OPTIMIZED TRAVERSE PLANNING FOR FUTURE 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.

Ground-truth measurements are required to fully understand the resource potential of lunar volatiles. A mobile polar prospector could address many outstanding questions by sampling a series of sites to assay resources not only along the surface, but also at shallow depths. These ground measurements are key in calibrating and understanding an array of remotely sensed observations and providing first order estimates of *tonnage* and *grade* of any resource deposit. As part of the mission concept, a precise landing system will deliver a rover to the surface to traverse into several permanently shaded regions (PSRs). By accessing several PSRs, the science payload will determine how volatile contents vary from one PSR to another at the surface and at depth. To optimize the mission and maximize the science return, we propose a traverse-planning algorithm that uses regional data products to identify the least-energy traverse paths around selected landing sites and regions of resource interest.

Traverse Planning: To locate potential traverse options, a digital terrain model (DTM) of the region is required. The DTM must be high enough resolution to capture all the major topographic features (<100 m/pixel) and contain very few areas of interpolation. Therefore, for the polar regions, we use the gridded DTM product produced by the Lunar Orbiter Laser Altimeter (LOLA) team due to their dense collection of points near the poles and their ability to accurately measure elevations in shadowed areas [7].

After selecting the DTM, a grid of evenly spaced nodes (typically several meters to 10s of meters apart) is superposed. 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 [8] 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 [9] 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.

Case Study: 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 [1,5,11]. The first images of the region provided by the Clementine UVVIS camera indicated that a portion of the rim was persistently illuminated [11]. With the recent images and topographic data returned by the Lunar Reconnaissance Orbiter (LRO), knowledge of these regions of persistent illumination were refined and quantified [5,12].

In order for a long-duration polar prospector to survive without the benefit of a Radioisotope Thermoelectric Generator, the rover needs to access and leverage these persistently illuminated areas throughout its mission to meet its power and thermal needs. Therefore, we first map out the traverses between three stations of persistent illumination along the rim of Shackleton crater that were identified by Speyerer and Robinson (2013) with LROC Wide Angle Camera (WAC) images. 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.

Using a 40 m/pixel LOLA-derived DTM of the south polar region and the traverse-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 the 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 and Future Work: The traverse-planning tool outlined here 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. From our analysis, we conclude that each of the five stations noted above are accessible without exceeding slopes of 12° (40 m scale).

Future work will focus on adding time-varying data sets to the traverse-planning tool. For example, synthetic illumination maps can be used to ensure the roving prospector is never in shadow for more than a predefined amount of time. In addition, by including time-varying thermal data, we can identify traverses where the prospector can sample potential deposits when the temperature of the regolith is at its maximum or minimum. We also plan to improve the DTM by integrating a merged NAC/LOLA product. 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.

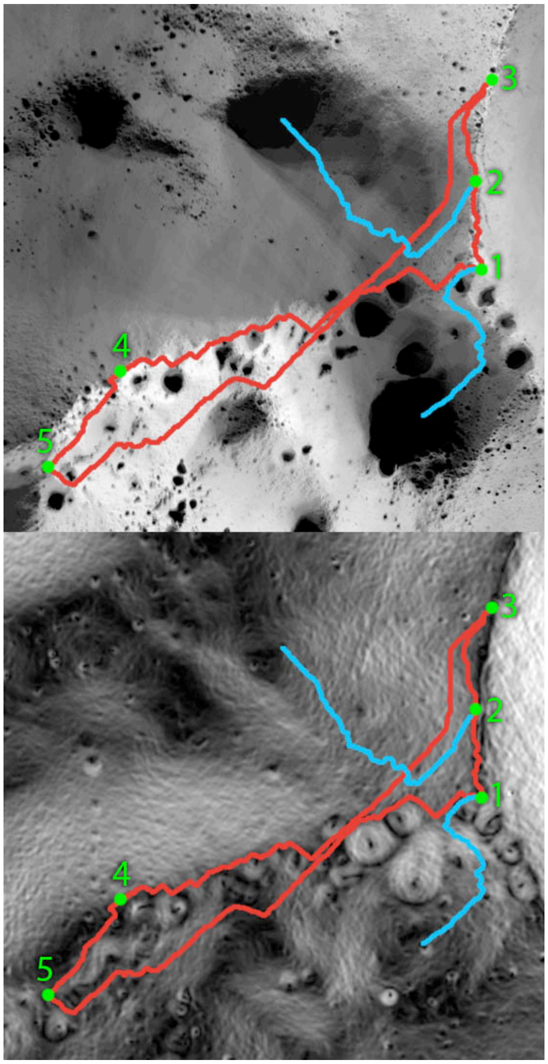

Fig. 1- *LROC NAC-derived illumination map (top) and LOLA slope map (bottom) overlaid with optimal traverses between persistently illuminated regions (red line; green dots) derived from a 40 m/pixel LOLA DTM. The blue lines highlight 6.8- and 4.8-km traverses inside two nearby PSRs. Stations 1, 2 and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

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