Enabling Global Lunar Access for Human Landing Systems Staged at Earth-Moon L2 Southern Near Rectilinear Halo and Butterfly Orbits

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NASA's Artemis program will return astronauts to the lunar surface using a Human Landing System staged at Gateway's 9:2 L2 southern NRHO. The current study explores global lunar access for Gateway's baseline NRHO and a comparable butterfly orbit. Additionally, increasing transfer time and loitering in low lunar orbit are analyzed to reduce lunar surface access costs. The results show selecting the optimal staging orbit for a landing site, increasing transfer times, and leveraging low lunar orbit loiter greatly reduce performance requirements.

I. Introduction

The National Aeronautics and Space Administration (NASA) has been directed under Space Policy Directive 1 [1] to "lead an innovative and sustainable exploration program with commercial and international partners that supports human expansion across our solar system." An integral part of this program is to establish a sustainable presence in lunar vicinity to facilitate the development and demonstration of key technologies necessary for human exploration to the Moon and onward to Mars.

A major step under this directive, NASA's Artemis program aims to land the first woman and next man on the surface of the Moon by 2024 [2]. To meet this goal, NASA has issued a solicitation to American companies under the Second Next Space Technologies for Exploration Partnerships Appendix H Broad Agency Announcement for the development and demonstration of a Human Landing System (HLS) to deliver humans to the lunar surface [3]. The initial 2024 mission will demonstrate the capability of the HLS and deliver two astronauts to a landing site near the Lunar South Pole for a surface stay of approximately 6.5 days. Subsequent missions will demonstrate technologies geared towards a sustainable presence in lunar vicinity including reusable vehicles and in-space refueling. By 2028, the HLS will be capable of transporting four astronauts to the surface, leverage pre-deployed surface assets, and use NASA's Gateway as a staging point. As Gateway is the aggregation point for the HLS architecture, sizing of each vehicle element is fundamentally tied to Gateway's cis-lunar orbit.

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A sustainable HLS would ideally be able to access and operate at any point on the Moon's surface. However, the fixed Earth-Moon orientation of Gateway's unique L2 southern Near Rectilinear Halo Orbit (NRHO) does not facilitate accessing all combinations of lunar latitudes and longitudes for time of flight constrained human missions. This paper investigates ΔV reduction strategies to enable global lunar access from Gateway including utilizing a L2 southern butterfly orbit, increasing outbound and inbound transfer times, and loitering in low lunar orbit (LLO).

First, a concise summary of Gateway and L2 southern NRHO and butterfly orbits is provided. A reference HLS architecture and concept of operations is then established that includes a ΔV budget to access the Lunar South Pole. This reference ΔV budget will be used for comparison as lunar surface access and performance mitigation options are analyzed. Finally, global lunar access and ΔV reduction strategies are discussed.

II. Gateway

NASA has significantly invested in studies examining the best approach for enabling sustainable human missions and concluded an asset in cis-lunar space is critical for long term sustainability. NASA's Gateway will be utilized to provide capabilities for scientific discovery, demonstrate critical deep space technology for human exploration, promote industry and international partnerships, and support human crewed missions to cis-lunar space, the lunar surface, and other deep space destinations. After extensive analyses of candidate cis-lunar orbits, the Gateway program has selected a 9:2 L2 southern NRHO as its operational orbit [4].

A. Near Rectilinear Halo Orbits

The Circular Restricted Three-Body Problem (CR3BP) is a classical dynamics model for studying orbits in cis-lunar space where the Earth and Moon are the two primary bodies. Five equilibrium points, called libration points, exists in the CR3BP equations of motion and are effectively stationary points in the Earth-Moon (E-M) rotating frame. Halo orbits are a continuous family of periodic orbits which bifurcate from planar Lyapunov orbits near the three collinear libration points [5, 6]. The families of Halo orbits at the L1 and L2 libration points near the Moon are shown in Fig. 1 [7]. NRHOs are a subset of the larger halo orbits and exhibit low perilune altitudes and favorable stability properties. The NRHOs have an elongated shape which resembles a two-body Keplerian highly elliptical orbit; however, their orientation rotates at the same rate as the Moon rotates about the Earth resulting in a fixed orientation when viewed in the Earth-Moon rotating frame.

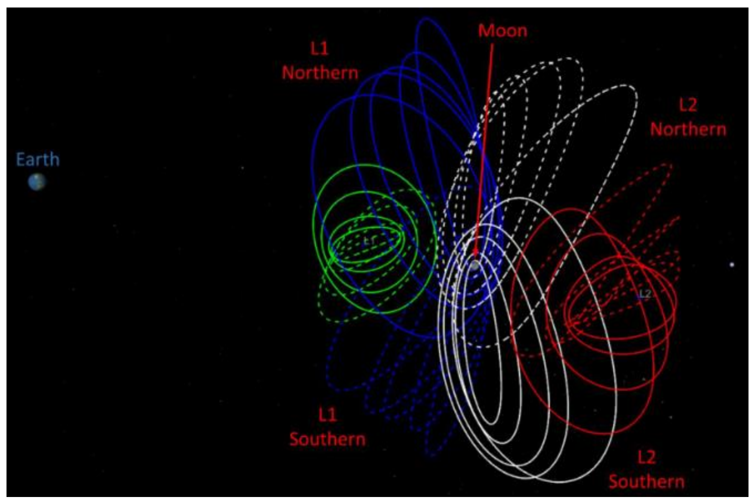


Fig. 1 Halo Orbit Families [7]

NRHOs offer distinct advantages as a cis-lunar aggregation point. Their favorable stability properties result in low orbit maintenance costs [8], ΔVs for fast transfers between Earth and NRHOs are within Orion's capabilities [9], ballistic lunar transfers can deliver un-crewed assets to NRHO with minimal ΔV requirements [10], and interplanetary missions could depart from NRHO [11]. Additionally, NRHOs offer access to the lunar surface with short trip times [12] and can provide extended coverage over one lunar pole [13].

A L2 southern NRHO was selected for its stability over L1 NRHOs [14, 15], coverage of the Lunar South Pole, and lower ΔV requirements for an Orion reentry and splashdown in Earth's northern hemisphere. The size of Gateway's selected NRHO corresponds to a 9:2 lunar synodic resonance and, with proper initial conditions, will naturally avoid eclipses [16].

B. Butterfly Orbits

L2 southern butterfly orbits are a family of periodic orbits that arise from a period-doubling bifurcation off the L2 southern NRHOs. A recent subject of interest, they have many of the same advantageous features as L2 southern NRHOs. Butterfly orbits with low perilune altitudes have favorable stability properties, and effective orbit maintenance algorithms for NRHOs can also be applied to the butterfly family [8]. Furthermore, L2 southern butterfly orbits have extended periods of Earth visibility and Lunar South pole coverage and are equally as accessible from Earth on a fast transfer trajectory or ballistic lunar transfer [17]. The two lobes of the butterfly also add mission design flexibility for insertion and departure maneuvers.

The tangent bifurcation results in two distinct lobes that wrap around the Moon. The smaller lobe is located on the L1 side and has a shorter period than the larger lobe on the L2 side. The orbital motion resembles a "figure-8" pattern, and the lobes don't strictly pass over the lunar rim. Figure 2 shows the L2 southern NRHO and butterfly orbit used in this study, and Table 1 contains their lunar distance ranges and respective periods. This butterfly orbit has a similar Jacobi constant, a measure of energy in the CR3BP, and perilune altitude as Gateway's NRHO. Note, the NRHO and butterfly orbit properties do slightly vary as a function of epoch in a full ephemeris model. Lastly, Gateway has the capability to perform low thrust transfers to different orbits in cis-lunar space, and minimal impulsive ΔV transfers between NRHO and butterfly orbits have recently been discovered [15].

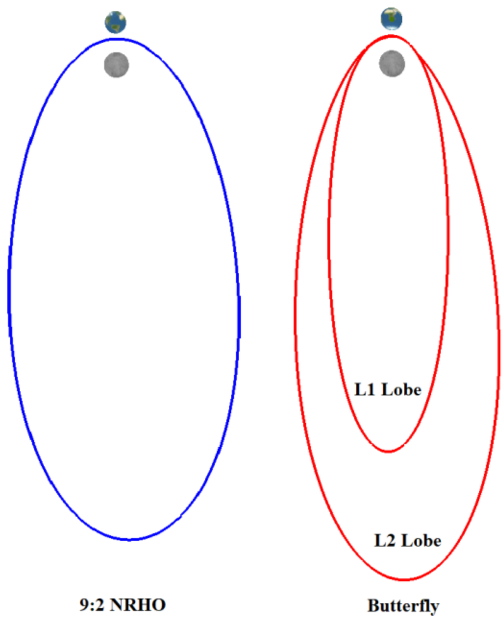


Fig. 2 NRHO and Butterfly in E-M Rotating Frame

Table 1 Staging Orbit Characteristics at Epoch

	Lunar Distance *km*	Period *Days*
9:2 NRHO	3250 - 71500	6.8
Butterfly	L1 = 3250 - 65800	L1 = 5.9
	L2 = 3250 - 71500	L2 = 6.8

III. HLS Reference Architecture

Figure 3 shows a reference concept of operations for a lunar landing mission.

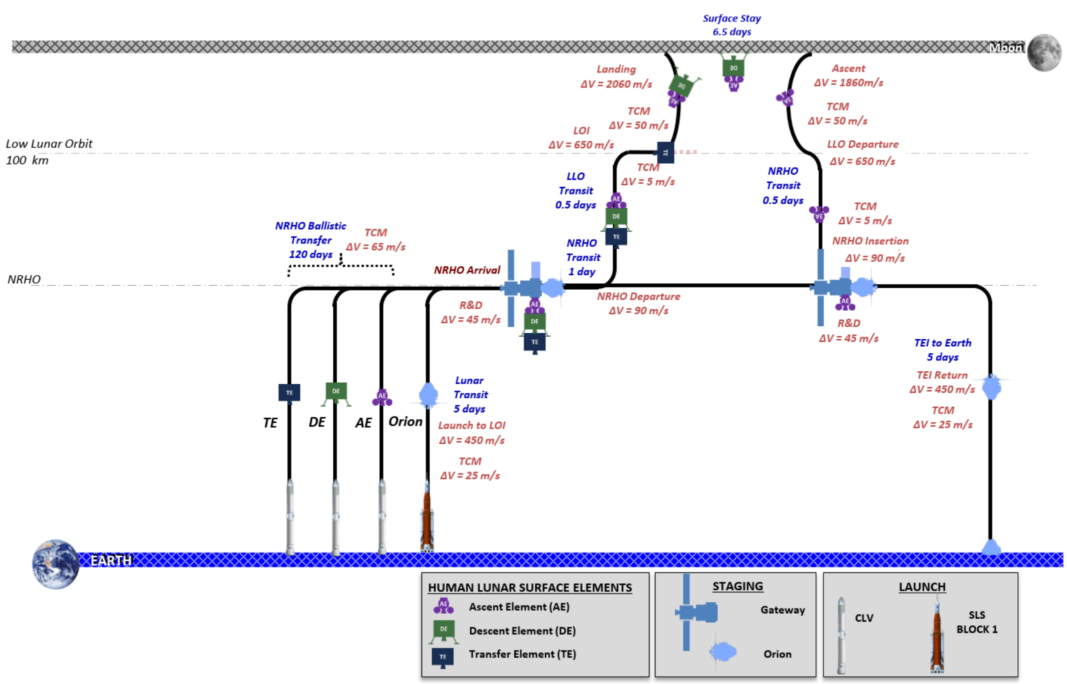


Fig. 3 Reference Lunar Landing Mission Concept of Operations

The three-element HLS architecture shown here is one of many possible design solutions for NASA's HLS [18]. Regardless, the outbound and inbound ΔV requirements between Gateway's NRHO orbit and LLO will remain principally the same.

Commercial launch vehicles (CLV) will inject each HLS element on a low-energy ballistic lunar transfer approximately 120 days in duration. Time of flight to Gateway is a relaxed constraint for un-crewed vehicles, so minimizing the ΔV costs to insert into NRHO is a primary objective. The three-element HLS stack will be assembled, rendezvous and dock (R&D) with Gateway, and undergo a full system checkout to verify readiness to receive crew and perform a lunar mission. An Orion crew of four on a Space Launch Systems Block 1 vehicle will depart Earth on a high-energy lunar transfer and use a lunar flyby to insert into NRHO and R&D with Gateway.

For the initial 2024 lunar surface mission, two crew members will board the HLS for transport to the lunar surface while two crew members will remain on Gateway. The HLS Transfer Element (TE) will perform a propulsive maneuver to depart NRHO, coast for 0.5 days, then execute a second maneuver to insert into a circular 100 km altitude LLO. The Transfer Element will separate from the Descent Element (DE)/Ascent Element (AE) stack, and the crew will loiter in LLO for 0.25 days to obtain a good navigation solution and perform final checkouts for descent and landing. A descent orbit insertion maneuver will lower the perilune altitude of the DE/AE stack for powered descent initiation, and the DE will execute the descent maneuvers to land at the South Pole. The crew will nominally explore the lunar surface for 6.5 days then use the AE to ascend and maneuver into a circular 100 km altitude LLO. After loitering in LLO again for 0.25 days, the AE will perform a propulsive maneuver to depart LLO, coast for 0.5 days, then insert into NRHO in proximity of Gateway for R&D. All four crew members will board the Orion capsule and perform a lunar flyby for Earth return on a high-energy transfer.

Figure 3 shows ΔV allocations for each maneuver throughout the concept of operations. Specific to this paper, a ΔV budget of 740 m/s for transfers between NRHO and LLO is considered the baseline.

IV. Global Lunar Access

A primary objective of Gateway is to facilitate access to the lunar surface and act as a two-way staging point. The primary design driver for robotic missions is to minimize the total ΔV costs, whereas human missions must carefully balance both ΔV and time of flight. Higher ΔV costs directly increase propellant requirements, while extended flight times increase propellant as a result of a higher vehicle dry weight from crew consumables. Although minimizing the total ΔV is a concern, the magnitude of the individual outbound and inbound ΔVs directly affects system sizing. In our reference HLS architecture, the TE is sized for the outbound transfer of the stack to LLO, while the AE is sized to perform the inbound transfer to LLO. While not analyzed here, the AE has the highest gear ratio in the system and putting priority on minimizing the inbound ΔV may be necessary to ensure the system closes from a launch vehicle capability perspective.

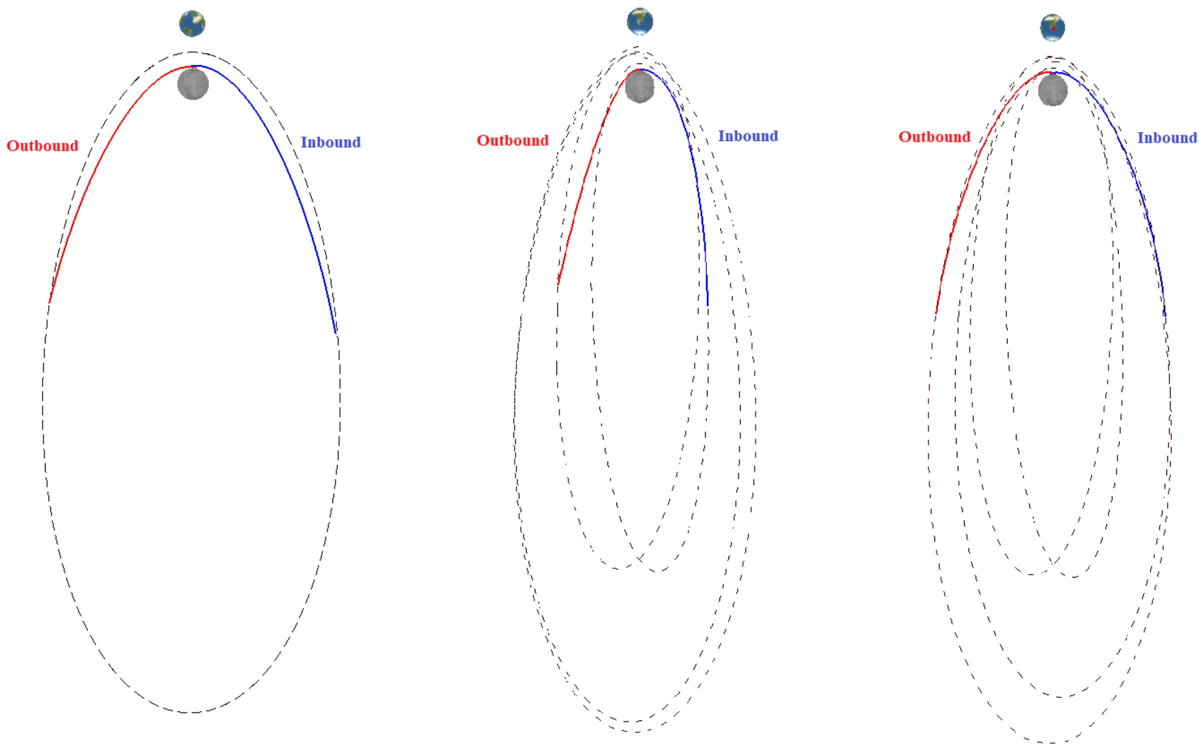
A previous analysis studied the cost to access the lunar poles and equatorial sites at either 0 or 180 degrees longitude from Gateway's NRHO and a butterfly orbit [17]. Increasing the NRHO transfer times from 0.5 to 1.0 days resulted in a significant reduction in ΔV, and the access cost for these specific sites was less for the butterfly orbit when constrained to 0.5 day transfers. That analysis is expanded here by quantifying the global ΔV costs for 0.5 day and 1.0 day transfers, and loitering in LLO is analyzed as an additional ΔV reduction method. Finally, subject to a set of transfer and loiter time constraints, the staging point with the minimum round trip ΔV is obtained for each point on the lunar surface.

A. Transfers Modeling and Assumptions

NASA's trajectory optimization tool Copernicus [19] is used to model the two-impulse outbound and inbound transfers between the staging orbits in Table 1 and a circular 100 km LLO orbit that passes over a desired landing site within one LLO revolution. The LLO inclination, longitude of ascending node, and insertion/departure true anomalies are optimized for each transfer and the total ΔV for each leg is minimized. For a set of landing sites spanning the lunar surface, optimal outbound and inbound trajectory solutions are solved for. The analysis is not constrained to use the same LLO for the outbound and inbound transfers as no elements are assumed to loiter in LLO for reuse on the inbound transfer. Since each LLO is constrained to pass over the desired landing site, no out-of-plane maneuvering is required for the DE during descent or the AE to ascend to LLO for the inbound transfer. As a result, the ΔV for both descent and ascent is assumed fixed based on vehicle thrust to weight assumptions. Branch 1 (B1) refers to outbound and inbound transfers from the butterfly L1 lobe while branch 2 (B2) refers to the L2 lobe.

B. 0.5 Day Transfers

Figure 4 shows the optimal 0.5 day transfer geometry for a Lunar South Pole mission staged from either NRHO, the butterfly L1 lobe, or the butterfly L2 lobe.

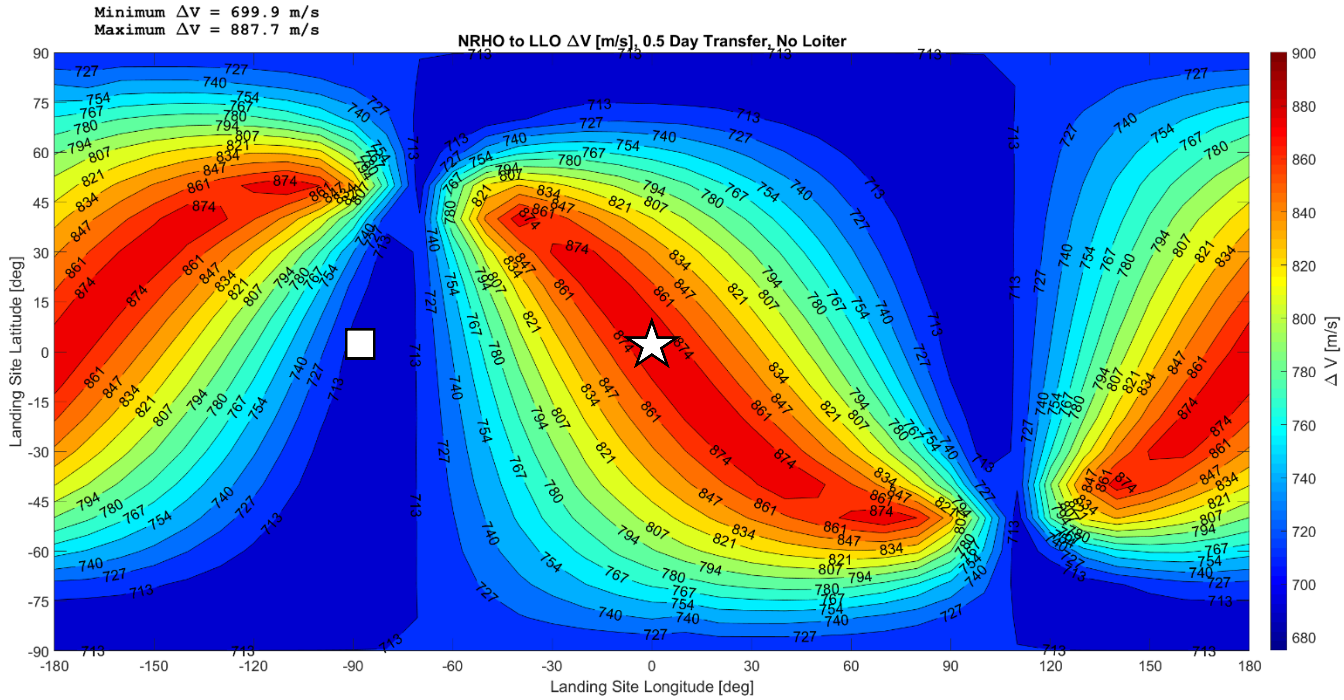


(a) NRHO (b) B1 (c) B2

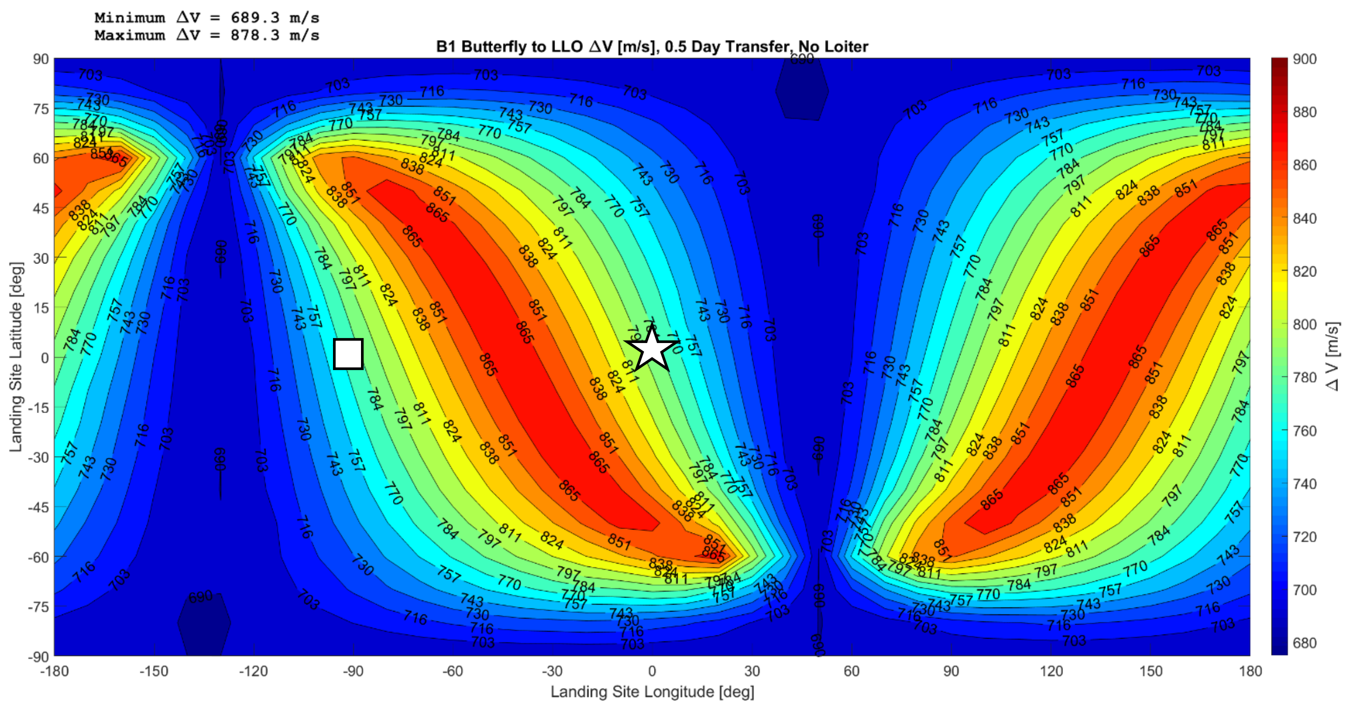
Fig. 4 Lunar South Pole Missions for 0.5 Day Transfers viewed in E-M Rotating Frame

For each case shown, the optimal LLO insertion and departure point occurs near perilune, and the initial outbound maneuver and final inbound maneuvers occur at similar lunar distances. This symmetry in the transfer legs results in the optimal time between LLO insertion and LLO departure consistently being roughly one period of the NRHO, L2 lobe, or L1 lobe respectively. Transfers from the L2 lobe have the shortest surface stay times followed by the L1 lobe and NRHO. A shorter stay time may be preferred as it reduces the overall time away from Gateway and consequently the amount of crew consumables the HLS must provide in transit and while on the surface.

Figure 5 shows the NRHO and B1 global access ΔV contours for 0.5 day outbound transfers.



(a) NRHO



(b) B1

Fig. 5 0.5 Day Outbound Transfer ΔVs

It's evident from these contours that the ΔV cost varies considerably with landing site location, and our reference outbound ΔV budget of 740 m/s is not sufficient for global access. Lunar surface access is a challenge for both the NRHO and butterfly due to the fact that they maintain roughly the same orientation with respect to the Earth-Moon system. The path of the NRHO over the lunar poles and along the lunar rim results in these areas being easier to access as depicted by the blue regions of lower ΔV costs near both poles and for all latitudes along the +/- 90 degree longitude lines. Compared to the poles or lunar rim, accessing the equatorial sites along the Earth-Moon line from NRHO require a ΔV increase of up to 188 m/s.

The minimum and maximum outbound ΔV costs are similar for B1, but the butterfly track results in differing high and low ΔV regions. The results show an outbound transfer from the L1 butterfly lobe can be used to access landing sites along -135 or 45 degree longitude lines for minimal cost. The stars further illustrate how specific regions are easier to access for a particular staging point. Consistent with previous work, the L1 butterfly lobe has lower ΔV costs to access the lunar poles and equatorial landing sites at 0 or 180 degrees longitude. Figure 11 in the appendix shows the global access ΔV contour for 0.5 day outbound transfers from B2. The B2 staging point has the highest maximum outbound ΔV costs but has reduced access costs for landing sites along -45 or 135 degree longitude lines.

Figures 12-14 show the access results for the NRHO, B1, and B2 inbound trajectories. In all three cases, the inbound 740 m/s ΔV budget is not sufficient to depart from any lunar landing site and return to Gateway. High ΔV regions are a consequence of the landing site not intersecting a LLO with a favorable alignment to depart and rendezvous with the target staging orbit. Ultimately, if we are constrained to a reference total ΔV budget of 1480 m/s, both the NRHO and butterfly enable access to the Lunar South Pole but not the entire lunar surface.

C. 1.0 Day Transfers

The first global access mitigation strategy investigated is increasing the flight time between the staging orbit and LLO since, in general, an increase in flight time results in reduced transit ΔVs. The 1.0 day transfer geometries maintain the same symmetry as in Fig. 4 with LLO insertion and departure maneuvers at lunar close approach. Thus, increasing the transfer time results in an equal increase in total flight time but does not decrease the surface stay time. Concerning global access, difficult landing sites require inserting or departing from an intersecting LLO that isn't favorably aligned with the staging orbit. With 1.0 day transfers, the optimal Gateway departure and arrival maneuvers occur at a greater lunar distance where the velocity is lower. This contributes in reducing the magnitude of the out-of-plane maneuvers necessary to reach or depart difficult sites. Although this mitigation strategy decreases ΔV, increased total flight time comes with the cost of more consumables and reduces the amount of time for crew operations at Gateway in order to prepare for an Orion departure back to Earth.

Figure 6 shows the ΔV contour for 1.0 day outbound transfers from NRHO.

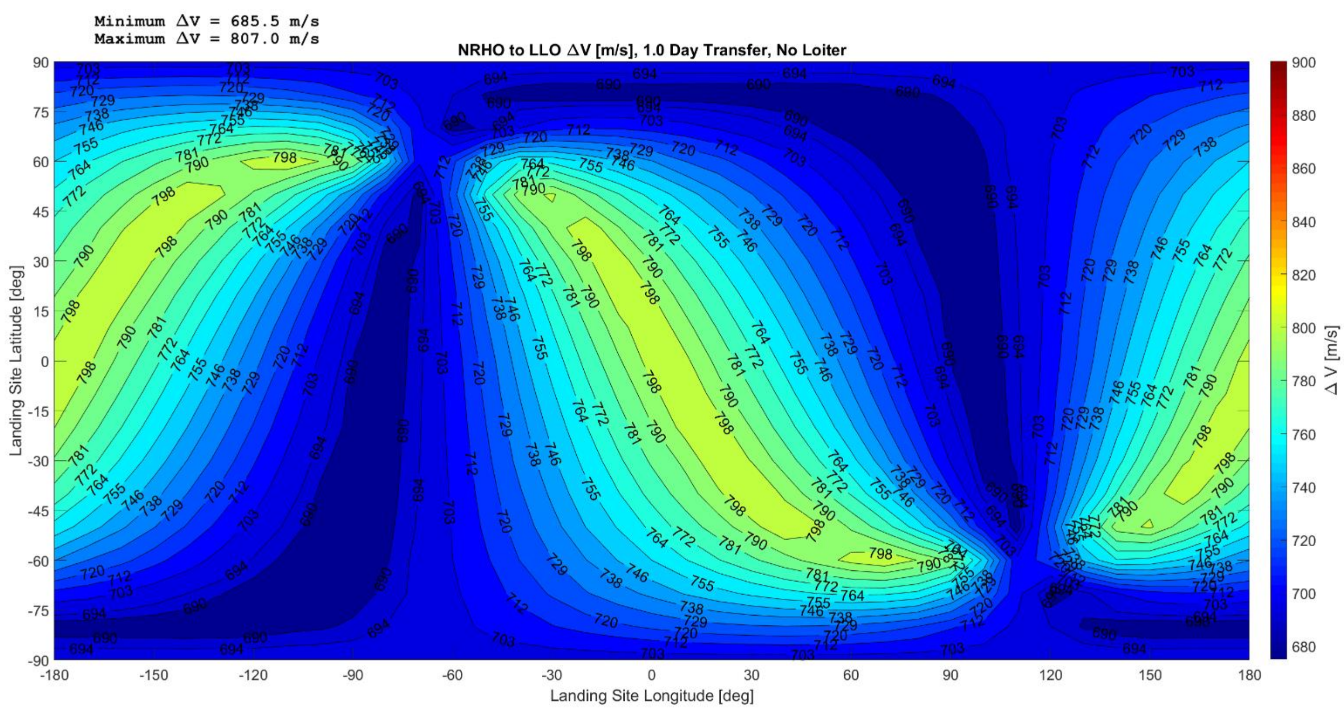


Fig. 6 NRHO 1.0 Day Outbound Transfer ΔVs

Increasing the outbound transfer time to 1.0 day reduces the minimum ΔV cost by 2%, the maximum ΔV cost by 9%, and significantly increases surface access for a 740 m/s ΔV budget. Figures 15-19 show the ΔV contours for all three staging points for 1.0 day transfers. Table 2-3 summarizes the effectiveness of increasing the transfer time as a ΔV reduction strategy.

Table 2 Outbound Transfers Minimum and Maximum ΔVs

	Outbound Transfer					
	Minimum			Maximum		
	0.5 Day	1.0 Day	Reduction	0.5 Day	1.0 Day	Reduction
	ΔV	*ΔV*	*ΔV*	*ΔV*	*ΔV*	*ΔV*
	m/s	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
NRHO	700	686	14	888	807	81
B1 Butterfly	689	677	12	878	801	77
B2 Butterfly	701	686	15	891	809	81

Table 3 Inbound Transfers Minimum and Maximum ΔVs

	Inbound Transfer					
	Minimum			Maximum		
	0.5 Day	1.0 Day	Reduction	0.5 Day	1.0 Day	Reduction
	ΔV	*ΔV*	*ΔV*	*ΔV*	*ΔV*	*ΔV*
	m/s	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
NRHO	693	681	13	890	806	84
B1 Butterfly	702	686	16	891	808	82
B2 Butterfly	697	685	13	886	807	79

D. LLO Loiter

Loitering in LLO is the second mitigation strategy investigated. Once the HLS has inserted into an LLO, it is stationed in a traditional Keplerian orbit with the Moon as the primary body. The LLO longitude of ascending node will naturally shift by approximately 13 degrees per day due to the Moon's rotation and oblate gravitational effects. Missions with relaxed time constraints could simply loiter in a polar lunar orbit and access any point on the lunar surface. The HLS system cannot loiter indefinitely due to consumables, and the time in lunar vicinity is constrained to enable an efficient inbound transfer to rendezvous with Gateway. Figure 7 shows a sample timeline for a NRHO lunar surface mission that includes LLO loiter.

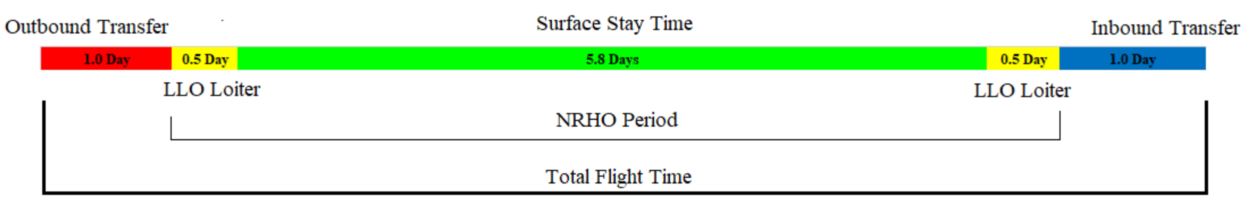


Fig. 7 NRHO Lunar Mission Timeline for 1.0 Day Transfers and Total LLO Loiter of 1.0 Day

Note, this timeline does not explicitly allocate the time required to descend and ascend from the surface, rather they are considered part of the surface stay time. An optimal inbound transfer requires the total time from LLO insertion to LLO departure equate to roughly one period of the NRHO. Similarly, optimal inbound transfers for the B1 and B2 solutions require the total time in lunar vicinity equating to the period of the L2 and L1 lobes respectively. Increasing the LLO loiter duration comes at the cost of reducing the surface stay time.

Figure 8 demonstrates how loitering can reduce surface access costs for the outbound transfer.

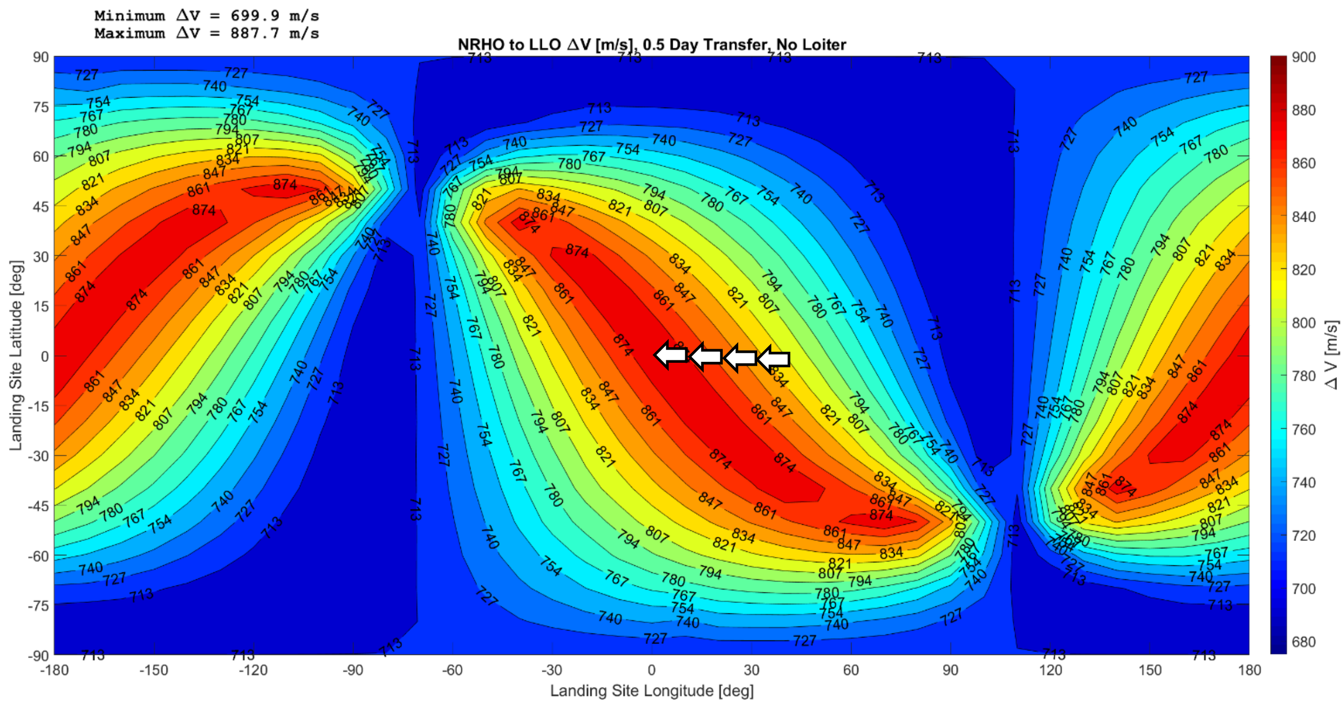
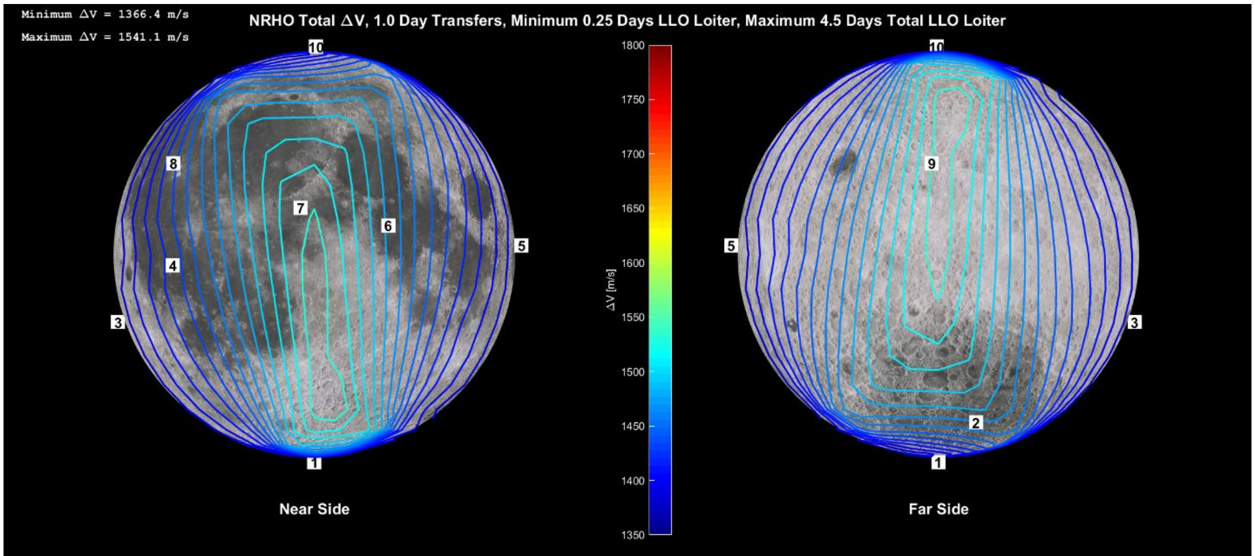


Fig. 8 NRHO 0.5 Day Outbound Transfer with LLO Loiter Strategy

Targeting an equatorial landing site at 0 degrees longitude could be reduced by inserting into a cheaper LLO with access to the equator and loitering for 4 days. Each day of loiter is represented as an arrow in Fig. 8. Loitering can also reduce the inbound transfer ΔV by inserting into LLO then waiting for a more favorable departure orientation. This mitigation strategy is effective for challenging land sites but has minimal effect for the low ΔV regions.

To investigate loitering in LLO for the 0.5 and 1.0 day transfer data sets, an optimization problem is defined that optimizes the outbound and inbound LLO loiter times to minimize the total ΔV. Optimal results are found for each staging orbit and the total LLO loiter time is constrained to either 0.5, 2.5, or 4.5 days. The minimum LLO loiter time on either side of the surface stay must be at least 0.25 days as specified in our reference HLS concept of operations. This analysis did not account for nodal regression due to J2 effects which can be up to 1 degree per day depending on LLO inclination. This wasn't considered significant for this study as the nodal regression due to the Moon's rotation is 13 degrees per day.

Figure 9 shows the NRHO global access total ΔV contour when 1.0 day transfers are used and the HLS total LLO loiter time is constrained to 4.5 days. In no particular order, the optimal solution for ten lunar sites of scientific interests are included. The values shown in red violate the ΔV allocation of 740 m/s for either the outbound or inbound transfer.



Site #	Name	$\phi°$	$\lambda°$	Out ΔV [m/s]	Out Loiter [days]	In ΔV [m/s]	In Loiter [days]	Total ΔV [m/s]	Stay Time [days]
1	South Pole	-89.9	-180	698	0.25	686	4.25	1384	2.3
2	Far-side Aitken Basin Floor	-54	-162	732	0.25	738	4.25	1469	2.3
3	Oriental Basin Floor	-19	-88	687	0.43	687	0.81	1373	5.56
4	Oceanus Procellarum	-3	-43	741	0.25	685	4.21	1426	2.34
5	Mare Smythii	2.5	86.5	687	0.87	684	0.39	1371	5.54
6	W/NW Mare Tranquillitatis	8	21	703	4.25	775	0.25	1478	2.3
7	Rima Bode	13	-3.9	800	0.25	726	4.25	1527	2.3
8	Aristarchus Plateau	26	-49	744	0.25	687	3.64	1431	2.91
9	Central Far-side Highlands	26	178	787	0.25	743	4.25	1530	2.3
10	North Pole	89.5	91	698	0.25	686	0.81	1383	5.74

Fig. 9 NRHO Global Access ΔV Contour for 1.0 Day Transfers and 4.5 Days Total LLO Loiter

Both increasing transfer time and loitering in LLO ΔV mitigation strategies are exercised here. The maximum total ΔV still violates our budget by 61 m/s. For cases in which the optimal loiter solution satisfies the ΔV budget, the objective function could be modified to maximize surface stay time. For example, in Fig 9 the optimal loiter solution for the South Pole is within the ΔV budget but uses the total LLO loiter time allocated. Ideally this solution wouldn't have this extended loiter and the surface stay time could be increased to 6.3 days for a marginal increase in total ΔV.

Figures 20-21 show a set of the LLO loiter optimization problems analyzed, and Tables 4-5 summarize the effectiveness of LLO loiter for both 0.5 day and 1.0 day transfers.

Table 4 Minimum and Maximum Total ΔVs for 0.5 Day Transfers with LLO Loiter

	0.5 Day Transfers					
		Total Minimum			Total Maximum	
	0.5 Days Loiter	4.5 Days Loiter	Reduction	0.5 Days Loiter	4.5 Days Loiter	Reduction
	ΔV	ΔV	ΔV	ΔV	ΔV	ΔV
	m/s	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
NRHO	1405	1397	9	1758	1669	89
B1 Butterfly	1394	1393	2	1736	1628	108
B2 Butterfly	1405	1404	1	1749	1704	45

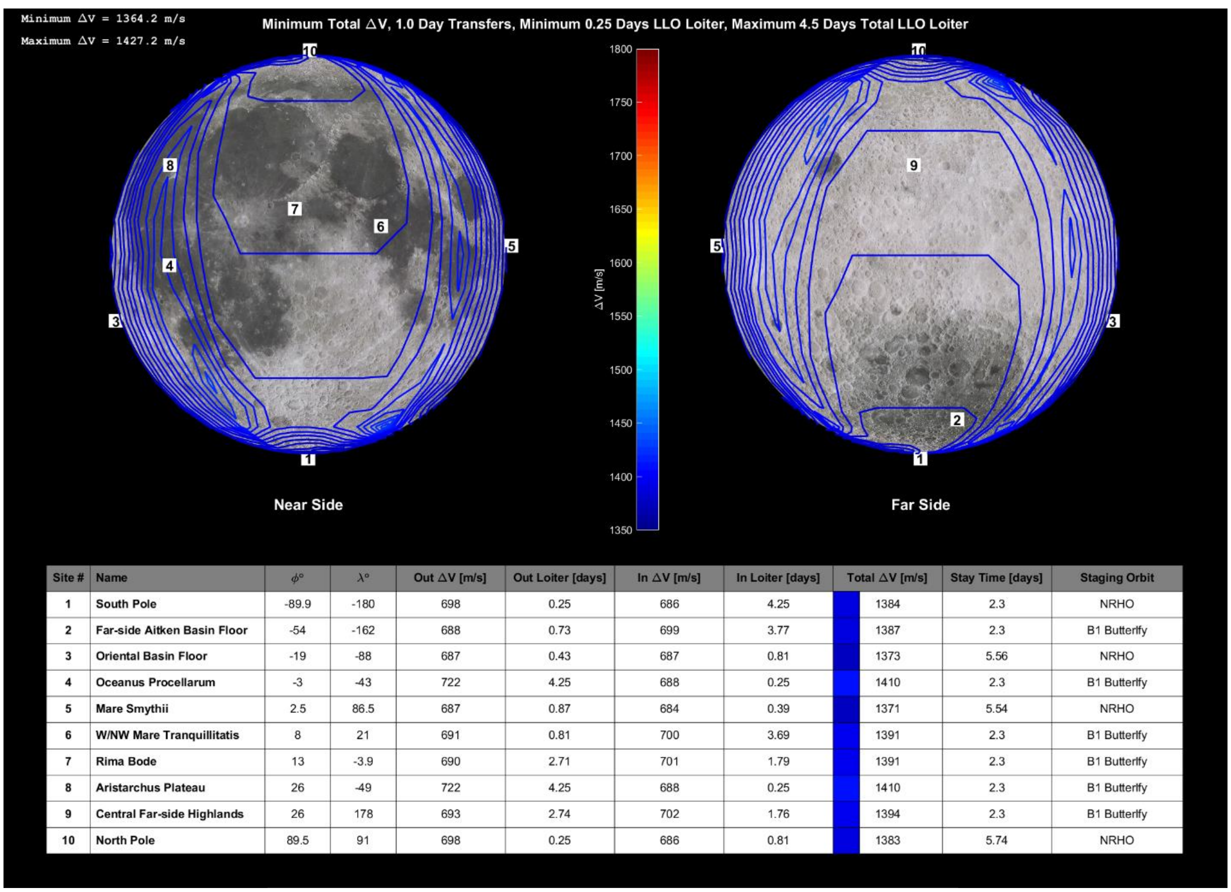
Table 5 Minimum and Maximum Total ΔVs for 1.0 Day Transfers with LLO Loiter

	1.0 Day Transfers					
	Minimum			Maximum		
	0.5 Days Loiter	4.5 Days Loiter	Reduction	0.5 Days Loiter	4.5 Days Loiter	Reduction
	ΔV	ΔV	ΔV	ΔV	ΔV	ΔV
	m/s	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
NRHO	1374	1366	8	1601	1541	60
B1 Butterfly	1367	1364	3	1562	1526	37
B2 Butterfly	1372	1371	1	1595	1561	34

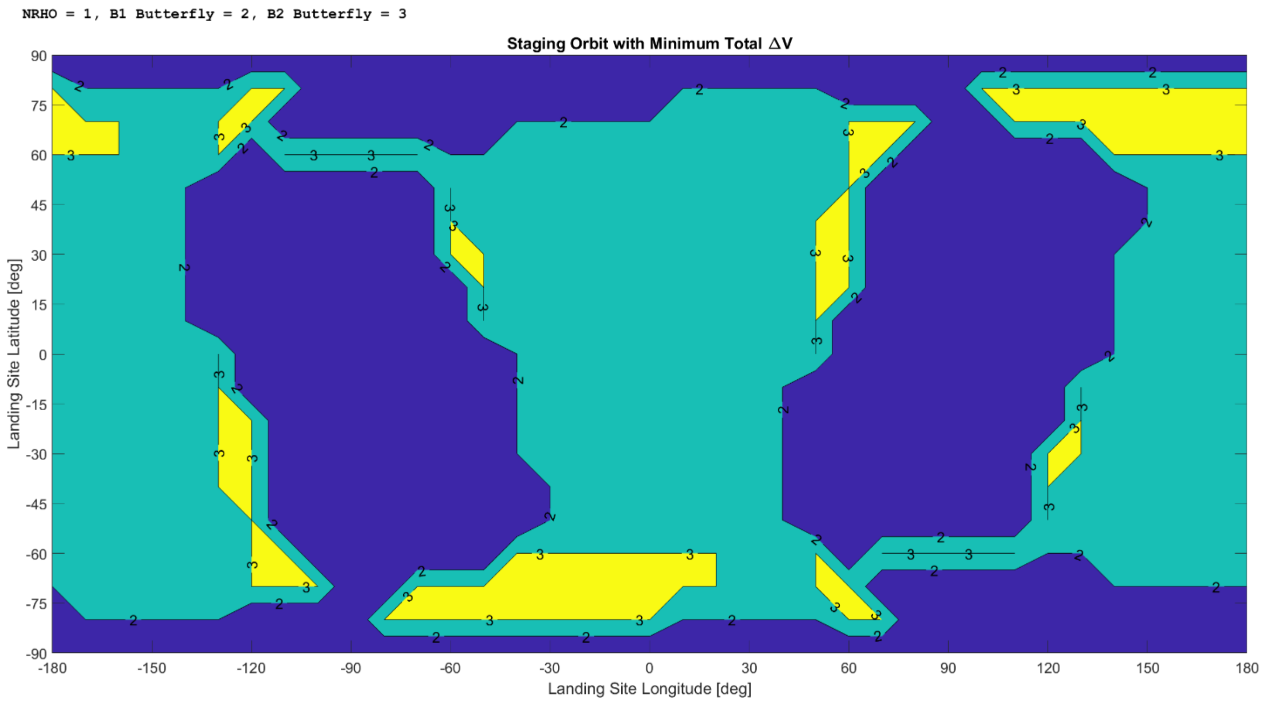
Increasing the total LLO loiter time from 0.5 to 4.5 days reduces the total maximum ΔV in all cases, while LLO loiter has minimal effect on the total minimum ΔVs. Table 5 shows the results when both ΔV mitigation strategies are fully exercised for a particular staging point. Implementing 1.0 days transfers and 4.5 total days of LLO loiter reduces the total maximum ΔV on the order of 200 m/s compared to the 0.5 day transfer with only 0.5 days of LLO loiter. Despite these reductions in the maximum total ΔV, neither staging orbit achieves global access for a total ΔV budget of 1480 m/s.

E. Minimum Total ΔV Staging Orbit

The global access problem is ultimately driven by a few challenging sites for the NRHO and butterfly orbit. These sites are not synonymous, so combining staging orbit surface access contours is a potential solution. Subject to a set of transfer time and LLO loiter time constraints, the staging orbit with the minimum round trip ΔV is obtained for each point on the surface. Figure 10 shows the minimum total ΔV contour for 1.0 day transfers, up to 4.5 total days LLO loiter, and utilizing both staging orbits.



(a) Global Access ΔV Contour using Optimal Staging Orbit



(b) Optimal Staging Orbit

Fig. 10 Minimum Global Access for 1.0 Day Transfers and 4.5 Days Total LLO Loiter

Global access is achievable for our reference ΔV budget if 1.0 day transfers are used, 4.5 days of total LLO loiter is allowed, and the optimal staging orbit is used for each site. In this scenario, the NRHO is the best option for accessing the lunar rims and poles, B1 for the equatorial regions along the Earth-Moon line, and B2 for very specific regions. Table 6 summarizes the minimum global access results for each combination of transfer time and total LLO loiter time.

Table 5 Minimum and Maximum Total ΔVs for 1.0 Day Transfers with LLO Loiter

Global Access using Optimal Staging Orbit		
	Minimum *Total ΔV* *m/s*	Maximum *Total ΔV* *m/s*
0.5 D Transfers, 0.5 D Loiter	1394	1578
0.5 D Transfers, 2.5 D Loiter	1393	1544
0.5 D Transfers, 4.5 D Loiter	1393	1487
1.0 D Transfers, 0.5 D Loiter	1367	1483
1.0 D Transfers, 2.5 D Loiter	1364	1458
1.0 D Transfers, 4.5 D Loiter	1364	1427

V. Conclusion

NASA's Gateway in cis-lunar space is critical for enabling sustainable human exploration to the Moon, Mars, and other deep space destinations. Gateway will serve as a two-way staging point for a Human Landing System to deliver astronauts to the lunar surface by 2024. The program has selected a 9:2 L2 southern NRHO as the operational orbit and, among many advantageous features, is ideal for Lunar South Pole missions. However, its fixed orientation in the Earth-Moon rotating frame does not lend to accessing the entire lunar surface. This investigation studied a butterfly orbit, comparable to Gateway's NRHO, as an alternative staging point to reduce surface access costs. The butterfly orbit can reduce the access to specific lunar regions, but at the expense of the time and fuel Gateway requires to maneuver into this alternative orbit. Increasing the Gateway outbound and inbound transfer times and exploiting loitering in LLO proved to be effective ΔV mitigation strategies but also come at the cost of increased time of flight or reduced surface stay time respectively. If all mitigation strategies are exercised, global surface access costs can be significantly reduced. An expansion of the analyses here might include not requiring the outbound and inbound transfer times to be equal, quantifying anytime abort costs for each landing site solution, and maximizing each site's surface stay time for a given ΔV budget.

Appendix

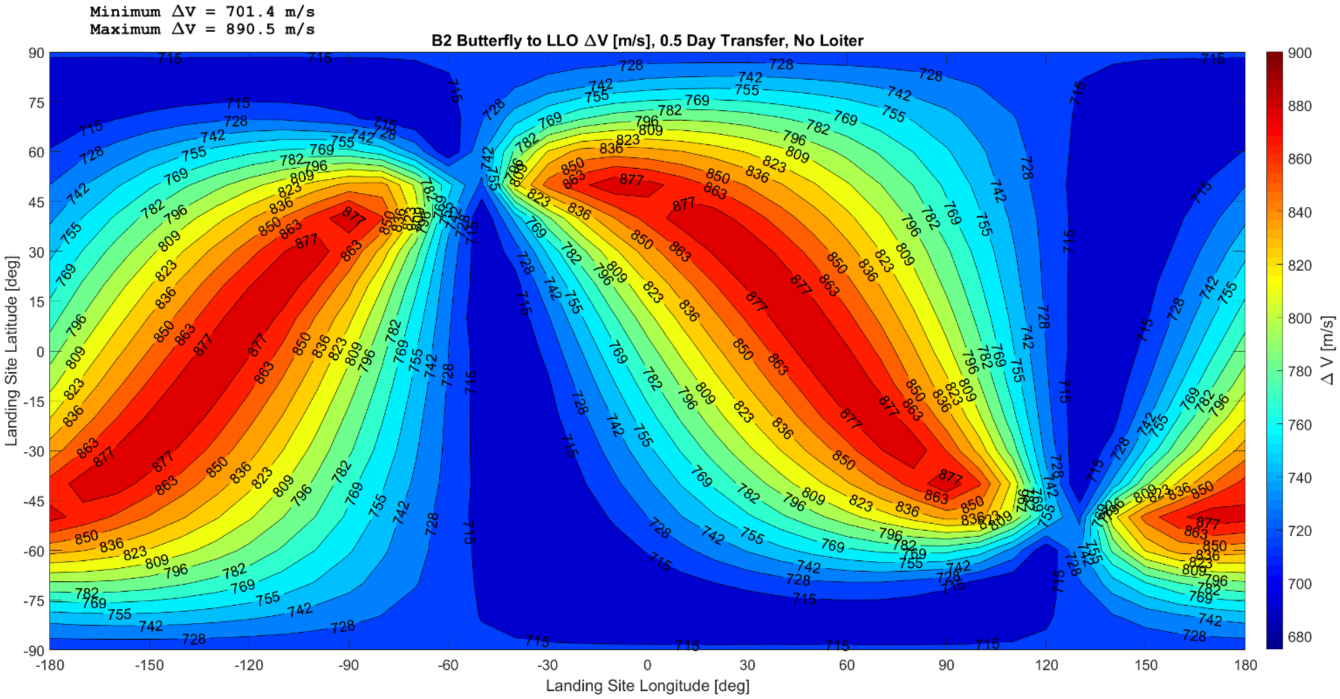


Fig. 11 B2 0.5 Day Outbound Transfer ΔVs

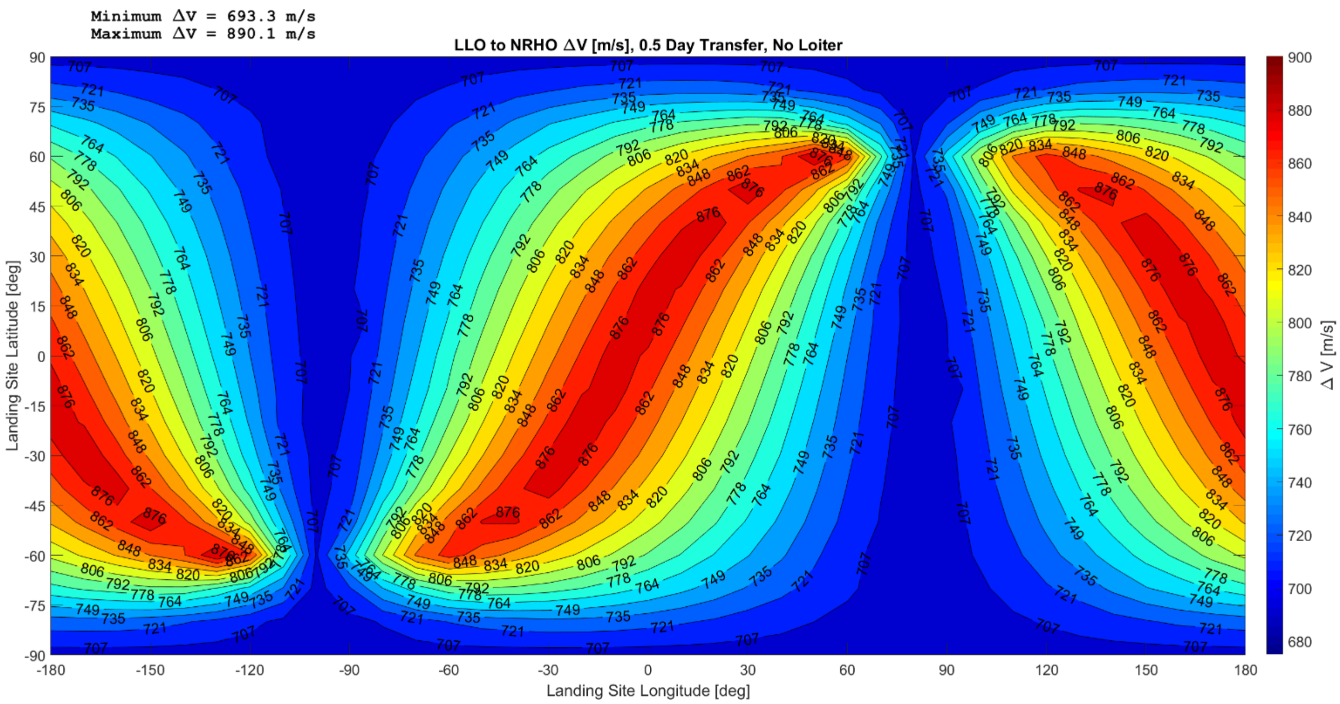


Fig. 12 NRHO 0.5 Day Inbound Transfer ΔVs

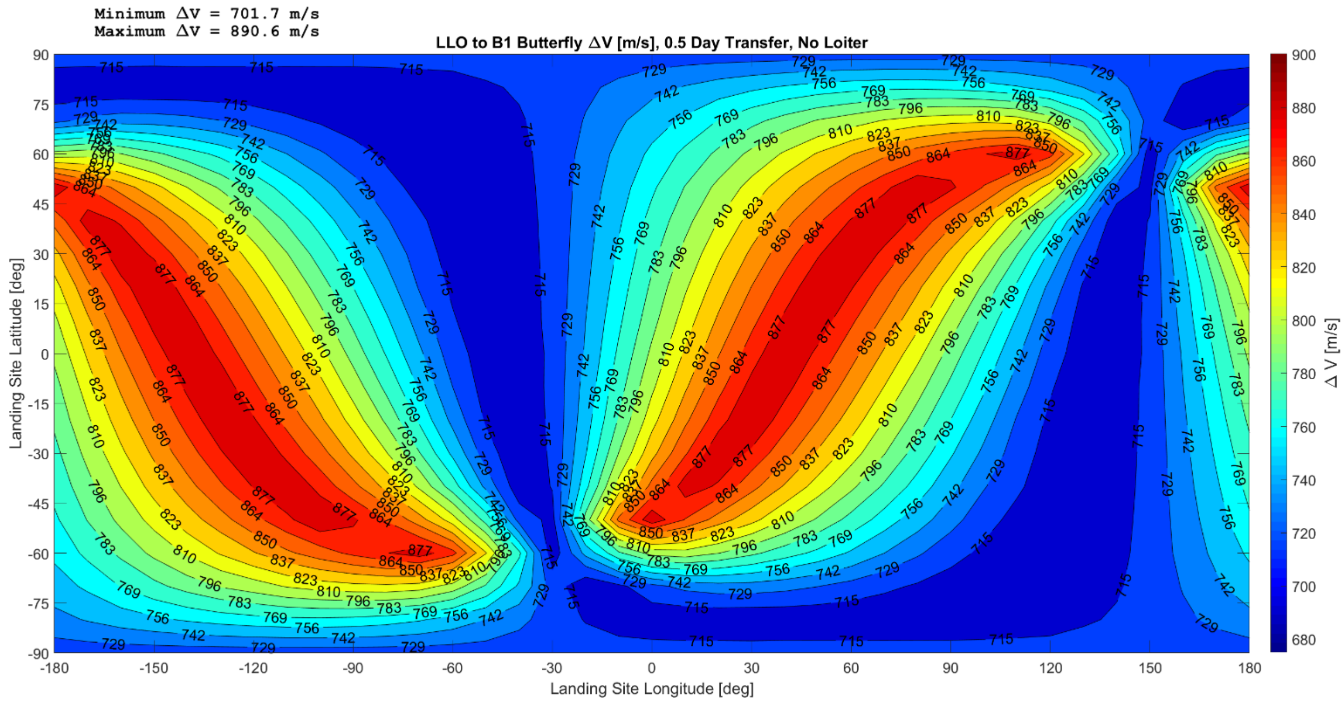


Fig. 13 B1 0.5 Day Inbound Transfer ΔVs

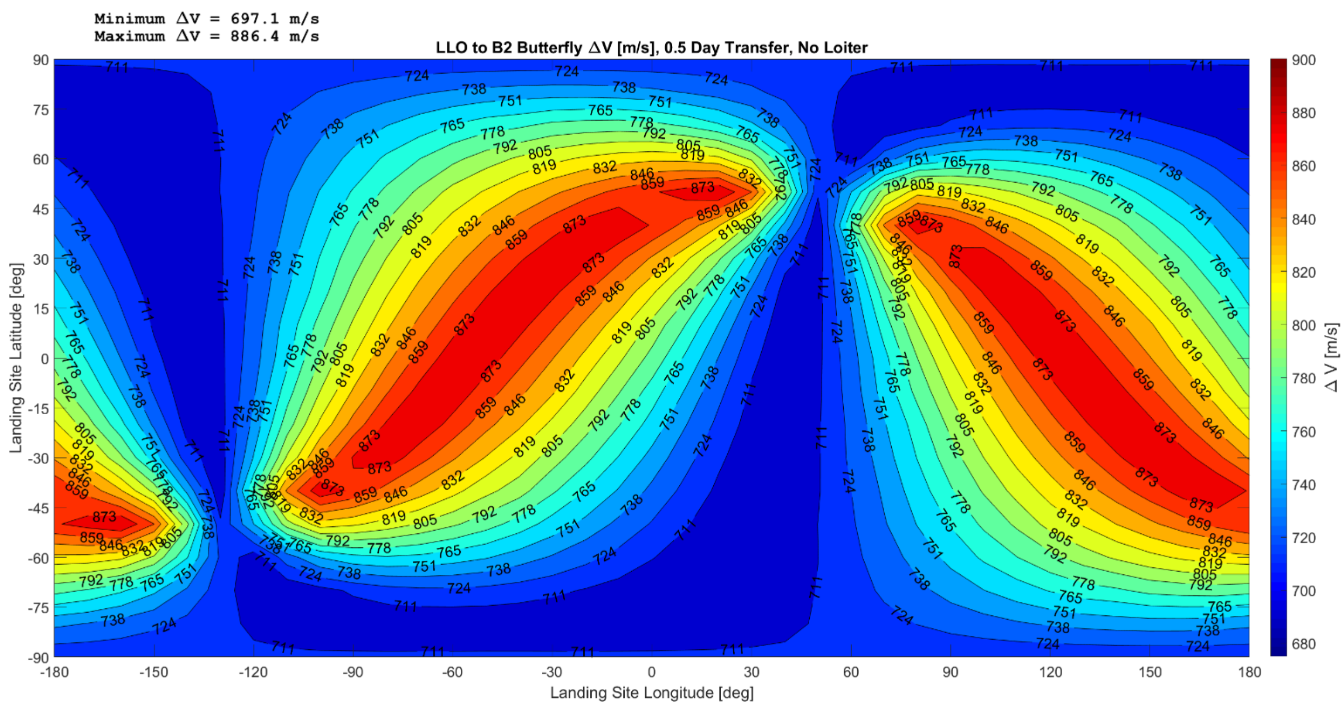


Fig. 14 B2 0.5 Day Inbound Transfer ΔVs

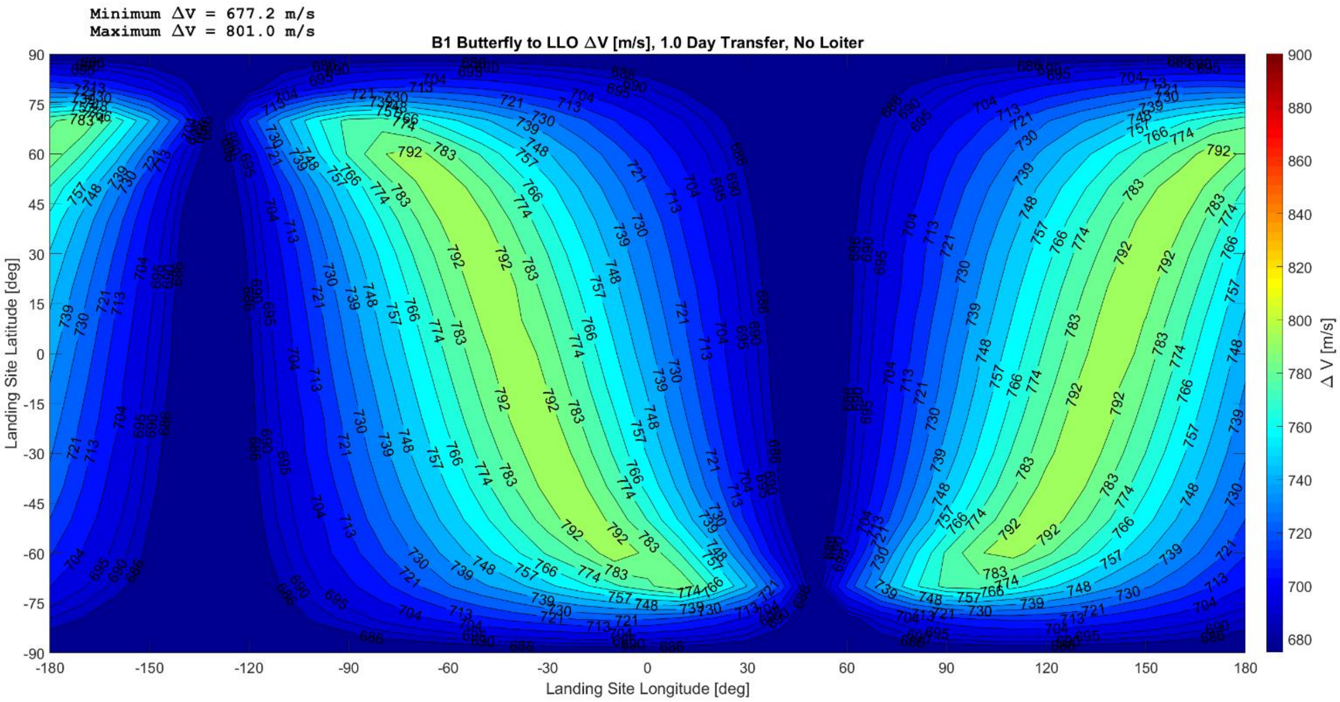


Fig. 15 B1 1.0 Day Outbound Transfer ΔVs

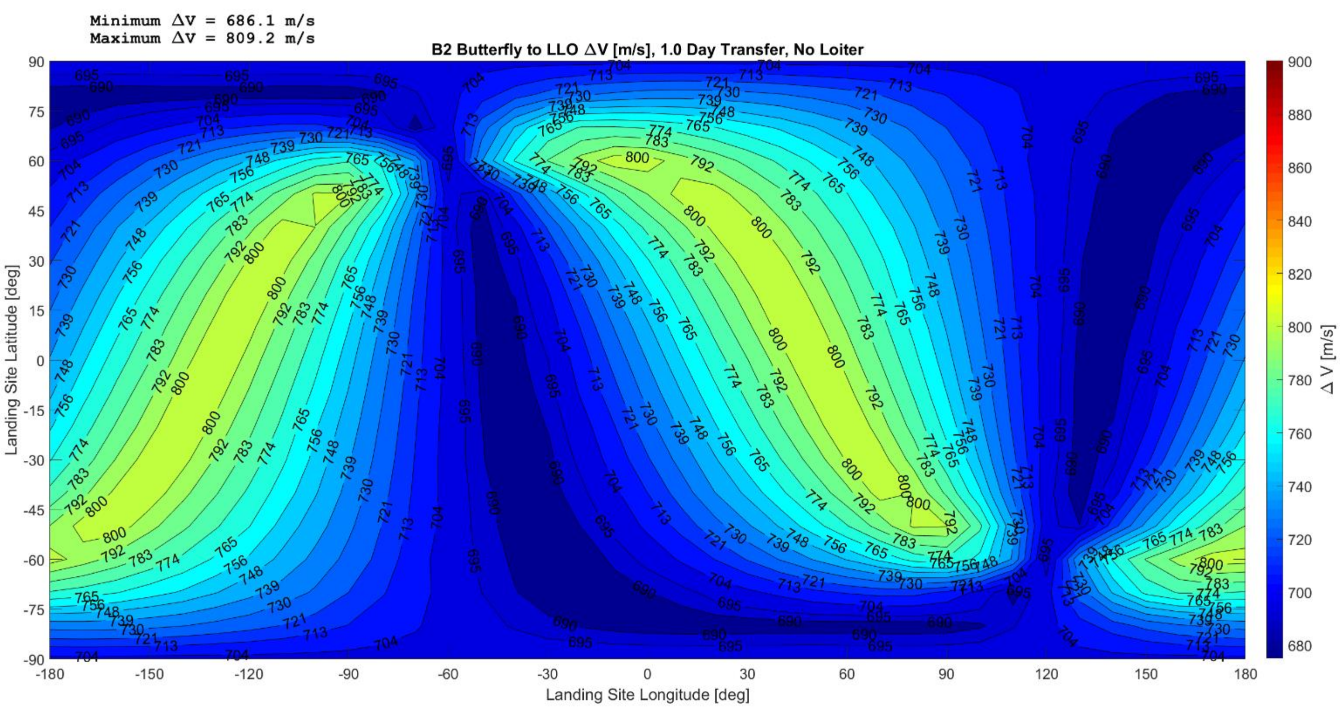


Fig. 16 B2 1.0 Day Outbound Transfer ΔVs

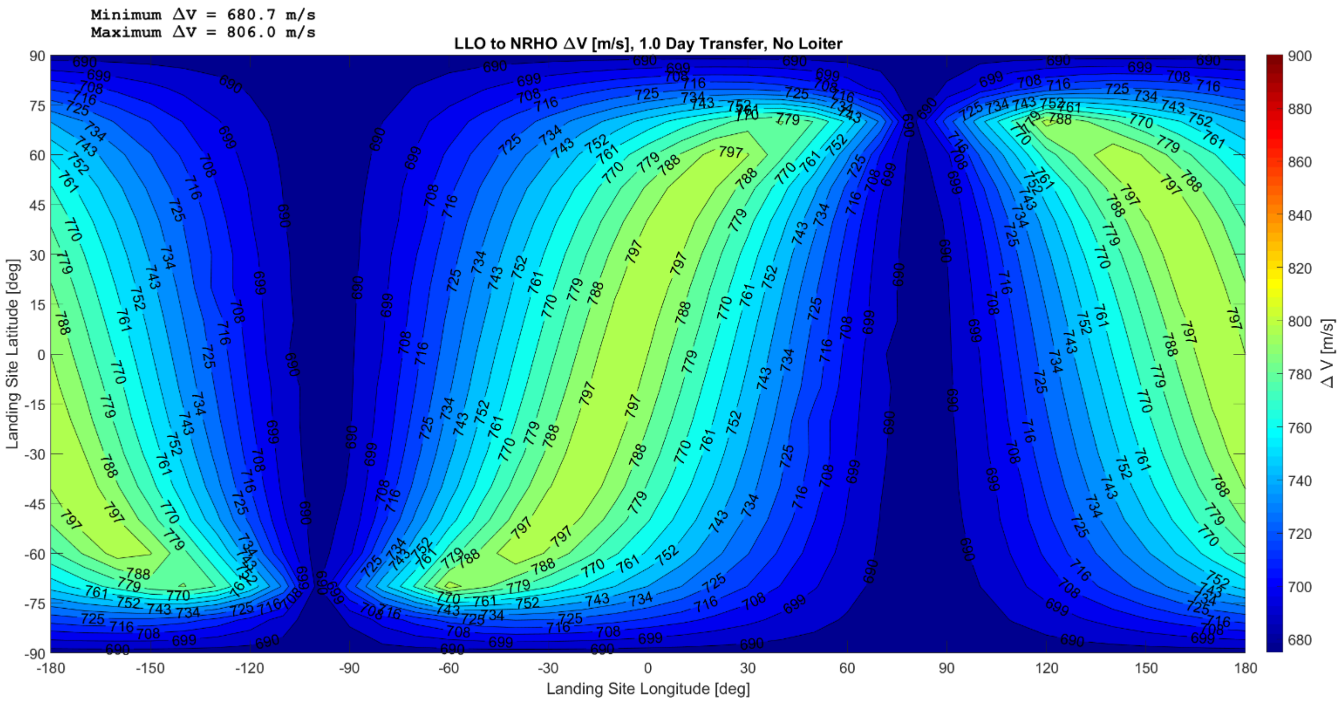


Fig. 17 NRHO 1.0 Day Inbound Transfer ΔVs

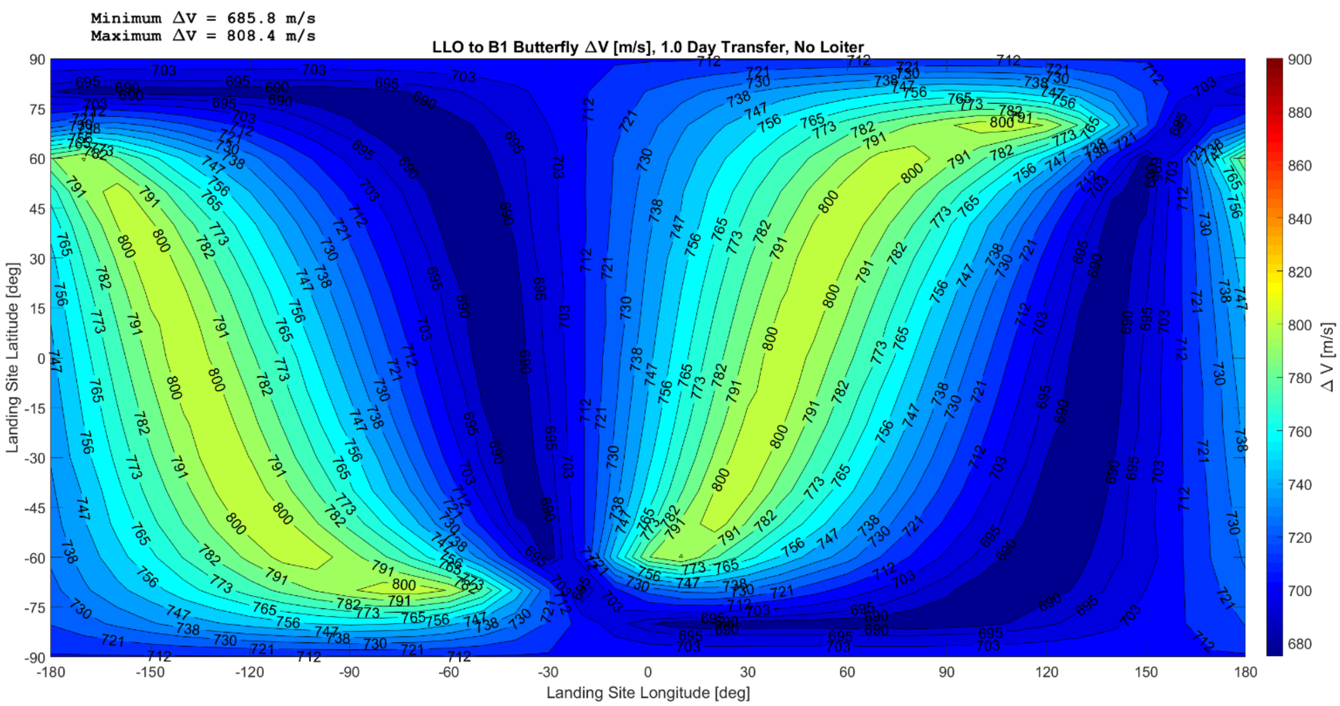


Fig. 18 B1 1.0 Day Inbound Transfer ΔVs

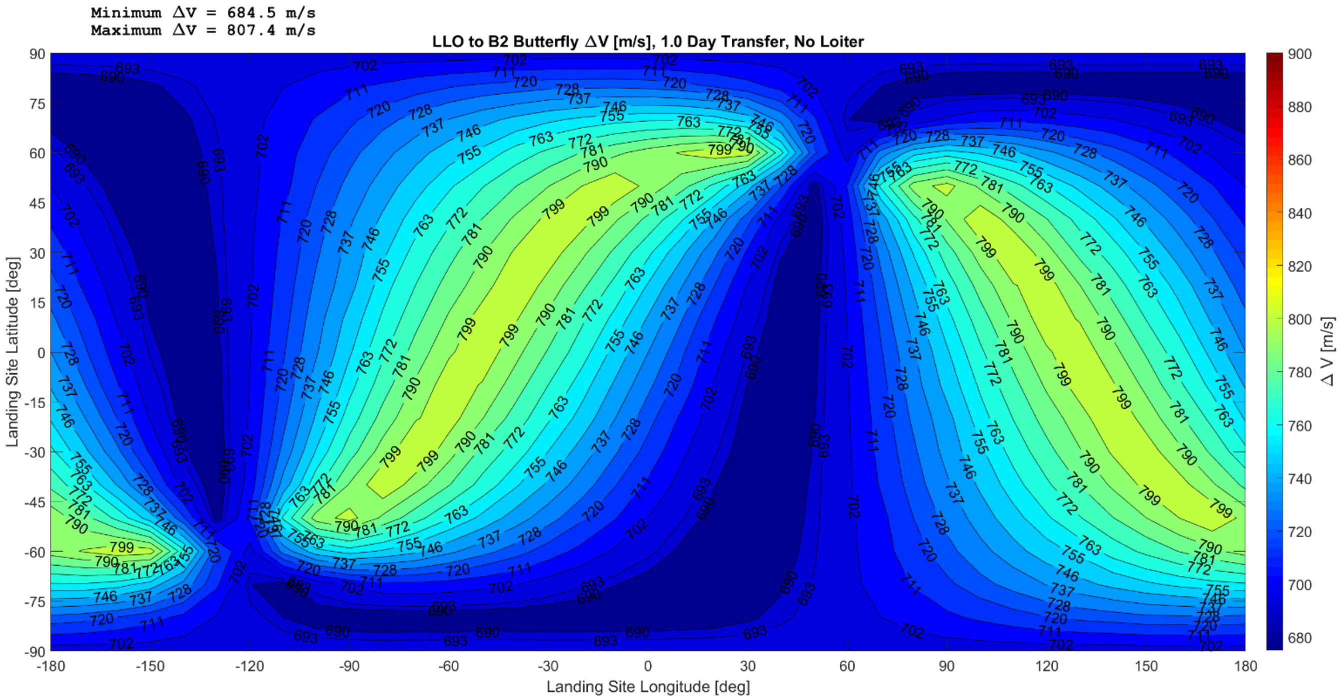
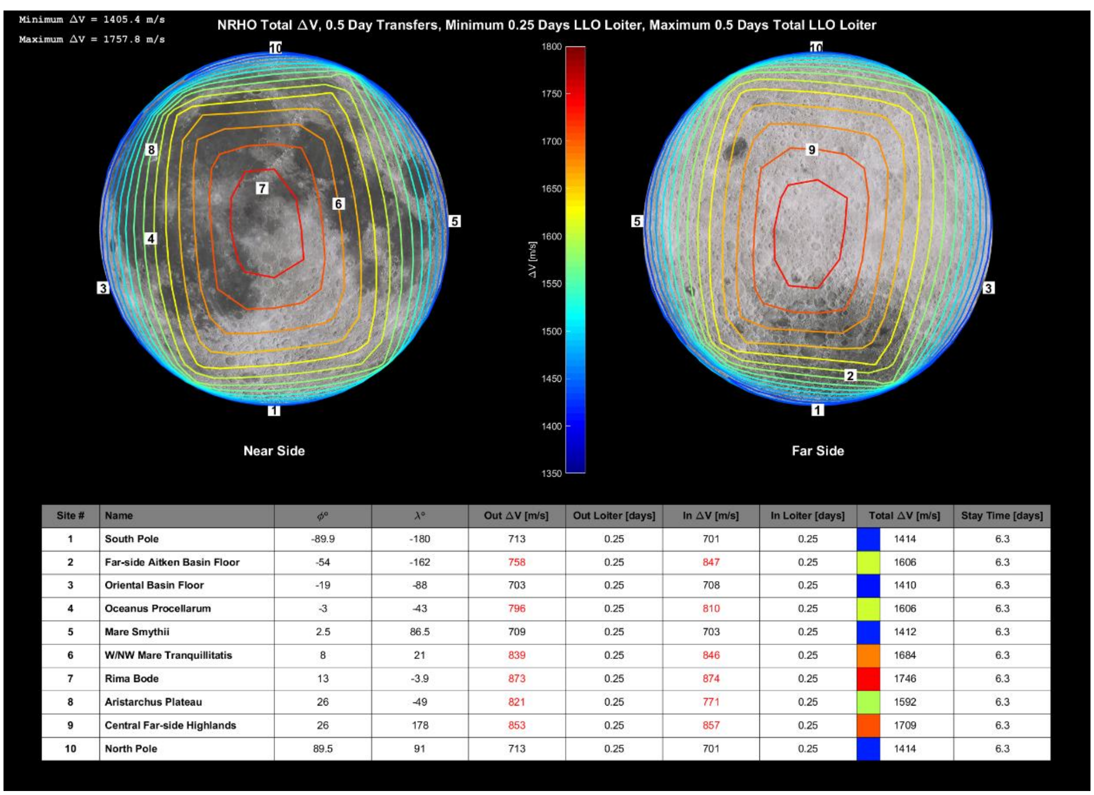
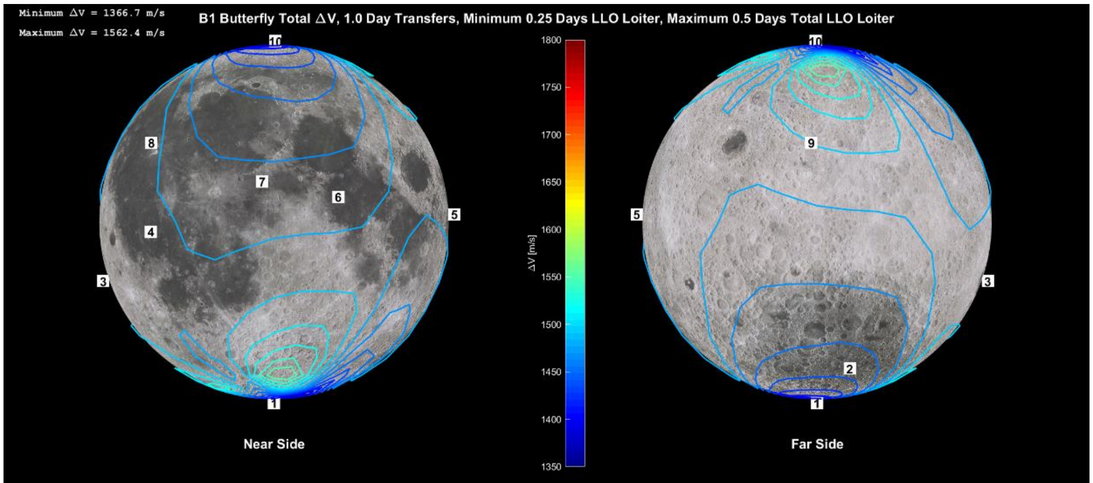


Fig. 19 B2 1.0 Day Inbound Transfer ΔVs



Site #	Name	$\phi°$	$\lambda°$	Out ΔV [m/s]	Out Loiter [days]	In ΔV [m/s]	In Loiter [days]	Total ΔV [m/s]	Stay Time [days]
1	South Pole	-89.9	-180	713	0.25	701	0.25	1414	6.3
2	Far-side Aitken Basin Floor	-54	-162	758	0.25	847	0.25	1606	6.3
3	Oriental Basin Floor	-19	-88	703	0.25	708	0.25	1410	6.3
4	Oceanus Procellarum	-3	-43	796	0.25	810	0.25	1606	6.3
5	Mare Smythii	2.5	86.5	709	0.25	703	0.25	1412	6.3
6	W/NW Mare Tranquillitatis	8	21	839	0.25	846	0.25	1684	6.3
7	Rima Bode	13	-3.9	873	0.25	874	0.25	1746	6.3
8	Aristarchus Plateau	26	-49	821	0.25	771	0.25	1592	6.3
9	Central Far-side Highlands	26	178	853	0.25	857	0.25	1709	6.3
10	North Pole	89.5	91	713	0.25	701	0.25	1414	6.3

Fig. 20 NRHO 0.5 Day Transfers and 0.5 Days LLO Loiter Total ΔVs



Site #	Name	$\phi°$	$\lambda°$	Out ΔV [m/s]	Out Loiter [days]	In ΔV [m/s]	In Loiter [days]	Total ΔV [m/s]	Stay Time [days]
1	South Pole	-89.9	-180	678	0.25	711	0.25	1389	6.3
2	Far-side Aitken Basin Floor	-54	-162	694	0.25	750	0.25	1444	6.3
3	Oriental Basin Floor	-19	-88	733	0.25	753	0.25	1486	6.3
4	Oceanus Procellarum	-3	-43	796	0.25	688	0.25	1484	6.3
5	Mare Smythii	2.5	86.5	730	0.25	752	0.25	1482	6.3
6	W/NW Mare Tranquillitatis	8	21	701	0.25	772	0.25	1473	6.3
7	Rima Bode	13	-3.9	738	0.25	730	0.25	1468	6.3
8	Aristarchus Plateau	26	-49	795	0.25	688	0.25	1482	6.3
9	Central Far-side Highlands	26	178	752	0.25	741	0.25	1493	6.3
10	North Pole	89.5	91	679	0.25	713	0.25	1392	6.3

Fig. 21 B1 1.0 Day Transfers and 0.5 Days LLO Loiter Total ΔVs

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An appendix, if needed, should appear before the acknowledgments.