Snow grain size from ice absorption features at 1030 nm and 1260 nm

Jeff Dozier notes, August 2021

Contamination by light-absorbing particles mainly affects snow albedo in the visible part of the spectrum where ice is transparent (Warren & Brandt, 2008). In the near- and shortwave-infrared wavelengths, beyond about 950 nm, ice itself is moderately absorptive so the spectral albedo varies inversely with the path length that a photon traces when it enters the snowpack. Therefore the albedo is smaller when the grains are larger (Warren, 1982).

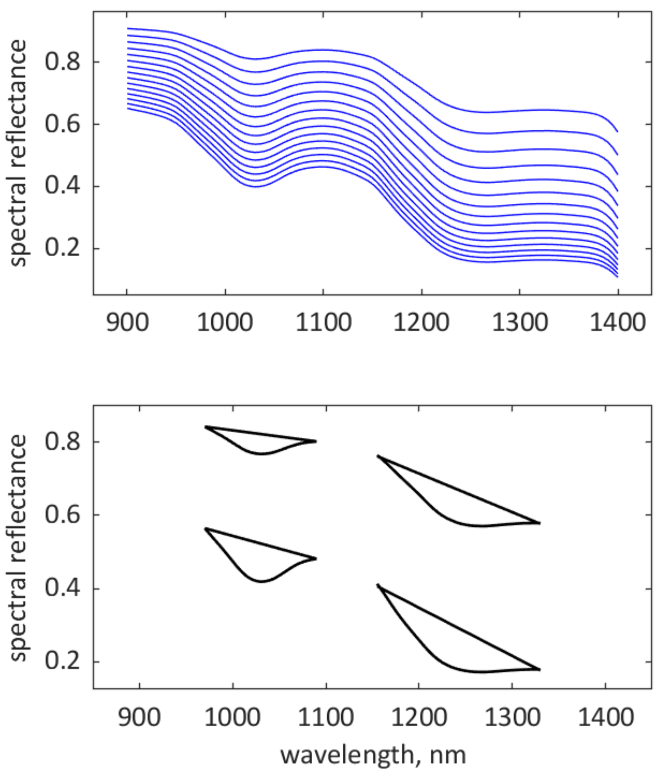

Figure 1. Top graph shows modeled snow spectral reflectance for grain size (effective radius) from 50 μm (top) to 1000 μm (bottom) at a solar illumination angle of 60°. Bottom graph illustrates the decrease in reflectance below the continuum around the ice absorption features at 1030 nm and 1260 nm, for snow radii of 78 μm and 892 μm.

Anne Nolin had the insight originally that a robust way to remotely sense snow albedo is to estimate its effective grain radius and then model the rest of the spectrum from the grain size and the illumination angle (Nolin & Dozier, 2000). Based on a spectral absorption feature for ice around 1030 nm, the depth of the absorption would increase with the grain size. Furthermore, integrating the decrease in reflectance across the absorption feature, say from 970 to 1090 nm, makes the retrieval less sensitive to noise. A similar analysis can be applied to the ice absorption feature at 1260 nm. The top graph in Figure 1 shows modeled spectral reflectance for deep snow in the wavelengths around the two absorption features.

The "area" A_b of the absorption (bottom graph in Figure 1) is the integrated difference between the the continuum reflectance $R_{c\lambda}$ and the snow reflectance $R_{s\lambda}$ across the absorption feature, scaled by the reflectance of the continuum. The integral has units of wavelength, so dividing by the wavelength range makes A_b dimensionless. The wavelength ranges chosen are 970 to 1090 nm for the 1030 nm feature, 1128 to 1358 nm for the 1260 nm feature.

$$A_b = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{R_{c\lambda} - R_{s\lambda}}{R_{c\lambda}} d\lambda$$

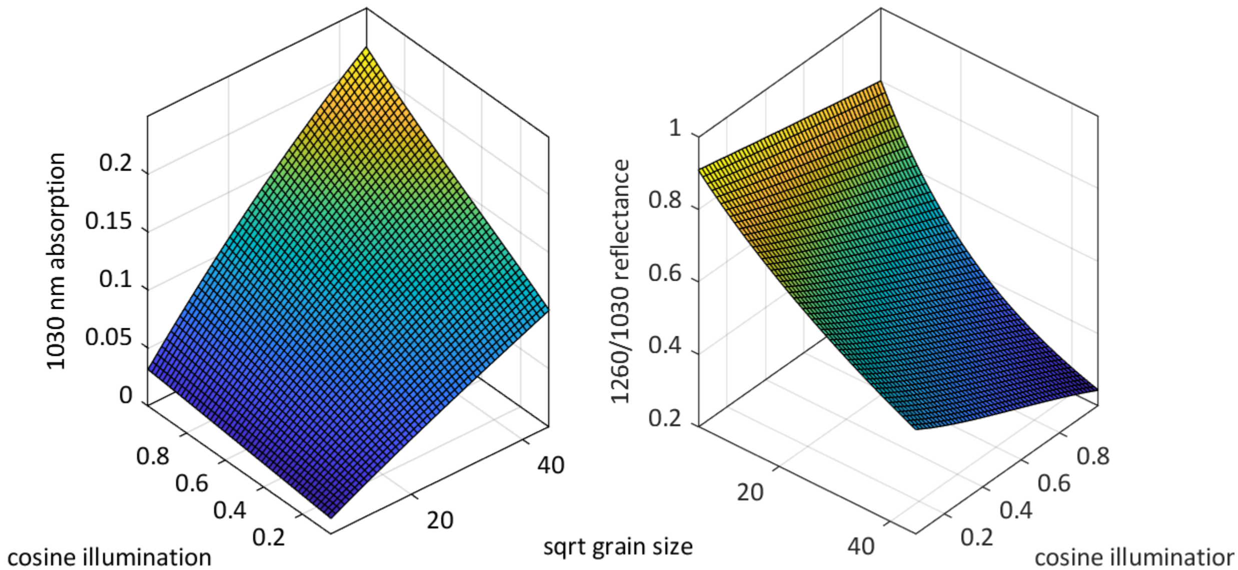

Figure 2. Scaled absorption features A_b for 1030 nm (left) and ratio of 1260 to 1030 nm reflectance (right), both as functions of grain size and cosine of illumination angle.

The advantage of analyzing the absorption feature in estimating grain size, the snow property that affects the clean-snow reflectance, over methods that use the magnitude of the snow reflectance itself lies in its resilience to uncertainties in sensor calibration and atmospheric correction (Nolin & Dozier, 2000). Residual sensitivity to the illumination angle remains, so retrieval of the grain size depends on an estimate of it (Figure 2).

In snow-covered locations of low relief, the local illumination angle is known. In the mountains, however, imprecision in the available digital elevation data introduces uncertainty in calculation of the local illumination angles on slopes. Figure 3 shows the interaction between grain size and illumination angle, with two nearly identical spectra from different combinations.

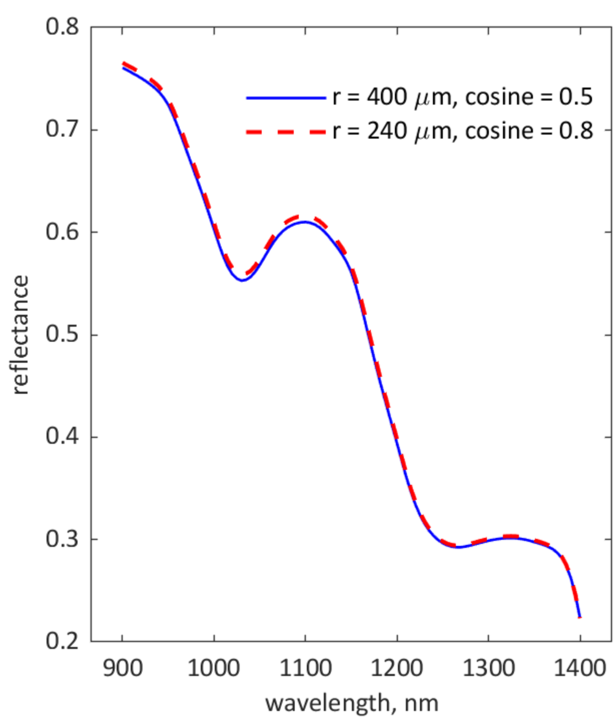

Figure 3. Nearly identical spectral reflectance of snow with different grain sizes at different illumination angles.

Light-absorbing particles

Understanding the effect of light-absorbing particles constitutes an important research area in cryospheric science, and assessing that effect requires an estimate of the grain size. In that context, "radiative forcing" is defined as the comparison between the solar radiation absorbed by a snowpack versus the radiation that would be absorbed if the snow were clean, based on its grain size (Skiles & Painter, 2019). The absorption largely occurs at wavelengths below 800 nm, where ice is transparent and reflectance of clean snow is only very slightly sensitive to grain size. However, larger grains enhance the effect of dust or carbonaceous aerosols in the snow (Warren, 2019).

Retrieving grain size from spectra

From a measured spectrum, A_b at 1030 and 1260 nm are estimated by numerically integrating the equation on page 1, with $R_{c\lambda}$ characterized in the data by a straight line from $[\lambda_1, R(\lambda_1)]$ to $[\lambda_2, R(\lambda_2)]$ and $R_{s\lambda}$ the actual spectrum under the straight line. If the integral A_b is not positive, then the pixel is unlikely to contain snow.

Otherwise, the grain size can be estimated if the pixel is fully snow-covered; dust and soot dot not affect the reflectance in the wavelengths where A_b values are calculated. If not, the other endmembers will affect reflectance in the wavelengths of the absorption features so the solution for grain size must be part of the solution for fractional snow cover. In the pure snow pixel, however, for the same wavelengths in the measured spectrum, pre-calculated values of the absorption features enable lookup interpolations of $\sqrt{r} = \mathrm{f}(A_b, \cos\vartheta)$ for each of the two absorption features, where ϑ is the local illumination angle. The square root is used in the interpolation instead of r itself because snow reflectance vs. $\sqrt{r}$ is closer to a linear relationship (Warren, 1982).

To build the lookup interpolation, $R_{s\lambda}$ and $R_{c\lambda}$ are calculated by the delta-Eddington approximation to the radiative transfer equation (Wiscombe & Warren, 1980). That model requires Mie scattering calculations, but the large snow grain sizes compared to the wavelengths allow use of the numerically efficient complex angular momentum approximation (Nussenzveig & Wiscombe, 1980).

Examples with AVIRIS-NG data

Figure 4 shows six example spectra measured by AVIRIS-NG over the Indian Himalaya in the Himachal Pradesh province during the February 2016 ISRO-NASA campaign. These spectra are from superpixels of the original data, which reduce measurement noise (Gilmore et al., 2011) and also provide illumination angle ϑ averaged over multiple pixels.

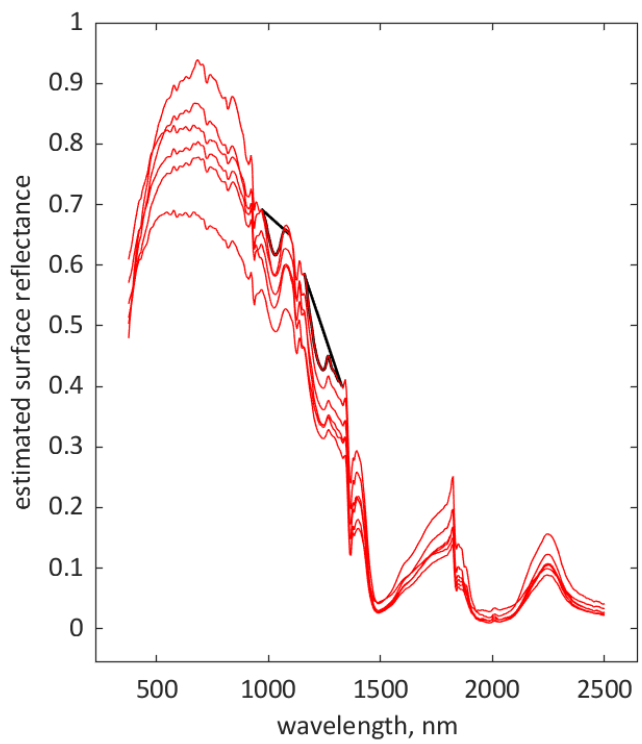

Figure 4. Example spectra from the Indian Himalaya, surface reflectance estimated from the top-of-atmosphere radiances by ATREM (Thompson et al., 2015). Absorption features A_b are shown for one spectrum for the 1030 nm and 1260 nm regions.

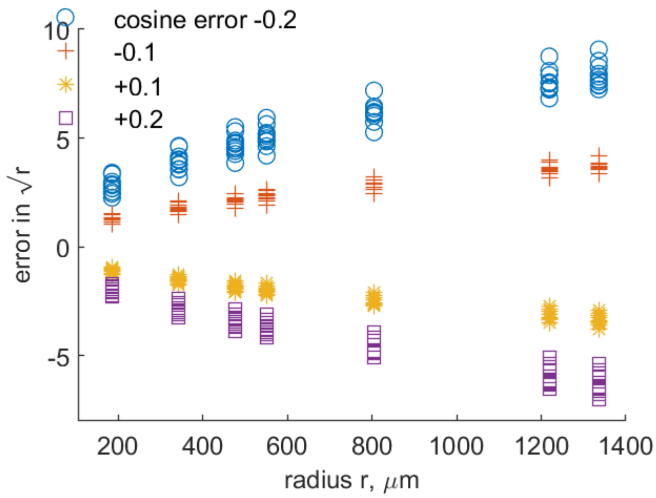

Figure 5. Errors in retrieval of radius r as functions of $\sqrt{r}$ and errors in estimating $\cos\vartheta$.

In simulations comparing retrievals to modeled input spectra, the retrieved grain sizes, the retrievals are identical from the 1030 nm and 1260 nm features. However, an error in specifying $\cos\vartheta$ causes a systematic error in the retrieved radii. An error in the negative direction causes retrieved grain sizes to be too large; an error in the positive direction causes them to be too small (Figure 5). The errors are only mildly sensitive to the value of $\cos\vartheta$ itself.

In the actual AVIRIS-NG data (Figure 4), the retrieved grain sizes from the 1260 nm absorption feature are smaller than from the 1030 nm feature (Table 1). Figure 4 shows that the change in reflectance *within* the feature, and in the associated continuum reflectance, makes the size of the feature more sensitive to noise in the signal or in the atmospheric correction. Note the slight spike in all spectra near the right edge of the 1260 nm absorption feature, which does not appear in the modeled snow reflectance (Figure 1). That spike, whose origin is unclear, reduces the size of the 1260 nm A_b value, thus causing the interpretation of a smaller grain size.

Table 1. Grain size retrievals from the spectra in Figure 1.

Superpixel ID	2081	462	1746	990	1585	1701
$\cos\vartheta$	0.6735	0.4060	0.5154	0.3708	0.7701	0.8356
From 1030 nm	68 μm	139	155	158	145	164
From 1260 nm	47 μm	85	90	95	63	94

What does "grain size" mean?

Because visually examining "grains" in snow leads to subjective estimates of their sizes, characterizing the snow by its specific surface area (the ratio of surface area to mass) provides an objective measurement. For scattering calculations, conversion to an "equivalent grain size" lies in picking a sphere or other volumetric shape that mimics the path length that incident radiation will travel through the grain. For spheres, the relationship between the radius and the specific surface area is:

$$r = \frac{3}{SSA \times \rho_{ice}}$$

SSA is specific surface area in $\mathrm{m^2 kg^{-1}}$, ρ_{ice} is density of ice (917 kg $\mathrm{m^{-3}}$), r is in meters.

Specific surface area can be objectively measured in laboratory samples by stereology (Dozier et al., 1987) or CH_4 absorption (Domine et al., 2006). In the field, measurements with a portable spectrometer can be used to derive grain size (Donahue et al., 2021).

Wet snow

An absorption for liquid water is centered around 980 nm, and Green et al. (2006) integrated across it and the 1030 nm ice feature to separate the absorption caused by water from that caused by ice. Water in snow also causes snow grains to cluster (Colbeck, 1979), so although liquid water directly affects snow reflectance around 980 nm, more importantly the clusters behave as larger grains, thereby causing snow reflectance to decline throughout the near-infrared and shortwave-infrared wavelengths. Analysis of the absorption around the ice-related features will retrieve the size of the grain clusters. O'Brien and Munis (1975) experimentally showed that when snow gets wet, the near-infrared reflectance declines, but when the snow refreezes, the reflectance does not return to its pre-wetted values, likely because the grain clusters remain as large frozen grains.

Code

MATLAB codes to create the interpolating lookup functions $\left[\sqrt{r} = \mathrm{f}(A_b, \cos\vartheta)\right]$ and to solve for grain size are available on github: https://github.com/DozierJeff/SnowGrainSize. The interpolating functions use a thin plated spline, but any interpolation that handles modest curvature will do.

The main functions that the user would call directly are:

- **generateLookupFunctions** builds the functions that retrieve grain size from wavelength, reflectance, and $\cos\vartheta$. These should be saved in the data file **thinPlate.mat** in the Functions folder.
- **grainSizeFromAbsorption** uses the lookup functions to estimate grain sizes from wavelength, reflectance, and $\cos\vartheta$. Multiple cosines can be entered to explore how uncertainty in estimating illumination angles affects grain size retrievals.
- **snowAbsorptionFeature** calculates A_b values from wavelength and reflectance data. **grainSizeFromAbsorption** calls this, but the user might occasionally want to call it directly.

The Examples folder includes tests to examine simulated and measured spectroscopic data. The Functions folder includes all other functions needed, along with the lookup functions in **thinPlate.mat** that **grainSizeFromAbsorption** needs and **LUT_Mie_ice.mat** that **lookupMie** uses in building the lookup functions.

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