Lunar Site Selection

Introduction

Lunar site selection is an iterative process that evolves as we learn about vehicle capabilities, objectives, and architecture use cases and functions. Selecting sites for lunar operations requires identifying locations that would enable stakeholders to address one or more of NASA's Moon to Mars Objectives: in essence, "where we want to go," balanced with locations where safe lunar landings can be conducted, or "where we can go."

Available capabilities will evolve throughout the Moon to Mars Architecture segments, as defined in the Architecture Definition Document,[1] which will affect the relationship between "where we want to go" and "where we can go." As Artemis missions progress from the Human Lunar Return segment through Foundational Exploration and Sustained Lunar Evolution segments, mission planning will benefit from increased access to reusable infrastructure on the lunar surface and in orbit, as well as a better understanding of the lunar environment (for a detailed description of Moon to Mars exploration segments, refer to NASA's Architecture Definition Document).

Human Lunar Return missions will need to find safe landing locations close to the intended destination of surface operations as new systems are tested for the first time. Subsequent missions will benefit from the lessons learned during the Human Lunar Return segment, improving awareness of the lunar surface and environment and enabling more accurate landings, the ability to traverse longer distances across the Moon, and longer duration missions.

These improvements will relax the need for proximity between safe landing locations and intended targets of interest for surface science operations. As the architecture evolves, "where we want to go" will influence requirements for new systems, leading to an architecture that can reliably send astronauts to locations of interest.

Objectives Traceability

The Moon to Mars Objectives define the locations that NASA and its partners will need to access on the lunar surface or in lunar orbits in order to address our goals.[2] Therefore, traceability to these objectives determines "where we want to go."

Some objectives can be addressed simply through access to lunar orbits or the surface in general, without location-specific needs (e.g., observations of the human response to the lunar environment or gravity transitions). However, some objectives require access to specific environmental conditions or physical locations on the lunar surface, such as access to lunar volatiles in persistently or permanently shadowed regions or locations near multiple diverse terrain types, which would enable us to study the history of the Moon.

Progression through the architecture segments will likely result in an evolution of emphasis on different objectives. For instance, objectives that require longer stays and increased capabilities will benefit from favorable conditions, such as sustained access to greater-than-average amounts of sunlight to reduce thermal variability or to enable better power generation. As missions progress throughout the segments, NASA must achieve a balance between visiting previously unexplored terrain and developing routine and repeatable presence at select locations.

Lunar Conditions

Human Lunar Return activities will focus on conducting safe lunar landings and returning crews to Earth while conducting science in a region of the Moon that has not yet been explored by astronauts. These early Artemis missions will test new systems in new environments and establish a path for more capable missions to follow in later exploration segments. As these new systems are tested, the initial landings will need to identify relatively flat terrain, with only small blocks and impact craters that are within the lander's hazard tolerance. This type of terrain is also of value for initial extravehicular activities, or spacewalks, as the capabilities of new suits and surface tools are tested. Awareness of the physical characteristics of a potential landing site requires adequate data for site characterization. Each lander will have a unique tolerance for surface roughness or obstacle size; knowing if those obstacles are present requires proper data. NASA-acquired lunar data is made publicly available via the Planetary Data System[3] (the Lunar Reconnaissance Orbiter team provides a useful tool for accessing the data).[4] The highest resolution image data for the Moon has a resolution of roughly a single meter, but this resolution is not universally available across the polar regions. Therefore, data availability (data collected prior to or during a landing) and surface characteristics affect site selection.

Lunar lighting must also be taken into consideration; early landings will be conducted at times for which the landing site is largely sunlit throughout the entire mission. Therefore, the initial Human Lunar Return landing site should be sunlit for approximately 6–6.5 days. As the architecture continues to develop, access to sunlight will allow Artemis missions to use long-lived, reusable infrastructure to generate solar power, optimize systems to account for expected thermal extremes, and maintain hardware and crew within certain temperature ranges.

The Moon's low axial tilt results in polar lighting conditions that can range from areas of continuous darkness to areas that are often sunlit (however, there is no known location in the South Pole region that is continuously sunlit). Generally, higher topography terrain will experience a longer duration of access to sunlight. Furthermore, any hardware that provides additional height off the surface will increase sunlight access. The architecture can take advantage of this characteristic as it evolves.

Every location experiences a unique ratio or pattern of sunlight/darkness. These patterns can be predicted on the surface, but the ratio can vary significantly over short distances. Thus, the concept of a lunar day/night cycle at the poles is not consistent across the region and does not match our experience on the Earth, or even elsewhere on the Moon.

Identifying initial locations with favorable lighting can restrict landing access to limited time periods throughout the year, and there will be times when a landing cannot be performed because the region will be in shadow (Figure 1). Therefore, depending on when the mission launches, a desired landing site with gentle sloped terrain might not be in sunlight, and the period of darkness could be brief or extensive, lasting weeks or months. For a more detailed description of the lunar south polar lighting, refer to the 2022 Architecture Concept Review white paper "Why Artemis Will Focus on the Lunar South Polar Region."[5]

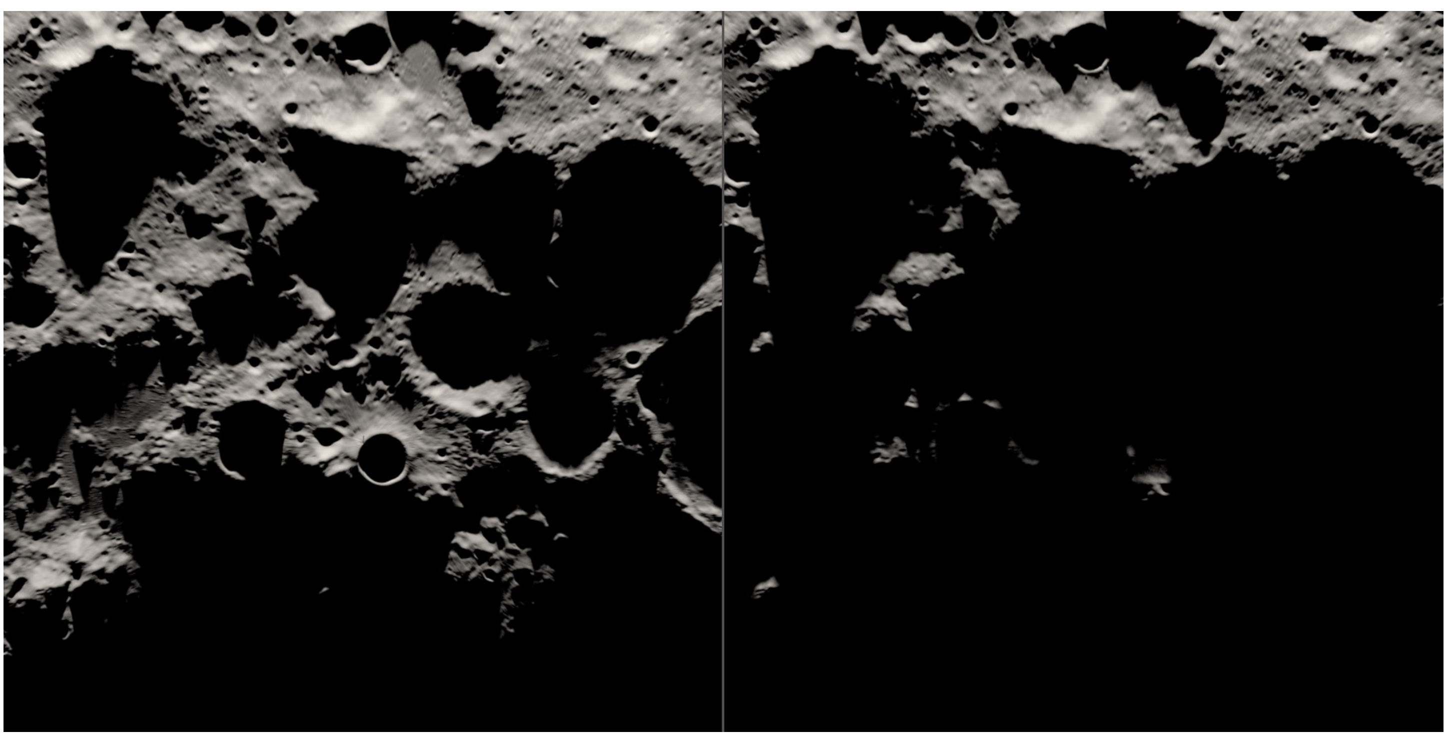

Figure 1. *Topographic maps of the lunar South Pole showing modeling lighting conditions during the summer season (left) and the winter season (right). Earth is to the top of the images. To see the full animated video of lighting conditions around the lunar south polar region please visit: [NASA SVS | Illumination at the Moon's South Pole, 2023 to 2030]*

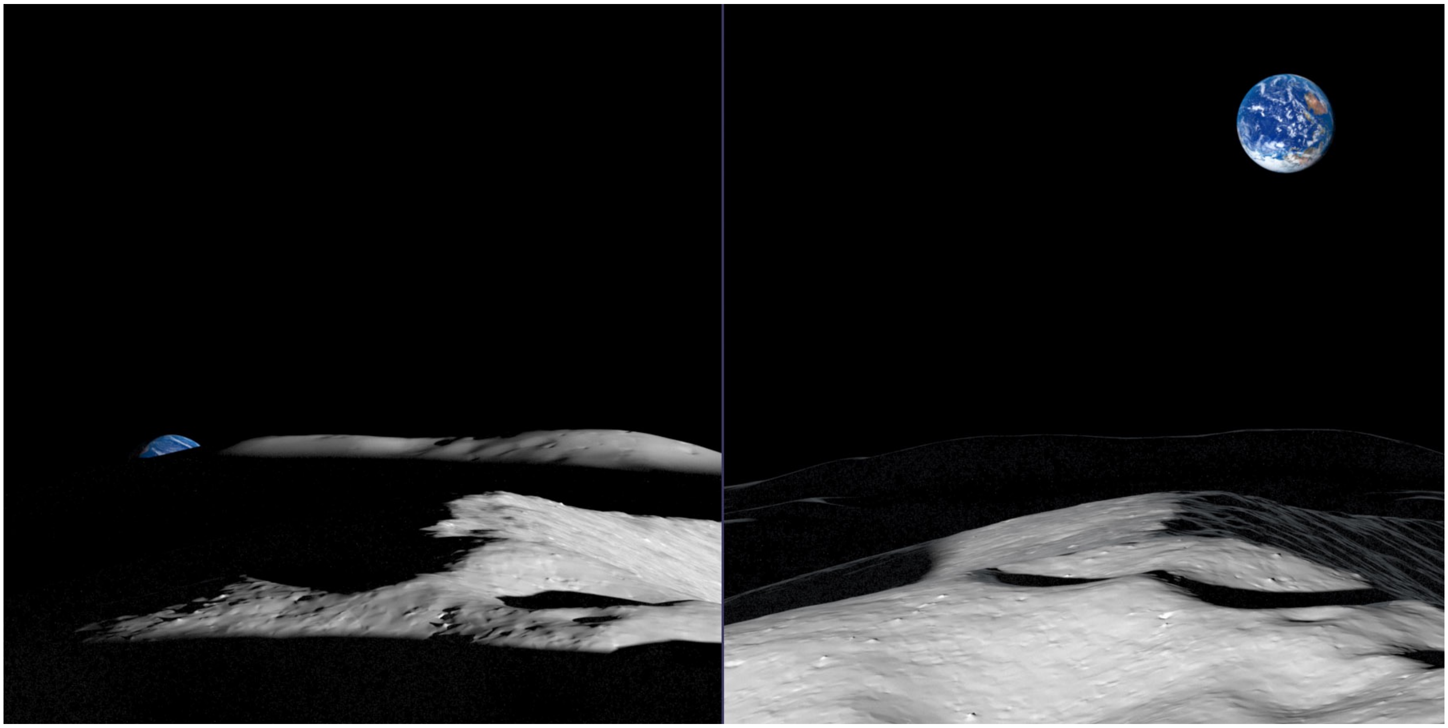

Figure 2. *Animations showing the same view of the Earth from a location near the South Pole. The degree to which the Earth is visible from this location changes over time, with the Earth being completely obscured at times throughout the year. To see the full animated video please visit: [NASA SVS | Earth and Sun from the Moon's South Pole]*

The lunar seasonal cycle does not overlap with Earth's seasonal cycle. The Moon will experience roughly 11 seasonal cycles per 10 Earth years. This means that over a decade, the alignment between lunar season and Earth season will shift. The lunar summer will slip against the Earth calendar over a series of years and the best months of lighting at the lunar South Pole will not be the same set of months on the Earth. Therefore, lighting at a given site will shift throughout the Earth year over time. Increasing capability to land in all lighting conditions will enable additional site opportunities.

Surface operations will require communications with personnel on the Earth. Prior to the establishment of communications infrastructure on or around the Moon, a Human Lunar Return landing site would likely need to depend on direct-to-Earth communications. This means that the Earth must be visible in the lunar sky from the landing site.

The Apollo missions landed on the Earth-facing side of the Moon, so the Earth was always visible in the lunar sky. However, the Earth is never visible from the far side of the Moon. The poles are located along the edge of the visible surface (disc) of the Moon as viewed from Earth, between the Earth-facing side and far side of the Moon (limbs of the Moon). Thus, much like lighting conditions, visibility of the Earth can vary (Figure 2).

The farther a location is past the pole toward the far side, the less likely the Earth is to be visible (and may only be visible from high-elevation terrain). Similarly, low-elevation terrain on the Earth-facing side of the Moon near the poles might also experience periods of time without direct Earth visibility. Additional architecture capabilities, such as communication relays, will enable more site selection options. As the exploration campaign progresses, surface mobility is likely to increase as well. As a result, planning for lighting and communications will not only need to account for landing, but also for traversing the lunar surface.

Mission planning will benefit from over five decades of lunar data collection. Although lunar conditions in the South Pole region are different from past Apollo experience, these conditions are repeatable and predictable. While no single location constantly — or even routinely — has ideal lighting and Earth visibility conditions, we can identify landing sites that are available over specific periods. As the architecture evolves through each exploration segment, lighting and communications considerations can be addressed to enable better access to locations of interest.

End-to-End Mission Availability

While the considerations above focus on the lunar surface environment, constraints, and operations, NASA assesses mission planning holistically. Building on lunar site conditions, developing end-to-end mission availability metrics requires incorporating when NASA's Exploration Ground Systems, Space Launch System (SLS), and Orion spacecraft can launch the crew to rendezvous with Gateway and/or the Human Landing System, which would be located in near-rectilinear halo orbit, to perform the lunar surface sortie.[6]

The Artemis enterprise's unique multi-vehicle, multi-launch architecture also creates additional ground processing challenges. For Artemis III, Orion will rendezvous directly with SpaceX's Starship Human Landing System. Rendezvousing with a prepositioned spacecraft creates additional constraints — mission planners must align the phasing of the target vehicle in lunar orbit with the window for Orion to intercept the Moon.

From an Exploration Ground Systems/SLS/Orion launch availability perspective, the vehicle configuration (SLS Block 1 or Block 1B) faces unique mission availability challenges. Artemis III will be the last flight of the Block 1 configuration. Artemis IV and beyond will use either the Block 1B or Block 2 configuration.

For SLS Block 1, the vehicle launches to an intermediate elliptical low-Earth orbit to best position the upper stage to perform the trans-lunar injection, placing Orion on a trajectory to intercept the Moon. Given the necessary launch geometry, Exploration Ground Systems/SLS/Orion can only achieve lunar orbit for roughly half of the Moon's orbit around Earth, nearly centered around the Moon's minimum lunar declination.

Orion's insertion into near-rectilinear halo orbit must also provide sufficient time for crew operations to prepare for the lunar surface mission. Thus, for Artemis III, mapping the intersection of available lunar landing sites with when the crew can launch and rendezvous with the Human Landing System is a critical component of mission availability.

Furthermore, once in near-rectilinear halo orbit, the Human Landing System is expected to be viable to conduct a lunar landing for about 90 days, meaning that the crew must arrive within that window of time to use the Human Landing System for a landing. Carrying multiple landing site options maximizes the likelihood of a successful landing across a calendar year within the multitude of mission constraints, one being the Human Landing System vehicle lifetime. In later segments of lunar exploration, the infrastructure could evolve to relax constraints on landing site availability and enable the selection of a single site.

For SLS Block 1B, the Exploration Upper Stage inserts into a circular low-Earth orbit. While this removes the performance constraint in the SLS Block 1 configuration, the new co-manifested payload capability can place additional performance demands on Orion. After the SLS Exploration Upper Stage performs the trans-lunar injection, Orion will be responsible for extracting the co-manifested payload and ferrying it to near-rectilinear halo orbit. The mass of that payload can significantly affect mission availability.

The mission designs for Artemis IV and beyond will also need to account for any timeline and consumable constraints. Mission availability for later Artemis missions will depend on the intersection of leveraging the range of the co-manifested payload capability and performing a lunar surface mission.

While this is a core component of near-rectilinear halo orbit accessibility, the later Artemis missions do benefit from the presence of Gateway and a lunar relay. The presence of these elements will help alleviate the challenges of direct-to-Earth communications for the Human Landing System and other future surface assets, ultimately opening additional lunar site availability.

In addition to all the nominal mission considerations above, protections for various contingency scenarios further restrict overall mission availability. The scope and coverage for these situations is a risk-informed decision that must maintain a delicate balance between the vehicle capabilities and protecting the crew.

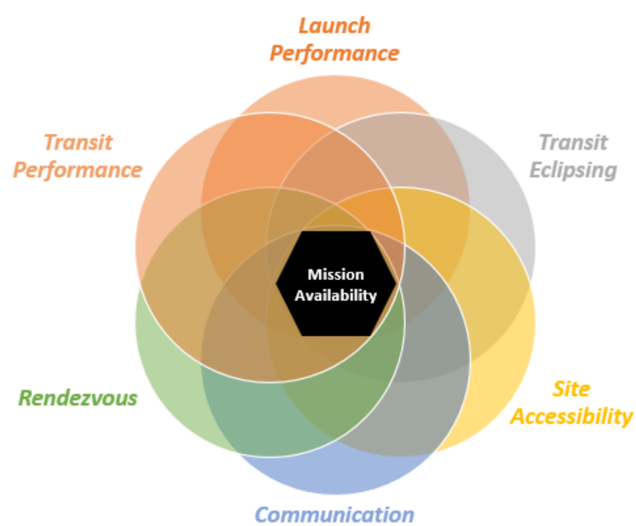

Figure 3. *Mission availability coordinates across multiple considerations, including vehicle capabilities and lunar environmental and physical characteristics. All of these factors must be considered when planning site selection for lunar surface operations.*

Site Selection Evolution

Lunar site selection considerations will evolve during the Foundational Exploration and Sustained Lunar Evolution segments. Both segments will involve an increase in capabilities to support lunar exploration from orbit and on the surface. Reusable hardware and surface infrastructure that can support longer stays and enable routine access to preferred locations and access to new locations will become key aspects of operations. Reusable surface assets are likely to be consolidated at one or more locations, which will have an impact on where we land, either to deliver new hardware or to use previously emplaced hardware.

As in the Human Lunar Return segment, the timing of a launch and landing can lead to different lighting and Earth. visibility conditions from different locations across the south polar region. However, our approach to landings will evolve as our knowledge of the lunar environment and terrain characteristics increases.

For instance, the addition of communications capabilities will decrease the need for Earth visibility during landing or throughout a surface mission, and knowledge of the terrain and possible hazards for landers might lead to landing options in regions that are partially or entirely dark.

As infrastructure is emplaced on the lunar surface, subsequent landings might need to be conducted at or around the same locations multiple times, meaning that site selection drives the mission. Returning to the same location will require relaxation of site accessibility constraints related to lighting, communications, and terrain awareness, which could be addressed through continued data acquisition for that location and contributions from the evolving architecture.

New landing site characteristics might need to be considered. Hardware that remains on the surface could become an obstacle to future landings and surface operations; if that hardware remains in use, future landings will need to account for the plume surface interactions that landers create during descent and ascent. Furthermore, deployed hardware could become an obstacle for sun visibility for previously deployed elements.

All partners operating on and around the Moon will need to consider these factors. As the architecture develops, it should use reusable infrastructure to relax some landing site constraints, thereby enabling mission planners to access locations of interest more dependably as missions progress. However, permanent infrastructure will also introduce important new considerations.

Summary

Identifying lunar sites for landing and surface operations is an iterative process that considers vehicle capabilities, objectives, and architecture use cases and functions. Any mission must balance "where we want to go" with "where we can go" safely with our crew and other assets based on the capabilities available at that time. Site selection must account for characteristics such as surface roughness and slope, lighting, and, in early missions, visibility of the Earth. Mission planers require lunar data about these characteristics to match with vehicle capabilities.

We must also consider the performance of multiple vehicles to enable spacecraft to reach Earth orbit, initiate the trans-lunar cruise, rendezvous with other previously deployed spacecraft in lunar orbit, and begin the descent to the lunar surface. Before we establish surface and orbital infrastructure to support these activities, early landing locations will be heavily influenced by when the crew launches from the Earth (Figure 3). As supporting infrastructure is emplaced and we learn about operations in the lunar south polar environment, mission planners will use the additional information to consider a broader range of sites to meet NASA's Moon to Mars Objectives.

Key Take-Aways

Physical and environmental lunar conditions will have a strong influence on site selection, including surface roughness and slope, lighting, and Earth visibility.

Coupled with vehicle capabilities, the early Human Lunar Return mission sites will largely depend on when the crew launches.

As supporting infrastructure is emplaced over time through the Foundational Exploration and Sustained Lunar Evolution segments, accessibility to sites of interest should increase and

References

1. NASA's Moon to Mars Architecture Definition Document
2. NASA's Moon to Mars Objectives
3. Planetary Data System
4. Lunar Reconnaissance Orbiter Lunar Quickmap
5. Why Artemis Will Focus on the Lunar South Pole Region
6. Why NRHO: The Artemis Orbit