Investigating evidence of a latitudinal-dependent lunar regolith compaction from the Diviner measured thermal signals.

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Aims: To investigate if there is evidence of a latitude-dependent density change in the lunar regolith using 1) the thermal infrared signal measured by the Diviner lunar radiometer and 2) new laboratory data of the Bidirectional Reflectance Distribution Functions (BRDFs) as part of the boundary condition in a 1D thermal model .

Introduction: The term lunar regolith describes the fine-grained particulate rock present on the lunar surface. Processes thought to have altered the properties of the regolith over billions of years include impacts from micrometeorite bombardment, Moon quakes and volcanism [1]. These cause impact gardening which compresses and churns the regolith causing a depth-dependent density. Recent experimentation has suggested that thermal cycling has a greater effect on the density of the regolith than that of micrometeorite impacts [2,3]. Thermal cycling is caused by thermal fatigue – the erosion of rocks due to thermal stresses [4]. It has been shown that more compaction occurs in the upper layers of the regolith if the amplitude of the diurnal thermal wave is larger [1,5,6]. Measurements taken by the Diviner Lunar Radiometer (Diviner) on the Lunar Reconnaissance Orbiter [7] show that there is a greater diurnal thermal wave amplitude at the equator than at higher latitudes. The diurnal thermal wave amplitude depends on the lunar latitude – the thermal wave amplitude is larger at the equator than at higher latitudes due to greater incident solar flux throughout the lunar day. These findings suggest that significantly less thermal fatigue occurs at higher latitudes leading to the formation of less dense regolith structures. This is currently the only established process affecting regolith density with a latitudinal dependence [1,5,6].

The H-Parameter: Using Diviner measurements to constrain the thermophysical properties of the upper layers of regolith, it is possible to globally map an estimate for its depth-dependent density structure. Within the Hayne et al. model [8] (hereafter referred to as the Hayne model), the 1-dimensional heat equation is solved to obtain thermophysical characteristics of the regolith from the Diviner nighttime data [7]. Diviner is a nine-channel filter radiometer consisting of 7 infrared and 2 visible light channels. Nighttime thermal emission is measured in 4 of the infrared channels: ~13–23, 25–41, 50–100, and 100–400 μm wavelengths [9]. From studies of the Apollo core samples, the regolith is shown to have a depth-dependent density [10], and Hayne uses this data, alongside modelled best fits to equatorial brightness temperatures [11] to parameterize the regolith density, ρ, as:

$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$$

where z is the depth, H is the H-parameter; ρ_s and ρ_d are the densities at the surface and at depths z >> H, respectively. The H-parameter determines the depth-dependence of the density: a smaller value for the H-parameter equates to a steeper depth-dependent density gradient (Figure 1).

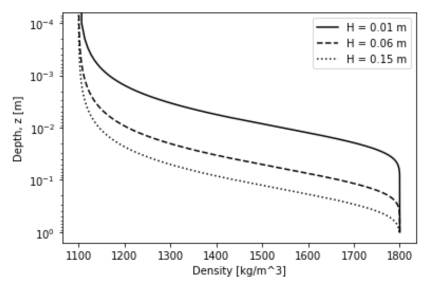

Figure 1: *Regolith model profile showing variation of density with depth for three different H-parameter values: 1cm (solid curve), 6cm (dashed curve) and 15cm (dotted curve) after Hayne [8].*

Lunar Surface Temperature: Due to the Moons' low obliquity, at local midday the sun always remains below the zenith at high latitudes. Therefore, the maximum and minimum surface temperatures at non-equatorial latitudes are highly dependent on surface albedo variation with solar incidence angle.

Bidirectional Reflectance Distribution Functions (BRDFs): In the Hayne model [8], the lunar albedo is assumed to have a dependence on the solar incident angle, derived from the Apollo missions [12]. This removes any latitudinal dependence of the H-parameter. The BRDF is defined as the ratio of scattered radiation at the detector, to the collimated incident radiation that illuminates the surface perpendicular to the direction of incidence, per unit area. Recent experimental studies in Oxford have measured visible wavelength BRDFs of regolith samples in ambient conditions (Figure 2), in agreement with E. Foote's 2010 work [13]. Conducted with the Visible Oxford Space Environment Goniometer instrument (VOSEG), these measurements have shown that an experimentally determined alternative parameterisation of the angular albedo dependence may be more valid [14].

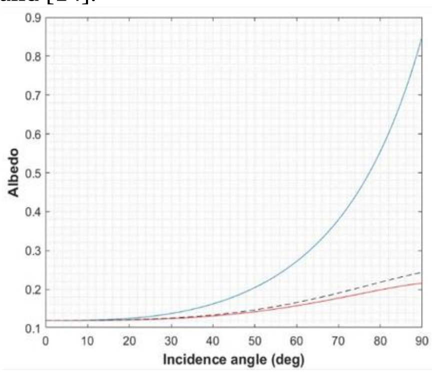

Figure 2: *Albedo scattering functions against incidence angle: blue line is function used by Hayne, red is the function determined by E. Foote et al. [13] and black dashed is the function determined by R. Curtis et al. [14]*

The surface layer temperature boundary condition for the Hayne model is calculated using the albedo scattering function. Inputting the VOSEG's laboratory measured albedo scattering function, derived from the incidence angle-dependence of laboratory measured BRDFs, into the Hayne model induces a latitudinal dependence for the H-parameter as shown in Figure 3.

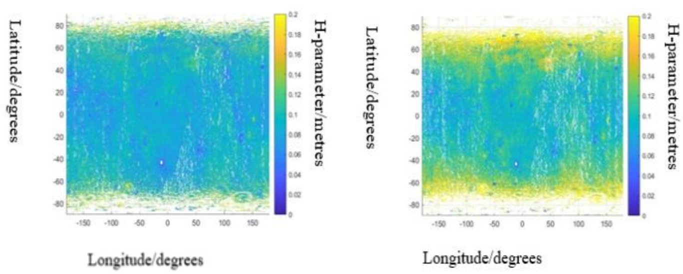

Figure 3 Left: *H-parameter against latitude with the previously assumed albedo scattering function*. **Right**: *H-parameter against latitude with the new laboratory measured albedo scattering function.*

With increase in latitude, the diurnal thermal wave amplitude decreases - the initial regolith compaction and H-parameter should both decrease. Figure 2 shows an increasing H-parameter with latitude, in disagreement with theory. This suggests that the model is physically incomplete. This could be due to the lunar surface infrared scattering, described by the Emission Phase Function (EPF).

Thermal Infrared Emission Phase Function (EPF) of the Lunar Surface: The Hayne model assumes Lambertian scattering of the lunar surface in the infrared. This defines a constant emissivity, independent of solar incidence angle. Recent Diviner off-nadir and laboratory measurements of the Lunar EPF suggest this assumption is incorrect, shown in Figure 4 [15]. Inputting a realistic EPF into the Hayne parameter will determine latitudinal-dependent lunar regolith compaction.

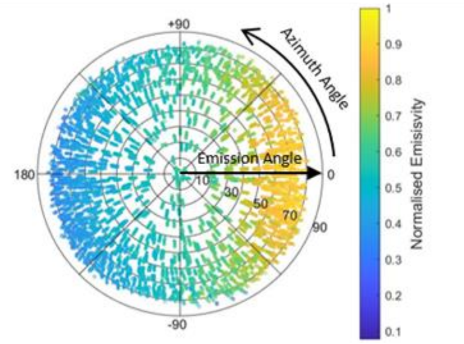

Figure 4: *Diviner-measured EPF at 70° incidence angle for the high-latitude highland target taken from [15]*

Conclusion: Updating the functions for the lunar albedo scattering and the emissivity into the Hayne model, using Laboratory and Diviner measurements of the BRDFs and EPF of the Lunar Surface, will improve its physical accuracy. Incorporating the latest EPF and BDRF data into the Hayne model may establish if the H-parameter has a latitude dependency that is in agreement with theory.

References: [1] I. Curren (2018), EGU2018 Abstract, [2] M. Delbo et al. (2014), Nature, 508(7495), [3] B. Molaro et al. (2017), Icarus 294, 247 [4] A. Luque et al. (2011), Environmental Earth Sciences, 62(7), [5] P. Metzger et al. (2018), Proceedings of Earth and Space 2018: Engineering, Science, Construction, and Operations in Challenging Environments, Cleveland, OH, April 9–12, 2018 [6] M. Hamm et al. (2019), Icarus 319, 308, [7] D. Paige et al. (2009), Space Sci. Rev. 150, 125, [8] P. Hayne et al. (2017), JGR: Planets, 122, [9] D. Paige et al. (2010), Science, 220(6003), 479, [10] J. Mitchell et al. (1973), Lunar and Planetary Science Conference Proceedings 4, 2437, [11] A. Vasavada et al. (2012), JGR 117, E00H18., [12] S. Keihm (1984), Icarus 60(3), 568, [13] E. Foote et al. (2010), AGU Fall Meet. Abstr, [14] R. Curtis et al. (2021), Review of Scientific Instruments 92(3), 34504, [15] T. Warren (2021), LPSC Abstract #2548