LUNAR SURFACE WATER: LATITUDE, LONGITUDE SYSTEMATICS AND DETECTION AND ABUNDANCES AT SMALL GEOLOGIC TARGETS FROM GROUNDBASED TELESCOPIC OBSERVATIONS. C. I. Honniball[1], P. G. Lucey[1], H. M. Kaluna[2], S. Li[1], L. Sun[1], and E. Costello[1], [1]University of Hawaii at Manoa, Department of Geology and Geophysics, 1680 East-West Rd, Honolulu, HI 96822, cih@higp.hawaii.edu, [2]University of Hawaii at Hilo Department of Physics and Astronomy, 200 W Kawili St, Hilo, HI 96720.

Introduction: Previously the Moon was believed to be completely dry, however it is now known that there is water present on the surface and in many lunar samples at the level of 100's of parts per million. Detection of 3 µm hydroxyl or water absorptions on the lunar surface by three spacecraft, Cassini, Chaandryaan-1, and Deep Impact, have created a new paradigm for the abundance of water on the surface of the Moon [1-3]. These observations established that a 3 µm absorption attributable to water or hydroxyl is present on the surface and has three characteristics; 1) the 3 µm absorption feature is present at high latitudes and away from the subsolar point at low latitudes; 2) it varies with lunar time of day; and 3) it varies in strength with local geology on the Moon.

The measurements of [1-3] were groundbreaking, but existing data have limitations. Data from M^3 covers the entire globe at high resolution and several times of lunar day, but is limited in wavelength range, only covering a portion of the critical 3 µm feature. Cassini and Deep Impact provide wavelength response covering the entire water band region but are limited in spatial resolution, coverage and time of day. However, groundbased telescopic spectroscopy offers access to the entire earth facing hemisphere at 1-2 km resolution with full coverage of the 3 µm feature excepting a small window from 2.5-2.9 µm.

In this project, we used the SpeX infrared cross-dispersed spectrograph [4] at the NASA InfraRed Telescope Facility (IRTF) at Mauna Kea Observatory to obtain data from 1.5 to 4 µm of small targets on the lunar surface. Our goals were: 1) to verify that lunar 3 µm absorptions could be detected using terrestrial observatories, 2) to collect data similar to previous spacecraft observations to both verify those measurements and validate our technique; and 3) to derive estimates of water/hydroxyl abundances independent of M^3 measurements.

This project combines the wavelength reach of Deep Impact and Cassini measurements needed to for confident thermal correction and mineralogic analysis, with access to the entire nearside hemisphere at resolution high enough to resolve small geologic features.

Data: On February 19, July 15 and November 9 and 10 2017, observations of the lunar surface were obtained under photometric conditions, at phase angles 100, 75, 74, and 87 degrees, respectively, all of the western hemisphere. Data from February were collected along the equator with varying longitude and lunar time of day similar to the Deep Impact equatorial profile [5]. July data were acquired along the terminator with varying latitude in approximately 10 degree increments from the equator towards the north pole to seek latitude variations in water abundances. Lastly, data were collected in November of small geologic sites that show anomalous enhancements of water above the background (Table 2) [6,7,].

Methods: Astronomical observations must be corrected for absorption by water in the terrestrial atmosphere. This calibration uses observations of spectrally solar-like stars at similar atmospheric path lengths as lunar observations, and the basic calibrated data are ratios of lunar radiance to these solar analogs. All of our lunar data were collected with regular observations of solar analog stars. Data were processed with SPEXTOOL software [8].

Data in this spectral region contain very significant thermal contamination that must be accounted for in spectral analysis. Thermal corrections used the algorithm of Clark (1979) [9] that explicitly includes the wavelength dependent effects of spectral emissivity via

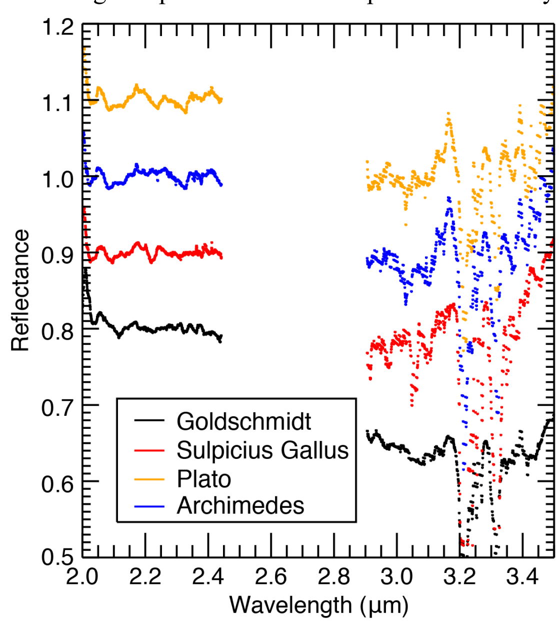

Figure 1: Strong water absorptions at small geologic sites reported as anomalous in M^3 data. Goldschmidt [13], Sulpicius Gallus, Plato and Archimedes pyroclastic deposits [7].

application of Kirchoff's Law. Data were converted to radiance from target/star ratios by application of appropriate photometric normalizations, and scaling to reflectance factor data from Kaguya Multiband Imager data [10]. Temperatures for each location used the assumption of radiative equilibrium of a rough surface with RMS slope of 20 degrees per Bandfield et al. 2015 [11]. The final data are in the units of radiance factor (surface radiance normalized to Lambert surface radiance normally illuminated) with thermal component removed. Water/hydroxyl abundances were estimated using the methods of [12] assuming a grain size of 60 µm.

Results: A strong 3 µm absorption feature is observed both at high latitudes and in local geologic features. Figure 1 shows examples of some of the strongest 3 µm bands with depths on the order of 10 percent or more, confirming that groundbased telescopic observations can detect lunar water at high spatial resolution.

In our latitude scan, with data obtained near the terminator to limit thermal contamination, water abundances were found to rise sharply and non-linearly with increasing latitude, with over 200 ppm detected in Goldschmidt crater at 75N (Figure 2).

In contrast, data collected along the equator from the terminator to the subsolar point (not shown) only showed hints of water absorptions near the terminator and none at local times nearer noon.

The small geologic targets called out by [7,8] that we were able to observe all show strong water bands. At the pyroclastic sites, high water abundances are derived (Table 2), similar to those reported by [7].

Finally, while atmospheric compensation is preliminary, some of our spectra appear to have band minima near 3 µm, consistent with the presence of molecular water.

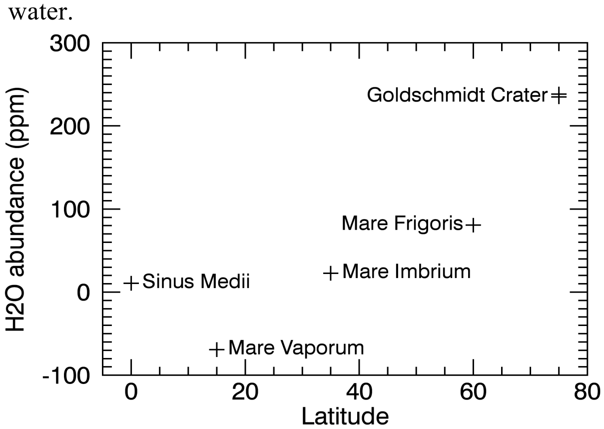

Figure 2: Terminator observations show increasing but non-linear water abundances with increasing latitude. The negative value is a feature of the algorithm used to determine abundance and indicates no water present [12].

Table 1: Water abundances for geologic sites derived from groundbased observations.

Location	Latitude	Longitude	H_2O pm
Plato Crater	50N	10W	436
Archimedes	28N	5W	331
Sulpicius Gallus	20N	6E	387
Rima Bode	13N	3W	171
Copernicus	10N	20W	152
Goldschmidt	75N	2W	238
Mare Frigoris	60N	3W	80
Mare Imbrium	35N	3W	22
Mare Vaporum	15N	1E	-69*
Sinus Medii	0N	0E	10

*Negative H_2O abundance is an artifact of the algorithm used at low latitudes when no water is present.

Conclusions: Groundbased observations of the lunar surface offers access to the entire lunar nearside with spatial resolutions adequate to resolve many geologic features, and a spectral range and resolution capable of accurate spectral characterization and thermal correction. Our observations showed latitude and time of day systematics consistent with measurements by Cassini VIMS [3] and Deep Impact [2]. Observations of localized 3 µm anomalies identified using M3 data [7,8] confirmed the presence of a 3 µm band using our greater wavelength coverage, and in the case of the pyroclastic deposits, we derived similar water/hydroxyl abundances using entire independent observations and thermal corrections. Finally, our data may indicate the presence of molecular water at these very small locations, conclusions not available from existing spacecraft data.

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