INVESTIGATING DIURNAL CHANGES IN THE NORMAL ALBEDO OF THE LUNAR SURFACE AT 1064 NM: A NEW ANALYSIS WITH THE LUNAR ORBITER LASER ALTIMETER. Ariel N. Deutsch[1], Gregory A. Neumann[2], James W. Head[1], Paul G. Lucey[3], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912 (ariel_deutsch@brown.edu), [2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [3]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI, 96822.

Introduction: The thermal environment of the lunar surface is extreme. At the equator, temperatures drop ~300 K between local noon and night [1]. Here we are interested in how this drastic thermal environment may affect the reflectance of the lunar surface. A variety of laboratory studies have demonstrated that minerals common to the lunar surface (e.g., pyroxene, olivine) show spectral changes with respect to temperature in near infrared wavelengths [e.g., 2–4]. Specifically, an increase in reflectance is observed with decreasing temperatures at key wavelengths [2–4]. Over temperature changes equivalent to the lunar thermal environment ($\Delta T \approx 300K$), the reflectance of pure pyroxene samples can vary by a factor of two [4].

For almost a decade, the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO) [5,6] has been acquiring measurements of the Moon's surface reflectance by measuring the strength of the returned altimetric laser pulse. Measurements are acquired at a wavelength of 1064 nm, which is coincident with a diagnostic absorption feature of pyroxene (centered near 1 µm) due to the presence of Fe^{2+} in the M2 site of the crystal [7]. At LOLA's wavelength, this iron absorption feature has been observed in laboratory studies to reveal temperature-dependent spectral changes [2–4]. Here we are interested in how the surface reflectance of the Moon as measured from orbit by LOLA changes during the extreme temperature fluctuations experienced by the surface over the course of a lunar day.

Methods: We analyze the normal albedo of the lunar surface using the highest quality calibrated LOLA data, which was acquired by Detector 3 on Laser 1 [8]. The normal albedo is the reflectance of the lunar surface measured at zero phase angle relative to a Lambertian surface illuminated at normal incidence angle and the same phase. During the nine years of still ongoing operations, LOLA has nominally collected data throughout the lunar day, although returns are minimal when the LRO spacecraft crosses the terminator due to instrument cooling and contraction [5]. Here we analyze the LOLA data for differences in mean normal albedo during the cycle of the lunar day by sorting the data into two groups based on the local time at which the data were acquired: mid-day (11:00–13:00) and morning/evening (06:00–07:00 and 16:00–17:00). These two groups are chosen to represent times at which surface temperatures are at a maximum and minimum, respectively, and times for which LOLA data exist.

We target regions of interest (ROIs) within the mare and highlands between 65°S and 65°N, latitudes between which temperature fluctuations are greatest. Each ROI is only 1° x 1° in spatial extent, representing surface areas that are ~30 km x 30 km depending on the specific location. The individual ROIs are binned to this size so that there are enough returns within each ROI for statistical analyses, yet compositional variations are minimized within each ROI. For example, latitude-dependent variations in reflectance have been observed with LOLA [6,8,9], and thus, larger ROIs may include latitudinal reflectance artifacts. Data that were acquired when the received energy was < 0.14 f, when the spacecraft was pointing off-nadir, or when the range was > 70 km, are excluded as well, due to cited reflectance anomalies [8]. To date, our analysis includes 65 ROIs located within the maria and 383 ROIs located within the highlands.

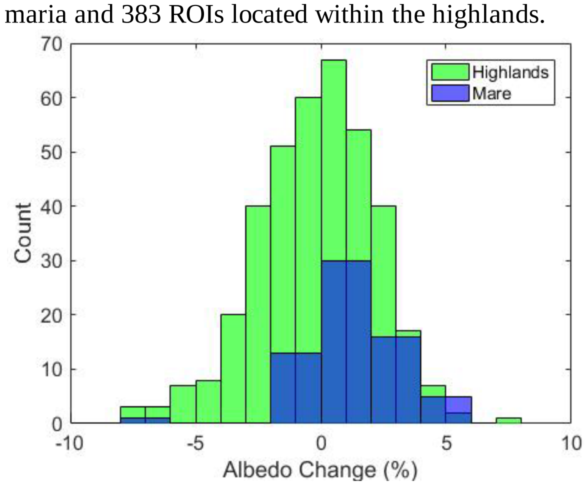

Fig. 1. Histogram displaying the distribution of % albedo change between mid-day and morning/evening for analyzed ROIs within the maria (blue) and highlands (green). The ROIs located within the maria are skewed towards a positive albedo change, meaning that typically the mean albedos are higher in the morning/evening than in the mid-day.

Results: *Maria.* Of the 65 mare regions analyzed to date, 78% display an inverse relationship between normal albedo and temperature, which is approximated by local hour (Fig. 1). The overall change in normal albedo is relatively low, on the order of a few %

change detected by co-adding the LOLA data that features single shot uncertainty of 12% [5] (Fig. 1).

Lunar highlands. For the 383 highland sites analyzed so far, there is no statistically significant temperature-dependent reflectance change detected; only ~49% of ROIs show a decrease in normal albedo during local mid-day (Fig. 1).

Discussion: The ROIs that show lower mean albedos during mid-day are consistent with laboratory studies that observe a temperature-dependent spectral change for common lunar minerals [2–4]. Of particular interest are previous laboratory measurements of returned lunar soils, which revealed a change in relative reflectance with temperature of ~1% or less per 100 K near-IR wavelengths [4]. This is similar to what we observe in the majority of mare ROIs (Fig. 1).

It is possible that we do not detect a clear temperature-dependent albedo change in the highlands due to a variety of factors. For example, surfaces that are low in iron will show a weaker change because iron is responsible for the temperature-dependent absorption near 1064 nm, the wavelength at which LOLA observes the surface [4]. In addition, mature soils show less contrast due to the attenuating effect of submicroscopic iron that has accumulated through time [10,11]. The reflectance may also be affected by grain size effects, where particularly fine-grained regions have a decreased reflectance in comparison to a region of similar composition with larger grains [12, 13].

Finally, although the ROIs are small in spatial extent (1° x 1°) with the intention of representing relatively compositionally uniform terranes, individual laser returns that were acquired mid-day and mid-night typically do not spatially overlap within an ROI (Fig. 2). Thus, for example, if mid-night measurements were acquired for a surface track that includes fresh, brighter material, it is possible that the mid-day measurements acquired within the same ROI did not intersect the same bright material (Fig. 2). Of course, the reverse is true as well.

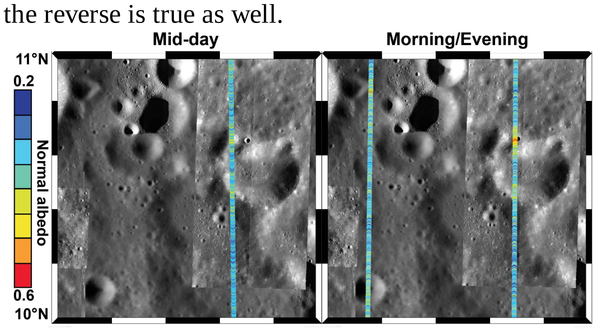

Fig. 2. An example ROI located within the highlands (10°–11°N, 159°E–160°E). Measurements of normal albedo acquired during mid-day are plotted on the left and measurements of normal albedo acquired during the morning/evening are plotted on the right. LOLA shots overlie a WAC basemap with available overlapping NAC images.

We find that removing individual laser shots that intersect fresh, bright material from both day-time and night-time data has an important effect on the albedo means. As a test case, we edited specific LOLA shots for 10 ROIs by visually inspecting the pulses for intersecting fresh, bright material identified in underlying LROC WAC and NAC images. We found that removing these shots from both day and night data increases the number of ROIs that have a higher mean normal albedo in mid-night data than in mid-day data.

Additional work is ongoing to analyze other ROIs across the lunar surface. The mid-day and mid-night tracks are also being analyzed for differences in sampling coverage of fresh, bright materials that may influence the results thus far. Finally, we will be using near-simultaneous surface temperatures from the Diviner instrument to complement the local time-of-day albedo measurements from LOLA.

Conclusions: Here we provide the preliminary results of a new analysis investigating diurnal changes in the normal albedo of the lunar surface. Our statistical analysis, incorporating over 200,000 individual LOLA shots, suggests that temperature variations do have a measurable effect on the normal albedo of the surface at 1064 nm wavelength in the maria, and this may be due to temperature-induced spectral changes. However, the diurnal differences discussed here are only on the order of a few % change in normal albedo, indicating that temperature changes do not have a large effect on measurements of the lunar surface at the sensitivity of the LOLA instrument. An ability to understand how the lunar surface varies with temperature will provide important constraints for future remote sensing observations of the Moon [e.g., 14, 15]. Such observations can help constrain the relative abundance of particular minerals (here, pyroxene) that exhibit a change in spectral reflectance with temperature independent of spectroscopic methods.

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