MULTIWAVELENGTH LIDAR FOR REMOTE SPECTROSCOPIC MEASUREMENTS OF THE LUNAR SURFACE.

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Introduction: Lunar volatile processes are fundamentally tied to their present abundance, distribution, and chemical state on the lunar surface. In addition, H_2O/OH is a valuable resource and the precise location and extent of high-concentration patches on the surface are targets for early ISRU efforts.

The possibility of ice at the lunar poles was proposed by Urey [1], who noted that the low obliquity of the Moon causes polar craters to be permanently shaded from sunlight, and so their interiors will achieve very low temperatures and may serve as cold traps for volatile compounds. The shadows and highly-variable lighting conditions are significant challenges to passive spectroscopy techniques used for characterization lunar volatiles.

In contrast, lidars provide their own light source and hence always collect data in darkness and with uniform lighting conditions. Here we present the case for using a surface multiwavelength laser spectrometer (*i.e.* multiwavelength lidar) for mapping lunar volatiles in the local region of a lander, rover, or via placement by astronauts during an EVA. This instrument can remotely detect the presence of surficial water ice, its location, and its distribution on scales relevant to human operations (centimeter to meter scale), which can be used to direct the sampling efforts undertaken by Artemis astronauts [4].

What are the Distributions, Concentrations, and Forms of Polar Water Ice? Orbital measurements suggest water ice is present at the surface of cold traps in the polar regions [3,4], though the distribution, heterogeneity, and form have not been conclusively determined. Models of these observations suggest that any surface ice is patchy since there are widespread regions within cold regions of permanent shadow that do not feature spectral or albedo characteristics indicating surface ice. The roughness of the lunar surface may lead to micro-cold traps that can be much smaller than the footprint of orbital instruments. This is a particular challenge for landed ISRU experiments that aim to locate and process ice at the poles since there are no reliable maps of the distribution of surface water ice to guide a successful landing. The goal of surveying polar volatile distribution, composition, and form has been highlighted as a strategic knowledge gap.

Challenges of Passive Spectroscopy at the Poles: Near-infrared (NIR) reflectance spectroscopy has played a critical role in our knowledge of the hydration state of the lunar surface via diagnostic molecular vibrations in the 1 to 3 µm region [5-7]. At the South pole, however, limiting illumination conditions make passive spectroscopy difficult (see Fig. 1). Indeed, some of the most promising locations for volatile discovery receive the least direct solar illumination (*e.g.* Shackleton Crater) [8].

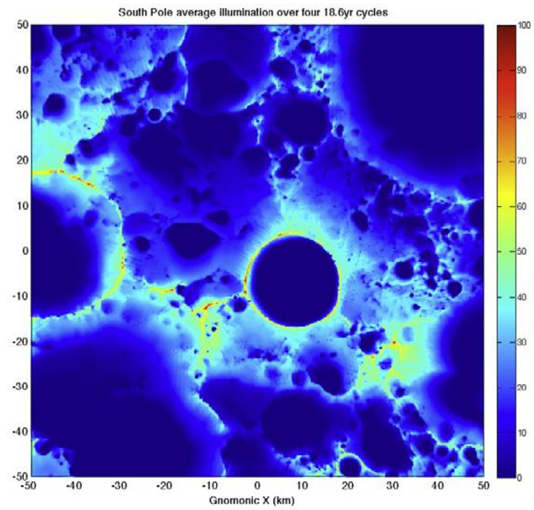

Fig. 1. Average illumination map of the South pole to 88° S, adapted from [9].

In permanently shadowed regions the illumination source is sunlight reflected off the other surroundings, and so passive measurements of the PSRs have the spectra of the reflecting region superimposed [10, 11]. From orbit it is in principle possible to characterize the illuminated surface surrounding a PSR to understand the spectral properties of the source, but from the surface the illuminated topography may be obscured from a lander spectrometer complicating calibration. No passive methods have been proposed to obtain quantitative reflectance spectra under these conditions.

The amount of light available for passive spectroscopy is also closely tied to the temperature of the surface. This is because the radiative input from surrounding illuminated terrain is the heat source that drives the temperature, except in the coldest, doubly shadowed regions where surface temperature is dictated by heat flow from the lunar interior (about 25K). The consequence of this is that very cold surfaces, for example those that may host CO_2 or other volatile ices, may not reflect enough light to collect useful spectra. Finally, the illumination conditions of the surface near the pole varies with time due to the complexity of lunar topography and the changing solar illumination angle. Areas of high interest, especially in topographic lows that may feature volatile deposits, may only be briefly illuminated each month, or even each year due to seasonal effects. This variable illumination imposes requirements on operations and planning that must be included in the cost of including this measurement capability.

Multiwavelength Lidar for Reflectance Spectroscopy: Active (lidar based) techniques offer unique capabilities to measure reflectance spectra in these conditions. We believe a multispectral laser lidar operating on the surface from a lander, rover, or deployed by Artemis astronauts will overcome most of the limitations of passive spectroscopy detailed above. This capability would be highly complementary to similar orbital approaches [12, 13].

Technique Description: Our approach operates as a lidar, but uses multiple laser wavelengths distributed across the mid-infrared region of the spectrum. The wavelengths are selected to sample the most relevant absorption features of hydroxyl, or other volatiles. The number of wavelengths and their spectral location can be varied to fit the science objectives (*e.g.* water ice in low or high concentrations, CO_2 ice, organics, *etc.*), as well as mission constraints. For each absorption feature, one to two reference wavelengths should be included to aid in removal of the lunar continuum to determine the band depth and, thus, the volatile concentration. In addition, including a wavelength at 1064 nm could be used to correlate the mid-IR reflectance measurements with LOLA measurements and provide context to the orbital polar reflectance measurements [14]. Our preliminary design of one instrument uses eight wavelengths and could operate at ranges up to 1 km regardless of illumination conditions [15].

Resilience to Thermal Effects. Sunshine et al. [6] reported temperature-dependent variations in the depth of the 3 µm water band which they interpreted to be due to variation in water abundance. Temperature variability of this signal implies water is mobile on the lunar surface, and this has major implications for supply of water to the Moon. However, on the illuminated Moon the solar reflected and thermal emitted radiances are roughly comparable near 3 µm where water absorbs strongly. This means passive spectroscopy measurements contain the competing effects of thermal emission and solar reflectance; reflectance variations must be separated from thermal emission. While some models support the interpretation of mobile surface water [16], other analysis suggests that there is no variation in the depth of the 3 µm feature, and hence no abundance variation [17]. The correct interpretation of the measurements hinges on subtle assumptions regarding the relationship between lunar emission and reflectance. For example, does Kirchoff's Law (emissivity and reflectance sum to one) hold in the presence of known strong thermal gradients in the lunar regolith?

In contrast, laser reflectance measurements are not influenced by thermal emission or by solar reflectance from the surface. This is because the detected optical power from these sources are small compared to the laser returns during the brief periods of the laser pulse, and so can be explicitly measured and removed by measuring the background signal between laser pulses.

Proposed Operational Use: This type of lidar is uniquely capable of remotely mapping the hydration state of the terrain near a rover or lander in darkness and independently of solar illumination. Line-of-sight surface volatiles surveys performed at the beginning of surface operations (requiring only several hours of operational time) would be invaluable in directing sampling operations, and greatly reduce the need to search large areas of interest. When used as a portable terrain scanning lidar, a multispectral lidar could be placed on a scan platform at overlook areas by Artemis astronauts to more fully map the composition of local terrain.

Summary: Accurate measurements of reflectance spectra near the South pole are essential to determine the distribution, quantity, and form of surface hydration. A multispectral lidar that operates in the mid-IR avoids the complications for passive spectrometers from surface thermal emission and solar illumination and allows accurate remote spectroscopic measurements in darkness and under all lighting conditions.

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