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Site selection and traverse planning to support a lunar polar rover mission: A case study at Haworth Crater

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ABSTRACT

Studies of lunar polar volatile deposits are of interest for scientific purposes to understand the nature and evolution of the volatiles, and also for exploration reasons as a possible in situ resource to enable long term human exploration and settlement of the Moon. Both theoretical and observational studies have suggested that significant quantities of volatiles exist in the polar regions, although the lateral and horizontal distribution remains unknown at the km scale and finer resolution. A lunar polar rover mission is required to further characterize the distribution, quantity, and character of lunar polar volatile deposits at these higher spatial resolutions. Here we present a case study for NASA's Resource Prospector (RP) mission concept for a lunar polar rover and utilize this mission architecture and associated constraints to evaluate whether a suitable landing site exists to support an RP flight mission. We evaluate the landing site criteria to characterize the Haworth Crater region in terms of expected hydrogen abundance, surface topography, and prevalence of shadowed regions, as well as solar illumination and direct to Earth communications as a function of time to develop a notional rover traverse plan that addresses both science and engineering requirements. We also present lessons-learned regarding lunar traverse path planning focusing on the critical nature of landing site selection, the influence of illumination patterns on traverse planning, the effects of performing shadowed rover operations, the influence of communications coverage on traverse plan development, and strategic planning to maximize rover lifetime and science at end of mission. Here we present a detailed traverse path scenario for a lunar polar volatiles rover mission and find that the particular site north of Haworth Crater studied here is suitable for further characterization of polar volatile deposits.

1. Introduction

Scientists have long considered the possibility that water ice deposits may exist in permanently shaded craters near both lunar poles [1,2]. We know that the floors of such craters should be extremely cold (<100 K) [3], and that 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 [4]. Early orbital missions have collected remote sensing measurements that further support the presence of increased volatile abundances near the lunar poles. The Lunar Prospector neutron spectrometer (LPNS, see Table 1 for a full list of acronyms) data indicated the presence of polar hydrogen enhancements [5–9], and anomalous bistatic radar returns from the Clementine lunar orbital mission have been interpreted in terms of icy materials [10,11]. Even more recent missions have discovered a range of forms, distributions, and concentrations of water and hydrogen-bearing compounds in the near-surface environment of the Moon. The LCROSS (Lunar Crater Observation and Sensing Satellite) detected on order of 5–6 weight % water in the permanently shadowed northern interior portion of Cabeus Crater near the lunar south pole [12]. The Lunar Reconnaissance Orbiter LEND (Lunar Exploration Neutron Detector) instrument data has also been used to produce hydrogen maps showing enhancements at the lunar poles [13]. In addition, the M3 spectrometer aboard the Chandrayaan-1 spacecraft detected surface OH and H_2O over extended regions on the Moon [14].

A combined analysis of these lunar datasets suggests complex spatial and temporal distribution of lunar polar ice. Impact gardening will create heterogeneity at lengths on the scale of ~10–100 m [15], and hence water ice deposits near the lunar poles are likely patchy and/or buried at different locations [16]. In addition,

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Table 1
List of acronyms used throughout this paper (in alphabetical order).

AIM	Area of Interest Mapping
DOC	Drill Operations Camera
DSN	Deep Space Network
DTE	Direct To Earth
GC/MS	Gas Chromatograph / Mass Spectrometer
HEOMD	Human Exploration and Operations Mission Directorate
ISECG	International Space Exploration Coordination Group
ISRU	In Situ Resource Utilization
LAVA	Lunar Advanced Volatile Analysis
LCROSS	Lunar Crater Observation and Sensing Satellite
LEAG	Lunar Exploration Analysis Group
LEND	Lunar Exploration Neutron Detector
LOLA	Lunar Orbiter Laser Altimeter
LP	Lunar Prospector
LPNS	Lunar Prospector Neutron Spectrometer
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
MET	Mission Elapsed Time
NIRVSS	Near InfraRed Volatiles Spectrometer System
NSS	Neutron Spectrometer System
OVEN	Oxygen and Volatile Extraction Node
PDS	Planetary Data System
PSR	Permanently Shadowed Region
ROE	Regolith Oxygen Extraction
RP	Resource Prospector
SKG	Strategic Knowledge Gap
VA	Volatiles Analysis
VIMS	Visual and Infrared Mapping Spectrometer
WDD	Water Droplet Demonstration
xGDS	Exploration Ground Data Systems

several datasets suggest a time-dependent surface component for volatile behavior [14]. For example, analysis of the 3 μm water absorption feature from the M3 instrument aboard Chandrayaan-1 and the Cassini Visual and Infrared Mapping Spectrometer (VIMS) spectrometer has revealed increased surface hydration at higher latitudes as well as at fresh feldspathic craters and the anorthositic highlands [14,17]. Diurnal changes in lunar surface OH and H_2O were observed by the Deep Impact spacecraft with hydration loss and the return to steady state occurring over one lunar day [18].

The complicated spatial and temporal water ice distributions inferred from spacecraft assets and our theoretical understanding regarding the behavior and distribution of lunar volatiles suggest that a dedicated rover mission equipped with surface mobility is required to further our understanding of lunar polar water ice. In situ data must be collected at surface resolutions not attainable from orbit ($<$ 100 m and smaller scale) to account for the expected lateral heterogeneity of volatile deposits [15]. In addition, subsurface measurements must be acquired with sub-meter vertical resolution to characterize the subsurface distribution of volatiles. Data suggests that a local region must be evaluated (1–3 km lengthscale) to measure a representative area and to understand the surface and subsurface distribution of volatiles [16].

Understanding the distribution of lunar water ice is important for both science and exploration. Scientifically, we seek to determine the sources and sinks for water ice, and place constraints on its longevity and distribution at the Moon. Such knowledge is critical for understanding the inventory and behavior of volatiles in the inner Solar System, and understanding the history and evolution of volatiles at the Moon [1,19–21]. In terms of exploration, lunar water can be a valuable in situ resource to enable long-term exploration and settlement of the Moon. For example, lunar hydrogen and/or oxygen can be used to provide life support for lunar crews, and/or rocket fuel for lunar ascent modules from the lunar surface, descent vehicles to L1/L2, and/or to power future lunar landers. In order to assess the viability of using lunar water as a resource to enable robotic and human exploration, one must (1) define the composition, form, and extent of the resource, (2) characterize the environment where the resource is found, (3) define the accessibility/extractability of the resource, (4) quantify the geotechnical properties of the lunar regolith where the resource is found, (5) traverse several km and determine lateral and vertical variability of the resource on meter scales, and (6) identify resource-rich sites for future missions [22].

To summarize the precursor information needed prior to future lunar exploration, the international exploration community has defined lunar Strategic Knowledge Gaps (SKGs) which identify gaps in our knowledge that are necessary to address to enable a sustained human presence on the Moon. NASA developed the concept of SKGs as a guide for precursor missions to outline key topics requiring further measurement and study. SKGs were externally vetted by the Lunar Exploration Analysis Group (LEAG) and then vetted by the international community via the International Space Exploration Coordination Group (ISECG). Lunar SKGs applicable to understanding the lunar water ice distribution focus in the broad categories of (1) understanding lunar resource potential and (2) understanding how to live and work on the lunar surface.

An optimal approach to address these outstanding scientific and exploration questions pertaining to lunar polar water ice is to collect relevant measurements from a lunar polar rover platform. A landed asset with a payload capable of determining the horizontal and vertical distribution of water ice over time is the next step in furthering our knowledge of this complex and important subject [16,23]. A rover mission of this nature necessarily requires careful planning and of critical importance is the traverse path executed by the rover. The locations where the rover drives dictates where data will be acquired, and thus the mission is highly dependent on optimal traverse path planning to maximize the science and exploration knowledge gained from this mission. To search for and characterize lunar ice requires a mission to the lunar poles since enhancements of lunar volatiles are found in polar regions. A rover mission to the lunar polar regions is non-trivial with several key aspects to consider to enable the mission. The lunar poles exhibit complex topography, which can be challenging to rover navigation, and locations thought to harbor ice have limited durations of sunlight given the orbital geometry, and thus the mission itself may be of short duration (assuming solar power and/or other thermal design constraints). These challenges, in combination with accessing the most interesting locations for the science, makes traverse path planning a key parameter to ensure mission success. Here we consider a notional case of rover exploration at Haworth Crater near the lunar south pole to determine the feasibility of such a mission given the science and engineering constraints, and seek to determine if such a mission is feasible and report on lessons-learned for lunar polar rover traverse path planning.

2. Case study: Resource Prospector

2.1. Mission overview

We consider the Resource Prospector mission as a case study to enable our assessment of lunar polar rover traverse path planning. RP is a robotic mission currently in formulation (Phase A) by NASA's Human Exploration and Operations Mission Directorate (HEOMD) to both prospect for water resources and conduct ISRU (in situ resource utilization) on the Moon [16,23]. For prospecting, RP is designed to characterize the distribution of water and other volatiles at the lunar poles. RP aims to map the surface and subsurface distribution of hydrogen-rich materials within the upper 1 m of the Moon, determine the constituents and quantities of volatiles, and provide limits on key isotope ratios (e.g., D/H,

$^{18}O/^{16}O$, $^{36}S/^{34}S$, $^{13}C/^{12}C$). RP is also an ISRU processing demonstration mission, using a hydrogen reduction process to extract oxygen from lunar regolith. RP will both demonstrate the hardware in the lunar setting and also capture, quantify, and display the water generated from the ISRU processing [16,23].

The RP mission includes several key capabilities required to address the prime science and exploration questions regarding lunar water and volatile distribution near the lunar poles. The RP payload capabilities are required to meet mission objectives and are verified through laboratory and field testing. The rover is a mobility platform that enables measurements from a variety of different locations across the lunar surface as a function of time. RP is capable of Resource Prospecting through the use of two key prospecting payload elements: the Neutron Spectrometer System (NSS) and Near InfraRed Volatiles Spectrometer System (NIRVSS). NSS is capable of detecting a water-equivalent hydrogen >0.5 wt% down to about 1 m depth, and thus is sensitive to volumetric hydrogen, whether as water or other compounds [24,25]. The active area of the helium-3 detectors used for NSS exceed that of the neutron spectrometer flown on the Lunar Prospector Neutron Spectrometer (LPNS), being 116 cm^2 (the LPNS system was $\sim$100 cm^2). At 1 eV, the RP NSS area-efficiency product is 80 cm^2, whereas the LPNS was $\sim$68 cm^2. This sensitivity means that the RP NSS is capable of measuring water-equivalent hydrogen >0.5 wt% down to 1 m depth with 2 m spatial sampling on the Moon [24,25]. NIRVSS is used for identification of surface H_2O/OH and other volatiles, near-subsurface sample characterization, drill site temperature characterization, and uses the NIRVSS drill operations camera (DOC) for drill site imaging [25,26]. The NIRVSS instrument is used for surface H2O/OH identification, measuring spectra between 1.6–3.4 µm. NIRVSS is capable of subsurface sample characterization by using the RP drill system to excavate material and bring the subsurface samples to the surface where multi-color imaging of drill cuttings and/or surface materials is collected with eight colors between 0.4–1.1 µm. In addition, NIRVSS is capable of measuring scene thermal radiometry at 8, 10, 14 and 25 µm.

RP also includes ISRU-relevant payload elements in the form of the Oxygen and Volatile Extraction Node (OVEN) and the Lunar Advanced Volatile Analysis (LAVA). OVEN is designed to measure a sample's volatile content and can conduct oxygen extraction by step-wise sample heating from 150 to 450 °C. LAVA is used for analytical volatile identification and quantification in a delivered sample with a GC/MS (gas chromatograph / mass spectrometer) system. LAVA is capable of measuring water content of regolith at 0.5% (weight) or greater and characterizing volatiles of interest below 70 amu. Subsurface sample acquisition to support the OVEN and LAVA instruments is achieved with a drill system [27,28]. The drill system is capable of auguring material to the surface for “fast” near-surface measurements as well as sampling to enable a detailed subsurface assay. The RP drill system is capable of subsurface sample acquisition down to 1 m in 0.1 m “bites”. The drill can also be operated in auger mode for faster subsurface assays with NIRVSS. Upon sample collection, the drill works with a sample transfer to the LAVA and/or OVEN instruments for a detailed subsurface characterization.

2.2. Mission goals

In order to achieve the high-level prospecting and ISRU objectives of the RP mission, specific requirements have been derived to outline mission success criteria. The RP measurement requirements can be broken into categories to achieve minimum success, full success, and stretch goals. Minimum success requires RP to make measurements from two places on the Moon separated by at least 100 m, and these can include surface or subsurface measurements. Full success requires measurements from two locations on the Moon separated by at least 1000 m, surface and subsurface measurements (where subsurface measurements are specifically obtained with a drill for sample collection), measurements in and a sample acquired from a shadowed area, and demonstration of ISRU. Stretch goals include making subsurface measurements (with an auger) in at least eight locations across 1000 m (point-to-point) distance, making subsurface measurements (sample and processing) at least four locations across a 1000 m point-to-point distance, and providing geologic context.

2.3. Mission concept of operations

A specific concept of operations (conops) has been developed for RP to achieve the mission objectives. The architecture of RP dictates several constraints relevant to RP conops. For example, RP is envisioned as a low cost mission and is reliant on solar power for operations [23]. This constraint requires either operations in sunlight or sufficient battery power to enable operations in shadow. The nominal mission profile includes the rover landing in an area illuminated by the sun and then traversing across the lunar surface to achieve the RP success criteria. Illumination conditions can change significantly during the course of a month at polar locations on the Moon, and thus the rover traverse path (and landing site) must be strategically selected to optimize the science and exploration return of the mission. The rover can, in some cases, “chase the light” to lengthen the mission duration and enable mapping of more lunar surface area.

In addition to operating in the sunlit regions, RP must also collect measurements in shadowed areas to provide information on volatile content in these colder regions. Thus both sunlit and shadowed operations are an integral element of the RP operations architecture. RP also requires direct to Earth (DTE) communications given the low cost nature of the mission concept; therefore the landing site and traverse path should remain in direct view of Earth as much as possible.

To achieve the mission objectives and operate within the given mission constraints, RP requires only 4–6 days of operations. The mission duration is a balance between targeting the most scientifically compelling region(s) that have high hydrogen abundances and are located in proximity to shadowed areas which also possess benign slopes and topography for rover trafficability plus access to DTE communications for the duration of the mission. These areas are by default relatively cold (e.g., high polar latitude) and only experience a few ($\sim$4–6) days of sunlight each month. Rover traverse planning must therefore maximize both science return and the operational timeline with the overarching objective of optimizing the information regarding volatile distribution and retention returned by the rover.

The RP surface conops has multiple modes of operation critical to mission success including (1) Prospecting, (2) Mapping, (3) Excavation, and (4) Demonstration. In Prospecting mode, the RP rover is traversing across the lunar surface as the prospecting instruments search for enhanced H_2O/OH, other volatiles, and/or volumetric hydrogen in the form of ice or other H-bearing compounds. When enhancements of volatiles are detected, a decision is made whether or not to map the area at higher spatial resolution (e.g., area of interest mapping, AIM) or immediately auger or collect subsurface samples. Once a decision has been made to collect samples, the rover enters Excavation mode where samples are acquired from the subsurface, processed by the onboard payload, and evolved gases are measured. Prospecting mode can continue throughout the primary mission as the rover maps volatiles and samples across a variety of environments, testing theories of emplacement and retention, and constraining the economics of extraction. Demonstration mode occurs at the end of the

Table 2
Activity dictionary to describe the various rover activities and their durations for mission planning. Note the duration for sunlit and shadowed prospecting and traverse activities is TBD (to be determined) based on the distance roved and rover speed.

Activities	Duration (h)	Instruments
Prospecting	TBD	NSS, NIRVSS
Area of Interest Mapping	0.5	NSS, NIRVSS
Near-surface assay	1.5	Auger, NSS, NIRVSS
Detailed subsurface assay	4.25	Drill Core, LAVA, OVEN, NSS, NIRVSS
Extended subsurface assay	4.25	Drill Core, LAVA, OVEN, NSS, NIRVSS
Shadowed area traverse	TBD	NSS, NIRVSS
Shadowed area near surface assay	1.5	Auger, NSS, NIRVSS
Shadowed area subsurface sampling	2 h + rove time to leave shadow	Drill Core, LAVA, OVEN, NSS, NIRVSS
ROE	3	Drill, core, LAVA, OVEN

RP primary mission when oxygen extraction from the regolith is demonstrated using hydrogen reduction, thus testing two possible ISRU pathways: ISRU from local volatiles and water production from "dry" regolith [28].

2.4. Activity dictionary

To achieve the objectives of the RP mission, a variety of different rover activities must be performed on the lunar surface during nominal operations. We have developed an activity dictionary to describe these different operations and each of these activities are described below. The activity dictionary is summarized in Table 2.

The rover is nominally in Prospecting mode during traverses when not stopped to conduct a different (specific) science function. During Prospecting mode, the NIRVSS and NSS are collecting data to map the surface and subsurface distribution of volatiles. The duration of prospecting is dependent upon waypoint separations and distances as well as the rover speed which all affect the total distance traversed. When the data gathered during prospecting mode exceeds a pre-determined threshold for volatile content based on NIRVSS and/or NSS data, or the Science Team deems a site of special interest for another reason, the rover can enter into AIM mode. Both NIRVSS and NSS are on during an AIM activity when the rover executes a predetermined traverse pattern (subject to alteration by the Science Team based on real-time science data) to systematically map out an interesting region with higher spatial resolution than is typically achieved by the prospecting mode. The purpose of the AIM activity is to determine the best location to investigate the surface/subsurface volatile content. An AIM typically takes 30 min to execute. Upon AIM completion and based on the science data returned from the AIM activity, the Science Team may decide to collect samples of the subsurface. The rover is relocated to the most desirable position resulting from the AIM for this sample collection. Near-surface assay mode invokes the use of an auger to deliver subsurface cuttings samples to the surface for examination with NIRVSS. NSS is also still collecting data during this procedure, and the near-surface augering procedure is slated to take 1.5 h, which includes margin for unknown subsurface properties such as unexpected rocks or hard materials that may hinder augering operations. If the Science Team desires further characterization of a site, a detailed subsurface assay can be performed. This operation takes 4.5 h to complete and utilizes the drill core, LAVA, OVEN, NIRVSS, and NSS instruments. The timeline includes two hours for core segment acquisition, two hours for Volatiles Analysis (VA) with LAVA and OVEN, and 30 min to discard the sample. An extended subsurface assay uses the same payload elements for a deeper subsurface profile. A shadowed area traverse is similar to the prospecting mode but is conducted within shadow. The NIRVSS and NSS are again used, and the shadowed area traverse time is dependent upon the distance traveled and the rover speed. A shadowed area near surface assay and shadowed area subsurface sampling have similar operations to their counterparts conducted in sunlight but are just conducted in a shadowed region. ROE (Regolith Oxygen Extraction) is a final mode of operation, using the drill, subsurface sample, LAVA and OVEN. A Water Droplet Demonstration (WDD) is performed after volatiles analysis and assumes a 2.5 hour duration. WDD condenses the water extruded from the lunar regolith from VA or ROE and then photographs this water drop as an ISRU demonstration and a public outreach activity.

2.5. Concept of operations assumptions

Given the nature of the RP mission concept, several guidelines regarding the concept of operations (conops) have been determined through joint science and engineering analysis and incorporated in this work. Here we discuss several of the conops assumptions that have direct bearing on the traverse planning activities.

We assume a conservative rover speed for the traverse planning. For example, the nominal rover speed ("speed made good") is assumed to be 0.02 m/s. By selecting a conservative rover speed, we intentionally aim to assess a minimum distance traveled in the allotted mission time. This strategy thereby increases the robustness of the findings to determine whether or not, even with intentionally slow rover speeds, the RP mission can meet its mission goals regarding distance traveled on the lunar surface. We also note that the rover uses hazard avoidance camera images and onboard processing to automatically avoid hazards while driving. This process (and subsequent adjustments to the planned traverse path) are also taken into account when considering the effective speed of the rover, which is additional rationale for using the conservative rover speed for this work. The rover speed is assumed to remain constant for the duration of the traverse, although theoretically the effective speed could increase after ~48 h of lunar rover once the team gains experience with operating in the lunar environment. Higher rover speeds allow the Science Team to gather more data across more terrain, which is beneficial to science, although the rover speed should not exceed 10 cm/s in order to obtain reliable data for the NSS. The NSS requires adequate integration time to collect enough neutrons for the data to be statistically meaningful, which yields an upper limit of 0.10 m/s rover speed [24].

Operations in shadow require special consideration given the unknown environmental characteristics and significant power and thermal constraints within a shadowed lunar environment. The rover will nominally operate in sunlight unless specifically entering a region of shadow for science purposes. Prior to entering a shadowed region, a 15 min decision-making halt is included in the mission timeline. This time allows the Science Team to assess the scientific value of entering the shadowed area on the basis of previous data collected during the mission, and allows the engineering and rover navigation teams time to assess the risk and safety of shadowed operations at the given location. Data will be used to assess optimal entry and exit routes to and from the shadowed region, and a final decision regarding shadowed operations will be made by mission management. The general approach to shadowed operations is cautious, where the first entry into shadow is a "toe-dip" where the rover briefly enters shadow and then returns to sunlight to allow the team to assess the science and operations. After this "toe-dip", then the rover can be commanded to re-enter the shadowed region and perform the necessary science activities (such as area of interest mapping, sample acquisition, etc). In such a case, due consideration of rover energy state and thermal condition will determine the timing and extent of the shadowed region operations.

There are several mission planning assumptions regarding the activities and sequences once the rover is on the lunar surface. At or just after landing, prior to the rover rolling off the lander, the NSS and NIRVSS instruments will be calibrated, and the drill, LAVA, and OVEN payloads checked out and confirmed to be operational. Localization activities will identify the landing site in the operating area map, and any immediate (tactical) updates will be made to the traverse plan. Once the rover has left the lander and is on the lunar surface, the rover will begin its first 48 h of roving and prospecting to understand the systems in the lunar environment and calibrate instrument thresholds. The traverse plan will focus on achieving the minimum success criteria of roving and collecting measurements across a distance of 100 m. After these first 48 h of prospecting during this "commissioning" phase, the mission should begin to pursue the full mission success goals. In priority order, the mission plan can include activities to accomplish the following goals: 1. First shallow subsurface assay (sunlit); 2. First sample acquisition and processing (sunlit); 3. Prospect to reach 1000 m baseline; 4. Second shallow subsurface assay (sunlit); 5. Second sample acquisition and processing (sunlit); 6. Prospect to selected PSR (permanently shadowed region); 7. Prospect in PSR; 8. Third shallow subsurface assay (shadow); 9. Third sample acquisition and processing (shadow); 10. Identification of location to sample material for ROE; 11. Rove to, sample and perform ROE demo.

Traverse plans must also consider engineering constraints regarding the rover itself. The rover must operate in regions of low slope in order to maintain rover trafficability. For these plans, we conservatively maintain a slope less than 10°, although the rover design allows for navigation on slopes as high as 15°. We also maintain direct to Earth (DTE) communications during any traverse plan. The only time DTE is not maintained is when the rover enters a PSR where DTE is not available given the lunar topography and orientation of the Earth-Moon system. We therefore take a conservative approach and since in general larger PSRs have larger areas of communications blackouts, we do not enter any of these large PSRs until the end of the mission, after full success and stretch goals have been achieved. The shadow science is conducted in smaller shadowed regions that have smaller (if any) regions of no DTE communications, and only at end of mission do we venture into the larger PSRs which do not have direct communication with Earth. Given this location near Haworth Crater, smaller PSRs are on the order of 10 s of meters in diameter whereas larger PSRs extend for several 100 of meters in diameter. In these cases, data collected in the non-DTE PSR can be stored onboard the rover and relayed to Earth when the rover returns to an area of DTE.

3. Case study: Haworth Crater

3.1. Landing site selection

The success of a lunar polar rover mission such as RP is highly dependent upon selecting the optimal landing site. Landing site criteria are in large part driven by mission requirements to land at a polar location that maximizes the potential for obtaining high volatile (hydrogen) concentration signature and mission duration within traverse capabilities. Thus, to meet these requirements, we have attempted to identify a candidate polar landing site based on the following four criteria (Fig. 1): (1) presence of surface/subsurface volatiles, (2) reasonable terrain for traversing, (3) direct view to Earth for communication, and (4) sunlight for the duration of the mission (power constraints). Regarding the presence of surface/subsurface volatiles, the main observational line of evidence is elevated hydrogen abundance. Both the Lunar Prospector (LP) and Lunar Reconnaissance Orbiter (LRO) have produced maps of polar hydrogen abundances [5,8,13], and apparent hydrogen concentrations of >150 ppm, as seen from orbit, are considered elevated and of further interest for this study [29]. Reasonable terrain for traversing is determined by assumed rover surface capabilities in terms of trafficability and navigation. Slopes less than 10° are considered navigable by current rovers [29], and the landing site should be outside and adjacent to a permanently shadowed region (PSR), such that the landing site is in light but the rover can access a PSR for study. Given the low cost nature of the mission concept, RP requires solar power for most operations (with limited battery power for shadowed operations), and relies on DTE communications coverage for downlink and uplink purposes.

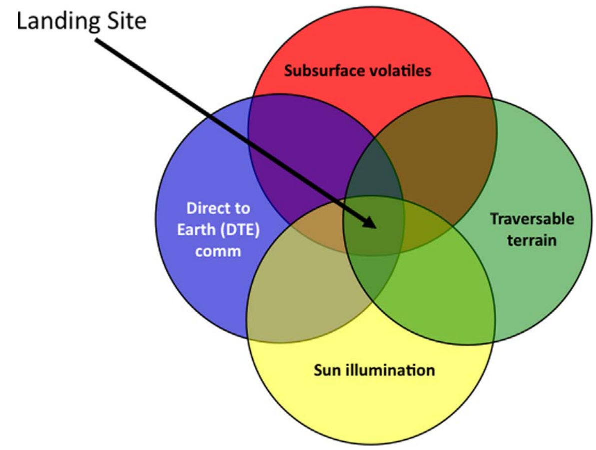

Fig. 1. A viable landing site to support a lunar polar rover mission is at the intersection (arrow) where there is a presence of subsurface volatiles, direct to Earth communications, sun illumination, and traversable terrain.

We note that a main goal of this work is to complete a thorough assessment of a reasonable location on the Moon that satisfies the aforementioned site selection criteria and determine if the RP mission is actually feasible or not. The main scientific requirements drivers for site selection are hydrogen and water stability depth, since RP seeks to characterize such lunar volatile deposits for ISRU purposes. In choosing a site to evaluate for this study, we seek to examine a site that is representative of typical polar highlands in terms of illumination, DTE, slopes, and hazards. Additional sites beyond Haworth Crater may also be found to be suitable for the RP mission, but this paper seeks to determine, for the first time, whether the RP mission is viable by conducting a detailed science and engineering study within the constraints of RP and determine whether the RP mission is feasible or not on the Moon.

3.2. Haworth Crater overview

We have conducted a multi-parameter analysis to identify a candidate lunar landing site compatible with the selection criteria outlined in Section 3.1. We seek to identify a region where traverse paths can be created to test whether or not the RP mission concept is feasible, and demonstrate whether or not a site exists on the Moon where this mission could be executed to achieve mission success. Based on this initial analysis, we have identified the North Haworth Crater site near the lunar south pole as a viable candidate for RP. We thus examine this site in more detail, and Fig. 2 shows

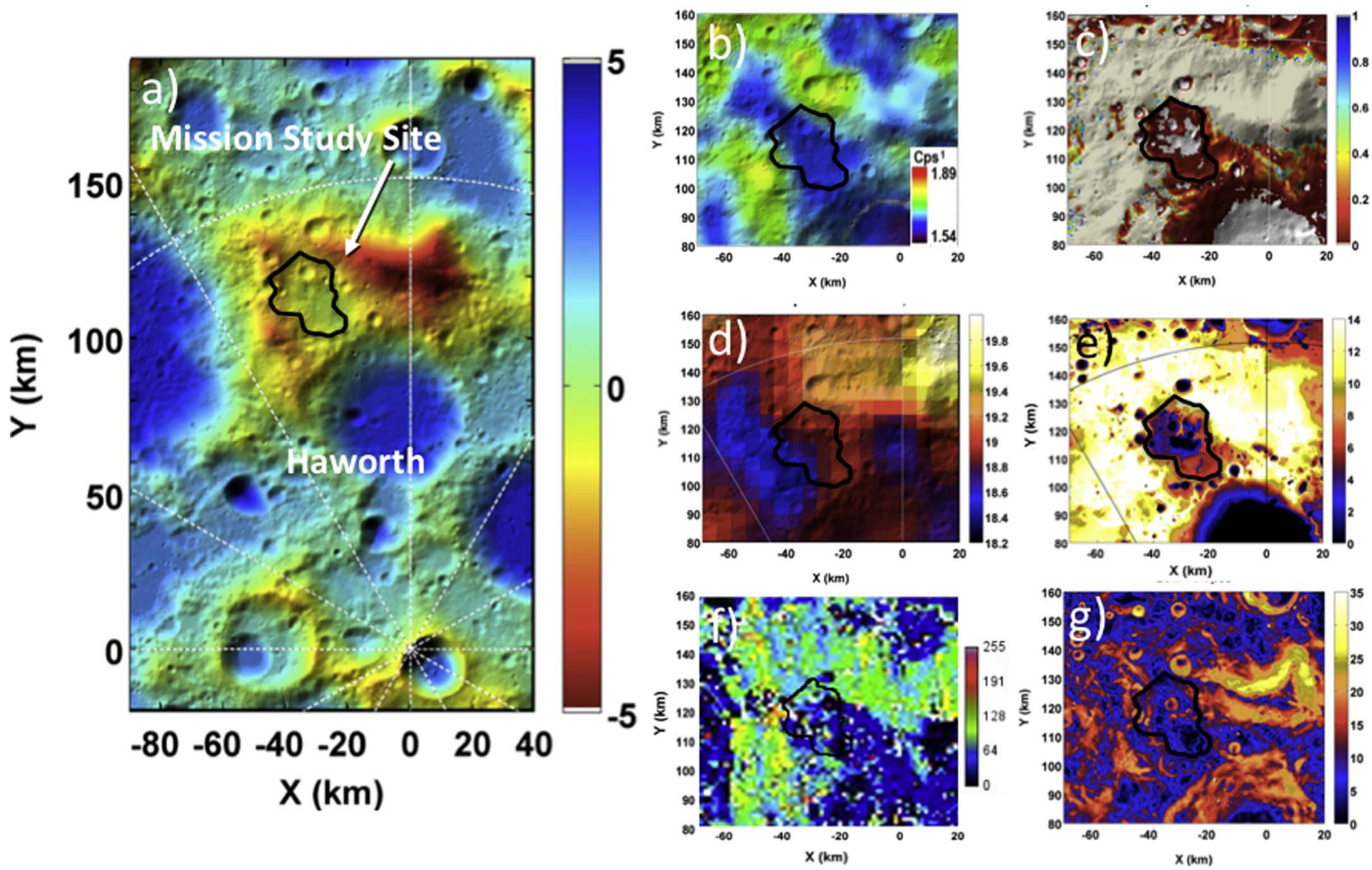

Fig. 2. North Haworth Crater area of interest on the Moon. Numbers on the *x* and *y* axes are distance from the lunar South Pole in km. Note Haworth Crater is 35 km in diameter. 2a. The mission study site is outlined in black and located just north of Haworth Crater. This figure represents LOLA gridded topography with a grid resolution of 240 m. The data have been rendered as a color-coded topographic elevation in kilometers (from mean lunar datum of 1737.4 km), with hill-shading to provide a sense of topographic texture. Color indicates elevation in km. 2b. Hydrogen abundances derived from LRO LEND data [37]. 2c. Frost temperature depth (m) calculated from LRO Diviner data [38]. 2d. Smoothed epithermal neutrons (counts/s) derived from Lunar Prospector Neutron Spectrometer data. 2e. Days of total sun illumination per month for March 2019 (centered on notional mission traverse timeframe). 2f. Water band depth observed by the M3 instrument. Color map displays the slope measured between the average of radiance between ~2377.3–2616.9 nm and 2656.8–2976.2 nm and scaled from 0 to 255, with a higher value indicating a greater water absorption band. 2 g. Terrain slopes derived from LRO LOLA data.

the North Haworth mission study site. Neutron data from LP and LRO suggest elevated levels of subsurface hydrogen in this region, which is indicative of elevated H-bearing volatile concentrations (Fig. 2b). This Haworth site contains slopes $< 10^{\circ}$ that are amenable to rover trafficability (Fig. 2), and has several days of sunlight per month (Fig. 2) to enable surface operations. Since the North Haworth site fulfills both the science and engineering constraints for the RP mission, we use this region as a notional site for this work.

3.3. Traverse plan tools

In order to accurately conduct traverse planning for the RP mission, a dedicated set of tools is required to ingest relevant planning inputs and provide a user interface to iteratively create and adjust plans in real time. Below we discuss the various input parameters required for this work, and the Exploration Ground Data Systems (xGDS) software capabilities utilized here to enable this traverse planning and analysis process.

3.3.1. Input parameters

Based on the mission and landing site requirements, there are a variety of data products and modeled inputs that serve to inform the traverse planning activity as described below. All information is considered for a notional mission window with lunar surface operations beginning on 3 March 2019 at 6:24 pm UTC. Given the NASA budgetary profile for RP and the resultant RP mission schedule, this start date was chosen as a result of a plausible launch window opportunity and corresponding date for commencing surface operations.

3.3.1.1. Solar illumination. Solar illumination conditions at the lunar surface are determined as a function of time for the region of interest. In this work we use modeled solar illumination maps which are generated at 1 h intervals as calculated over a full lunar day, centered on the mission mid-point for this notional traverse plan. Sunlit and shadowed areas are displayed as light and dark regions, respectively (Fig. 3a). Each pixel in the region of interest map, which represents a possible location for the rover, is analyzed at each time step to determine if the pixel has line of sight to any part of the Sun or if the pixel is in shadow. If the angle between the pixel's zenith vector and a vector from the pixel to the top of the Sun is greater than the angle from the zenith vector to the highest terrain peak, in the direction of the Sun, then the pixel is in shadow. Otherwise the pixel sees at least a small portion of the Sun [30]. Fig. 4 depicts the geometry for this scenario where the Sun is modeled as an extended source. These results are based on the work of McGovern et al. [30] and consistent with the findings of Speyerer and Robinson [31].

3.3.1.2. Communications. The RP mission concept assumes a direct to Earth (DTE) communications architecture. We therefore

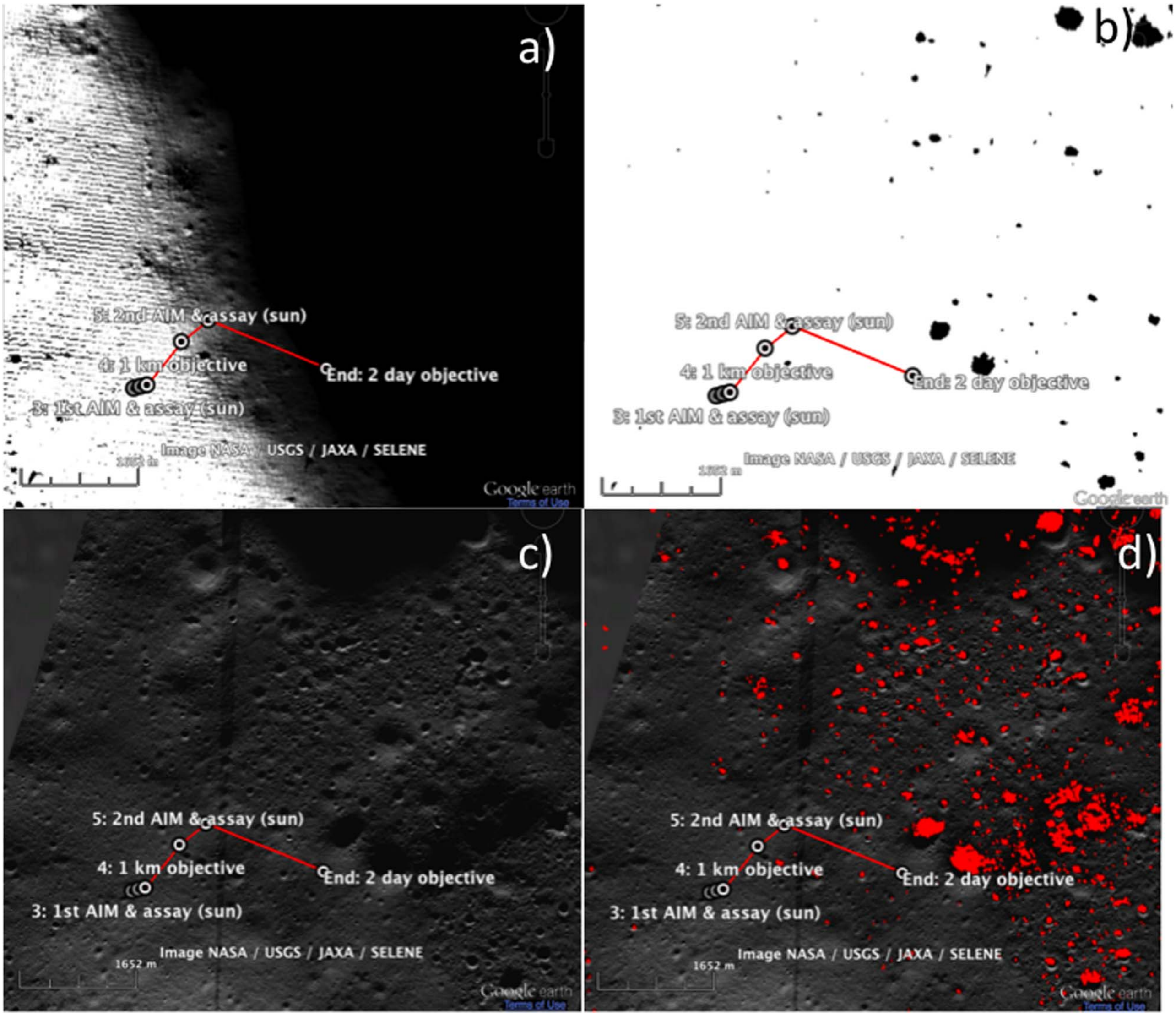

Fig. 3. Information used in xGDS for traverse planning purposes within the area of interest near Haworth Crater. Solar illumination and direct to Earth communication conditions are shown for time at the beginning of the mission (MET=0). 3a. Solar illumination (white=illuminated, black=in shadow). 3b. Direct to Earth communication (DTE) shown in white. 3c. LRO LROC (Lunar Reconnaissance Orbiter Camera) camera imagery. 3d. Permanently shadowed regions (PSRs) are shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

consider rover to DSN (Deep Space Network) station coverage with maps showing when each DSN station's elevation angle to the rover is above a minimum allowable angle available (Fig. 3b white regions) intersected with times when the rover has an unobstructed view (Fig. 3b dark regions) to the station with a minimum terrain clearance angle at 1 min intervals. This analysis assumes a minimum DTE angle as 4° relative to the local topographic horizon, which means that the Earth (as seen from the rover on the lunar surface), must be greater than or equal to this elevation angle in the sky to enable communications. The communications antenna is two meters above the lunar surface. Fig. 5 depicts the geometry for direct to Earth (DTE) communications where each available Earth station is modeled as a point source in the line of sight analyses. In the case of DTE communications constraints are enforced for line of sight clearance above the terrain path and for a minimum allowable elevation angle for the Earth-based antenna. We note that for nominal operations, the rover is in constant DTE communications with Earth and communications occurs simultaneously with rover activities; the rover is not required to stop specifically to enable communication with Earth.

3.3.1.3. Terrain slopes. Slope maps have been generated based on LRO LOLA (Lunar Orbiter Laser Altimeter) altimetry (20 m baseline data product publicly available on the PDS (Planetary Data System)). Slopes remain static over the timescales of the RP mission, and thus the map in Fig. 2g is used for traverse planning as a static, non-time dependent map to ensure the rover stays on slopes below the maximum slope allowed to ensure rover safety ($<10°$, Section 2.5). For reference, the range in slopes on the lunar terrain for this Haworth Crater region of interest is 0° to approximately 20°.

3.3.1.4. Camera imagery. High resolution camera imagery from the LRO LROC (Lunar Reconnaissance Orbiter Camera) NAC is used for traverse planning as a prime means of understanding the lunar terrain and geologic setting of the area of interest (Fig. 3c). Traverse planning relies on Narrow Angle Camera images from the LROC instrument onboard LRO, which can resolve meter-scale features relevant to traverse planning of a meter-scale vehicle. Imagery is used, in combination with altimetry data, for hazard avoidance (e.g., avoiding large boulders, steep walled slopes, etc). Camera imagery is also used for scientific planning (e.g., to

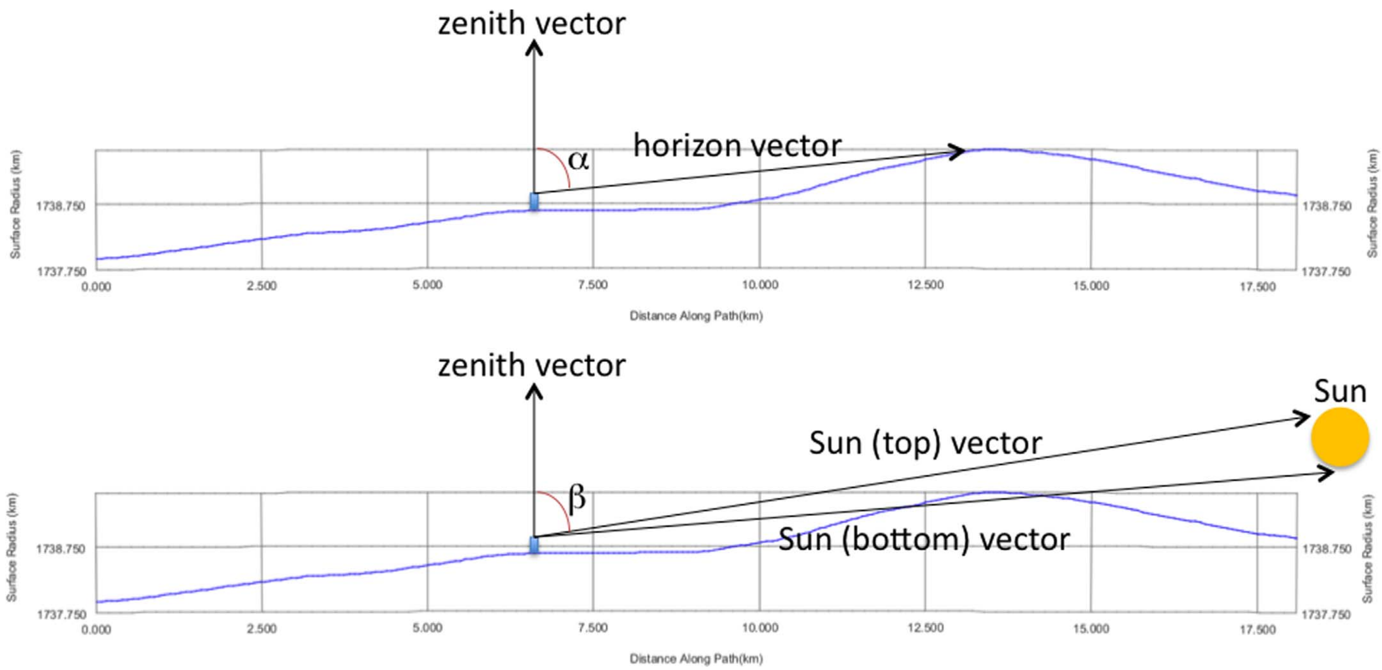

Fig. 4. Two diagrams showing the same terrain profile in the plane of the lander or rover, the center of the Moon, and the Sun. For a given location and time illumination can be calculated by comparing the angles α and β. If the angle β (the angle measured from zenith to the top sun vector) is less than the angle α then the site has at least some illumination. Full illumination occurs when the angle from zenith to the bottom of the Sun (β + angular width of the Sun) is less than α (the angle measured from zenith to the horizon).

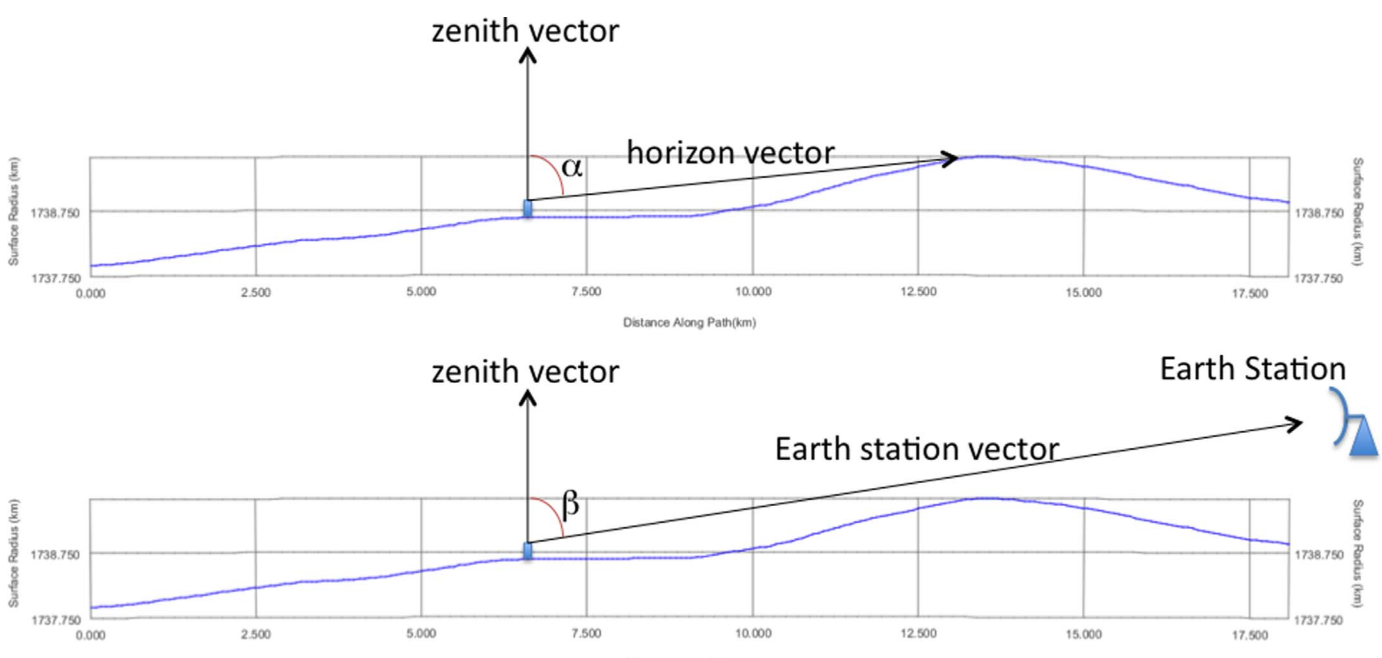

Fig. 5. Two diagrams showing the same terrain profile in the plane of the lander or rover, the center of the Moon, and an Earth Station. For a given location and time direct to Earth communications can be determined by comparing the angles α and β, as well as other constraints. If the difference (α−β) is greater than the required lunar terrain clearance and the ground antenna is pointed at the location and at or above the minimum allowable elevation angle, then the site has access to the Earth station.

interrogate regions near impact craters or flat expanses of terrain). Camera imagery can also indicate differences in light versus darker toned materials on the lunar surface which is useful for the scientific aspects of traverse planning to understand when a different material or geologic feature is within the measurement capability of the rover (e.g., light toned crater rays emanating from a relatively fresh impact crater). Such differences in geologic terrains are likely valuable to investigate from a geologic perspective. Another key use of the LROC imagery is to perform a qualitative inspection of meter-scale roughness and avoid obvious hazards when planning the rover traverse path.

3.3.1.5. PSRs. A map of PSRs has been generated based on geometry and the LOLA-derived terrain models of the lunar surface [30]. PSRs, by definition, do not change over the course of the RP mission, and thus the map of PSRs remains constant in time for this traverse planning exercise (Fig. 3d). The map of PSRs was generated using a similar technique as previously described for generating the solar illumination maps as a function of time. We have generated PSR maps specifically for this work to incorporate the maps, in the appropriate format, into the RP mission planning software (Exploration Ground Data Systems, xGDS, see Section 3.3.2) to enable the mission traverse planning for RP. The results of these PSR maps are consistent with the findings of other PSR analyses [31–35].

3.3.2. Exploration ground data systems (xGDS)

xGDS is a suite of software tools developed to support mission planning, monitoring, visualization, documentation, analysis, and search functionalities [36]. xGDS is a web-based service which caters to both science and operations needs, and we use xGDS here to support RP traverse planning. The RP mission uses the xGDS platform as xGDS has been customized specifically to support a lunar polar rover mission. Other commercially available software packages lack the capabilities required to support RP (notably the mission planning, position- and time-dependent sun and direct-to-Earth communications access, and real-time monitoring capabilities), and hence xGDS has been developed by NASA to support RP's unique needs. Here we focus on the Planning aspect of xGDS which uses a-priori map information described in Section 3.3.1, e.g., remote sensing data, known operational hazards or constraints, targets of interest etc. to enable teams to import, create and share map content and collaboratively edit plans. The xGDS planner capability displays a map view and a nested list of waypoints and segments designated by a traverse planner, activities at waypoints and on segments, and parameters for activities such as instrument settings. xGDS shows map layers for context, and computes plan timelines using information such as activity durations defined in the Activity Dictionary (Section 2.4) and estimated average rover speed. Note that figures presented in this paper depicting the notional RP rover traverse path with labeled waypoints were generated using the xGDS software.

3.4. Notional traverse plan

We have used the xGDS platform to construct a traverse plan which can meet the RP mission objectives while still operating within the known mission constraints previously discussed (Section 2). We focus on the Haworth site, which has been shown to meet the high-level site selection criteria of elevated hydrogen abundances, acceptable slopes, DTE, and sunlight availability, and here we present a notional traverse plan developed through this work. We have identified specific waypoints, which are important for their location and/or activities conducted at these sites, and we track the mission elapsed time (MET) throughout the course of the traverse. A summary of the Waypoints and associated times and distances traveled by the rover is shown in Table 3.

Fig. 6 shows the nominal landing site near Haworth Crater. The landing site is chosen in a region of low slope (less than 5° slope) and in sunlight. We choose this site such that the traverse path can proceed towards the east as the sunlight (terminator) also moves to the West such that shadows cast by topographic relief swing to the East. Upon reaching the lunar surface, the rover drives in prospecting mode for 100 m to reach the minimum success threshold (Fig. 7) at 1 h 23 min MET. Following minimum success, the rover can execute the first AIM and complete the first assay in sun at 9 h 19 min MET. The 1 km roving objective is met at 20 h 23 min MET, and the second AIM and assay in sunlight is complete at 33 h 53 min (Fig. 8). The two day driving objective is met at 61 h 05 min MET (Fig. 9). Note that this time represents 48 h of roving and prospecting since 13 h are consumed when the rover is conducting the prior AIMs and assays. In a strict sense, the AIMs are driving exercises and could count towards the needed 48 h of driving such that the 48 h rove time is reached at 60 h MET.

Table 3
A summary of the notional lunar rover traverse plan for the Haworth Crater site. Waypoint numbers are listed with the associated time duration at each Waypoint, the cumulative mission elapsed time (MET) for surface activities, the distance between Waypoints, and the cumulative distance traveled by the rover.

Waypoint number	Duration of waypoint (H:M)	Cumulative time (H:M)	Cumulative Distance (meters)
Start	0:00	0:00	0
2	0:00	1:23	100
3	6:30	9:19	203
4	0:00	20:23	1000
5	6:30	33:53:00	1503
6	0:00	61:05:00	3462
7	0:00	63:23:00	3628
8	0:15	68:50:00	4002
9	0:00	69:12:00	4028
10	1:53	71:24:00	4051
11	6:30	78:15:00	4076
12	16:54	95:22:00	4093
13	1:30	100:33:00	4357
14	1:30	103:31:00	4463
15	1:30	106:17:00	4554
16	1:30	108:60	4641
17	0:00	109:49:00	4701
18	0:15	112:44:00	4893
19	6:30	120:39:00	4994
End	18:24	140:19:00	5086

At this point, the rover is allowed to explore its first PSR. The first PSR is deliberately chosen as a small (20 m diameter) PSR. A small crater harboring a PSR is selected in order to maintain relatively benign slopes for the rover and maintain DTE for communications (both of which are typically lost for the largest PSRs of 10–100 s of km in size). The rover is commanded to stop at the edge of the penumbral shadow to assess the path forward into the PSR (15 min halt), and then enter the PSR, cross the PSR mid-point, and egress the PSR. Upon PSR egress, the rover again halts for 15 min for the team to assess the first foray into shadow as well as recharge the rover batteries after being in shadow. The rover, upon concurrence from the mission team, can then re-enter the PSR, conduct an AIM and assay, and then exit the PSR. Upon return to sunlight the rover conducts the ROE, and full mission success is thereby achieved at 95 h 22 min MET (Fig. 10).

The traverse plan continues from this small PSR towards the larger PSR of interest to the north (Fig. 11), because it is of scientific interest to know if volatile sequestration is a function of PSR size. The route is planned to avoid topography (higher slopes) and allows the opportunity to conduct four auger activities in sunlit regions en route to the PSR in order to achieve the stretch goals (Fig. 11). Upon completion of these activities, the rover reaches the edge of penumbral shadow near the PSR. We note that the edge of the shadow at this time is ~85 m away from the edge of the actual PSR. The rover halts for 15 min at the shadow edge to allow for team decision-making activities, and then enters the PSR to perform a shadowed AIM and sample acquisition. The rover then egresses from the shadowed region and remains in operation until DTE is lost (we note that this site on the ridge of the PSR is still illuminated when DTE is lost). This plan then ends at 140 h 19 min MET, having achieved minimum success, full success, and the stretch goals as identified for the RP mission.

4. Lessons learned

Performing this landing site study and conducting the associated traverse path planning activity, multiple key lessons learned have been identified which are summarized here.

The landing site chosen for this mission is critical to all future

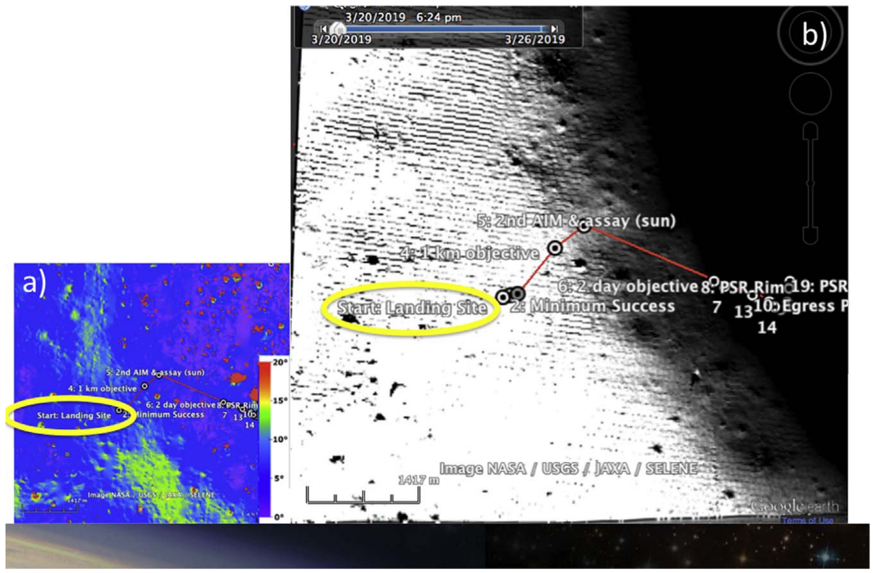

Fig. 6. The notional traverse plan landing site. The landing site is circled in yellow. The landing site is selected in a region of low slope and in sunlight. The traverse path remains in sunlight as the terminator moves west and shadows cast by topographic relief move to the east. 6a. The landing site region is shown on a shaded topography map with waypoints along the traverse path. PSRs are shown in red. Colorized slope scale bar is shown as derived from LOLA data and applies to Figs. 6–11. 6b. The landing site region is shown on an illumination map for the assumed rover mission start time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

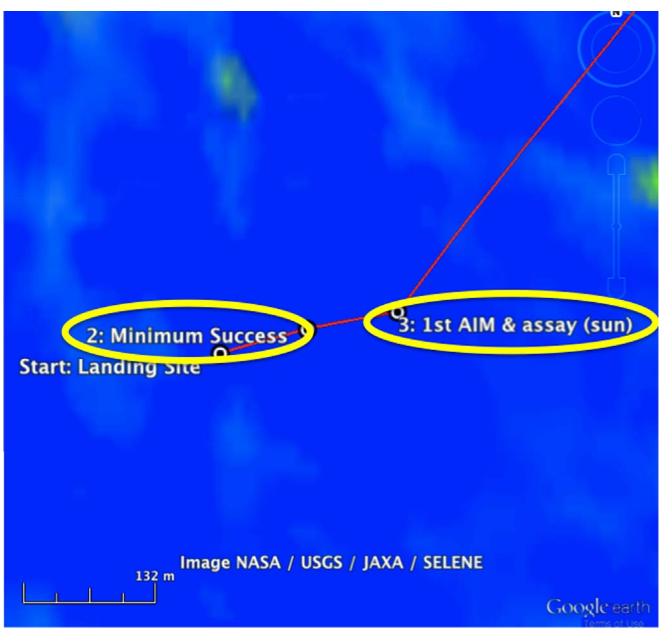

Fig. 7. Traverse plan showing that Minimum Success is achieved at Waypoint 2 (100 m distance traveled at 1 h 23 min MET) and the first AIM and assay (in sunlight) is complete at Waypoint 3 (9 h 19 min MET).

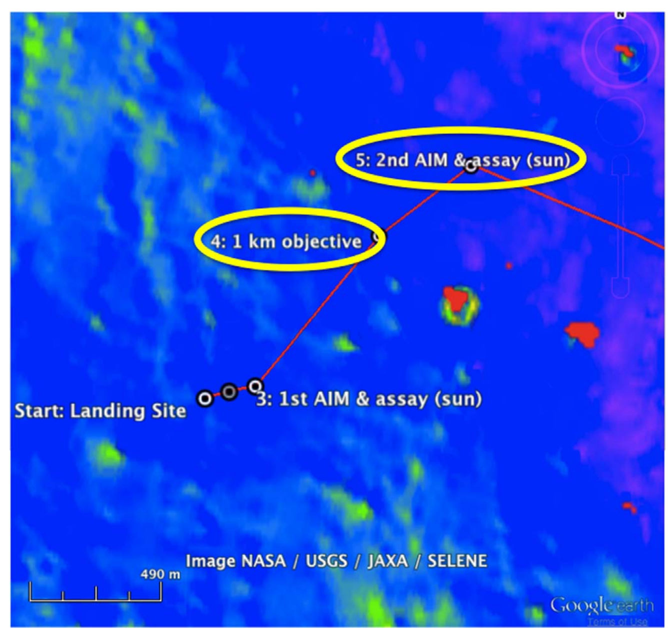

Fig. 8. Traverse plan showing that the 1 km roving objective is reached at Waypoint 4 (20 h 23 min MET) and the second AIM and assay in sunlight is conducted at Waypoint 5 (33 h 53 min MET).

surface planning and activities. The plan discussed in this paper lands at edge of shadow and follows the sunlight as the sun itself moves west in the sky. Sites outside of this region experience significant periods of shadow during this time period and thus are not suitable for an RP traverse. We note that the potentially most interesting areas with the highest density of PSRs (and thus colder temperatures likely harboring increased concentrations of volatiles) occur in regions where shadow prohibits solar powered rover traverses. This situation highlights the necessity of identifying the "sweet spot" between the presence of suitable PSRs (and hence shadowed regions) and the required illumination conditions to enable the mission.

The illumination condition and its variation over time are significant drivers in terms of traverse planning. The changing illumination conditions as a function of time are shown in Fig. 12. Owing to significant south polar relief, and the low sun angle, illumination conditions change significantly on timescales of hours and days. Due to these significant changes over timescales relevant to the RP mission, illumination drives the general traverse plan location (10–100 s of km scale) and also affects tactical traverse plan decisions (< 10 m scale).

Also regarding illumination, we note that permanent shadow is not the same as shadow. Non-permanent shadows are caused by changes in sunlight reaching the ground due to topographic barriers and can change in size and location over the lunar day. Particularly near large PSRs, the rover will often enter a region of

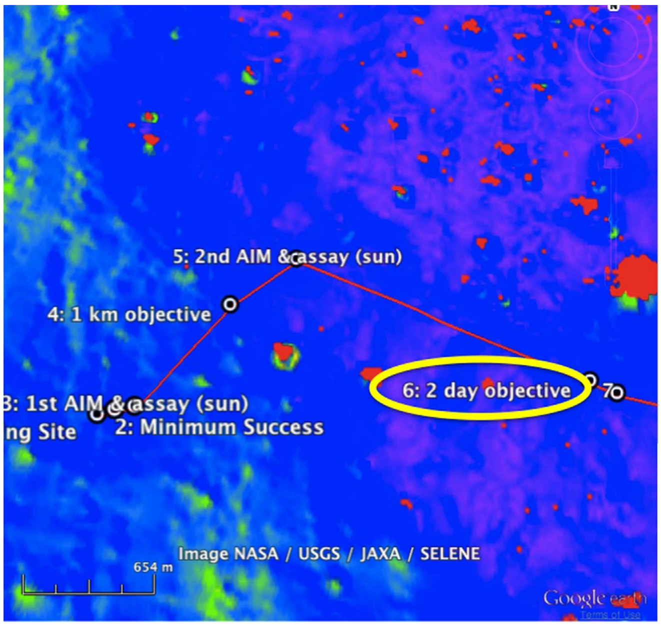

Fig. 9. The two day roving objective is achieved at Waypoint 6 (circled) at 61 h 05 min MET.

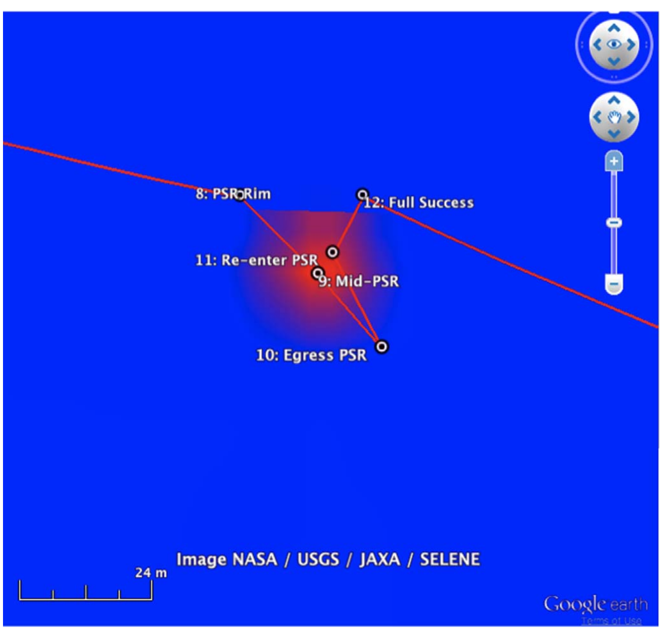

Fig. 10. A detailed view of the traverse plan for exploration of the first permanently shadowed region (PSR). This PSR is ~20 m in diameter. At Waypoint 8 (68 h 50 min MET) the rover stops at the crater rim (15 min halt) for decision-making purposes. The rover enters the PSR (Waypoint 9 is at the PSR midpoint), and egresses the PSR at Waypoint 10. Batteries are recharged in sunlight, and another 15 min decision making halt is implemented. The rover re-enters the PSR (Waypoint 11) and conducts an AIM and assay in shadow. The rover exits the PSR (Waypoint 12, 95 h 22 min MET) and conducts ROE to achieve full mission success.

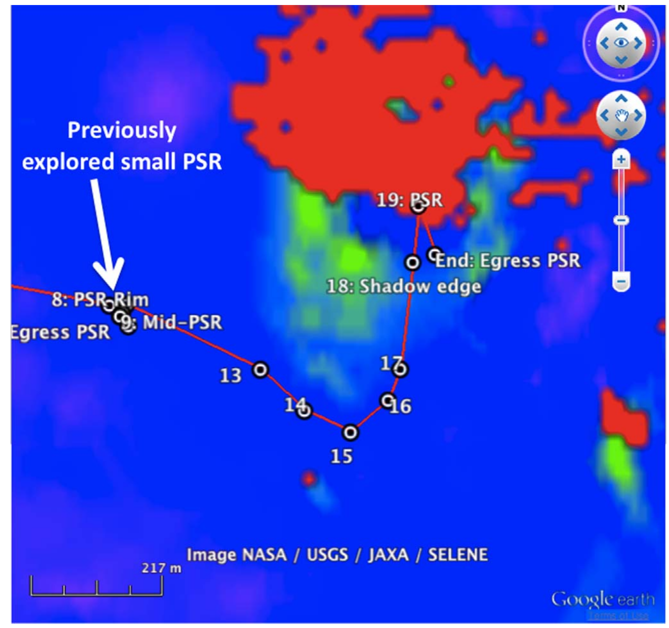

Fig. 11. The rover continues along the traverse plan from the small PSR (Fig. 10) towards the large PSR of interest (labeled in Fig. 11). The traverse path follows a route to avoid topography (higher slopes) and conducts auger activities in sunlight along the way (Waypoints 13, 14, 15, and 16) to achieve stretch goals.

shadow before entering the PSR itself. Traverse planners must be aware of the time-dependent illumination conditions, and consider both permanent and non-permanent shadow conditions when outlining rover traverse routes.

The presence of varying shadow surrounding the PSRs has implications for the mission timeline. Since non-PSR shadow often surrounds PSR regions (for example, in our notional traverse plan there is ~85 m of shadow prior to entering the large PSR at the end of the mission), it takes a significant amount of time to traverse into the PSR, return to an area of sunlight, and recharge batteries. For this reason, the first PSR visited is small, several 10 s m diameter, which allows for faster access to the PSR of interest and requires less driving distance in shadow to access the PSR itself.

Unlike illumination, DTE does not change significantly over the ~6 days of the mission for this site because of the higher elevation of the Earth above the local horizon. DTE exists in most locations and only at the very end (final hours) does DTE disappear as DTE loss enters from the east. However, DTE does not exist is most large PSRs in this particular region of study at any time, so traveling into a large PSR most likely results in a communications loss, which is an important consideration for traverse planning.

The final stages of the nominal RP mission can be strategically chosen to maximize the time in sunlight. The plan presented here "ends" in a location that is still in sunlight when DTE is lost. It is conceivable that an advanced version of the mission concept presented here could continue the rover mission when DTE returns to this site. By remaining in sunlight, the rover can continue to receive power to stay alive and not have to mitigate against the extra complexities of surviving the dark and cold of lunar night, thereby extending the mission duration and allowing more time to collect science data.

The traverse plan presented in this paper reflects a conservative case where the rover speed is kept constant throughout the duration of the mission. However, it is likely that as more experience is gained in operating the rover in the lunar environment, a faster effective roving speed could be achieved. Increasing the effective rover traverse speed allows for additional exploration and science. Increasing the rover speed from our notional 0.02 m/s to 0.10 m/s after the 48 h roving threshold is reached results in 25 additional mission hours before loss of DTE coverage, which would allow additional exploration of the sea of PSRs near the ending location in this traverse plan.

The traverse plan presented here is the result of manual route mapping and addition of rover activities into the xGDS framework. At each timestep (dictated by the frequency of map updates for the input parameters such as illumination and DTE), the rover location and route was manually cross-checked to ensure compliance with

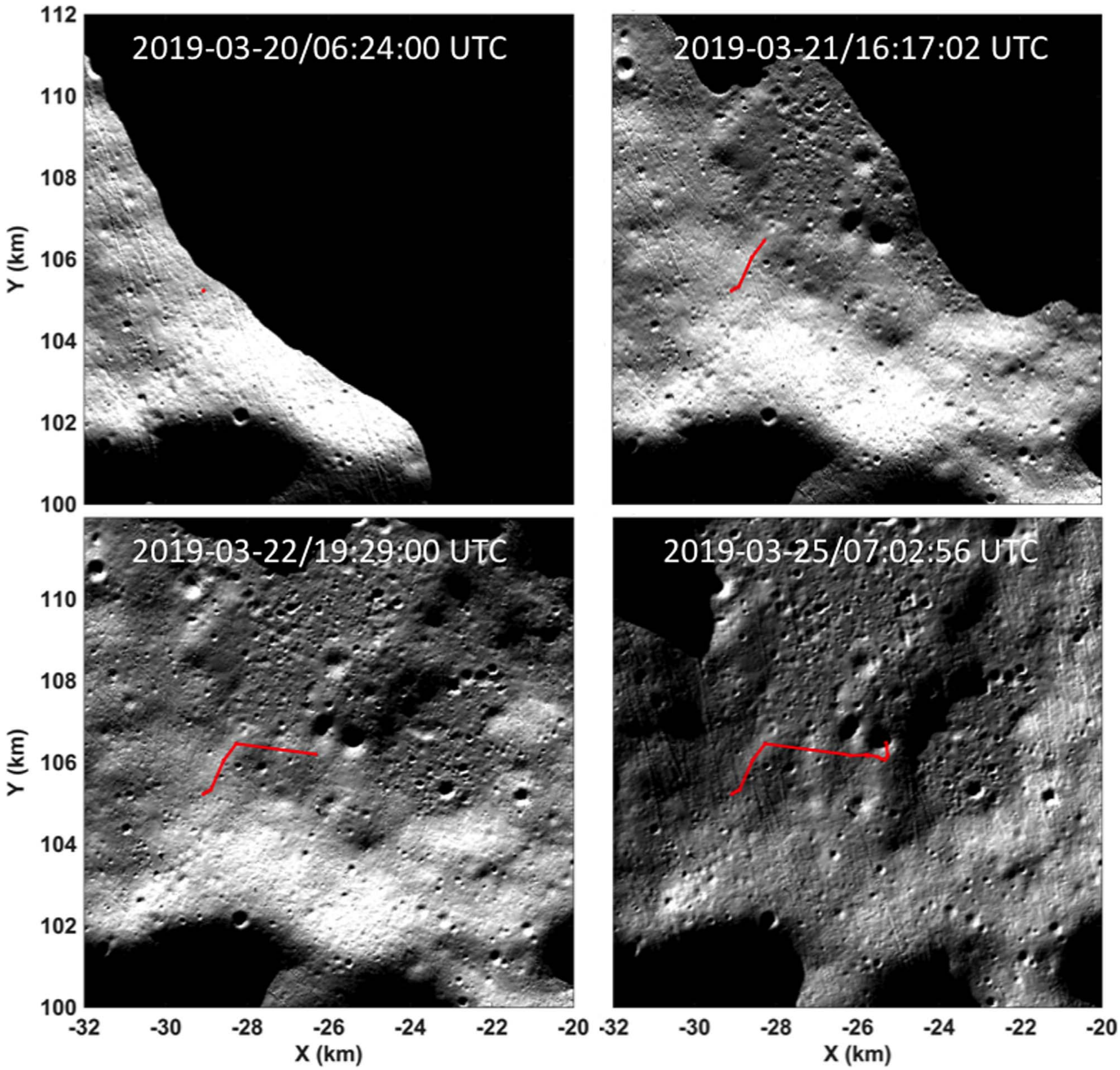

Fig. 12. Time step series demonstrating the changing illumination conditions in the landing site area immediately north of Haworth Crater over the time period examined for the notional RP traverse plan presented in this paper. Map axes represent distance (km) from the lunar south pole. The red line shows the progress of the RP rover as a function of time for the notional traverse plan presented in this paper.

the mission constraints as a function of location and time. This process is cumbersome and time consuming; the current framework is unsuited to enabling the rapid replanning that will be required for real-time operations on the Moon when time is critical [25]. Going forward, the RP mission would benefit from an automated cross-check of the traverse plan against all known constraints and/or inputs. Automated traverse planning software packages [39] that can also take into account the prioritized scientific objectives and/or locations to generate traverse plan options optimized for both science and engineering could also prove valuable in maximizing the limited time available for data collection on the lunar surface.

5. Conclusions

Recent missions and analysis of existing datasets suggests that volatiles are likely sequestered near the lunar poles. The form and distribution of these volatiles is poorly constrained, although it is important to gather more information on this topic for both scientific and exploration purposes. The Resource Prospector (RP) mission was conceived to provide surface and subsurface measurements both in sunlight and in shadow at relevant length scales on the lunar surface to identify and map lunar volatile distributions. The RP mission is a short duration robotic lunar polar rover, which will operate primarily in sunlight but venture into shadow to collect valuable data pertaining to volatile distribution. Here we have shown that the RP mission can be successfully completed at the North Haworth Crater near the lunar south pole; this work demonstrates that the RP mission is viable from a site selection and surface planning and execution standpoint. We have identified several lessons-learned in terms of rover traverse planning for real-time operations such as the critical nature of the landing site, the importance of accounting for the time variable nature of the illumination and DTE conditions, and the impact of rover speed on science return. Any real-time lunar mission would benefit from the development of enhanced software planning tools which can automate many of the processes required to generate surface traverse plans to optimize the scientific return while adhering to the engineering constraints of the mission.

Acknowledgments

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