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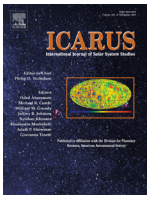

# Optimized traverse planning for future polar prospectors based on lunar topography

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ABSTRACT

To fully understand the extensive collection of remotely sensed polar observations by the Lunar Reconnaissance Orbiter and other recent lunar missions, we must acquire an array of ground-truth measurements. A polar rover can sample and assay potential polar resources both laterally and at shallow depths. To identify ideal, least-energy traverses for such a polar prospecting mission, we developed a traverse planning tool, called *R-Traverse*, using a fundamental wheel–regolith interaction model and datasets from the Lunar Reconnaissance Orbiter Camera, Lunar Orbiter Laser Altimeter, and Diviner Lunar Radiometer Experiment. Using the terramechanics model, we identified least-energy traverses at the 20 m scale around Shackleton crater and located one traverse plan that enables the rover to remain illuminated for 94.4% of the lunar year. By incorporating this path planning tool during mission planning, the feasibility of such a mission can be quantified.

## 1. 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 spatial and temporal distribution of persistently illuminated regions and broad-scale evidence for volatiles captured in cold traps (Bussey et al., 1999; Feldman, 1998, Feldman et al., 2000; Colaprete et al., 2010; Mitrofanov et al., 2010; Speyerer and Robinson, 2013; Gläser et al., 2014). 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 (Spudis and Lavoie, 2010; Spudis 2011). However, there are still many questions regarding the chemistry and extent of these cold-trapped resources.

A polar rover can address many outstanding questions by sampling a series of sites to assay resources not only along the surface, but also at shallow depths (~1 m). These ground measurements are essential to calibrate remotely sensed observations and provide first order estimates of *tonnage* and *grade* of any resource deposit. NASA's Human Exploration and Operations Mission Directorate's proposed Resource Prospector mission (Andrews et al., 2014) aims to have a rover traverse across an area near the lunar South Pole. Along the traverse, the selected payload would detect and map volatile concentrations while examining an array of small permanently shaded regions (PSRs) of various sizes, locations, and types (i.e., inside of an impact crater or inside a local shaded depression not associated with an impact event) as well as areas that receive limited solar illumination. These measurements will help determine the form of volatile-element deposits and how concentrations and compositions vary from location to location within a PSR and from one PSR to another at the surface and at depth. Such measurements are needed to interpret and maximize the return on data from neutron spectrometer measurements of hydrogen (Feldman, 1998, Feldman et al., 2000; Mitrofanov et al., 2010) and interpretations and inferences drawn from the results of the LCROSS mission (e.g., Colaprete et al., 2010; Hurley et al., 2012). By tying these with remote measurements from LRO and other recent missions, we could select potential resource-rich sites for future exploration missions. Therefore, to optimize and ultimately maximize the science return from future polar as well as equatorial rover missions, we developed a traverse-planning algorithm, called *R-Traverse*. The algorithm uses regional data products from the Lunar Reconnaissance Orbiter (LRO) mission to identify least-energy traverse paths around key science and exploration targets while also considering the illumination conditions around the selected landing site and regions of resource interest.

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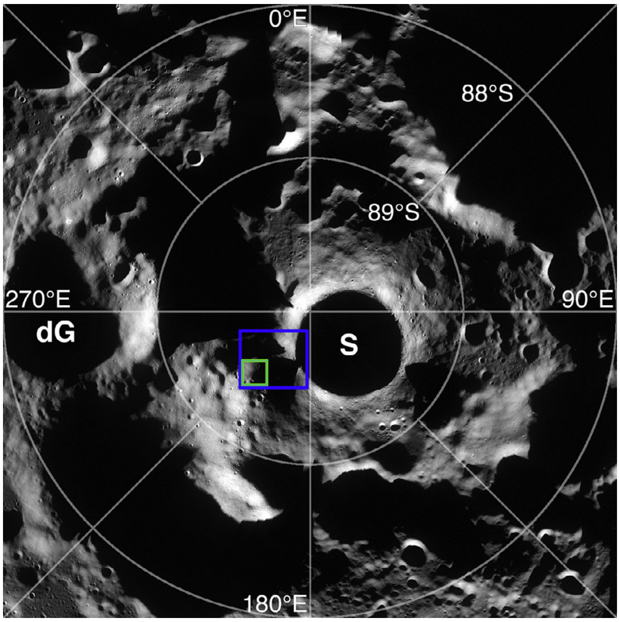

**Fig. 1.** LROC Wide Angle Camera context mosaic of the south pole with a blue box outlining our entire case study area and the smaller, green box outlining the area with stereo coverage. Shackleton and de Gerlache crater are marked with S and dG, respectively.

## 2. Resources for characterizing lunar exploration sites

The Lunar Reconnaissance Orbiter (LRO) mission and subsequently selected payload collect key observations to facilitate the planning of future surface missions. The orbital configuration enables observation of each polar region every 2 h, thus resulting in multi-temporal datasets that monitor variations over the year (i.e., visual and thermal observations) and strengthens datasets that accrue over thousands of successive orbits (i.e., altimeter and neutron measurements). For this study, we use data from the Lunar Reconnaissance Orbiter Camera (LROC), the Lunar Orbiter Laser Altimeter (LOLA), and the Diviner Lunar Radiometer Experiment collected near the south pole to analyze and construct optimal traverse paths for a potential polar rover on the rim of Shackleton crater and an adjacent ridge structure between Shackleton and de Gerlache crater (Fig. 1). The datasets and framework described in the following sections can be applied to many potential robotic and human exploration targets around the polar region as well as equatorial targets to optimize traverse paths and ensure scientific and/or exploration targets are accessible well before the launch of the mission.

### 2.1. Lunar Reconnaissance Orbiter camera (LROC)

LROC comprises a Wide Angle Camera (WAC) as well as twin Narrow Angle Cameras (NACs) with a nadir ground sampling distance of 75 m and 0.5 m from a 50 km orbit, respectively (Robinson et al., 2010). Since the start of the mission until 15 December 2015, the LROC team has acquired over 52,000 WAC and 114,000 NAC observations of the polar regions (poleward of ±85°). These images enable mapping of the entire polar region as well as the identification of persistently illuminated regions (Speyerer and Robinson, 2013). The LROC team also acquired a subset of NAC images with increased exposure time (>11.8 ms; nominal polar exposures are 0.7 ms) for imaging inside regions that never receive direct sunlight, but only secondary illumination from nearby, sunlit crater rims (Koeber et al., 2014).

Additionally, over a series of orbits, the LROC NAC acquired a set of geometric stereo observations near the lunar poles. Unlike at equatorial sites, where the spacecraft is slewed in the cross-track direction to reimage the same area as the previous orbit (Henriksen et al., 2016), polar stereo observations require the spacecraft to pitch forward in one orbit, acquire an image, and reimage the same terrain in a nadir orientation during a subsequent orbit. Since the lighting is not always favorable near the poles (i.e., large areas in shadow), the LROC Science Operations Team commands an additional set of stereo observations when the solar azimuth shifts to illuminate areas previously in shadow in the original stereo pair. This process results in a set of stereo pairs collected at a pixel scale of 1.0 m due to cross-track pixel binning (pixel averaging) and increased integration time to boost the signal to noise in these images with grazing incidence angles (Robinson et al., 2010).

Each stereo pair in this study was processed using photogrammetric software developed by the German Aerospace Center (DLR) (Gwinner et al., 2009, 2010) to produce Digital Terrain Models (DTMs) sampled at 2.0 m/pixel (Fig. 2A). The individual DTMs were then mosaicked together to increase spatial coverage, which covered the illuminated portion of the connecting ridge between Shackleton and de Gerlache crater. The mosaicked NAC DTM has a mean absolute elevation offset of 0.62 m and a standard deviation of 1.20 m when compared to co-registered altimeter profiles discussed in the following section. While the resulting stereo derived DTMs provide precise knowledge of the illuminated terrain, the models lack topographic information inside areas shadowed during each set of stereo observations (i.e., such as persistently shaded craters) as well as areas along the rim of Shackleton crater.

### 2.2. Lunar Orbiter Laser Altimeter (LOLA)

The laser altimeter on LRO (LOLA) measures the distance between the instrument and the lunar surface with a range accuracy of 10 cm using a Q-switched Nd:YAG laser at 1064 nm and a set of avalanche photo diodes (Smith et al., 2010). The laser simultaneously illuminates five spots on the lunar surface, which are sensed by a set of detectors in the LOLA instrument. By measuring the time-of-flight, an accurate range measurement is derived for each laser spot. This configuration enables the LOLA instrument to collect measurements regardless of illumination conditions, including areas in permanent shadow. Using spacecraft ephemeris, these range measurements are reduced to elevation profiles. By combining the elevation profiles over many thousands of orbits, raster or gridded DTMs can be generated (Fig. 2B).

However, since the spacecraft ephemeris is not as accurate as the LOLA measurements, the gridded DTMs contain small vertical (up to 1 m) and horizontal (typically up to 6 m) offsets (Fig. 2B). Owing to the extensive number of orbit crossovers in the polar region, these relatively small offsets are visible in the final products and cause unrealistic values in derived slope maps. Recent work by Gläser and coworkers (2013) improved the precision and accuracy of these polar DTMs by combining the strengths of both LROC NAC stereo derived terrain models, which are very precise (horizontal accuracy = spatial resolution; Henriksen et al., 2016), and LOLA altimeter profiles, which are highly accurate (<10 m horizontally; Mazarico et al., 2013). After alignment, the LOLA tracks had a mean absolute elevation offset of 0.40 m and a standard deviation of 0.68 m when compared to the new regional DTM.

The resulting, adjusted DTM (Fig. 2C; Gläser et al., 2014) is both accurate and precise and thus makes it possible to sample elevation and compute accurate slopes on length scales relevant to a future polar prospector. The adjusted and refined DTM, which we sampled at 20 m/pixel, contains not only the portion of the connecting ridge covered by NAC stereo images, but also the entire