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HUMAN LANDING SYSTEM (HLS) PROGRAM WHITE PAPER: INITIAL EVALUATION OF NON-POLAR ACCESS IMPLICATIONS FOR THE HUMAN LANDER SYSTEM

REVISION AND HISTORY PAGE

Revision No.	Change No.	Description	Release Date
-		Released with Appendix N RFP Attachment C4.1	06/29/21
A		Released with Sustaining RFP	02/03/22
B		Updated formatting, changed Figure 14	03/29/22
C		Updated Figures 6-8 with higher resolution plots	06/08/22

National Aeronautics and Space Administration (NASA)

White Paper:
Initial Evaluation of Non-Polar Access Implications for the Human Lander System

June 3, 2022

Introduction

Expanded lunar surface access beyond the south pole is a goal of the Sustainable Phase of NASA's HLS program. There are several unique mission and vehicle design challenges associated with this goal and the NASA HLS team has performed a preliminary evaluation of those challenges as part of the HLS program formulation effort. A qualitative evaluation of environmental variations and their impacts on vehicle design was performed. Additionally, a preliminary investigation of trajectory design implications was completed, outlining the relationships between timing, starting orbit, feasible surface stay durations, and mission ∆V profile. The results of this investigation are provided in this paper. Although the focus of this paper is on non-polar access, the results and data are generally inclusive of the poles, thus the term "global", instead of "non-polar", is used throughout the narrative.

Qualitative Overview of Potential Design Impacts

Environmental Variation

The environment on the lunar surface varies significantly from location to location. In addition to variations in surface features, landing site latitude will greatly affectthe solar cycle at the various landing sites. At the poles, the sun appears to sit very low along the horizon. The sun at "lunar noon" will appear higher as sites approach the equator, with "lunar noon" solar position directly overhead in equatorial regions.

The variation in solar angle results in variations in thermal environments and solar power availability as a function of landing site latitude. Both albedo and infrared thermal heat sources will fluctuate as a function of the local solar angle. Table 1 shows the monthly average temperatures and variation of various surface locations on the Moon [1]. While polar regions, which are the focus of the early lunar sortie missions, have relatively little variation because of the low sun angle, lower latitude regions exhibit both higher average temperatures and greater variation over a given month due to the passage of the sun overhead. Overhead sunlight also increases albedo thermal loads due to reflected energy while low sun angles at the poles will promote uneven direct solar heating on spacecraft surfaces with the illuminated side being warmer than the opposite side, which will be facing deep space. Therefore, while average temperatures remain lower at the poles, the uneven heat load on the spacecraft may present a different set of design challenges.

Table 1. Lunar Surface Temperature Mean and Extremes as a Function of Landing Location

Location	Mean Temperature K	1 Sigma Max or Min Temp K	Solar conditions
Equatorial maximum	391	394	Local noon
Equatorial minimum	96	94	Before sunrise
45 degree latitude maximum	350	357	Local noon
45 degree latitude minimum	89	83	Before sunrise
85 degree latitude maximum	182	224	Local noon
85 degree latitude minimum	61	41	Approx. 3am equivalent
Coldest permanently shadowed crater	18		

Figure 1 [1] illustrates the variability of surface temperature with latitude and local solar time.

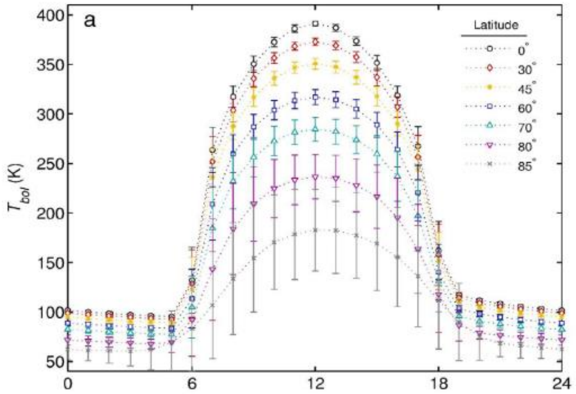
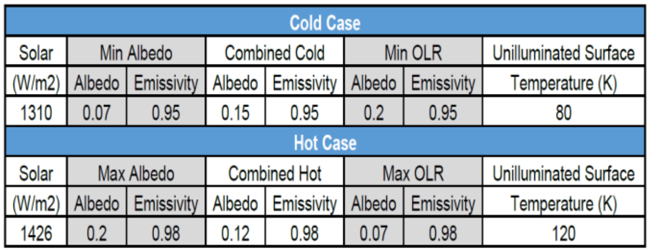


Figure 1. Zonal Bolometric temperature as a function of latitude and 24-hour equivalent local solar time [1].

Calculations of thermal performance are normally done for the extreme hot and cold cases which should use the combinations of albedo, emissivity and temperature given in Table 2 [2] with the maximum temperatures expected at a given latitude following the procedure described in [2] section 4.3.1. For cases where the maximum temperature at intermediate latitudes is needed, the algorithm given in [2] section 4.3.1 may be used for lower latitudes. The temperatures in Table 1 should be used for the polar regions.

Table 2. Lunar Outgoing Long-wave Radiance (OLR), Albedo and Emissivity Equation Inputs [2]



Cold Case							
Solar	Min Albedo		Combined Cold		Min OLR		Unilluminated Surface
(W/m2)	Albedo	Emissivity	Albedo	Emissivity	Albedo	Emissivity	Temperature (K)
1310	0.07	0.95	0.15	0.95	0.2	0.95	80
Hot Case							
Solar	Max Albedo		Combined Hot		Max OLR		Unilluminated Surface
(W/m2)	Albedo	Emissivity	Albedo	Emissivity	Albedo	Emissivity	Temperature (K)
1426	0.2	0.98	0.12	0.98	0.07	0.98	120

The same solar angle variability that causes thermal variations will also impact power availability for photovoltaic power generation systems. Solar incident angles and sun location will change depending on the latitude of the selected landing site.

Lander and Mission Design Impacts due to Environmental Variation

Surface feature variability may impact the design and operation of landing guidance and hazard avoidance systems. Most notably, the spatial resolution of surface features is higher for the Lunar South Pole, based on Lunar Reconnaissance Orbiter data, than it is for mid and low latitude regions. Sun angles and shadowing will also be different in the mid and low latitude regions than it is at the Lunar South Pole. While this is not anticipated to have a design impact on the sensor suite used to support lunar landing guidance and navigation, it is worth noting that the data resolution and operating environment may differ from the initial missions.

The variation in solar angle will have impacts to vehicle thermal and power system designs. To track the sun during the surface stay, the degrees of freedom and ranges of the solar array gimbals will be different for mid and low latitude sites compared to the Lunar South Pole. For sites near the equator, the sun will appear to pass directly overhead at “lunar noon” which may require solar arrays to lay horizontal with respect to the lunar surface in order to maximize solar incidence angle on the arrays. In addition to a different gimbal axis than arrays designed to track the sun as it passes along the horizon at polar locations, this also means that lunar regolith may be more likely to collect on the arrays due to their horizontal configuration. The back of the arrays will also have a large view factor to the lunar surface and the reflected sunlight and emitted infrared radiation will heat them and reduce their performance.

Thermally, the lander will be required to survive at higher temperatures as sites are selected further away from the poles. Polar regions on the Moon experience average temperatures of 220K with a very narrow variance of +/-10K. Mid and low latitude sites can see temperatures upto 256K and variances in excess of +/-100K depending onthe solar angle. With lunar day/night cycles lasting 29.5 days, surface stay duration will be a key determining factor in the thermal control impacts of landing site latitude. With maximum 6.2 day surface stay, it may be challenging to avoid the "lunar noon" solar irradiance and the lander may need to be capable of operating in temperatures in excess of 166K greater than those required by the polar sortie missions.

Flight Mechanics Impacts of Expanded Surface Access

Overview of Flight Mechanics Investigation

In previous mission analyses, the HLS Program had considered polar sortie missions with 0.5 day transits between an L2 9:2 resonant Near Rectilinear Halo Orbit (NRHO) and a Low Lunar Orbit (LLO) phasing orbit. The general mission profile has the Integrated Lander departing the Gateway in NRHO, transiting for 0.5 days to LLO, loitering in LLO for 0.25 days (3 revs) and then proceeding to land. After completion of the nominal 6 day surface mission, the crew would return to LLO, loiter for 0.25 days, transit from LLO to NRHO for 0.5 days and return to Gateway. This mission profile results in an approximate ΔV of 740 m/s on the transit maneuvers between NRHO and LLO.

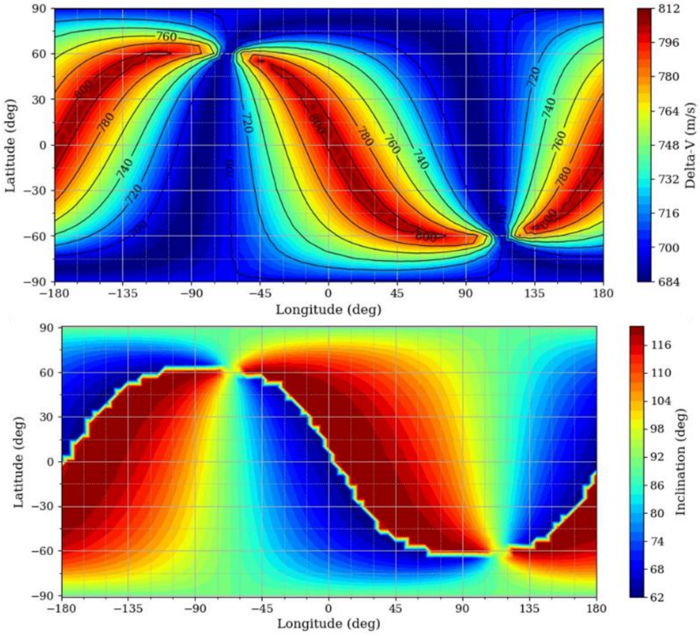


Figure 2: NRHO-LLO Transit ΔV (above) and LLO orbit inclination (below) as a Function of Landing Site

The first step in evaluating the flight mechanics challenge was to assess the transit ΔV requirements for landing sites across the lunar surface. For the purposes of this analysis, it was assumed that ΔV impacts to the descent and ascent legs of the mission would be minimal and therefore not evaluated for all landing sites. Figures 2 and 3 show the NRHO-LLO and LLO-NRHO transit ΔV requirements over the entire lunar surface. Sites with ΔV requirements at or below a nominal polar sortie case of 740 m/s are represented by the darker shades of blue showing that only ~28% of the lunar surface (mostly areas that are close to being in plane with NRHO) is accessible within the polar sortie budget and the maximum one way transfer can be as much as 890 m/s. Figure 4 shows the sum of the NRHO-LLO and LLO-NRHO ΔV requirements.

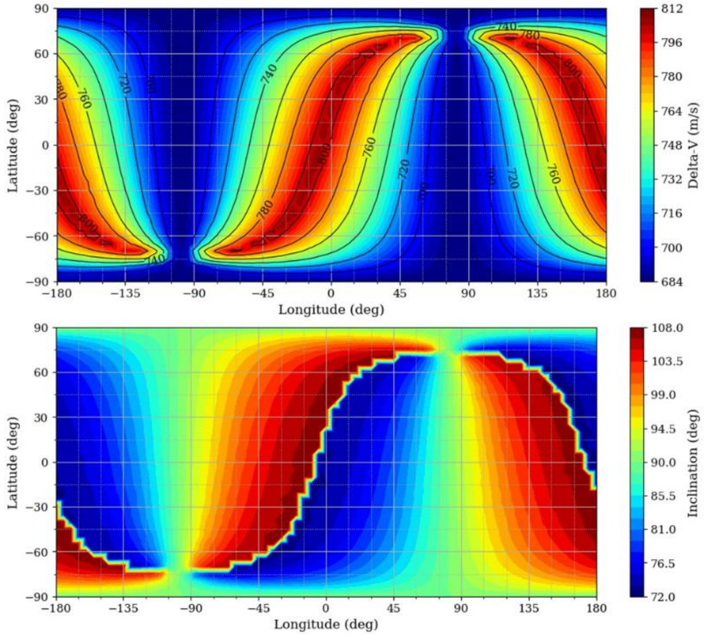


Figure 3: LLO-NRHO Transit ΔV (above) and transfer orbit inclination (below) as a Function of Landing Site

Alternatives Investigated to Increase Surface Coverage

Surface site access challenges largely stem from the fact that the NRHO maintains roughly the same orientation with respect to the Earth-Moon system at all times. While not actually an elliptical orbit around the Moon (the NRHO is actually part of a family of Lagrange Point halo orbits) it appears as a north-south elliptical orbit which always maintains a plane perpendicular to the Earth-Moon line. When planning excursions from this orbit to the lunar surface, this means that while the poles are always relatively easy to access, the mid and low latitude regions of the Moon present a significant ΔV challenge. In this preliminary investigation of expanded surface access, three mitigation strategies were evaluated to help relieve this challenge.

The first mitigation strategy was to extend the time of flight between NRHO and LLO. Generally speaking, a small reduction in transit ΔV can be achieved by increasing the time of flight. In order to truly result in a reduction in ΔV, this increase in time of flight must come through an increase in time away from the NRHO and cannot come as a function of reduced surface stay time. For the cases investigated in this study, this resulted in an approximate ΔV reduction of 10% to just over 800 m/s for the most difficult to reach sites when increasing flight time from 0.5 day each way to 1 day

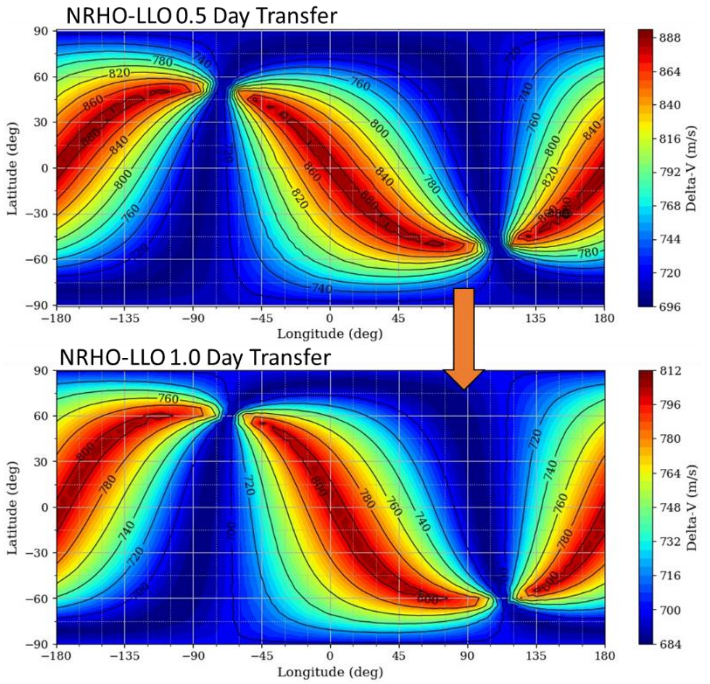
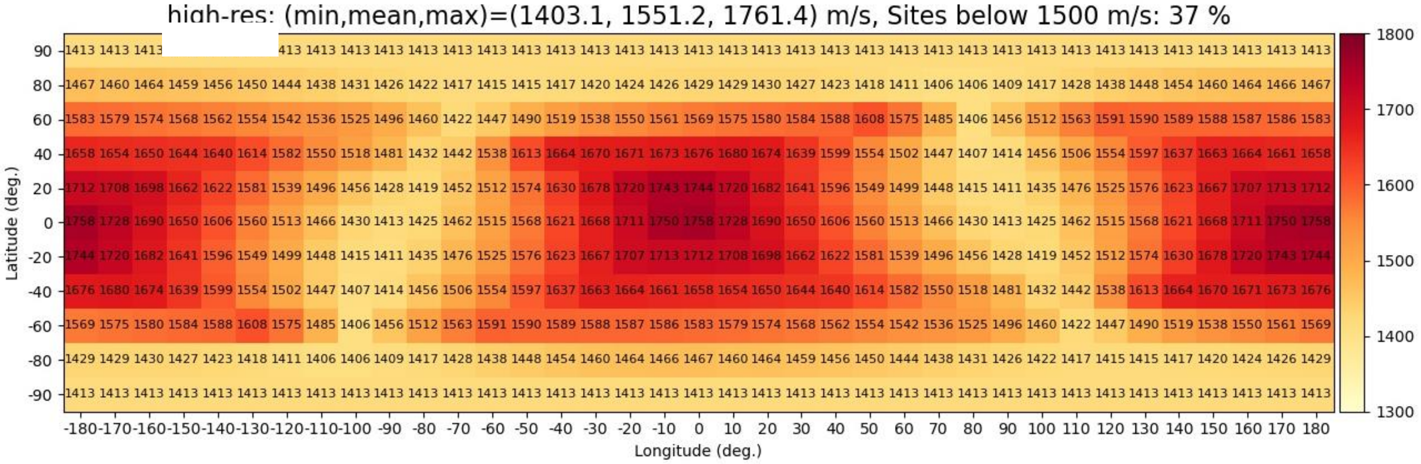


Figure 5: NRHO-LLO Transit ΔV Reductions for Longer Transit Times



	-180	-170	-160	-150	-140	-130	-120	-110	-100	-90	-80	-70	-60	-50	-40	-30	-20	-10	0
90	1413	1413	1413				413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413
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20	1712	1708	1698	1662	1622	1581	1539	1496	1456	1428	1419	1452	1512	1574	1630	1678	1720	1743	1744
0	1758	1728	1690	1650	1606	1560	1513	1466	1430	1413	1425	1462	1515	1568	1621	1668	1711	1750	1758
-20	1744	1720	1682	1641	1596	1549	1499	1448	1415	1411	1435	1476	1525	1576	1623	1667	1707	1713	1712
-40	1676	1680	1674	1639	1599	1554	1502	1447	1407	1414	1456	1506	1554	1597	1637	1663	1664	1661	1658
-60	1569	1575	1580	1584	1588	1608	1575	1485	1406	1456	1512	1563	1591	1590	1589	1588	1587	1586	1583
-80	1429	1429	1430	1427	1423	1418	1411	1406	1406	1409	1417	1428	1438	1448	1454	1460	1464	1466	1467
-90	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413

	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
90	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413
80	1429	1430	1427	1423	1418	1411	1406	1406	1409	1417	1428	1438	1448	1454	1460	1464	1466	1467
60	1575	1580	1584	1588	1608	1575	1485	1406	1456	1512	1563	1591	1590	1589	1588	1587	1586	1583
40	1680	1674	1639	1599	1554	1502	1447	1407	1414	1456	1506	1554	1597	1637	1663	1664	1661	1658
20	1720	1682	1641	1596	1549	1499	1448	1415	1411	1435	1476	1525	1576	1623	1667	1707	1713	1712
0	1728	1690	1650	1606	1560	1513	1466	1430	1413	1425	1462	1515	1568	1621	1668	1711	1750	1758
-20	1708	1698	1662	1622	1581	1539	1496	1456	1428	1419	1452	1512	1574	1630	1678	1720	1743	1744
-40	1654	1650	1644	1640	1614	1582	1550	1518	1481	1432	1442	1538	1613	1664	1670	1671	1673	1676
-60	1579	1574	1568	1562	1554	1542	1536	1525	1496	1460	1422	1447	1490	1519	1538	1550	1561	1569
-80	1460	1464	1459	1456	1450	1444	1438	1431	1426	1422	1417	1415	1415	1417	1420	1424	1426	1429
-90	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413	1413

Figure 4: Sum of NRHO-LLO and LLO-NRHO DV

each way, as shown in Figure 5. While this option does help increase surface access, time of flight cannot be increased too much, or little time will be left for the required crew operations at Gateway to prepare their vehicles for flight, be it the HLS on the way to the Moon or Orion for the flight back to Earth. The second mitigation strategy was to increase loiter time in LLO. Once the transition to LLO is complete, the spacecraft is now stationed in a more traditional lunar orbit. While Gateway maintains a relatively consistent ground track over the Moon, the ground track of an LLO will shift by approximately 13° per day of loiter, predominately due to the Moon’s self-rotation, with slight variations from orbit nodal precession. The inclination of the optimized LLO can be anywhere between 60° to 120° depending on the landing site. While this does not reduce the magnitude of the ΔV profiles shown in Figures 2 and 3, it does shift their locations on the lunar surface. Depending on how long a spacecraft loiters in LLO, this may be enough of a shift to place the regions of lower ΔV in alignment with the landing site of interest. This is exhibited in Figure 6 where two landing sites, Site X and Site Y, are depicted both before and after the loiter periods. Site X appears to shift into a region of lower transit ΔV over several days of LLO loiter time. SiteY, on the other hand, actually shifts into a region of higher ΔV, showing that this solution is very site specific. The drawback to this approach is that loiter time in LLO cuts into the surface stay time, resulting in less time for EVA science on the lunar surface.

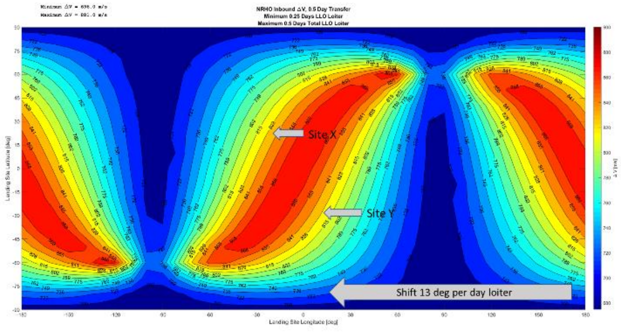


Figure 6: NRHO-LLO Transit ΔV Profile Shift using LLO Loiter

The third mitigation strategy is to employ an alternative staging orbit for expanded sortie missions. While the initial polar sortie missions will be staged from the NRHO, the Gateway PPE is capable of maneuvering the Gateway into some alternative orbits. One orbit alternative that proves to be useful for enabling expanded access with minimal ΔV impact to the lander is the Butterfly orbit. This orbit is described in detail in reference [3]. In general, the Butterfly orbits are stable like NRHO orbits. However, they possess two lobes wrapping around the Moon. By taking advantage of one of these lobes, the transit ΔV can be reduced for a certain sub-set of desirable landing sites. The specific Butterfly orbit investigated in this study is one that is accessible by Orion and one that Gateway can maneuver into from its standard NRHO parking orbit. To execute a mission in this scenario, the lander would be moved into this Butterfly orbit using the Gateway. The crew would rendezvous with Gateway in the Butterfly orbit rather than the NRHO and execute the surface mission in a similar manner to the other alternatives investigated. The resulting shift in transit ΔV profile is shown in Figure 7. While this can be an effective method for managing ΔV and achieving expanded access, additional Gateway propellant usage and maneuvering time must be accounted for.

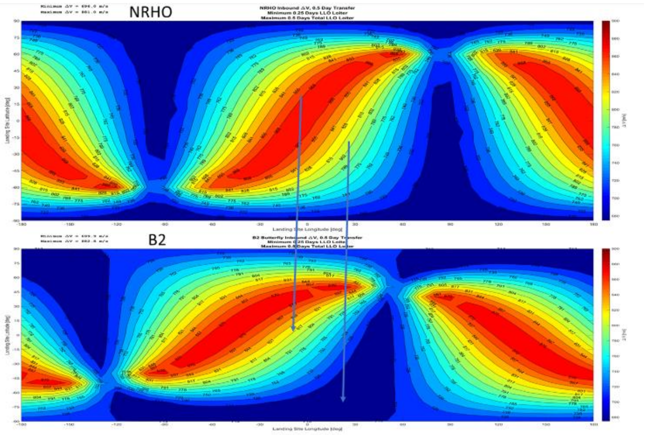


Figure 7: NRHO- LLO Transit ΔV Profile Shift using Butterfly Orbits

Combined Strategies for Expanded Surface Access

Of the three strategies investigated, no single alternativecan reduce the ΔV requirements to the level of the nominal polar sortie mission. However, by employing combinations of mitigation strategies, global access with polar sortie ΔV budget is achievable. Figure 8 shows the Staging Orbit to

LLO and LLO to Staging Orbit transit ΔV budgets when all three mitigation strategies are evaluated together. Figure 9 shows the NRHO-LLO and LLO-NRHO transit ΔV budgets when employing a combination of increased transit time of flight (up to 1 day each way) and additional LLO loiter (up to 4.5 days of outbound and inbound combined). Global access in this scenario is achievable with an increase in transit ΔV from the polar sortie value of 740 m/s to 800 m/s each way or a combined total ΔV of 1550 m/s. While the ΔV reduction is not as profound, this scenario does avoid the use of Butterfly orbits, simplifying the overall mission profile.

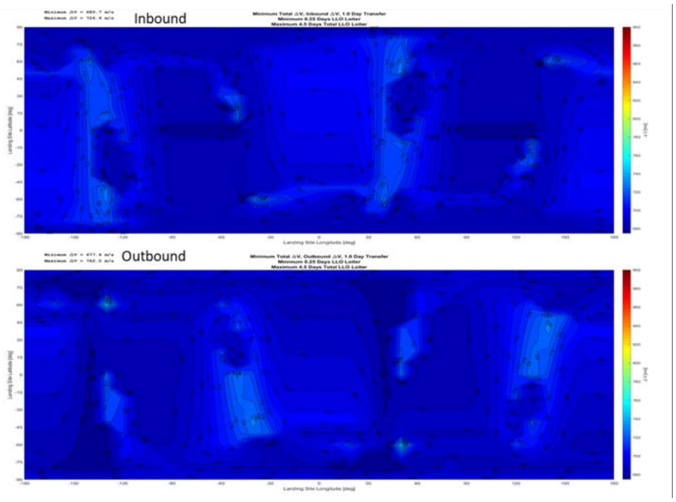


Figure 8: Transit ΔV Profiles using all Three Mitigation Strategies

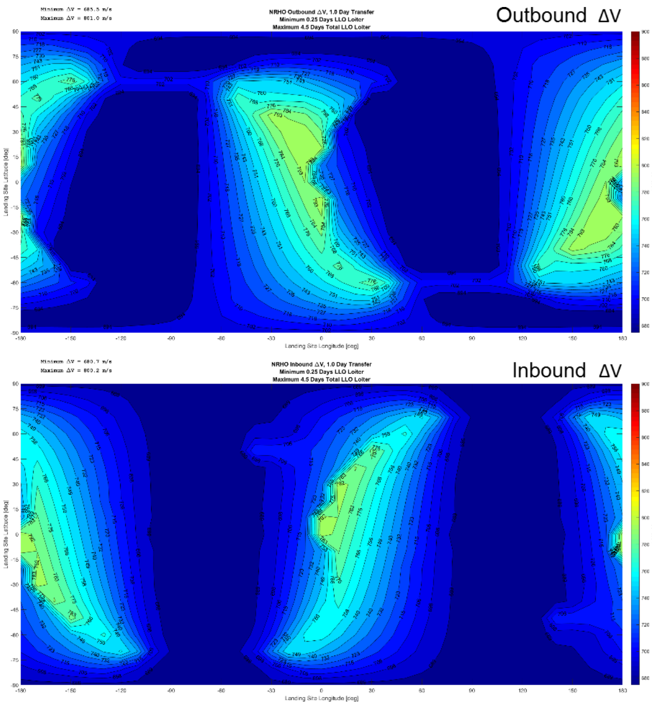


Figure 9: Transit ΔV Profiles using Combination of increased Time of Flight and Increased LLO Loiter

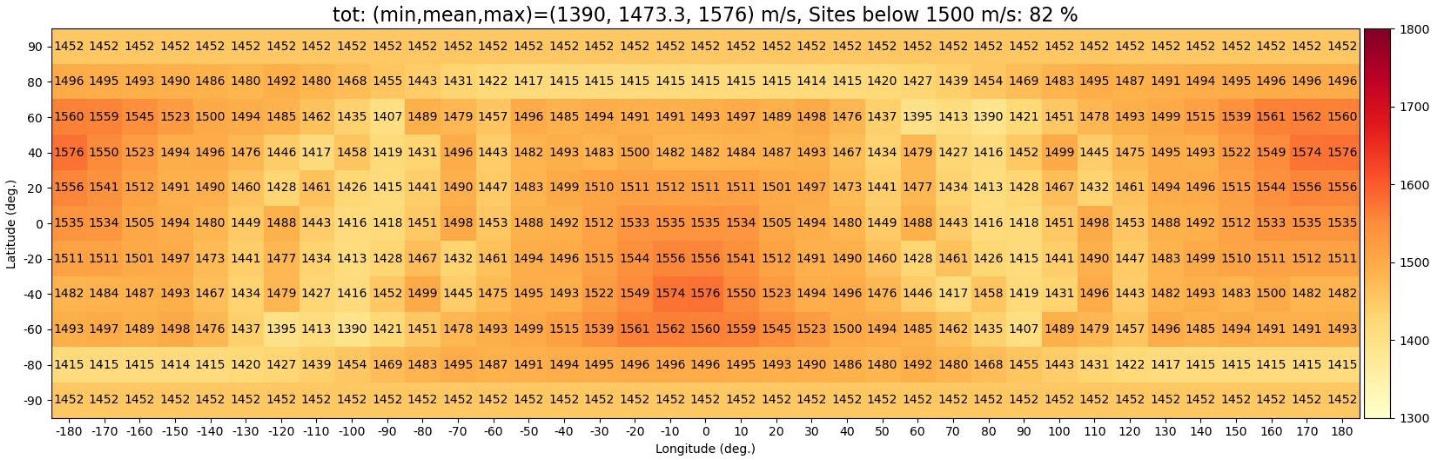
Figures 10-12 show the global access heat maps of the combined transit ΔV, surface stay duration, and the total duration from NRHO departure to NRHO injection after completing the surface mission. These estimates are generated by using the transit durations either 0.5 or 1 day long as well as optimizing the total number of LLO loiter revs between 2 (~0.2 day) and 48 (~4 days). The maximum combined transit ΔV for global access is estimated to be 1576 m/s for this case with 82% of the lunar surface requiring combined transit ΔV below 1500 m/s as seen in Fig. 10. The low latitude regions with longitudes close to 0° and 180° require the maximum transit ΔV for access. Therefore, these regions require maximum loiter time in LLO as well as maximum transit durations, which leads to reduced surface stay durations and increased mission duration as seen in Figs. 11 and 12, respectively.

There are several interesting points to note based on these preliminary results. The first is that implementing slightly longer times of flight can result in a reduction in ΔV. Time of flight does impact overall mission operations and crew timeline considerations so it must be applied with an eye towards operational requirements. However, it can be a powerful tool for managing ΔV impacts.

Second, it should be noted that all of these strategies are compared to a polar sortie flown with a specific mission profile. There are a host of potential mission profiles to access polar landing sites from the NRHO. The specific mission profile selected uses equal duration transit legs of 0.5 days to support a maximum 6.2 day nominal surface stay mission. However, by changing this nominal mission profile, the nominal ΔV budget could be altered and global access mission requirements would need to be compared to those alternative ΔV budgets to understand the full impact of global access.

Lastly, it must also be noted that impacts to ΔV budget are ultimately landing site specific. While the global access ΔV maps shared in this paper identify the ΔV impacts for the entire surface of the Moon, other factors, including surface conditions and scientific interest, will eventually lead to the identification of specific sites of interest. These sites may or may not represent the global maximum impacts. Additionally, by using LLO loiter as one of the mitigation strategies for minimizing ΔV impact, surface stay time will also vary from site to site depending on how much LLO loiter is required to minimize increases in ΔV.

Figure 13 shows one way to look at the specific impacts of mitigation strategies in the context of specific landing site selection. In this figure, the total transit ΔV impact map is overlaid on a map of the lunar surface which calls out 10 sites of interest. These sites are not provided as a ranked priority list but rather as an example of how specific sites



tot: (min,mean,max)=(1390, 1473.3, 1576) m/s, Sites below 1500 m/s: 82 %

	-180	-170	-160	-150	-140	-130	-120	-110	-100	-90	-80	-70	-60	-50	-40	-30	-20	-10	0
90	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452
80	1496	1495	1493	1490	1486	1480	1492	1480	1468	1455	1443	1431	1422	1417	1415	1415	1415	1415	1415
60	1560	1559	1545	1523	1500	1494	1485	1462	1435	1407	1489	1479	1457	1496	1485	1494	1491	1491	1493
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-20	1511	1511	1501	1497	1473	1441	1477	1434	1413	1428	1467	1432	1461	1494	1496	1515	1544	1556	1556
-40	1482	1484	1487	1493	1467	1434	1479	1427	1416	1452	1499	1445	1475	1495	1493	1522	1549	1574	1576
-60	1493	1497	1489	1498	1476	1437	1395	1413	1390	1421	1451	1478	1493	1499	1515	1539	1561	1562	1560
-80	1415	1415	1415	1414	1415	1420	1427	1439	1454	1469	1483	1495	1487	1491	1494	1495	1496	1496	1496
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	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
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80	1415	1415	1414	1415	1420	1427	1439	1454	1469	1483	1495	1487	1491	1494	1495	1496	1496	1496
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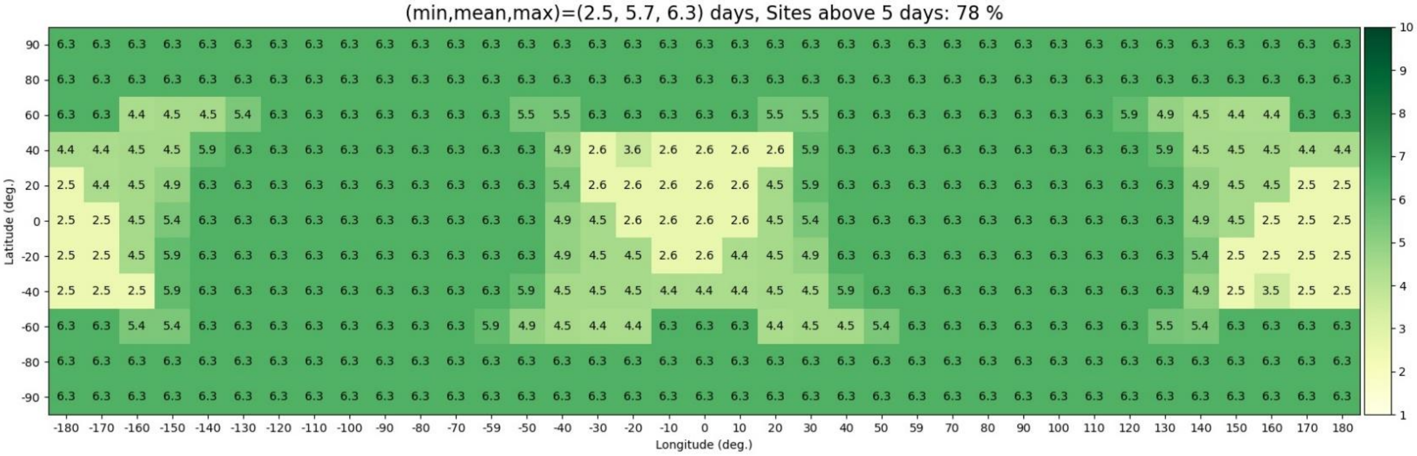
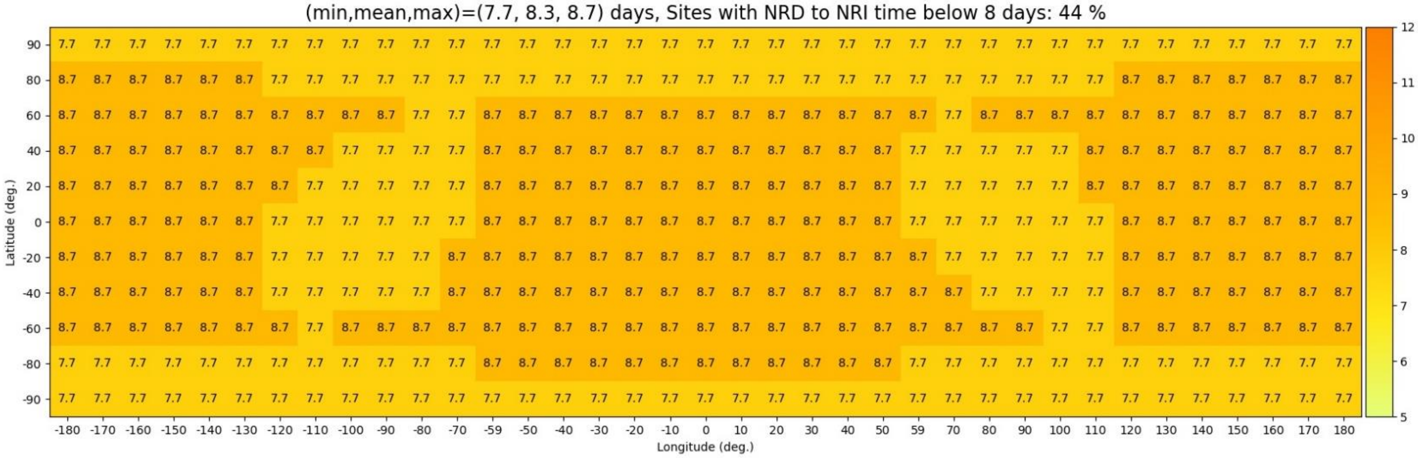
0	1534	1505	1494	1480	1449	1488	1443	1416	1418	1451	1498	1453	1488	1492	1512	1533	1535	1535
-20	1541	1512	1491	1490	1460	1428	1461	1426	1415	1441	1490	1447	1483	1499	1510	1511	1512	1511
-40	1550	1523	1494	1496	1476	1446	1417	1458	1419	1431	1496	1443	1482	1493	1483	1500	1482	1482
-60	1559	1545	1523	1500	1494	1485	1462	1435	1407	1489	1479	1457	1496	1485	1494	1491	1491	1493
-80	1495	1493	1490	1486	1480	1492	1480	1468	1455	1443	1431	1422	1417	1415	1415	1415	1415	1415
-90	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452

Figure 10: Combined Transit ΔV with Time of Flight between 0.5 and 1 day along with Increased LLO Loiter (up to 4 days)


(min,mean,max)=(2.5, 5.7, 6.3) days, Sites above 5 days: 78 %

	-180	-170	-160	-150	-140	-130	-120	-110	-100	-90	-80	-70	-59	-50	-40	-30	-20	-10	0	10	20	30	40	50	59	70	80	90	100	110	120	130	140	150	160	170	180
90	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
80	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
60	6.3	6.3	4.4	4.5	4.5	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.5	5.5	6.3	6.3	6.3	6.3	6.3	5.5	5.5	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.9	4.9	4.5	4.4	4.4	6.3	6.3
40	4.4	4.4	4.5	4.5	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	2.6	3.6	2.6	2.6	2.6	2.6	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.9	4.5	4.5	4.5	4.4	4.4
20	2.5	4.4	4.5	4.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.4	2.6	2.6	2.6	2.6	2.6	4.5	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	4.5	4.5	2.5	2.5
0	2.5	2.5	4.5	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	4.5	2.6	2.6	2.6	2.6	4.5	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	4.5	2.5	2.5	2.5
-20	2.5	2.5	4.5	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	4.5	4.5	2.6	2.6	4.4	4.5	4.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.4	2.5	2.5	2.5	2.5
-40	2.5	2.5	2.5	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.9	4.5	4.5	4.5	4.4	4.4	4.4	4.5	4.5	5.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	4.9	2.5	3.5	2.5	2.5
-60	6.3	6.3	5.4	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.9	4.9	4.5	4.4	4.4	6.3	6.3	6.3	4.4	4.5	4.5	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	5.5	5.4	6.3	6.3	6.3	6.3
-80	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
-90	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3

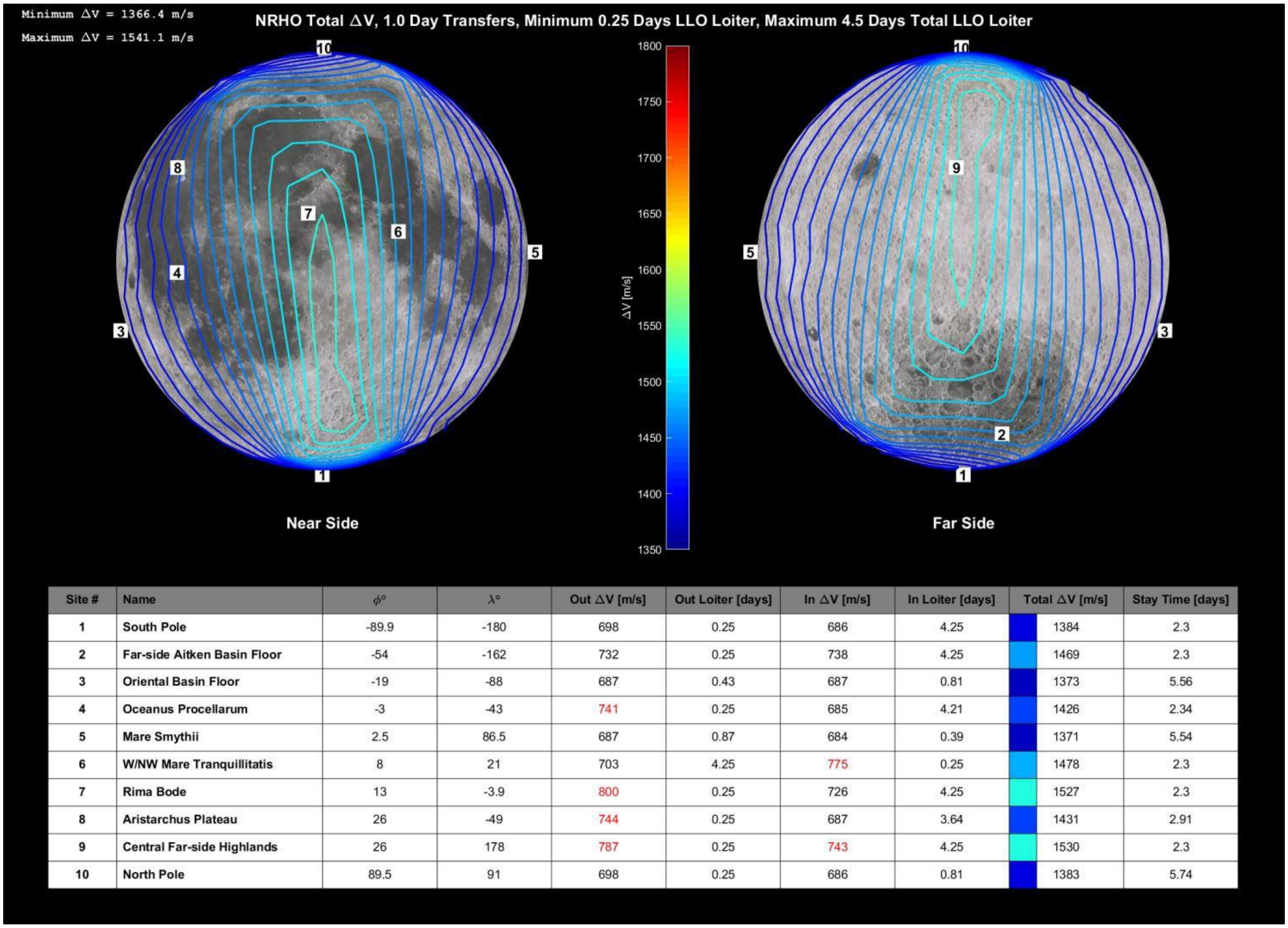
Figure 11: Surface Stay Durations with Transit Time of Flight between 0.5 and 1 day along with increased LLO Loiter (up to 4 days)


(min,mean,max)=(7.7, 8.3, 8.7) days, Sites with NRD to NRI time below 8 days: 44 %

	-180	-170	-160	-150	-140	-130	-120	-110	-100	-90	-80	-70	-59	-50	-40	-30	-20	-10	0	10	20	30	40	50	59	70	80	90	100	110	120	130	140	150	160	170	180
90	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
80	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
60	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
40	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
20	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
0	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
-20	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
-40	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
-60	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
-80	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
-90	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7

Figure 12: Mission Duration from NRHO Departure to NRHO Injection with Transit Time of Flight between 0.5 and 1 day

of interest can impact the ΔV budget. These sites represent a dispersed set covering many different latitudes and longitudes. Note that the loiter times vary from site to site, with some sites adding loiter on the way down to the surface while others add loiter on the way back up. The stay times on the surface range from 2.3 to 5.5 days. This ΔV map does not include options to use Butterfly orbits, so the transit ΔV can reach as high as 800 m/s, but only three sites require transit ΔVs higher than 775 m/s.

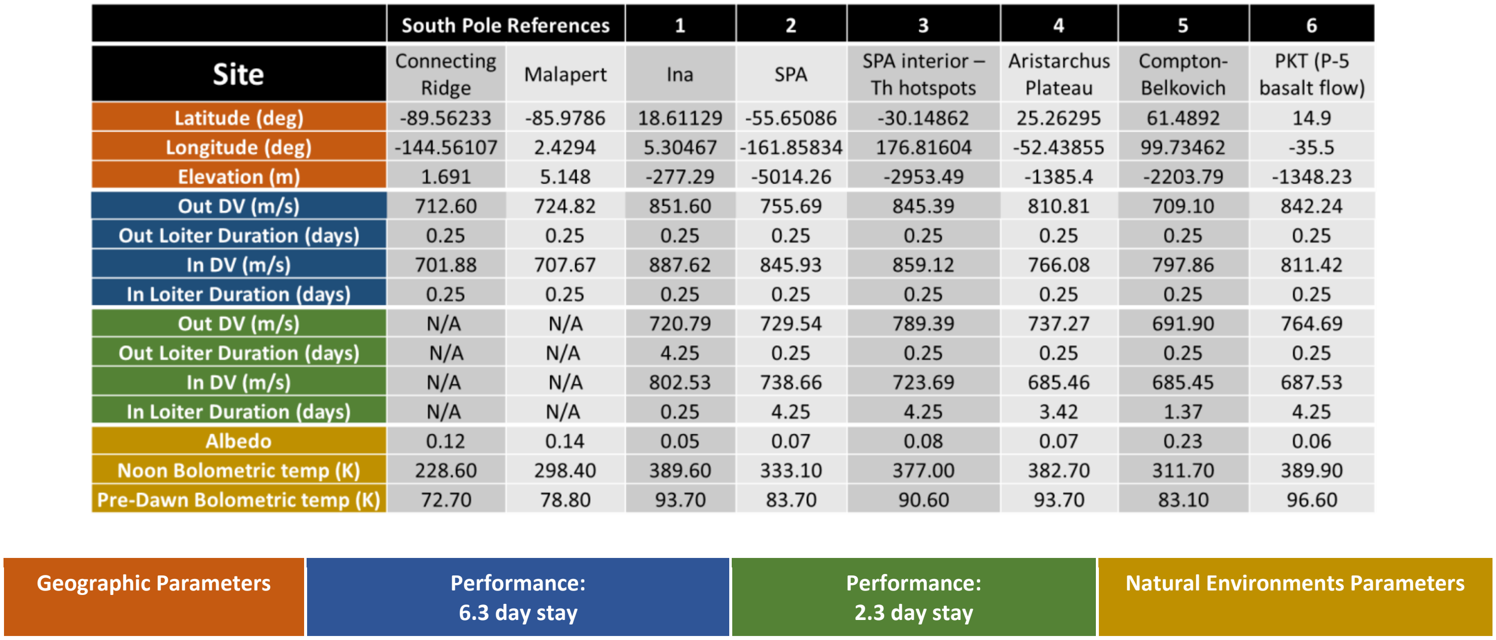


Site #	Name	ϕ°	λ°	Out ΔV [m/s]	Out Loiter [days]	In ΔV [m/s]	In Loiter [days]	Total ΔV [m/s]	Stay Time [days]
1	South Pole	-89.9	-180	698	0.25	686	4.25	1384	2.3
2	Far-side Aitken Basin Floor	-54	-162	732	0.25	738	4.25	1469	2.3
3	Oriental Basin Floor	-19	-88	687	0.43	687	0.81	1373	5.56
4	Oceanus Procellarum	-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

Figure 13: Representative Site-Specific Mission Profile Impacts (Timeline and ΔV Budget)

Required Lander-Accessible Non-Polar Sites

As part of the HLS Sustained Phase, the contractor-partners will assess their landers' ability to access six different non-polar landing sites. Figure 14 lists the coordinates and other characteristics of the sites - Ina, SPA, SPA interior, Aristarchus Plateau, Compton-Belkovich, and PKT - along with two South Pole Reference sites, Connecting Ridge and Malapert. By design, these sites represent a range of thermal and solar environments. The in-bound and out-bound ΔVs and loiter durations are shown for each of the sites for a reduced 2.3 day lunar surface stay duration (long enough to permit 1 EVA) and for a nominal 6.3 day stay.



	South Pole References		1	2	3	4	5	6
Site	Connecting Ridge	Malapert	Ina	SPA	SPA interior – Th hotspots	Aristarchus Plateau	Compton-Belkovich	PKT (P-5 basalt flow)
Latitude (deg)	-89.56233	-85.9786	18.61129	-55.65086	-30.14862	25.26295	61.4892	14.9
Longitude (deg)	-144.56107	2.4294	5.30467	-161.85834	176.81604	-52.43855	99.73462	-35.5
Elevation (m)	1.691	5.148	-277.29	-5014.26	-2953.49	-1385.4	-2203.79	-1348.23
Out DV (m/s)	712.60	724.82	851.60	755.69	845.39	810.81	709.10	842.24
Out Loiter Duration (days)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
In DV (m/s)	701.88	707.67	887.62	845.93	859.12	766.08	797.86	811.42
In Loiter Duration (days)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Out DV (m/s)	N/A	N/A	720.79	729.54	789.39	737.27	691.90	764.69
Out Loiter Duration (days)	N/A	N/A	4.25	0.25	0.25	0.25	0.25	0.25
In DV (m/s)	N/A	N/A	802.53	738.66	723.69	685.46	685.45	687.53
In Loiter Duration (days)	N/A	N/A	0.25	4.25	4.25	3.42	1.37	4.25
Albedo	0.12	0.14	0.05	0.07	0.08	0.07	0.23	0.06
Noon Bolometric temp (K)	228.60	298.40	389.60	333.10	377.00	382.70	311.70	389.90
Pre-Dawn Bolometric temp (K)	72.70	78.80	93.70	83.70	90.60	93.70	83.10	96.60

Geographic Parameters	**Performance: 6.3 day stay**	**Performance: 2.3 day stay**	**Natural Environments Parameters**

Figure 14: Non-Polar Landing Sites

Conclusion

Achieving expanded access for lunar surface missions will impact lander design. Thermal and solar environments vary significantly with latitude. Any system required to operate over a range of potential landing sites will need to consider variations in surface temperature, including extremes around the "lunar noon" period, in the design of thermal systems. Solar incidence angle and the track of the sun as it crosses landing sites will drive the designof solar power generation elements. A system designedto operate solely in the polar regions will require modification to support operations at any site on the lunar surface.

Design impacts are not the only challenge associated with expanded access. Due to the unique characteristics of the NRHO, landing site access can have a significant impact on the ΔV budgets.

Transit ΔV between NRHO and LLO can be as much as 25% higher for some landing sites compared to the polar sortie mission. These impacts can be mitigated by applying a combination of transit time offlight and LLO loiter duration variations (resulting in reduction in surface stay time) and the use of alternativeButterfly orbits (requiring Gateway transfers). If appliedin the right combination, expanded access can be achieved with modest ΔV increases resulting in 2.3 – 6.2 day surface missions anywhere on the surface of the Moon with minimal ΔV budget impacts to landers designed to execute polar sortie missions.

References

[1] SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE). Available from NASA Technical Reports System

[2] HLS-UG-001 Lunar Thermal Analysis Guidebook. Available from HLS Document Library

[3] R.J. Whitley, et.al. "Earth-Moon Near Rectilinear Halo and Butterfly Orbits for Lunar Surface Exploration," AAS 19-406, AAS/AIAA Astrodynamics Specialist Conference, Aug. 2018