Launch strategy for Indian lunar mission and precision injection to the Moon using genetic algorithm

V Adimurthy*, R V Ramanan, S R Tandon and C Ravikumar

Aeronautics Entity, Vikram Sarabhai Space Centre, Thiruvananthapuram 695 022, India.
e-mail: v_adimurthy@vssc.org

The Indian lunar mission Chandrayaan-1 will have a mass of 523 kg in a 100 km circular polar orbit around the Moon. The main factors that dictate the design of the Indian Moon mission are to use the present capability of launch vehicles and to achieve the scientific objectives in the minimum development time and cost. The detailed mission planning involves trade-off studies in payload optimization and the transfer trajectory determination that accomplishes these requirements. Recent studies indicate that for an optimal use of the existing launch vehicle and spacecraft systems, highly elliptical inclined orbits are preferable. This indeed is true for the Indian Moon mission Chandrayaan-1. The proposed launch scenario of the Indian Moon mission program and capabilities of this mission are described in this paper, highlighting the design challenges and innovations. Further, to reach the target accurately, appropriate initial transfer trajectory characteristics must be chosen. A numerical search for the initial conditions combined with numerical integration produces the near accurate solution for this problem. The design of such transfer trajectories is discussed in this paper.

1. Introduction

Trajectory design and carrying out manoeuvers to achieve the desired lunar trajectory minimizing the fuel requirement is an important aspect of mission planning. The methods can be broadly divided as direct and indirect transfers (Beisbrock and Janin 2000; Adimurthy 2003). A traditional direct transfer to the Moon essentially puts the spacecraft into a Lunar Transfer Trajectory in one go from a low Earth orbit. Other unconventional methods employ either **(a)** highly elliptic phasing orbits, or **(b)** transfer via Lagrangian points to reach the Moon. In the post-Apollo era, the unconventional methods are being increasingly considered for lunar mission design because of their low-energy requirements. All these approaches were evaluated for the Indian lunar mission.

Polar Satellite Launch Vehicle (PSLV) is a 4-stage launch vehicle with six 9-ton solid propellant boosters (6S9) augmenting the first stage of 139 ton solid propellant booster; 40 ton liquid propellant second stage (L40); 7 ton solid third stage booster (S7); 2.5 ton liquid upper stage (L2) (Ramakrishnan *et al* 2003). It is capable of launching 1500 kilogram class spacecraft into 700 km circular Sun Synchronous Polar Orbit (SSPO). It can also carry out a variety of Low Earth Orbit (LEO) missions of 200 m to 400 m perigee and apogee altitudes and Geosynchronous Transfer Orbit (GTO) missions (240 km $\times$ 36,000 km). PSLV-C4 launched METSAT spacecraft of 1050 kg in GTO in a planar trajectory with an inclination of 18°. A number of trade-off strategies are considered while considering PSLV as the carrier for lunar mission, namely, Parking Earth Orbit which is usually a Low Earth Orbit (LEO), Elliptic Parking Orbit (EPO) with a low perigee altitude, and apogee in the range of 18,000 to 42,000 km and Direct to Trans Lunar Injection (TLI) without any parking orbit. After

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detailed analysis, a PSLV launch is chosen for the Indian lunar mission with an EPO similar to GTO.

Many techniques and algorithms exist to generate the lunar transfer trajectory characteristics. They are based on point conic, patched conic or pseudo conic techniques and they provide quick data for preliminary mission design and analysis. The transfer trajectories generated using these techniques achieve the target parameters with some error. The only way to determine the precise transfer trajectory by including all the major perturbing forces is to search by numerical simulation. The precise transfer trajectory design obtained based on an approach using genetic algorithms is discussed.

2. Methods of reaching lunar orbits

2.1 *The traditional direct transfer*

In this approach, the mission begins from a parking orbit around the Earth. Then, for Lunar Transfer Trajectory the apogee of the parking orbit is raised to the Moon's distance or higher. Duration for this transfer is about 5 days. The perigee burn can be accomplished in a single burn or multiple burns of smaller duration. An important criterion for the mission is that the spacecraft be launched when the Moon's declination is less than the inclination of the parking orbit. All the lunar missions from 1960s to the 1980s used this traditional approach. For direct missions like this the velocity requirement for travelling from the parking Earth orbit to Lunar Transfer Trajectory is of the order of 3.1 km/s. This normally requires separate propulsive stage in the launch vehicle.

2.2 *Transfer via GTO/EPO*

One of the primary ways to reduce the launch cost is to reduce the total delta velocity requirement. Two possible options are available, namely, utilizing energy from other celestial bodies or launch from an EPO like GTO.

Since the energy of GTO is considerably higher than that of a Low Earth Orbit, it leads to savings on the Lunar Transfer Trajectory (LTT) requirements. Thus the launch vehicle itself provides considerable energy and that required from the spacecraft is correspondingly less. However, this approach implies a limitation in the launch opportunity since a plane change is required because the apsidal line of GTO will be normally near the equatorial plane. In one lunar month, the Moon will arrive twice near to its node, and this determines the launch window for the lunar mission via EPO. Transfer from a highly elliptic parking orbit greatly simplifies the developmental requirements and is the best-suited approach for PSLV.

2.3 *Weak stability boundary (WSB) transfers*

We know that reduced velocity requirement reduces the mission cost. However, the Lunar Transfer Trajectory velocity requirements cannot be reduced beyond a certain value. So the velocity requirements for lunar orbit insertion could be reduced further by reducing the requirement through arriving at the Moon with a low relative velocity. This can be achieved by taking the spacecraft to the region of Lagrangian points of the Earth–Sun system. A small manoeuver within such a region can lead to a significant change in the lunar arrival conditions. This is known as the Weak Stability Boundary approach. However, the disadvantages of the weak stability boundary method are that **(a)** the time taken to achieve lunar orbit is several months (instead of a few days for direct methods), **(b)** the spacecraft is required to traverse large distances of the order of four times the lunar distance, and this puts a very high burden on the communication power requirements. If these problems can be handled, the WSB methods offer a highly energy efficient way to reach the Moon. This type of transfer was used in the Japanese Hiten spacecraft.

3. Indian launch capabilities for lunar mission

The following trade-off strategies are considered:

> Parking Earth Orbit which is usually an LEO, EPO with a low perigee altitude, and apogee altitude in the range of 18,000 to 42,000 km and direct to TLI without any parking orbit.

The WSB transfer mode described earlier is not considered for the initial Indian lunar mission because it involves long travel duration and poses difficulties for telemetry, tracking, command and mission operations because they involve distances several times more than the lunar distance.

Detailed trade-off studies show that the best strategy is to reach the moon via an EPO. Further it is emphasized that the EPO can be geo-transfer orbit itself, since Liquid Apogee Motor (LAM) size and the lunar spacecraft design remain similar to METSAT, the GSO spacecraft launched in PSLV-C4 flight. The first burn of LAM injects the spacecraft in to an LTT. On reaching the Moon via LTT, the further burns of the LAM are used for insertion of the spacecraft into the desired lunar polar orbit of 100 km, referred to as Lunar Orbit

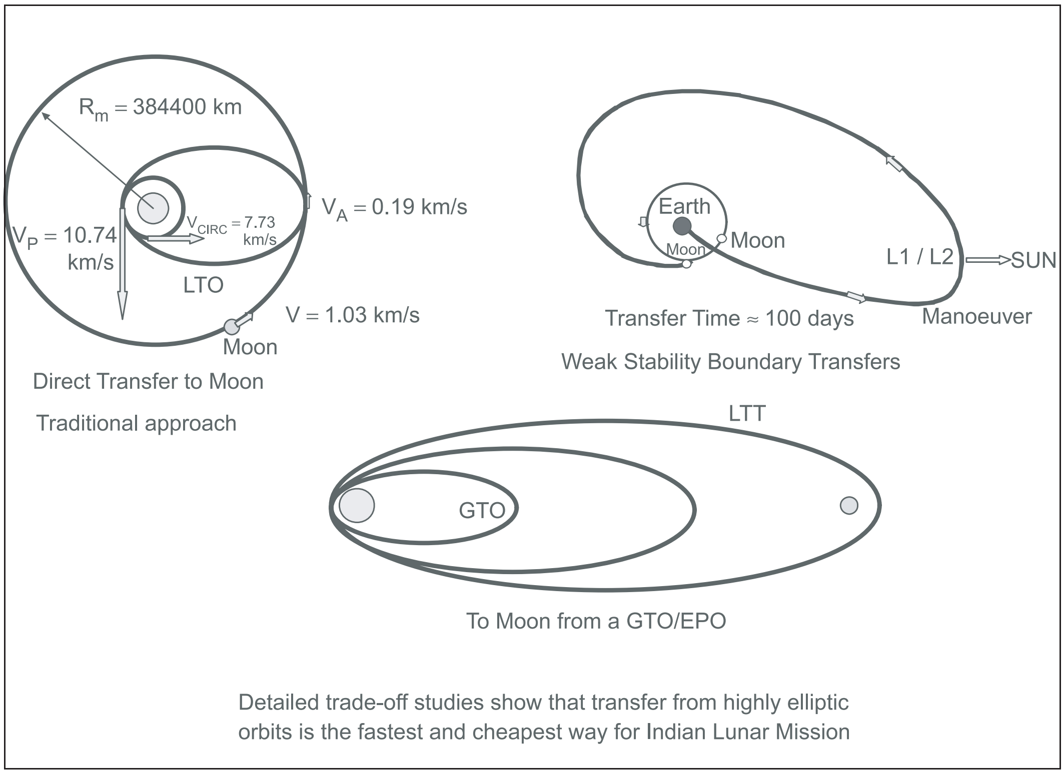

Figure 1. Three ways to the Moon.

Table 1. *Nominal PSLV mission to the Moon.*

Vehicle (identical to PSLV C4 metsat mission)	: $[6S9 + S139] + L40$ $+S7(H) + L2.5$
Launch azimuth	: 102° from North
Mission strategy	: EPO-TLI-LOI
EPO ≅ GTO	: 240 × 36000 km
Inclination	: 18°
Argument of perigee	: 178.5°
EPO/GTO mass	: 1050 kg
LAM first burn propellant	: 239 kg
TLI mass	: 811 kg
LAM subsequent burns	: 287 kg
LAM total loading	: 526 kg
Lunar orbit	**: 100 × 100 km polar**
Initial lunar orbital mass	: 523 kg
Propellant for 2-year maintenance and attitude control, etc.	: 83 kg
Dry mass of lunar spacecraft	**: 440 kg**

Insertion (LOI). The summary of PSLV payload to the Moon via GTO route is shown in table 1, which yields lunar orbital mass of 523 kg.

4. Launch constraints and launch opportunities to the Moon

Various constraints related to vehicle-safety (aerodynamic, wind loads), range-safety (stage-impact), visibility and parking orbit are the same for the lunar mission as followed in PSLV-GTO launch. It may be noted that a GTO launch will have an argument of perigee (ω) constraint for ensuring line of apsides on the equatorial plane. While this constraint is not applicable for the Moon mission, it is found that the identical ω constraint at injection has a feasible solution for the Moon mission.

In general, two-time zones of launch opportunities exist in each lunar month. To be able to reach the vicinity of the Moon in its orbit around the Earth, besides the EPO inclination, the orientation of the trans-lunar orbit is also critical. These are defined by the argument of perigee (ω) and the longitude of the ascending node (Ω). The argument of perigee ω and the launch day are arrived at as per mission requirements. For the chosen launch day, the required Ω can be achieved through appropriate selection of launch time. These parameters are depicted in figures 2 and 3. These figures correspond to flight duration of 5 days.

5. Precision injection to the Moon using genetic algorithm

Many techniques and algorithms exist to generate the lunar transfer trajectory characteristics. They are based on point conic, patched conic (Battin 1987, Brown 1992) or pseudo conic techniques and they provide quick data for preliminary mission design and analysis. The impact algorithm (Ramanan 2002) generates the transfer trajectory that impacts the Moon. The transfer

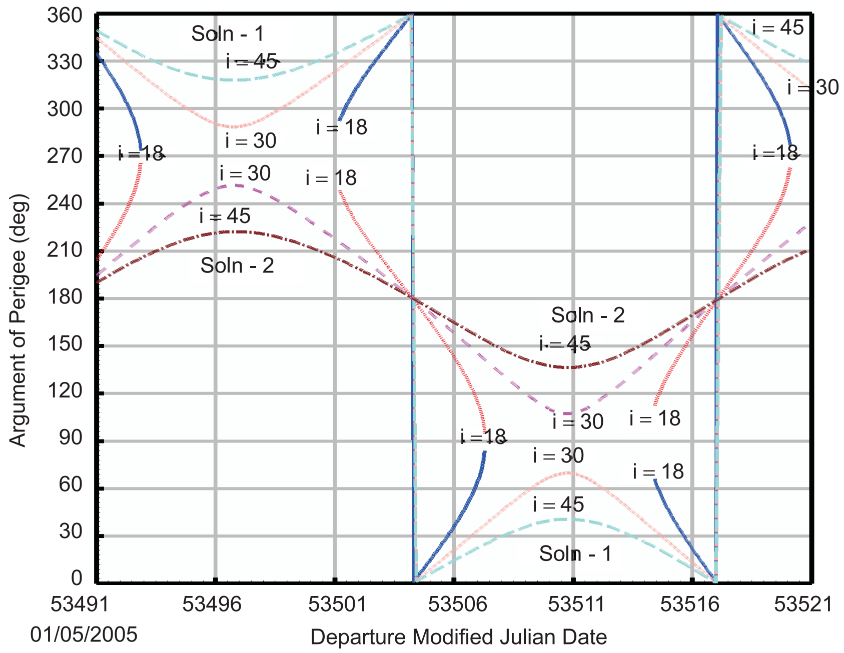

Figure 2. Variation of argument of perigee with departure date.

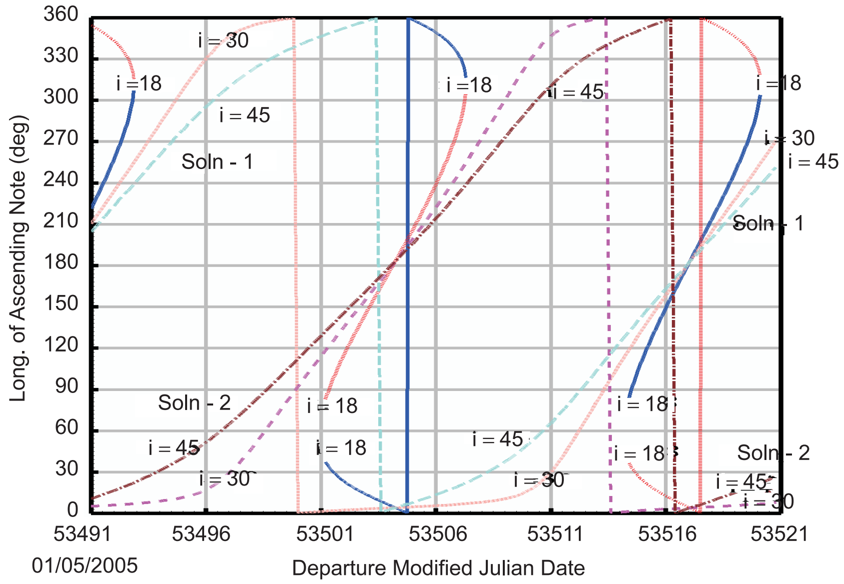

Figure 3. Variation of longitude of ascending node with departure date.

trajectories generated using the non-impact algorithm (Ramanan and Adimurthy 2005), achieves the target parameters with some error. These errors are removed by the concept of biased targeting using the non-impact algorithm and the numerical simulation. This biased non-impact algorithm (Ramanan and Adimurthy 2005) generates accurate transfer trajectory under a force field of n-body spherical masses. However, the asphericity of the bodies involved is not included in the trajectory determination process. The resulting trajectories deviate from its targets substantially when the asphericity of the bodies is included. The asphericity of the Earth is a major perturbing force on these trajectories. The only way to determine the precise transfer trajectory by including these perturbations is through search by numerical simulation. Evidently, the search must be regulated using some optimization technique. The genetic algorithm is used to regulate the search. Because of high sensitivity of the transfer trajectories, the convergence is poor with the regular genetic algorithm. A modified version of genetic algorithms (Adimurthy *et al* 2002) referred to as

GAAB (Genetic Algorithm with Adaptive Bounds) that accelerates the convergence process is used. The details of the methodology and the efficiency are discussed separately (Ramanan and Adimurthy 2005).

5.1 *Perturbations and the lunar transfer trajectory*

The transfer trajectory determined by biased non-impact algorithm includes the spherical gravity fields of the target bodies. But, in reality, the lunarcraft is subjected to the asphericity of the Earth and the Moon. Table 2 presents the details of the influence of the Earth J_2 and other perturbing forces such as the Moon's asphericity, Earth's higher zonal harmonics and other planets for a typical transfer trajectory departing on 24th 0 hrs, January 2009 from an Earth parking orbit of 300 km perigee. These conditions where 'sma' is semi-major axis and e is eccentricity, are derived using biased non-impact algorithm for flight duration of 5 days. The initial conditions of the transfer trajectory (also given therein) are propagated under different force models to assess the deviations in the target parameters. The targets achieved with Earth's J_2 are 29.787 deg of inclination and 4811.79 km of periselenum altitude.

Table 2. *Effect of force models on the LTT propagation. Initial conditions of transfer trajectory: sma* = 200991.963 *km; $e = 0.96677$; $i = 18.0°$; $\omega = 168.4453°$; $\Omega = 352.7318°$.*

Force model used in propagation	Achieved target periselenum altitude (km)	Achieved target inclination (degree)
(a) Earth + Moon (both spherical)	1000.22	90.000
(b) a + Sun	1246.60	103.401
(c) b $+EJ_2$	4811.79	29.797
(d) c + other planets	4811.77	29.797
(e) d + E(4 × 0)	4816.70	29.776
(f) e + M(9 × 0)	4816.70	29.776

It is clear that the Earth's second zonal harmonic plays the major role in deviating the trajectory from achieving its target. Other bodies except the Sun and the moon's asphericity deviate the trajectory marginally. Because numerical propagation under full force model is computationally expensive, a force model consisting of Earth, Moon and Sun together with $E\ J_2$, is considered to derive precise transfer trajectory using genetic algorithm.

5.2 *Precise lunar transfer trajectory*

The precise transfer trajectory characteristics are generated using numerical simulation by search that is regulated using GAAB. The unknown parameters of the initial transfer trajectory characteristics that are floated are: apogee altitude, argument of perigee and right ascension of ascending node. The bounds for search for these parameters are set using the biased non-impact characteristics. The parameters that are fixed for these numerical simulations are: initial Earth parking orbit perigee and inclination. The function for minimization is set as a function of the differences of the achieved and the required minimum altitudes and inclinations of the lunar parking orbit. Table 3 presents the initial characteristics of the transfer trajectory obtained using genetic algorithms (GA) and compares it with the biased non-impact solution. Only Earth's J_2 effect is included besides the Sun and the Moon in the force model for numerical propagation.

Table 3. *Comparison of transfer trajectory characteristics of biased non-impact algorithm and genetic algorithm.*

	Initial conditions of transfer trajectory (Earth centered)		Achieved hyperbolic approach trajectory[2] (Moon centered)	
	Using biased non-impact algorithm[1]	Using genetic algorithm	Biased non-impact algorithm	Genetic algorithm[3]
a, km	200137.656	206171.3364	−7824.174	−7695.922
e	0.96663	0.96761	2.0142	1.3557
i,°	18.0	18.0	25.483	90.000
ω°	168.6142	168.5031	132.226	142.5924
Ω°	352.6493	352.7066	62.059	76.8179
Periapsis altitude, km	–	–	6196.98	1000.20

[1]The biased non-impact algorithm model is limited to spherical gravity fields of the Earth, the Moon and the Sun.

[2]Achieved hyperbolic approach trajectory parameters are obtained with full force model (f of table 2).

[3]The precision trajectory of GA in addition also includes Earth's J_2 effect.

6. Conclusions

The strategy using GTO launch with PSLV requires no configuration change, and additional stage development; has similar propellant requirement as that of METSAT; offers short-development-time route to Moon; has good payload capability with adequate margin; and has the advantage of launch vehicle segment including all the range safety related issues completely tested during the PSLV-C4 mission. Launch opportunities under various constraints are discussed. The influence of major perturbing forces is highlighted. Accurate lunar transfer trajectory design obtained using genetic algorithms is presented.

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