Snow Microstructure Characterization and Numerical Simulation of Maxwell’s Equation in 3D Applied to Snow Microwave Remote Sensing

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ABSTRACT

In this paper, we summarize our recent research on snow microstructure characterization, the dense media radiative transfer (DMRT) and the fully coherent scattering model based on numerical solution of Maxwell’s equation in 3D (NMM3D) for microwave remote sensing of terrestrial snow. We also report a new radar retrieval algorithm of snow water equivalent (SWE) based on absorption loss using X- and Ku-band backscatter. The study domain is focused on the Snow Cold Land Process experiment (SCLP) that was recommended in the previous decadal study. The SCLP consists of radar backscattering at X- and Ku band and radiometric brightness temperatures at Ku- and Ka band.

Keywords: Snow microstructure, dense media radiative transfer (DMRT), NMM3D, terrestrial snow, retrieval algorithm, snow water equivalent (SWE)

SNOW MICROSTRUCTURE CHARACTERIZATION AND BICONTINUOUS MEDIA

In snow microstructure, we use the densely packed spheres and the bicontinuous media, both of which can be characterized by correlation functions. We use the bicontinuous media model to generate computer snow. The correlation function of bicontinuous media has been derived. For densely discrete scatterers, in the past, we used the pair distribution functions of sticky spheres and multiple size spheres. Recently, we show that the correlation functions can be derived from the pair distribution functions. In Figure 1, we show the pair distribution functions and the corresponding correlation functions. Thus the correlation function can become the common basis of comparisons of bicontinuous media, densely packed spheres, and real snow. The derived correlation functions are distinctly different from the traditional exponential correlation functions. They are exponential near the origin but have tails for longer distances, Figure 2. Thus, two parameters are needed to characterize the correlation function which are the short distance correlation length and the tail.

Field measurements of snow microstructure typically provide a visual grain size, which is the maximum extent of the dominant snow grains. On the other hand, the emerging measurements of the specific surface area (SSA) is more sensitive to fine snow grains. The SSA can be converted to an equivalent optical grain size. Knowing the optical grain size and the visual grain size, we will approximate the correlation function of snow microstructure. Figure 3 shows the comparison between computer generated snow and real snow.

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PHYSICAL MODELS FOR MICROWAVE REMOTE SENSING OF TERRESTRIAL SNOW: DENSE MEDIA RADIATIVE TRANSFER (DMRT) AND NUMERICAL SOLUTION OF MAXWELL’S EQUATION IN 3D (NMM3D)

The bicontinuous media has been combined with dense media radiative transfer (DMRT) to provide look up tables of backscatter and brightness temperatures of snowpack under various conditions. In DMRT, Maxwell’s equation is solved within several cubic wavelengths of statistically homogeneous snow volume to compute the phase matrix. The phase matrix, accounting for the coherent near field and intermediate field interactions, is then substituted into the radiative transfer equation to propagate the intensity over the snow volume, accounting for the incoherent far field and volume/surface interactions. It is called a partial coherent approach in that the coherent component of the model consists of calculating the phase matrix by using Maxwell equation for several cubic wavelengths of snow. The incoherent part consists of using this phase matrix in the radiative transfer theory which is incoherent. The scattering model has been shown to be successful when tested over the Finland SnowScat data (2010~2011 data used in Figure).

A fully coherent snowpack scattering model is also developed to compute the backscattering coefficients and the brightness temperatures of a snowpack. The model is based on numerically solving the Maxwell’s equation in 3D (NMM3D) directly over the entire domain of snowpack. We use a half-space to represent the soil or sea ice under the snowpack, and use the bicontinuous media to represent the snow volume. The fully coherent approach predicts the complex scattering matrix from the snowpack, including both magnitude and phase. In passive remote sensing, this approach allows arbitrary temperature and layer profiles of the snowpack. In Figure 5, the backscatters of the fully coherent model are compared against the results of DMRT for various snowpack configurations. In Figure 6, we illustrate the co-polarization phase difference of an anisotropic snow layer extracted from full wave simulations.

RADAR SWE RETRIEVAL ALGORITHM BASED ON DMRT AND BICONTINUOUS MEDIA

In new radar retrieval algorithm (Xiong et al. 2014a), the dual channel co-polarization backscatters and their background scattering are used as input parameters to estimate the snow optical thickness and the scattering albedo, from which the SWE is then derived from the accumulative absorption loss of the snowpack. First, the background scattering is subtracted. Then, by applying the radiative transfer solution for volume scattering, relationships between first order volume backscattering and the optical thickness and the albedo of these two bands are built. The DMRT model with bicontinuous media is used in the forward scattering, with which multiple scattering solution for the snow volume scattering are simulated. Then linear regression between first order and multiple scattering solution are derived as the key equations for SWE retrieval. With the key equations, we search the optimal matching optical thickness and albedo for the dual band volume backscattering.

We have applied the new retrieval algorithm for radar remote sensing of snow at X band and Ku band. The radar algorithm has been applied to the Finland SnowScat/ SnowSAR data and validated, achieving a mean error of ~15 which is smaller than the 2cm RMSE requirement of SCLP. Figure illustrates the SWE retrieval performance using two channels of XVV and KuVV backscatter.
Figure 1. (Left) Correlation function of sticky spheres (Right) Pair distribution function of sticky spheres.

Figure 2. Correlation functions of the bicontinuous media, multi-size spheres, and the sticky spheres model compared against the exponential correlation function.

Figure 3. (Left) Computer generated snow. (Right) real snow.
Figure 4. (Left) Backscatter against SWE for vertical co-pol at 10.2GHz, 13.3GHz, and 16.7GHz. (Right) Brightness temperature against SWE at (a) 10.65GHz, (b) 18.7GHz and (c) 36.5GHz.

Figure 5. Bistatic scattering from 3D full wave simulation (100 realization, 40° incidence, 17.2 GHz) compared with DMRT over the same bicontinuous media.

Figure 6. The co-polarization phase differences computed from NMM3D simulation of anisotropic bicontinuous media: (Left) Density 0.2 gm/cc, Anisotropy 0.25; (Middle) Density 0.2 gm/cc, Incidence angle 40°; (Right) Anisotropy 0.25, Incidence angle 40°.
Figure 7: Validation of the SWE retrieval algorithm using ESA NoSReX campaign SnowScat data of 2010-2011 and SnowSAR data of 2011. (Left) Retrieved SWE against measurements with dry snow conditions using SnowScat data; (Right) Retrieved SWE against measurements using SnowSAR data.

REFERENCES:


