PLANNING AND OPTIMIZING FUTURE TRAVERSES FOR LUNAR POLAR PROSPECTORS.

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Introduction: Recent lunar missions provide the planetary science community with vast amounts of new data enabling important insights into the geology and evolution of the Moon on a global scale. Remotely sensed observations of the polar regions reveal the location of persistently illuminated regions and evidence for volatiles captured in cold traps [1-5]. In-situ resource utilization (ISRU) of these volatiles has the potential to transform these regions into fueling stations for future lunar missions as well as create a sustainable architecture for the exploration of the Solar System [6]. However, there are still many questions regarding the chemistry and extent of these cold-trapped resources.

To fully characterize the region and ground-truth remote datasets, a future mobile lunar prospector, such as VIPER or a next generation long lived polar rover, could survey a series of sites to assay resources not only along the surface, but also at shallow depths. Just like previous lunar and Martian rovers, the available power to the rover would be limited by solar panel and/or radioisotope thermoelectric generator (RTG) output. However, unlike previous planetary rovers, the polar prospector would be exposed to intense cold (75-200 K) for extended periods of time due to the extreme illumination environment. Therefore, rover energy management planning will seek to maintain adequate reserves for component heating. Thus, optimal traverse planning that conserves energy (and increases reserves for heating and science instrumentation) will enhance the overall success and longevity of a polar prospector.

Modeling the Environment and Energy Usage: To effectively identify optimal traverses, the local topographic and illumination environment need to be characterized. Stereo images collected from the LROC Narrow Angle Camera (NAC) have been co-registered to elevation profiles from the Lunar Orbiter Laser Altimeter to create merge products that provide accurate and precise elevation models of the polar region [7,8]. In addition, these elevations models along with observed illumination conditions from the Wide Angle Camera (WAC) can be used to characterize the illumination conditions in the region [5,8]. Combining these datasets, we assess the traversability of the terrain and identify optimal traverses and timed sequences.

To model the energy usage of the polar prospector along the simulated surface, we use a terramechanics model that simulates the wheel/soil interaction [9-11]. This model enables us to calculate the torque required to move the rover across the lunar surface using the elevation model and the lunar soil trafficability parameters outlined in Carrier et al. [12].

Optimized Traverse Planning: To identify potential traverse options, a grid of evenly spaced nodes (typically several meters to 10s of meters apart) is superposed over the elevation model. Each of the nodes is connected to up to eight neighboring nodes and each connection, or edge, is assigned a value that corresponds to the amount of energy required for the rover to traverse from the current node to the corresponding neighboring node.

Next, we use the A* (“A star”) search algorithm [13] to calculate the least energy required and associated path for the model rover to traverse from an initial waypoint to a goal waypoint in the DTM. The A* algorithm is similar to the Dijkstra’s graph search algorithm [14] with the exception that a heuristic estimate is used to optimize the search. By varying the order of the waypoints, an optimal mission plan can be derived.

To further optimize the traverse, time-varying data, such as solar illumination, can be incorporated to identify paths and time depending traverse sequences to extend the amount of illumination the mobile prospector receives. By varying mission parameters (e.g., maximum period allowed in shadow, maximum average speed, etc.), a custom mission plan can be evaluated.

Case Study: To test and appraise our optimized traverse tool, we examined several traverses near Shackleton crater. Shackleton is a 21 km diameter impact crater near the south pole (89.655°S, 129.2°E) with 235 km^2 of its interior in perpetual shadow; however, portions of its rim are persistently illumined [1,5,15]. We first mapped out optimal traverses between three stations of persistent illumination on the rim of the crater that were identified by Speyerer and Robinson (2013) with WAC images [5]. All three stations are within close proximity to one another (~2 km) enabling a mobile prospector to travel between stations to increase the overall available solar energy throughout the lunar year (up to 94% of the year).

Using a NAC/LOLA-derived elevation of the south polar region and the R-Traverse e-planning tool described above, we identified the optimal path between each pair of stations along the crater rim (**Fig. 1**). The optimal (least-energy) traverse from Station 1 to Station 2 is 2.0 km long with an average absolute slope of 2.3° and a maximum slope of 10.3°. From Station 2 to Station 3, the optimal traverse is 2.5 km long with an average absolute slope of 1.7° and a maximum slope of 6.0°. These slopes are well within the range of previous rover designs and many proposed rovers designs. By leveraging several of the persistently illuminated areas, the amount solar radiation received throughout the year could be increased and the longest eclipse period could be minimized (Table 1).

In addition to looking at the rim of Shackleton, we also investigated traverse options for a pair of local topographic highs near a large flat region that is an ideal site for a lander to deliver the rover to the surface. These sites (Station 4 & 5), which are each illuminated for 45.6% and 63.3% of the lunar year, respectively, collectively remain illuminated for 91.8% of the year and are eclipsed for only 104 h [5]. The optimal traverse from Station 3 to Station 4 is 11.8 km long with an average absolute slope of 4.1° and a maximum slope of 11.7°, while the optimal traverse between Station 4 and 5 is 2.7 km long and has average absolute slope of 2.1° and a maximum slope of 6.5°.

While each of these five stations is illuminated for a majority of the year, areas nearby and along the traverse are in permanent shadow. These relatively small PSRs provide access to potential cold traps that may harbor volatiles. A long duration polar prospector would be able to evaluate the resources in multiple small PSRs, examine how the quantity of volatiles change in areas that receive different percentages of sunlight, and study the mobility of volatiles over short time scales as a region falls in and out of shadow. In addition, Stations 1, 2, and 3 offer ideal views inside of a large PSR (floor of Shackleton crater). Standoff instruments, particularly those with long-integration measurements, could assess surface deposits without risking a traverse down the steep walls (~30°).

Table 1- *Persistently illuminated regions identified in [5]:*

Station	% illumination	Longest eclipse
#1 (89.685°S, 196.7°E)	69.0	147 h
#2 (89.740°S, 201.2°E)	71.6	145 h
#3 (89.808°S, 205.9°E)	63.0	155 h
Station #1 and #2	86.9	63 h
Station #2 and #3	85.5	60 h
Station #1, #2, and #3	**92.1**	**43 h**
#4 (89.500°S, 222.1°E)	45.6	281 h
#5 (89.418°S, 221.3°E)	63.3	308 h

Discussion: The R-Traverse tool outlined here, which we are continuing to improve and refine, provides a means to examine and identify optimal (least-energy) traverses around the lunar poles as well as any region of interest on the Moon or other terrestrial body with accurate topographic data. The planning tool now more accurately considers trafficability parameters, including power usage. Using time-varying data, such as solar illumination estimates, we can create timelines dictating when areas are traversable given the lighting forecast and constraints of the lunar rover design. Overall, this framework, along with the ability to model different size rovers and configurations, enables mission planners to accurately design traverses that maximize the science return while certifying the safety of the prospector.

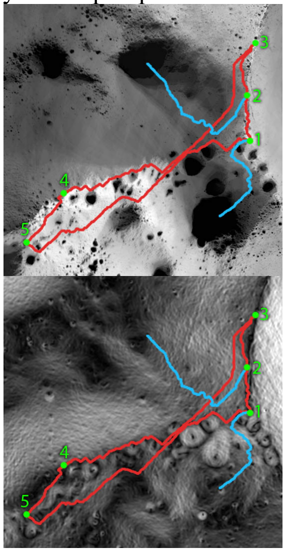

Fig. 1- *LROC NAC-derived illumination map (top) and LOLA slope map (bottom) overlaid with optimal traverses between persistently illuminated regions (red line; green dots) derived from a 40 m/pixel LOLA DTM. The blue lines highlight 6.8- and 4.8-km traverses inside two nearby PSRs. Stations 1, 2 and 3 are all on the rim of Shackleton crater; the map is 11.2 km across.*

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