WATER ICE DETECTIONS IN THE POLAR REGIONS USING THE KAGUYA SPECTRAL PROFILER.

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Introduction: Direct evidence of exposed water ice in some permanently shaded regions (PSRs) of the Moon was found in spectral measurements in the UV and near-IR [1,2]. Using hyperspectral data from the Moon Mineralogy Mapper (M3), Li et al. [2] investigated light reflected from PSRs indirectly illuminated by nearby terrain. The spectral signature of pixels displaying the three overtone and combination mode vibrations for H_2O ice near 1.3, 1.5 and 2.0 µm were investigated further using the spectral angle (SA) mapping method. A SA <30° between an M3 spectrum and the spectrum of pure water ice was considered consistent with the presence of some water ice. This analysis revealed that water ice (as much as 30 wt.% intimately mixed with dry regolith) is present at the optical surface in many PSRs within 20° of both poles. However, some questions remain. For example, no surficial detection was found in some of the large current cold traps such as Amundsen, Hedervari, Idel'son L and Wiechert. Is it because *there is* no surficial water ice or is it because the M3 data *did not detect it*? The M3 data used in this analysis was acquired during a relatively short timeframe (optical period 2C: May to August 2009) [2,3] which corresponds to approximately half of the 2009 south polar winter (Fig. 1).

While more clues will arise from upcoming orbital (e.g., Trailblazer) and robotic (e.g., VIPER) missions, data acquired by another past orbital mission can currently be used. Here we use data acquired by the Kaguya Spectral Profiler (SP) between November 2007 and June 2009 (~two full seasonal cycles, Fig. 1) to search for the presence of water ice in PSRs.

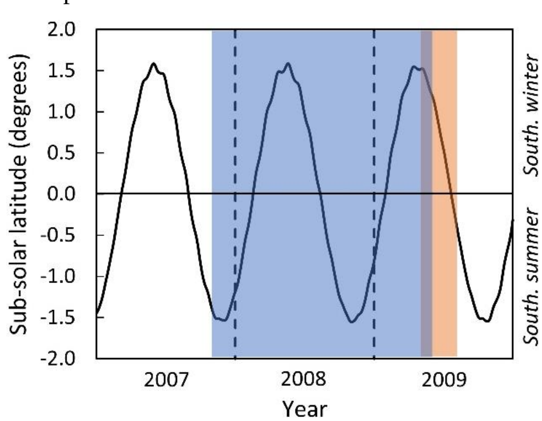

Figure 1. Sub-solar latitude and south polar seasons for the 2007-2009 period including SP observations (blue) and M3 optical period 2C observations (orange). Values were calculated using JPL's Horizons system.

Data: The SP is a point spectrometer that acquired data using three detectors: VIS (0.5-1.0 µm), NIR1 (0.9-1.7 µm) and NIR2 (1.7-2.6 µm) [4], at a spatial resolution of ~500 m/pixel (coarser than the M3 data spatial resolution of 280 m/pixel). Through its lifespan, the SP acquired an impressive amount of >7000 orbits of data which translates into millions of reflectance measurements in each polar region.

Methods: We use the method of Li et al. [2] to search for the presence of water ice in PSRs, and constrain our analysis to the SP observations acquired at latitudes between 65 and 90° N/S. We use the location of PSRs mapped by [5] at 240 m/pixel to determine if observations fall within PSRs or not. For observations within PSRs, we extract their radiance (I) and calculate their true reflectance (R_T), compensating for the fact that the surface is indirectly illuminated [2].

$$R_T = \frac{I}{(J/\pi)R\alpha},$$

J is the solar irradiance spectrum, R the average reflectance spectra of illuminated regions near the poles and α the amount of light scattered into the shaded region (1). For observations outside PSRs, we convert their radiance into reflectance using the photometric model of [6]. We smooth all spectra and remove their continuum around the 1.3 and 1.5 µm water absorption bands. The SP data near 2.0 µm is too noisy to be used as was done in the M3 data analysis. Finally, we calculate the SA and correlation between each SP spectrum and the spectrum of pure water ice (as measured by the USGS).

Preliminary results: We first compare the SA values of SP observations within PSRs to those outside PSRs (here referred to as "sunlit" pixels, although we did not determine if those observations were made when the surface was illuminated or not) for both polar regions. We find that almost all "sunlit" observations have an SA value >30°, while PSR observations have SA values both > and <30° (Fig. 2a). The graph shown in figure 2a for the south polar region is almost identical for the north polar region (not shown). These values appear consistent with the SA cutoff value (<30°) used by [2] to infer the potential presence of water ice in the M3 dataset. We then compare the correlation values of SP observations within PSRs to those outside PSRs. We find that "sunlit" observations have negative correlation with the spectrum of water ice, and PSR observations have both negative and positive values (Fig. 2b), with a local maximum at r=0.94.

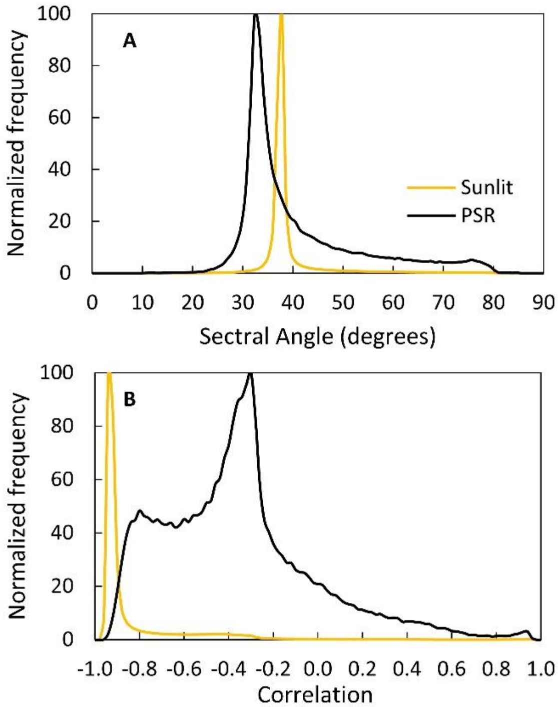

Figure 2. Calculated spectral angle (A) and correlation (B) between each SP spectrum and the spectrum of pure water ice (as measured by the USGS) in the south polar region (65-90°S).

We then constrain our analysis to PSR observations only and investigate the correlation between each SP spectrum and the spectrum of pure water ice for potential water ice detections (SA <30°) versus dry surfaces (SA >30°). Dry PSR surfaces exhibit a negative correlation with the spectrum of pure water ice, while potential water ice detections exhibit a positive correlation. That positive correlation follows a bimodal distribution, with a global maximum at r=0.34 and a local maximum at r=0.94. It thus appears that the most likely SP water ice detections are those characterized by a shallow SA (<30°) and a high correlation (>0.8).

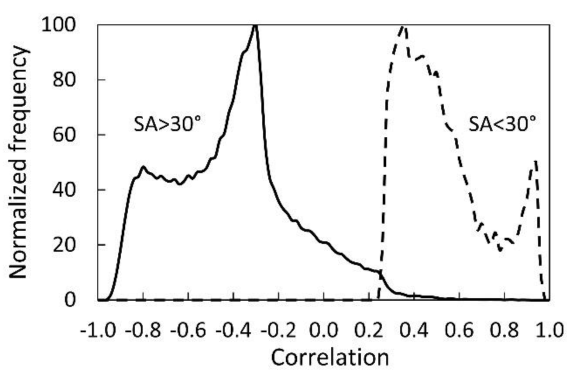

Figure 3. Correlation between SP spectrum in PSRs and the spectrum of pure water ice in the south polar region for different SA values.

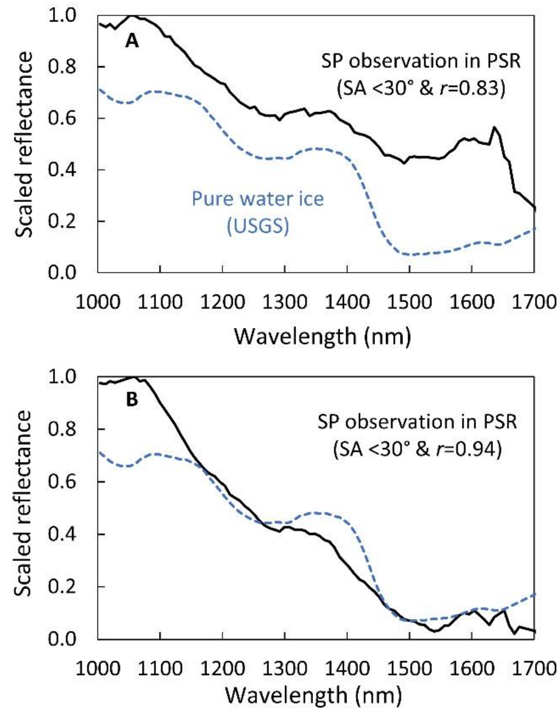

Figure 4. Examples of potentially ice-bearing (smoothed and scaled) SP spectra in PSRs and the spectrum of pure water ice.

Potential SP water ice detections generally display well-defined ~1.3 and ~1.5 μm absorption bands and some also display the weaker ~1.1 μm band. Using the actual constraints (SA <30° & r >0.8), the number of potential SP water ice detections is comparable to those identified by M3 in the south polar region (~1100), while there are more potential water ice detections by SP than M3 in the north polar region (~3300 versus ~400). If this is true, it might indicate that seasonality could play a role in the sequestration of water ice in some PSRs, as M3 observations were restricted to the south polar winter only.

Conclusion: The analysis of SP data is promising in the search for water ice in the polar regions. SP spectra with SA <30° & r >0.8 seem consistent with the presence of water ice in PSRs but must be confirmed. Most of them display well-defined ~1.3 and ~1.5 μm absorption bands and some display the much weaker ~1.1 μm band. We will next investigate (1) how these potential SP detections geographically compare with the M3 detections, and (2) how they vary with time.

References: [1] Hayne et al. (2015) *Icarus, 255*, 58-69. [2] Li et al. (2018), *PNAS, 115(36)*, 8907-8912. [3] Isaacson et al. (2011), M3 Data Tutorial. [4] Yamamoto et al. (2011), *IEEE Geo and RS, 49(11)*, 4660-4676. [5] Mazarico et al. (2011), *Icarus, 211*, 1066-1081. [6] Yokota et al. (2011) *Icarus, 215*, 639-660.