NASA's Planned Return to the Moon: Global Access and Anytime Return Requirement Implications on the Lunar Orbit Insertion Burns

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Abstract. Lunar orbit insertion LOI is a critical maneuver for any mission going to the Moon. Optimizing the geometry of this maneuver is crucial to the success of the architecture designed to return humans to the Moon. LOI burns necessary to meet current NASA Exploration Constellation architecture requirements for the lunar sortie missions are driven mainly by the requirement for global access and "anytime" return from the lunar surface. This paper begins by describing the Earth-Moon geometry which creates the worst case ΔV for both the LOI and the translunar injection (TLI) maneuvers over the full metonic cycle. The trajectory which optimizes the overall ΔV performance of the mission is identified, trade studies results covering the entire lunar globe are mapped onto the contour plots, and the effects of loitering in low lunar orbit as a means of reducing the insertion ΔV are described. Finally, the lighting conditions on the lunar surface are combined with the LOIand TLI analyses to identify geometries with ideal lighting conditions at sites of interest which minimize the mission ΔV.

Nomenclature

ΔV	=	Change in Velocity
CEV	=	Crew Exploration Vehicle
EDS	=	Earth Departure Stage
EVA	=	Extra-Vehicular Activity
LAN	=	Longitude of the Ascending Node
LEO	=	Low Earth Orbit
LLO	=	Low Lunar Orbit
LOI	=	Lunar Orbit Insertion
RAAN	=	Right Ascension of the Ascending Node
TEI	=	Trans-Earth Injection
TLI	=	Tran-Lunar Insertion
V_∞	=	Velocity at Infinity
Δ_{radius}	=	Correction to apparent magnitude due to radius
Δ_{albedo}	=	Correction to apparent magnitude due to albedo
M_{Earth}	=	Apparent magnitude of the Earth as seen from the Moon
M_{Moon}	=	Apparent magnitude of the Moon as seen from the Earth
V	=	Variation in brightness
R_{radius}	=	Ratio of the Moon's radius to the Earth's radius
R_{albedo}	=	Ratio of the Moon's albedo to the Earth's albedo

I. Introduction

Lunar orbit insertion (LOI) is a critical maneuver for any mission going to the Moon. High magnitude ΔV's are required to not only allow the spacecraft to be captured by the Moon's gravity well, but also to place the spacecraft into the desired lunar orbit. Optimizing the geometry of this maneuver is crucial to the success of the architecture designed to return humans to the Moon. The LOI burns necessary to meet current NASA Constellation Program architecture requirements for the lunar sortie missions are driven mainly by the requirement for global access and anytime return from the lunar surface. It should be noted that this "global access, anytime return" requirement is very different from that of the Apollo missions, which either had landing sites close to the lunar equator or did not require anytime return capability.

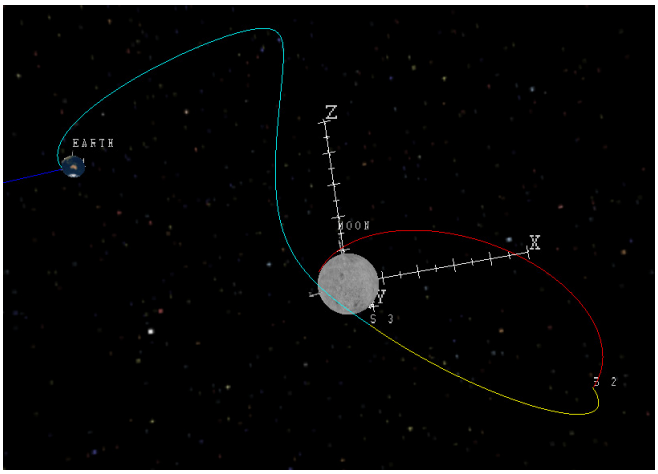

FIGURE 1. Lunar transfer trajectory. *Example depiction of a 4 day Earth to Moon transfer followed by the 24 hour 3 burn LOI sequence.*

For any landing site that is not on the lunar equator or at the poles, the site starts to move away from the initial LLO where the Crew Exploration Vehicle (CEV) is parked. Since the ascent stage is designed to perform only a coplanar ascent, the CEV must perform a nodal plane change to line up with the ascent orbit in the case of "anytime return". To minimize the nodal plane change at LLO, the CEV needs to be placed in a "node walking" orbit such that the wedge angle between the LLO and anytime ascent orbit is small throughout the surface stay. The LLO is uniquely defined depending on the landing site and the surface stay duration. Contrasting to the one-burn maneuver utilized in the Apollo missions, the LOI maneuver is split into 3 burns occurring over a 24-hour period (Figure 1) as most landing sites can become more difficult to reach with a single burn.

Analysis was performed with the location of the second LOI burn constrained to occur at apolune. Subsequent analyses freed the location of the second burn, but required it to be a pure plane change, resulting in a reduced ΔV. Findings from the analyses also include the need for additional ΔV to support missions with a worst case geocentric wedge angle; identification of a method to decrease in ΔV by freeing constraints on the LOI timeline, and recommendation of a possible method to further reduce the required ΔV.

On-going and future work will expand the LOI and TLI data set beyond the worst case epoch to include the entire metonic cycle. This expanded data set will be combined with the corresponding Trans-Earth Injection (TEI) data. This will provide on-orbit mission analyses across the 19-year metonic cycle considering the combined TLI, LOI, and TEI maneuvers.

II. Methodology and Initial Assumptions

The focus of this paper is on the outbound portion of the lunar trajectory. Earth departure is from a 28.5º inclined circular parking orbit at 296 km (160 nmi) altitude. A 6-hour Earth departure window must be protected in case the nominal departure burn is missed. Lunar arrival is a three-maneuver sequence that puts the vehicle into a circular low-lunar orbit of 100 km altitude with its inclination and longitude of the ascending node (LAN) tied to a particular landing site for a 7-day surface stay. While the lander takes the crew to the lunar surface, the CEV stays in low-lunar orbit and is capable of performing up to 6.2º of nodal plane change to line up with the ascent trajectory for rendezvous at anytime during the 7-day stay. The low lunar orbit is also assumed to be retrograde due to a lower propellant requirement in return abort scenarios. The initial outbound mission timeline consists of a 4-day Earth-Moon transfer phase, a 1-day LOI phase and a 1-day orbit checkout phase prior to descent and landing. A more flexible time split between the phases as well as extended post-LOI loitering have also been studied as ways to reduce the overall ΔV requirements for the entire mission.

The Earth-Moon transfers are ballistic-type trajectories modeled in Copernicus, an integrated trajectory design and optimization tool developed at University of Texas, Austin [Ref. 7]. Maneuvers at both Earth departure and lunar arrival are assumed to be impulsive, with Sun, Earth, and Moon gravities included in the modeling. In order to understand the performance requirement for global access, a series of trajectories are optimized in Copernicus targeting low-lunar orbits covering the entire lunar globe set on a 5º grid in inclination and longitude of the ascending node (LAN). After the worst case epoch is identified, the overall ΔV requirements of TLI and LOI are optimized for both the beginning and the end of the Earth departure window, and the results are stored in a database which is then post-processed in Excel. The Excel post-processor tool can either calculate or optimize the target orbit inclination and LAN based on landing site, stay time and loiter time limit, then evaluate the ΔV using a 2-dimensional spline interpolation of the Copernicus database results. A Java based tool called "Astro-Globe" was developed to map the LOI ΔV cost onto a lunar globe and allows the user to interactively visualize the correlation between landing site, LLO, loiter, surface duration and ΔV in a 3-D environment. Satellite Tool Kit® (STK) is also used to independently spot check the trajectory results generated by Copernicus.

It should be noted that all of the ΔV data in this paper are based on impulsive approximation of finite thrust maneuvers and do not account for gravity losses, which are dependent on the vehicle thrust to weight ratio at the beginning of each maneuver and can be added later. The ΔV cost for on-orbit plane changes during the LOI maneuver sequence are based on a "fail-safe" arc-type maneuver designed to maintain a safe osculating periapse altitude throughout the burn. Such a maneuver carries a slightly higher ΔV cost but provides sufficient time for the flight crew to resolve any propulsion system problems that might interrupt the burn.

III. Analysis: TLI, LOI, Lighting

This section will cover the analysis performed in 3 subsections. First the TLI analysis will be covered including discussion of the TLI window frequency, the departure opportunities within a given TLI window, and the effects of the geocentric wedge angle. Second, the LOI analysis will be covered outlining several methods that could be used to reduce LOI ΔV and show the results of several of those methods. And finally, lunar lighting analysis including both light from the sun and Earthshine are covered.

A. TLI

The Earth-Moon transfer is achieved by the Trans-Lunar Injection (TLI) burn from an initial Earth parking orbit of 28.5º inclination. To minimize the total ΔV, the TLI maneuver is assumed to be tangential to the velocity direction, which keeps the transfer orbit in-plane with the initial parking orbit. For any desired lunar arrival epoch, the RAAN of the Earth parking orbit and launch time must be chosen such that at the time of arrival the Moon enters the transfer orbit plane. Two possible parking orbits of different RAAN's exist for a given arrival

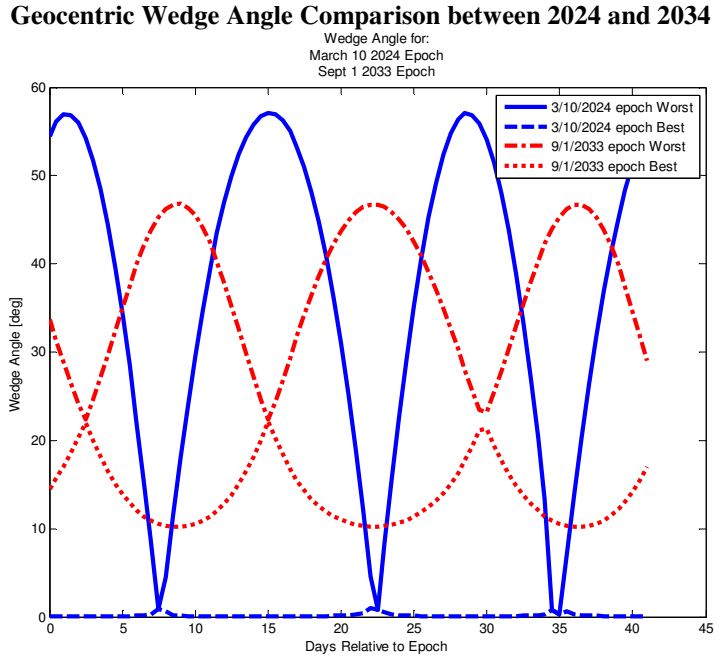

FIGURE 2. Geocentric wedge angle. *Could protect for worst case wedge angle in worst year (2024), best case wedge angle in worst year (2034).*

epoch, and one may be more favorable than the other due to the differences in orbital geometry, which may impact the ΔV budget as well as mission timeline for later departure opportunities. One of the parameters characterizing this orbital geometry is the geocentric wedge angle between the transfer orbit plane and Moon's orbital plane, which can range anywhere between 0º and 57º throughout the metonic cycle. Figure 2 shows how the geocentric wedge angle varies in a typical month in 2024 and 2034. In 2024 the geocentric wedge angle varies between 0º and 57º due to Moon's inclination of 28.5º. In 2034 the geocentric wedge angle varies between 10º and 47º due to Moon's inclination of 18.5º.

In case the nominal injection burn is missed, the next injection opportunity awaits after the spacecraft makes roughly a full revolution in the parking orbit. The orbital period at a low-Earth orbit is around 90 minutes, which provides five injection opportunities within a 6-hour departure window (Figure 3). To ensure that the Moon enters the transfer orbit plane at the time of arrival, the Earth-Moon transfer time would also need to be shortened for subsequent injections opportunities, resulting in higher ΔV requirements for both TLI and LOI. In most cases the spacecraft needs to arrive earlier than the nominal arrival time due to the nodal regression of the low-Earth parking orbit. Figure 4 shows how the Earth-Moon transfer time varies in subsequent departure opportunities and Figure 5 shows that the Earth-Moon transfer time is shortened more dramatically at the end of the 6-hour window when the geocentric wedge angle is small. Initially the Constellation Program planned to protect for up to five departure opportunities, but that has been reduced to two in the most recent studies.

In case TLI is completely missed during the nominal departure window, the next TLI

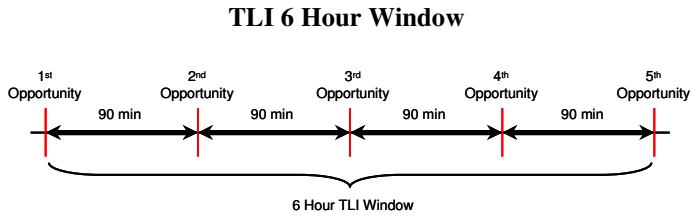

FIGURE 3. Protecting the 6 hour TLI window. *For 90 minute earth parking orbit, a 6 hour TLI window has 5 coplanar departure opportunities.*

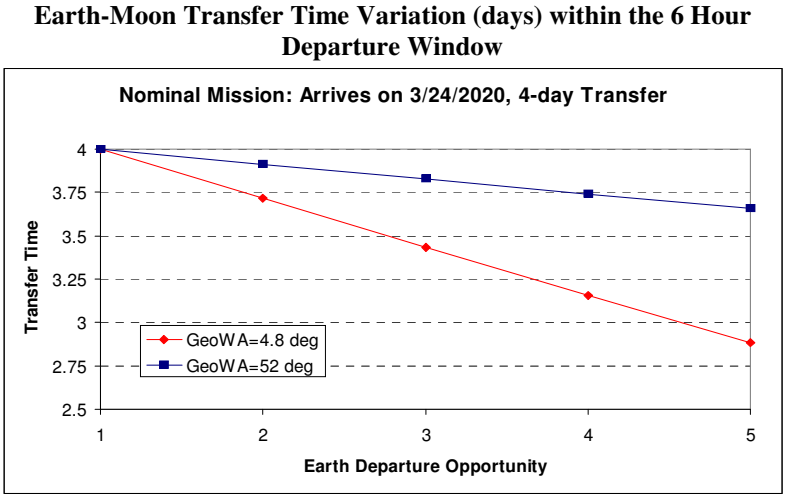

FIGURE 4. TLI departure opportunities.

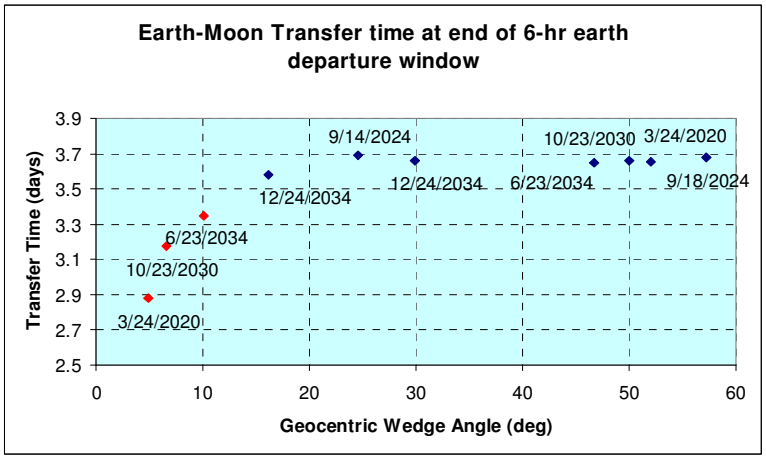

FIGURE 5. TLI departure window. *Geocentric wedge angle effects on the TLI transfer time. Reducing transfer time increases ΔV requirement.*

TLI Opportunities for a Fixed LEO Orbit (Initial Ascending Node = 180 degrees)

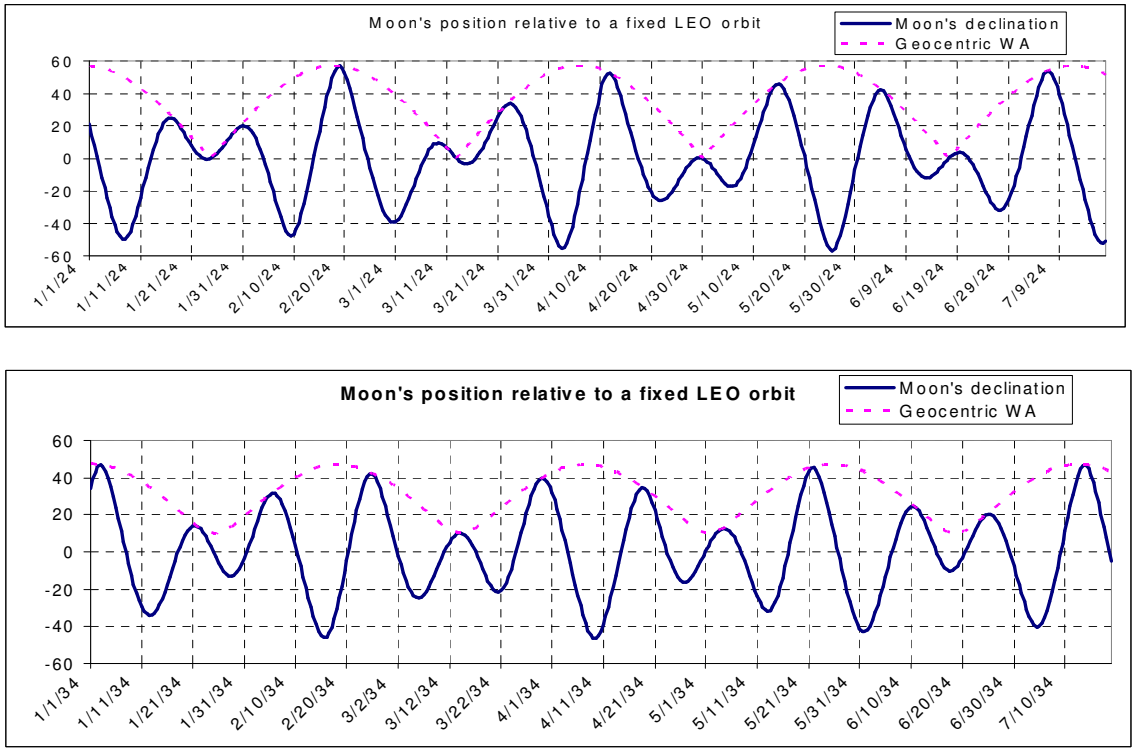

FIGURE 6. TLI opportunities and the associated geocentric wedge angle. *The curves shift horizontally as the initial ascending node is changed. Each time the moon's declination crosses zero (blue solid curve) there is a TLI opportunity. Notice in 2034 the opportunities are a little more regularly spaced whereas in 2024 there can be multiple crossing close together. This corresponds to the TLI window opportunities.*

departure window arises when the declination of the Moon relative to the parking orbit plane reaches zero at the time of arrival. Figure 6 shows that in 2024 the frequency of such a TLI window can vary anywhere between a few hours to up to around 12 days, while the frequency is much more regularly spaced at 6-10 days in 2034. During periods of the cycle when the geocentric wedge angle was low, opportunities were more frequent, with 1 or 2 days between them, whereas during periods when the wedge angle was high, the intervals between opportunities were less frequent, with 10 or 12 days between opportunities. It is important that the geocentric wedge angle, TLI window, lunar lighting conditions as well as ΔV budget all be taken into consideration in selecting the appropriate departure epoch when the mission timeline is being designed.

The main contributing factors to the TLI ΔV cost are Earth-Moon transfer time, Earth parking orbit altitude and Moon's distance to Earth at arrival. Everything else being equal, the TLI ΔV cost for reaching different parts of the lunar surface does not vary much, which is why most of the data presented in this paper are focused on LOI. However, the geocentric wedge angle, the TLI window and frequency at Earth departure are important aspects of the outbound trajectory and must be studied in detail as they have a significant impact on the performance requirements at lunar arrival.

B. LOI

The cost of LOI ΔV to a given landing site is essentially determined by the V_∞ vector of the hyperbolic orbit coming to the moon and its declination relative to the site-specific targeting "node walking" orbit plane. This relative declination indicates the amount of plane change that must be performed for LOI, which can be as much as 90 degrees for global access to the lunar surface. This section describes the three-burn LOI sequence and methodologies used to reduce ΔV requirements, including maneuver optimization and including loiter time. In general, the LOI sequence is a three-burn maneuver to place the CEV/Lunar Lander into a desired circular LLO with specified altitude, inclination and LAN. The desired LLO orbit plane is a function of the landing site latitude and longitude, surface stay time, and maximum on-orbit

rendezvous plane change allocation in order to meet the any-time return requirements. References 1 and 2 discuss the methodology for calculating the desired LLO based on these inputs.

The cost of overall LOI ΔV for global access is determined by the magnitude of the incoming V_∞ vector to the moon. Several factors contribute to the V_∞ vector: transfer time between TLI and lunar arrival (first burn of the LOI), moon's velocity relative to Earth at lunar arrival, and the geocentric wedge angle between the transfer orbit and moon's orbital plane. The worst case arrival epoch has been identified as September 18th of 2024 when the moon is at perigee and in the year when the moon is at its highest inclination of 28.7º. Furthermore, the moon is at nodal crossing relative to Earth's equatorial plane, therefore creating the highest possible geocentric wedge angle of 57.2º, with the assumption that the initial low-Earth orbit (LEO) orbit has an inclination of 28.5º.

The basic LOI sequence is based on a three-burn maneuver sequence to allow for up to 90º plane change to support global access to the lunar surface. The first burn is an energy-reducing maneuver, the second burn is primarily a plane change maneuver at or near the apolune of the transfer ellipse, and the third burn is a circularization maneuver at a specified altitude. An upper limit of 5 days is placed on the overall flight time, including 1 day for the three-burn LOI sequence. Given these guidelines and LLO targeting information, several methods for generating trajectories can be used. These methods are listed below, in order of complexity:

- Method 1: 2nd LOI burn occurs at apolune, pure plane change
- Method 2: 2nd LOI burn location freed, pure plane change
- Method 3: 2nd LOI burn location freed, arbitrary burn
- Method 4: Split time between 4 days Earth to Moon and 1 day LOI freed (maintain overall 5 days), 2nd LOI burn pure plane change
- Method 5: Split time freed, 2nd LOI burn is arbitrary

The Method 1 approach assumes that the second LOI burn is fixed at apolune and is a pure plane change maneuver. Method 2 frees the location of the second LOI burn to be anywhere along the transfer ellipse but is still constrained to be a pure plane change. Method 3 is a further generalization of Method 2 in which the second LOI burn is arbitrary in purpose (combined plane and energy change) as well as location. Method 4 allows for changes in the flight time between TLI and LOI using a fixed upper bound of 5 days for the total duration, but restricts the second LOI burn to be a pure plane change. Method 5 is the most general method considered in this paper, which also frees the second LOI burn as well as the time split. A sixth method can be envisioned whereby the total transfer time is allowed to vary, but that case is not considered in this paper. In addition, a maximum loiter time in LLO may be considered for each method as a means for reducing the LOI ΔV.

The various methods are illustrated with the following example. Consider a particular case with a target LLO inclination of 105º and LAN of 5º, with a departure epoch of September 14th, 2024, 12:00 universal time coordinate (UTC) and LLO insertion epoch of September 19th, 2024 12:00 UTC (the worst-case epoch). No loiter is considered for this particular case. The results of this example have been calculated using Copernicus and are shown in Table 1. This table shows the ΔV required for each maneuver using each of the five methodologies. The parenthetical value for ΔV2 shown in the table corresponds to the optimal ΔV with additional margin for handling fail-safe plane change maneuvers [Ref 3]. Considerable gains may be found by using the more complicated methods for trajectory optimization with more free variables, as is expected.

Table 1 - Single Case Comparison of Methods 1-5

	ΔV 1 [km/s]	ΔV 2 [km/s]	ΔV 3 [km/s]	Total ΔV [km/s]
Method 1	0.484	0.305 (0.334)	0.565	1.382
Method 2	0.442	0.327 (0.345)	0.565	1.352
Method 3	0.375	0.372 (0.384)	0.565	1.324
Method 4	0.444	0.233 (0.242)	0.593	1.279
Method 5	0.385	0.271 (0.278)	0.596	1.259

Next, these methodologies are applied to a matrix of landing sites corresponding to a 5x5 degree grid of target orbit inclination and LAN for the worst-case LOI arrival epoch of September 18th, 2024 12:00 UTC

using the worst-case wedge angle. For this study the full lunar surface 5x5 degrees was run for Methods 1, 2, and 4. Method 3 and 5 were not applied to the full surface access problem due to the additional complication of handling fail-safe plane-change ΔV for combined energy and plane change maneuvers.

Method 1 results. The results of applying Method 1 to the full surface access problem are shown in Figures 9-13 in the Appendix. These figures show the total LOI ΔV as contours on a latitude vs. longitude global surface scale. Note that the top ten landing sites from the Exploration Systems Architecture Study (ESAS) [Ref. 4] are indicated with the letter symbols. This method assumes a 4 day transfer from TLI to the first LOI burn, a 1 day transfer orbit from the first to third LOI burn, with the second LOI burn consisting of a pure plane change maneuver at the apolune of the transfer orbit. The TLI maneuver is assumed to occur at the beginning of the TLI window. Results for 0, 3, 5, and 7 day LLO loiter times are shown. In these results the CEV plane change required for the 7 day lunar sortie global access mission is minimized. The minimum LOI ΔV for this method is 0.883 km/s. With no loiter the maximum LOI ΔV is 1.382 km/s, which exceeds the program requirement of 1.25 km/s total ΔV. For the baseline mission assumption of 3 days of loiter, the maximum ΔV is reduced to 1.265 km/s. This result also exceeds the program requirement of 1.25 km/s LOI ΔV, however, the result can be reduced by using the more sophisticated trajectory optimization methods as will be shown in later sections. The effect of an extended 7 day loiter can reduce the maximum ΔV to 1.126 km/s. Additional loiter can further reduce the total ΔV for landing sites such as the Aitken Basin (site B), however, similar results can also be achieved by shortening the Earth-Moon transfer time without adding additional loiter, as is shown in the following sections.

The percent surface coverage is shown as a function of the ΔV for the 4-loiter time cases and is calculated based on an area-preserving projection. In the Method 1 result, surface coverage for fixed ΔV is only increased by adding loiter time. Other methods shown later can increase surface coverage by varying the Earth-Moon transfer time.

Method 2 results: Figures 14-18 in the Appendix show the results of applying Method 2 optimization to the same epoch for the global surface access analysis. These results are based on the assumption that Earth departure covers the full TLI window. Recall that Method 2 is a generalization of Method 1 in which the location of the second LOI burn is no longer restricted to the apolune of the transfer ellipse, but is still restricted to be pure plane change in nature. The results are shown in the ΔV contours on a latitude-longitude plot in Figures 14-17, corresponding to 0, 3, 5, and 7 days of LLO loiter time. In this case, the minimum total ΔV is 0.899 km/s. The maximum ΔV for the case with no loiter is 1.354 km/s, which is a reduction from the Method 1 result but still exceeds the program requirement. Consideration of the baseline 3 day loiter reduces the maximum ΔV to 1.243 km/s, which meets the program requirement. Extended loiter time up to 7 days can decrease the maximum total ΔV to 1.099 km/s.

The percent surface coverage is shown as a function of the ΔV for the four loiter time cases. These results show slightly different trends than the results for Method 1 since in this case the full 6 hour TLI window is used rather than the first opportunity.

Method 4 results: In order to further reduce the LOI ΔV, it is possible to free the Earth-Moon transfer time and include it as an optimization variable, maintaining the overall 5 day total for the transfer time and the three LOI burns. This generalization of Method 2 is known as Method 4 in the nomenclature discussed above. Figures 19-23 in the Appendix show the ΔV surface contours for 0, 3, 5, and 7 day loiter times generated using Method 4. In these results the CEV plane change required for the 7-day lunar sortie global access mission is minimized and based on the assumption the Earth departure covers the full TLI window. For the case without loiter, the minimum ΔV is 0.893 km/s and the maximum ΔV is 1.272 km/s, which is lower than the Method 2 result but still exceeds the program requirements. If 3 days of loiter is added then the maximum ΔV is reduced to 1.184 km/s which is well below the program requirements and is also substantially lower than the Method 2 result for the same loiter period. Similar trends occur as the loiter time is increased. For the 7 day loiter case, the maximum ΔV is reduced to 1.075 km/s. Figure 24 shows the difference between Method 2 and Method 4 results for the global access case with zero loiter.

For the more costly sites to reach, such as the far side Aitken Basin, freeing the Earth-Moon transfer time allows the spacecraft to reach the site faster in such a way that the total plane change is reduced. For these more costly sites, the rotation of the Moon causes these sites to move away from the orbit plane. Approaching slightly earlier can reduce the magnitude of the plane change requirement on the 2nd LOI burn, which in turn reduces the total LOI ΔV, keeping the TLI ΔV under the program requirements of 3.15 km/s. Little to no improvement is found for the easier to reach landing sites such as equatorial regions.

Figure 21 shows the percent surface coverage as a function of ΔV for the 4 loiter time cases. These results can be directly compared to Figure16 corresponding to Method 2 since both cases protect against

the full 6 hour TLI window. As expected, the Method 4 results show an improvement in the surface coverage over the Method 2 result.

It should be noted that the LOI ΔV results presented in this paper are based on a worst case arrival epoch that results in the highest incoming V_∞ magnitude for a 4-day Earth-Moon transfer. While on any other epoch the overall ΔV requirement covering global access is expected to be less than the worst case epoch, it is not guaranteed that this is also the case for every single landing site. Variations in the V_∞ directions can cause the peak site for LOI to shift on different arrival epochs. More thorough studies are ongoing to assess missions covering the entire metonic cycle and to determine both the surface coverage as well as the temporal coverage for any lander design with a certain ΔV capability.

C. Lighting

Surface lighting conditions are a critical element of mission planning, as they can place additional constraints on mission events such as descent or ascent, as well as on surface activities including extravehicular activities (EVA's).

Solar Lighting: The lighting condition at the landing site is crucial to the planning of surface operations as the lunar night lasts for approximately 14 days over much of the lunar surface and increases dramatically in the polar regions, where night can last for months [Ref 6]. The simplest means of characterizing the surface lighting condition is by analyzing the elevation angle of the sun at the location of interest on the surface. Assuming a spherical Moon and neglecting local terrain, a negative elevation angle indicates the Sun lies below the horizon and that the location is in darkness. Depending on the activity, more specific constraints may be necessary. For example, during landing operations, an elevation angle near 90° would prevent hazards such as boulders and craters from casting shadows, making them difficult for the crew to detect and avoid. Additionally, constraints on the solar azimuth may also be required. For example, having the sun down range on the lander's trajectory could place the sun directly in the line of sight of the crew, creating a dangerous glare [Ref 6]. Figure 7 shows the results of the solar lighting

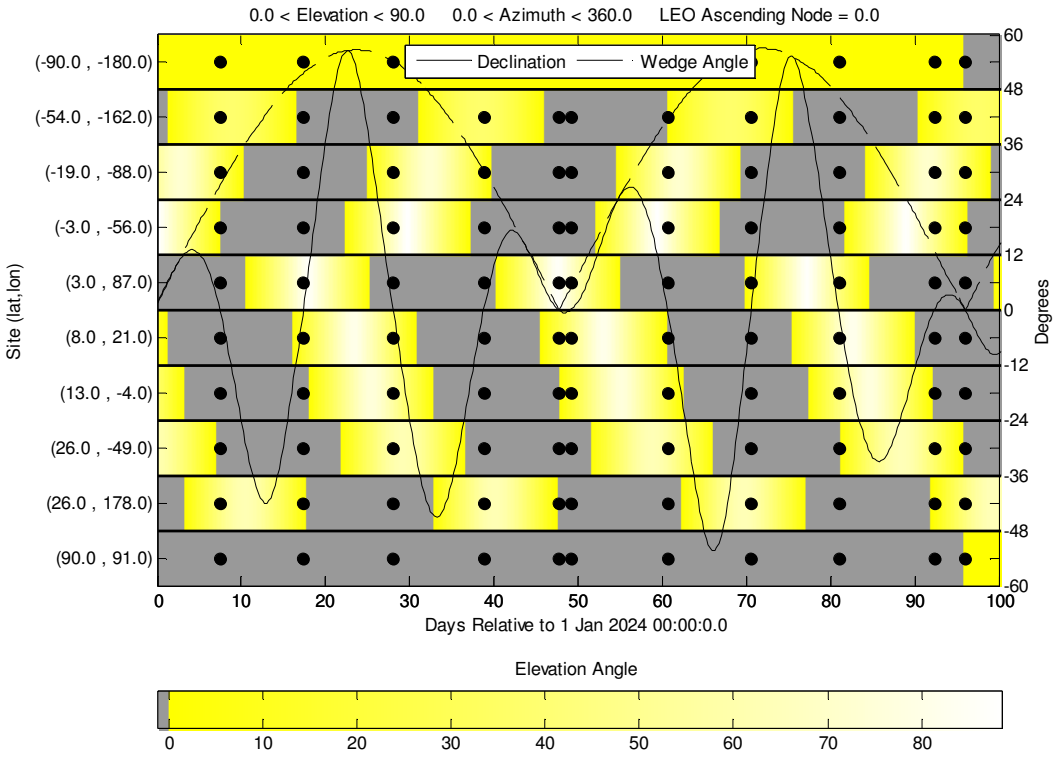

FIGURE 7. Solar lighting conditions on the lunar surface.

analysis for the 10 ESAS sites, listed on the left hand vertical axis. Each horizontal bar in the figure shows the lighting condition at the corresponding site over time by mapping the solar elevation angle according to the color scale shown at the bottom. Overlayed on top of the lighting data are two curves representing the relative declination of the moon to the LEO at the time of arrival and the magnitude of the geocentric wedge angle. As previously discussed, a value of 0 degrees for this relative declination corresponds to an arrival opportunity. At each time that the declination curve crosses 0 degrees, a column of dots is placed on the figure to indicate the possible arrival times based on the initial ascending node of the LEO.

Earthshine: Light reflected off of the Earth can improve the lighting conditions on the lunar surface during periods of darkness, just as light reflected from the Moon does on Earth, during a full moon in particular. Two angles are required to characterize the effect of Earthshine on the surface lighting condition: the elevation angle of the Earth as viewed from the location of interest and the Sun-Earth-Moon phase angle. Assuming a spherical Moon and neglecting local terrain, a negative elevation angle indicates the Earth lies below the horizon and there cannot be any Earthshine at that location. Values of the phase angle approaching 180º indicate that the Earth lies almost directly between the Sun and the Moon, preventing light from being reflected off of the Earth to the lunar surface. These two angles are used to create a figure of merit to describe how ideal the Sun-Earth-Moon geometry is for Earthshine at a given

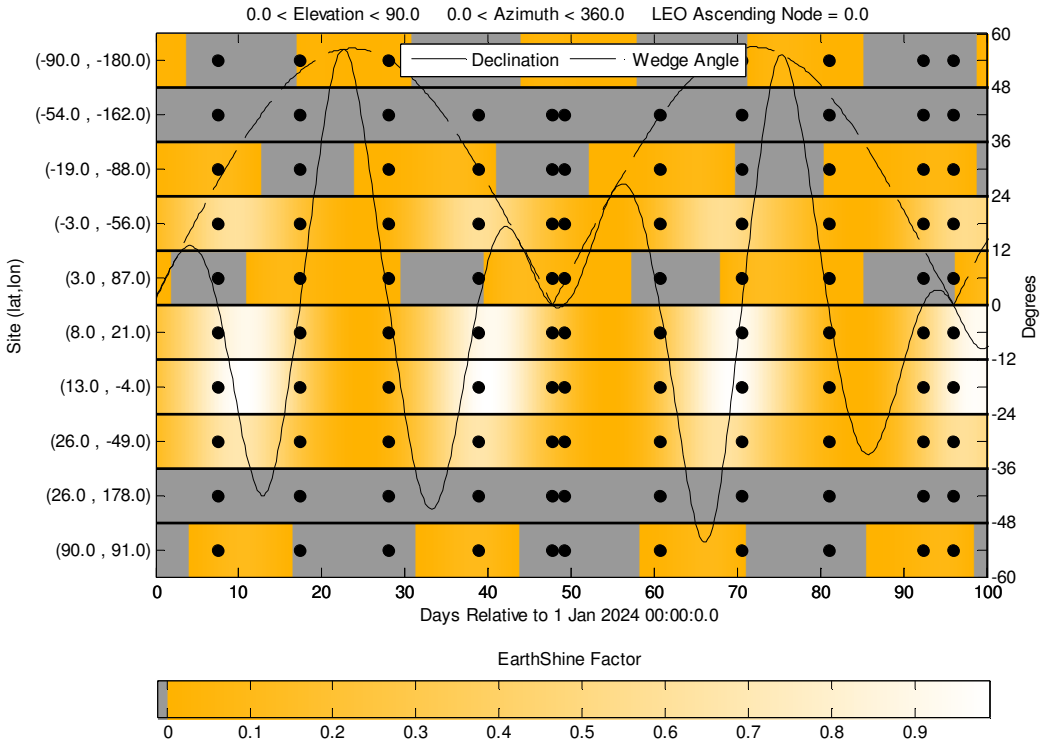

FIGURE 8. Earthshine on the lunar surface.

point in time. Figure 8 shows the results of the Earthshine lighting analysis for the 10 ESAS sites in a format similar to Figure 7. However, rather than showing the elevation angle on the color scale, this figure uses a figure of merit termed 'Earthshine Factor' which describes how well the Sun-Earth-Moon geometry is suited for Earthshine at the location of interest. As previously stated this figure of merit is based on the Sun-Earth-Moon phase angle as well as the elevation angle of the Earth as seen from the location of interest. A value of 0 corresponds to a geometry where Earthshine is impossible, whereas a value of 1 indicates that the geometry is ideally suited for Earthshine. For example, the elevation angle of the Earth as

seen from a site on the far side of the Moon would always be negative since the Earth lies below the horizon. The Earthshine factor for that site would be 0.

The brightness of Earthshine under ideal conditions can be approximated based on the apparent magnitude of the full Moon, the ratio of the radii of the Moon and Earth, and the ratio of the albedos of the Moon and Earth. If the Earth and Moon had identical radii and albedo ratios, full Earthshine on the Moon would appear just as a full Moon appears on the Earth and provide the same lighting characteristics. However, the Earth is much larger than the Moon. So, when viewed from the lunar surface the Earth will have a larger angular size. Additionally, the average albedo of the Earth is greater than that of the Moon so more light will be reflected from the Earth to the Moon. Starting with the apparent magnitude of a full Moon as $M_{Moon} = -12.55$, the ratio of the Moon's and Earth's radii as $R_{radius} = 0.272$, and the ratio of the Moon's and Earth's albedos as $R_{albedo} = 0.324$ the apparent magnitude of the full Earth as seen from the lunar surface can be determined as follows

$$\Delta_{radius} = 2.5\log(R_{radius}{}^2) = -2.827$$

$$\Delta_{albedo} = 2.5\log(R_{albedo}) = -1.223$$

$$M_{Earth} = M_{Moon} + \Delta_{radius} + \Delta_{albedo} = -16.600$$

The difference in brightness, V, of the full Earth and full Moon can be determined based on the apparent magnitudes as follows

$$V = 2.5^{(M_{Moon} - M_{Earth})} = 40.89$$

So under ideal conditions Earthshine will appear approximately 40 times brighter than a full Moon. It should be noted that this approximation is sensitive to the ratio of the Moon and Earth's albedo. The Moon's albedo is constant and approximately 0.12, whereas the Earth's albedo varies based on weather conditions and surface type. For example, the albedo of clouds, snow, or water can be as high as 0.8 as compared to the average Earth albedo used in this calculation of 0.37. If the calculation is redone using an Earth albedo of 0.8, the factor changes from approximately 40 to closer to 90.

IV. Summary of Results

For the TLI with the initial Earth parking orbit of 28.5º inclination, two possible parking orbits of different RAAN's exist for a given arrival epoch, and one may be more favorable than the other due to the differences in orbital geometry. The geocentric wedge angle between the parking orbit plane and the Moon's orbital plane can range anywhere between 0º and 57º throughout the metonic cycle. There are five injection opportunities within a 6-hour TLI departure window. If the nominal injection burn is missed, the Earth-Moon transfer time would need to be shortened for subsequent injection opportunities, resulting in higher ΔV requirements for both TLI and LOI. The transfer time drops more dramatically at the end of the 6-hour window when the geocentric wedge angle is small. Initially the Constellation Program planned to protect for up to five departure opportunities, but that has been reduced to two in the most recent studies in order to reduce propellant requirements. In case the TLI departure window is completely missed, the next TLI departure window arises in different frequencies throughout the metonic cycle.

The LOI sequence is based on a three-burn maneuver sequence to allow for up to 90º plane change to support global access to the lunar surface. The first burn is an energy-reducing maneuver, the second burn is primarily a plane change maneuver at or near the apolune of the transfer ellipse, and the third burn is a circularization maneuver at a specified altitude. An upper limit of 5 days is placed on the overall flight time, including 1 day for the three-burn LOI sequence. Five methods for generating trajectories are used in order of complexity. The results of these five methods are presented for the worst-case arrival epoch of September 18th, 2024 12:00 UTC. Then, these methodologies are applied to a matrix of landing sites corresponding to a 5x5 degree grid of target orbit inclination and LAN for the same epoch using the worst-case wedge angle. For this study the full lunar surface was run for Methods 1, 2, and 4. Method 3 and 5 were not applied to the full surface access problem due to the additional complication of handling fail-safe plane-change ΔV for combined energy and plane change maneuvers. The results of applying Method 1 and 2 are based on full surface access, up to 7 days LLO loiter, and the minimized CEV plane change. For Method 1, the minimum LOI ΔV is 0.883 km/s. The maximum LOI ΔV is 1.382 km/s with no loiter and

1.126 km/s with 7 days loiter time. For Method 2, the minimum LOI ΔV is 0.899 km/s. The maximum LOI ΔV is 1.354 km/s with no loiter and 1.243 km/s with 3 days loiter time and 1.099 km/s with 7 days loiter time. No global surface access analysis was conducted using Method 3 and 5 due to computational intensity inherent to this method. For Method 4, the minimum ΔV is 0.893 km/s and the maximum ΔV is 1.272 km/s with no loiter. For the 7 day loiter case, the maximum ΔV is reduced to 1.075 km/s.

Surface lighting conditions are a critical element of mission planning since they can place additional constraints on mission events such as descent or ascent, as well as on surface activities. Solar lighting condition can be characterized by analyzing the elevation angle of the Sun at the location of interest on the surface. A negative elevation angle indicates the Sun lies below the horizon and that the location is in darkness. Depending on the activity, more specific constraints may be necessary. Light reflected off of the Earth can improve the lighting conditions on the lunar surface during periods of darkness, just as light reflected from the Moon does on Earth, during a full Moon in particular. Two angles are required to characterize the effect of Earthshine on the surface lighting condition: the elevation angle of the Earth as viewed from the location of interest and the Sun-Earth-Moon phase angle. A negative elevation angle indicates the Earth lies below the horizon and there cannot be any Earthshine at that location. Values of the phase angle approaching 180º indicate that the Earth lies almost directly between the Sun and the Moon, preventing light from being reflected off of the Earth to the lunar surface. These two angles were used to create a figure of merit to describe how ideal the Sun-Earth-Moon geometry is for Earthshine at a given point in time. The brightness of Earthshine under ideal conditions can be approximated based on the apparent magnitude of the full Moon, the ratio of the radii of the Moon and Earth, and the ratio of the albedos of the Moon and Earth. Under ideal conditions Earthshine will appear approximately either 40 or 90 times brighter than a full Moon, assuming Moon's albedo is 0.12 and Earth's albedo is 0.37 or 0.8 respectively

V. Conclusion

The frequency of TLI opportunities was found to vary over the course of the metonic cycle since it is dependent on the geocentric wedge angle. During periods of the cycle when the geocentric wedge angle is low, opportunities are more frequent, with 1 or 2 days between them, whereas during periods when the wedge angle is high, the intervals between opportunities are less frequent, with 10 or 12 days between opportunities. The geocentric wedge angle was also found to affect the Earth-Moon transfer time for off nominal Earth departures. A nominal 4 day Earth-Moon flight time was found to require a transfer time of ~3.7 days for a departure at the end of the 6 hour window for large geocentric wedge angles and ~2.8 days for low wedge angles. The reduced flight time requires a higher magnitude TLI maneuver, potentially increasing the ΔV above the TLI requirement and reducing the length of the TLI window.

Loiter in LLO was found to have a significant reduction on the ΔV cost for the three-burn LOI maneuver in all methodologies examined, showing 7-10% reductions with 3 days of loiter and 15-18% reductions at 7 days. This loiter, successfully reduces the LOI ΔV below the program requirement of 1250 m/s for complete global access. Method 2 was able to reduce the global maximum ΔV while fully protecting for a 6 hour TLI window. Method 4 was able to reduce the ΔV further, particularly for difficult to reach sites like the Aitken Basin.

Lighting conditions on the lunar surface were examined at the 10 ESAS sites of interest over an extended period of time. For most of the sites the lunar night was found to last ~14 days except in regions near the poles where the night extends much longer, ~3 months. Earthshine was also investigated and under ideal conditions found to provide illumination significantly brighter than the light of a full Moon.

Appendix

This section includes the full surface LOI ΔVs including loiter cases for methods 1, 2, and 4.

Method 1 LOI ΔV (km/s), No Loiter, CEV Wedge Angle Minimized
Min = 0.833 Max = 1.382

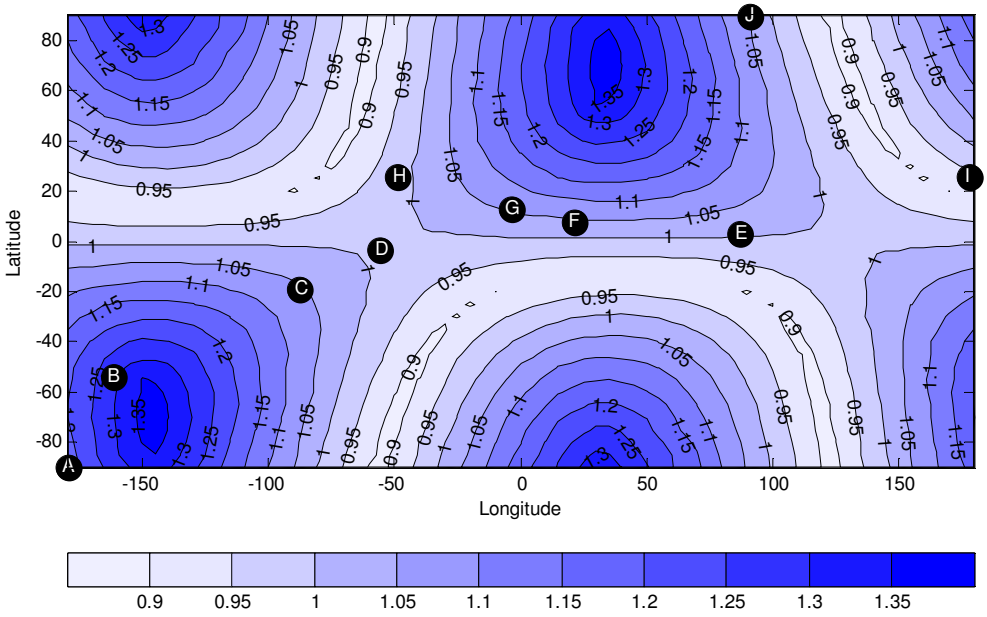

FIGURE 9. Method 1, no loiter. *No LLO loiter method 1 four day transfer time from the earth to the moon, 2nd LOI burn at apolune as a pure plane change, nominal mission with earth departure at the beginning of the TLI window using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 1 LOI ΔV (km/s), Loiter Limit = 3 days, CEV Wedge Angle Minimized
Min = 0.833 Max = 1.265

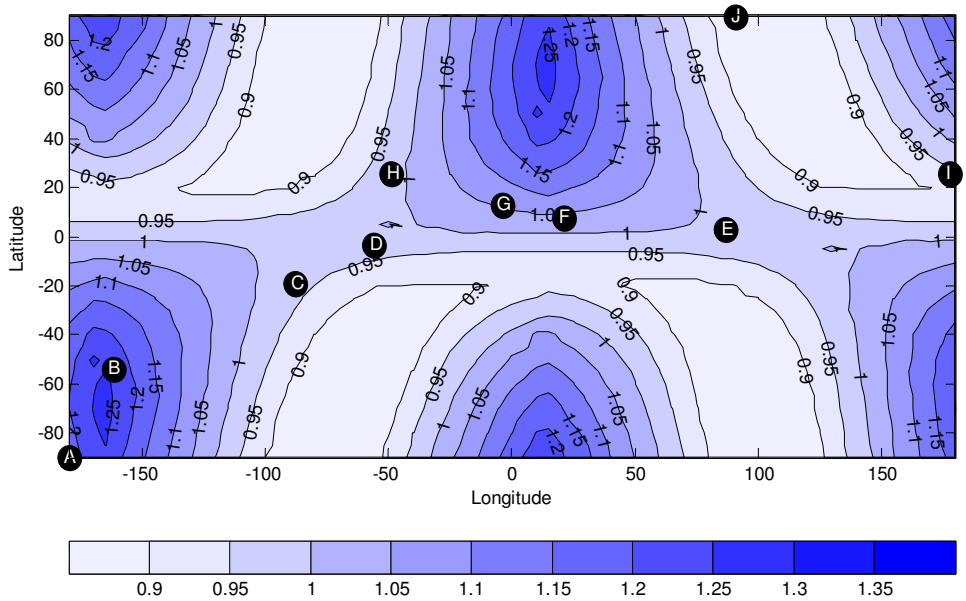

FIGURE 10. Method 1, loiter limit = 3 days. *Up to 3 days of LLO loiter for method 1 four day transfer time from the earth to the moon, 2nd LOI burn at apolune as a pure plane change, nominal mission with earth departure at the beginning of the TLI window using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 1 LOI ΔV (km/s), Loiter Limit = 5 days, CEV Wedge Angle Minimized
Min = 0.833 Max = 1.198

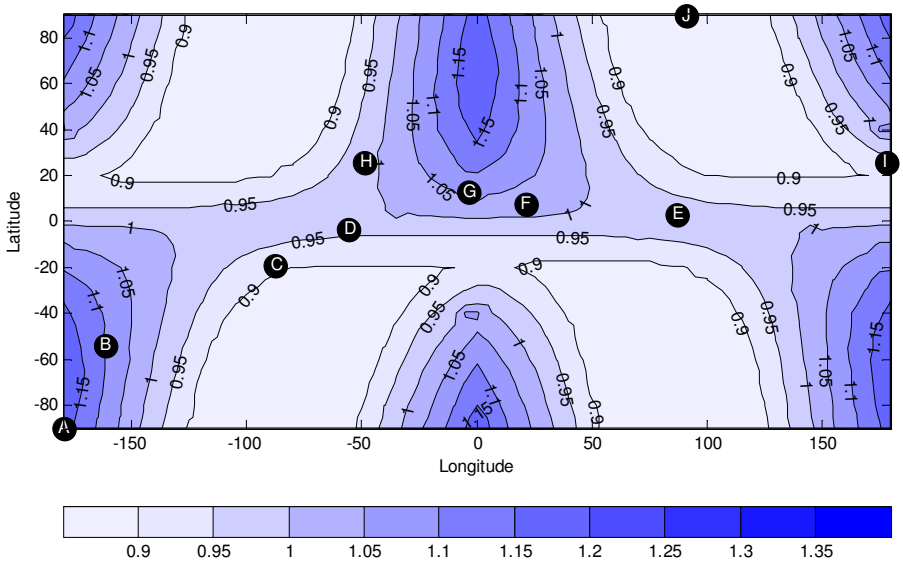

FIGURE 11. Method 1, loiter limit = 5 days. *Up to 5 days of LLO loiter for method 1 four day transfer time from the earth to the moon, 2nd LOI burn at apolune as a pure plane change, nominal mission with earth departure at the beginning of the TLI window using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 1 LOI ΔV (km/s), Loiter Limit = 7 days, CEV Wedge Angle Minimized
Min = 0.833 Max = 1.126

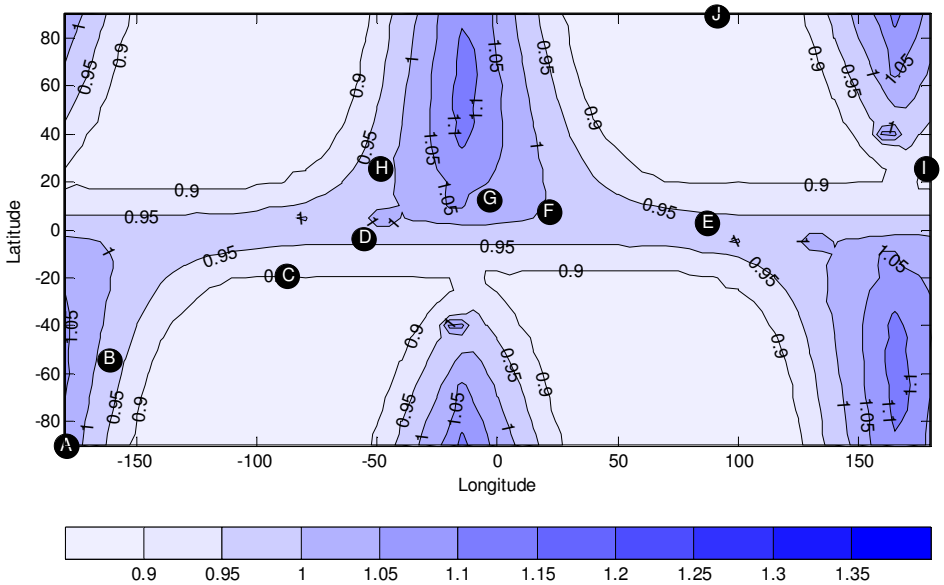

FIGURE 12. Method 1, loiter limit = 7 days. *Up to 7 days of LLO loiter for method 1 four day transfer time from the earth to the moon, 2nd LOI burn at apolune as a pure plane change, nominal mission with earth departure at the beginning of the TLI window using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

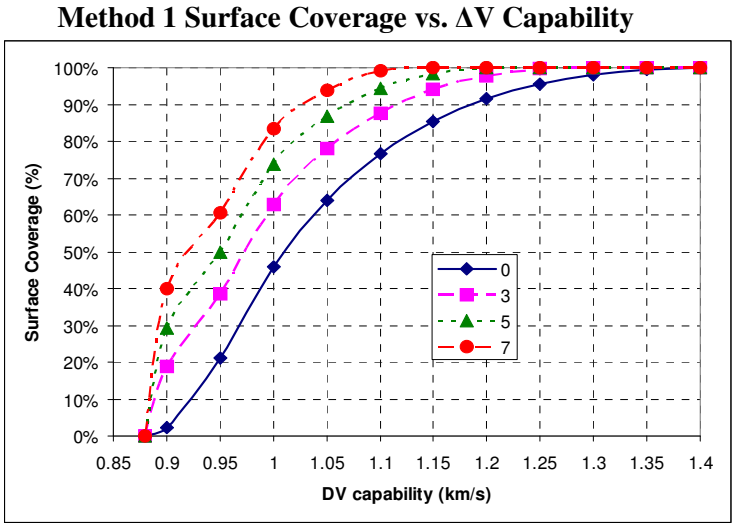

FIGURE 13. Method 1, surface coverage. *Percentage of surface coverage for method 1 for different maximum LLO loiter cases.*

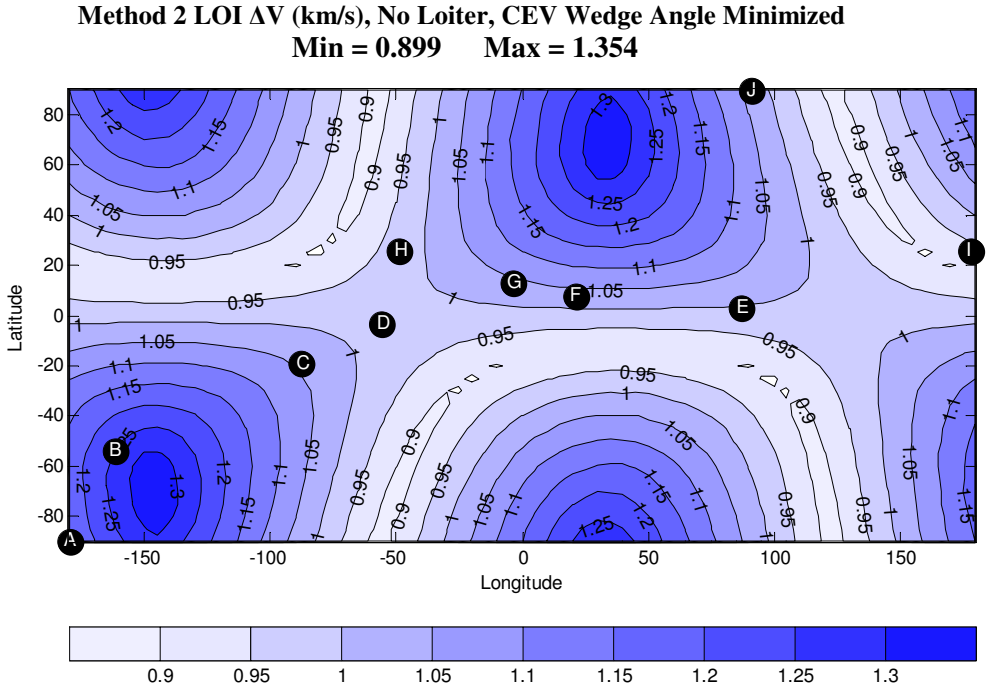

FIGURE 14. Method 2, no loiter. *No LLO loiter method 2 four day transfer time from the earth to the moon, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 2 LOI ΔV (km/s), Loiter Limit = 3 Days, CEV Wedge Angle Minimized
Min = 0.885 Max = 1.243

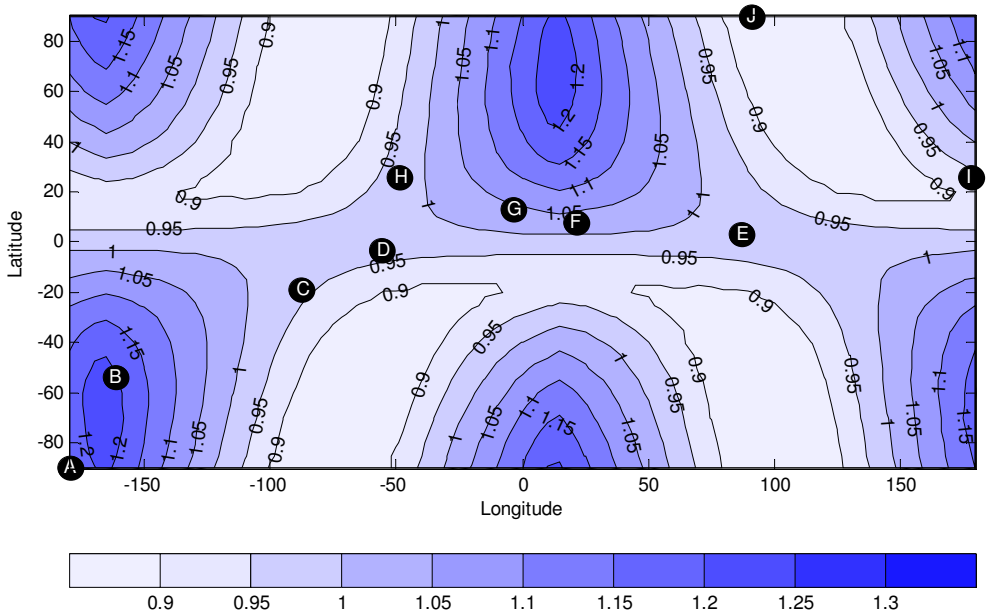

FIGURE 15. Method 2, loiter limit = 3 days. *Up to 3 days LLO loiter method 2 four day transfer time from the earth to the moon, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 2 LOI ΔV (km/s), Loiter Limit = 5 Days, CEV Wedge Angle Minimized
Min = 0.885 Max = 1.171

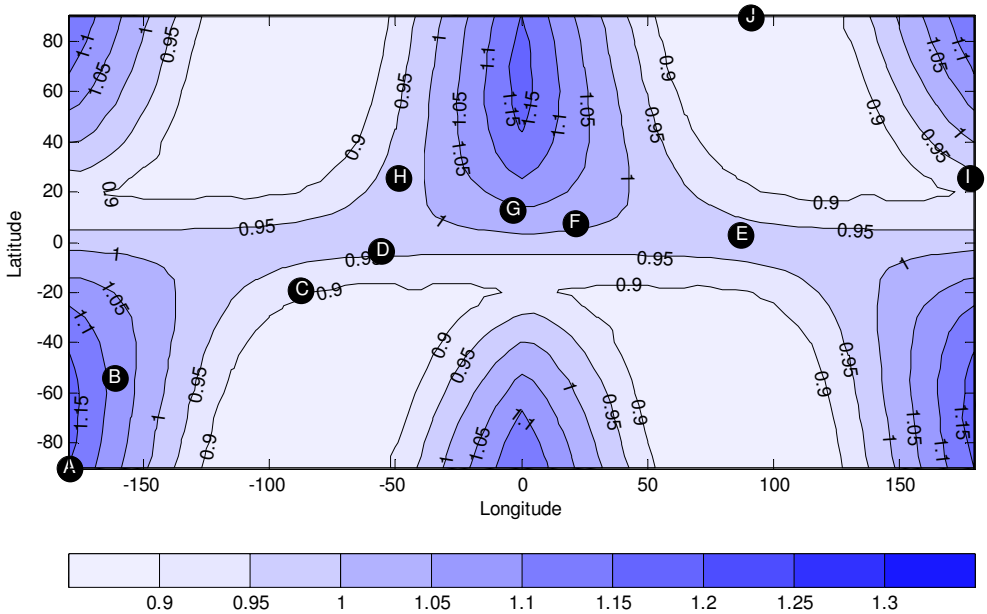

FIGURE 16. Method 2, loiter limit = 5 days. *Up to 5 days LLO loiter method 2 four day transfer time from the earth to the moon, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

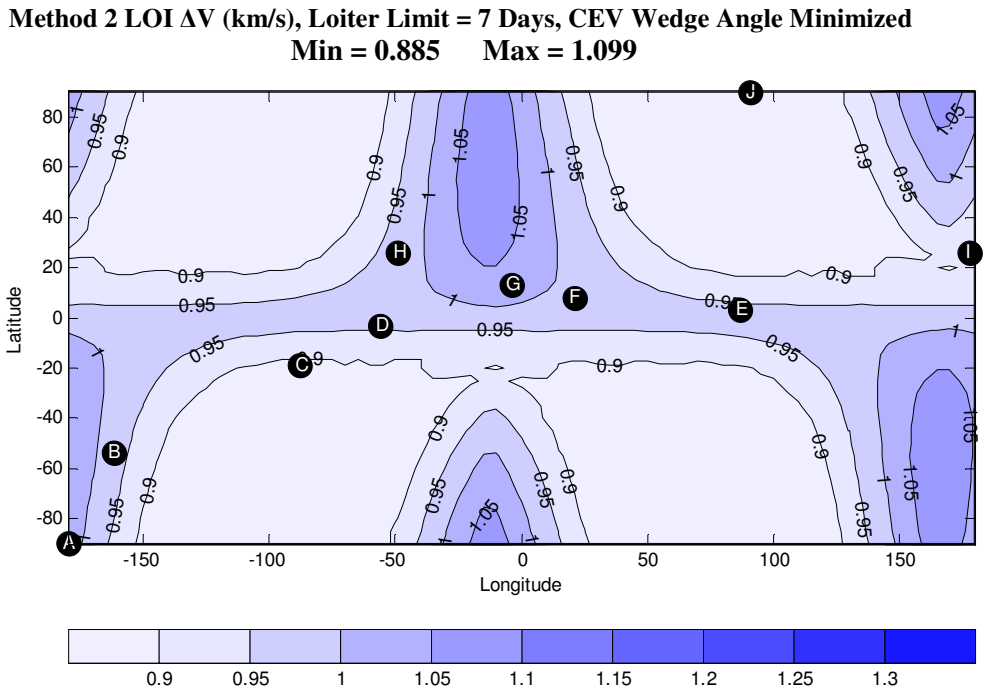

FIGURE 17. Method 2, loiter limit = 7 days. *Up to 7 days LLO loiter method 2 four day transfer time from the earth to the moon, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

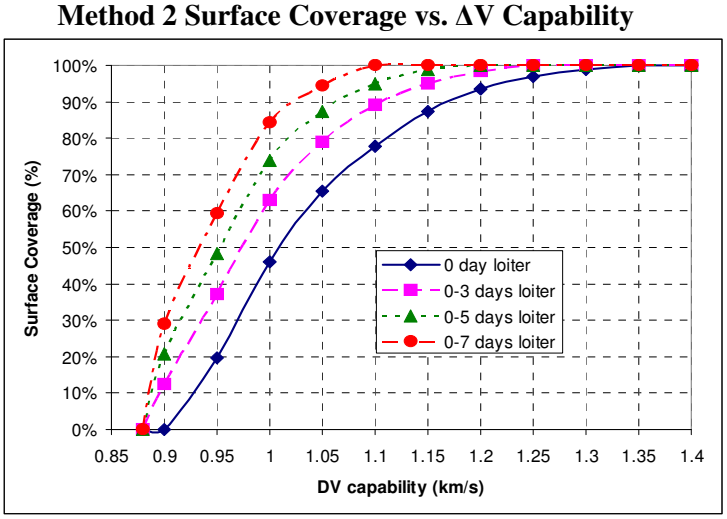

FIGURE 18. Method 2, surface coverage. *Percentage of surface coverage for method 2 for different maximum LLO loiter cases.*

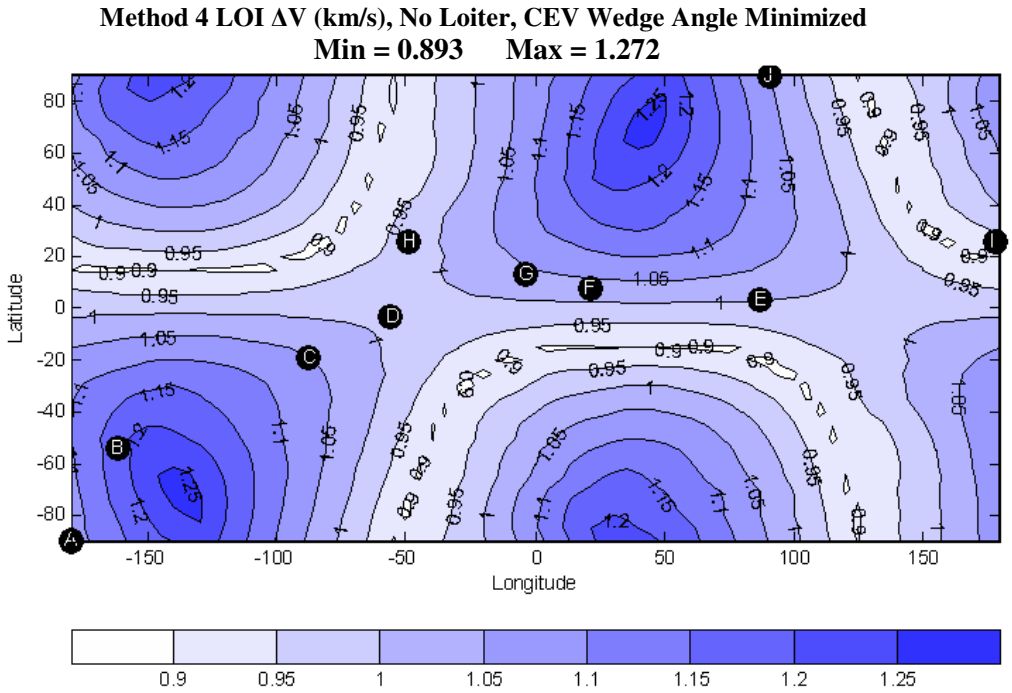

FIGURE 19. Method 4, no loiter. *No LLO loiter method 4, transfer time from the earth to the moon freed, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

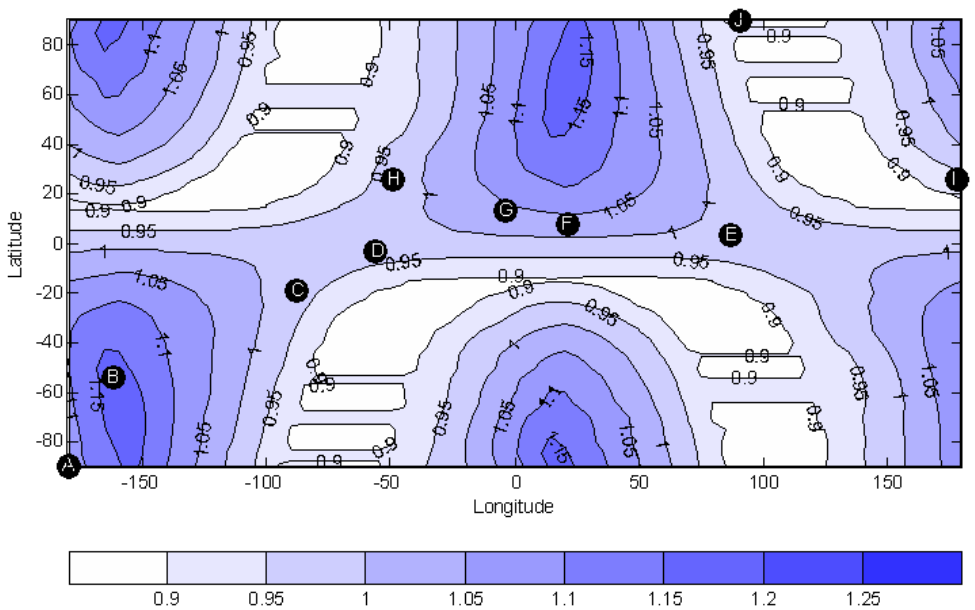

FIGURE 20. Method 4, loiter limit = 3 days. *LLO loiter limit = 3 days, method 4, transfer time from the earth to the moon freed, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 4 LOI ΔV (km/s), Loiter Limit = 5 Days, CEV Wedge Angle Minimized
Min = 0.892 Max = 1.124

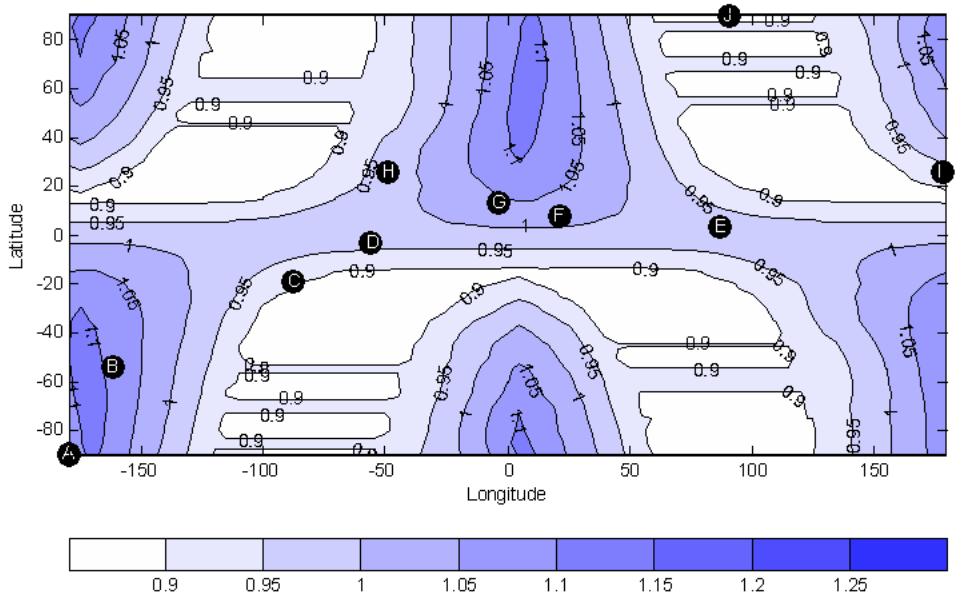

FIGURE 21. Method 4, loiter limit = 5 days. *LLO loiter limit = 5 days, method 4, transfer time from the earth to the moon freed, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

Method 4 LOI ΔV (km/s), Loiter Limit = 7 Days, CEV Wedge Angle Minimized
Min = 0.892 Max = 1.075

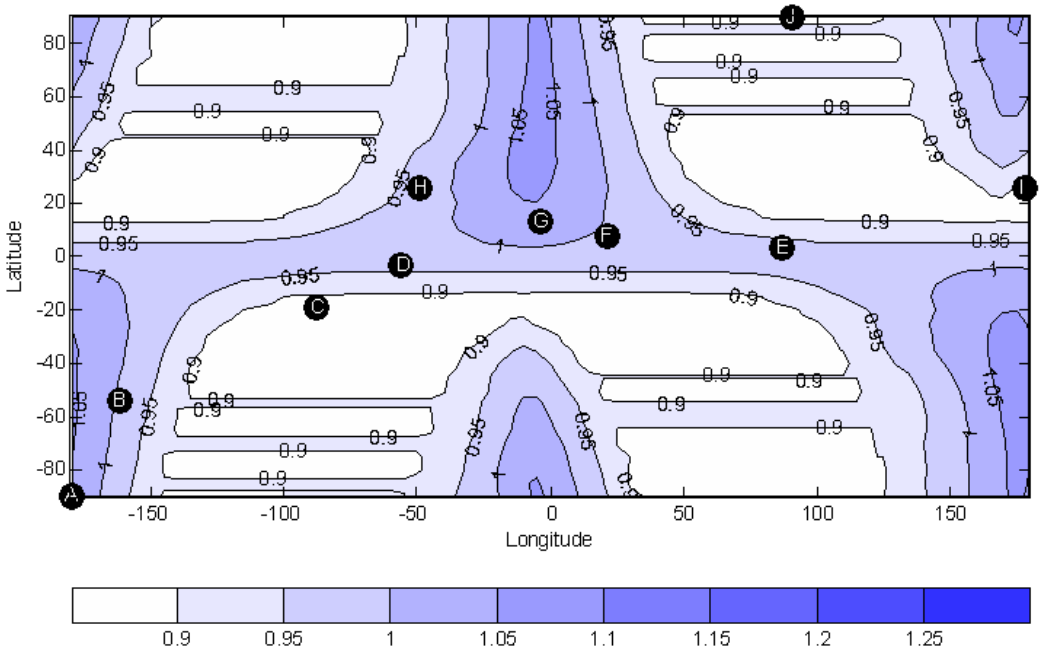

FIGURE 22. Method 4, loiter limit = 7 days. *LLO loiter limit = 7 days, method 4, transfer time from the earth to the moon freed, 2nd LOI burn time freed, burn is a pure plane change, earth departure covering the full TLI window, using the worst case Epoch for LOI and using the worst case geocentric wedge angle.*

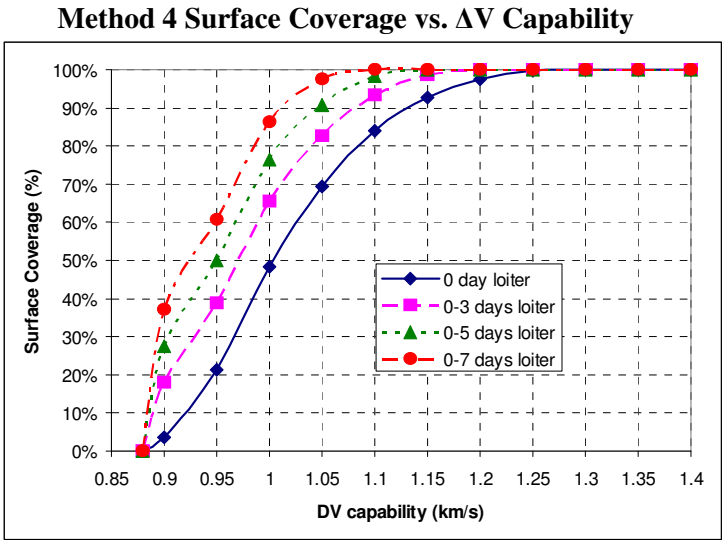

FIGURE 23. Method 4, surface coverage. *Percentage of surface coverage for method 4 for different maximum LLO loiter cases.*

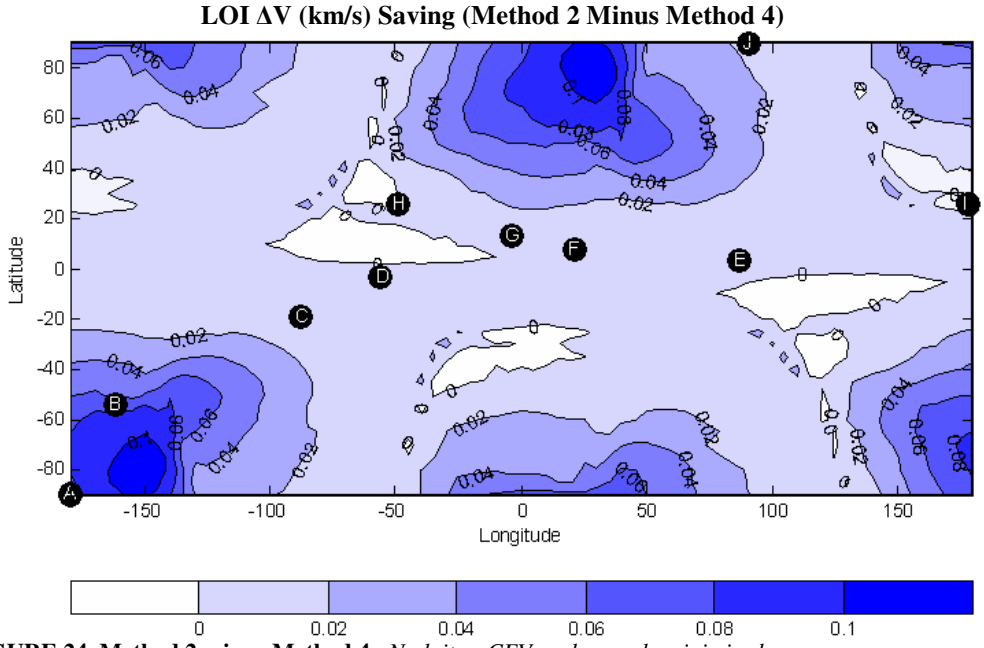

FIGURE 24. Method 2 minus Method 4. *No loiter, CEV wedge angle minimized.*

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