

BLT (Ballistic Lunar Transfer) Cheat Sheet

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A ballistic lunar transfer (BLT) is a type of “low-energy” transfer from the Earth to the Moon that uses the gravity of the Earth, Moon, and Sun to reduce the required ΔV . [1], [2], [11], [3]–[10] Rather than transferring directly to the Moon (as in the crewed Apollo and Artemis missions), a BLT travels on the order of a million km away from the Earth, to the point where the Sun’s gravity becomes the dominant force acting on the spacecraft. The trajectory is designed such that the gravity of the Sun raises the perigee radius up to the Moon’s orbit and changes the inclination relative to the Earth to match the desired orbit plane. The solar gravitational influence thus enables insertion into a wide range of lunar orbits for reduced ΔV compared to direct transfers.

This goal of this “cheat sheet” is to summarize high-level mission design considerations for BLTs to the Gateway near-rectilinear halo orbit (NRHO) or other lunar orbits. Requirements for ΔV are described, along with a discussion of the driving factors. Example transfers are presented and discussed.

1 High-Level ΔV Requirements for BLTs

BLTs have been studied by a variety of authors [citations] in the literature. The results presented here are motivated by NASA’s Gateway mission, where BLTs are an attractive option for uncrewed launches (such as cargo delivery or modular Gateway construction) to the Earth-Moon reference NRHO destination. Figure 1 shows a representative example BLT to NRHO in an Earth-centered inertial frame. This view highlights the effect of the Sun’s gravity in raising perigee and changing inclination.

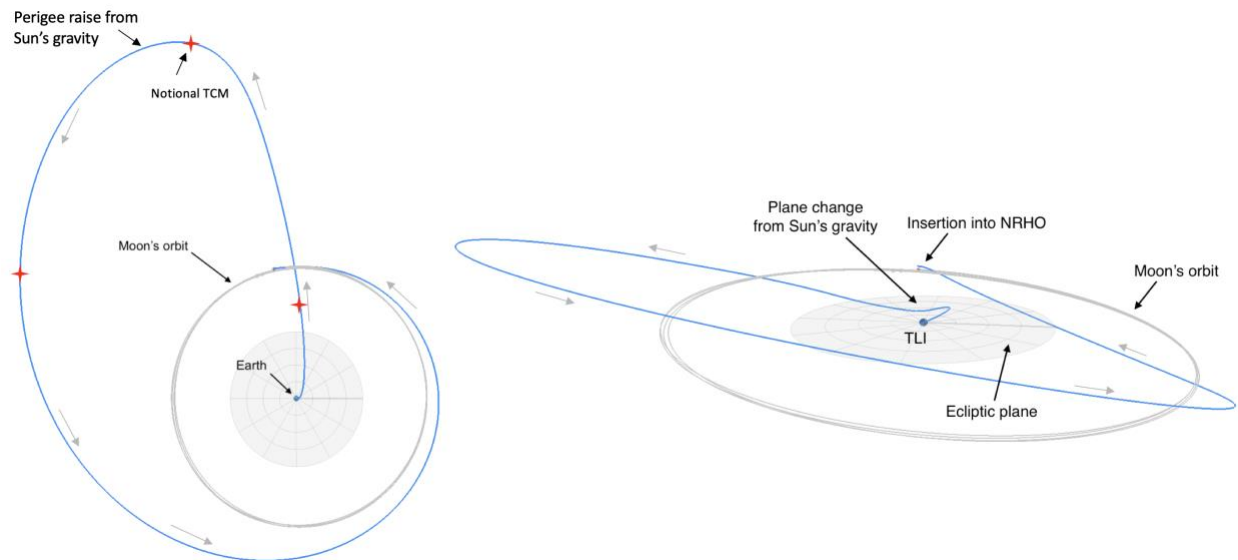


Figure 1. A BLT viewed in an Earth-centered inertial frame, top-down and inclined views. [4]

The primary motivating factor for flying a BLT is the ΔV savings compared to a direct transfer. The total spacecraft ΔV for a BLT to NRHO is highly dependent on a number of factors, such as:

- maneuver execution error,
- navigation accuracy,
- launch vehicle accuracy,
- perilune vs apolune NRHO insertion,
- option to “wind on” to the NRHO over a few revolutions,
- thrust and burn duration constraints,

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- communications constraints,
- desired availability of launch periods (i.e. minimum duration of a launch period, # of days per month to be able to launch, eclipse constraints, etc.), and
- time of flight constraints.

When the destination orbit is an NRHO or other neutrally stable or unstable orbit, the ΔV is mostly comprised of statistical cleanup maneuvers. To get the truly optimal ΔV , the trajectory correction maneuvers and insertion maneuvers must be optimized for the expected maneuver execution and navigation errors. Many missions can safely fly a BLT to NRHO for as little as 70-100 m/s, but 150 m/s is recommended as a safe starting point for early designs. This ballpark figure is valid for all types of BLTs considered here.

2 Families of BLTs

Parrish et al. [4] defined 16 families of BLTs that together provide launch opportunities almost every day. These families are identified by four key characteristics:

- Trans-lunar injection (TLI) near ascending or descending node;
- Apogee in Quadrant II (apogee towards the Sun) or IV (apogee away from the Sun) of the Sun-Earth rotating frame;
- Outbound lunar flyby to raise apogee or direct injection;
- For families with an outbound lunar flyby, number of lunar orbits between flyby and insertion.

This is not a comprehensive description of all low-energy transfers, but it provides a helpful starting point. Trajectories with the TLI near the ascending node or descending node are largely similar; the main difference is in the first few hours of the transfer. The choice between ascending node or descending node is mainly driven by eclipse constraints immediately after TLI and nominal trajectory correction maneuver (TCM) ΔV difference up to ~ 80 m/s.

Figure 2 shows the difference between BLTs with apogee towards the Sun vs away from the Sun, where there is no outbound lunar flyby. These two families of BLTs are rotated 180° about the Sun-Earth angular momentum axis – a trend observed for all of the families of BLTs. Each of these can exist with TLI near the ascending node or descending node.

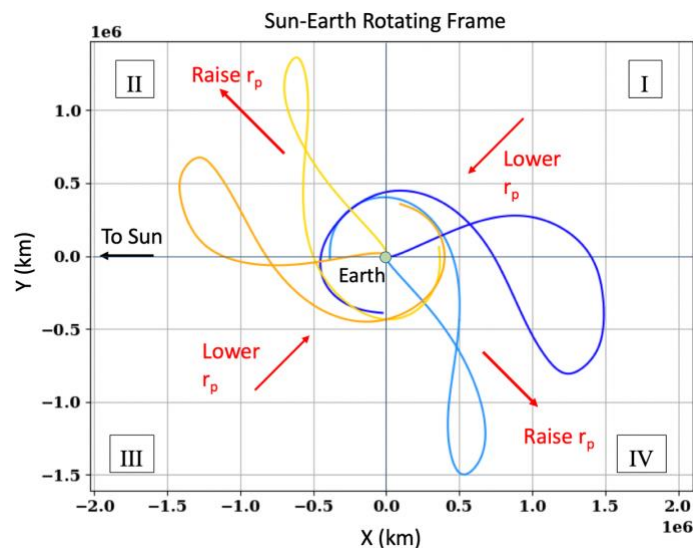


Figure 2. Two BLT families without a lunar flyby in Sun-Earth rotating frame. The first family (orange colors) has apogee in Quadrant II; the second (blue colors) has apogee in Quadrant IV. [4]

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An outbound lunar flyby can be included in the BLT design to reduce the required C3 at launch. Figure 3 shows six families of BLTs with an outbound lunar flyby. As was previously observed in Figure 2, the families come in pairs, rotated 180° from each other about the Sun-Earth angular momentum axis. Each of the six families shown in Figure 3 also has another pair (indistinguishable at this scale) with TLI near the ascending or descending node.

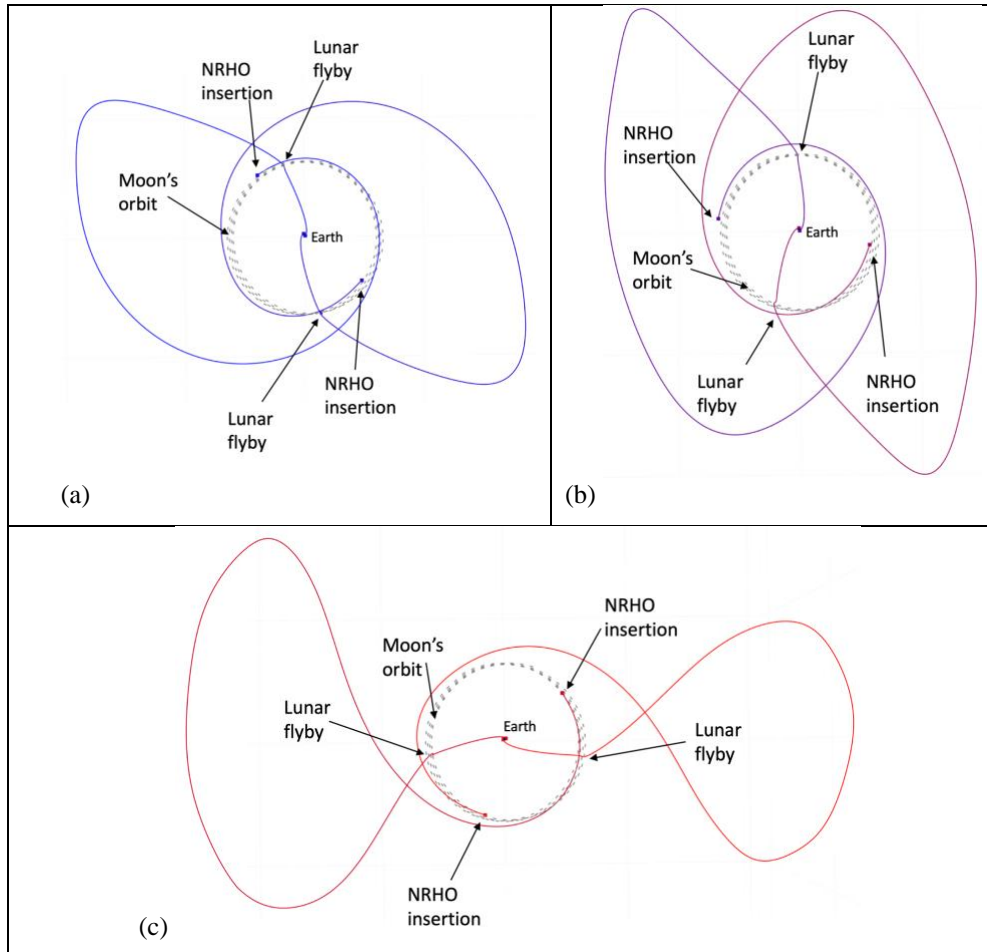


Figure 3. “Short” (a), “medium” (b), and “long” (c) families of BLTs with outbound lunar flybys. Shown in the Sun-Earth rotating frame, with the Sun far to the left. The “short” family is the shortest time of flight BLT solution that does not require a large deep space maneuver at apogee.

Every family of BLTs repeats once per synodic month (~29.5 days). As the Earth and Moon travel around the Sun, the families of solutions evolve in a cycle that approximately repeats itself every year. The “best” family will change depending on the time of year, launch constraints, and target orbit.

The main reason to choose to use a lunar flyby is to reduce the launch vehicle C3 requirement, typically with a corresponding increase to the time of flight. With a lunar flyby, the launch C3 is comparable to the requirement for direct transfers. Representative values of C3 and time of flight are presented in Table 1.

Table 1. Transfer time and C3 with and without outbound lunar flyby.

	Time of Flight	Launch Vehicle C3
Without Lunar Flyby	80 to 130 days	-0.7 to -0.3 km ² /s ²
With Lunar Flyby	110 to 180 days	-2.2 to -1.5 km ² /s ²

As a result of the additional geometry constraint imposed by a lunar flyby, the typical launch period is only a few days long, compared to 10-20 days when there is no lunar flyby. However, this limitation is offset by the existence of many more families to choose from. Launch periods are discussed further in Section 6.

3 Example BLT to NRHO

The first mission to fly a BLT to NRHO is NASA's CAPSTONE pathfinder mission, developed by Advanced Space and planned for launch in mid 2021. CAPSTONE will launch on a Rocket Lab Electron onto a BLT without a lunar flyby. Thorough Monte Carlo analyses have been completed for CAPSTONE, resulting in the ΔV budget presented in Table 2. For each component of the mission, the nominal and statistical ΔV are provided, where statistical ΔV represents the 99th percentile ΔV from Monte Carlo analysis. This is presented as an example. Note that when statistical ΔV is taken into account (representing launch injection errors, navigation errors, and maneuver execution errors), the ΔV more than doubles compared to the nominal. This underscores the importance of understanding mission-specific error sources and carrying out Monte Carlo analysis for low-energy trajectories.

Table 2. Example ΔV budget for CAPSTONE mission.

Component	ΔV		Notes
	Nominal	ΔV_{99}	
Cruise	22 m/s	57 m/s	Nominal driven by launch window constraints; statistical driven by errors in navigation, maneuver execution, and launch injection
Insertion	18 m/s	35 m/s	Single nominal maneuver at perilune with no wind-on, followed by two cleanup maneuvers $\sim\frac{1}{2}$ orbit after insertion
Stationkeeping (6 mo.)	0 m/s	1 m/s	OMMs executed at TA=200°, target v_x at perilune 6.5 revs later, driven by navigation & maneuver execution error
Momentum Desaturation	N/A	10 m/s	RCS propulsive reaction wheel desaturation
End of Life Disposal	5 m/s	7 m/s	Targeted lunar impact
Total Requirement	52 m/s	110 m/s	Total ΔV will be within this with 99% confidence
Spacecraft Capability	>200 m/s		Tank size chosen to provide substantial margin above statistical analysis, to account for unexpected situations

Additional discussion of statistical ΔV allocations for BLTs is provided in Parrish et al [3].

4 NRHO Insertion from BLT

NRHO insertion is a rich trade space, and the optimal strategy depends on many mission-specific factors, including: spacecraft propulsion system constraints (thrust/mass ratio, maximum burn duration), ΔV constraints, navigation constraints, time of flight constraints, and constraints from potential rendezvous with Gateway. The CAPSTONE mission will perform NRHO insertion at the first perilune approach, dubbed here a 0-revolution "wind-on", as in the left subplot of Figure 4. The spacecraft will then execute two cleanup maneuvers near apolune to clean up the insertion and begin standard operations.

By making slight alterations to the BLT, spacecraft can approach an NRHO more gradually into a 1- or 2-revolution wind-on, also shown in Figure 4. In principle, this can be extended to any number of revolutions, with a trend for slight decrease of nominal ΔV for each revolution of wind-on. Increasing the number of wind-on revolutions reduces nominal ΔV but also increases operational complexity and the time of flight before reaching the operational orbit.

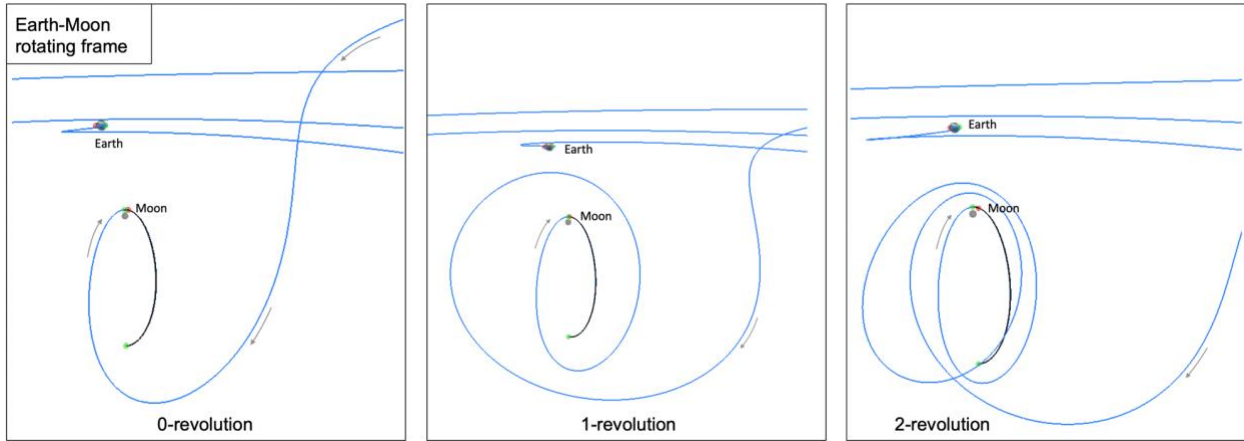


Figure 4. Comparison of NRHO wind-on arrival options.

The number of wind-on revolutions also gives another free parameter to mission designers to extend a launch period. Parrish et al [4] found that a launch period can be extended by approximately one week by opening up the option of using a different number of wind-on revolutions depending on the launch day.

NRHO insertion can also be performed at other “true anomalies”, such as at apolune, or the insertion maneuver can be broken into multiple maneuvers spaced out in time. An example split insertion is summarized in Table 3, where maneuver #1 is performed at perilune, and maneuvers #2-4 are performed at the subsequent apolune. This approach is robust to varying the time spacing of the apolune maneuvers, with the ΔV remaining unchanged for variations in time between maneuvers ranging from 8 to 36 hours.

Table 3. Nominal ΔV for an example NRHO insertion strategy split between perilune and apolune.

Insertion Maneuver	ΔV #1	ΔV #2	ΔV #3	ΔV #4	Total ΔV
Maneuver Magnitude	10 m/s	10 m/s	10 m/s	3 m/s	33 m/s

An important result of the multi-body dynamics is that the optimal insertion maneuver direction is not always intuitive in terms of two-body dynamics. For example, if insertion is performed at perilune, the maneuver is mostly in the anti-velocity direction (similar to two-body motion). However, if insertion is performed at apolune, the maneuver is mostly along the Earth-Moon line (perpendicular to what two-body intuition would imply).

5 Examples of BLT to Elliptical or Circular Lunar Orbit

Low-energy transfers can be flown to any cislunar orbit, including captured two-body orbits about the Moon. One of the benefits of a BLT is that inclination at Earth launch and Moon arrival are both highly flexible. BLTs exist with equivalent C3, ΔV , and time of flight for both polar and equatorial lunar orbits and for any Earth launch site. Figure 5 shows two example BLTs arriving into different lunar orbits, one polar and one equatorial. Low- ΔV solutions, such as the ones in Figure 5, tend to approach the Moon from outside the Moon’s orbit. Additional launch and/or rendezvous opportunities can be opened up (at the expense of spacecraft ΔV) by designing the BLT such that the spacecraft approaches the Moon from inside the Moon’s orbit.

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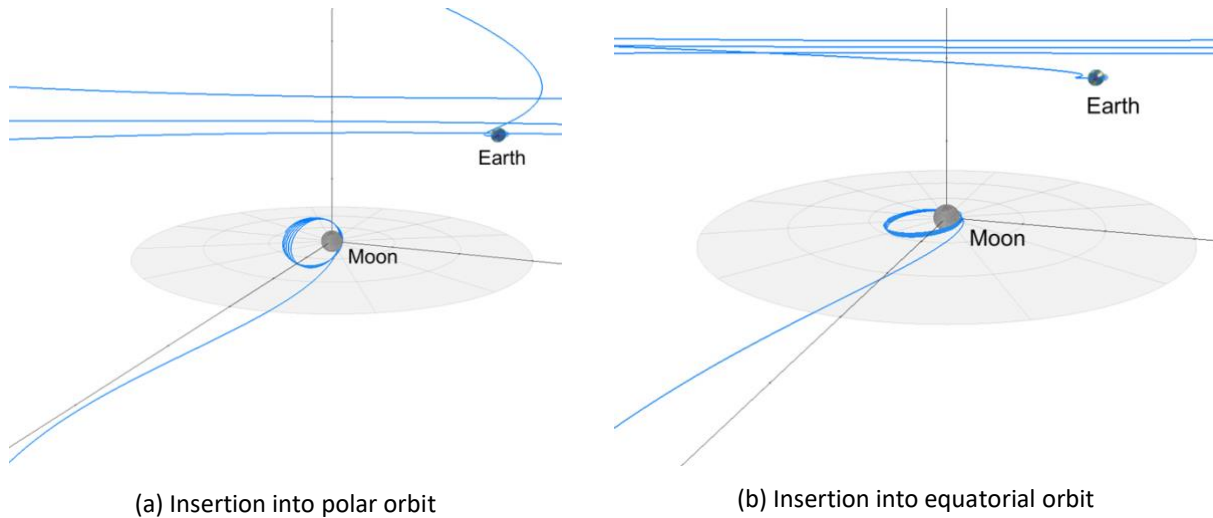


Figure 5. Example insertions into lunar orbit from a BLT, viewed in the Earth-Moon rotating frame.

Key parameters of several example BLTs to lunar orbit are presented in Table 4. Notice how the lunar orbit orientation (polar vs equatorial) can be selected for “free” (negligible impact on C3, insertion ΔV , or time of flight). Notice also that the insertion ΔV is much lower than for an equivalent direct transfer. Parker and Anderson [2] discuss the trade space for direct vs BLT transfers to a polar 100 km LLO (low lunar orbit), finding that direct transfers require at least 820 m/s compared to 640 m/s for BLT.

Table 4. Example optimized launch and insertion, launching late March or early April of 2024.

		Launch C3 (km^2/s^2)	Insertion Maneuver (m/s)	Time of flight (days)
Highly Elliptical Orbit (900 km x 14500 km)	Polar	-0.598	95.366	106.707
	Equatorial	-0.791	95.425	105.360
Elliptical (100 km x 6500 km)	Polar	-0.767	184.205	107.100
	Equatorial	-0.788	183.838	105.210
High Lunar Orbit Circular (9500 km)	Polar	-0.605	181.958	94.584
	Equatorial	-0.805	189.207	106.865
LLO (100 km)	Polar	-0.763	639.679	107.133
	Equatorial	-0.787	639.255	105.030

If the spacecraft traversing a BLT is required to insert into a particular orbit orientation and phase (i.e. to rendezvous with other spacecraft during a particular time period), these constraints increase the insertion ΔV requirements by 25-50% and/or reduce the launch period availability. Note that similar restrictions and/or increased ΔV apply to constrained direct transfers. Additional mission-specific analysis is required when the lunar orbit is highly constrained.

6 Launch Period Considerations

Each family of BLTs evolves over the course of a month. Figure 6 shows examples of four families of BLTs, each evolving over the course of a reasonable launch period.

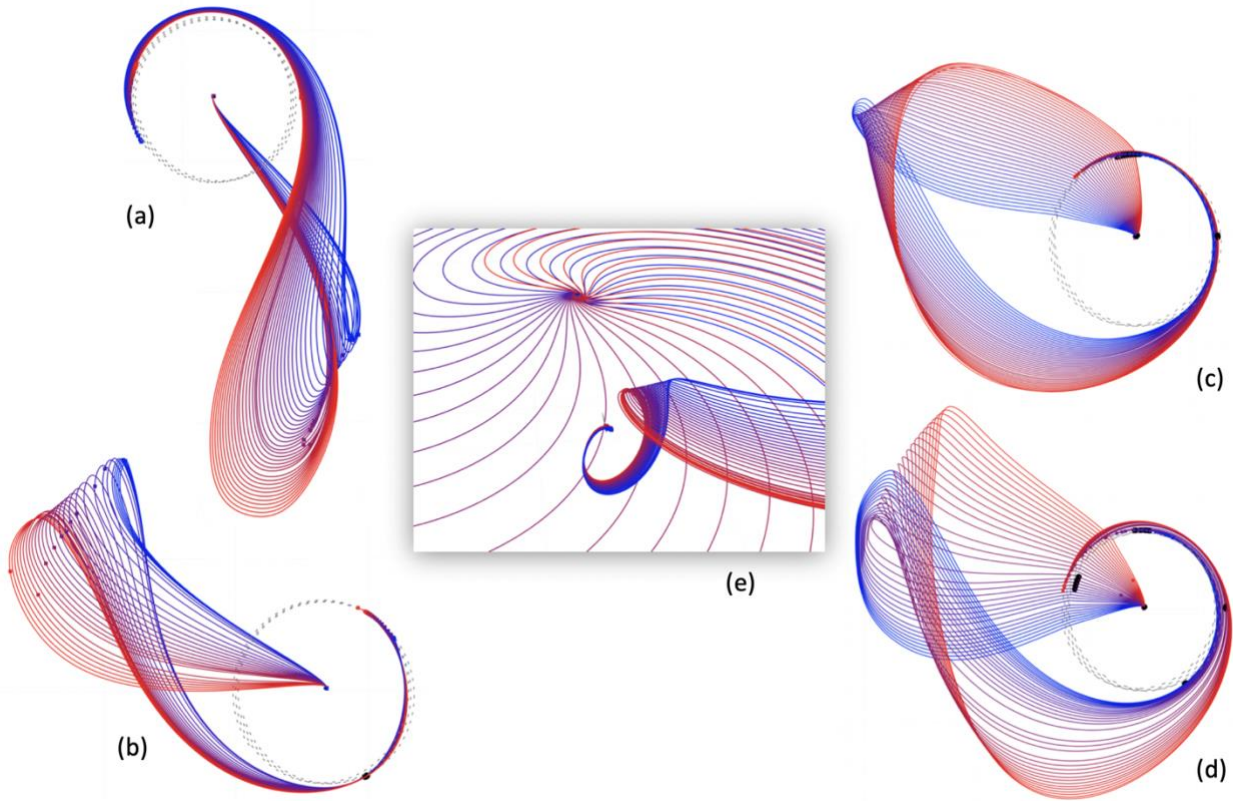


Figure 6. Examples of 4 families of BLTs. (a) Quadrant IV apogee, no lunar flyby; (b) Quadrant II apogee, no lunar flyby; (c) Quadrant II apogee, with lunar flyby, short time of flight; (d) Quadrant II apogee, with lunar flyby, medium time of flight. Subplots (a)-(d) are plotted in a Sun-Earth rotating frame, with the Sun to the left. Subplot (e) shows the same trajectories as (b), but in an Earth-Moon rotating frame.

BLTs without a lunar flyby typically have a low- ΔV launch period of ~ 10 - 20 days, while BLTs with a lunar flyby typically have an equivalent ΔV launch period of ~ 1 - 5 days. There are many more families of solutions to choose between for BLTs with a lunar flyby, so the total number of launch opportunities is similar for BLTs with or without a lunar flyby. Of course, spacecraft ΔV is not the only constraining factor in the selection of launch opportunities. Other factors include launch C3, transfer duration, and eclipses passages.

A summary view of example launch opportunities is presented in Figure 7. The blue bar indicates launch days with at least one lunar flyby launch opportunity where the total deterministic spacecraft ΔV is under 100 m/s. The yellow bar indicates launch days with at least one lunar flyby launch opportunity where the C3 is under -1.5 km²/s², and the green bar indicates launch days where both criteria are met simultaneously. With the assumptions made here, launch periods are mostly constrained by the spacecraft ΔV requirement. Other families beyond those studied can increase the “menu” of launch opportunities further.

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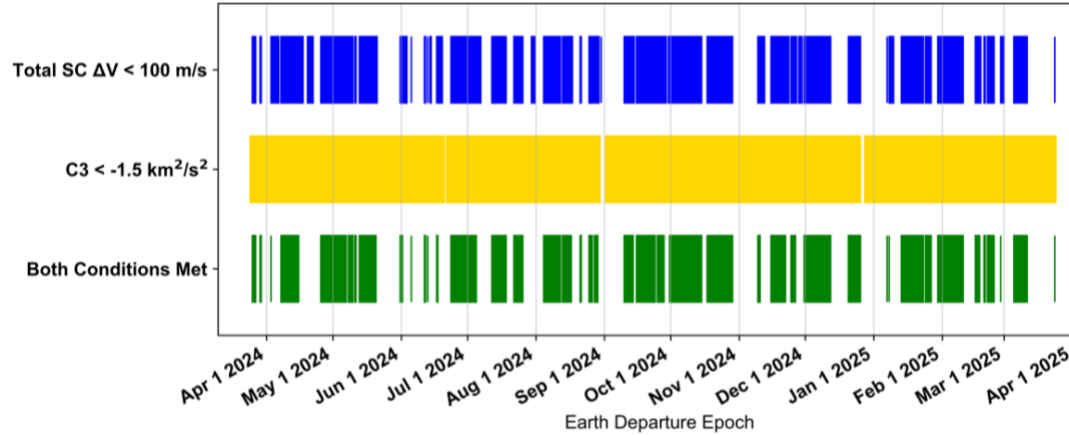


Figure 7. Lunar flyby BLT opportunities to Gateway reference NRHO. [4]

Note that the launch periods available for either direct or low-energy transfers to the Moon depend on the Moon's inclination relative to the Earth equatorial plane. The Moon's inclination relative to the Earth's equator varies in the range ~ 18 - 28.5 degrees. When the Moon's inclination is greater than or equal to the launch site latitude, it is possible to efficiently launch towards the Moon at any time in the month. During the year 2024, the Moon's inclination will be approximately 28.5 degrees, so longer-than-usual launch periods exist. The variation in the Moon's orbital inclination over time is shown in Figure 8.

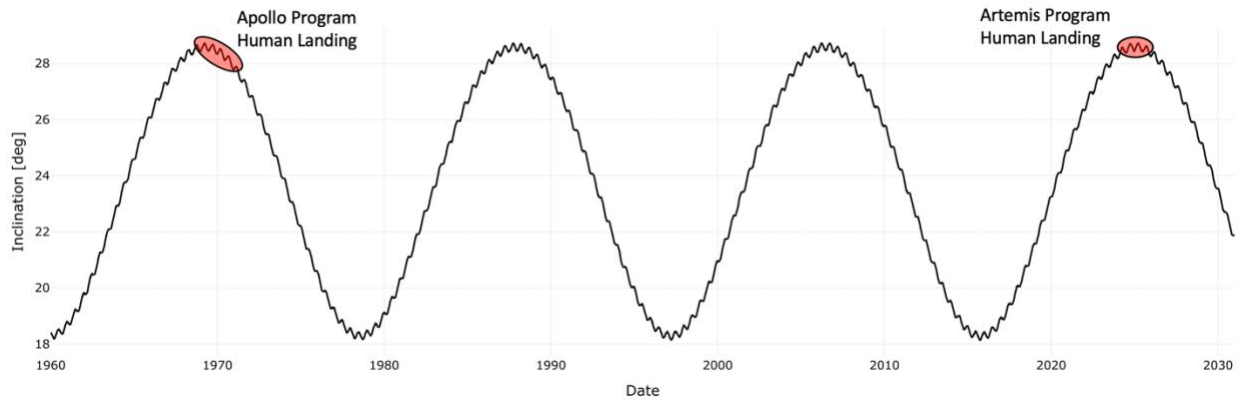


Figure 8. Moon inclination relative to Earth equator over years 1960-2030.

7 Eclipse Considerations

During most of the BLT transfer, the spacecraft is far from both the Earth and the Moon, so eclipses are not common during the middle portion of the transfer. Eclipses are more common immediately after launch (when close to the Earth) or in the final weeks leading up to NRHO insertion (when close to the Moon). Figure 9 shows an example with typical eclipse durations caused by the Moon leading up to NRHO insertion. Here, the eclipses last 2-3 hours. If it is necessary to avoid eclipses, it is simple to choose a different launch family that has eclipses on different launch days.

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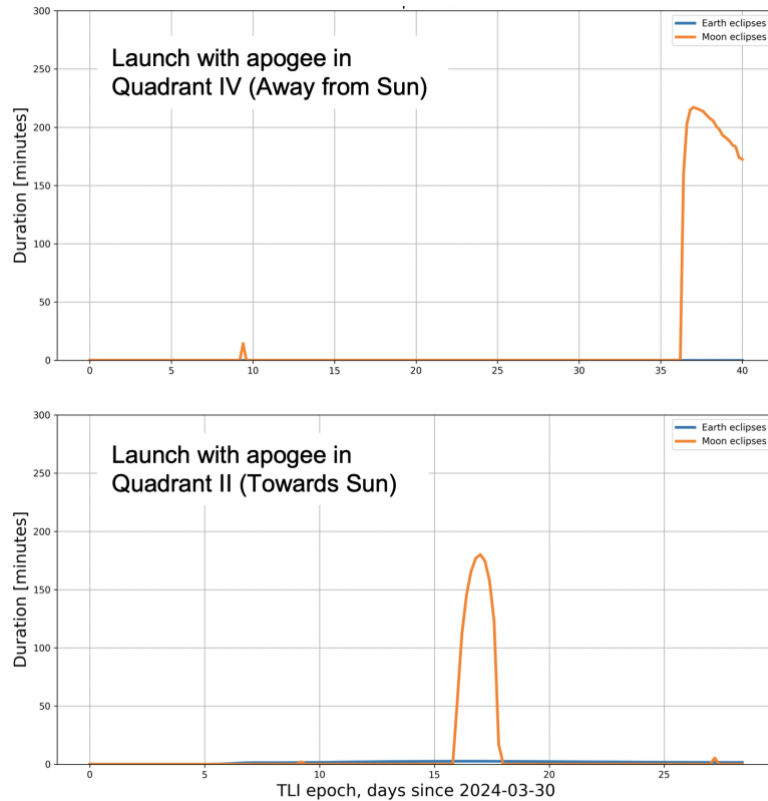


Figure 9. Total eclipse duration for two example families of BLTs.

8 Navigation

Parrish et al [3] studied navigation of a BLT with simulated DSN (deep space network) tracking at a range of different tracking cadences. For the sake of brevity, only some of the key results are included here. The following tracking cadences are considered:

- Continuous
- 8 hours per pass, 7 passes per week
- 8 hours per pass, 3 passes per week
- 8 hours per pass, 2 passes per week
- 2 hours per pass, 7 passes per week
- 2 hours per pass, 3 passes per week
- 2 hours per pass, 2 passes per week

A BLT without a lunar flyby is considered, with five TCMs (trajectory correction maneuvers) executed at optimal times throughout the transfer. The BLT and approximate TCM locations are shown in Figure 10.

For each of the tracking cadences described, navigation filter performance is considered for the state estimate leading up to each TCM. The uncertainty of the corresponding navigation solutions is presented in Figure 11 for position and Figure 12 for velocity.

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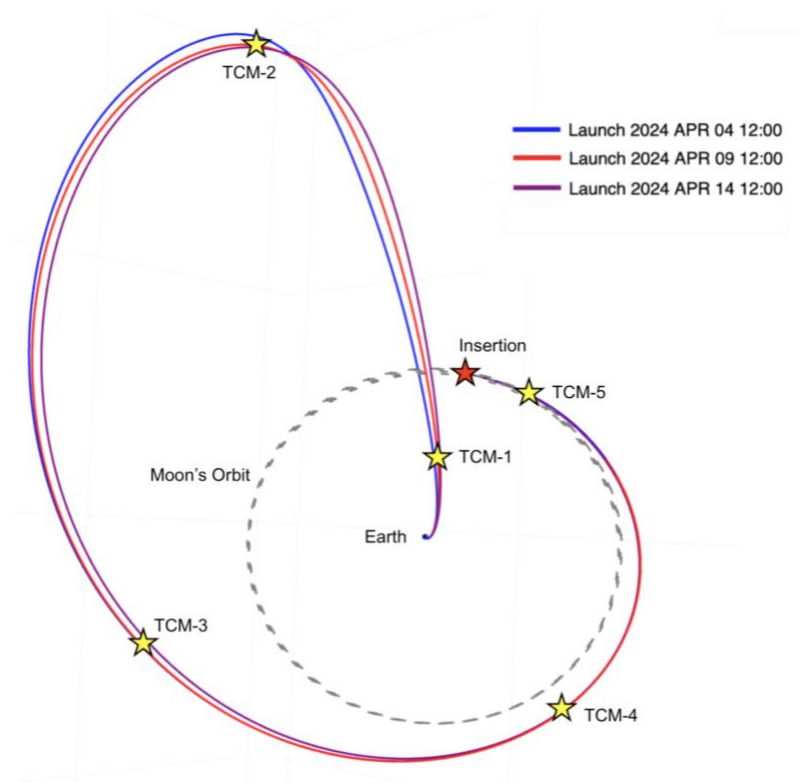


Figure 10. Approximate locations of each TCM for the example BLT studied, showing the open, middle, and close of the launch period. Plotted in the J2000 inertial reference frame. [3]

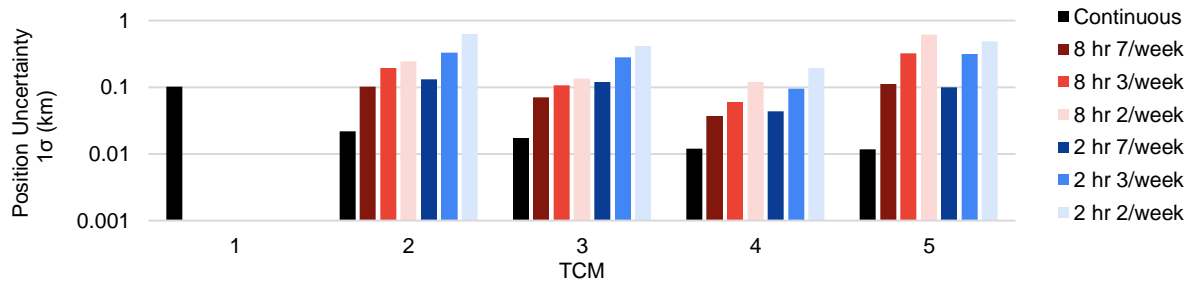


Figure 11. Position 1- σ uncertainty at each TCM for various tracking cadences. [3]

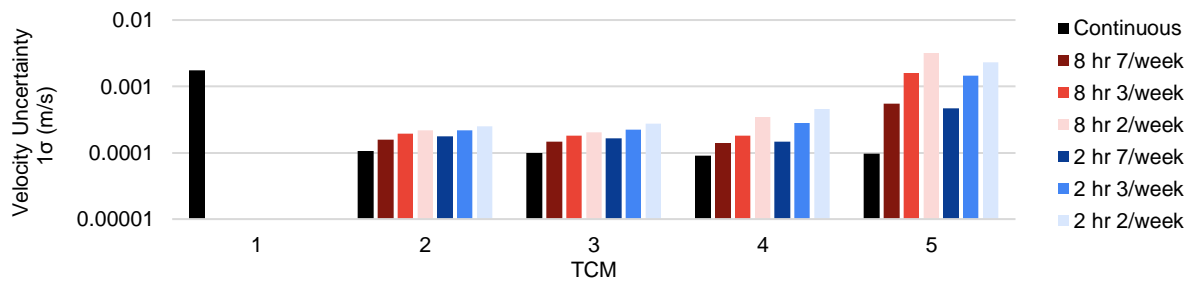


Figure 12. Velocity 1- σ uncertainty at each TCM for various tracking cadences. [3]

Understanding the expected navigation performance is important for determining the number of TCMs required and developing an accurate estimate of the statistical ΔV that must be budgeted for. The results presented here demonstrate that the navigation error is typically smaller than the expected maneuver execution error, so the overall ΔV budget is driven by the maneuver execution errors, which in turn are driven by the ADCS (attitude determination and control system) and propulsion systems of the spacecraft.

9 References

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