

Prospecting for Subsurface Lunar Water-Ice Using Infrared Reflectance Spectroscopy of the Moon's Surface.

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Introduction: Water ice exists on the Moon's southern pole, sequestered in PSRs at a few to several percent abundance [1] and possibly buried in partially lit terrain where the low subsurface temperature is maintained by an insulated overburden of regolith [2]. Water ice, inferred to be frost, has been found to cover portions of the surfaces of PSRs [3,4,5]. The nature and specifically the grain size of the surficial ice may potentially be informative on the origin of the ice and related processes; fine-grained surface frost may be indicative of an active process [e.g. 6] while larger-grained ice may represent excavated or exposed subsurface ice deposit [7,8].

Infrared reflectance spectroscopy can be effective at discriminating the grain size, abundance and crystallinity of water ice when present at significant abundances [e.g. 9] but its effectiveness at small ice abundances, where multiple scattering between ice grains is less probable and inquisitive photons may never even sense an ice grain, has not been demonstrated. We present laboratory results exploring the 1- 2.5 μm , and 1- 7 μm reflectance for characterizing small amounts of size-sorted ice grains intimately mixed with mare and highland simulants as well as that of frost deposited on top of desiccated highland simulant.

Measurements: We collected reflectance spectra of water ice grain separates of < 63 μm , 63 – 250 μm , and 250 – 500 μm ice intimately mixed at 5 and 10% by weight with lunar highland simulant (LHS-1) and lunar mare simulant (LMS-1) from 1- 2.5 μm under N_2 -purge at $\sim 110\text{K}$. We also collected spectra of frost deposited on top of LHS-1 from 1- 7 μm , and of 250 – 500 μm ice at 10% abundance mixed with LHS-1 under vacuum at ~ 140 to 180K .

Results and Discussion: Low abundances (5 – 10% by weight) of water ice intimately mixed into LHS-1 lunar highland regolith simulant and water frost that is precipitated on top of the regolith have similar spectral features in the 1 to 2.5- μm region. Each possesses 1.5 and 2- μm features but not a 1.25- μm feature (Figures 1a and 2a), which is unexpected for mixtures of large-grained ice given larger grained ice has a deep 1.25- μm feature [e.g. 9]. Additionally, the relative depths of the 1.5 and 2- μm features vary linearly for both the mixtures as well as frost, independently of grain size (Figures 1b and 1b) and reflectance of the non-ice matrix material. The rate of increase in the depth of the 1.5- μm band is a constant $\sim 60\%$ of the 2- μm band. We have not explored if this linear relationship would hold

for mixtures of higher ice abundance (other than for frost) and expect this relationship to break down for mixtures with a sufficient amount of larger grain ice for which the 2- μm band saturates.

It is also worth noting that vacuum desiccated LHS-1, with no ice present, possess a 2- μm feature (but shifted to $\sim 1.92 \mu\text{m}$) indicative of adsorbed water. This results in a non-zero x-intercept in Fig. 2b. It also implies polar lunar highland material, even outside of PSRs, should tend to adsorb molecular water, if either the source term exceeds the loss term (ie. there is an active source implying the presence of this band on the Moon could be evidence for an active water cycle), or previously protected material has been recently exposed.

The 6- μm band is also sensitive to molecular H_2O but possibly not when in the form of ice, which is the implication of the invariant 6- μm band in Fig 2b. If confirmed, the band could potentially be used in conjunction with the 3- μm band to reliably distinguish between adsorbed water and water ice and hydroxyl.

The 3- μm band, unlike the 1.5 and 2-micron bands does not show a consistent trend with ice abundance or grain size. It is also sensitive to OH as well as H_2O , which is also evident for the ice-free LHS-1. However, the 3- μm band is clearly anomalously deep for frost compared to 250-500 μm ice, with a depth of $\sim 95\%$ compared to a depth of only about 5% for the 1.5- μm band, ie. frost has a 3- μm band twice as deep as the 10% ice mixture yet a 1.5- μm band that is only about half as deep as for the mixture.

Conclusions: While inferring a potential water-ice subsurface reservoir or merely surface frost is viable via grain size characterization of ice exposed on the surface, when only a few to several percent of water ice is dispersed in lunar regolith, this determination requires the use of both NIR and Mid-IR wavelengths. The spectral features of water ice at 2 and 3 μm in particular offer sufficient capability for this discrimination. Additional information on the presence of other phases of water can be obtained by adding the 1.5 and 6- μm spectral features. For instance, there is a linear relationship with abundance between the 1.5 and 2- μm bands. Adding the 3- μm band depth information provides the ability to discriminate between frost and larger grained ice. The 6- μm band provides sensitivity to molecular water that is not ice, and thus can potentially be used to distinguish between OH, ice, and

molecular adsorbed water when combined with the other absorption features.

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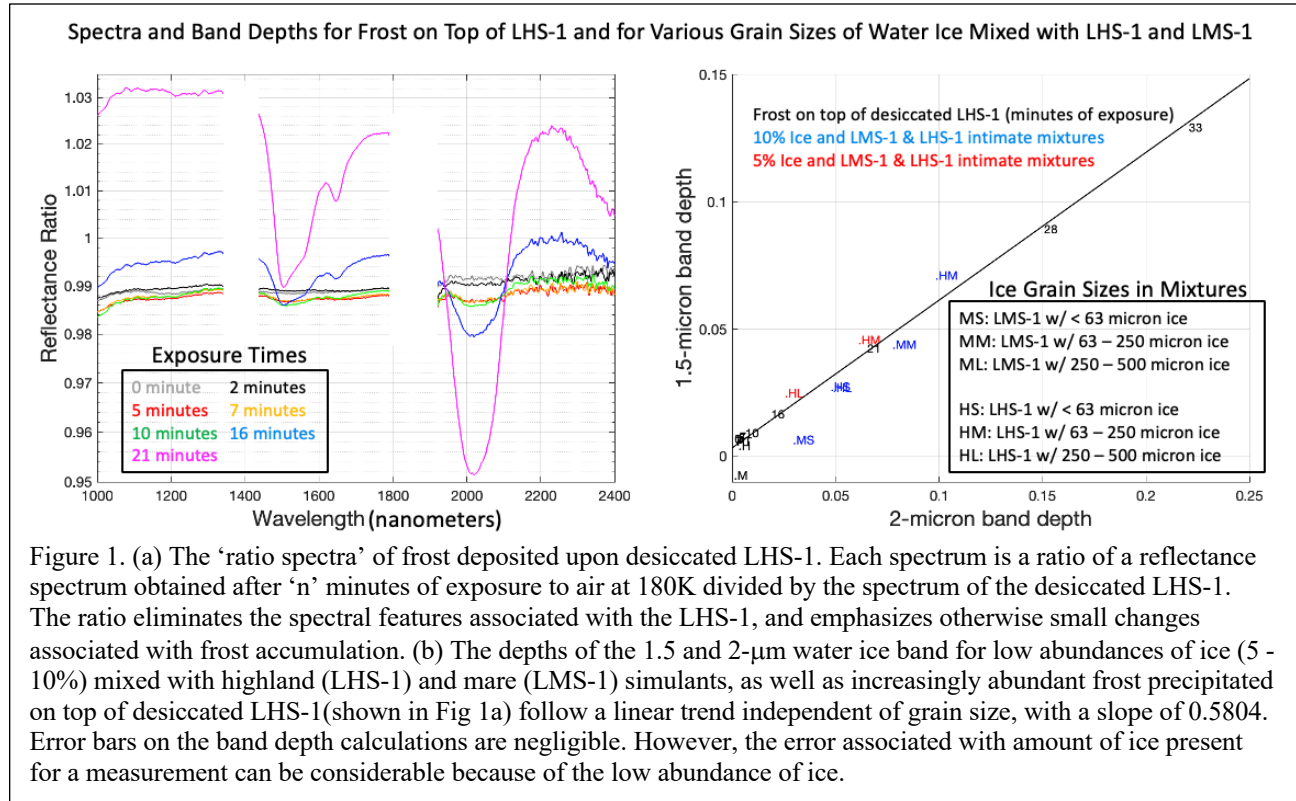


Figure 1. (a) The ‘ratio spectra’ of frost deposited upon desiccated LHS-1. Each spectrum is a ratio of a reflectance spectrum obtained after ‘n’ minutes of exposure to air at 180K divided by the spectrum of the desiccated LHS-1. The ratio eliminates the spectral features associated with the LHS-1, and emphasizes otherwise small changes associated with frost accumulation. (b) The depths of the 1.5 and 2- μ m water ice band for low abundances of ice (5 - 10%) mixed with highland (LHS-1) and mare (LMS-1) simulants, as well as increasingly abundant frost precipitated on top of desiccated LHS-1 (shown in Fig 1a) follow a linear trend independent of grain size, with a slope of 0.5804. Error bars on the band depth calculations are negligible. However, the error associated with amount of ice present for a measurement can be considerable because of the low abundance of ice.

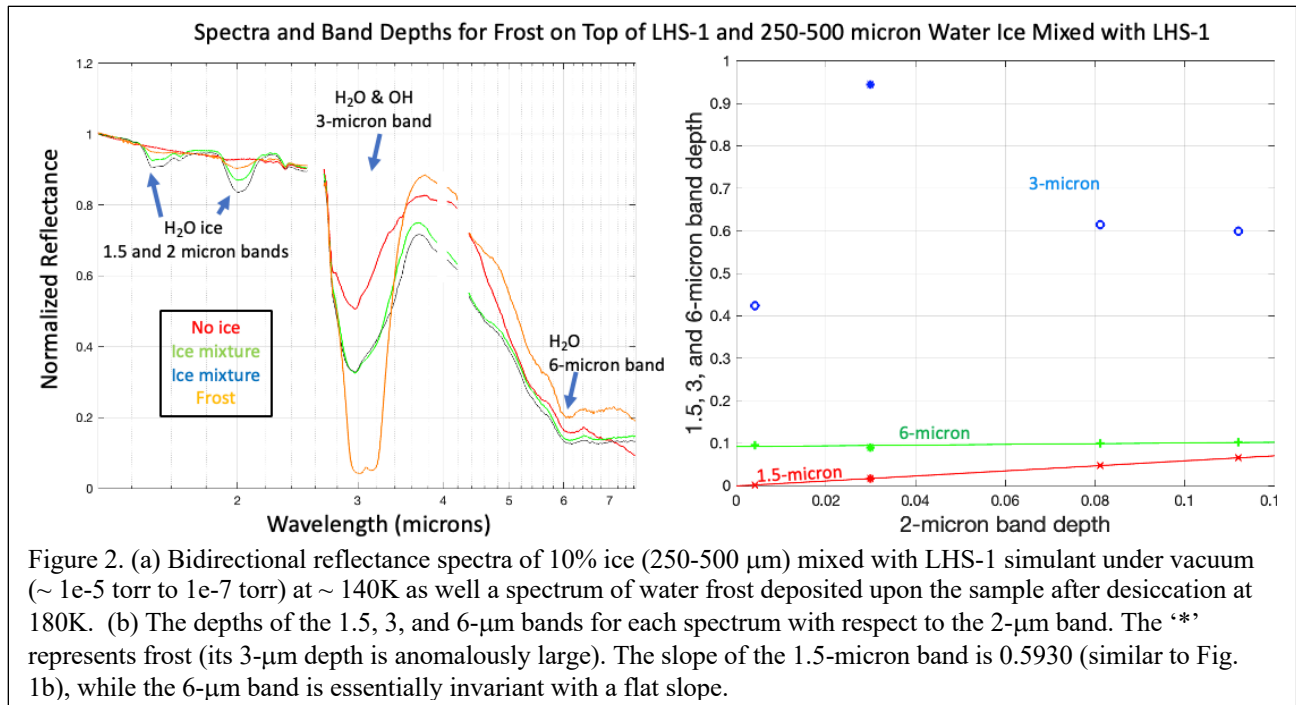


Figure 2. (a) Bidirectional reflectance spectra of 10% ice (250-500 μ m) mixed with LHS-1 simulant under vacuum ($\sim 10^{-5}$ torr to 10^{-7} torr) at ~ 140 K as well as a spectrum of water frost deposited upon the sample after desiccation at 180K. (b) The depths of the 1.5, 3, and 6- μ m bands for each spectrum with respect to the 2- μ m band. The ‘*’ represents frost (its 3- μ m depth is anomalously large). The slope of the 1.5-micron band is 0.5930 (similar to Fig. 1b), while the 6- μ m band is essentially invariant with a flat slope.