LUNAR POLAR SURFACE FROST: THE VIEW FROM LOLA. P. G. Lucey[1], G.A. Neumann[2], D.E. Smith[2], M.T. Zuber[3], D.B. J. Bussey[4], J. T. S. Cahill[4], E. M. Mazarico[2], D. A. Paige[5], Hawaii Institute of Geophysics and Planetology, University of Hawaii, Manoa, 1680 East-West Rd., Honolulu, HI 96822, lucey@higp.hawaii.edu, [2]NASA Goddard Space Flight Center, Code 698, Greenbelt, MD 20771, [3]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, [4]Applied Physics Laboratory, Laurel, MD 20723, USA, [5]Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA

Introduction: In addition to its function as a laser altimeter, the Lunar Orbiter Laser Altimeter (LOLA) on LRO also measures the reflectance of the lunar surface by comparing the strength of the returning altimetric pulse to the transmitted laser energy, compensating for the dependence of the signal upon range. Exploiting this capability, one of the goals of the experiment was to measure the reflectance of the Moon within regions of permanent shadow at the poles in a search for possible surface frosts [1]. LOLA measurements of reflectance at the laser wavelength of 1064 nm have demonstrated that regions in permanent shadow (PSR) consistently exhibit higher reflectance than nearby surfaces that sometimes receive illumination [2,3]. Whether this increased reflectance is due to surface frost is the subject of on-going investigation.

The many processes that affect the albedo of the lunar surface challenge establishing the presence of surface frost from reflectance measurements. Outside the polar regions, and at visible and near-IR wavelengths, composition and space weathering dominate albedo variations. Space weathering darkens the lunar regolith by producing both dark glass and nanophase iron, while fresh impacts and mass wasting act to renew the surface locally. Composition also has a strong effect on reflectance; more iron rich materials are darker than feldspathic rock, and also contribute more iron to the space weathering process to enhance its effects. To attribute a reflectance anomaly to the presence of frost, these sources of "geologic noise" must be mitigated.

The nature of polar regions helps to some extent. There is no evidence for strong polar compositional variations in Lunar Prospector gamma ray data, and LOLA's reflectance maps do not reveal evidence of any significant mare or pyroclastic deposits. Dark albedo anomalies are rare and highly localized. Therefor, interpreting LOLA reflectance data is a matter of separating geologic processes that enhance space weathering variations from exposures that may indicate the presence of frost.

Zuber et al. 2012 [2] grappled with these issues in the first study using LOLA reflectance data. They showed that the south polar crater Shackleton was locally strongly anomalous, with its floor exhibiting higher reflectance than the surroundings. While they cautioned that mass wasting within the crater revealing immature lunar regolith could account for this local reflectance enhancement, they ventured that several percent water frost could also account for the anomaly. They also suggested that the sheltering effect of the deep crater could partly shield the floor of Shackleton from the solar wind and micrometeorites that are the engine of space weathering.

So, Zuber et al. 2012 offer three hypotheses for polar brightening: surface frost, routine mass wasting, or an environmental influence upon space weathering. With the availability of quantitative reflectance data within the PRSs we can begin to test these hypotheses.

Controlling for mass wasting and sky visibility: Because PSRs must be in local topographic lows, it was plausible that they might systematically feature steeper slopes and hence exhibit generally higher reflectance because of generally steeper slopes. To control for this we examined the reflectance of PSR and nearby surfaces that sometimes receive illumination and constrained the slopes to less than 10 degrees where mass wasting cannot operate. We find that even on these flat surfaces PSRs are strongly brighter than areas that receive illumination. Interestingly, controlling slopes to greater than 25 degrees where mass wasting is active also reveals systematically brighter surfaces in permanent shadow.

To control for exposure to space, we calculated the solid angle of sky subtended as viewed from every pixel in the polar regions. Like the case for slopes, PSRs with large sky access (mountains and large flat surfaces) are brighter than illuminated regions with the same access. Similarly, the reflectance of surfaces with very restricted sky access (crater bottoms, cliff bases) are more reflective in PSRs than illuminated surfaces.

Discussion: The reflectance of polar surfaces in permanent shadow is systematically different than that of areas that sometimes receive illumination. But are they frosty? While we appear to have eliminated topographic shielding as a systematic effect, Gladstone et al. 2012 [5] suggested that the porosity of polar surface in shadow may be systematically higher than other areas due to unique charging properties of the cold polar soil. The albedo of the polar regions shows strikingly the uniqueness of the permanently shadowed regions at the Lyman alpha wavelength (122 nm). At this wavelength space weathering has a relatively weak effect on reflectance, so the polar images collected by the LAMP spectrometer show vividly that the PSRs have lower albedo than their surroundings. Increased porosity does have a strong darkening effect on regoliths, however theory [5] suggests this effect is not wavelength dependent and so porosity alone cannot account for the LOLA reflectance anomalies.

Another alternative is that the low temperatures within the PSRs inhibit the production of either nanophase iron, or dark impact glass. This possibility is subject to experimental verification. However, as noted, space weathering is relatively ineffective at altering reflectance at LAMP wavelengths.

Combinations of porosity and decreased space weathering, or porosity and surface frost can both account for the LOLA 1064 nm and LAMP 122 nm reflectance. We use methods developed by [5] to arrive at these conclusions for "typical" PSR surfaces. In summary, porosity and surface frost require 9% frost by area, or 14% ice by weight to account for the two albedoes. In contrast, the space weathering model requires that polar soil contain only half the nanophase iron of similar mature surfaces that are illuminated.

The ice abundances result in strong predictions regarding the spectral properties of the permanently shadowed regions. Even small amounts of ice mixed with the regolith would have a powerful effect on absorption at 3um, and patchy exposures of ice at the few percent level will produce strong ice overtone bands at 1.4 and 1.9 microns. It is possible that some PSRs can be observed at these wavelengths using groundbased telescopes, but the ideal experiment would be a LOLA-like experiment operated at a few near-IR wavelengths. Such an experiment would definitively detect and map the presence of surface ice at abundances above ~ 1wt %.

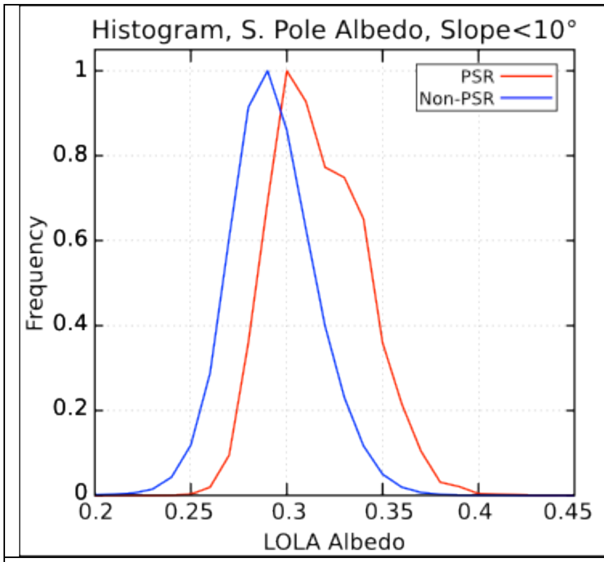

Figure 1. Distribution of reflectances for south polar PSR and illuminated areas showing that PSR are systematically more reflective than illuminated surfaces.

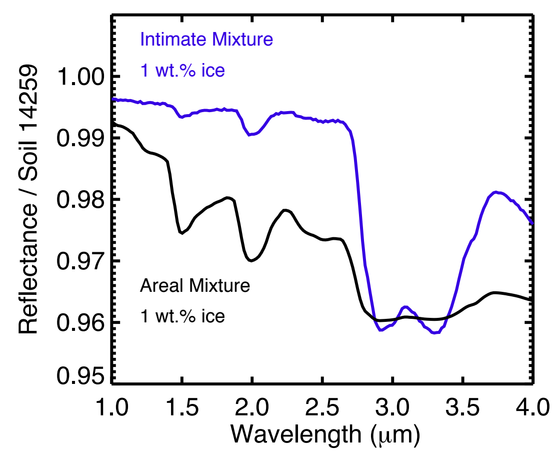

Figure 2. Spectra of intimate (well mixed) and areal (patchy) mixtures of ice, divided by dry lunar regolith. Intimate mixtures are best revealed by measurements near 3um, while patchy ice exposures are better detected near the overtone bands near 1.4 and 1.9 microns.

References: [1] Smith, D. E. et al. (2010b), Space Sci. Rev., 150(1-4), 209–241, doi:10.1007/s11214-009-9512-y. [2] Zuber, M. T. et al. (2012), Nature, 486(7403), 378–81, doi:10.1038/nature11216. [3] Lucey et al. 2014, JGR, in press. [4] Gladstone, G. R. et al. (2012), JGR 117, E00H04, doi:10.1029/2011JE003913. [5] Hapke, B. (1993), Theory of reflectance and emittance spectroscopy, 1st ed., Cambridge University Press, Cambridge, UK.; Hapke, B. (2001), JGR, 106(E5), 10039, doi:10.1029/2000JE001338; Hapke, B. (2008), Icarus, 195(2), 918–926, doi:10.1016/j.icarus.2008.01.003.