Simulating Multispectral Lidar Measurements of Lunar Surface Hydration. D. R. Cremons\textsuperscript{1} and C. I. Honniball\textsuperscript{2}, \textsuperscript{1}NASA Goddard Space Flight Center, Greenbelt, MD, 20771, daniel.cremons@nasa.gov, \textsuperscript{2}NASA Postdoctoral Program, NASA Goddard Space Flight Center, Greenbelt, MD, 20771.

Introduction: Any variability of hydration (H$_2$O/OH) on the illuminated lunar surface as a function of latitude, temperature, lunar time of day, or surface composition would be directly indicative of the generation, migration, and destruction mechanisms. However, the spectroscopic feature at 3 μm through which this variation has been primarily observed is complicated by the need to remove the contribution of thermal emission, which can modify or even eliminate the observed hydration feature variation depending on the data processing methods and thermal model used [1-3]. An orbital multispectral lidar, in which laser sources are used with key diagnostic wavelengths within and around the 3 μm band, would be agnostic to the thermal state of the surface. It would also control for viewing geometry effects by providing a uniform, zero-phase illumination geometry and allow complete latitude and time of day coverage from a circular polar orbit. To test whether sparse spectral sampling could measure variations in the 3 μm feature we have performed measurement simulations of a four-wavelength multispectral lidar using spectral mixtures of hydrated mid-ocean ridge basalt (MORB) glasses and lunar regolith endmembers.

Lidar Wavelengths and Measurement Error:

The benefits of an active reflectance measurement, mainly the fixed, zero-phase viewing geometry and ability to remove the effects of surface temperature, come at the cost of providing a spectral illumination source. We chose a limited set of four lidar wavelengths at which to measure the zero-phase surface reflectance, distributing the wavelengths based on our desire to constrain the 3 μm band depth and shape. We selected lidar wavelengths at 1.50 μm, 2.65 μm, 2.80 μm, and 3.10 μm. The wavelengths at 1.50 and 2.65 μm constrain the lunar continuum, while those at 2.80 μm and 3.10 μm constrain the OH band depth and shape to enable a more accurate retrieval of the total water (OH + H$_2$O) content. The band minimum of the MORB glass hydroxyl absorption occurs at 2.80 μm and thus offers the highest contrast between the 3 μm total water feature and the lunar continuum.

The reflectance measurement precision at each lidar wavelength depends on the ability to accurately measure the transmitted and return laser pulse energies from the lidar. Based on the demonstrated performance of an OPO-based laser transmitter subsystem and a TRL-6 HgCdTe APD used for trace gas measurements we baselined a per-wavelength SNR of 250 assuming a 1-second integration time from a 50 km altitude. We accounted for the lidar measurement precision by adding randomly distributed Gaussian noise with a variance equal to the noiseless reflectance divided by the SNR to the reflectance spectra.

Spectral Datasets and Mixing Methodology: We simulated lunar reflectance spectra from 1 to 4 μm under varying levels of hydration using a Monte Carlo mixing method. We generated intimate single scattering albedo (SSA) mixtures using laboratory reflectance data of Apollo samples from the RELAB Database and reflectance data from step-wise heating experiments of water-bearing MORB glasses as a lunar glass analog source with precisely known water content [4]. The endmember laboratory reflectance spectra were converted to SSA using the methods of Hapke [5] and least-squares minimization. Each simulated spectrum was generated from a random mixture of mature and immature Apollo sample spectra (mare and highlands), an Apollo pyroxene spectrum, and a MORB spectrum. Once the SSA spectrum of each intimate mixture was calculated, we converted the spectra to reflectance in the lidar geometry (zero phase) and added SNR-based noise.

Spectral Unmixing and Monte Carlo Results:

We used a non-negative linear least-squares algorithm to solve for the total water abundance from the four lidar measurements of the noisy reflectance spectra. Our method is based on those of Mustard and Pieters [6], and Li and Li [7]. The four reflectance values at the lidar wavelengths were first converted back to SSA using the Hapke model. We used four endmember spectra to solve for each four-wavelength spectrum. Two endmembers were from the MORB glass step-heating experiment: the 1522 ppm total water and 22 ppm total water experimental spectra. The 1522 and 22 ppm spectra represent the two extremes of the 3 μm band shapes in these mixtures. The other two endmembers were a mature mare and an immature highlands spectrum.

Figure 1 shows example results of the spectral unmixing technique described above for one of the simulated highlands spectra. The four lidar SSA values denoted by the blue dots in Figure 1 were the only values used to solve for the abundances of each of the endmember spectra. Multiplying the lidar-derived endmember abundances by their respective SSA spectra gives the green retrieved spectrum in Figure 1.
This highlands simulation had a randomly chosen input glass fraction of 0.27 and an independently selected interpolated MORB spectrum with 581 ppm total water (0.27 × 581 ppm = 156 ppm total abundance). The least-squares algorithm was tasked with fitting this spectral mixture using the two MORB endmember spectra (1522 ppm and 22 ppm), as well as the mature mare spectrum and immature highlands spectrum. Assuming a linear relationship between SSA and water content the line shape of the input MORB spectrum (581 ppm) is about 1/3 of the way between the two endmembers (22 ppm and 1522 ppm), and the least-squares algorithm accurately selected a 1:2 mixture of the two MORB endmembers (0.06 of the 1522 ppm endmember and 0.12 of the 22 ppm endmember). The total water error for this example, defined as the measured total water abundance minus the input total water abundance was -37 ppm.

Conclusions: The simulation results indicate that a four-wavelength multispectral lidar with laser wavelengths at 1.5 µm, 2.65 µm, 2.80 µm, and 3.1 µm to measure the lunar continuum and the 3 µm band depth and shape could measure the hydration signature with a bias of -39 ppm and a root mean square error of 55 to 65 ppm. This precision and accuracy, combined with the ability to measure over the entire diurnal cycle (with even higher precision for unilluminated surfaces due to an increased lidar SNR) and at all locations with a fixed viewing geometry, suggests orbital multispectral lidar in this wavelength regime would be a valuable technique for validating models of OH/H₂O generation, migration, and destruction as a function of surface temperature, latitude, time of day, and solar wind flux.