Ways to the Moon?

R. Biesbroek
JAQAR Space Engineering, Den Haag, The Netherlands

G. Janin
Mission Analysis Section, ESA Directorate of Technical and Operational Support, ESOC, Darmstadt, Germany

ESA has conducted several studies on missions to the Moon in recent years. The lunar trajectories for most of these missions differ substantially from those of the lunar missions flown in the 1960s and 70s. In particular, the use of shared Ariane-5 launches to reduce cost puts the spacecraft into a transfer orbit from which novel transfers and trajectories are needed to minimise the propellant required to reach lunar orbit. This has led to intensive studies of Weak Stability Boundary (WSB) transfers, which exploit the presence of low-gravity fields in which small manoeuvres can have large effects on the spacecraft's motion. The long travel times incurred with this approach are compensated by the large reduction in propellant mass.

Previous lunar missions

Lunar exploration began on 1 February 1959 when the Soviet satellite Luna-1 flew past the Moon. The 360-kg spacecraft was originally designed to impact on the Moon, but missed and escaped from the Earth-Moon system. That same year Luna-2 did hit the Moon and became the first spacecraft to impact another world (Fig. 1). Luna-3 was the last of the first generation of Luna spacecraft (launched by Vostok) and became the first spacecraft to view the far side of the Moon. The second generation (Lunas-4 to14) were landers and orbiters, launched by Molniya rockets due to the larger spacecraft masses involved (1500 - 1600 kg). Many of these attempts resulted in failure, but Luna-9 was the first spacecraft to land softly on the Moon, and Luna-10 was the first to orbit another world, in 1966. The third generation were 5700 kg spacecraft (Lunas-15 to 24) launched by Proton rockets. They were sample-return, rover and orbiter missions, with Luna-16 being the first robotic mission to return a lunar sample, and Luna-17 the first mission to put a rover (Lunokhod) on another world. Several Zond missions were launched by the Soviets in the 1960s, mainly as test missions for future manned Moon missions. Zond-5 was the first mission to return to the Earth from lunar orbit.

The USA's lunar programme included several unmanned missions. The 330 kg Rangers (1962-65) were the first objects sent to the Moon by the United States and were meant to deliver television images before impact. Ranger-4 crashed on the lunar far side, and is

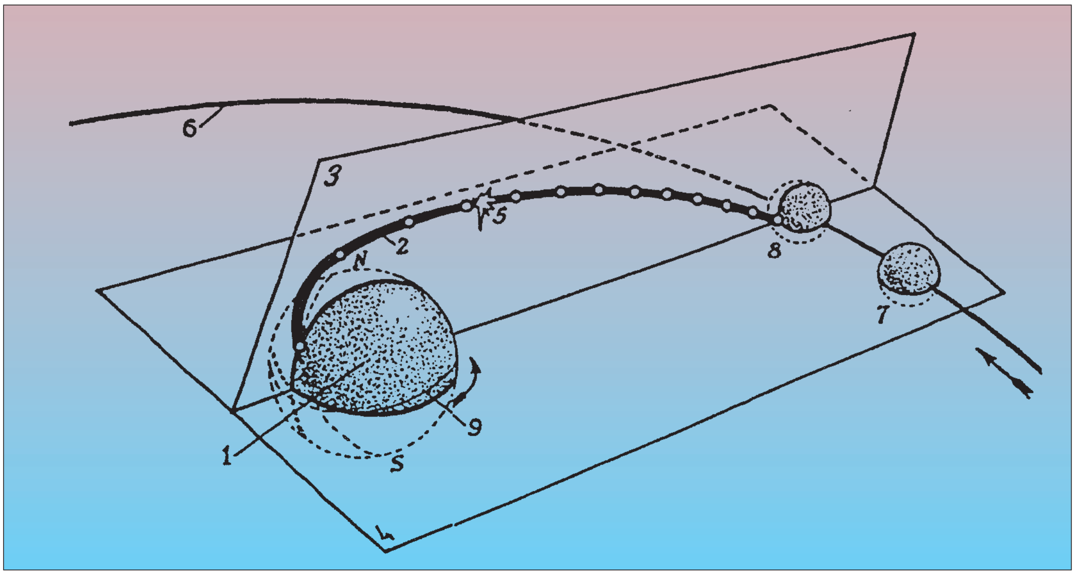


Figure 1. The Luna-2 mission profile

therefore the only known human object on that side. Between 1966 and 1968, five 1000 kg Surveyors landed in the near-side equatorial region. During that same period, five Lunar Orbiters (mass 390 kg) successfully mapped the equatorial region of the Moon for Apollo landing-site selection. The famous Apollo Programme followed. In 1968, Apollo-8 became the first manned mission to orbit another world. On 20 July 1969, Apollo-11 became the first manned landing on another world, and in 1971 Apollo-15 put the first manned rover on the Moon.

Figure 2 shows the Apollo mission profile. The first three stages of the Saturn-V rocket put the spacecraft into a 160 km Low Earth Orbit (LEO). After about 2.5 hours, the S-IVB upper stage performed the Translunar Injection. The Moon was reached after about 70 hours. The first Lunar Orbit Insertion manoeuvre was performed by the Service Module (SM) motor when Apollo was on the far side of the Moon, putting the spacecraft into an elliptic 270 km x 100 km orbit. The second insertion manoeuvre circularised the orbit to 100 km height. The Lunar Module (LM) was de-coupled and a Descent Orbit Insertion changed its orbit to 15 km x 100 km. Finally, a Powered Descent Initiation took the LM to the lunar surface. Apollos-8, 10, 11, 12 and 13 used 'free-return trajectories', i.e. the orbital energy of the Translunar Trajectory was chosen such that the spacecraft could not escape from the Earth-Moon system if the SM motor failed to operate, and could return safely to Earth within a few days. All these missions used a 'direct' transfer to the Moon, which meant that the transfer time was at most four days, but the Δv requirement (velocity increase to be given to the spacecraft) was high. A high Δv means a high propulsion-mass/total-mass ratio, thereby reducing the mass available for payload.

The 1990s brought a 'return to the Moon', when four more spacecraft passed close to or orbited the Moon. These unmanned craft were more interesting from a mission-analysis point of view, because alternative trajectories were used to lower the Δv requirement. For example, the Japanese Hiten mission used both a lunar swing-by and a Weak Stability Boundary (WSB) trajectory to reach the Moon with favourable conditions for capture into a highly elliptic lunar orbit. The transfer time was 6 months and the launch mass was only 196 kg. The US Clementine mission, launched in 1994, used a direct transfer with intermediate orbits and went into a lunar polar orbit. The launch mass was 1690 kg and the transfer time about three weeks. The Hughes Global Services-1/Asiasat-3 satellite became the first commercial satellite to reach the Moon's sphere of gravitational influence, after its launcher failed to put it into the correct orbit. There was not enough propellant on the spacecraft for it to directly reach Geostationary Orbit (GEO), but there was sufficient to place it into a Translunar Orbit to swing by the Moon twice and return to GEO. This showed the power of using the Moon's gravity field to increase orbital energy. Lunar Prospector was launched in 1998, by an Athena-II launcher, directly into Translunar Orbit, which meant that the on-board propellant mass was limited. The lunar insertion was performed in three stages to place the 300 kg spacecraft into a 100 km circular polar orbit.

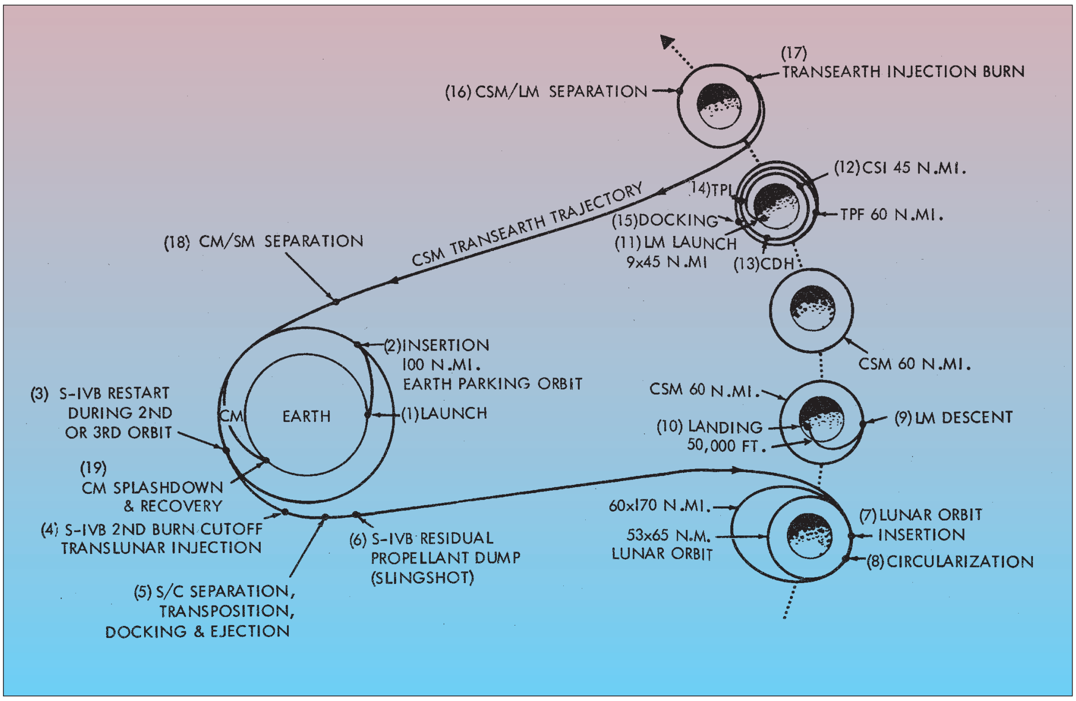


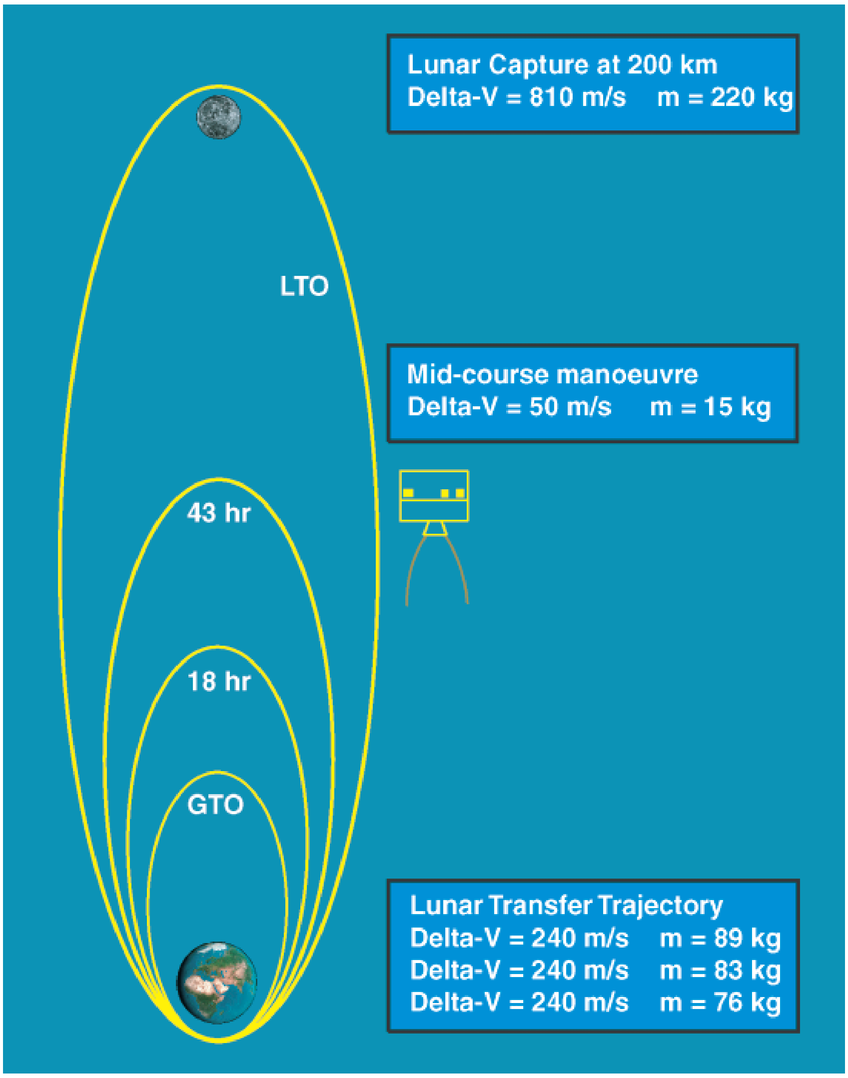
Figure 2. The Apollo mission profile

ESA studies of lunar missions

Studies on missions to the Moon within ESA began in 1980 when scenarios for a Polar Orbiting Lunar Observatory (POLO) were studied. The POLO mission involved two spacecraft: an orbiter and a relay satellite. The baseline for the POLO (total mass 1050 kg) launch was either a deployment from the Space Shuttle into a circular 300 km orbit using a PAM-A solid-rocket stage for Translunar Orbit Injection, or a dedicated Ariane launch. A direct transfer to the Moon was selected, but the mission was never flown.

Ten years later, MORO (Moon Orbiting Observatory) was an unsuccessful candidate for an ESA M3 medium-size scientific mission. MORO highlighted the use of a shared Ariane-5 launch into Geostationary Transfer Orbit (GTO). A direct Translunar Orbit would have been used to reach the Moon, where the spacecraft would have been inserted into a 100 to 200 km circular polar orbit. The Translunar Orbit Injection consists of three manoeuvres (Fig. 3) of 240 m/s to increase the apogee (largest distance to the Earth, within the orbit) from the GTO apogee to the Earth-Moon distance. This was done to minimise gravity losses (which occur because the thruster burns are not impulsive shots, but take a finite time during which the spacecraft has changed its position) during the burns at perigee (shortest distance from Earth). The transfer time would have been 8 days, and the total Δv, including mid-course correction and Lunar Orbit Injection, was 1580 m/s, resulting in a launch mass of 1207 kg.

Figure 3. The MORO mission profile



In 1994/5, an assessment study of LEDA (Lunar European Demonstration Approach) was performed to define an exploration mission that would land on the lunar surface after having been put into GTO by Ariane-5. This again highlighted the problems of starting from a GTO orbit when going to the Moon, due to the different planes of the GTO and the Moon's orbit. This resulted in a high Δv for the transfer to the Moon (1730 m/s) and long transfer times of up to 2 months. The spacecraft mass was 3347 kg due to this high Δv and the fact that a large amount of propellant had to be included for the landing.

EuroMoon 2000 was an ESA initiative for a lunar South Pole expedition at the start of the new millennium. The prime objective of the mission was to perform a soft landing on the lunar South Pole Peak of Eternal Light. This place, constantly illuminated by the Sun, is unique in the Solar System and is ideally suited for future lunar bases. The baseline for the 1300 kg EuroMoon spacecraft was a direct launch into Translunar Orbit using a Soyuz-Molniya launcher. In order to reduce gravity losses during the insertion into lunar orbit, it was divided into three phases: (i) a capture manoeuvre to a 150 km x 5000 km elliptic orbit, (ii) a manoeuvre to reach a 100 km x 5000 km orbit, and finally (iii) circularisation of the orbit at 100 km altitude. After an initial orbital phase, the lander would descend toward the South Pole. Following an ESA Council decision, the project was abandoned in March 1998.

LunarSat (Lunar Academic and Research Satellite) is a 100 kg satellite designed by students, scientists and young engineers that functions as the focus for a variety of educational activities. The project's Phase-A and B were sponsored by ESA's Office for Educational Project Outreach Activities. The mission study demonstrated lunar access via the Ariane-5 auxiliary payload capability. However, as with LEDA, the spacecraft would have to reach the Moon starting from GTO. Since only 40% of the spacecraft mass could be allocated to propellant, this led to a Δv budget of only 1450 m/s (compared to LEDA's 1730 m/s), and so a different approach was necessary. This resulted in a study on using Weak Stability Boundary transfers, performed at the end of 1998.

SMART-1 (described in detail in ESA Bulletin No. 95) is an approved ESA project intended, inter alia, to demonstrate Solar Electric Propulsion as a primary drive mechanism. 250 days will be needed to get from GTO to a 1000 km x 10000 km lunar polar orbit.

Going to the Moon now

The Moon is the Earth's only known natural satellite. According to the most popular theory, it exists as a result of a violent encounter between a heavy celestial body and the Earth about 4 billion years ago, which caused the ejection of Earth matter. It is gravitationally bound to the Earth and part of its direct environment. Going to the Moon is therefore a natural continuation of the exploration of planet Earth. This was well understood at the First International Lunar Workshop in Beatenberg, Switzerland, in 1994, where ESA proposed a four-phase lunar programme:

Phase-1: Lunar robotic explorer
Phase-2: Permanent robotic presence
Phase-3: First use of lunar resources
Phase-4: Lunar human outpost.

It is the pursuit of Phase-1 of this programme that has led to the investigation of more novel, and less expensive, ways of reaching the Moon. These are discussed below, after first recalling the classical direct route.

The direct way: fast but expensive

The 'classical' lunar mission begins from a so-called 'parking orbit' around the Earth. The orbit's apogee (farthest point from the Earth) is then raised to the Moon's distance or higher by a Translunar Injection, using either the spacecraft's own main engine or the launcher's upper stage. When starting, for example, from a circular orbit at 300 km altitude, the orbital velocity is 7.7 km/s. A Translunar Orbit with perigee at 300 km and apogee at 384 400 km has a perigee velocity of 10.8 km/s. The Δv for Translunar Orbit Injection is therefore 10.8 – 7.7 = 3.1 km/s (Fig. 4). This single 'perigee burn' can also be divided into several smaller burns.

Since the orbital angular momentum is constant, the spacecraft's velocity decreases as it gets further away from the Earth. On reaching the Moon, its velocity has fallen to only 0.2 km/s and since the Moon travels with a velocity of 1 km/s, the spacecraft will be in an orbit relative to the Moon with a velocity of about 0.8 km/s. Therefore, another Δv has to be applied to the spacecraft to match the Moon's velocity, to be captured by the Moon, and then orbit around it. This is usually done when passing the periselenium (closest point of the orbit with respect to the Moon). This burn can also be divided into several smaller burns to minimise gravitational losses. The location of the periselenium cannot be chosen arbitrarily, but depends on the arrival geometry.

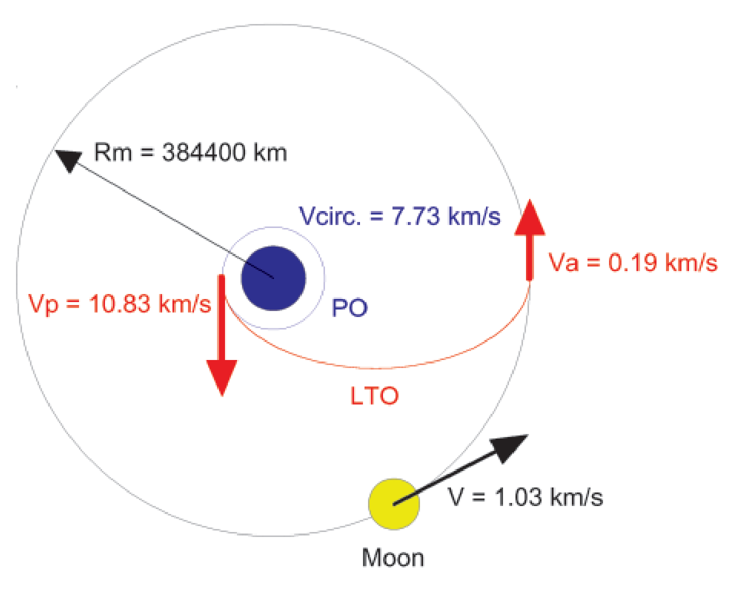
The lowest Δv is needed when using a Hohmann transfer, when the apogee of the Translunar Orbit is equal to the Earth-Moon distance. To reduce the transfer time, the apogee of the Translunar Orbit could be chosen higher, at the expense of a slightly greater Δv. A direct transfer typically takes 2–5 days. The spacecraft should be launched when the declination of the Moon is smaller than the inclination of the parking orbit (usually equal to the latitude of the launch site). Since the maximum declination of the Moon at the Earth's equator is 29 deg, launches from higher latitudes (such as Cape Canaveral and Baikonur) are preferable, where there are two launch opportunities per day.

This 'classical' direct transfer was used for all lunar missions from the 1960s to the 1980s, including the Luna and Apollo missions.

Indirect ways: slow but cost-effective

The launch is a major part of the total cost of any space mission; the smaller the launcher, the less costly will be the mission. The choice of launcher depends on its performance and the mass of the spacecraft to be launched. To reduce cost, the spacecraft's mass has to be reduced. A large part of that mass is dedicated to the propellant needed for the various injection and insertion Δv's. Reducing Δv

Figure 4. Direct transfer to the Moon



requirements will therefore reduce mission cost, and there are two options available:
- piggy-back with a ‘rich’ passenger, or
- ‘steal’ energy from other celestial bodies.

Piggy-back launches

The Ariane launcher offers a dual-launch capability, which can be used to reduce the cost of injecting satellites into orbit. Ariane-5 offers a specially designed structure, the Ariane Structure for Auxiliary Payloads (ASAP), for the piggy-back launching of micro- and mini-satellites.

However, companion satellites are usually only sought for Geostationary Transfer Orbit (GTO) launches, making GTO the most likely parking orbit for a dual launch. This is nevertheless quite interesting for our purposes because the energy of a GTO is considerably higher than that of a low Earth parking orbit, allowing savings on the Translunar Orbit injection. Unfortunately, GTO and Translunar Orbit missions are normally not compatible, because the GTO apsidal line (line through perigee and apogee) lies in the equatorial plane, whereas the Moon’s orbit is in a plane inclined between 18 and 29 deg.

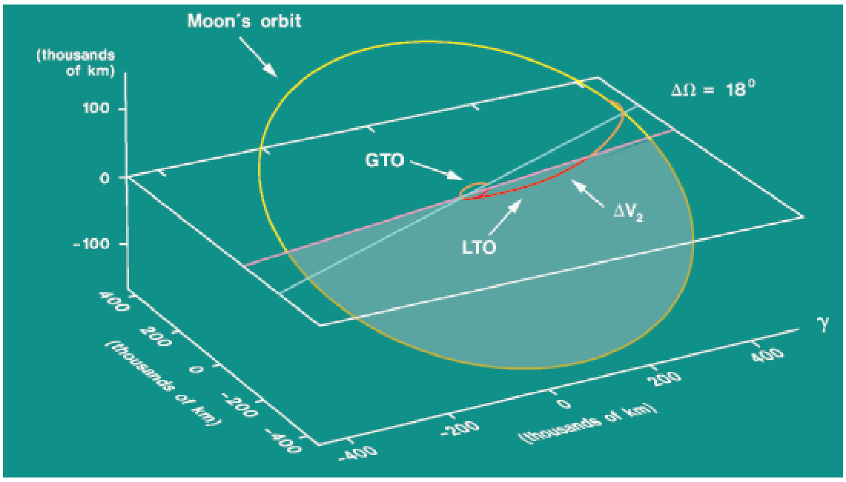


Figure 5. Direct transfer from GTO. The GTO and the Moon’s orbit nodal line are close together (here within 18 deg). A mid-course plane-change manoeuvre (Δv_2) is performed before apogee

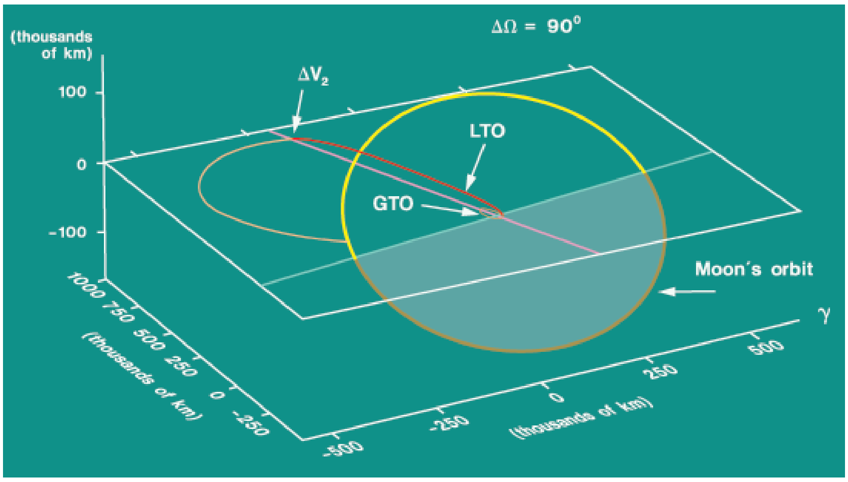


Figure 6. Bi-elliptic transfer from GTO. The GTO and Moon’s orbit nodal line are far apart (in this drawing 90 deg). A mid-course plane-change manoeuvre (Δv_2) is performed at the LTO’s apogee, about 1 million km from Earth

Short transfers from GTO

The Moon can only be reached by direct Translunar Orbit from GTO without a plane change when it is at its nodes (where the Moon’s orbital plane crosses the Earth’s equatorial plane). The GTO apsidal line depends on the direction of the Sun; it is almost tangential to the projection of the Earth-Sun line on the equatorial plane. Therefore, a direct-transfer Translunar Orbit can reach the Moon only when the Sun is along the line of nodes of the Moon’s orbit, which occurs just twice per year. Otherwise, a plane-change manoeuvre is needed. If the GTO node is close to the Moon orbit node, the plane change manoeuvre needed is small and can be accomplished as a mid-course correction on the way to the Moon. This is illustrated in Figure 5, where the node difference is 18 deg. The waiting time for the Moon to arrive at its node is up to one lunar month.

Long transfers from GTO

If the GTO node is distant from the Moon’s orbital node, a different strategy has to be used because a large plane change is required. The manoeuvres for plane changes can be very costly, but the cost can be reduced if the velocity of the spacecraft is low. This is the case at apogee, and higher apogees lead to lower velocities at apogee. Therefore, the following strategy is therefore proposed:
- Raise the apogee to about 1 million km, so hat the apogee velocity is very small. This adds only about 72 m/s to the Δv compared with an apogee raise to the Moon’s distance.
- Perform a plane change at apogee (Δv = 300 m/s approximately), so that the orbit’s return leg meets the Moon’s orbit.

The long transfer (also called a ‘bi-elliptic transfer’) reduces the cost of the plane change considerably. However, the transfer duration extends to 50 days and up to one lunar month is required to wait for the Moon to be present at spacecraft’s arrival. Figure 6 is an example of a bi-elliptic transfer when the node difference is 90 deg.

It can be shown, however, that when starting from a circular orbit with radius R_1 and going to a higher circular orbit with radius R_2, a bi-elliptic transfer is more efficient than a direct transfer, if $R_2/R_1 \geq 12$. This is the case, for example, when starting from a 300 km circular Earth parking orbit and arriving at the Moon’s orbit at 384 400 km radius.

Arrival conditions at the Moon are comparable to those of a direct transfer, but the spacecraft now arrives around the perigee of the Translunar Orbit. Since its velocity is now higher, the relative velocity with respect to the Moon is lower and therefore the Δv needed for Lunar Orbit Insertion is also lower. The location of the periselenium cannot be chosen, but depends on the arrival geometry. Additional burns are needed to position the periselenium, for example, above the lunar South Pole.

Long transfers from GTO, though more complex, make Moon missions less dependant on appropriate launch windows.

Weak Stability Boundary transfers
How can the Δv requirements be further reduced? Lowering the Translunar Injection Δv would mean that we could not reach the Moon, and therefore this is not an option. The only other option is to try to reduce the requirements on the Lunar Orbit Injection. This could be achieved by arriving in the vicinity of the Moon with a low relative velocity, which implies increasing the Translunar Orbit energy level up to the Moon's orbit energy level.

How can the orbital energy be increased without paying for it? A practical way is to 'steal' orbital energy from other celestial bodies, such as the Sun and the Moon. A bi-elliptic orbit already provides enhanced arrival conditions, and gives a Δv saving compared with the direct transfer if the GTO node is distant from the Moon's orbital node. The total Δv requirement could be further reduced if the apogee manoeuvre were not provided by a main-engine burn, but by a perturbation from the Sun's gravity, for example.

This implies taking the spacecraft to a Weak Stability Boundary (WSB) region, where the Sun's or the Moon's gravity is of the same order as that of the Earth. A small manoeuvre within such a WSB region can lead to a drastic change in lunar arrival conditions. These WSB regions are located around the Lagrangian points (see Fig.12).

The concept is not new; in Jules Verne's book 'Journey to the Moon' (1872), the spacecraft 'Columbiad' is shown orbiting the Moon with an aposelenium close to the L1 point. A small Δv given close to the L1 point, achieved using fireworks, was just enough to send the Columbiad back to Earth! More than a century later, the Japanese Hiten spacecraft was the first non-fictional mission to exploit the power of the 'Jules Verne procedure'. After the failure of the Muses-B spacecraft to nominally reach the Moon, an attempt was made to send its companion spacecraft Muses-A, renamed Hiten, towards the Moon. There was insufficient propellant available for a classical transfer, and so a WSB transfer was performed to salvage the mission (Fig. 7).

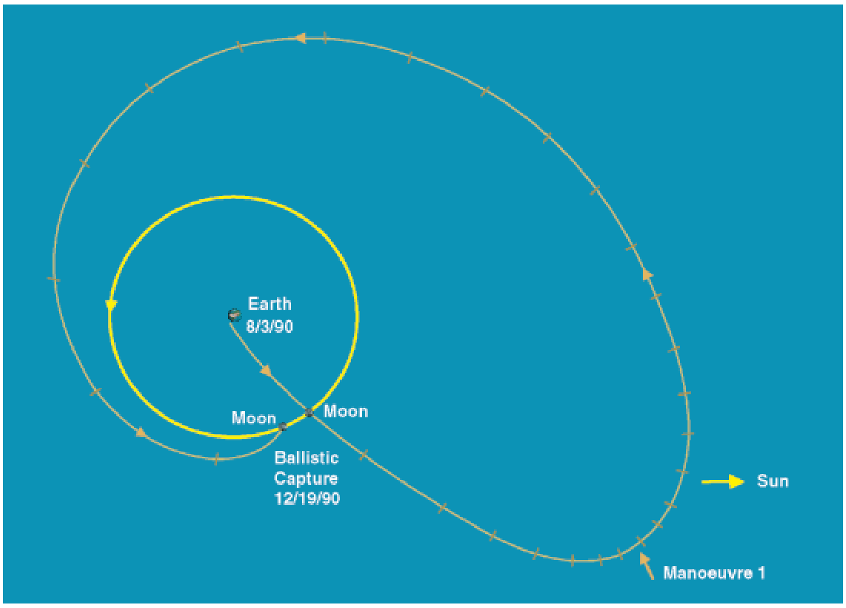


Figure 7. Hiten mission profile (the Sun's direction is shown at Earth departure) Tick marks are at 5 day intervals

A WSB transfer as used by the Hiten spacecraft involves crossing the Sun-Earth WSB at a distance of about 1.4 million km from Earth, where the solar perturbation can substantially increase the Translunar Orbit energy, i.e. increase the perigee to close to the Earth-Moon distance. Figure 8 shows the field-line directions of the Sun's gravity gradient in a rotating co-ordinate system (x-axis always points towards the Sun) with the Earth at the origin. The gradient gets stronger as one moves further away from the Earth, and the greatest effect is therefore at apogee. Figure 8 also shows two highly elliptical orbits with the spacecraft moving in an anti-clockwise direction. It can be seen that the gravity

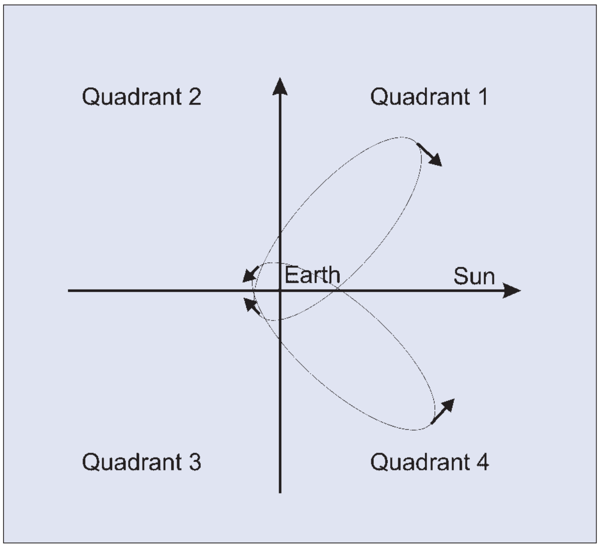


Figure 8. Field-line directions of the Sun's gravity gradient. Two orbits are shown where the Sun's gravity would decrease (quadrant 1) or increase (quadrant 4) the orbital energy

gradient is directed alongside the velocity vector at apogee in the second and fourth quadrants of the co-ordinate system. In the first and third quadrants, it is directed in the opposite direction to the velocity vector at apogee. Therefore, if the apogee is located within the second or fourth quadrant, the Sun increases the orbital energy which, integrated over the long period that the spacecraft spends in the apogee region, raises the perigee towards the Moon's distance.

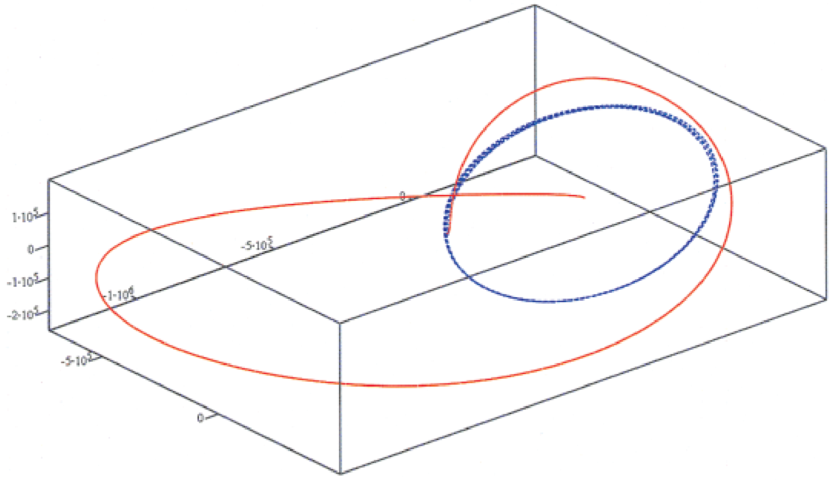


Figure 9. A WSB transfer for a 1 December 2000 launch. The red line shows the spacecraft's orbit, the blue line the Moon's orbit. The Earth is located at the origin of the plot

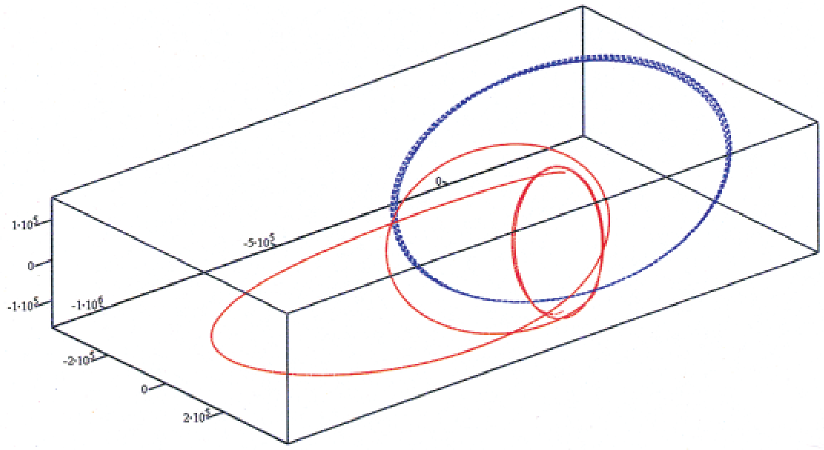


Figure 10. A creative WSB transfer with multiple gravity assists and resonance orbits, for a launch on 31 December 2000

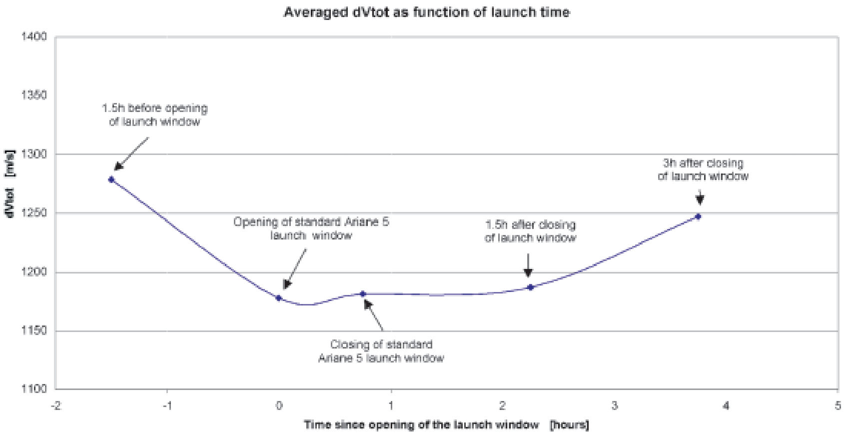


Figure 11. Influence of the time of launch on the total Δv

Upon arrival at the Moon, the Earth-Moon WSB can be used to further reduce the Δv requirement. If the Translunar Orbit energy is close to the Moon's orbital energy, the spacecraft can be captured by the Moon. When reaching the Moon, Earth's gravity can be used to lower the orbital energy relative to the Moon so that the spacecraft can no longer escape from it. A ballistic capture occurs because the Earth has provided the spacecraft with just the right amount of energy to be captured by the Moon.

For such a ballistic capture, the resulting orbit around the Moon has an aposelenium close to the Lagrangian-point distance. A small Δv is then required to lower the aposelenium, since further Earth perturbations could again send the spacecraft into a higher energy escape orbit.

Application to LunarSat

LunarSat is a 100 kg spacecraft, 40 kg of which is propellant and 6 kg is payload. An Ariane-5 could put the spacecraft into GTO within the 2000-2001 time frame. The Δv budget amounts to 1450 m/s. Studies have shown that a direct transfer would require 1270 to 1770 m/s, depending on the GTO and Moon's orbit node difference (i.e. launch date). A bi-elliptic transfer would call for 1380 to 1490 m/s, also depending on the launch date. As an auxiliary passenger, LunarSat has to be compatible with the standard Ariane-5 dual-launch window for any launch date.

A study was performed at ESTEC to see if a WSB transfer would be compatible at all times with the constraint on the Δv. WSB transfers were calculated for a six-month period from December 2000 to May 2001, using genetic algorithms to optimise towards low Δv's. Figure 9 shows a WSB transfer for a launch on 1 December 2000. The solar perturbation raises the perigee to the Moon's distance, and raises the inclination of the Translunar Orbit (7 deg at GTO) towards the inclination of the Moon's orbit (22 deg at end-2000). The transfer takes 93 days, and the apogee is at 1.4 million km. The apogee manoeuvre was optimised to 0 m/s.

Some creative solutions were found by the genetic algorithm using lunar swing-bys and resonance orbits like the example (launch on 31 December 2000) shown in Figure 10. The trajectory resembles the one described previously, but upon reaching the Moon, a swing-by occurs that puts the spacecraft into a

The Lagrangian Points

When considering one celestial body in circular rotation around another one, such as the Moon around the Earth or the Earth around the Sun, there are particular points in space fixed relative to the celestial bodies where the force acting on a spacecraft vanishes. This was discovered by the French mathematician Comte Louis de Lagrange (1736-1813) and these points are therefore called the Lagrangian or libration points. There are five of them: three (L1, L2 and L3) are along the axis going through the two celestial bodies and two others (L4 and L5) are located at the extremity of an equilateral triangle with the two bodies. It is even possible to define orbits around these points. They are unstable, but the corrective manoeuvres needed for keeping a spacecraft in such an orbit are relatively modest. ESA's solar observatory SOHO is in such a Halo orbit around point L1 of the Earth-Sun system, located 1.5 million km from Earth towards the Sun.

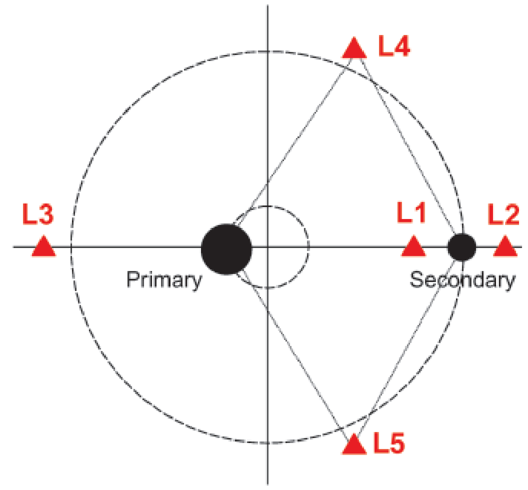


Figure 12. The five Lagrangian points, with the primary and secondary celestial bodies rotating about their common centre of mass

resonance orbit with the Moon, enabling another lunar encounter after 28 days. Another swing-by at this encounter puts the satellite into a new resonance orbit (1:2) such that, after another 28 days, Lunar Orbit Insertion occurs. The total transfer time is 105 days.

The results of the study showed that the Δv ranged from 1130 to 1340 m/s, well below the budget. Another positive finding scientifically speaking was that LunarSat's periselenium was located above the lunar South Pole. The study showed that the spacecraft could arrive in any lunar orbit, in contrast to direct and bi-elliptic transfers, which need extra manoeuvres to adjust the lunar orbit.

For LunarSat, then, WSB transfers reduce the Δv required by approximately 200 m/s compared with direct or bi-elliptic transfers, allowing the overall Δv budget to be reduced from 1450 to 1350 m/s. This implies a reduction in propellant mass of more than 2 kg, which in turn means an increase in payload from 6 to 8 kg, or a 33% increase!

These results were confirmed by a later study conducted by Grupo de Mecánica del Vuelo (GMV, Madrid), in which a parametric analysis for LunarSat was performed for the entire year 2002. The Δv requirement showed a periodic behaviour, with maxima occurring around January-February and July-August, depending on whether the perigee is located in either the 'correct' or the 'incorrect' quadrant. The longest waiting time in GTO is 16 days, with a monthly repetition pattern due to the Moon's rotation period. The transfer duration ranges between 80 and 120 days. Shorter transfer times can be achieved at the expense of a slightly higher Δv.

The GMV study therefore showed that several solutions for a WSB transfer are possible, whatever the launch date and time within the standard Ariane-5 dual-launch window (Fig. 11). It also confirmed the feasibility of WSB transfers from a navigational point of view, in that no exceedingly large correction manoeuvres are needed to reach the target. In addition, the combination of WSB transfers with multiple swing-bys to escape the Earth and reach other planets which was investigated showed substantial savings in terms of Δv.

Conclusions

A variety of scenarios for missions to the Moon have been studied in Europe. Recent studies have focussed on the Geostationary Transfer Orbit as a starting point due to the possibility of reducing launch costs by sharing an Ariane-5 launcher making a commercial flight to GEO. One of the most promising options from such a parking orbit is the use of a Weak Stability Boundary transfer to reach the Moon. The longer transfer times involved are compensated by large savings in Δv, and the possibility of having all types of lunar arrival orbits, which are not possible with the classical approaches.

Acknowledgements

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