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Space Administration

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HUMAN LANDING SYSTEM (HLS) LANDING SITE CONSIDERATIONS FOR SUSTAINED PHASE MISSIONS

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REVISION AND HISTORY PAGE

Revision No.	Change No.	Description	Effective Date
-		Released with Option A RFP	09/08/20
2		Released with Sustaining Lander Development RFP	01/13/22
3		Replacing "LETS" with some version of "Artemis Sustained missions"	05/26/22

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1.0 INTRODUCTION

Site selection for the Artemis sustained mission phase has not been determined. Many factors, including environmental, system and mission design, affect the ability of the Artemis missions to land and operate at specific locations within 6 deg of the Lunar South Pole. Therefore, the combined interaction of these factors will determine a site's available for a particular landing opportunity. The goal is to develop landing systems that are robust to maximum number of factors to offer flexibility to land at a maximum number of available sites regardless of arrival date or surface stay duration. This document provides descriptions of key environmental, system and mission considerations that affect site availability and presents data to aid in the vehicle design and ultimately the site selection process.

Factors that affect site availability described herein include environmental factors such as surface illumination, slopes, rocks, craters, lunar libration and Earth visibility. System design factors include considerations for communicating directly with Earth and with vehicles in the Near-Rectilinear Halo Orbit (NRHO). Mission design constraints include the Space Launch System (SLS)/Orion/Gateway launch opportunities and NRHO departure opportunities (every six days) as well as surface Extravehicular Activity (EVA) mission restrictions.

Artemis mission concept of operations are very different from the historical Apollo missions. Key differences that effect site availability are described in Section 2.0. Details of the HLS Design Reference Missions are provided in Section 3.0. Section 4.0 describes the effects of the environmental, system and mission design factors and why they are critical in the site availability assessment for both sortie and basecamp missions. Finally, specific requirements that affect landing site criteria for Sustaining Lander Development (SLD) and base camp planning guidelines are presented in Section 5.0.

1.1 SCOPE

The Human Lander System (HLS) Landing Site Considerations for the Artemis sustained mission phase includes general characterization of the considerations for site selection for both sortie and sustained sites within 6 deg latitude of the Lunar South Pole. Characterizing non-polar sortie landing sites is not within the scope of this paper and are not discussed further. Additionally, this document implies no presumption of site selection and should be used only as a reference for assessing environmental, system and mission design considerations at various locations at the South Pole. Site Availability is evaluated to a set of Site Availability Criteria as detailed in Section 5.0 as applicable to the Polar Sortie and Extended Excursion Reference Missions only. Assessments of sites from a scientific and/or strategic perspective are also outside the scope of this document.

1.2 APPLICABLE DOCUMENTS

Table 1.2-1 list applicable documents, including specifications, models, standards, guidelines, handbooks, and other special publications. The documents listed in this paragraph are applicable to the extent specified herein.

Table 1.2-1 – Applicable Documents

Document Number	Document Title
HLS-CONOP-001	HLS Program Concept of Operations
HLS-CONOP-006	Sustained Phase HLS Program Concept of Operations
HLS-RQMT-001	HLS Program System Requirements Document
HLS-RQMT-006	Sustained Phase HLS Program System Requirements Document
SLS-SPEC-159	Design Specification for Natural Environments (DSNE)
HLS-UG-001	Lunar Thermal Analysis Guidebook

2.0 BACKGROUND: APOLLO VS. ARTEMIS MISSIONS

Lunar South Pole landings present a different set of challenges compared to equatorial Apollo missions. This section summarizes key differences in illumination, communication with Earth and staging orbits used prior to descending to the surface.

2.1 ILLUMINATION CONDITIONS

Generally, high elevation sites within a few degrees of the Lunar South Pole, due to the Moon's 1.5º obliquity to the ecliptic plane, are characterized by continuous or near-continuous solar illumination during seasons where the sub-solar point is below the equator. However, because of the low solar elevation angles, sites within proximity to "peaks of eternal light" can experience prolonged periods of darkness. Figure 2-1 shows a comparison of imagery taken during the Apollo mission at an equatorial site (on the left) and Lunar Reconnaissance Orbiter imagery of the Connecting Ridge location near the South Pole (on the right).

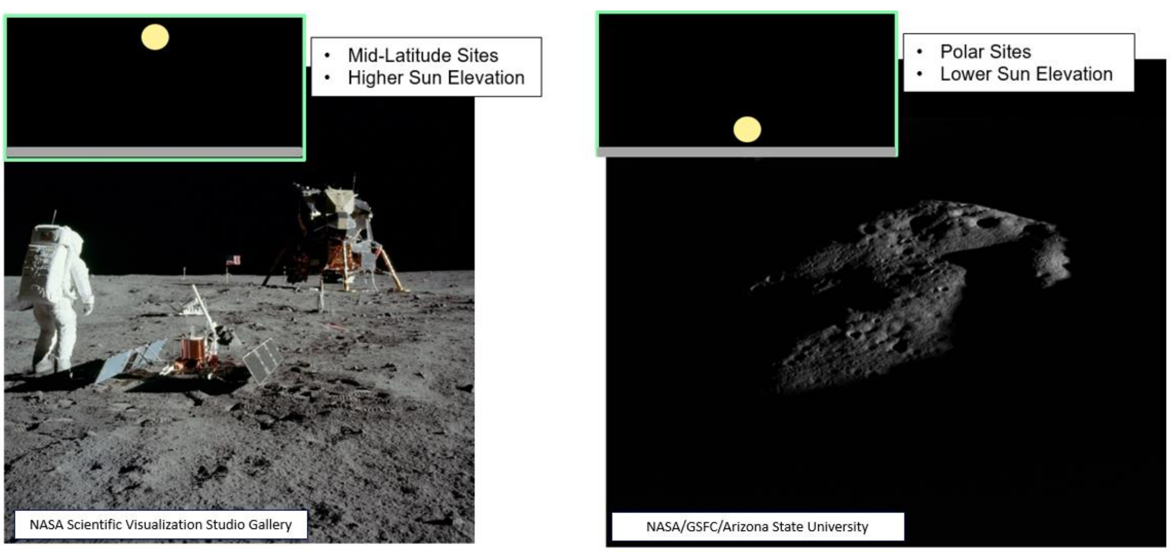

Figure 2-1 – Apollo (left) vs Artemis (right) imagery comparison.

The Apollo imagery shows the relatively short shadow length indicative of the higher Sun elevation angles experienced during the missions. The Lunar Reconnaissance Orbiter imagery shows the long shadows that create areas of favorable illumination near areas that can experience much longer periods of darkness.

2.2 EARTH COMMUNICATIONS

The Artemis missions are also expected to experience different Earth visibility conditions that impact Direct-with-Earth (DWE) Communications. The Apollo missions targeted near-side, equatorial sites. The tidally locked nature of the Moon results in a relatively fixed Earth position for near-side sites that allowed for continuous DWE communication. At the Lunar South Pole, however, the libration, or "wobble", due to the inclination and eccentricity of the Moon's orbit around Earth, creates approximately two-week intervals where the Earth goes slightly above and below the horizon for polar sites. Sites further away from the pole but within the 6º of the pole, experience more Earth communication visibility and tend towards periodic solar illumination as latitude increases. Figure 2-2 shows images from the Kaguya spacecraft of Earth setting. The images provide a view of half of the two-week cycle of low Earth elevation angles that may be experienced at polar sites.

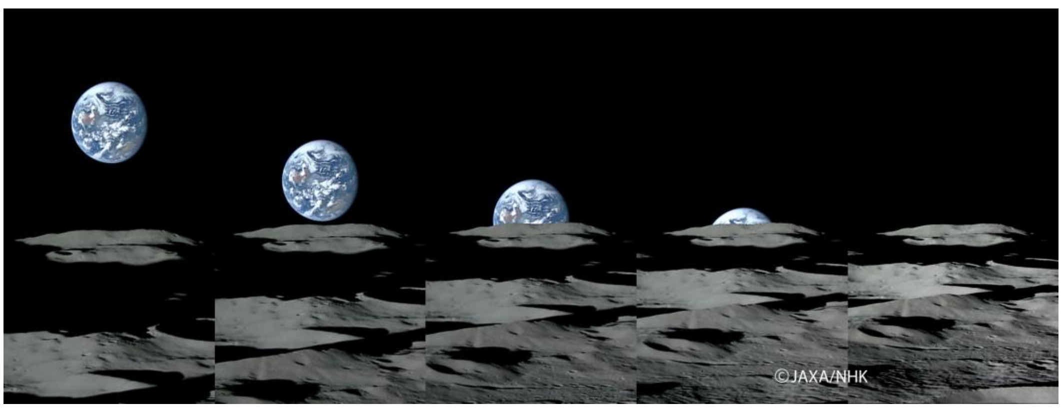

Figure 2-2 – Kaguya "Earth-Set" from the Lunar South Pole

Due to the low Earth elevation angles, local terrain is also a major factor in the availability of DWE communication. For example, Malepert Ridge provides excellent DWE availability on the ridge near 86 degrees latitude, but the ridge casts long shadows behind it so that large nearby areas never see the Earth. Site availability for sustained missions will depend not only on DWE communication like Apollo. Instead, communication with relay assets is expected to play an important role in the HLS missions.

2.3 MISSION CONCEPT OF OPERATIONS COMPARISON

Apollo missions used the Saturn V rocket to get to the Moon and the service propulsion system to place the command, service and lunar modules (LM) in a ~60 x 70 km equatorial obit around the Moon. After approximately 10 orbits, the LM separated from the command and service module and fired engines to reduce periapsis to 9 km. The vehicle coasted for approximately 60 minutes before starting an eight-minute powered descent burn that delivered the LM to the surface. The vehicle was on the lunar surface for approximately three days. While the initial free return mission inclination/latitude constraint for Low Lunar Orbit (LLO) was 40 degrees, and later relaxed to 70 deg, all Apollo landing sites were at latitudes less than 30 deg.

The Artemis mission, however, is taking a different approach. Sustained mission will utilize a 9:2 synodic NRHO with a periapsis of ~1500 km and apoapsis nearly 70,000 km. NRHO is characterized by its long, six-day dwell over the South Pole and is shown in Figure 2-3. For the sustained missions, Gateway, the lunar orbiting outpost, will be staged in NRHO. Likewise, commercial providers will launch HLS to the Moon and place it in NRHO. The Space Launch System (SLS) will be used to launch crew in Orion. Orion will dock either with HLS directly or with Gateway in NRHO. The crew will transfer to HLS, separate from Gateway (or Orion), and descend to a 100x100 km circular polar orbit for up to only three orbits prior to the deorbit burn that lowers periapsis to approximately 15 km when powered descent is initiated for the final approximately eight-minute descent to the South Pole. While two to four crew may descend to the surface some crew members may remain at Gateway. For this reason, communication with Gateway is desired for sustained missions and maintaining communication may affect site availability. While a summary of the Artemis sustained mission concept of operations is provided here for comparison to Apollo, a more complete description of the Artemis HLS design reference missions is provided in the next section.

As will be shown in Section 4.0, several of the features of staging from NRHO affect site availability in ways that did not affect Apollo missions. Data will show how the libration of the Moon and the variability in the NRHO orbit affect the approach direction of the descent trajectory, the duration of surface missions, in-space DV and ultimately, which South Pole sites are available for each NRHO deorbit opportunity.

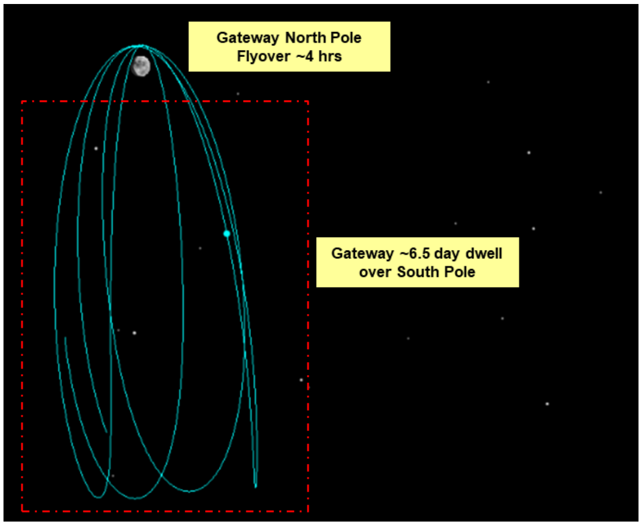

Figure 2-3 – Gateway in NRHO

3.0 HLS MISSION SUMMARY

The sustained mission phase includes two types of missions. The first are short stay (~6 days) sortie missions that may or may not land near the South Pole. The second are extended excursion missions to a South Pole base camp that may last approximately 30 days.

The HLS is a vehicular system that transports logistics and mission support equipment necessary for lunar surface exploration from Earth to NRHO, transports crew members from a staging vehicle (e.g., Gateway and/or Orion) in a NRHO to the lunar surface, enables the crew to perform EVAs and access surface assets on the surface, and then safely returns the crew to the staging vehicle for Return to Earth (RTE). In addition to returning the crew to NRHO, the HLS also returns lunar samples and other equipment to NRHO to enable sample return to Earth for scientific study.

HLS mission segments affected by site availability are limited to De-orbit, Descent, and Landing (DDL) which includes the departure and deorbit burn from NRHO to the 100 x 100 km circular low lunar staging orbit and descent to the surface, the surface mission segment, and ascent back to NRHO.

3.1 REFERENCE MISSION REQUIREMENTS

Table 3.1-1 provides an overview of the reference mission requirements pertaining to site availability for the Artemis sustained phase. Reference HLS-RQMT-006 Sustained Phase HLS Program System Requirements Document for the full system requirements set on the sustained phase.

Table 3.1-1 – Reference Mission Requirements

Mission Phase	Sortie	Extended Excursion
Location	84-90 deg S or Non-polar sites	84-90 deg S
Communication Relay	Yes	Yes
Direct With Earth Communication	Yes	Yes
Illumination Height	10 m	10 m
Landed accuracy	50 m	50 m + 10 deg slope
NRHO CSV	Orion or Gateway	Gateway

3.2 REFERENCE CONCEPT OF OPERATIONS

This section provides a brief overview of the concept of operations (ConOps) and design reference missions (DRMs) for the sustained phase. Reference HLS-CONOP-006 Sustained Phase HLS Program ConOps for more detail on the sustained phase ConOps.

HLS may consist of a single stage, two element or multiple elements to deliver crew and cargo to the surface of the Moon. Figure 3-1 shows a notional sustained phase mission using a three-element architecture from commercial launches to Orion's RTE. Table 3.2-1 shows an overview of DRM differences. HLS-CONOP-006 also contains DRM-001 variants, a non-polar sortie mission, that are not shown here. A summary of the sortie and extended excursion DRM are provided in the following subsections. Understanding the differences in the DRMs is important to determining the sites available to each.

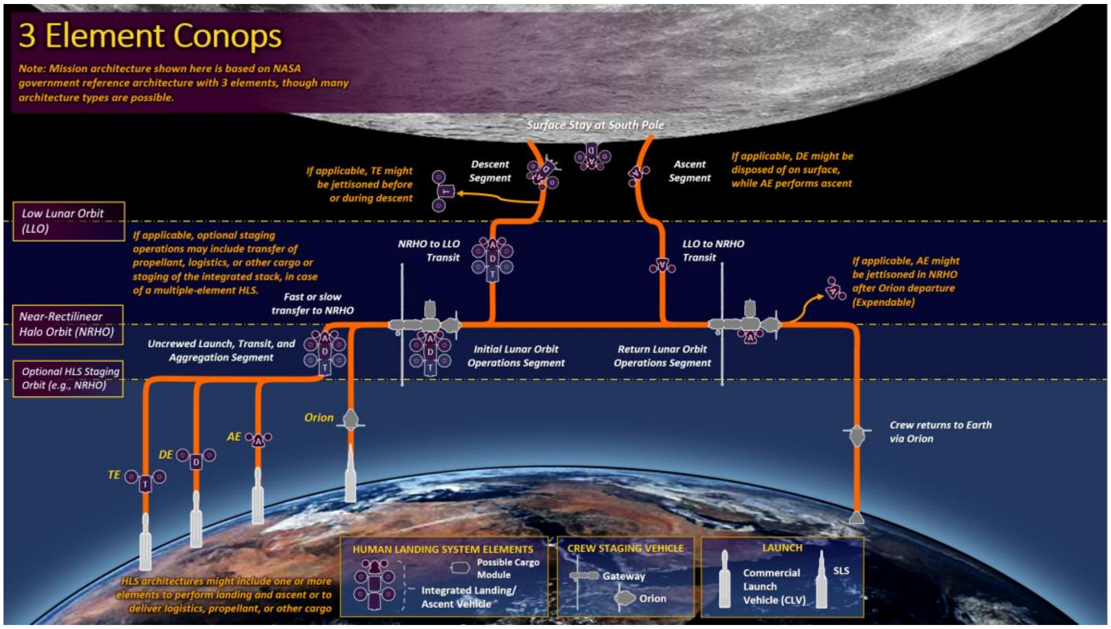

Figure 3-1 – Reference sustained phase mission architecture

Table 3.2-1 Design Reference Mission Overview

	DRM-001 Polar Sortie	DRM-002 Extended Excursion
Crew Staging Vehicle	Gateway	Gateway
Crew Size	2	4
Surface Stay (days)	~6	~33
Landing Location	South Pole	Artemis Base Camp
Darkness (hours)	0	120
Surface Habitation	HLS	Artemis Base Camp Elements
Number of EVAs	5	N/A

3.2.1 HLS-DRM-001 2-CREW SORTIE MISSION TO SOUTH POLE

HLS-DRM-001 is a 2-crew sortie to the lunar South Pole region with two crew members and a surface stay of up to 6 days. This DRM is depicted in Figure 3-2 with additional details.

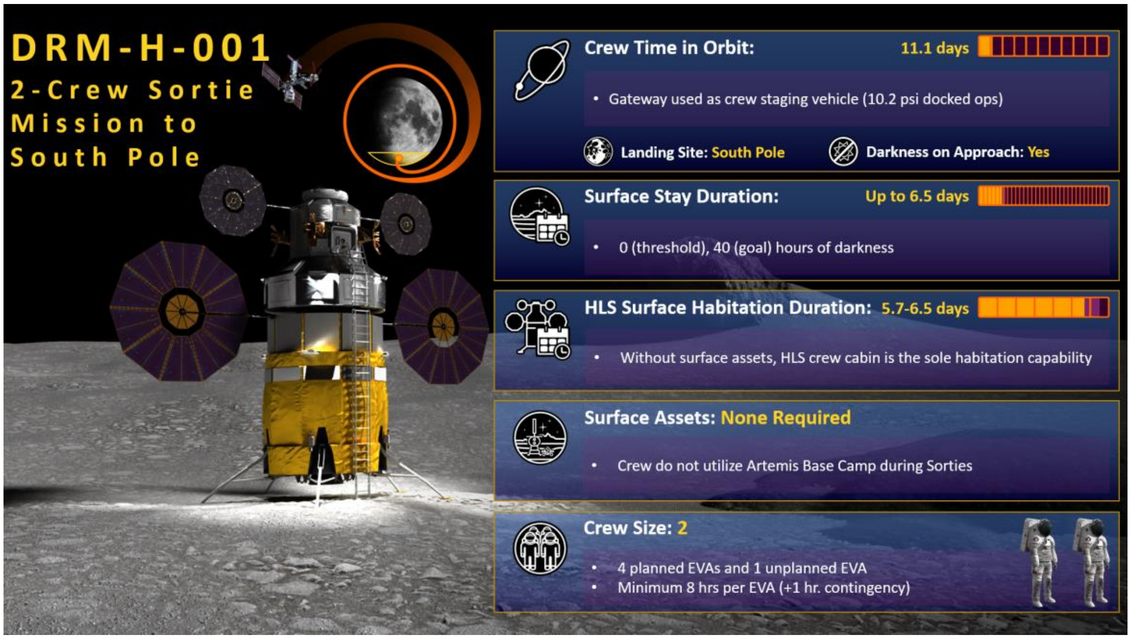

Figure 3-2 – Two-Crew Sortie Mission to the South Pole

3.2.2 4-CREW POLAR EXTENDED SURFACE EXCURSION MISSION

HLS-DRM-002 is a 4-crew surface excursion that will leverage pre-placed assets on the lunar surface to support four crew members for a longer duration surface mission of up to 33 days. This DRM is depicted in Figure 3-3 with additional details.

Figure 3-3 – Four-Crew Polar Extended Surface Excursion Mission

4.0 HLS SITE AVAILABILITY CONSIDERATIONS

As discussed in previous sections, landing site availability is affected by many aspects of the environment, system, and mission. Considerations are divided in two categories. The first category includes those considerations that affect *getting to the site*, and include launch opportunities from Earth, departure opportunities from NRHO, approach and site illumination, surface rocks and slopes, and communication with the CSV and Earth. The second category focus on those considerations that effect working *at the site*. These include similar considerations for solar availability, DWE communications and surface slope and rocks distributions, but from the EVA and surface operations perspective. Likewise, the considerations vary for short sortie missions compared with basecamp locations as the basecamp will have many more elements delivered to the same location over time. A description of key site availability considerations is provided here.

4.1 DESCENT CONSIDERATIONS (GETTING TO A SITE)

4.1.1 Mission Opportunities

Ultimately site availability will depend on the SLS/Orion launch availability. While assessments of SLS/Orion mission availability are outside the scope of this document, the impact of the SLS/Orion considerations can be viewed in terms of mission opportunities, or specific NRHO revolutions where a surface mission can depart. These occur every 6 days. The NRHO is described in Section 2.3. Once dates for SLS/Orion launch are known, viable sites can be selected from data corresponding to the specific opportunity.

4.1.2 Descent Phase Approach Direction

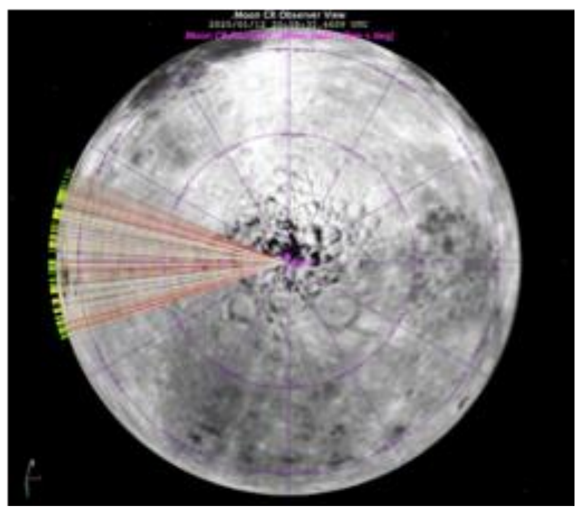

Figure 4-1 – Image of Lunar South Pole with NRHO departure/South Pole approach trajectories shown from 2024 to 2025.

Due to the libration, or "wobble", of the Moon that results from the inclination and eccentricity of the Moon's orbit around Earth, as well as the variability in the NRHO trajectory, the descent approach angles can vary ± 20 deg in longitude (see red lines on in

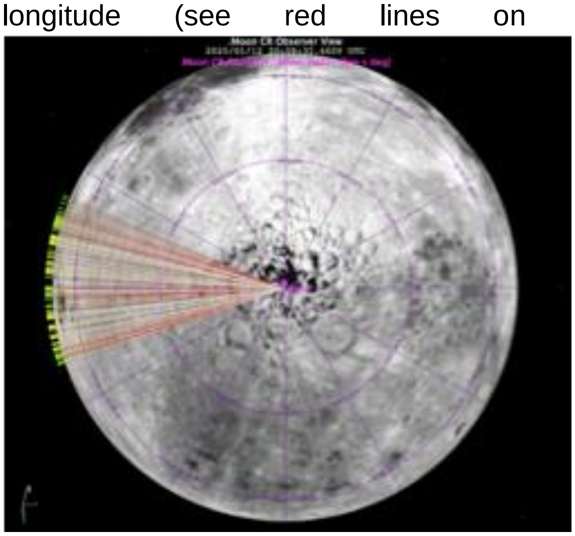

Figure 4-1) for each six-day departure opportunity from NRHO in 2024 and 2025. The image is looking at the Lunar south pole where 0 longitude corresponds to 12 o'clock. This knowledge informs the size and location of digital elevation maps needed for performing Terrain Relative Navigation. However, the approach trajectory has other impacts on site availability which are discussed in the next subsection.

4.1.3 Total In-Space ΔV

The previous section showed that the approach angle can vary from one NHRO orbit to the next. Therefore, another consideration for site availability is the amount of propellant needed for a plane change to reach a landing site if the NRHO departure trajectory is not aligned with it. This is important for basecamp locations where multiple missions will be landing at the same landing site on different, and potentially nonfuel optimal, opportunities. The assessment presented here assumes a reference ΔV allocation of 1500 m/s total for in-space maneuvers per the HLS Government Reference Design. The plane change during the NRHO insertion and departure maneuvers will drive the total in-space ΔV when considering de-orbit and descent from the reference NRHO staging orbit. Most Lunar South Pole sites will not exceed the reference ΔV allocation for in-space burns; however, there is some epoch-to-epoch variation. Sites along the 0ºE longitude line that are closer to 84ºS present stressing cases when considering a 1500 m/s allocation for total in-space burns. For example, consider three regions, also candidate locations for Option A, with landing epochs between 2024 and 2025. Figure 4-2 highlights three regions including Malapert Crater (denoted as A), Malapert Massif (B) and Connecting Ridge (C). Figure 4-3 shows the ΔV per epoch for the three regions. Some epochs for sites such as Malapert Massif and Malapert Crater exceed 1500 m/s.

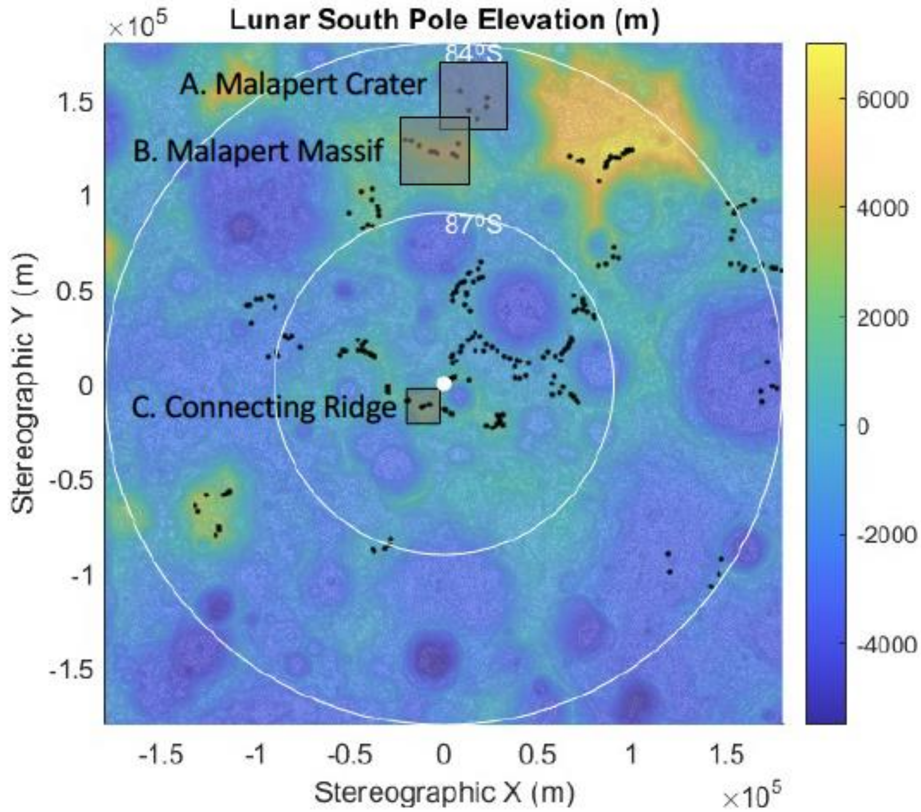

Figure 4-2 – Stereographic projection of the Lunar South Pole with three regions highlighted.

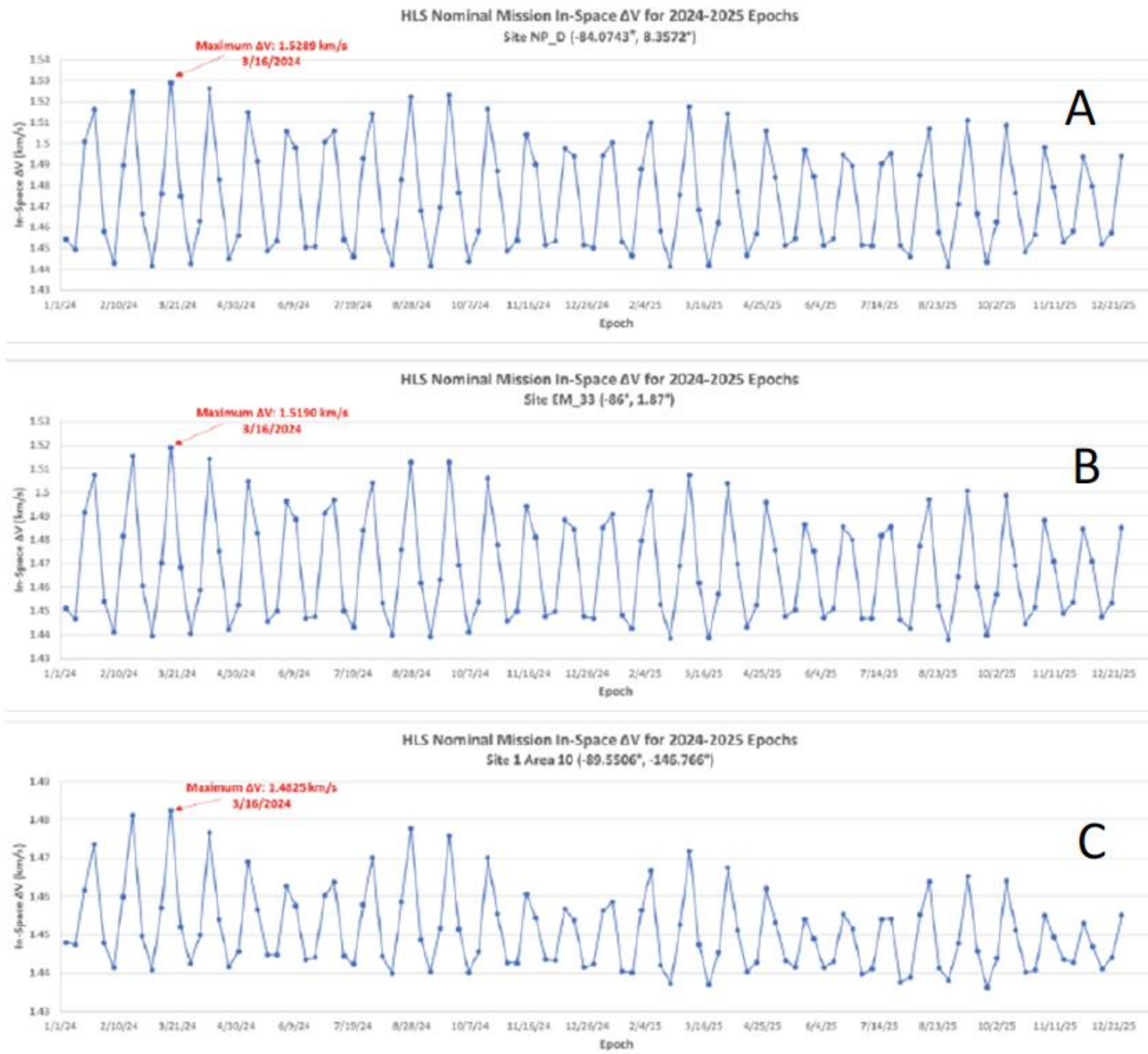

Figure 4-3 – HLS Nominal Mission In-Space DV for epochs between 2024 and 2025 for three regions (A=Malapert Crater, B= Malapert Massif, C=Connecting Ridge)

4.1.4 Site Illumination and Approach Lighting

The polar illumination environment results in continuously changing patterns, such that images of a specific location vary significantly from one landing opportunity to the next. The impacts of this are shown in Figure 4-4. The red lines in the image on the left show the possible range of descent approach trajectories. The blue line shows the approximate trajectory ground track that corresponds to that specific to the landing opportunity. Not only is the lighting different each opportunity, but the approach terrain is also different. Therefore, different terrain maps may be needed for missions approaching the same landing site. Crew training for expected approach lighting conditions will have to be expanded to consider a wide range of conditions.

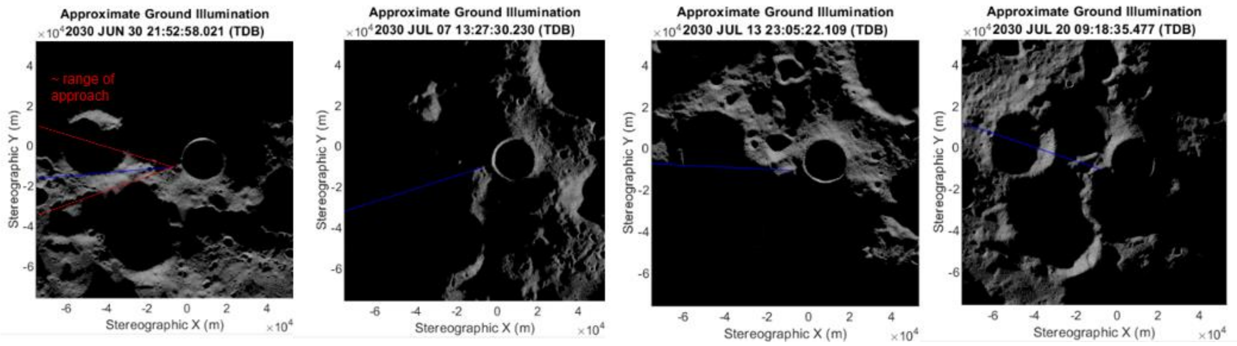

Figure 4-4 – Approximate ground illumination of same location near the Lunar South Pole for four consecutive landing opportunities between June 30 and July 20, 2030.

Another characteristic of the lunar polar environment is the irregular light/dark terminator at the pole. Figure 4-5 shows the irregular terminator for 90º rotations of Sun position.

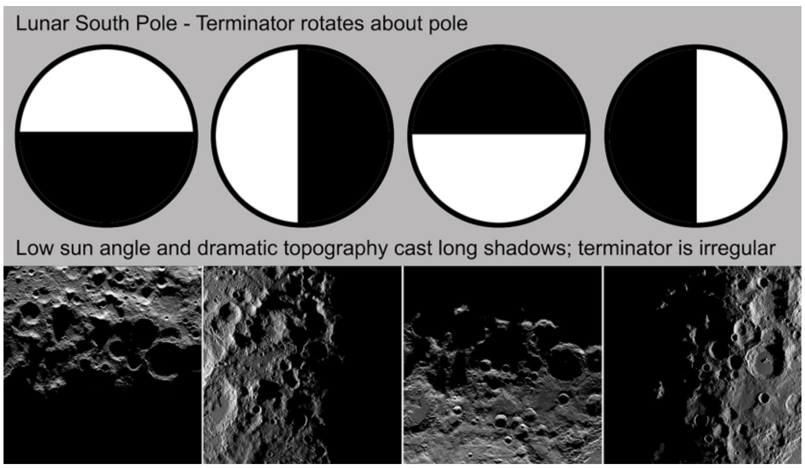

Figure 4-5 – Lunar South Pole Terminator [LPI]

4.1.5 Descent Communications

From an HLS site availability perspective, the orientation of the polar low lunar orbit (LLO) with respect to a targeted landing site is a relevant criterion to analyze because of the potential for loss of line-of-sight to Earth depending on the specific site and epoch under consideration. In addition, potential RF multipath degradation is relevant because it can have a detrimental effect on line-of-sight communications between the lunar surface (and lunar orbit) and Earth. Other considerations are made for descent phase communications, like communication with Gateway or Orion, but a presentation of those details is outside the scope of this document. Figure 4-6 and Figure 4-7 show the HLS RF Communications Concept of Operations for the NRHO departure and LLO orbit phases of descent, respectively.

After NRHO departure the HLS vehicle will insert into the LLO for several orbits before initiating descent to the lunar surface. The orientation of the LLO is site and epoch dependent, driven by the plane change from the NRHO departure maneuver. This site and epoch dependent LLO orientation may result in Earth occultation, resulting in loss of line-of-sight to Earth ground stations and/or periods of signal degradation resulting from signal multipath. Site availability will consider the impact to communication and navigation during this phase of the mission.

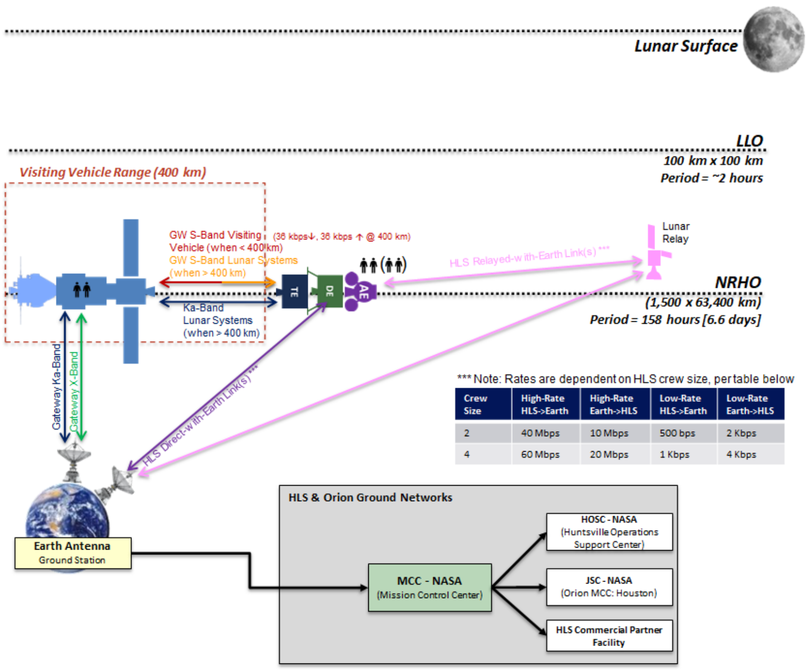

Figure 4-6 – HLS RF Communications Concept of Operations for the NRHO departure

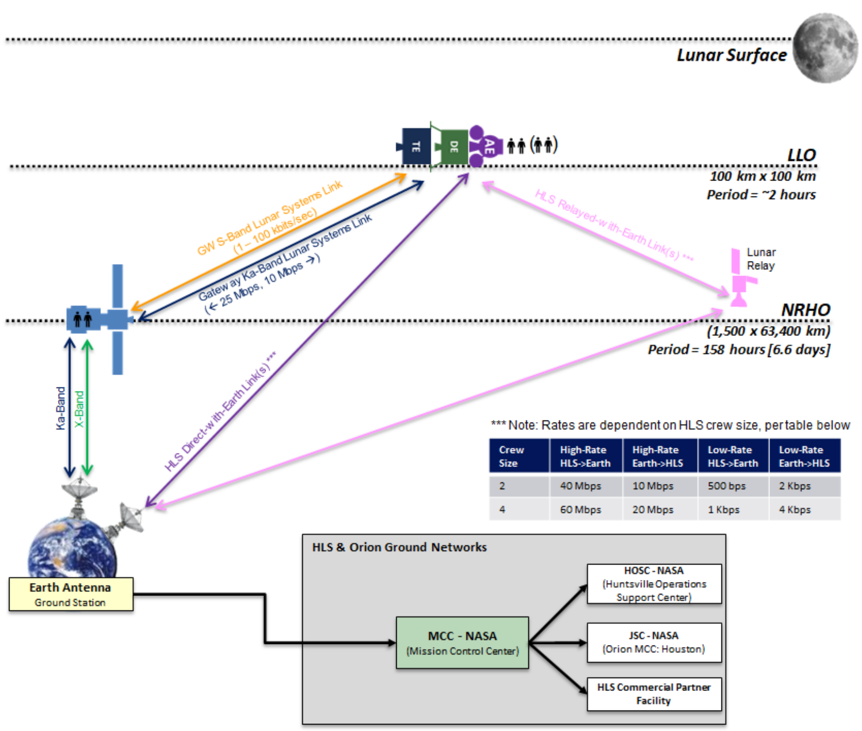

Figure 4-7 – HLS RF Communications Concept of Operations for the LLO

4.1.6 Landing Site Characteristics

4.1.6.1 Slope/Rock/Craters

Another landing consideration is surface roughness. This roughness is generated by local ground slopes and the presence of rocks and craters. Accurate characterization of the surface roughness in the landing zone (50 m radius circles around the target for sustained missions) is critical to ensure landing safety and vehicle stability. Typically, high-resolution data is needed to resolve rocks and slopes that might impact the lander. Unknown surface characterization can be mitigated with robust landing gear and/or vehicle capability to detect and divert away from surface hazards. Smaller landing accuracy requirements allow for more landers to be delivered to single base camp locations. However, the final sustained phase landing separation distance requires additional work to understand and characterize surface roughness and engine plume interactions with the regolith. Characterizing rocks and craters at each landing site is beyond the scope of this paper and is considered forward work as higher resolution or ground truth data become available.

4.1.6.2 Slope Distributions

While high resolution images of rocks and craters are not available, fractions of continuous slope can be determined from the available Lunar Orbiter Laser Altimeter (LOLA) data. Fraction of continuous slope denotes the fraction (percentage) of the landing area (50 m radius circles around the target) for which the slope is greater than the minimum specified slope. For example, in a landing area that contains 10 deg ground slope, an 80% fraction of continuous slope means that 20% of the landing area around the target exceeds the 10-degree slope limit. The implication is that the viable landing area in the landing ellipse is smaller than the requirement. This is not a problem for vehicles with active hazard avoidance sensors and a divert capability. Figure 4-8 shows how the valid landing region (in yellow) grows as the fraction of continuous slope is decreased from 100% to 65%.

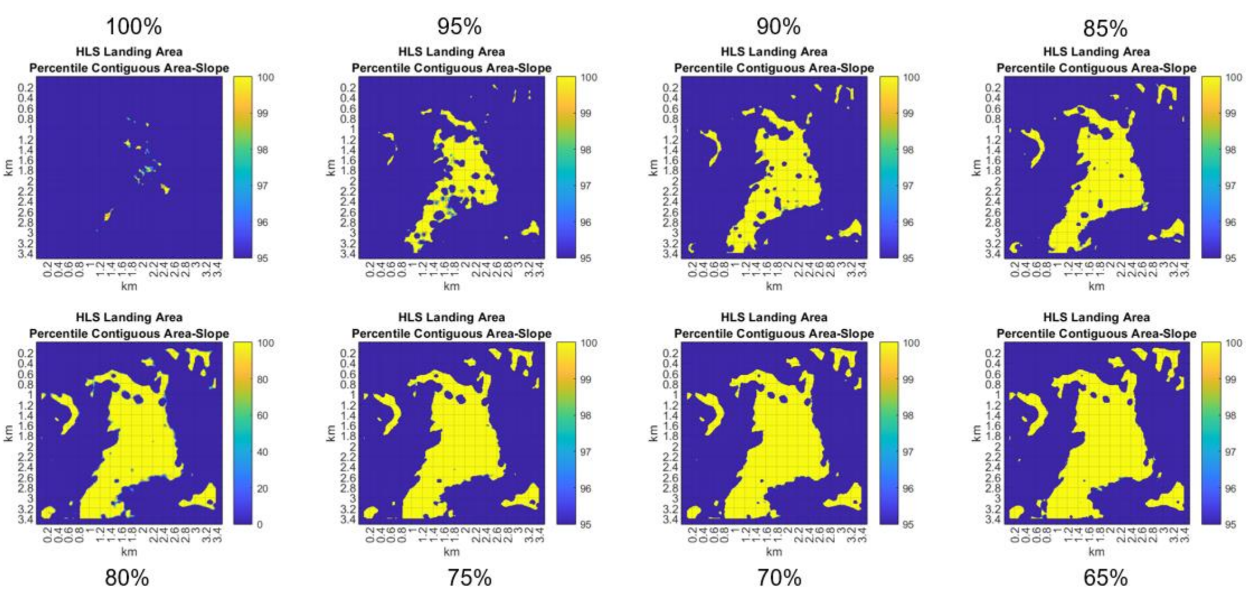

Figure 4-8 – Notional valid landing area at a South Pole location for varying fractions of continuous slope

4.2 SURFACE MISSION (AT THE SITE)

Key site availability considerations for descent and landing were presented in the previous section. This section focuses on those site considerations that affect the surface operations. Early sustained missions will likely rely on solar power. Therefore, not only is placement and orientation of solar arrays on the vehicle critical, selecting sites with sufficient lighting for the duration of the surface mission is a driving constraint for determining site availability. For the analysis considered herein, the solar arrays are assumed to be mounted at 10 m heights above the surface. As expected, arrays that are located at higher altitudes have reduced shadowing from surface features and therefore are more effective. Trades will show the how the areas of illumination increase with height above the surface.

4.2.1 Solar Illumination and Solar Availability

Solar availability at the Lunar South Pole can be characterized by the solar elevation dependence on the relative timing of the ascending and descending nodes with respect to the ecliptic plane over an 18.6-year cycle. Sun elevation angles depend on landing site latitude. Sites farther from the pole will experience higher sun elevations. Between the pole and 84 deg latitude, the region designated for sustained mission polar sites, the sun elevation angle can vary from 0 to 7 deg. **Error! Reference source not found.** Figure 4-9 shows, in yellow, how the Sun elevation angle changes throughout two years. The epoch hours in this example extend from June of 2024 to May of 2026. The gray shaded region represents the altitude of the terrain in the direction of the sun, or terrain mask, at Connecting Ridge site 1. It is noted that during Lunar South Pole summer months when the sun is well above the terrain mask, this site will remain illuminated. However, in the Lunar South Pole winter months when the Sun falls below the terrain, there are short periods of illumination. The total fraction (or ratio) of the solar disk that is visible at this site is shown in Figure 4-10.

However, for the longer 30+ day sustained surface missions some amount of continuous darkness is expected. HLS-S-R-0070 Surface Lighting Conditions requires a minimum of 120 hours of continuous darkness with a goal surviving 230 hours for missions to base camp to minimize the mass of fuel cells. Therefore, sites with largest areas of minimum continuous lighting are sought. These sites allow for more sustained landers to be delivered to the same base camp location.

This must be cross referenced with other factors such as communication relay availablity on the surface during each mission opportunity which is discussed in the next section.

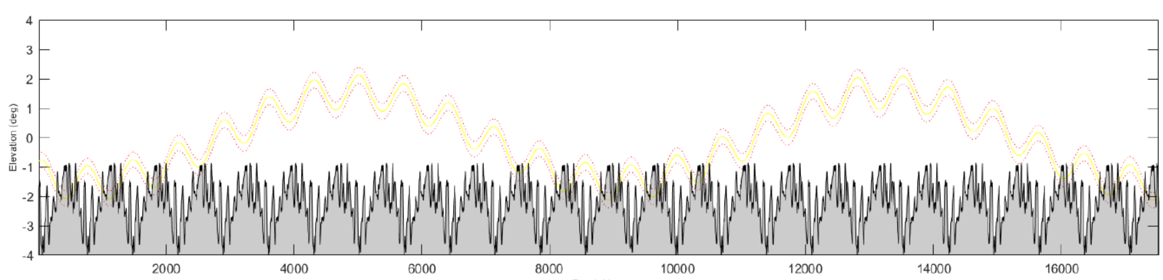

Figure 4-9 – Yellow line shows the elevation of the sun compared to the terrain mask in gray at site Connecting Ridge Sample Site 1

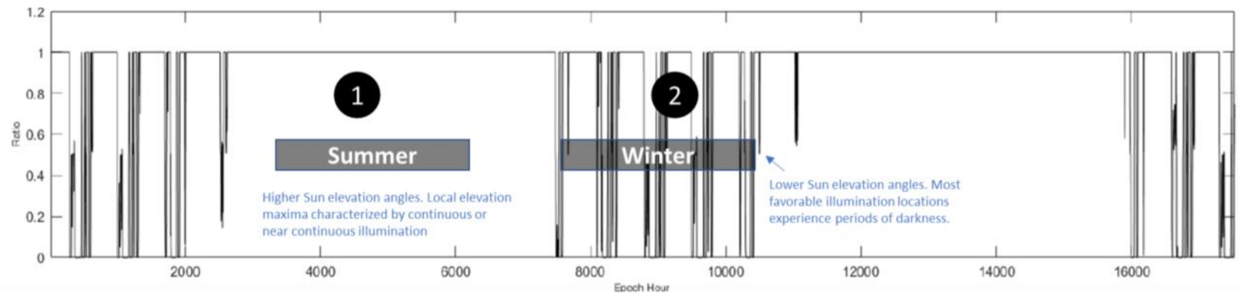

Figure 4-10 – Fraction of solar disk (per hour) visible at Connecting Ridge Site 1

4.2.2 Direct-With-Earth Communications for surface missions

For Direct-with-Earth communications, the landing site and date is chosen to ensure good line-of-sight visibility between HLS and Earth. For HLS Missions that will land near/on the Lunar South Pole, lunar libration can limit line-of-sight visibility to alternate two-Earth-week periods (two weeks of visibility followed by two weeks of being hidden), which limits opportunities for Direct-With-Earth communications. As the lunar landing location progresses away from the South Pole, the effects of libration will gradually diminish, becoming negligible at approximately 83° South latitude. With HLS operating near the lunar pole, the apparent local elevation of the Earth will lie between approximately 0˚- 8˚ above the local lunar horizon. Because of the very low elevation angles, directional antennas onboard the HLS will be pointed nearly horizontally and thus subject to blockages from local lunar terrain features, as well as degradation from multi-path interference. As a result, HLS Direct-with-Earth communication link(s) are highly time-dependent and potentially variable, necessitating a concurrent, dis-similar communication link with Gateway (including crew remaining aboard the Gateway), and/or other lunar relay assets.

An example data product that illustrates the Earth elevation above the terrain, and thus where EVA activities would maintain DWE communication, at landing site Amundsen/Nobile Rim DM1 for two different dates is provided in Figure 4-11. This illustrates just how variable the conditions are for different landing opportunities. For a 30-day surface stay, DWE will be unavailable for approximately 14 consecutive days for sites within two deg of the South Pole.

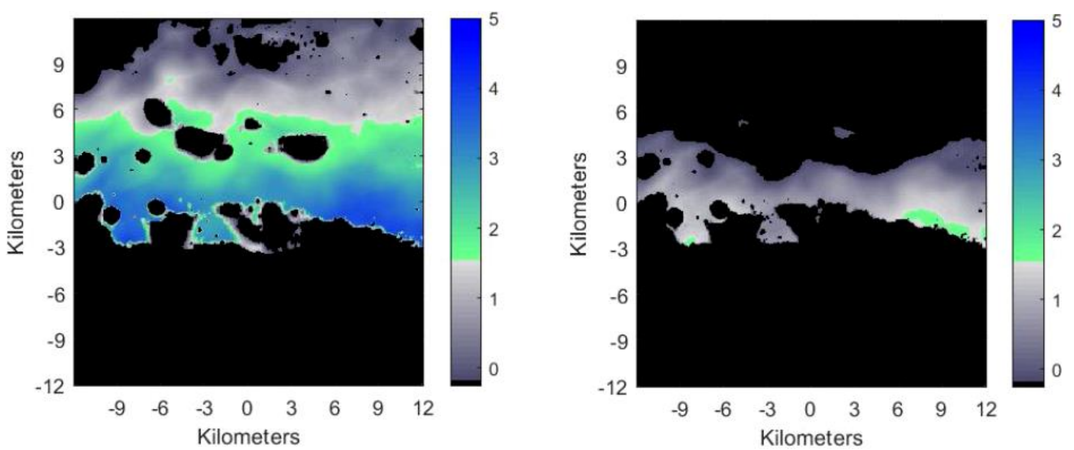

Figure 4-11 Earth elevation (in degrees) above the terrain for Amundsen/Nobile Rim DM on December 11, 2024 (left) and February 1, 2025 (right)

4.2.3 EVA Considerations

This document does not provide detailed EVA planning but is meant to guide it. Each site will have unique terrain that will need to account for path planning to locations of scientific interest.

The primary consideration being made is for line of sight (LOS) between the proposed HLS landing sites and the surrounding terrain is for communication and site planning. For sustaining sortie missions, without surface assets, EVAs are expected to have a walking radius of at least 2 km from the HLS landing site.

Sustaining extended excursion missions with surface assets can extend EVA distance beyond 2 km. Figure 4-12 shows an image of sample landing site 7 with a 2 km radius circle plotted. Assuming the vehicle is delivered to the center of the 2 km radius circle shown, the green shaded regions denote areas of direct line-of-sight at 5 m observer height. At this landed location crew EVAs would be limited to traverse in these areas. If the observer height is increased to 10 m, crew could explore to the purple regions. Finally, if the observer is at 50 m above the terrain at site 7, the additional area shaded in yellow is in the line-of-sight. Data such as this is considered in the site availability assessments.

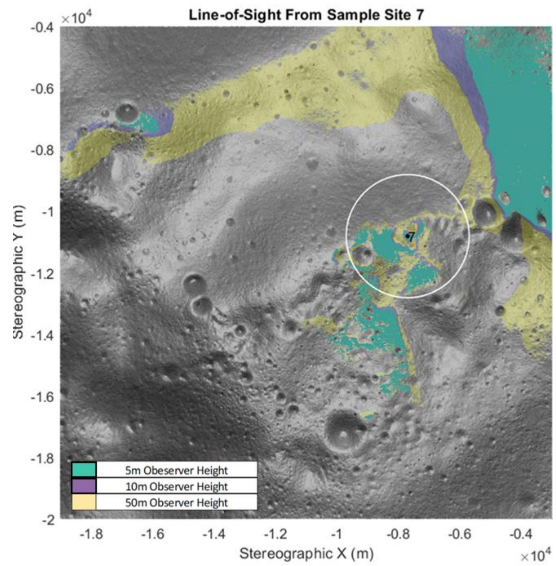

Figure 4-12 Line-of-Site from Sample Site 7

5.0 SITE AVAILABILITY CRITERIA

While the previous section summarized site availability considerations to help vehicle designers understand the dynamic nature of illumination and communication along with other environmental, system and mission constraints, there are six top level sustaining mission requirements that establish the landing criteria. They are listed in Table 5 - 1. Note that there is no in-space ΔV requirement for sustained mission vehicles, the table provides the value used in the site availability analysis presented herein. Different considerations are made for sortie and base camp missions and are described in the following subsections.

TABLE 5 - 1 SUSTAINED MISSION SITE AVAILABILITY RELATED REQUIREMENTS

Site Availability Criteria	Description	HLS Sustained Requirements	Figure of Merit
Landing Site Location	Some sortie and all basecamp Artemis Missions are constrained to 84ºS to the pole. Accessible areas that minimally exceed this requirement are noted in evaluation process.	HLS-S-R-0306	Polar locations 90ºS - 84ºS

TABLE 5 - 1 SUSTAINED MISSION SITE AVAILABILITY RELATED REQUIREMENTS

Site Availability Criteria	Description	HLS Sustained Requirements	Figure of Merit
Total In-Space ΔV	ΔV Required for maneuvers: NRHO Departure, Descent Lunar Orbit Insertion, Ascent Lunar Orbit Departure and NRHO arrival burns		< 1500 m/s
Landing Accuracy	The HLS shall be capable of landing within 50 m of target landing site for all descent lighting conditions.	HLS-S-R-0021	50 m from a target
Landing Terrain	The HLS shall be able to land and launch in terrain that contains ground slopes of at least 10 degrees as well as rock and crater distributions as defined in SLS-SPEC-159 DSNE section 3.4.1.	HLS-S-R-0022	Land on at least 10 deg slope
Slope	Sample sites are selected with an 8º slope mask derived from LOLA DEM data. Considerations for local siting include slope distributions within a 50m landing ellipse.	HLS-S-R-0071	Leveling to 8º threshold, 5º goal
Surface Lighting Conditions	Evaluated at observer heights corresponding to minimum or effective solar panel height. Consider recharging periods for sustained missions. Thermal considerations are captured in design specific criteria. Sortie missions will land on lit surfaces and remain lit for the duration of the surface mission. Extended missions need to be capable of operating in continuous daylight conditions with intermittent periods of darkness up to 120 hour (Threshold)	HLS-S-R-0070	Extended stay missions up to 120 hours continuous darkness
Communications	The HLS shall be capable of concurrent RF communications with crew staging vehicle, Mission Systems, Spacesuits and Surface assets. Evaluated to DSN 34m network with 10º DSN uplink/downlink mask. Earth elevation angle constraint included if required.	HLS-S-R-0029	

5.1 SUSTAINED – SORTIE

Sustained mission will not be constrained by the approach illumination due to the requirement to land in all approach lighting conditions. However, for sortie missions, the landing area will need to remain illuminated for the full six-day surface stay. Additionally, Gateway and other communications assets will be available for sustained sortie missions. The implementation of additional communications assets is still under development.

5.2 SUSTAINED – EXTENDED EXCURSION

Long-term exploration, or extended excursions, of the lunar South Pole will be executed from the Artemis Base Camp (ABC). A base camp is the operational origin and core for operations and activities, utilization, potential growth or expansion, and development. The ABC will leverage assets such as a surface habitat, pressurized and unpressurized rovers, and other infrastructure elements, to serve excursions to the Moon for various mission lengths. Leveraging these capable surface elements, subsequent excursion crews will return to the ABC repeatedly where they will live and work on the Moon.

The ability to return to the same site again and again on a regular cadence carries a unique set of challenges. A set of capabilities can be specified to address these challenges to support near and long-term operations. While sustained mission landers will most likely only service the initial buildup of ABC, there are several factors during initial buildup that must be considered to ensure long-term sustainability and use of the ABC. These considerations can be influenced by lander designs and placement. This section provides an overview of some of the key aspects of current ABC planning efforts and outlines some of the known challenges and potential mitigations being considered by NASA to support long-term ABC sustainability.

5.2.1 Site Planning

Long-term exploration of the lunar surface will involve repeated visits to the ABC and surrounds. General design and layout of an exemplary ABC has begun to take shape and evaluations of candidate ABC sites are underway. The ABC elements and functions for short- and long-duration occupancy include a habitat(s), science and research stations, communication, navigation, energy, resource utilization, lighting, surface mobility and transportation, logistics, waste management, sample caching, etc. The capability of the ABC will build over time as elements are delivered to the Moon's surface.

Preservation and protection of the ABC lunar habitation area(s) and sites of interest are essential to support near- and long-term NASA goals on the lunar surface. Proper site planning, design, and management will ensure physical clearance and arrangement to accommodate services and utilities essential for enduring habitation and scientific exploration and decrease the vulnerability and disruption that repeated landings and ascents will cause to the terrain, base camp systems, and operations. Access needs and interactions between surface elements, functions, and resources have been characterized by NASA's Human Exploration and Operations (HEO) System Engineering and Integration (SE&I) Lunar Architecture Team to better plan development, placement, and management of specific assets and systems to support operations and mitigate negative and undesirable interactions.

Operations, such as spacecraft landings and ascents, that have the potential to disrupt or contaminate habitation, science, resource, and reusable landing areas via plume/ejecta impingement, etc., must be located with sufficient distance and elevation from those areas to mitigate their negative effects. Additionally, landing locations must be balanced with surface mobility constraints (e.g., extravehicular activity including walking, rovers, robotics). The delivery and placement of the habitat itself will be strategically located to account for subsequent ABC elements and landers. Also, contingencies associated with circumstances such as lander instantaneous impact point(s) or approach and landing diversions, must also be accounted within the separation geometry of these sensitive areas and other landing areas. Table 5-2 provides a subset of key site planning and design guidelines specifically relevant to location and arrangement of landers serving the ABC.

TABLE 5 - 2 BASE CAMP PLANNING GUIDELINES

Guideline	Notes
Assets will be placed to avoid negative impact on habitation and exploration areas.	Efficient and effective placement of surface elements is required to accommodate ideal exploration, preservation, non-contamination, and utilization of habitation and resource areas.

TABLE 5 - 2 BASE CAMP PLANNING GUIDELINES

Guideline	Notes
Landing and ascent areas will be utilized to reduce plume impingement effects from repeated landings/ascents and to reduce their footprint, increasing logistical and resource efficiencies.	A reduced operations footprint is required both for efficient and effective use of desirable areas for landing/ascent and to mitigate the negative effects on surface elements that can be caused by landing/ascent plume impingement. This need suggests use of reusable landing and ascent areas or pads.
Plume surface interactions and landing accuracy capabilities will be considered when determining landing site location and the relative distance required to protect assets on the lunar surface.	The Apollo lander was estimated to have liberated 2400 kg (+/- 1400 kg) of regolith during descent which impacted surface assets 160 meters away.
The landing site shall be placed no further than TBD cumulative walking distance from the Surface Habitat (SH).	In the event of a rover mobility failure, the crew would be forced to walk between the landing site and the SH after landing or for ascent. Maximum walking distance for suited extravehicular activity (EVA) crew is based on the average EVA crew walking speed for the maximum EVA time permitted.
Landing area components will be positioned to accommodate expected landing approach paths (obstacles, shadows, etc.).	Safe landing operations require accounting for naturally induced and human-induced obstacles, shadows, and other effects posed by elements at or near expected landing sites.
If reusable, landing areas and ascent areas will be managed/maintained between landings/ascents.	Safe landing and ascent operations require appropriate preparation, debris removal, and hazard mitigation of landing/ascent surfaces and surroundings.
Surface elements will be arranged for efficient access to natural and emplaced resources, functional areas, and exploration areas.	Overall site design must accommodate access to resources, operational efficiencies, environmental management, and science value for long term surface architecture and sustainability.

5.2.2 Landing Zone Considerations

Careful evaluation of several characteristics, including landing accuracy, surface slope, terrain, and illumination, provide a basis by which to determine the number and placement of potential landing locations. For example, a landing accuracy of 50 m or less from an intended target ensures that more “parking spots” are available per square kilometer of a designated landing zone. That is, the greater the landing accuracy, the greater the number of landers that can be accommodated within a limited area. This, coupled with sufficient illumination conditions, also increases the likelihood of locating landing spots within a landing area that have surface roughness and slopes that can accommodate safe landings.

5.2.2.1 Slope, Terrain, and Landing Accuracy

The ability to land on steeper slopes also increases the number of viable landing spots. Allowing fractions of the area within a landing ellipse to exceed the slope requirement further increases the capacity (total number of landers) of valid landing locations but relies on the lander’s guidance and control system to detect and divert from more hazardous regions. A recent NASA study compared the lander capacity of a notional landing region while varying the percentage of different slope values within non-overlapping and overlapping landing ellipses (i.e., different landing accuracies). As an example, a multivariate comparison was conducted between conditions of a) 80% of each 100 m radius landing circle to have a surface slope of 8 deg or less and b) 80% of each 50 m radius landing ellipse to have a slope of 10 deg or less, both over a 200 m x 200 m area. The study did not consider restrictions due to surface plume and blast ejecta interactions. Results revealed that

1. the viable landing area increases as landing accuracy and slope tolerance increase

2. higher landing accuracy increases the number of landers that can be delivered to an area, and
3. allowing for overlapping landing ellipses increases the number of landers that can be in an area

5.2.2.2 Illumination

In addition to landing accuracy and slope tolerance, extending the vehicle capability to survive periods of longer hours of continuous darkness increases the size and number of viable landing areas, e.g., areas of 120 hours or less of continuous darkness are significantly more restrictive in presenting viable landing areas than tolerance for 230 hours.

The ability to land in any lighting conditions reduces the dependency of landing site viability to time of year. Sun angles, shadows, etc. change over time and lander designs that are dependent on certain lighting conditions will find it difficult to return to the same site from mission to mission. Therefore, sustained missions will need alternatives to passive terrain relative navigation (TRN), such as use of active lidar-based TRN, beacons (surface and/or orbiting), or other navigation aids systems that do not require illuminated descent trajectories and promote greater flexibility in landing site availability.

5.2.2.3 Plume/Ejecta Impingement

Mitigation of plume/ejecta impingement on ABC elements via landers is of utmost importance. Without adequate mitigation strategies, damage to lunar orbital assets may occur due to contact by ejecta, and dust may contaminate the docking mechanism of lander ascent vehicle(s) potentially jamming or compromising docking of the vehicle to an orbiting asset such as Gateway. Mitigation techniques can be offered by lander design approaches as well as strategic surface placement considering natural terrain features such as elevation, slope, natural berms, and human-made “obstacles” and berms, and other non-critical objects, etc.

5.2.2.4 Communication

Landing site flexibility will be enhanced with use of a communication relay. It will ensure that surface assets will not need to rely on direct-to-Earth or direct-with-Gateway (orbiting crew vehicle) communication links, both of which would limit lander location and surface stay duration.

5.2.3 Landing Zone Traffic Management and Long-term Sustainability

NASA will control and specify landing zones directly serving ABC and will parse and designate landing sites by lander type and lander capabilities. Expanding the capacity of viable landing zones serving ABC will support traffic management. That is, any planning for long-term sustainability of the ABC must address the potential crowding of designated landing zones starting with pre-ABC conditions. That is, even early landing missions targeted for the ABC may contribute to long-term overcrowding. In addition to crew Human Landing System landings, the ABC will be periodically visited by cargo supply landers. Cargo landers will support expanding capabilities through the delivery of large support elements and logistics to keep ABC operational. They may arrive on the surface well in advance of crewed landers to reduce potential risks associated with crewed launches such as range and weather constraints, and other technical issues. Additional landers delivering science and technology payloads and instrumentation are also planned.

If not removed from a landing site or area, overtime, these various landers have the potential to impede and divert efficient access to ABC habitation, science, and resource areas of interest.

Therefore, long- term mitigations focus on removing lander components from the landing zone to leave individual landing sites available for future use. The following are only a few potential mitigation solutions, and NASA encourages industry partners to help identify additional approaches for long-term traffic management.

5.2.3.1 Lander-Executed Solutions

Lander Reuse: Any lander concept that returns to orbit after completion of its surface mission will, by definition, mitigate landing zone crowding by leaving its landing site available for use by future landers. While lander reuse is not required for sustainability, there would be a residual benefit to the long-term sustainability of ABC.

Lander Relocation: After completion of its primary mission, lander components remaining on the surface relocate to a “disposal zone”

- Some landing missions may support a Skycrane approach to delivery of cargo, allowing the cargo to be retrieved from the landing zone by crew or robotic assets while the lander, having never actually touched down in the landing zone, is redirected to a NASA-identified disposal zone
- Landers could carry additional impulse provisions to “hop” to a NASA-identified disposal zone after their primary mission is complete

5.2.3.2 ABC-Executed Solutions

Lander Zone Assignment: NASA will designate and assign specific landing areas and sites according to lander type, capabilities, and payloads, e.g., crew, logistics, science, and other assets

Robotic Landing Site Clearance: Landers and lander components could be towed out of the landing site to a NASA-designated disposal area by ABC-provided rovers

Accumulation of spent landers that serve ABC will consume and deplete prime landing acreage and increase operational complexity, mobility consumables, safety risk, and plume impingement / plume-induced ejecta damage to base camp assets, science and resource areas of interest, and surrounds. NASA’s integrated ABC site planning and design effort has identified numerous risks associated with repeated landings to a particular area(s), and lander systems with lander components remaining in place, that will negatively impact long-term sustainability of the ABC. Increased lander accuracy, and slope, terrain, and illumination/darkness tolerances will widen the span of viable landing areas to serve ABC and thus help to reduce risks. Proactive traffic management, including smart landing site assignments as well as identification and implementation of long-term mitigation strategies must be instituted to ensure that the goals of long-term lunar presence and the ABC can be achieved.

6.0 SUMMARY/CONCLUSION/TRENDS AND OBSERVATIONS

This document summarized the differences between the Apollo and Artemis mission concepts of operations in Section 2, and how those differences affect landing site availability at the South Pole. Section 3 described the variations on polar mission concepts of operation for Artemis sortie and sustained excursion design reference missions. Site availability considerations, accounted for thus far for the sustained phase period of performance, based on the environmental, system and mission design factors and why they are critical in the site availability assessment for both sortie and basecamp missions were described in Section 4. Landing site considerations are divided in two categories. The first category includes those considerations that affect *getting to the site*, and include launch opportunities from Earth, departure opportunities from NRHO, approach and site illumination, surface rocks and slopes, and communication with the crew staging vehicle and Earth. The second category focus on those considerations that effect working *at the site*. These include similar considerations for solar availability, DWE communications and surface slope and rocks distributions, but from the EVA and surface operations perspective. Finally, Section 5 described the considerations that vary for short sortie missions compared with basecamp, which will have many more elements delivered to the same location over time. While specific landing sites have not been identified, the site considerations described herein provide guidance for vehicle design.

APPENDIX A
ACRONYMS AND ABBREVIATIONS AND GLOSSARY OF TERMS

A1.0 ACRONYMS AND ABBREVIATIONS

TABLE A1-1 ACRONYMS AND ABBREVIATIONS

CLPS	Commercial Lunar Payload Services
ConOps	Concept of Operations
CSV	Crew Service Vehicle
DRM	Design Reference Mission
DSNE	Design Specification for Natural Environments
DTE	Direct to Earth
DWE	Direct with Earth
EVA	Extravehicular Activity
HLS	Human Lander System
LLO	Low Lunar Orbit
LM	Lunar Module
LOLA	Lunar Orbiter Laser Altimeter
LOS	Loss of Signal
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
NRD	NRHO Departure
NRHO	Near Rectilinear Halo Orbit
NRI	NRHO in
RF	Radio Frequency
SLS	Space Launch System

A2.0 GLOSSARY OF TERMS

TABLE A2-1 GLOSSARY OF TERMS

Term	Description