HIGH-PHASE ANGLE PHOTOMETRIC OBSERVATIONS OF THE MOON WITH THE LUNAR ORBITER LASER ALTIMETER (LOLA).

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Introduction: The reflectance behavior of the lunar surface under different viewing and illumination conditions informs regolith properties such as mineralogical composition, surface roughness, porosity, and individual grain characteristics like size, shape and the presence of inclusions and asperities [1]. We can, thus, learn about these properties by studying how the reflectance measured by remote sensing data depends on location and viewing geometry. Given the wealth of lunar remote sensing data and returned lunar samples, the Moon is a benchmark for our understanding of the link between reflectance behavior and surface properties on airless planetary bodies in general. The photometric characterization of the lunar surface by the Lunar Reconnaissance Orbiter (LRO) is limited to phase angles < 120° due to instrument solar keep-out zone constraints. The Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) can reach phases up to 120° during periods of high β-angle (the angle between LRO's orbital plane and the Sun) [2]. The Lunar Orbiter Laser Altimeter (LOLA) Laser Ranging (LR) telescope [3] can point close to the Sun allowing observations at phases > 120°, a region of parameter space not previously probed by LRO. Such high-phase observations are of interest because they can place new constraints on the regolith reflectance and surface properties like roughness and the relative strength of forward- and backward-scattering in the single particle phase function [1,2].

Instrument Description: For the high-phase angle photometric observations discussed here, we are using LOLA in its passive radiometry mode [4] in which the instrument passively collects solar photons reflected off the lunar surface. This mode is routinely used whenever LRO is too high for normal lunar ranging. The primary difference between how this mode is normally implemented and how it is used for the high-phase observations is that, for the latter, we are using receiver Channel 1 with the LR telescope at 532-nm instead of Channels 2 - 5 with the normal LOLA receiver telescope at 1064-nm. The LOLA-LR telescope has a 19 mm diameter aperture with a 1.75° field-of-view (FOV), and is mounted on and co-boresighted with the LRO high-gain antenna. It is connected to the LOLA Channel 1 detector assembly 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 system with an extended light source imaged at various distances found stray light levels < 1%. The signal level measured in each channel depends on the detection threshold, which can be manually set for each channel via flight software commands. The results presented here were obtained with a Channel 1 threshold of 10.94 mV. From several months of in-flight data obtained with this threshold, off-axis transmission from the Sun was measured to be less than the detector dark current noise level for solar elongation angles ≥ 15° meaning the maximum phase angle we can reliably observe with this threshold is ~ 165°. This phase angle limit could be increased by using a higher threshold at the cost of a lower sensitivity and signal-to-noise ratio. The exposure time is 0.0357 sec (28 Hz).

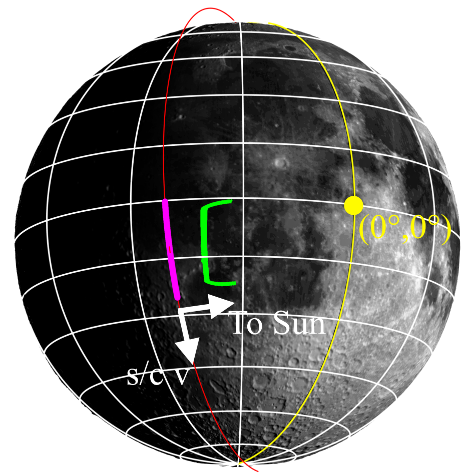

Figure 1 - Viewing geometry and illumination conditions for the slew on 2016 DOY 275. The red line shows the LRO orbit and the magenta points show LRO's location during the slew. The green points show the location observed. The yellow line is the central meridian and the yellow dot marks (0°,0°). Lon/lat grid lines are spaced 30°/15°.

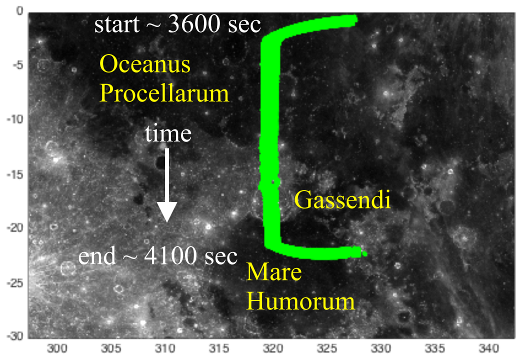

Figure 2 - Close-up of the region observed (green points) overlaid on a WAC 566-nm albedo mosaic.

Data and 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 (Figure 1). At this time, β was 79° and the Sun was ~30° above LRO's horizon. The LR telescope viewed a surface swath 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 (Figure 2). Because of the high β, 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° (Figure 3).

The signal measured by the LR telescope (blue points, Figure 4) is expressed as the radiance factor (RADF), 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 a model RADF (red points, Figure 4) by performing a full 3-D ray-tracing with the 64 PPD LOLA shape model using the illumination code of [5]. 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 [2] 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. This is due mostly to the large FOV and the ability of the LOLA shape model to accurately reproduce changes in photometric angles (Figure 3). Future work will include adjusting the Hapke model parameters to improve the agreement with the data. As LRO's extended science mission continues, we will conduct more of these high-phase observations at different locations and lower β, when it is possible to observe a range of high phase angles in a single slew. This will help refine the photometric properties of major geologic units and improve our understanding of lunar composition and regolith surface properties.

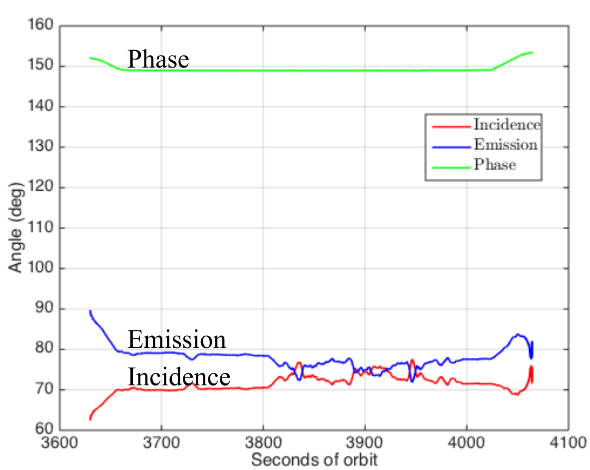

Figure 3 - The range of photometric angles observed during the slew on 2016 DOY 275.

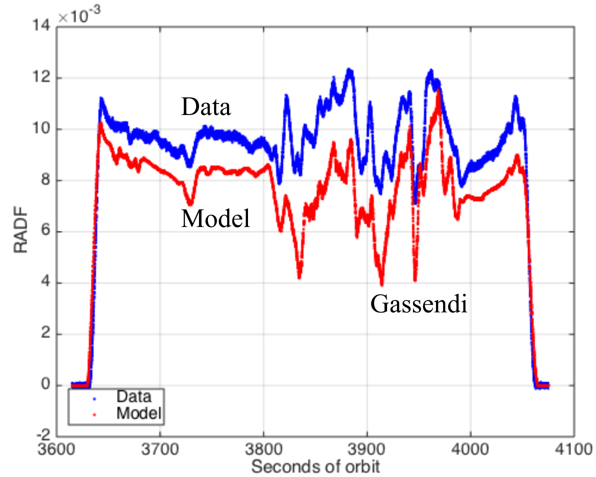

Figure 4- Comparison between the measured RADF (blue) and model (red). The model is calculated from a full 3-D ray-tracing with the 64 PPD LOLA shape model and the spatially-varying Hapke model of [2] interpolated to the actual wavelength and surface locations observed.

References: [1] Hapke, B. (2012) Camb. Univ. Press, *Theory of Refl. and Emittance Spectroscopy*, 2nd ed. [2] Sato, H. et al. (2014) *JGR Planets,* 119, 1775. [3] Zuber M. T. et al. (2010) *Space Sci. Rev.,* 150, 63. [4] Barker, M. K. et al. (2016) *Icarus*, 273, 96. [5] Mazarico, E. et al. (2011) *Icarus*, 211, 1066.