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OPTICAL SIZING OF IRREGULAR SNOW GRAINS

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ABSTRACT. We discuss a possibility of snow grain size determination using spectral reflectance measurements in the near-infrared part of the electromagnetic spectrum. Errors related to often made assumption of the sphericity of grains are studied. Also we introduce a new method for the snow albedo and snow pollution monitoring using measurements in the visible part of the electromagnetic theory. Both exact and approximate methods of the radiative transfer are used for the solution of corresponding inverse problem. It is assumed that snow grains can be presented as randomly distributed irregular fractal particles. The developed techniques are applied to both ground and satellite data.

1. Introduction

Understanding global physical properties of snow and also trends in snow cover and pollution is of a great importance for a number of disciplines including climate studies, environmental physics and snow hydrology. In this contribution we address a question of subsurface snow grain size monitoring using optical measurements. It is known that the snow grain size determines the level of light absorbance by snow and this parameter is needed to asses the heat balance in snow, and also timing and magnitude of snowmelt. In some cases the model of spherical grains is utilized in respective snow grain size retrieval algorithms. The model of fractal snow grains is used in the algorithm developed by us in combination with the assumption of a semi-infinite snow layer. Such an assumption makes it possible to use the Ambartsumian nonlinear integral equation for the calculation of respective look-up-tables. The approximate results valid at low level of light absorption are also used for the parameterization of LUTs and simplification of the inverse problem solution. The paper is structured as follows. In the next section we introduce the method and its validation. The concluding section is aimed at presentation of results derived using optical measurements as performed from a satellite.

2. Theory and its validation

The snow is presented as a vertically homogenous semi-infinite turbid layer contaminated by various types of pollutants such as soot, dust, etc. The ground snow reflectance at the cosine of the solar zenith angle μ_0, the cosine of the observation zenith angle μ and the relative azimuthal angle φ is presented in the following form [1]:

$$R\left(\mu,\mu_0,\varphi\right)=R_0\left(\mu,\mu_0,\varphi\right)r^{f\left(\mu,\mu_0,\varphi\right)}, \tag{1}$$

where

$$r=\exp\left\{-4s/\sqrt{3}\right\},\ s=\sqrt{\frac{1-\omega_0}{1-g}}, f=\frac{u\left(\mu_0\right)u\left(\mu\right)}{R_0^{-1}\left(\mu,\mu_0,\varphi\right)},\ u\left(\mu\right)=\frac{3}{7}\left(1+2\mu\right). \tag{2}$$

The values of $R_0\left(\mu,\mu_0,\varphi\right)$ correspond to the case of a nonabsorbing snow layer and they are stored in respective LUTs generated by us. The calculations have been performed using the code prepared by Mishchenko et al. [2] for the model of fractal snow grains. The dense media effects are small in the optical range for snow and they are neglected. It is assumed that the asymmetry parameter g=0.75 and also it does not depend on the wavelength and the size of particles. Because values of $R_0\left(\mu,\mu_0,\varphi\right)$ depend just on the phase function, which is determined by the shape of particles and not on their size (outside of forward peak irrelevant to the problem at hand), we conclude that from measurements of $R\left(\mu,\mu_0,\varphi\right)$, the single scattering albedo can be directly derived for each wavelength. In particular, it follows from equations given above for the value of $\beta=1-\omega_0$:

$$\beta=\kappa\ln^2 r, \tag{3}$$

where $\kappa=3(1-g)/16, r=(R/R_0)^{1/f}$. This makes it possible to derive the single scattering albedo for each wavelength from spectral reflectance measurements and pre-calculated LUTs of $R_0\left(\mu,\mu_0,\varphi\right)$. The derived spectrum $\omega_0\left(\lambda\right)$ can be used for the estimation both spectral snow albedo and snow grain size. We found that the value of β can be parameterized in the following way for particles of various shapes in the geometrical optics domain:

$$\beta=\beta_\infty(1-\exp(-\ell/\ell_0)). \tag{4}$$

Here $\ell_0=\lambda/4\pi\chi$, λ is the wavelength, χ is the imaginary part of the refractive index of particle, ℓ is the particle absorption length (PAL) proportional to the value of the effective grain size a_{ef} defined as the ratio of the average volume of particles to their average surface area multiplied by 3 ($\ell=ca_{ef}$). The value of β_∞ corresponds to the limiting case $\ell/\ell_0\to\infty$. It can be calculated using the model of spherical particles in the geometrical optics domain [3]. We have studied the dependence of c on the shape of particles and found that $c=2.63$ for irregular snow grains presented as randomized Koch fractals [4]. The dependence of c on the size particles is negligible.

Therefore, we can determine PAL as:

$$\ell=\ell_0\ln(1-\varepsilon)^{-1}, \tag{5}$$

where $\varepsilon=\beta/\beta_\infty$ and β is related to the measured reflectance via Eq. (3). Taking into account that $a_{ef}=\ell/c$, one can also derive the effective radius under assumption of a particular shape of the snow grain. The algorithm described above and also the model of snow reflectance (see Eqs. (1), (2)) were verified using ground measurements of snow grain size and also snow reflectance. It was found that the snow spectral bidirectional distribution function is well described by the model proposed. There is strong correlation of the derived grain size with ground measurements. Therefore, we are confident in the developed method. The technique was also slightly modified to account for the snow blackening in the visible due to impurities. The modification was performed by means

Figure 1. Browse image.

of introduction of additional terms in the value of β(e.g., due to light absorption by soot). In the next section the application of the algorithm to the satellite data is described.

3. The application of the algorithm to the satellite data

The algorithm was applied to MERIS on board ENVISAT data obtained over a site in Greenland on June 21, 2004 (15:42 UTC). The MERIS browse image of the snow field under study is shown in Fig.1. MERIS is composed of five cameras disposed side by side, each equipped with a pushbroom spectrometer. These spectrometers use two-dimensional CCDs. One of the sides of the detector is oriented perpendicular to the trajectory of the satellite and simultaneously collects, through the front optics, observations for a line of points at the Earth's surface (or in the atmosphere). The spectrometers acquire data in a large number of spectral bands, but, for technical reasons, only 16 of them are actually transmitted to the ground segment (one of which is required for the low-level processing of the raw data). This instrument thus provides useful data in 15 spectral bands (412, 443, 490, 510, 560, 620, 665, 681.25, 708.75, 753.75, 760.625, 778.75, 865, 885, 900nm), which are actually programmable in position, width and gain.

As seen in Fig.1, clouds are also present in the region under study. They are screened out effectively by the cloud screening algorithm developed by us. Also the atmospheric correction of the image was performed for the standard Arctic atmosphere. The retrieved grain size is shown in Fig.2. The average effective grain size (EGS) is around 0.2mm for the whole scene and 0.15mm for the left part of the scene. Unfortunately, *in situ* data for a_{ef} at this location during the satellite measurements is not available to us. It is planned to perform a comprehensive validation of the technique both using ground and satellite measurements over regions with extended snow deposited on smooth surfaces such as sea and like ice. We also have plans to extend the method on the case of a mountainous terrain.

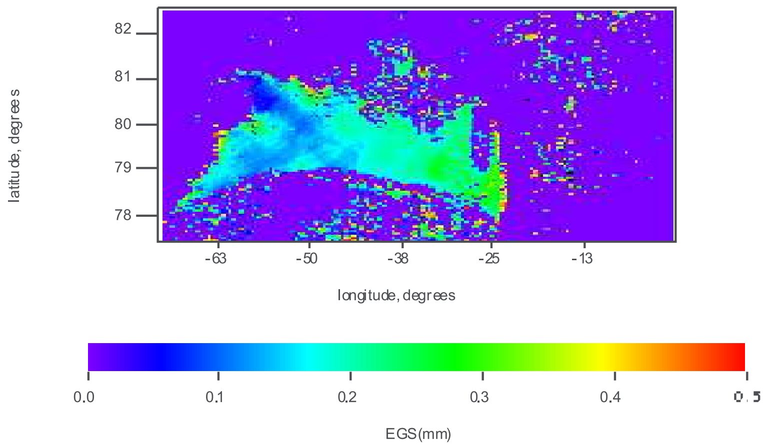

Figure 2. Retrieved effective grain size.

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