Trajectory Design of the Lunar Impactor Mission Concept

Min-Kun J. Chung*, Timothy P. McElrath†, and Ralph B. Roncoli‡
Jet Propulsion Laboratory, Pasadena, CA, 91109

[Abstract] The National Aeronautics and Space Administration (NASA) solicited proposals in 2006 for an opportunity to include a small secondary payload with the launch of the Lunar Reconnaissance Orbiter (LRO) scheduled for October 2008. The cost cap of the proposal was between $50 and $80M, and the mass cap was 1,000 kilograms. JPL proposed a Lunar Impactor (LI) concept for this solicitation. The mission objective of LI was to impact the permanently shadowed region of a South polar crater ultimately to detect the presence of water. The detection of water ice would prove to be an important factor on future lunar exploration. NASA Ames Research Center also proposed a similar concept, the Lunar Crater observation and Sensing Satellite (LCROSS), which was selected by NASA for the mission. However, in this paper, the trajectory design of the LI proposed by JPL is considered. Since the LI spacecraft was to be launched on the LRO launch vehicle as a secondary payload, its initial trajectory must be diverted at some later time from the LRO trans-lunar trajectory for the subsequent impact. Several such trajectories have been considered, where each trajectory option yields some specific values for the mission parameters. The mission parameters include the availability of LRO instruments at the time of impact for the observation by LRO, the mission duration, the impact velocity, the impact angle, etc. It is possible for the LI to be deflected with a relatively low delta-V to impact a South polar crater at a reasonable impact velocity and impact angle directly with no delay. However, the instruments on-board LRO may not be ready for observation. Thus, several delayed trajectory options have been considered further. The lunar phase at the time of impact may also play an important factor for observation, especially from Earth. Several lunar flyby trajectory maneuvers have been identified to arrive at the Moon for impact at the desired lunar phase. By using a combination of these successive lunar flyby maneuvers, the impact lunar phase may be adjusted to the desired location. A few such trajectories have been suggested. Also, some attempts have been made to maximize the impact velocity by converting the impact trajectory into a retrograde orbit with respect to Earth. Since these types of trajectories take advantage of the Sun-Earth three-body region to minimize the delta-V, the mission duration is relatively long. A few such trajectories are suggested. Also, an attempt has been made to adjust the lunar impact within a desired time period for the optimum Earth observation for the above trajectories. The mission parameters resulting from each trajectory option above are considered and weighed against the cost and robustness of the mission in a brief summary.

Nomenclature

ΔV	=	delta-V (an instantaneous velocity discontinuity)
FT	=	flight time
LI	=	Lunar Impactor
LLO	=	low lunar orbit
LOI	=	lunar orbit insertion
LRO	=	Lunar Reconnaissance Orbiter

* Group Member, Inner Planet Mission Analysis Group, GNC Section, 4800 Oak Grove Dr., M/S 301-140L.
† Group Supervisor, Inner Planet Navigation Group, GNC Section, 4800 Oak Grove Dr., M/S 301-276.
‡ Section Staff, Guidance, Navigation, and Control Section, 4800 Oak Grove Dr., M/S 301-125L.

I. Introduction

THE mission objective of LI is to impact in the permanently shadowed region of a South polar crater to detect the presence of H_2O. However, LI spacecraft is to be launched on the LRO launch vehicle as a secondary payload. Thus, its initial trajectory must be diverted at some later time from the LRO trans-lunar trajectory before the impact.

First, in this section, we specify some assumptions made for the LRO nominal trans-lunar trajectory, LOI, the lunar insertion orbit, and the final LRO lunar orbit in this section. Also, we define some LI mission parameters and concepts. Finally, we give some further assumptions made for the analysis also.

A. Assumptions on the LRO Nominal Trans-Lunar Trajectory and Lunar Orbit

A typical direct trans-lunar trajectory takes about 4 days from the Earth injection to LOI. For a resulting polar orbit, LOI may take place either past the North Pole or past the South Pole. Our earlier analysis was based on the nominal LRO launch date of early October, 2008, when the Moon is near the opposite side of the Sun with respect to the Earth (or around the full moon) and LOI taking place past the North Pole according to an older version of the LRO mission plan. However, an updated version of LRO mission plan, later in the second phase of our proposal, showed the nominal launch dates of a few days around 16-Oct-2008 and 02-Nov-2008 and LOI occurring past the South Pole. Thus, our earlier analysis was performed with early October launch and with LOI occurring past the North Pole, whereas our later analysis was performed with two launch dates, 16-Oct-2008 and 02-Nov-2008, and with LOI occurring past the South Pole. A different launch date determines a different initial lunar phase. And the different direction of the incoming LRO trans-lunar trajectory before LOI will require a change in the divert procedure and the divert ΔV amount a bit. However, most analysis would remain valid in principle.

Refer to Fig. 1 for the LRO trans-lunar trajectory and LOI geometry. In the Sun-Earth rotating frame centered at the Earth, the Sun direction is fixed along the negative X-axis, and the Moon rotates counter-clockwise around the Earth once in about 29.5 days, the synodic period of the Moon. The 4-day nominal LRO trans-lunar trajectory is injected from the Earth park orbit with the injection energy, C3, of about -2 km^2/s^2. After 4 days, LOI takes place at the 100-km altitude about 50° past the North Pole (or the South Pole in our later analysis). At LOI, the LRO decelerates with ΔV of about 335 m/s to insert into a 12-hour elliptical polar orbit. It eventually descends into a two-hour LLO.

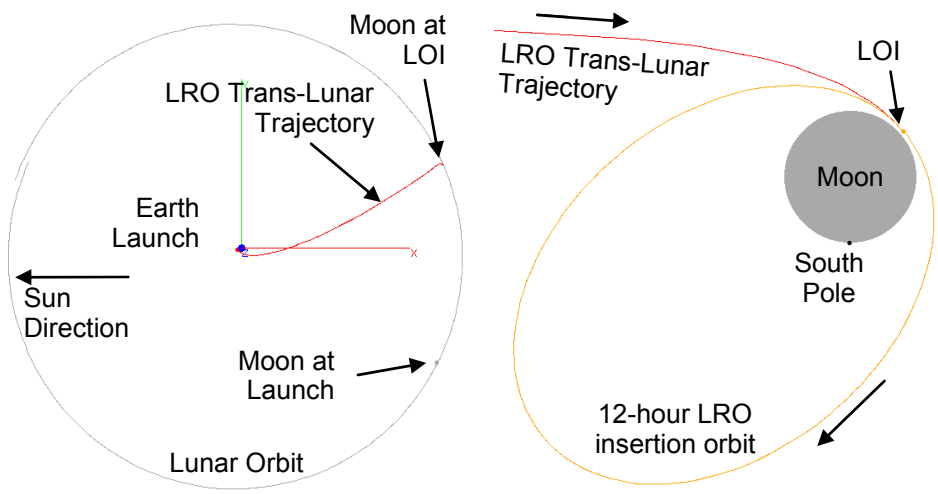


Figure 1. (a) Nominal LRO trans-Lunar trajectory in Sun-Earth rotating frame (left); (b) LOI and LRO insertion orbit (right). *In Sun-Earth rotating frame the lunar phase is easily identified since the direction of the Sun remains fixed with respect to Earth. This particular figure displays LOI occurring past the North Pole. However, our later analysis is based on LOI occurring past the South Pole.*

B. Trajectory Categories and Parameters

Given the above assumption on the LRO trajectories, we have identified two basic categories for LI trajectories according to their impact time: (1) direct; (2) delayed. The direct impact option is a relatively simple concept for diverting from the LRO trans-lunar trajectory to impact the Moon at the first approach near the time of LRO LOI. The delayed impact option is a more sophisticated concept for diverting LI to fly by the Moon at the first lunar approach to impact the Moon by returning at a later date.

The trajectory parameters include the following: (1) the mission duration, (2) the divert ΔV, (3) the impact velocity, (4) the impact angle, and (5) the impact lunar phase:

(1) The mission duration refers to the total FT between the Earth launch and the final lunar impact. The mission duration for the direct option is about 4 days while that of the delayed mission is much longer. The availability of LRO instruments (which may take several weeks) at the impact time for the observation of H_2O IR scattering may be an important factor in selecting a trajectory option, if indeed LRO instruments are to be used for observing the impact.

(2) The divert ΔV is the thrust in terms of instantaneous velocity discontinuity that must be exerted to divert from the nominal LRO trajectory to impact the Moon. The total ΔV budget for the LI mission concept was 80 m/s, which originated from an unmodified 19 inch hydrazine tank that would fit well without modification in one of six modules of the ESPA (EELV Secondary Payload Adapter) ring.

(3) The impact velocity refers to the speed at which LI hits the local site. In general, a higher impact velocity is desirable since the impact energy is proportional to the square of the impact velocity.

(4) The impact angle refers to the elevation angle of the incoming impact velocity with respect to the local horizon of the impact site. The impact azimuth refers to the azimuth of the direction of the incoming impact velocity. A preferred impact angle is 30° or above to produce enough plume without skidding. The impact azimuth may not be so critical to the mission.

(5) The impact lunar phase refers to the lunar phase at the time of impact. The ideal lunar phase for the Earth observation of the impact is identified as the half-moon, either waning or waxing, which corresponds to the lunar phase of 90° or 270° in the Sun-Earth rotating frame, respectively.

C. Further Assumptions

For this analysis, any permanently shadowed crater within 60 km of the South Pole may have been used as the impact target location such as Shoemaker, Faustini, or Shackleton. The one used for the current analysis is the Shackleton crater, whose coordinates are assumed to be 89.9° South latitude and 0° longitude.

All ΔV numbers given in this analysis are assumed to be instantaneous and deterministic unless indicated otherwise.

II. Direct Impact

LI is diverted from the LRO trans-lunar trajectory only enough to impact the crater at the first approach to the Moon near the time of LRO LOI. In this section, an optimum divert maneuver position is determined as well as the divert ΔV magnitude.

A. Optimum Divert Maneuver Position

Several divert positions of LI have been considered along the LRO trans-lunar trajectory. Fig. 2 shows the deterministic ΔV that must be exerted at various points in time after the Earth injection in order to divert the LRO trajectory to impact the crater. The plot reveals that the minimum divert ΔV occurs at about 18 hours past the Earth injection. But the divert position at one day after the Earth injection is reasonable in the divert ΔV magnitude, although it is not exactly the minimum point. Also, while the divert position of one day may seem a bit close from the Earth injection, it may coincide with the Earth injection correction time. In addition, it gives a sufficient time for the divert maneuver correction. Thus, the nominal divert position of one day after launch is assumed for the further analysis.

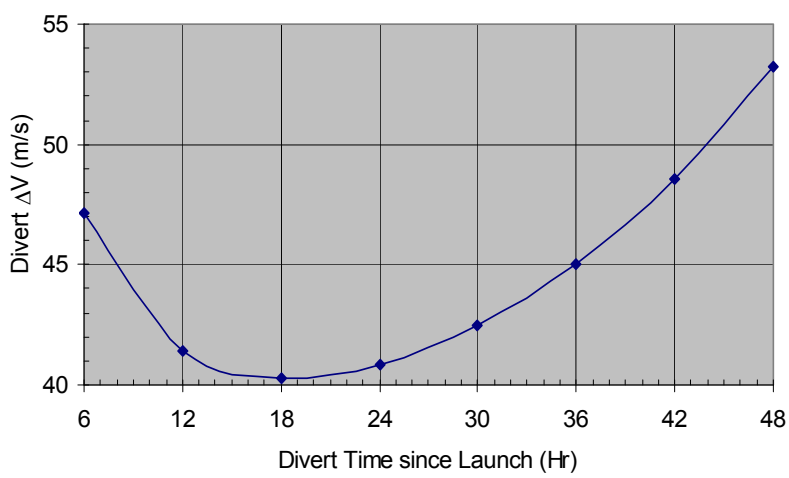


Figure 2. Optimum Divert Maneuver ΔV at Various Divert Times. *The divert maneuver point of one day after the Earth injection was chosen because it is close to the minimum and it may coincide with the time of the injection clean-up. Also, it provides a sufficient time for the divert maneuver correction before the first lunar approach.*

B. Direct Impact Trajectory

As already indicated above, in this option LI is diverted from the LRO trans-lunar trajectory only enough to impact the crater at the first approach to the Moon. Since there is only one such optimum divert trajectory, the trajectory parameters are relatively fixed for this option. The mission duration is about 4 days with an optimum divert maneuver of 41 m/s (This assumes LRO LOI occurring past the North Pole. If LRO LOI occurring past the South Pole is assumed, the divert ΔV would be much less, probably about 10 m/s or less) about a day after launch. Fig. 3(a) shows the direct impact trajectory in relation to the LRO trans-lunar trajectory, LOI, and LRO insertion orbit. The impact velocity is 2528 m/s, the impact angle 31°, and the impact azimuth 99°. Fig. 3(b) illustrates the relative geometry of the incoming impact velocity direction in relation to the Sun and Earth directions and the local horizon. The observer is looking "upwards" at the South polar region of the Moon. Thus, the direct divert trajectory is possible and yields acceptable mission parameters. Its simplicity and short duration allow a simpler flight system design and lower operations cost.

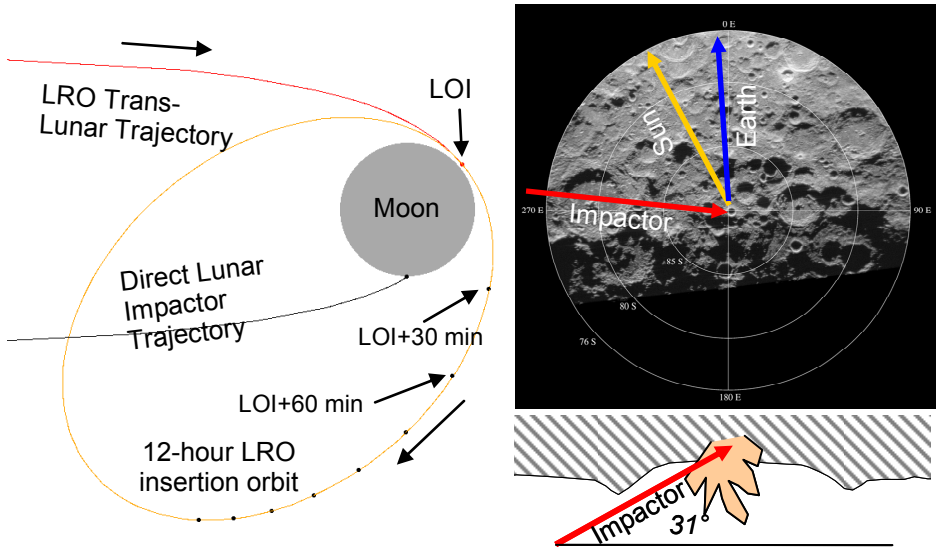


Figure 3. (a) Direct Impact Trajectory Plot (left); (b) Impact Velocity Geometry Illustration (right). *The tick marks (black dots) on the LRO insertion orbit show 30 minute steps after LOI. Delaying the direct impact time to between LOI+30 min and LOI+60 min places LRO in a reasonably good position to observe the impact (left). The direction of impact velocity is shown with respect to the Sun and Earth directions as well as the local horizon (right).*

C. Delaying the Direct Impact

Refer to Fig. 4 for the total divert maneuver ΔV required to delay the direct impact. The minimum occurs immediately before LOI, and it rises rather sharply both before and after. The delay of the impact time beyond a few hours for observation by LRO is probably unreasonable. Refer back to Fig. 3 for the direct impact trajectory in relation to LRO LOI and the subsequent LRO trajectory points in the 12-hour LRO insertion orbit. The impact delay between 30 to 60 minutes places LRO in a relatively good spot for observation opportunity. In Fig. 3(a), the tick marks are placed on the LRO insertion orbit at every 30 minutes from LOI to LOI + 4 hours.

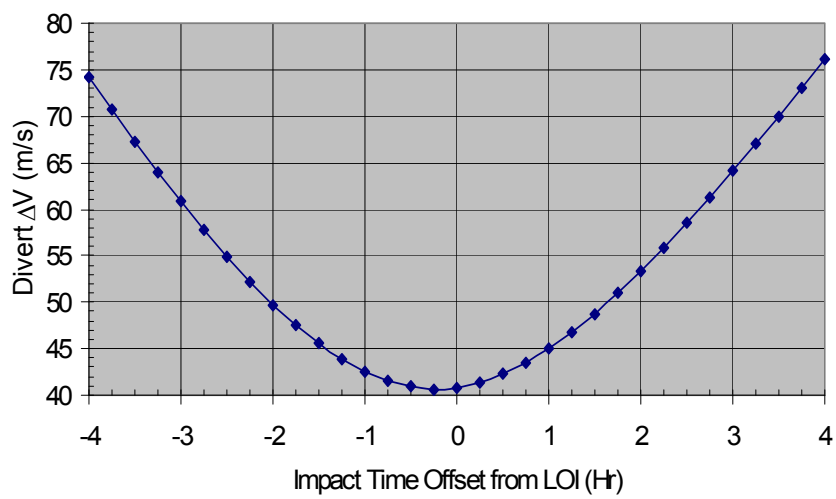


Figure 4. Divert Maneuver ΔV Required to Delay Direct Impact Time. *The minimum occurs shortly before the LRO LOI. Delaying the direct impact for an hour places LRO in a relatively good position according to Fig. 3 with only 4 m/s additional ΔV.*

However, the LRO instruments may not be ready that early in the mission, as we assume that an instrument check out period may take several

weeks. While the distant observation is certainly possible for the extended signature of UV fluorescence of OH from the vapor plume, the initial signature from H_2O IR scattering may be observed only by LRO. Thus, if we assume that LRO is the primary viewer and scientific platform for observation, the unavailability of LRO instruments would be the greatest drawback for the direct impact option.

Thus, the direct impact option, despite its attractive features, is not pursued further in depth due to the unavailability of the LRO instrument at the time of direct impact. The rest of this paper will focus on the delayed impact option.

III. Delayed Impact

The delayed impact option assumes a lunar "backflip" maneuver at the first lunar flyby, where LI is diverted from the LRO trans-lunar trajectory to "flip behind" the Moon under the lunar South Pole (if LRO LOI occurs past the South Pole, or above the North Pole if LRO LOI occurs over the North Pole—this is to minimize the divert ΔV) into a highly inclined orbit with respect to the lunar orbital plane.

A. Backflip Loops

The simplest kinds of such delayed trajectories are backflip loop trajectories. Each loop (or rev around the Earth) may be roughly an integer multiple of a lunar month near at the lunar distance from the Earth. The period of such an orbit is close to the integer multiple of the sidereal period of the Moon, about 27.3 days. One-month single loop is possible without any intermediate ΔV since the trajectory does not depart too far from the Earth; however, two or more month loop may require a small intermediate ΔV to accommodate the third body (solar) perturbation.

Fig. 5(a) shows a two-month, two-rev backflip trajectory plot in the Sun-Earth rotating frame, where the Sun direction is fixed along the negative X-axis. The mission duration of this kind of backflip trajectory is the sum of 4 days from the trans-lunar portion and the integer multiples of 27.3 days, the sidereal period of the Moon. To avoid the premature collision with the Moon, the period of the the backflip trajectory is made slightly shorter than the sidereal period of the Moon. The mission duration can be more flexibly planned in the increment of 27.3 days (i.e., 31, 58, 85, etc.) as opposed to the 4-day fixed direct impact option. For the two-month backflip trajectory in Fig. 5(a), the total flight time is 58 days (4 days from the trans-lunar trajectory plus about 54 days from the two revolutions of the sidereal period). The divert ΔV is 66 m/s (again, this value assumes LRO LOI occurring past the North Pole. If LRO LOI was assumed to occur past the South Pole, it would be about 20 m/s). The impact velocity is 2522 m/s, similar order to the direct impact case. The impact angle is 69°, significantly higher than the direct case. The impact azimuth is 59°. Figure 5(b) illustrates the impact velocity direction in relation to the Sun and Earth directions and the local horizon.

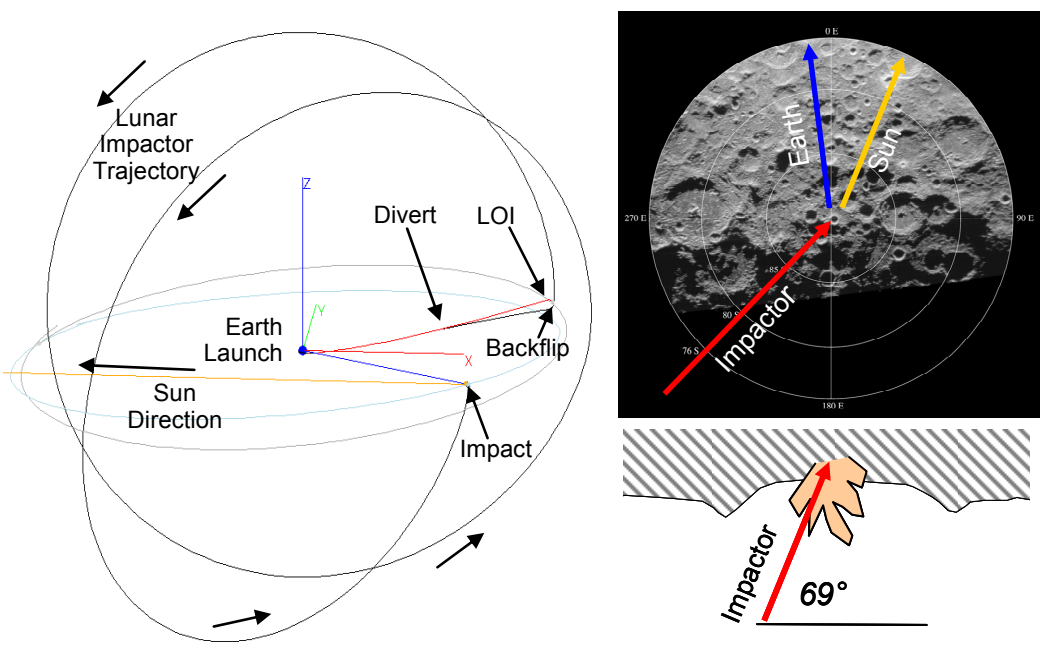


Figure 5. (a)Two-loop Backflip Trajectory; (b) Impact Geometry. *A two-loop, 58-day backflip loop trajectory is displayed in the Sun-Earth Rotating Frame. The impact velocity direction is displayed in relation to Sun and Earth Directions and the local horizon.*

A half-month loop and the odd multiples of a half-month loop are also possible. In this case, LI would have to fly over the North Pole to impact the Moon near the South Pole on the opposite side of the lunar orbit.

The delayed impact option requires a more sophisticated spacecraft design and longer mission operations than the direct; thus, it is expected to cost more. However, the delayed impact can be accommodated by LRO instruments during its orbiting phase for viewing and observing. The observation geometry by the Earth-trailing telescopes such as Hubble or the viewing from Earth are probably unaffected, whether the direct impact or the delayed impact.

A further analysis shows that the impact can be delayed further for one or two months in an extra loop with an additional ΔV of 30 m/s or 10 m/s (respectively) up to about 10 days before the impact, should there be any need for a further delay on a scheduled impact time after the initial divert burn.

B. Controlling the Lunar Phase at Impact

Note that there is a constant clockwise lag of the inertial axis in the Sun-Earth rotating frame; so, the lunar phase lags behind at about 30° per lunar month. Thus, for example, the two-month backflip trajectory in Fig. 5 impacts at the location about 60° clockwise away from the initial lunar flyby. Impacting with a specified lunar phase regardless of the starting lunar phase at launch requires a strategy. Such a strategy may be necessary if there is a preferred lunar phase at impact. Indeed, a half-moon, either waxing or waning, which corresponds to the lunar phase of either 90° or 270°, may be preferred for Earth observation.

Table 1 shows some sample Moon-to-Moon flyby legs. Each is associated with an approximate FT in days as well as an approximate lunar phase change in degrees. Since the lunar flyby V-infinity can be made to remain relatively small at approximately 0.9 km/s, the turn angle of approximately 90° is possible during the lunar flybys. Thus, starting from the initial lunar phase at launch, one can heuristically add up the changes in the lunar phase to arrive at a desired lunar phase by successive lunar flybys as he chooses alternately one from out-of-plane legs and another from in-plane legs, of course, at the expense of arbitrarily longer FT.

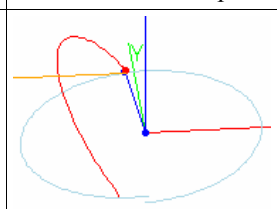
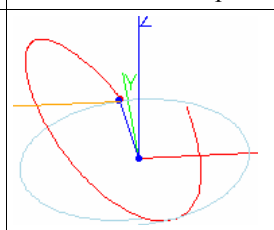
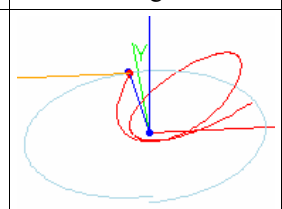
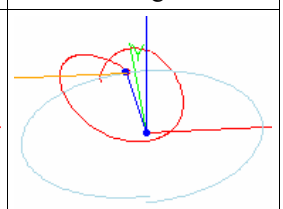
Name	half-rev backflip	full-rev backflip	trailing 3/4	leading 1+
Figure				
Plane	Out-of-plane	Out-of-plane	In-plane	in-plane
FT (days)	14	27	24	30
Phase (°)	+160	-36	-76	+13

Table 1. Lunar Flyby Legs Toolbox. *Figures are drawn in Sun-Earth rotating frame where the direction of the Sun is fixed (shown in orange attached to the Moon at the first flyby) toward the negative X-axis (shown in red). The lunar orbit is shown in light blue. Phase angles are positive counter-clockwise. The list is not exhaustive.*

Once a desired sequence of lunar flyby legs are selected, they can be differentially corrected to form a complete integrated trajectory. Fig. 6 shows two such trajectories. The launch date of the left one (a) is 16-Oct-2008 whereas that of the right one (b) is 02-Nov-2008, nearly the opposite lunar phase to the other. However, the impact is made to occur nearly the same lunar phase at around 270° by adding together a proper series of lunar flyby legs to each initial trans-lunar trajectory.

The divert ΔV of the left one (a) is 38 m/s with the impact velocity of 2508 m/s, the impact angle of 73°, the impact azimuth of 78°, and the total FT of 79 days. The divert ΔV of the right one is 10 m/s with the impact velocity of 2.563 km/s, the impact angle of 67°, the impact azimuth of 77°, and the total FT of 67 days.

Please note that the divert ΔV of the left one is a bit higher than that of the right one because the first flyby maneuver of the left one is in-plane. It costs more ΔV to divert the out-of-plane (polar) LRO trans-lunar trajectory into an in-plane, incoming V-infinity. Another example of 16-Oct-2008 launch (not shown in the figure), which does an out-of-plane half-rev backflip after the first lunar flyby rather than an in-plane "trailing 3/4" as in Fig. 6 (a), expends only 23 m/s divert ΔV as opposed 38 m/s. In general, it is cheaper (10-20 m/s) to do an out-of-plane backflip over the same pole as LRO LOI at the first lunar flyby. An in-plane maneuver at the first lunar flyby costs about 40 m/s divert ΔV. But an out-of-plane backflip maneuver over the opposite pole would cost about 60 m/s.

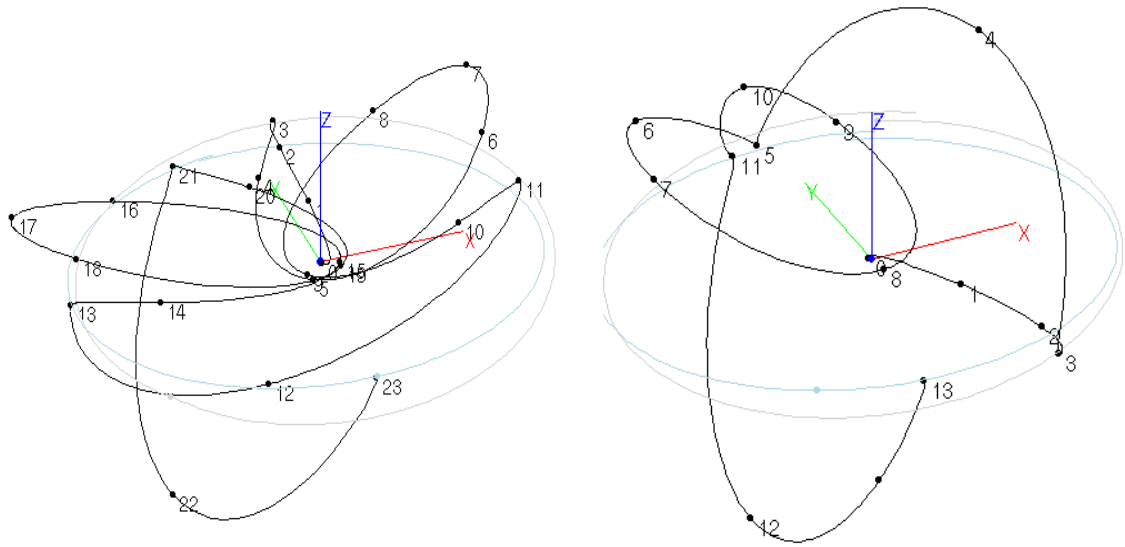


Figure 6. Trajectories with Lunar Phase Controlled at Impact: (a) 16-Oct-2008 launch (left); (b) 02-Nov-2008 launch (right). *These trajectories are constructed by patching together the lunar flyby legs to the initial trans-lunar trajectory. Although the launch times are nearly opposite in the lunar phase, by selecting a proper sequence of legs, the impact is made to occur near the waxing half-moon in both trajectories. The light gray represents the Moon's orbit at launch whereas the light blue that at impact.*

Although these "acrobatic" flyby maneuvers appear rather difficult to navigate, JPL NAV team has verified that no more than a few m/s of statistical ΔV is necessary per lunar flyby for precision navigation and targeting by strategic placement of maneuvers.

C. Increasing the Impact Velocity

All the trajectories described thus far have the impact velocity in the neighborhood of 2.5 km/s. Since the impact energy is proportional to the square of the impact velocity, a higher impact velocity is desirable. Probably the best way to achieve a higher impact velocity is to make the LI orbit retrograde with respect to the Earth before impacting the Moon. The cheapest way to achieve a retrograde orbit is probably to make LI enter the vicinity of the Sun-Earth three-body region after a lunar flyby to be perturbed by Sun's gravity. This Sun-perturbed lunar flyby leg is at least 3 months in length. After it returns from the Sun-Earth three-body region, LI may fly by the Moon once more in a 1.5+-month half-rev backflip or 2+-month full-rev backflip to impact the South Pole region. A half-month half-rev

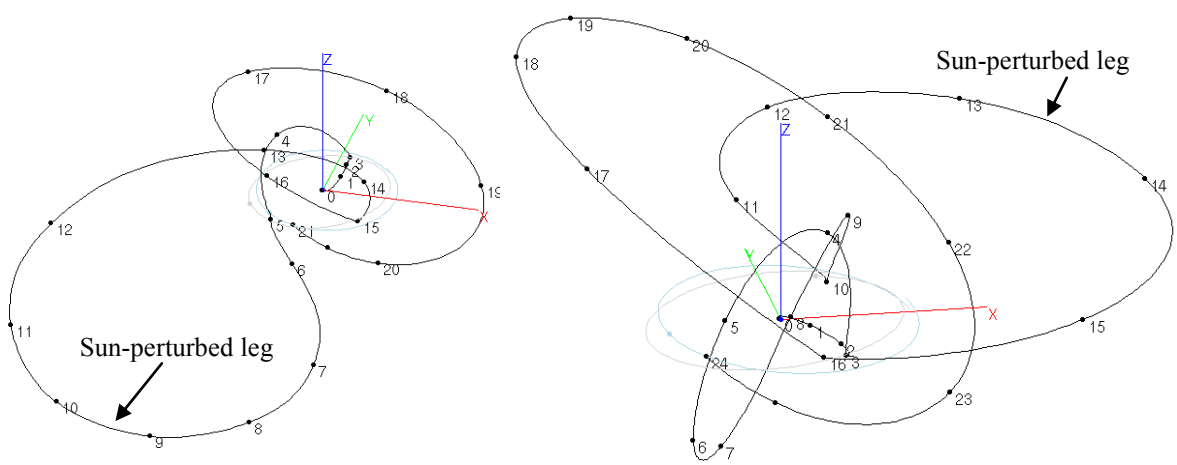


Figure 7. Trajectories with Higher Impact Velocity: (a) 16-Oct-2008 launch (left); (b) 02-Nov-2008 launch (right). *A Sun-perturbed lunar flyby leg that enters the Sun-Earth three-body region is added to the LI trajectory followed by a 2+-month full-rev backflip for an impact velocity exceeding 3.2 km/s without any divert ΔV penalty.*

backflip or one-month full-rev backflip in Table 1 cannot be used due to the higher V-infinity exceeding 2.2 km/s with respect to the Moon.

Fig. 7 shows two such trajectories both with the impact velocity of 3.2 km/s or higher: (a) the left one (16-Oct-2008 launch) achieves the impact velocity of 3.27 km/s with the impact angle of 32° and the impact azimuth of 93° after 255 days of FT with 23 m/s divert ΔV; (b) the right one (02-Nov-2008 launch) achieves the impact velocity of 3.28 km/s with the impact angle of 36° and the impact azimuth of 102° after 235 days of FT with 10 m/s divert ΔV.

Please note that there is hardly any loss in the divert ΔV for the higher impact velocity. But an obvious drawback is the long FT, which may add cost to the mission. However, the long delay may actually be more advantageous from the standpoint of LRO instruments preparation since they may need several months for calibration and collection of background data. Another concern is that it may not be as easy to target a particular lunar phase at impact due to the high V-infinity; nevertheless, the impact can be made to occur in the neighborhood of the desired lunar phase.

IV. Synchronizing the Impact Time for Observation

The impact time may need to be synchronized with observation by LRO as well as with observation at a specific location on Earth. Since LRO orbit at the time of impact may not be predictable until near the time of impact, the former case must assume an additional deterministic ΔV post the initial divert burn. However, since the latter case may be fully determined by the geometry before launch, the initial divert burn may be adjusted to satisfy the condition.

A. Observation by LRO

The impact time may have to be synchronized with the LRO orbit. Since the period of the final LRO lunar orbit is about two hours, an additional deterministic ΔV must be budgeted to be able to change the LI impact time up to ±1 hour. A further analysis shows several m/s are necessary up to about 10 days before the impact for most of the trajectories described above.

B. Observation from a Specific Location on Earth

The impact time may also need to be synchronized with an Earth observation at a specified location, for example, an observatory in Hawaii. As already mentioned above, a preferred lunar phase for the Earth observation may be a half moon, either waning or waxing, which corresponds to the lunar phase angle of 90° or 270°. A preferred condition around those lunar phases is when the Sun elevation is far below the local horizon (for example, about -18° or below) and the Moon's elevation is well above the horizon (for example, +20° or above). Such condition limits the observation duration at a specified location to several hours to only a few hours per day. The goal is to adjust the LI trajectory so that the impact occurs within one of those observation opportunities. A further analysis shows that such is possible with a total deterministic ΔV budget of 40 m/s for the phase controlled trajectories. The longer, Sun-perturbed trajectories are flexible enough to delay even a whole day without any ΔV penalty.

V. Summary

The trajectories described above are summarized in Table 2 with brief statements of their characteristics. The final decision must weigh these against the constraints of the mission.

Trajectory Case	*FT (days)*	*Divert ΔV (m/s)*	*Impact Velocity (km/s)*	*Impact Angle (°)*	*Number of Lunar Flybys*	*Target Lunar Phase*	*Sync with LRO Observation (m/s)*	*Sync with Earth Observation*
Direct	4	10-40	2.5	~30	0	N/A	N/A	N/A
Backflip loops	31, 58, 85, etc.	10-40	2.5	~70	1	N/A	~10	N/A
Lunar Phase Controlled	70+	10-40	2.5	~70	3-4	Yes	~10	Small additional ΔV
Sun-perturbed	200+	10-40	3.2	~30	3-4	Vicinity	~10	no additional ΔV

Table 2. Trajectory Summary. *Four types of trajectories are summarized with some pertinent characteristics.*

In summary, the direct impact case suffers from observation by LRO. The lunar phase controlled case has advantage over the simple backflip loops in that it can target a desired lunar phase at impact with the complexity of a few more lunar flybys. The Sun-perturbed case has a distinct advantage of a higher impact velocity with a relatively long FT, which may raise the mission cost.

Acknowledgments

Thanks to the JPL LI proposal team led by Leon Alkalai, to the JPL NAV team for validating the trajectories for navigation, to George Hockney for the LTool software support, to Roby Wilson for the use of Two-level differential correction, and to Prof. Philip Gill for the use of NPOPT.

References

[1]Alkalai, Leon., "Lunar Impactor Proposal," JPL, March 21, 2006 (unpublished).

[2]Roncoli, Ralph., *Lunar Constants and Models Document*, JPL D-32296, September 23, 2005.

[3]Sereyevsky, Andrey B., Snyder Gerald C., and Cunniff, Ross A., *Interplanetary Mission Design Handbook*, Volume I, Part 2, JPL PUBLICATION 82-43, September 15, 1983, pp. 18-24.