orbits with world-class accuracy. All these testify to the elegance of the system architecture, robustness of design, high quality of workmanship in fabrication and assembly and world-class performance of the vehicle subsystems.

The main purpose of this brief article is to assess the improvement over the years in orbital injection accuracy and growth of the payload capability of the launch vehicles of ISRO. To provide the perspective, the different types of orbits, satellites and launch vehicles needed to realize the objectives of India's space programme are described. The differences in the launch sequences and orbit injection methodologies used in ASLV and PSLV are explained. Pre-launch estimates and actual performance of the landmark missions, namely, SLV-3-D2, ASLV-D4 and PSLV-D2 are discussed to assess the improvement in orbital injection accuracy. Finally, the actual and projected capabilities of the vehicles for different orbits are presented to bring out the growth in payload capabilities.

Space programme objectives and launch vehicles needs

As is well known, the major objectives of India's space programme are to use space technology to strengthen the infrastructure in the country for weather monitoring and forecasting, communications and natural resources monitoring and management. The chosen pathway to these objectives is through progressive self-reliance. Accordingly, a related objective is to conduct research and development in space science and technology. To realize these objectives, suitable satellites need to be placed in their specific orbits, namely, low earth orbits



VEHICLE	SLV-3	ASLV	PSLV	GSLV
GROSS LIFT-OFF WEIGHT	17 t	[illegible]	276 t	400 t
MAX. DIA	1.0 m	1.0 m	2.8 m	2.8 m
HEIGHT	22.0 m	23.5 m	[illegible]	51.0 m
No. OF STAGES	4	5	4	3
PROPELLANTS	SOLID	SOLID	SOLID & LIQUID	SOLID, LIQUID & CRYO
GUIDANCE	OPEN LOOP INERTIAL	CLOSED LOOP INERTIAL	CLOSED LOOP INERTIAL	CLOSED LOOP INERTIAL
ORBIT INJECTION	SPIN STABILIZED	SPIN STABILIZED	3 AXIS STABILIZED	3 AXIS STABILIZED
ORBIT	LEO	LEO	SSO	GTO
MAIN PAYLOAD	ROHINI 40 kg	SROSS 150 kg	IRS 1000 kg	INSAT 2000-2500 kg
PRIMARY MISSION	SPACE SCIENCE & TECHNOLOGY	SPACE SCIENCE & TECHNOLOGY	REMOTE SENSING	COMMUNICATION & METEOROLOGY
DEVELOPMENT PERIOD	1972-1983	1982-1994	[illegible]	[illegible]

Figure 1. ISRO launch vehicles and missions

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(LEO), sun-synchronous orbits (SSO) and equatorial geo-stationary transfer orbits (GTO) as depicted in Figure 1. As the size and calibre of the vehicle to launch the various types of satellites in different orbits are different, ISRO needs to have in its stable different types of launch vehicles. Of course, one large vehicle can, in theory, service all the requirements once the development is completed. However to use a large launch vehicle for a mission which can be performed by a smaller launch vehicle is neither efficient nor cost-effective, unless there is a real need for putting a number of such satellites in orbit in one launch. In any case, the *ab initio* development of technologies needed for launch vehicles and forced on ISRO by international restrictions and the absence of substantial expertise in the country requires going through a few carefully planned steps from the small to the large vehicles.

Figure 1 also gives the various types of satellites and the corresponding launch vehicles along with their general characteristics and approximate period of development. The figure brings out the increase in the variety of propellants used, from solid only in SLV-3 and ASLV to solid and liquid in PSLV and, finally, to solid, liquid and cryo in GSLV. In the guidance area switchover from open-loop inertial to the more sophisticated closed-loop inertial may be noted. Similarly, the adoption of the expensive but more accurate three-axis stabilized orbital injection technique in PSLV and GSLV in place of the economic but less accurate spin-stabilized injection method in SLV-3 and ASLV may be noted. A progressive reduction in the number of stages to improve the reliability and vehicle preparation effort is also noteworthy. In the case of geostationary satellites, the job of the launch vehicle is generally over once the satellite is injected into GTO. Hence, the geostationary satellite launch vehicles are configured for a GTO mission. The apogee kick motor (AKM) on-board the satellite takes it from GTO to GSO (geostationary orbit) through ground-based orbit tracking and telecommand.

Guidance and orbit injection technique

The launch sequence and trajectory of a mission are designed to achieve the required orbital injection conditions, namely, the altitude and the magnitude and direction of velocity of the satellite at the burn-out of the last stage of the vehicle. Optimization is attempted to maximize the satellite mass while respecting the range safety considerations and the maximum limit prescribed for the loads on the vehicle structure during the flight under the expected wind conditions and auto-pilot operations. One important result of the launch sequence and trajectory design is the vehicle attitude variation required to be implemented in flight, known as the vehicle attitude programme (VAP), from lift-off to injection. A typical VAP of the three components of vehicle attitude, namely, pitch, yaw and roll, is shown in Figure 2. In the open-loop guidance scheme, this programme is determined before launch and stored on-board the vehicle and implemented as it is during the flight. Variation in flight from the preflight estimates of the performance of the propulsion and control systems and aerodynamics may cause deviations in the injection conditions. In the open-loop guidance these deviations are left uncorrected, whereas in the closed-loop guidance the VAP is calculated in flight, amounting to these deviations being detected on-board and corrected in real time, resulting in higher accuracy in the orbit so achieved. To execute closed-loop guidance, the position and velocity of the vehicle has to be measured during the flight, preferably by an on-board autonomous navigation system, and the vehicle attitude programme update is continuously calculated by the guidance algorithm with the help of on-board computers. Navigation and closed-loop guidance systems are sophisticated and are used only when closed-loop guidance is essential. Obviously, the navigation and VAP update systems are not needed in open-loop guided vehicles. It may be noted that during the atmospheric phase of the flight, i.e. up to an altitude of about 30 km, generally, open-loop guidance is adopted in all vehicles and missions.

The equipment bay (EB) of a vehicle, dubbed as the 'brain' of the vehicle, houses the inertial navigation, auto-pilot and guidance computers, telemetry, tracking and other avionics system of the vehicle. The EB has considerable mass comparable to that of the satellite.

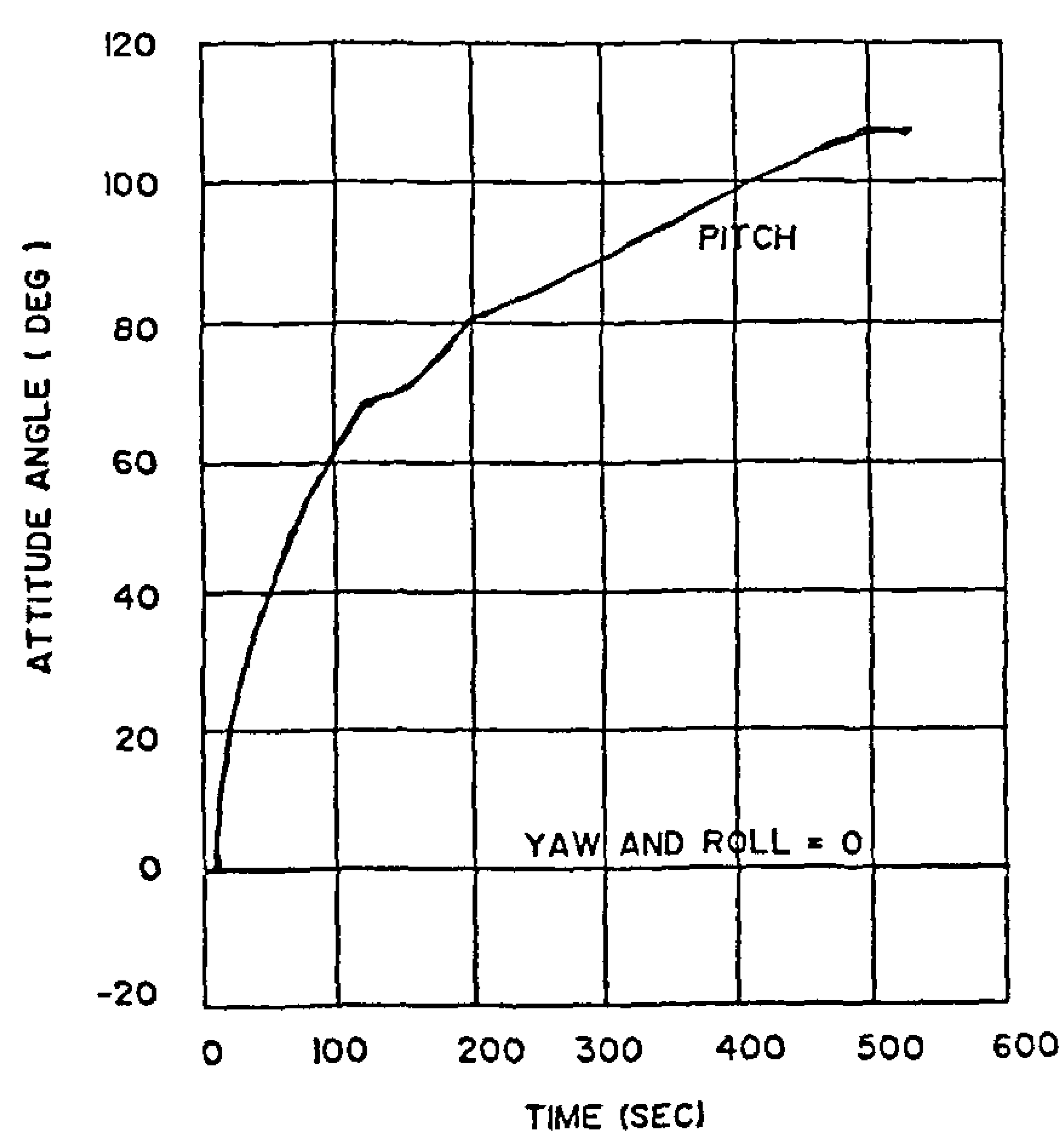

Figure 2. A typical vehicle attitude program.

If the orbital injection is to be achieved with a high degree of accuracy, as demanded by the IRS and INSAT class of satellites, the vehicle has to remain in closed-loop guidance and three-axis stabilization mode till the satellite is injected into the orbit; this usually requires termination of the thrust of the last-stage motor. This implies that the EB is retained till orbital injection and is indeed in the same orbit as the satellite. Of course, the EB is generally deorbited after satellite separation, but the mission would have already paid a heavy payload penalty, nearly equal to the mass of the EB, to achieve the orbit accuracy. Figure 3 shows a typical launch sequence of a three-axis-stabilized and guided injection mission. As already mentioned, this technique is used for the PSLV missions and will also be used for the GSLV missions.

If the specification of the accuracy of orbital injection can be relaxed, a simpler and payload promotive technique could be used. In this technique, the guidance is terminated at the separation of the penultimate stage of the vehicle, which takes place at the end of a long coast phase following the burn-out of the penultimate-stage rocket motor. Before the separation, the vehicle is oriented in the desired direction and in some cases the last stage and the satellite combination mounted on a spin table are first spun up and then separated. Alternatively, the last stage and satellite combination is first separated and then immediately thereafter spun up. The last stage is then ignited and at its burn-out orbital conditions are reached. Separation of the last stage from the satellite completes the work of the vehicle and the satellite is in orbit. Thus, in this technique the EB is needed only till the separation of the penultimate stage and the last stage is not burdened with the extra mass of the EB. Hence, higher payload becomes available. However, since the deviation in orbital injection conditions due to various reasons remains unattended, the injection accuracy is inferior to the guided injection accuracy. Figure 4 shows a typical launch and orbit injection sequence using this technique. As mentioned earlier, this technique is used for the SLV-3 and ASLV missions.

SLV-3 used open-loop guidance throughout the flight, whereas ASLV used closed-loop guidance from the second core stage ignition till the burn-out of the third core stage.

Improvement in orbital injection accuracy

Figures 5–7 give some relevant details in respect of orbit injection performance of the missions of SLV-3-D2, ASLV-D4 and PSLV-D2. The pre-flight estimates of the nominal (target) orbits and 3-σ dispersions are given. Also given are the orbits actually achieved and the deviations in case of SLV-3-D2 and ASLV-D4 in terms

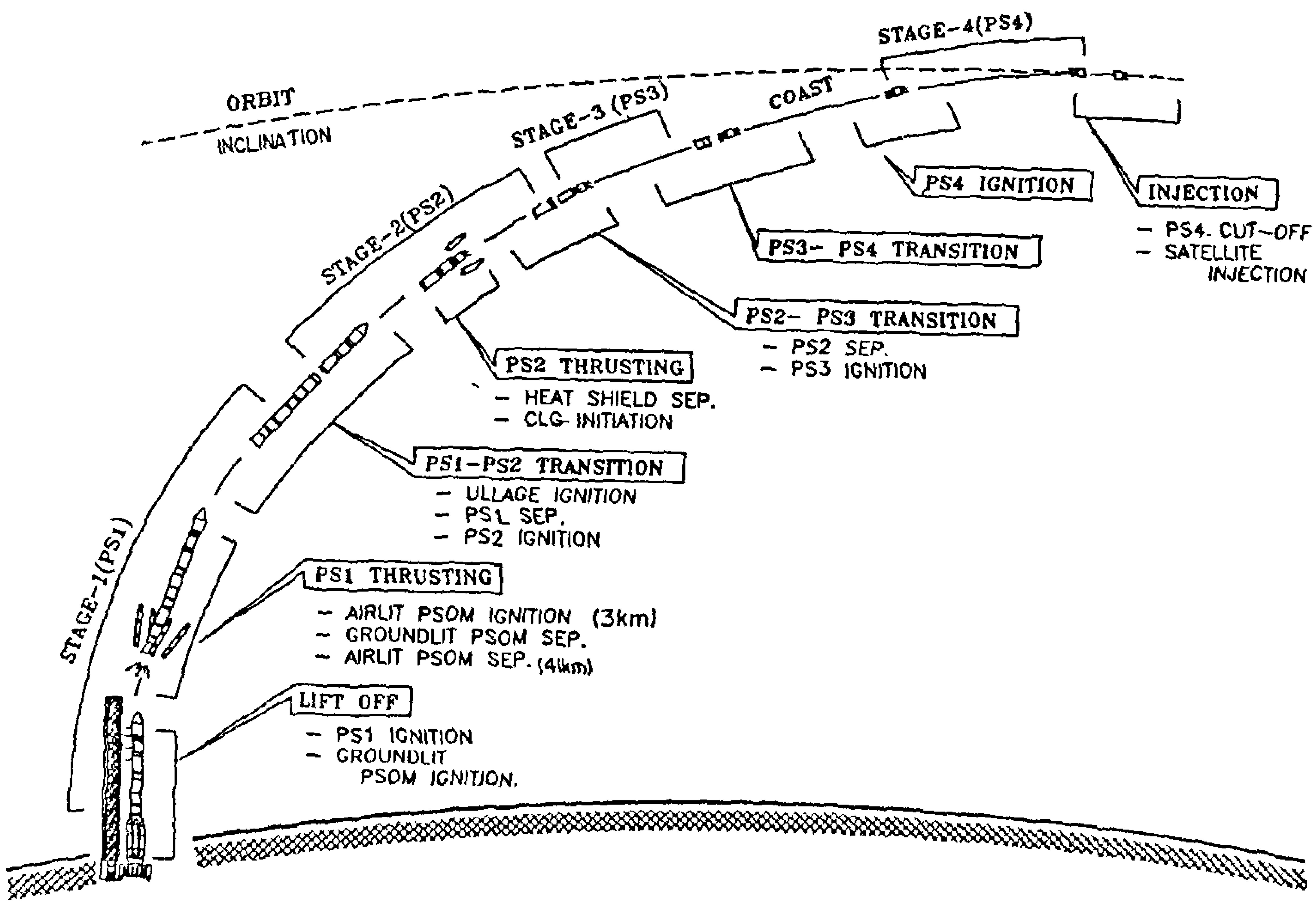

Figure 3. PSLV flight sequence.

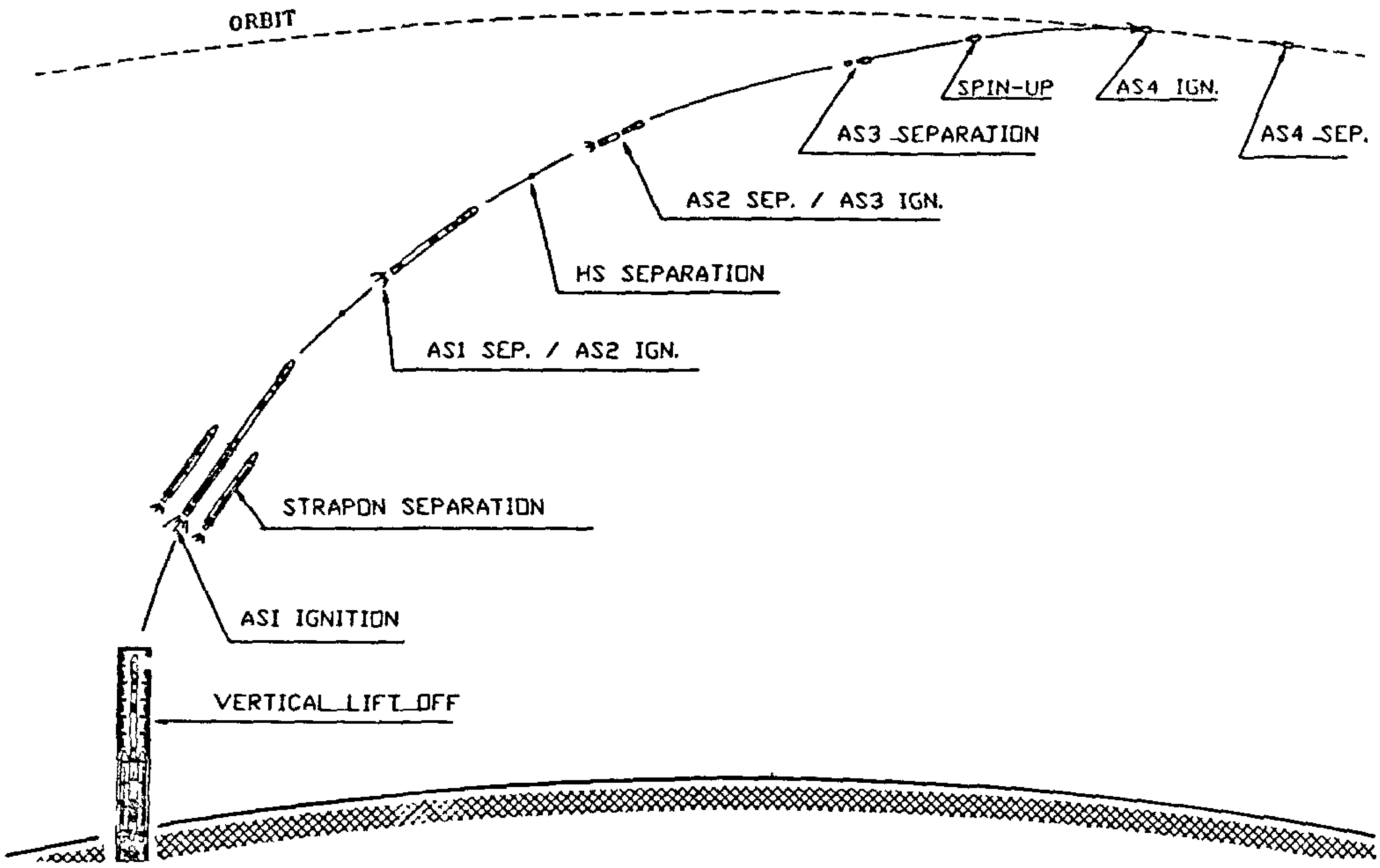

Figure 4. A typical ASLV flight sequence.

Launch Date - April 17, 1983
Payload - ROHINI - D2; 41 kg
Nominal Orbit - 436 x 1021 km

Estimated 3 sigma dispersions:
Perigee - 62 km
Apogee - 232 km

Actual Orbit - 388 x 851 km

Δhp* - 436-388= 48 km $\approx$ 2.3 sigma
Δha* - 1021-851=170 km $\approx$ 2.2 sigma

*hp = perigee altitude; ha = apogee altitude

Figure 5. SLV-3-D2 mission

Launch Date - May 4, 1994
Payload - SROSS C2; 113.4 kg
Nominal Orbit - 423 x 747 km; i=45.7 deg

Estimated 3 sigma dispersions:
In hp - 18 km
" ha - 253 km
" i* - 0.63 deg

P.O.D at T+400 sec 439x938 km; i = 45.7 deg
(AS3 Separation at 485 sec)
P.O.D at T+35 Min. 437x938 km; i = 46.05 deg
Δhp = 437 - 423 = 14 km ~ 2.3 sigma
Δha = 938 - 747 = 191 km ~ 2.3 sigma
Δi = 46.05 deg - 45.7 deg = 0.35 deg ~ 1.7 sigma

*i = inclination

Figure 6. ASLV-D4 mission

of the standard deviation. It is interesting to note that the dispersions in perigee and apogee achieved for both SLV-3-D2 and ASLV-D4 are at nearly 2.3-σ level. It may be noted that keeping the 3-σ deviations in apogee nearly the same, the deviations in perigee were brought down from 62 km in SLV-3-D2 to 18 km in ASLV-D4. SLV-3 did not have a specification on orbit inclination, whereas ASLV had, and the achieved dispersion was 1.7-σ.

In the case of PSLV-D2, the injection accuracy is specified in a more direct manner. The target orbit being a sun-synchronous orbit, i.e. specific altitude and inclination values, the orbit imparted by the launch vehicle is corrected by the satellite-borne propulsion system. The accuracy of orbital injection achieved by a launch vehicle is measured in terms of the velocity correction to be made by the propulsion system of the satellite to achieve the desired orbit. Generally, even in a precise sun-synchronous orbit the argument of perigee keeps on varying. In order to simplify the processing of the imaging data, it is useful to freeze the perigee by an additional velocity correction[2]. However, the frozen perigee has been implemented for the first time in IRS missions for IRS-P2. Hence, to facilitate comparison of injection accuracy of IRS-P2 with that of IRS-1A and IRS-1B, which were launched by world-class foreign vehicles, the corrections needed to achieve only the sun-synchronous orbit are compared. Figure 7 gives the

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Launch Date        -    Oct. 15, 1994
Payload            -    IRS-P2; 804.2 kg
Nominal Orbit      -    823 x 838 km; i = 98.77 deg

Estimated 3 sigma dispersions:
Perigee/Apogee        - 35 km

Inclination           - 0.2 deg
P.O.D at Injection - 806 x 872 km; i = 98.6 deg
Orbit determination}
after 16 hrs. of      }801.35x874.65km;i = 98.695 deg
tracking data         }

Δ V to achieve Sun-Synchronous Orbit
          for IRS-P2 = 11 m/s (= 23 m/s for frozen perigee)
  "    "  for IRS-1A = 17  "
  "    "  for IRS-1B = 27  "
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Figure 7. PSLV-D2 mission.

Vehicle	Configuration	Payload (kg) LEO (400 km circular) i=45 deg	SSO (817 km)	GTO
SLV-3	S9+S3+S1+S0.3	40	-	-
ASLV	2S9+S9+S3+S1+S0.3	125	-	-
PSLV	(2+4)S9+S129+ L37.5+S7+L2	2600*	850	400*
GSLV	4L40+S129+ L37.5+C12	5400*	2400*	2200*

* Projected capability

Figure 8. Payload capability of ISRO launch vehicles.

velocity corrections, ΔV required to achieve sun-synchronous orbit for IRS-P2, IRS-1A and IRS-B. The value of 11 m/s required for IRS-P2 compares quite impressively with the values of 17 m/s and 27 m/s required for IRS-1A and IRS-1B, respectively.

While it is recognized that the data cited above do not constitute statistical adequacy, the low dispersion values achieved in terms of standard deviations and comparability with world-class precision are considered significant.

Growth of payload capabilities

Figure 8 gives the nominal payload capabilities of SLV-3, ASLV and PSLV for their main missions[3]. It also gives the projected payload capabilities for the different missions which become feasible to be launched by modifying only the VAP and guidance software. It is interesting to note that the LEO capability has grown from 40 kg for SLV-3 to 125 kg for ASLV and 2600 kg for PSLV. Also, GSLV will be able to provide nearly 3 times the present PSLV capability in SSO and over 2 times the projected PSLV capability in LEO. These capabilities can serve the Indian Space Programme for a long time.

Conclusion

In addition to giving a brief explanation of the role of the launch vehicles in India's space programme, a bird's eye view of the various missions and launch vehicles is given. Using the mission performances of the landmark launches of SLV-3, ASLV and PSLV, progressive improvements in the orbital injection accuracy are examined. Injection accuracy of PSLV-D2 imparted to IRS-P2 is compared with that of IRS-1A and IRS-1B to conclude that PSLV-D2 achieved world-class accuracy. The growth of payload capability is also examined for the LEO and SSO missions.

1. India's first Polar Satellite IRS-P2 launch by PSLV-D2, *Curr. Sci.*, 1994, **67**, 565–570.
2. Communication from Shivakumar, MPAD, ISAC.
3. Gupta, S. C., Launch vehicle technology development in ISRO, talk at Astronautical Society of India, meet at Trivandrum, 28th Jan. 1994.