

THE PERFECT LANDING SITE FOR THE FIRST LUNAR SOUTH POLAR LANDER David A. Paige¹
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Introduction: The south polar region of the moon is a key target for future robotic and human exploration. Its rugged topography and extreme thermal environments present opportunities for cold-trapping of volatiles as well as technical challenges for surface and sub-surface exploration. While there has not yet been a successful landed lunar polar mission, plans are under way to target multiple landers to the south polar region during the next decade. Here we examine some of the scientific and practical issues associated with targeting landers to the lunar south polar region based on what we have learned through the analysis of remote sensing data and modeling during the last decade.

Sun and Earth Visibility: For solar powered landers with direct-to Earth communications, the visibility of the Sun and Earth are key drivers for mission planning. The monthly rotation of the Moon about the Earth results in a ~28 day diurnal insolation cycle that is modulated by a low-amplitude seasonal variation due to the 1.54° obliquity of the Moon's spin pole. These factors combine to yield optimal insolation conditions during the daylight hours of the three-month lunar southern summer season, which occurs on ~11 month centers. Due to the Moon's synchronous rotation, the sub-Earth longitude is fixed near 0° longitude, but the sub-Earth latitude varies by $\pm 6^\circ$ over the course of a month. Periods with optimal simultaneous Sun and Earth visibility in the south polar region occur during ~3-month lunar southern summer seasons, which peak every ~11 months. From a programmatic point of view, the temporal spacing of favorable south polar mission opportunities is analogous to the ~26 month spacing for Mars missions.

Large Scale Topographic Considerations: The visibility of the Sun and the Earth are strongly affected by topographic relief, which can either frustrate or enhance Sun/Earth visibility. There is no fixed location of "eternal" sunlight in the south polar region, but many locations on the lunar near-side poleward of 84°S can experience periods of continuous simultaneous Sun and Earth visibility lasting up to ~14 days during favorable landing seasons during lunar southern summers (See Fig. 1). For fixed landers, the requirement to land in locations that have direct Sun and Earth visibility rules out the interiors of most large polar craters as landing sites. Even out of these keep-out zones, landers that are not designed to survive lunar nighttime thermal conditions should expect continuous operational lifetimes of <14 Earth days. Nighttime survival has the potential to extend mission lifetimes into multiple months, but for

the first lunar polar lander missions, it would seem prudent to plan to accomplish the majority of key mission goals during the first month of operations.

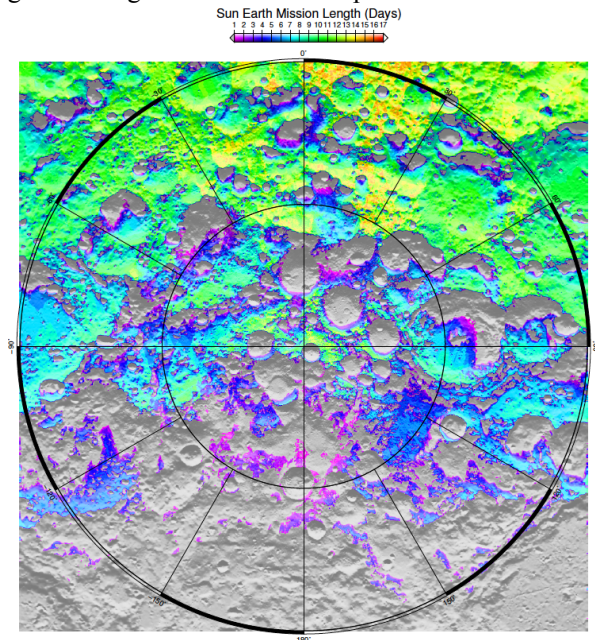


Fig. 1. Map of the lunar south polar region to 80°S showing the number of Earth days that both the Sun and the Moon are both more than 1° above the local horizon for a typical favorable lunar southern summer landing season, which generally occur every 11 months.

Small Scale Topographic Considerations: Small-scale lunar relief features pose hazards to safe landing, as well as to Sun and Earth visibility. Because of concerns regarding the potential effects of small-scale topography on Sun and Earth visibility, as well as concerns about multi-path interference for direct-to-Earth radio communications, it is customary to assume a "horizon mask" of at least 1° above the local horizon for mission planning purposes (See Fig. 1). Note that locating Earth ground stations at a high southerly latitudes could potentially provide an additional ~1° of Earth communications visibility for lunar south polar missions. The sub-Earth latitude as seen from the Moon will be closest in phase with the sub-Moon latitude as seen from the Earth in 2035.

Access to Volatiles: From a technical perspective, planning and executing a robotic or human mission to the lunar south polar region appears to be accomplishable given currently available knowledge and capabilities. However, if the overall scientific and exploration goal of these missions is to find and study frozen lunar

polar volatiles, then the overall success of these missions is not 100% assured. While the general theoretical case for the presence of frozen lunar volatiles has existed for almost 60 years¹, we still lack sufficient information regarding the abundance, distribution, and composition of these volatiles to guarantee that they will be accessible at any given landing site². We know from orbital neutron spectrometer measurements that the uppermost ~50 cm of the polar regolith contains enhanced hydrogen abundances relative to the equatorial regolith³. However, the implied area averaged abundance of water in polar near-surface soil is < 100 ppm, and given the extreme diverse thermal environments that exist in the south polar region^{4,5}, it is highly likely that water is preferentially concentrated in permanently shadowed polar cold traps. As a consequence, surface soil in regions that receive direct solar illumination may be as devoid of volatiles as the Apollo lunar samples. Therefore, to increase the probability of accessing volatiles, it would seem almost mandatory for a polar lander to access surface or sub-surface cold-trap regions.

Subsurface Cold Traps: Analysis of Diviner thermal mapping results has shown that the Moon's surface cold traps areas are surrounded by extensive areas of sub-surface cold traps that experience episodic periods of direct sunlight, but maintain cryogenic temperatures at ~10 cm depths below the surface⁴. The existence of these near-surface cold traps has suggested that the first lunar polar lander missions might employ the same volatile access strategies as the first Mars polar lander missions such as MPL and Phoenix. In these missions, the lander was targeted to a seasonally illuminated region and planned to dig into the cold underlying soil. This strategy worked brilliantly for Phoenix, but it is not entirely clear whether this same strategy would work as well for the Moon, as the atmospheric processes responsible for concentrating ice in the high-latitude regolith on Mars, while still mysterious, are not likely to have operated on the airless Moon.

Surface Cold Traps in Small Shallow Craters: Based on experience gained from studying the extensive polar ice deposits that currently exist on Mercury, it appears that thick deposits cold-trapped volatiles on airless bodies are primarily the result of surface accumulation, rather than subsurface diffusion. This is evidenced by the purity of Mercury's water ice deposits, and the fact that they have clear topographic signatures in that small (3-10 km diameter) high-latitude craters on Mercury appear to be literally filled with ice⁶. In the lunar south polar region, we observe a similar tendency for small impact craters to become shallower near the pole, which also suggests that surface ice has accumulated in these cold traps at some earlier point in the Moon's history⁶. These results appear suggest that the high volatile

abundances revealed by the LCROSS impact in the uppermost meters of Cabeus Crater⁷, may in fact be typical. The fact that these deposits do not exhibit strong radar signatures, or obvious indications for the presence of abundant surface ice, suggests that space weathering and impacts have buried and/or reworked these deposits over time (Fig. 2). From a purely thermal perspective, small shallow craters on the Moon should be just as effective cold-traps as a larger shallow craters⁸. New modeling results show that permanently shadowed craters as small as 1 m in diameter should be effective cold traps, despite the effects of lateral heat conduction⁹. Fortunately, shallower craters not only create colder cold traps, but also enable easier overland entrance and egress. To avoid the potentially dominant effects of surface reworking, craters with diameters of >10m would be preferred.

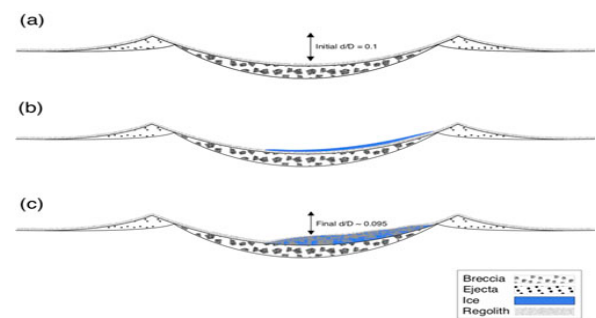


Fig 2. Diagrammatic cross-section through a volatile-rich shallow polar crater⁶.

The Perfect Landing Site: From the above discussion, the perfect landing site for the first lunar polar lander would include the following characteristics:

1. Direct continuous views of the Sun and Earth over multiple days
2. Cold sub-surface temperatures ~10 cm below the surface to enable characterization of possible cold-trapped volatiles underlying sunlit regions
3. Proximity to multiple small shallow craters that contain regions of permanent shadow. Accessing these cold-trapping regions by rover or by foot would enable us to assess the extent to which surface volatiles are being cold-trapped on the surface today. Based on presently available information, the ability to sense or dig into these surface cold traps could reveal the presence of significant volatile concentrations.

References: [1] Watson et al, JGR 66, 1961. [2] Lawrence, JGR Planets, 2016. [3] Feldman, JGR 106, 2001. [4] Williams et al, JGR Planets, 2019, [5] Paige et al., Science, 2010, [6] Rubanenko et al, Nature Geosciences 2019 [7] Coloprete, Science, 2010. [8] Vasavada, et al., JGR, 1999, [9] Powell et al., this workshop, 2020.