QUANTITATIVE MAPPING OF LUNAR SURFACE HYDRATION WITH MOON MINERALOGY MAPPER (M³) DATA.

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Introduction: The giant impact hypothesized to have formed the Moon was also believed to have depleted the Moon of volatiles, including H_2O[1]. Due to technical limitations in the 1970s, the analyses of Apollo samples either showed the Moon was 'bone dry' or had uncertainties that were too large to draw clear conclusions[2]. However, visible-near infrared reflectance spectra have recently demonstrated that the lunar surface is hydrated[3-5], and recent laboratory measurements have shown that the certain Apollo glasses and melt inclusions also contain appreciable water[6]. These latter analyses show that the H_2O content of the lunar mantle may be as mush as several hundred ppm[6,7]. In contrast, surface hydration may be the product of ongoing interactions between the regolith and the solar wind, and remote sensing data have shown that lunar surface hydration may exhibit diurnal changes[5].

However, previous studies that have utilized remote sensing data to explore surface hydration have focused largely on qualitiative rather than quantitative aspects. Small-scale variations in hydration have been difficult to assess in data such as from the Moon Mineralogy Mapper (M³) due to the need to separate thermally emitted energy from the surface-reflected component[4], which requires precise knowledge of surface temperature at the time of data acquisition. Previous studies have employed an empirical thermal correction to produce initial results on the distribution of lunar surface hydration[4], but quantitative estimates of lunar surface hydration at regional and local scales using M³ data have yet to be fully realized.

Other questions that remain include: what are the factors that control the distribution of lunar surface hydration? How much, if at all, does the hydration level vary over a diurnal cycle? Is lunar surface hydration correlated to optical maturity or composition? Here we discuss a new semi-empirical thermal correction model for M³ data that allows us to convert refelctance spectra to single-scattering albedo and make quantitative maps of lunar surface hydration to address these questions.

Methods: A new thermal correction model is developed based on the relationship between reflectance at 1.55 μm (Band 49 of M³ images) and 2.53 μm (Band 74 of M³ images) for Apollo and Luna soils that have been measured in the RELAB facility at Brown University[9]. The 1.55 μm band is outside of major absorption features and has no thermal emission for typical lunar surface temperatures. The 2.53 μm band is outside of the 'hydration' band but at a long enough wavelength that thermal effects may be present in M³ data. Lab spectra show that reflectane values at 1.55 μm are stongly correlated to those at 2.53 μm, allowing the latter to be predicted from the former. Any observed increase from this expected value as seen in M³ data is assumed to be the result of thermal emission; Kirchoff's Law is used to estimate emissivity and any excess radiance is then modeled by a Planck function and removed from the observed radiance. This lab-based empirical model was validated with radiative transfer modeling of M³ data and independently measured brightness temperatures from Diviner bolometric data.

The resulting model can be used to estimate lunar surface temperature on a pixel-by-pixel basis directly from each M³ image, which in turn allows thermal emission to be removed from all affected wavelengths. Thermally-corrected reflectance spectra are converted to single-scattering albedo and Hapke's ESPAT parameter is then calculated for the hydration feature at 2.8-2.9 μm[12]. It has been shown that there is a linear relationship between water content and ESPAT values for a wide range of hydrated materials, including hydrated basaltic glass, and that this method minimizes effects associated with changes in albedo[10,11].

For this study, minerals of direct relevance to the lunar surface (e.g., basalt, anorthosite) were measured in RELAB to determine the slope of the ESPAT-H_2O trend and its variations with particle size. Lunar surface hydration can then be quantitatively mapped by multiplying the ESPAT values derived from M³ data by the desired ESPAT-H_2O slope as derived from the laboratory spectra; maps of the ESPAT value are presented here because they provide a clear proxy that is linearly correlated to water content.

Results and discussion: Figure 1 presents the global mosaic of ESPAT values at a scale of 1 km/pixel. White stripes are areas where no M³ data were acquired. If we assume the slope between water content and ESPAT is 2.5, as we have measured for hydrated basaltic glasses, then greenish regions represent ~100 - 500 ppm water and reddish regions are ~500 – 2000 ppm . It is clear from Figure 1 that the distribution of lunar surface hydration is most strongly correlated with latitude, where higher latitudes display increased hydration. These latitudes receive less solar wind compared with lower latitudes, thus it might be expected that they should have lower water content if lunar surface hydration is dominantly formed by solar wind implantation. The higher water content may be the result of: 1) lower temperatures at higher latitudes

prohibit/retard dehydration, promoting accumulation; 2) migration of H^+ from low to high latitudes[3]. At a given latitude, we also observe variations in hydration that are correlated to variations in optical maturity (e.g., OMAT[13]); mature regions have greater hydration whereas immature regions and young craters exhibit much lower hydration. This positive correlation to maturity is consistent with observations from H^+/D^+ ion-beam experiments[8]. Thus, the optical maturity is the second major factor that controls the present-day distribution of lunar surface hydration.

At a smaller scale, there are several regions between +/-30° latitude that exhibit anamolous hydration signatures compared to their surroundings. Regions with unusually low hydration include ejecta from young craters such as Tycho, which may indicate that the bulk lunar crust is significantly drier than the optical surface. Regions of high hydration, including those near Aristarchus, the southwest edge of mare Humorum, and the boundary between mare Serenitatis and mare Vaporum, are associated with pyroclastic deposits[14]. Hydration at these locations are ~3 - 4 times higher than the average of water content at the same latitude, thus some of this hydration may be indigenous (e.g., hydrated glass sourced from the lunar interior) and not simply from solar wind implantation. This hypothesis is consistent with analyses of Apollo volcanic glasses[6] and current geophysical modeling[15].

To investigate the variation in surface hydration with lunar local time, ESPAT values for ~10^6 overlapping M^3 pixels (morning - noon - afternoon) are presented in Figure 2. Approximately 90% of these overlapping pixels show a decrease in ESPAT from morning to noon, followed by an increase in the afternoon. These ESPAT changes are equivalent to a decrease in hydration followed by rehydration through the course of a lunar day, similar to the observations of *Sunshine et al., [2009]* and also consistent with the Lunar Exploration Neutron Detector (LEND) observations[16]. This change is not observed at higher latitudes (~> 55°) where temperatures are lower,

indicating that diurnal changes in lunar surface hydration have a temperature threshold.
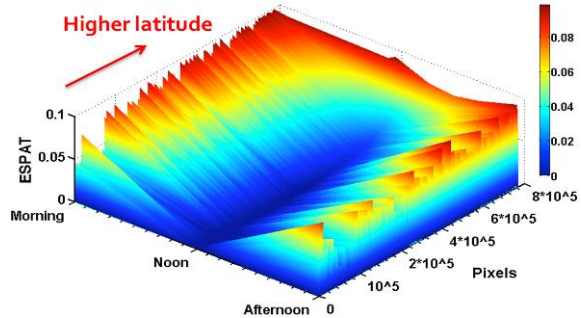

Figure 2. ESPAT functions for overlapping pixels change at three time periods: morning, noon and afternoon and latitudes.

Conclusions: Quantitative maps of lunar surface hydration have been derived from M^3 data after those data have been corrected using a new semi-empirical thermal correction model. Based on ESPAT-H_2O trends for hydrated basaltic glass, water contents between +/-60° latitude range from 0 - 500 ppm (except pyroclastic deposits), whereas latitudes poleward of 60° exhibit water contents up to several thousand ppm. Lunar surface hydration is dominantly controlled by latitude; for a given latitude the next most important factor appears to be maturity. Lunar surface hydration shows diurnal changes in equatorial and mid-latitude zones that is not observed at colder high latitudues.

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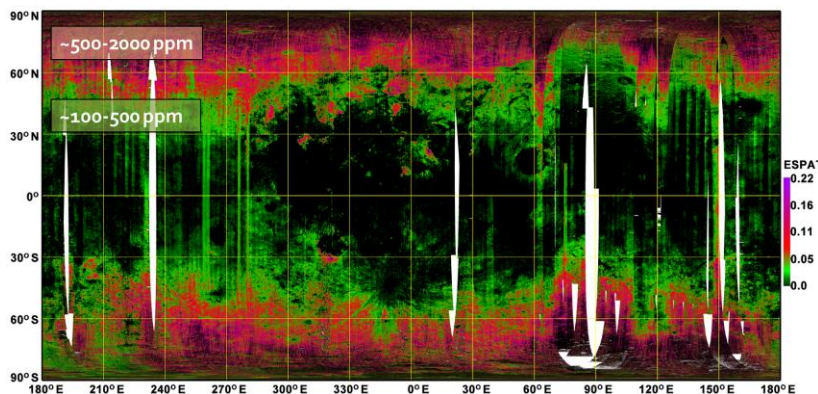

Figure 1. Global mosaic of lunar surface hydration (ESPAT values). Water content estimates are based on ESPAT-H_2O trend for basaltic glass. White strips represent lack of data. Dark regions near the poles represent areas that have been masked because the signal to noise ratio is too low for the ESPAT results to be reliable.