A NEW GRAIN SIZE LOOKUP TABLE FOR THE AIRBORNE SNOW OBSERVATORY

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ABSTRACT

The Airborne Snow Observatory (ASO) is a coupled lidar and imaging spectrometer system developed by NASA-JPL to more accurately quantify important snowpack properties. Along with snow depth and water equivalency, ASO has the ability to drastically improve measurements of snow albedo, a major factor regulating the absorption of solar radiation and consequently snowmelt. Snow grain size is one of the primary parameters controlling the broadband albedo of a snowpack. Imaging spectrometry has provided the ability to examine snow grain size over basin-wide scales. Nolin and Dozier (2000) developed a method using imaging spectrometer data to estimate the optical grain size of a snow surface by relating the reflectance centered around an ice absorption feature at 1030 nm to optical grain size. Due to the operational demands of product delivery (24-hour turnaround time), the Nolin-Dozier approach to grain size retrievals has not yet been implemented in the CASI processing pipeline. Additionally, the CASI imaging spectrometer only covers a portion of the grain size absorption feature, requiring an updated relationship between the ice absorption feature and the grain size. Here, we created a look up table for the CASI spectral range and resolution using two methods, and compare grain size retrievals to current operational methodology. (KEYWORDS: snow hydrology, snow melt, snow energy balance, optical grain size, remote sensing)

INTRODUCTION

Snowmelt is a major water resource that contributes to meet domestic and agricultural water demands in many regions globally, and also exerts controls on regional climate and ecology. In the Western US, over 75% of freshwater runoff originates from snowmelt (Bales et al., 2006). Studies have shown the mountain snowpack is changing, with trends toward shorter duration and less snow water equivalent (Mote et al., 2005; Clow, 2010). With increasing populations and an anticipated decrease in annual snowpack contribution, managing water efficiently in the Western US becomes more critical. Predicting peak streamflow and overall water volume for a season can be difficult for water managers as data in mountainous regions often relies on limited point sources from the SNOTEL network.

Due to the high amount of variability in the physical characteristics of snowpack, additional resources are required to equip water managers with the tools to accurately supervise and plan for water needs in the west (Painter et al., 2016; Figure 1). NASA-JPL's Airborne Snow Observatory (ASO) was created to remedy the lack of information in snowpack characteristics. Multiple airborne flights may occur during the winter season in order to gather essential information regarding the snowpack properties for a particular watershed of interest. Snow albedo is one of the most important properties determining the timing and magnitude of snowmelt, but remains poorly defined in most regions throughout the Western US and globally. Here we test two methods to improve grain size estimations for different study areas, utilizing data acquired from ASO. Once implemented, these methods will improve our understanding of snowpack characteristics and better inform values for snow albedo in each region.

BACKGROUND

Along with snow depth and water equivalency, ASO has the ability to measure spectral and broadband snow albedo, a major factor regulating the absorption of solar radiation and consequently snowmelt. Snow grain size is one of the primary parameters controlling the broadband albedo of a snowpack (Wiscombe and Warren, 1980), and is a critical retrieval step in accurately translating snow reflectance to snow albedo. Imaging spectroscopy has

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Figure 1. Photo taken out the side window during an ASO flight. Spatial variability of the mountain snowpack is exhibited. Photo by McKenzie Skiles

provided the ability to examine such snowpack characteristics over basin-wide scales by leveraging the unique spectral signature of snow. The ASO pipeline currently uses a band ratio method, the normalized grain index, to estimate snow grain size. This method doesn't utilize all of the spectral information gathered by ASO and introduces some amount of error into ASO albedo products.

Nolin and Dozier (2000) used and validated a method for estimating the radius of an optically equivalent sphere using spectral data from the Advanced VIS/IR Imaging Spectrometer (AVIRIS), which features 241 bands from 380-2500 nm. This method utilized spectral wavelengths surrounding an ice absorption feature centered at 1030 nm, and has been the community standard method for estimating snow grain size. ASO has on board an *itres* CASI 1500 imaging spectrometer with a spectral resolution of ~10 nm across the wavelength range of 380-1050 nm and uses algorithms initially developed for AVIRIS. Additionally, the CASI imaging spectrometer has a poor signal-to-noise ratio (SNR) in the near infrared (NIR) and only captures a portion of the grain size absorption feature upon which the Nolin and Dozier (N-D) approach is based. As such, a revised association between grain size and ice absorption is required. Here, we compare a new grain size retrieval method alongside an updated version of the N-D model for the CASI spectral range and resolution (Figure 2).

METHODS

The N-D method uses the DIScrete-Ordinates Radiative Transfer (DISORT) model to calculate the scaled absorption band depth around the ice absorption feature centered at 1030 nm for multiple known optical grain sizes. The integrated absorption depth is then compared with the integrated values of the Advanced VIS/IR Imaging Spectrometer (AVIRIS) over the same wavelengths. The strength in using a scaled band depth is that it reduces the effect of noise in the instrument. This method has been validated and is the standard method for retrieving optical grain size within the snow community.

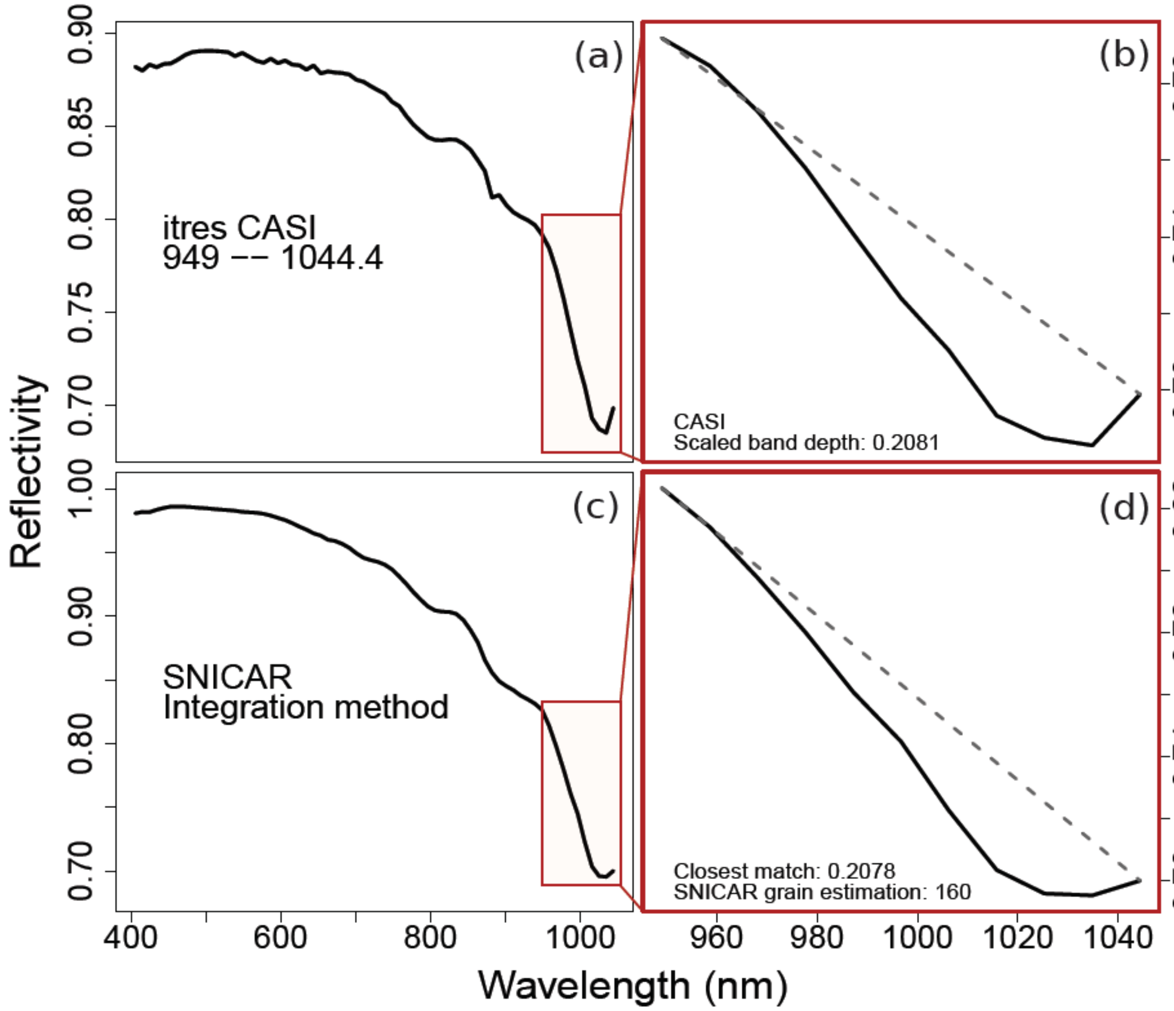

Figure 2. The modified N-D method for estimating grain size. Modified for CASI wavelengths. (a) full CASI spectra, (b) ice absorption feature and continuum, (c) and (d) show the corresponding modeled spectra using SNICAR. The scaled band depth (or integrated value) is used to match the corresponding grain size used in the modeled spectra.

The challenge in incorporating this method with the ASO pipeline is that the on board *itres* CASI imaging spectrometer has a spectral range of 365-1050 nm, which only partially covers the ice absorption feature. We apply this method over the partial wavelength coverage of the absorption feature for two CASI images. In place of DISORT we use the Snow, Ice, and Aerosol Radiation model (SNICAR). Figure 2 shows the spectral reflectance values for a pixel located in Senator Beck Basin on February 20, 2017. Figure 2b shows the CASI wavelengths used for the scaled absorption band depth method, which we will refer to as the integration method. Figures 2c and 2d show the corresponding SNICAR spectra that matches the integrated value in the CASI pixel, which provides the optical grain size at that location.

In addition to the integration method, we also test a new method which uses the spectral slope of the left shoulder at the ice absorption feature (Figure 3). There is a distinct relationship across the slope from 930-1025 nm wavelengths and grain size in SNICAR. Because of the limited coverage of the ice absorption feature for the integration method, we are interested in other methods to estimate grain size in order to improve the ASO albedo products.

SNICAR includes a grain size range of 30-1500 µm, with a resolution of 1 µm. It is important to note that CASI values which fall outside the range of SNICAR are excluded from the results for both the integration and

spectral
slope

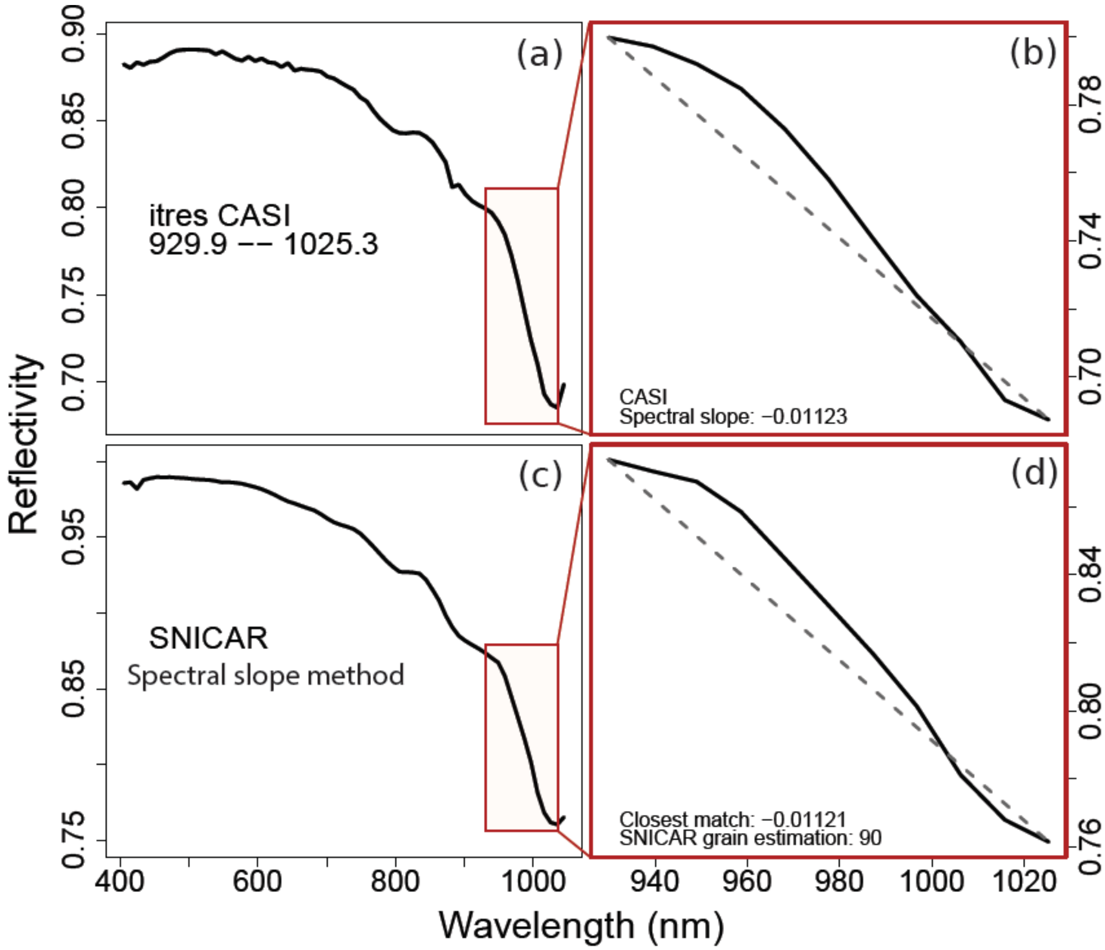

Figure 3. Same as Figure 2 only for the spectral slope method.

methods. Additionally, all CASI scenes used have a spatial resolution of 3 meters, which can introduce mixed pixel values in some areas, particularly areas surrounded by dense vegetation or rock exposure. Here we compare the capability of these two methods to solve for the optical grain size in Sagehen Creek, CA on April 17, 2016, and Senator Beck Basin on February 20, 2017.

INITIAL RESULTS AND DISCUSSION

Sagehen Creek, CA

Sagehen Creek is a field research study area on the eastern slope of the northern Sierra Nevada, 20 miles north of Lake Tahoe. The location is extremely vegetated, which can cause mixed pixel values from the combination of spectra for snow and vegetation. These mixed spectra can create a lot of noise in the instrument signal, in particular across the near-infrared wavelengths of the CASI range. For this image we found a spike in reflectance values over the middle of the absorption feature (1030-1044 nm), which are the two largest wavelengths on the CASI imager. This causes a large amount of error when solving for grain size with the integration method.

Figure 4a shows the results for the integration method over Sagehen Creek. Based on our understanding of snow metamorphism, the grain size distribution contains too many large grains to be physically realistic. An almost speckle-like pattern is generated across the image showing a myriad of grain sizes. In comparison, Figure 4b shows the results for the spectral slope method, which displays a more well-defined distribution. Although the calculated grain sizes for the spectral slope method are smaller than we would expect for April snow in this region, the initial results for the spectral method are more promising than the integration method. It is also possible that the area experienced a recent snowfall during this time period, in which case the spectral slope values would be representative.

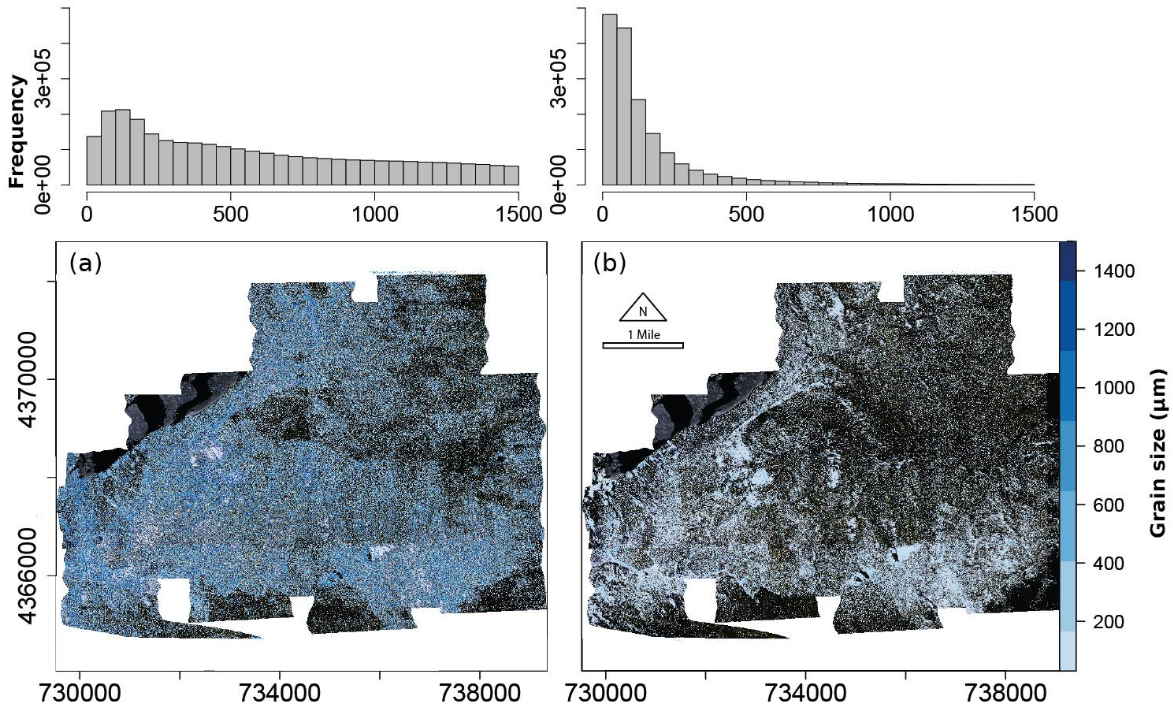

Figure 4. Results for Sagehen Creek (April 17, 2016), showing the integration (a) and spectral slope (b) methods. Above each, the corresponding distribution of values for the area. The vegetation affects both methods, but 4b appears to yield more believable results, based on smaller values and a more defined distribution of grain sizes for this day. Histogram bin sizes are 50 µm.

Senator Beck Basin, CO

Senator Beck Basin (SBB) is a study area in the Uncompahgre watershed within the San Juan mountains of Colorado. Two energy balance stations reside in SBB at different elevations, making this an ideal location to study snow energy balance and melt. The majority of the basin is above tree line, though there are evergreens near the lowest elevation site. The snowpack in this area receives heavy dust loading from the southern Colorado Plateau during the spring time (Skiles et al., 2015), however this ASO flight occurred on February 20, 2017 right after a freshly fallen snow event. As such, we would expect to see smaller grain sizes.

Once again, the distribution of grain sizes is more well defined for the spectral slope method (Figure 5). The integration method appears to fail throughout the scene, often showing values well outside the range of SNICAR. Across SBB, we observe smaller grain sizes than expected using the spectral slope method, however, the method appears to produce values similar to fresh, dry snow that fall within the spectral slope values of SNICAR. The spatial homogeneity and the overall range of values produced on this day suggests that the spectral slope method is likely a viable method for determining grain size, but validation is necessary to gauge the discrepancy between observed grain sizes and these results.

This ASO flight occurred in conjunction with part of the NASA SnowEx ground campaign, which included GPS marked ground spectroscopy measurements in SBB at upper and lower elevation sites. We use this data to assess the accuracy of our spectral slope method.

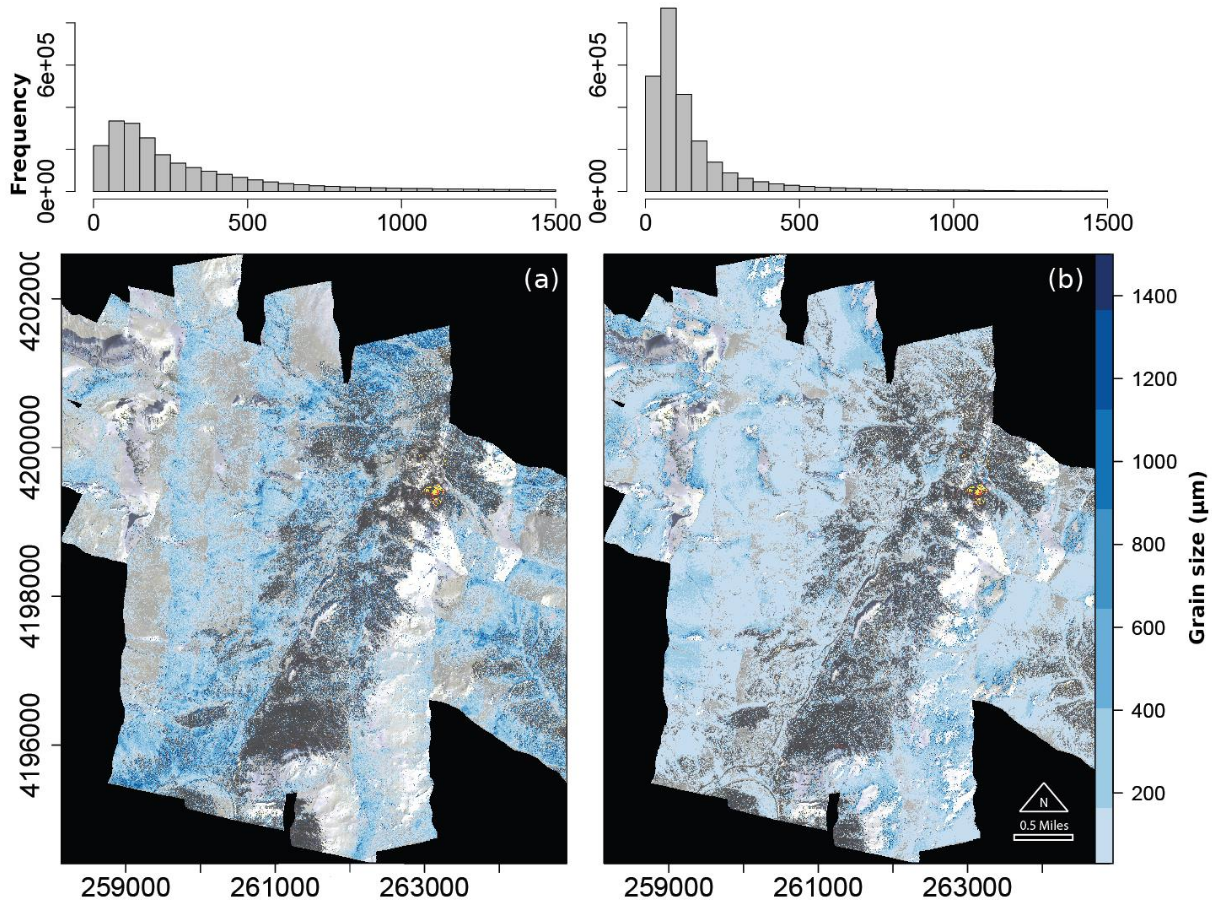

Figure 5. Results for Senator Beck Basin (February 20, 2017), showing the implementation of the integration method (a), and the spectral slope method (b). Above each method shows the distribution of values observed on a day with freshly fallen snow. Again, the spatial homogeneity and distribution for the spectral slope method appear more reliable than the integration method. Histogram bin sizes are 50 µm.

Validation in Senator Beck Basin

Corresponding fieldwork from NASA SnowEx occurred in SBB during the time of the ASO flight. Measurements were taken with a 2500 ASD FieldSPec4 Hi-Res imaging spectrometer along four transect lines at the Senator Beck Basin Study Plot (SBSP), and four more at the Mid Basin (MIDB) location. The wavelength range of the ASD FieldSpec4 is 350-1500 nm and features 2151 bands (Figure 6). We use this spectral data to estimate optical grain size using the standard N-D method in order to assess the accuracy of our spectral slope method. Figure 6 shows the CASI grain size estimations with the spectral slope method against the ASD FieldSpec4 values, which use the N-D method. The spatial resolution of the ASO spectral reflectance imagery is 3 meters, and the values at each point along the transect were extracted using bilinear interpolation to help account for uncertainty in the handheld GPS measurements.

Although the correlation is not linear, grain sizes retrieved with the CASI spectral slope method are generally near the upper range of uncertainty (±50 µm) in the standard N-D method (Nolin and Dozier, 2000). These results suggest that this method is close to accurately estimating grain size, but may need further adjustment in order to reduce error. The root mean square error and mean absolute error for SBSP are 43.38 and 39.10 respectively; and are 68.50 and 59.16 for the MIDB location.

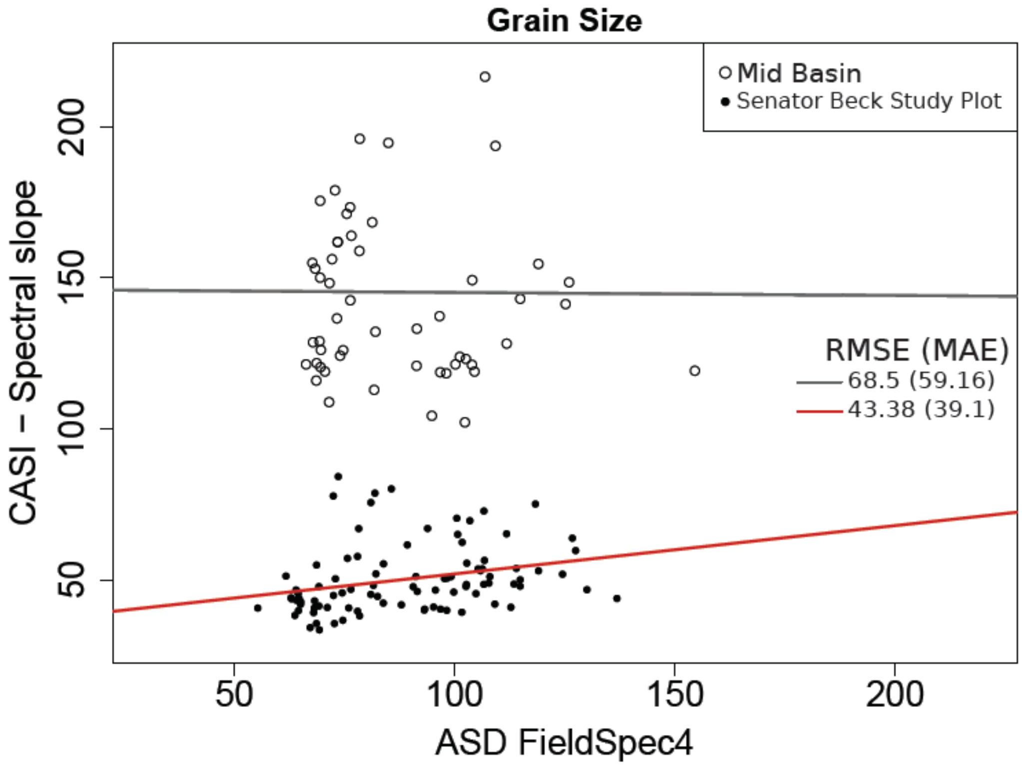

Figure 6. Ground validation of spectral slope grain sizes compared with measurements from a handheld ASD FieldSpec4 in SBB. Results from the CASI data are relatively near (±50 µm) the ASD measurements, under-estimating grain size at the lower elevation site (SBSP), and over-estimating at higher elevations (MIDB). Data points are taken along transect lines.

CONCLUDING THOUGHTS

Here we present a new method to calculate optical grain size for ASO imagery. We compare this new method with a standard method adapted for the CASI imaging spectrometer wavelengths. Due to signal noise in the CASI near-infrared bands, the standard N-D method (Nolin and Dozier, 2000) appears to give unbelievable grain size values, many of which fall outside the range of values produced from our radiative transfer model (SNICAR). This is also likely due to the smaller quantity of bands available using the N-D method over the CASI wavelength range.

The spectral slope method appears to produce more matches with the SNICAR look-up table and shows a distribution of values that appear more realistic based on meteorological conditions at that time. However, additional ground validation, along with a more robust inter-comparison is essential in order to accurately assess the viability of using the spectral slope method for grain size retrieval. Another possible benefit of the spectral slope method is that only a unique range of slope values occur near the left shoulder of the ice absorption feature. As such, it is likely that data will be automatically masked to only include snow spectra, and consequently only snow-covered area in the image. Quantities falling outside the range of the SNICAR slope values are labelled as non-snow. Though an added benefit, this may complicate the accuracy of calculating grain sizes within mixed pixels. However, this can be an issue for either grain size retrieval method.

Overall, this analysis was preliminary, but initial results proved to be promising for the spectral slope method. We hope to assess the reliability of this model with further ground validation in the future. We also plan to use the spectral slope method in conjunction with the ASD FieldSpec4 data for a more direct one-to-one comparison. After further validation of this model, along with improvements or adjustments, we plan to implement an accurate grain size retrieval method into the CASI pipeline in order to create more precise albedo estimates from ASO flights.

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