
Introduction: The Moon is a benchmark for understanding the effects of space weathering and geologic processes on the surface properties of airless planetary bodies [1]. By studying the reflectance behavior of the lunar surface under different viewing and illumination conditions, we can learn about regolith properties such as surface roughness [2]. In the Hapke reflectance model, the surface roughness is parameterized by θ, the mean surface slope on photometrically relevant size scales [2]. Evidence suggests that, at visible wavelengths, these scales are on the order of 0.1 mm to 0.1 cm and that θ may vary systematically with geologic context [3,4]. Using WAC data, Sato et al. [5] derived spatially-resolved multi-wavelength Hapke parameter maps of the Moon and found that θ had a mean value of 23.4° with no significant geologically-correlated variations. However, roughness effects on the reflectance can be difficult to measure at the phase and emission angles typically observed by the WAC (phase < 100°, emission < 30°). Higher phase and emission angles can provide more leverage on photometric roughness effects [6]. To that end, here we demonstrate that the Lunar Orbiter Laser Altimeter (LOLA) Laser Ranging (LR) telescope [7] can make photometric measurements at phase angles > 120°, a region of parameter space not previously probed by the Lunar Reconnaissance Orbiter (LRO) due to solar keep-out zone constraints.

Instrument Description: For the high-phase angle photometric observations discussed here, we are using LOLA as a passive radiometer to collect solar photons reflected off the lunar surface. The laser is not involved in any way. These measurements are similar to the 1064-nm passive radiometry routinely collected by Channels 2 - 5 with the LOLA receiver telescope [8] except that, here, we are using Channel 1 with the LR telescope at 532-nm. The LOLA-LR telescope has a 1.75° field-of-view (FOV), and is mounted on and co-boresighted with the LRO high-gain antenna on the anti-nadir deck of LRO. It is connected to the LOLA Channel 1 detector assembly (on the nadir deck) via fiber optic cable which feeds the signal through a narrow band filter with central wavelength and band width of 532 ± 0.15 nm. The LR telescope can withstand direct solar illumination for up to ~2 hours, roughly the length of the LRO elliptical polar orbit. Pre-flight testing of the LR telescope measured an off-axis transmission < 10^-6 for angles > 10°. The exposure time and sampling rate is 0.0357 sec (28 Hz).

Results: On Oct. 2, 2016 (DOY 275), LRO performed a ~110° roll to point the LR telescope toward the horizon in the general direction of the Sun, which was ~30° above the horizon. The LR telescope viewed a surface swath (Fig. 1) reaching from Oceanus Procellarum to Mare Humorum about 300 km from LRO yielding a projected FOV ~ 9 km wide. The area of the actual region observed was larger due to the oblique viewing geometry. The observing geometry did not change much over the course of the slew, with the incidence angle ~ 70 - 78°, emission angle ~ 72 - 80°, and phase angle ~ 150°.

The signal measured by the LR telescope (Fig. 3a) is expressed as the radiance factor (I/F), the ratio of the measured radiance to that of a perfectly diffuse Lambert sphere illuminated vertically. The measured signal shows a clear correlation with terrain type, with more variation over the rugged highlands (including crater Gassendi) at ~ 3800 - 4000 sec compared to the maria at earlier and later times. We compute an initial model I/F (Fig. 3a) by performing a full 3-D ray-tracing with the 64 PPD LOLA shape model using a ray-tracing illumination code [9]. The FOV is sampled with 500 sightlines and, for each one, we determine its intersection point on the shape model and whether or not that point can see both the Sun and LRO. The predicted radiance from each unobscured sightline is calculated...
by interpolating the spatially-resolved multi-wavelength Hapke parameter maps of [5] in lon/lat and in wavelength. Thus, it uses Hapke parameters appropriate for the actual surface locations in the FOV at ~532-nm. Note that variations in the parameters on scales smaller than the map resolution of 1° will not be completely captured by the interpolation. Nevertheless, the model does reproduce many of the relative signal variations within and between terrain types. We compute the best fit to the LOLA-LR data (Fig. 3a) by varying one free parameter from its initial value in 20 1°-square bins (Fig. 3b). Here, we consider two alternative models: varying the roughness \( \theta \) or the Henyey-Greenstein (HG) asymmetry parameter, \( c \), which controls the relative strength of forward vs. backward scattering in the single particle phase function [2]. Initial values of \( c \) range from ~ 0 to 0.1. Changes to \( \theta \) or \( c \) can resolve the initial model's residuals with the LOLA-LR data equally well (Fig. 3a). However, variations in \( c \) significantly degrade the model’s agreement with the WAC data at the same locations at lower phase (Fig. 4). These preliminary results suggest that the LOLA-LR data are most easily explained by variations in roughness, \( \theta \), and that Gassendi is rougher than the surrounding maria on sub-mm to sub-cm scales.

Future work will attempt to improve the fit quality by adjusting other Hapke model parameters and by using a higher-resolution shape model and albedo map. As LRO’s extended science mission continues, we will conduct more such high-phase observations of the maria, cold spots, pyroclastic deposits, and Copernican-age craters, shedding new light on the effects of space weathering and geological history on regolith surface properties.