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FEASIBILITY AND DEFINITION OF A LUNAR POLAR VOLATILES PROSPECTING MISSION

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The recent Lunar Crater Observing and Sensing Satellite (LCROSS) mission has provided evidence for significant amounts of cold-trapped volatiles in Cabeus crater near the Moon's south pole. Moreover, LRO/Diviner measurements of extremely cold lunar polar surface temperatures imply that volatiles can be stable outside of areas of strict permanent shadow. These discoveries suggest that orbital neutron spectrometer data point to extensive deposits at both lunar poles. The physical state, composition and distribution of these volatiles are key scientific issues that relate to source and emplacement mechanisms. These issues are also important for enabling lunar in situ resource utilization (ISRU). An assessment of the feasibility of cold-trapped volatile ISRU requires a priori information regarding the location, form, quantity, and potential for extraction of available resources. A robotic mission to a mostly shadowed but briefly sunlit location with suitable environmental conditions (e.g., short periods of oblique sunlight and subsurface cryogenic temperatures which permit volatile trapping) can help answer these scientific and exploration questions. Key parameters must be defined in order to identify suitable landing sites, plan surface operations, and achieve mission success. To address this need, we have conducted an initial study for a lunar polar volatile prospecting mission, assuming the use of a solar-powered robotic lander and rover. Here we present the mission concept, goals and objectives, and landing site selection analysis for a short-duration, landed, solar-powered mission to a potential hydrogen volatile-rich site.

I. INTRODUCTION

The Lunar Crater Observing and Sensing Satellite (LCROSS) mission has recently confirmed the presence of significant quantities of volatiles in Cabeus crater near the lunar south pole[1,2]. A surprising finding from the Lunar Reconnaissance Orbiter (LRO) mission is the possibility of polar volatile deposits located just centimeters below the lunar surface in areas that receive only a few days of sunlight each month[3,4,5,6]. These deposits would be much more accessible than volatiles found in permanent shadow and thus could be explored *in-situ* by a small, low-cost solar powered rover. This paper describes a short duration low-cost solar powered rover mission to explore these regions of lunar permafrost (Figure 1).

A solar–powered, continuously operated, lunar polar rover prospecting mission is unlike any prior planetary rover mission. The rover must navigate 3-5 km of lunar highlands-like terrain and excavate multiple sites in a very short time, some of which must be reserved for system checkout, lander egress and contingencies. Operational decisions must be made in near real time throughout the mission, requiring immediate situational awareness, data analysis and decision support tools. Short duration focused missions are not unprecedented in planetary exploration and often yield tremendous science and exploration results. Examples of successful focused, short duration missions include LCROSS (Lunar Crater Observation and Sensing Satellite) (4 minutes), Cassini Huygens (~1 hour 10 minutes), Galileo Jupiter Probe (58 minutes), and the Venera landers (hours). In this paper we explore the scientific and exploration rationale for a lunar polar rover mission, discuss the rover mission

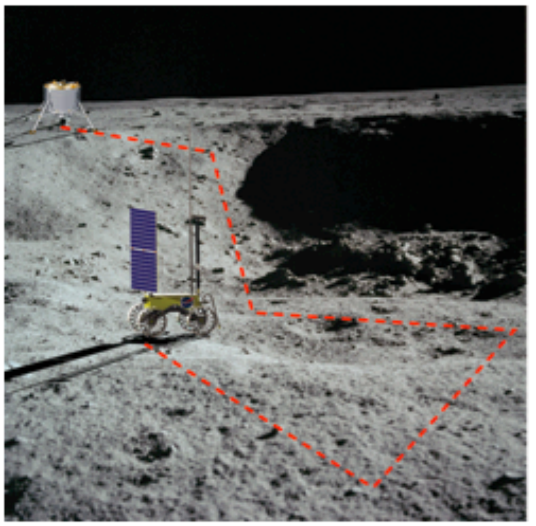


Fig. 1: Low-cost 50 kg class solar powered rover concept to investigate surficial and subsurface volatiles at briefly lit lunar polar regions wherein subsurface volatiles could be retained at shallow depths.

concept, and identify potential landing sites to enable the characterization of lunar polar volatiles within the briefly lit sunlit regions.

II. SCIENCE AND EXPLORATION RATIONALE FOR LUNAR POLAR ROVER MISSION

Interest in the presence of water ice on the Moon has both scientific and exploration foundations. It is thought that water has been delivered to the Moon over its history from multiple impacts of comets, meteorites and other objects. The water molecules migrate in the Moon's exosphere though ballistic trajectories and can be caught in polar cold traps that are cold enough to hold the water for billions of years. An improved understanding of the quantity, form, and distribution of lunar polar volatiles would help constrain models of the impact history of the lunar surface and the effects of meteorite gardening, photo-dissociation, and solar wind sputtering. Measurements of the ice distribution and concentrations would provide a quantitative basis for studies of the Moon's history, especially the delivery of primitive biogenic volatiles to the inner solar system.

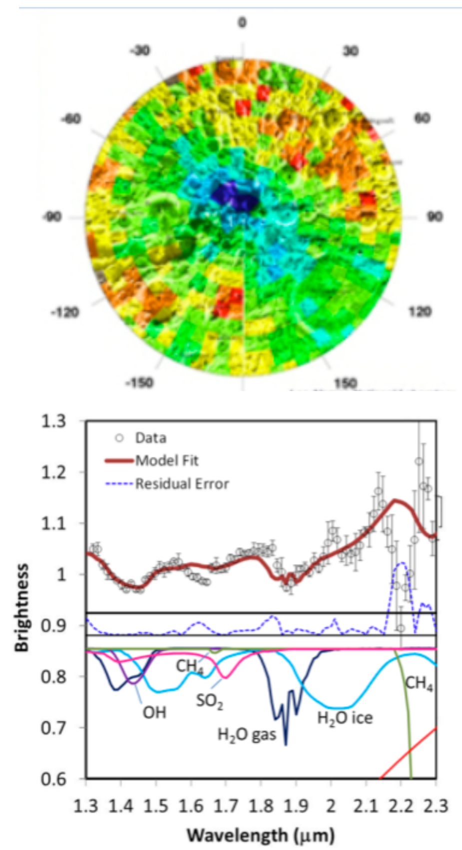


Fig. 2: Lunar Prospector neutron data showing enhanced south pole hydrogen. Bottom: LCROSS data showing water ice and vapor.

Deposits of ice could have practical implications for future human activities on the Moon as well. A source of water could enable long duration human activities and serve as a source of oxygen, another vital material that otherwise must be extracted by melting and electrolyzing the lunar regolith or delivering oxygen from Earth. Hydrogen derived from lunar ice could be used as a rocket fuel. However, prospecting must be performed prior to making use of volatiles as we cannot exploit lunar resources until they are mapped and characterized.

II.I Lunar Polar Hydrogen – What We Know and Do Not Know

Scientists have long considered the possibility that water ice deposits may exist in permanently shaded craters near both lunar poles[7,8]. We know that the floors of such craters should be extremely cold (<100K)[9] and indeed LRO Diviner has measured some permanently shadowed regions as colder than 40 K. A significant number of water molecules delivered by meteoric infall can survive loss processes, find their way to these craters and be cold-trapped for billions of years[10].

Implanted solar wind hydrogen could yield impact-liberated water molecules, leading to concentrations as high as 4 wt% in polar shadow[11]. The recent LCROSS (Lunar Crater Observation and Sensing Satellite) mission measured ~5 wt% water in Cabeus crater[1] (Figure 2). In addition, recent subsurface temperature modelling based on LRO Diviner data suggests that ice can be stably trapped for long times even in polar locations that receive small amounts of oblique sunlight at solstice[3].

However, the distribution of cold-trapped water ice (and other volatiles) near the lunar poles is unknown at scales of a few tens of km. Lunar Prospector neutron spectrometer (LPNS) data indicated the presence of polar hydrogen enhancements[12,13,14,15,16] (Figure 2), and anomalous bistatic radar returns from the Clementine lunar orbital mission have been interpreted in terms of icy materials[17,18]. But Earth-based radar imaging of the Moon has not revealed large, bright, depolarized features like those seen at Mercury[19,20]. The Earth-based radar returns from the lunar poles are similar to those seen for crater ejecta and blocky terrain at lower latitudes, where ice could not possibly exist[21]. However, cold-trapped ice residing in the spaces between regolith grains at several tens of percent by volume would not produce anomalous radar backscatter[19,20,21]. Indeed, Lunar Prospector neutron data allow upwards of ~20 wt% H_2O ice concentrations in limited (10%) areas of permanently shadowed crater floors[16]. If cold-trapped volatiles are truly only concentrated in limited areas, then orbital techniques will not be sufficient to localize them. Only by exploring the surface can we determine unambiguously the presence, abundance, composition and spatial distribution of cold-trapped volatiles.

Since the LCROSS mission impacted into an area of permanent shadow within Cabeus crater near the lunar south pole and detected on the order of 5 wt% water ice along with multiple other volatile species, we have evidence that at this one location near the lunar south pole, volatiles do indeed exist in significant quantities[1] (Figure 2). However, because of its localized nature, LCROSS did not tell us about the spatial distribution of volatiles elsewhere within Cabeus or near the poles of the Moon.

Remote sensing data from the Moon Mineralogy Mapper (M3), Deep Impact (EPOXI), and Cassini missions indicates the presence of surface-bound volatiles (adsorbed OH/H_2O) on the lunar surface in areas of sunlight[22,23,24] (Figure 3). Since these volatiles are observed in areas of sunlight, they may be easily exploitable since they do not necessarily require cold temperatures and/or permanent shadow. OH and H_2O desorbed from regolith grains at lower-latitudes could also be a source for cold traps at high latitudes.

<u>II.II The History of Lunar Volatiles: Sources and Sinks</u>

Whether deposited in large quantities in discrete events (comets) or accumulating slowly and steadily for eons (migrating water vapor), volatiles that are delivered to the lunar poles have the advantage of low temperature to help preserve them against sublimation. However, there are other processes at work in the permanently shadowed regions that can remove the volatiles. Although sunlight never reaches these places, Earthshine, UV starlight, and scattered UV of zodiacal light may photolyze exposed volatiles. In addition, solar wind and magnetospheric plasma may sputter volatiles away. Both photons and ions affect volatiles only at the extreme surface. However, the lunar surface is constantly evolving as a result of meteoroid impacts on all scale sizes. Nearby impacts bury exposed volatiles and may protect them from future loss. Closer to the impact site, localized portions of volatile deposits are vaporized, but may recondense in a nearby cold trap. It is currently unknown which processes dominate the source and sink of volatiles in lunar PSRs (permanently shadowed regions), nor whether they are the same at the Moon as Mercury. It is clear that one must understand the sinks in order to relate the present day volatile contents to the sources.

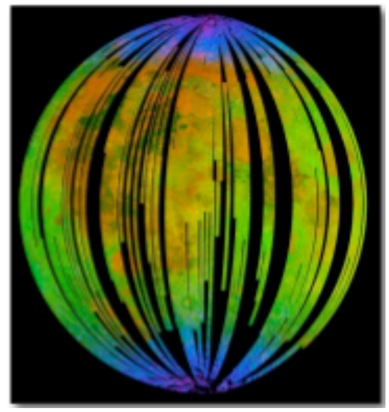
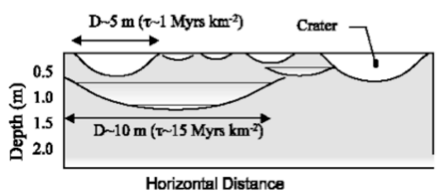


Fig. 3: M3 data showing surface bound hydroxyl in blue[22].

III. LUNAR POLAR VOLATILES ROVER MISSION CONCEPT

The lunar polar volatile rover mission concept is a lunar polar rover which has the main goals of 1) confirming the presence of lunar volatiles and measuring their distribution and 2) determining if these volatiles are exploitable to enable future lunar exploration. To achieve these goals, measurement objectives are to 1) measure subsurface volatiles (hydrogen) with an abundance of >0.5 weight percent and correlate these abundances with surface processes and 2) measure surface-bound volatile (adsorbed OH and H_2O) abundance and distribution. Subsurface and



D (m)	N
5	40
10	5
20	1
40	0.1
80	0.01

Crater size distribution for a 100 mya surface

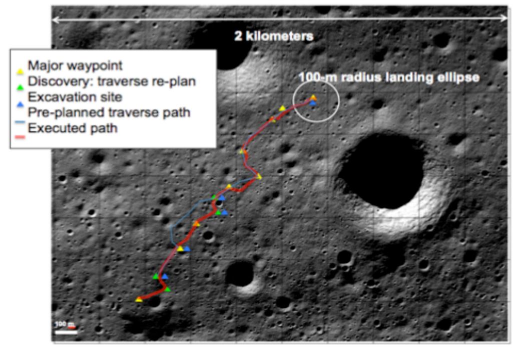


Fig. 4: Left: Typical crater sizes and depths with associated mixing timescales. Center: Crater size distribution for a 100 mya surface showing expected number of craters (N) of various sizes (D=crater diameter). Right: Notional rover traverse covering craters of multiple sizes near Cabeus crater (LRO NAC image).

surface-bound volatiles are expected in regions of short duration daylight whereas only surface-bound volatiles are expected in more persistently lit sites[5,6].

The lunar polar volatile rover mission is unique compared with previous missions that have been proposed to land near the Moon's poles. Several previous mission concepts have focused on a static lander in a region of persistent light (such as the rim of Shackleton Crater) to enable long-duration operations[25,26,27]. The lunar polar volatile rover mission, however, has a scientific and exploration focus of locating and characterizing volatiles. This mission goal has two important implications for mission architecture: 1) mobility is required to determine the spatial distribution of volatiles and 2) the landing site must be an area expected to harbor polar volatiles. For #1 (mobility), the mission requires the use of a rover capable of traversing the lunar terrain and acquiring the needed measurements to locate and characterize the volatiles. For #2 (landing site), the need to land where volatiles are expected drives the landing site to a region where volatiles are stable. Surface-bound volatiles (OH and H_2O) may be stable in areas of persistent sunlight, although subsurface volatiles require cold temperatures for retention, a requirement that is incompatible with a persistently sunlit site. However, recent LRO (Lunar Reconnaissance Orbiter) data and modelling suggests that temperatures are cold enough just below the surface (cms to 10s of cm depth) to retain volatiles in regions that are sunlit for just several days each month[3]. Recent LEND data also suggests that hydrogen, possibly in the form of volatiles, is present in the near-subsurface in these same sunlit regions[4]. Therefore the mission to study **both** surface and subsurface volatiles can be achieved in sunlight (permanent shadow is not required) which greatly simplifies mission operations and rover design. The mission therefore is optimized as a solar-powered rover operating at a polar site that experiences direct sunlight for several days per month[5,6].

III.I Rover Mobility Requirement

The expected distribution of subsurface volatiles drives the mission requirement for mobility. The spatial distribution of volatiles is likely governed by small impact cratering. Neutron spectrometers can detect wt% water-equivalent hydrogen to 1 m depth (if the overburden is dry, 0.1 wt% or less). The average distance between 10 m wide craters (~1 m deep) on a lunar 100 mya surface is ~500 m and the distance between 5 m wide craters (~0.5 m deep) is ~150-200 m. Consequently, the top 0.5 meters is likely to be patchy at scales of 100-200 m. The "mixing time scale" will increase with depth (less frequent larger impacts), and thus horizontal spatial uniformity should increase with depth (Figure 4). This information implies that increased mobility reduces the depth requirement for sampling. Figure 4 shows a notional rover traverse on actual lunar terrain which follows a typical crater size distribution for a 100 mya surface. An ideal traverse extends at least 1 km radially from the initial landing site in order to sample craters of varying sizes. Such a traverse allows for investigation at or near craters of varying sizes, allowing the rover to study a plausible range of mixing depths and expected volatile heterogeneities.

The rationale for the 1-km radial scale is based on the abundance of 10-m diameter craters, which will have excavated to 1-m depth when they formed. Sampling the ejecta blankets of craters with different ages will reveal possible volatile emplacement history. In 1 Ga, approximately 60-70 10-m diameter craters form per km^2. The typical spacing between such craters is thus ~120 m. The rover must sample at least 10 of these in the course of the overall traverse, which may require a total traverse distance of 2-3 km. The total distance travelled, and the total mission duration (driven by sunlight and communications), less the time required to carry out activities at sample stations, sets the mean speed of the rover. With regolith gardening rates of approximately 1 m/Ga, sampling 10-meter craters provides a look into the past roughly 1 billion years of polar volatile emplacement.

III.II Measurement Goals

Subsurface Volatiles

Notional measurements for studying volatiles that may be cold-trapped in the lunar subsurface have been identified for this mission concept[5,6]. Objectives for studying the subsurface volatiles include the following:

1) Confirm presence (or absence) of volatiles in locations identified via remote sensing data, 2) Quantify spatial distribution (lateral and vertical) of volatiles, 3) Quantify form, amount and accessibility of volatiles, and 4) Characterize influence of topography, surface mineralogies, grain sizes, etc. on volatile retention.

Specific measurements to achieve these objectives are shown in Table 1.

1) Locate Volatiles
•*SS-1*: Measure concentrations of at least 0.5 wt% (H_2O weight equivalent) water-equivalent hydrogen (WEH) abundance in a surface layer of at least 5 cm thickness (on top of otherwise dry regolith)
•*SS-2*: Detect at least 1.0 wt% (H_2O weight equivalent) WEH abundance to 1 m depth (dry regolith layer)
•*SS-3*: Measure spatial distribution of subsurface volatiles (Lateral: 1 km radius (1-2 m resolution; Vertical: to "frost line" depth (down to 50 cm))
•*SS-4*: Measure surface conditions where volatiles are found (Note shadowing (visible imaging); topography (3D shape at 1-2 m resolution)
2) Characterize Volatiles
•*SS-5*: Measure the form (physical state) of volatiles to 50 cm depth (Adsorbed gases? Disseminated ice grains? Massive ice? Implanted solar wind species?)
•*SS-6*: Measure the primary chemical species (those contributing more than 10% by weight of the volatile fraction) to 50 cm depth
3) Evaluate Accessibility of Volatiles
•*SS-7*: Measure regolith properties where volatiles are found (and not found) to 50 cm depth (soil cohesion, hardness (cementation), strength/retention, etc)

Table 1. Listing of measurements to characterize subsurface (SS) volatiles.

Surface-bound OH/H_2O

Notional measurements for studying surface-bound volatiles on the Moon have been identified for this mission concept[5,6]. Objectives for studying the surface-bound volatiles include the following: 1) Confirm presence (or absence) of adsorbed OH and H_2O in sun-lit regions, 2) Quantify daily cycle of OH/H_2O production, 3) Determine if OH/H_2O is a volumetrically important resource, 4) Characterize influence of topography, surface mineralogies, grain sizes, etc. on volatile retention.

Specific measurements to achieve these objectives are shown in Table 2.

1) Characterize Volatiles
•*SB-1*: Measure variation in surface and volume abundance with time and solar illumination (Lateral: 1 km radius (1-2 m resolution))
•*SB-2*: Measure variation in surface and volume abundance with geologic context (crater rim, interior, inter-crater, etc.) and surface temperature (Note shadowing (visible imaging), temperature (point measures at 1-2 m resolution), topography (3D shape at 1-2 m resolution)
•*SB-3*: Determine what factors influence the deposition, retention, and desorption (if applicable) of volatiles on surface regolith grains
2) Evaluate Accessibility of Volatiles
•*SB-2*: Determine if volatiles (OH and H_2O if present) can be readily extracted through modest heating or mechanical agitation

Table 2. Listing of measurements to characterize surface bound (SB) volatiles

III. ROVER DESIGN CONSIDERATIONS

III.I Prospecting rover concept

The mission calls for a rover to traverse at least 2-3 km of lunar surface and excavate at least 10 sites. We assert that a 50 kg class, solar powered rover including approx. 6 kg of instruments (Table 3) can accomplish this in 5-7 Earth days of sunlit operations (Table 4). A smaller rover would likely not be unable to handle the terrain, nor achieve the required range. A larger rover would likely be significantly more expensive and difficult to launch.

The notional rover concept design is shown in Figure 5. Power is provided by a vertically mounted solar panel on a swivel joint which tracks the Sun. Avoiding a requirement for lunar night survival eliminates the risk and cost of radioactive heating units, complex thermal control systems and unproven cryo-capable components. Communications are routed through the lander and thence directly to Mission Control. Four skid-steered wheels on a differentially linked rocker suspension provide sufficient mobility for this mission, while avoiding mechanical complexity. A mast supports a forward-looking stereo pair of cameras for navigation and teleoperated driving from Earth.

Instrument	Principal Measurement	Mass (kg)	Power (W)	Size (cm)	Date Rate (bps)
Neutron Spectrometer	Hydrogen at depth (to 1 wt% water @ 100 cm)	1.3	2	18x12x6	89
NIR Reflectance Spectrometer	Volatiles and ice state (1.3 – 2.9 um)	2	4	10x10x3	540
Pneumatic Excavator	Subsurface access (5 to 20 cm depth)	2 (est.)	0	TBD	0

Table 3. Science instrument payload.

Driving 3 km at 5 cm/s	*0.7 days*
Acquiring, processing and down-linking stereo navigation images every 1m	*0.9 days*
Total driving + navigation time (assume rover drives while down-linking and processing images)	**1.3 days**
Excavating 10 sites and analyzing exposed regolith with NIR spectrometer (assume 3 hours data interpretation and replanning at each site)	**1.5 days**
System checkout and rover egress	**1 day**
Total	**3.8 days**
Total + 50% Margin	**5.7 days**

Table 4. Rover activity time duration.

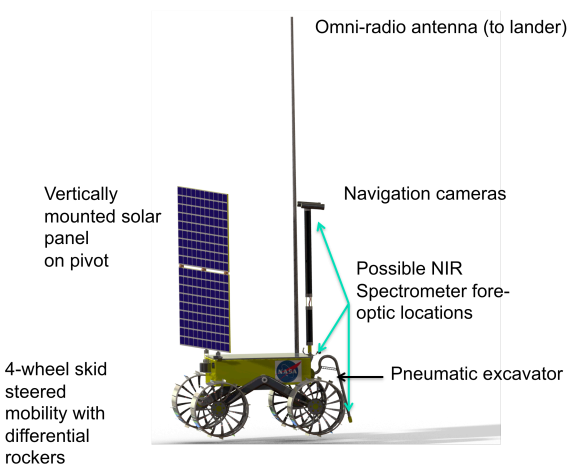


Fig. 5. Notional rover concept.

The notional rover science payload (Table 3) consists of a neutron spectrometer for mapping lateral hydrogen concentrations[28], a pneumatic excavator[29] for digging shallow trenches, and NIR reflectance spectrometer (heritage from the LCROSS mission[30]) for analysis of the exposed material.

III.II Concept of Operations (CONOPS)

The mission calls for traversing 3-5 km and excavating at least 10 locations. These tasks be completed during the 5-7 days of available sunlight if we are to avoid the considerable risk and expense of surviving the lunar night.

A continuous 112 kbps rover to Earth link is sufficient for the rover to drive continuously at 5 cm/s whilst down-linking navigation stereo image pairs every 1 m. These images can be *processed on Earth* to create a terrain hazard map, localize the rover, and allow operators to determine the next immediate waypoints for the rover (Figure 6). A modest level of onboard autonomy is necessary for the rover to endure a short duration loss of communication (at reduced average speed). A rover speed of 5 cm/s is sufficient for the mission. Greater speeds do not significantly reduce overall mission time, and reduce the resolution of the neutron spectrometer measurements (continuously acquired as the rover moves)[28].

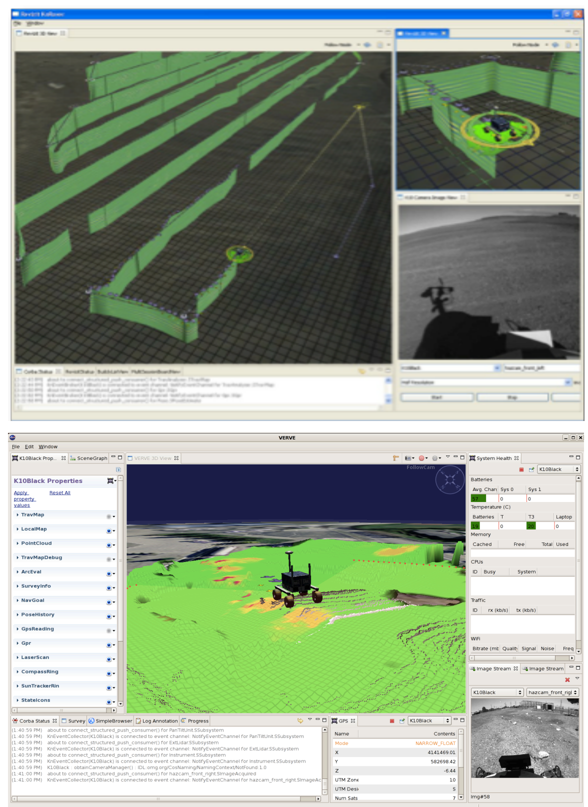


Fig. 6. Teleoperated rover control console. Top: Display of rover traverse path. Bottom: Visualization of accumulated neutron flux map.

Human factors may dominate the time required to excavate and analyze the 10 sites, chosen in near real-time based on the accumulated neutron flux map (Figure 6). We assume that less than 30 minutes are required for excavation and NIR spectral acquisition at each site. We also assume three hours is sufficient for the science team to digest the data at each site in order to decide on subsequent activity.

Table 4 indicates the approximate times required for rover operations. Assuming continuous line of sight to Earth, landing at start of daylight, and one day for egress and checkout, the mission can be performed in less than seven days, including 50% margin.

III.III Avionics, Power and Communications

The notional rover design makes use of avionics, which includes a radiation-hardened 266 MIPS CPU with 1 GB RAM, power controllers, and LVDS IO. For position estimation, an inertial measurement unit, such as the LN200 IMU (used on MER), would be used in conjunction with odometry. The total avionics power budget is 32 W.

The solar power system is sized to accommodate an expected total 110 W average load (including 30% margin) while the vehicle is driving, with a space qualified Li-Ion battery to accommodate one-hour of operations in shadowed conditions.

An actively pointed, high-gain antenna (2-3 degree beam-width) is required for DTE communications from lunar polar locations. Locating this antenna and space segment radio on the stationary lander allows the rover to maintain communications (via a light weight omni-directional surface link to the lander) while moving.

III.IV Thermal

The lunar polar thermal environment is relatively mild (at 210 to 250 K) during the entire sunlit period. Thermal modeling (Figure 7) indicates that operating temperatures can be passively maintained by coating the rover body in 0.88 emissivity and absorptivity material (Maxorb).

Surviving the lunar night would require a combination of radioactive heating units, insulation, radiative elements, or unproven electronics and batteries capable of surviving night-time temperatures.

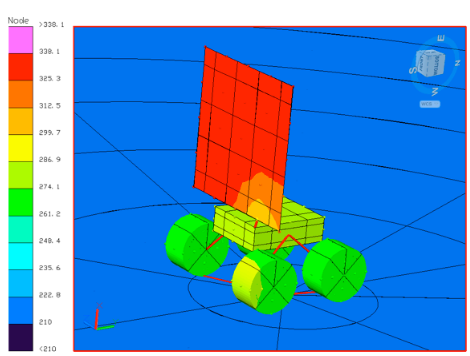


Fig. 7. Thermal model of rover in full sunlight on 250 K regolith with 100 W heat output.

IV. LANDING SITE CONSIDERATIONS

The ability to address the mission measurement objectives is highly dependent upon the landing site, which must satisfy multiple site selection criteria. For example, the rover must interrogate an area where subsurface volatiles are likely, meaning that low subsurface temperatures are sustained that are conducive to volatile retention, but which also are consistent with the orbital neutron spectrometer hydrogen signatures. The site must have sufficient daylight illumination to enable multi-day surface operations with solar power and have a clement surface temperature for rover survival during the mission. Suitable direct-to-Earth (DTE) communications are required to enable rover operations and data relays. Also, the lunar terrain must be traversable by the rover which limits slopes to < 10 degrees and limits the density of rocks in the region. The optimal landing site is a convergence where each of these site selection criteria is best satisfied.

1a) Communication with DSN. The rover must be able to communicate with Earth in order to receive commands from the ground and also to downlink data and other telemetry information. Therefore the availability and duration of line-of-sight with sufficient link margin to Deep Space Network (DSN) stations (Canberra, Goldstone, Madrid) must be considered during site selection. An ideal site has adequate clearance from intervening terrain to avoid ground effects on the signal quality. The exact clearance required will depend on specific lander antenna diameter (and mass), but > 2 degrees clearance above the local horizon provides adequate link margin against multi-path and other interference.

1b) Communication with lander. It is also desirable that the rover have the ability to communicate with the lunar lander as a backup for communications. The lander will ideally land and remain stationary in a location with DTE communications. Therefore if the rover is in communications with the lander, the lander can be used as a relay for communication with Earth. An ideal landing site would have a maximum fraction of the surrounding terrain (up to 1 km distant from lander where the rover is moving) that is in radio loss of signal from lander.

2) Sunlight. The rover is nominally a solar-powered rover, and therefore the length of the mission is subject to sunlight availability. Greater DTE availability and longer duration of continuous sunlight will enable a longer rover mission.

3) Expected presence of volatiles. The rover must explore a region expected to harbor volatiles. As previously discussed, certain conditions are most

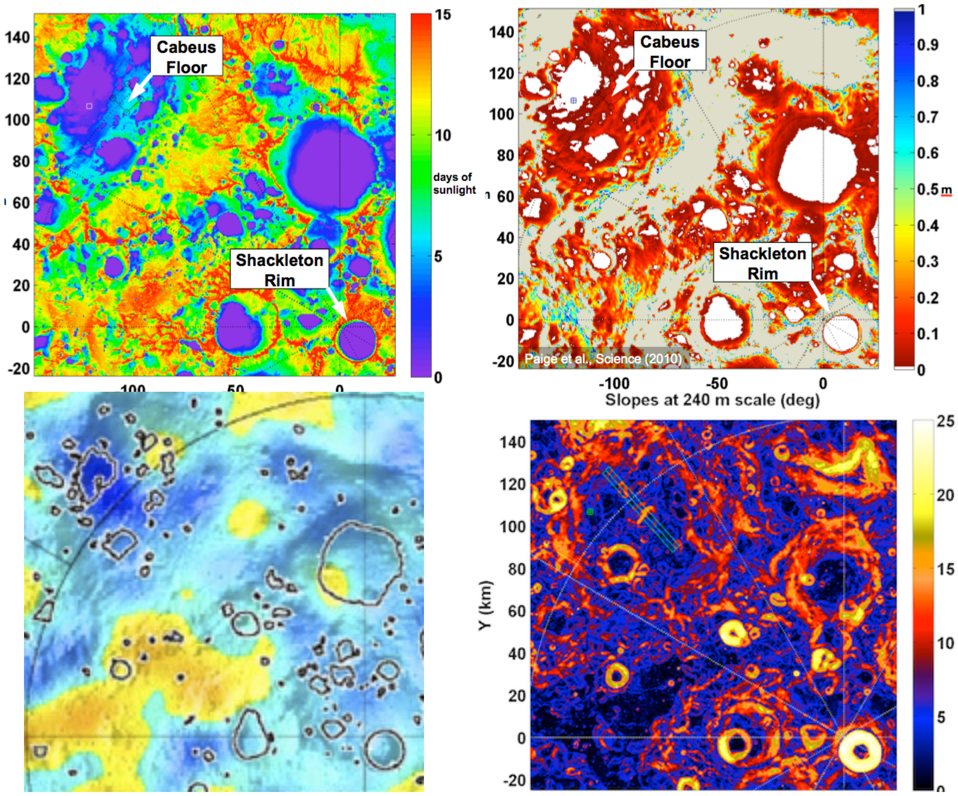


Fig. 8: A) Net days of sunlight for May 2017. B) Depth to stable ice conditions. C) LRO LEND neutron data. D) LOLA DTM slope data.

conducive to increasing the chances regarding the existence and retention of sub-surface volatiles. Such criteria include subsurface temperatures cold enough to harbor volatiles[11], LEND and Lunar Prospector and LEND neutron spectrometer hydrogen signatures, and results from other missions such as LCROSS and Chandrayaan/M[3].

4) Navigable Slopes. Based on rover capabilities for a small lunar lander and small (50 kg) class rover, slopes less than 10 degrees are required for landing and slopes less than 15 degrees are required for rover trafficability. The landing site must thus comply with these requirements and have adequate roving terrain within 1 km of the landing site traversable with <15 degree slopes.

5) Rock size and density distributions. A small lunar rover is capable of traversing rocks that are less than ~0.5 m in size. Therefore the landing site must have traversable terrain with rock distributions compatible with this requirement. Although rocks smaller than 0.5 m can represent hazards, the navigation cameras on the rover are capable of detecting smaller hazards to ensure hazard avoidance.

IV.I Current State of Knowledge

Thanks to recent missions, we now have extensive knowledge of lunar polar topography, surface temperatures, and high-resolution surface imaging. Together with what we know from previous missions, it is possible to assemble the key data relevant to our study as described below.

Topography and Medium-scale Slopes

High precision altimetry measurements from the Lunar Orbiter Laser Altimeter aboard the Lunar Reconnaissance Orbiter (LRO) has made possible the characterization of polar topography and slopes at a few ten's of meters and greater. LOLA (Lunar Orbiter Laser Altimeter) has released gridded topographic data of the poles at a resolution of 20 m/post for poleward of both 80°N and 80°S, and 10 m/post for poleward of 85°N and 85°S. These products are incomplete, so the gridding process necessarily adds smoothed interpolations to the higher-resolution track data. However, these data are adequate for our purposes now, and this project will also make use of improved versions of the gridded data as they are released by the LOLA team. These data are available both from PDS Planetary Data System) and the LOLA MIT (Massachusetts Institute of Technology) website.

Subsurface and Surficial Volatiles

Remote sensing data indicates the presence of significant amounts of subsurface volatiles in lunar polar cold traps. Lunar Prospector neutron data[12,14], Lunar Reconnaissance Orbiter LEND neutron data[4], LRO Diviner temperature mapping and ice stability modelling[11], along with the recent LCROSS (Lunar Crater Observation and Sensing Satellite) findings[1] suggest that subsurface volatiles exist near the lunar poles.

Remote sensing data from the Moon Mineralogy Mapper (M^3), Deep Impact (EPOXI), and Cassini missions indicates the presence of surface-bound volatiles (adsorbed OH/H_2O) on the lunar surface in areas of sunlight[22,23,24]. Since these volatiles are observed in areas of sunlight, they may be easily exploitable since they do not necessarily require cold temperatures and/or permanent shadow. Figure 3 shows the inferred distribution of surficial OH.

Thermal Conditions: Surface and Subsurface

LRO/Diviner has measured extremely low surface temperatures in areas of permanent shadow at the lunar poles[3]. However, modelling reveals that there are also extensive areas of persistent shadow for which near-subsurface thermal conditions are favorable for the retention of ice and other volatile species for over one billion years. This result opens up considerable real estate as potential subsurface cold traps.

The series of maps in Figure 8 shows the days of sunlight in May 2017 (summer solstice, an ideal time to conduct the mission to have maximum daylight for mission operations), depth to stable ice conditions, LEND neutron spectrometer data, and LRO/LOLA DTM slopes at 240-m scales (degrees) for the Cabeus floor. Other suitable landing sites may exist in the north and/or south polar regions.

Hazards and Obstacles

LROC (Lunar Reconnaissance Orbiter Camera) NAC (Narrow Angle Camera) imagery provides information on rocks down to resolutions of ~0.5 m. Although rocks smaller than 0.5 m can represent hazards, we can infer their distributions from other observable features, such as larger rock fragments and craters[27]. We note that the density of hazards is consistent with Apollo 16 terrain, and thus is traversable by a small rover.

Based on these criteria, preliminary analysis has identified the floor of Cabeus crater as a notional landing site[5,6]. We note that the density of hazards is consistent with Apollo 16 terrain, and thus is traversable by a small rover.

V. SUMMARY

A small lunar polar rover is an ideal follow-on to the recent discoveries of significant reservoirs of water ice and volatiles near the lunar poles. Areas of lunar permafrost exist in regions where sunlight persists for 7-10 days per month. These conditions enable daytime operations in a benign thermal environment while cold temperatures exist in the near subsurface to sequester volatiles. We present a nominal rover design capable of meeting the mission measurement objectives. We also identify nominal landing sites based on scientific merit and landing site safety. A lunar polar volatiles prospecting mission is a logical follow-on to the recent remote sensing and LCROSS discoveries and can further characterize the spatial distribution of lunar polar volatiles.

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