Introduction: Surface-exposed water ice in the lunar permanently shaded regions (PSRs) was confirmed by three near infrared (NIR) absorption features near 1.3, 1.5 and 2.0 µm in M² data [1]. However, the effect of ice abundance and viewing geometry on the VNIR (visible to near-infrared) spectra of water ice is still poorly constrained, posing important limitations for detecting water ice on airless bodies via remote sensing. The characterization of diagnostic spectral features of water ice in a laboratory environment is fundamental for interpreting potentially large spectral variations in VNIR data gathered by future missions dedicated to remote sensing of water ice. The purpose of our study is to characterize spectral features of mixtures between water ice and a highland regolith simulant (HRS) at the VNIR region (350-2,500 nm). We investigated variations in bidirectional reflectance at 700, 1350, 1850, and 2250 nm and NIR absorption bands at 1.0, 1.25, 1.5, and 2.0 µm, with varying ice abundance and phase angles (g). These results are fundamental for interpreting VNIR data on the Moon and other airless bodies.

Methods: Water ice production. We prepared fine ices (<50 µm) by nebulizing water droplets into liquid nitrogen, and coarse ices (>50 µm) by freezing distilled water into ice cubes and blending them with liquid nitrogen. We sieved the ices using liquid nitrogen. Both procedures were conducted in a freezer purged with dry, cold air to avoid condensation from atmospheric water.

Simulant preparation. We used simulant CSM-LHT-1 (Colorado School of Mines) to represent the Moon's anorthositic highland terrain. We dehydrated the HRS in an oven for 5 days at 350° to remove any residual internal water. The dehydrated simulants were intimately mixed with water ice in a freezer to simulate the distribution of lunar ice in the regolith [2] [3].

Spectral measurements. The ASD spectrometer was calibrated using Labsphere Spectralon disk as a white reference standard. Spectral measurements were conducted outside of the freezer. To avoid melting, the samples were rapidly (>5 secs) transported onto a dewar with liquid nitrogen. Each measurement was taken within 30 seconds of the sample being outside of the freezer to avoid condensation. We rotated the sample cup every two measurements to ensure even sampling of the sample surface.

Data processing. We discarded any spectrum with kinks and steps produced by instrument errors, and averaged the remaining spectrum to calculate reflectance. We calculated band depth of the NIR absorption features using a continuum removal analysis. For measurements with varying g, we performed an additional correction due to the slight forward scattering effect of the Spectralon disk [4].

For the ice abundance experiments, we varied the ice content from 0-50 weight percent (wt.%) for three particle size groups of ice: 20-32 µm, 63-90 µm, and 150-180 µm. The incidence angle (i) was fixed at 30° and the emittance angle (e) was set at 0° (i.e: g= 30°). For the viewing geometry experiments, g varied from 0-105°, at 5° increments (i= 45°, e= -60° to 45°).

Results: Increasing ice abundance yields deeper NIR absorptions at the 1.25, 1.5, and 2.0 µm bands (Fig. 1). The weaker absorption at 1.0 µm remains too faint to be discerned. Mixtures containing coarse-grained ice yield stronger absorption features.

The VNIR reflectance across all phase curves increases at high phase angles, demonstrating forward scattering (Fig. 2). Forward scattering is an intrinsic property of ice, hence it increases in mixtures with higher ice abundances. The phase curves also demonstrate backscattering, evidenced by the increased reflectance at low phase angles. The strong backscattering in phase curves with low ice abundances (0, 3 wt.%) suggests backscattering produced by the simulant. Furthermore, the depth of the 1.25, 1.5, and 2.0 µm absorptions increases near phase angles of 40-60° as ice abundance increases (Fig. 3). This enhancement band strength at 40-60° does not occur in mixtures with low-water ice content (0, 3, 5 wt.%).

Figure 1. Increase in band depth of NIR absorption features with ice abundance in water ice/HRS mixtures. Absorption features are indicated in the grey boxes. Phase angle = 30°.
The NIR absorption features diagnostic of water ice vary between 40 and 60° when observed at high phase angles, which are generally observed under high phase angles by orbiters due to the low positioning of the Sun along the polar horizon.

The NIR absorption features diagnostic of water ice at 1.25, 1.5, and 2.0 µm are stronger when observed at phase angles between 40 and 60° (Figure 3). This effect is more evident in the stronger 1.5 and 2.0 µm absorptions, where the increase in band depth becomes apparent at 15 ± 5 wt.%. At the 1.25 µm absorption, the band depth only increases at phase angles of 40-60° at ice abundances of 20 ± 8 wt.%. Hence, this enhancement in band depth at phase angles between 40-60° will likely not be produced by surface-exposed water ice intimately mixed with the highland regolith, which is estimated to exist in the range of a few weight percent (wt. %) [1].

**Conclusion:** Our study shows that increasing the amount of water ice in intimate mixtures with a HRS linearly strengthens the diagnostic NIR absorptions of water ice at the 1.25, 1.5, and 2.0 µm bands. Particle size estimations are only viable when ice abundances are ≥30 wt.%. While high phase angles (>105°) are optimal for detecting ice using VNIR reflectance, lower angles between 40-60° yields the strongest NIR absorptions of water. The results presented in this study facilitate the detection of water ice intimately mixed with anorthositic material using VNIR spectroscopy.