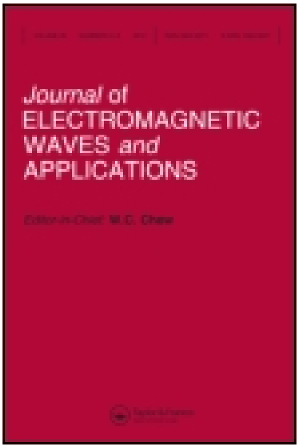

Journal of Electromagnetic Waves and Applications
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tewa20

Modeling of Millimeter Wave Backscatter of Time-Varying Snowcover — Summary

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Version of record first published: 03 Apr 2012.

Journal of Electromagnetic Waves and Applications, Vol. 11, 1289–1298, 1977

MODELING OF MILLIMETER WAVE BACKSCATTER OF TIME-VARYING SNOWCOVER — Summary *

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Abstract–The temporal variation of millimeter wave backscatter signature of snowcover is studied based on a dense medium radiative transfer (DMRT) theory and a one-dimensional mass and energy balance model of snow named SNTHERM. The multilayer DMRT scattering model of snowcover developed in this work takes into account the reflection and refraction at the snow-snow interfaces. Appropriate boundary conditions, quadrature points and weights are selected for using the discrete-ordinate eigenanalysis method to solve the multilayer DMRT equations. It shows that the inclusion of reflection and refraction at the snow-snow interfaces may affect the model prediction. Cohesive spherical particles are applied to account for the clustering feature of snow grains. To model the time-varying behavior of snowcover, SNTHERM is employed to simulate the aging process of snow. SNTHERM provides pertinent snow parameters, such as grain size, density, liquid water content, and stratification with a high resolution in time and depth. These snow properties are then used in modeling the temporal radar signatures of snowcover. The comparisons of temporal model responses with time series polarimetric backscatter data at 35 and 95 GHz are presented. Good agreement is demonstrated between model and measurements in both timing and magnitude. The results indicated that the coupled DMRT and SNTHERM model can be useful in studying the electromagnetic interactions with time-varying snow microstructure.

* The complete text appears in *Progress In Electromagnetics Research.*

1. INTRODUCTION

Seasonal snowcover is a major environmental factor over the earth surface. It imposes impacts on the radiation and energy budget between atmosphere and surface. For hydrologic applications, snow is also a major contributor to runoff in rivers and to ground water resource. On the ground, snow is generally inhomogeneous and stratified. Furthermore, the effects of snow metamorphosis typically cause the snow grain size, shape, density, and liquid water content to vary from one stratigraphic layer to another [1, 2]. The time-varying snowpack structure greatly complicates the analysis of electromagnetic wave interactions with snow-covered terrain. Stereological methods have analyzed the undisturbed snow microstructure based on images taken from plane sections of snow specimens [3]. The estimated snow parameters have been used in the study of microwave remote sensing of snow [4]. However, these ground truth measurements are usually laborious and thus very difficult to acquire as time series. Several experiences have been reported in the literature on the millimeter wave interaction with snowcover [5–7] and the diurnal variation of radar signatures of snow [8, 9]. Although these investigations indicate that the backscatter of snowcover is strongly influenced by the presence of liquid water, electromagnetic modeling of snow undergoing internal changes, due to metamorphism and phase change, still lacks a systematic study.

Snowcover models have been developed to predict the mechanical, thermal, and optical properties for various applications, such as remote sensing, climate modeling, avalanche forecasting, and hydrology [10]. SNTHERM, a one-dimensional mass and energy balance model of snow physics, was developed at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) for predicting temperature profiles within snow and frozen soil [11]. The model is formulated to consider a snowcover over soil with high vertical and time resolutions. The model solves a set of governing equations for the mass and energy balance of the snowpack, subject to meteorologicaly determined boundary conditions at the snow-air interface. In addition to temperature prediction, SNTHERM simulates various bulk physical processes of a snowcover, such as accumulation, densification, ablation, subsurface melt, and water flow. SNTHERM provides a physical insight into the snow metamorphosis process as well as the evolution of snowpack structure, including temperature, grain size, liquid water content, and stratigraphy, under varying environmental conditions. As we know, these snow parameters significantly affect the electromagnetic sensor response of snowcover; however, they are frequently difficult to obtain from field measurements. In this work we apply SNTHERM to simulate the dynamic variation of a snowcover with observed meteorological data. With the knowledge of these snow properties, the backscatter from snowpack can be derived by solving the dense medium radiative transfer (DMRT) equations which serve here as our electromagnetic scattering model of snow.

The DMRT equations were derived from wave theory under the quasi-crystalline approximation with coherent potential (QCA-CP) on the first moment of the field and the ladder approximation of correlated scatterers on the second moment of the field [12–14]. The DMRT theory has been applied to the remote sensing of snow terrain [15, 16]. However, in the previous DMRT models of snowcover, the ice particles are assumed to have no bonding with each other, and the effects of reflection and refraction between the strata of snow are not considered. In this paper, we apply a model of cohesive spherical particles [17] to account for the clustering feature of snow grains, and take into account the reflection and refraction at snow-snow interfaces by using appropriate boundary conditions, qudrature points and weights to solve the multilayer DMRT equations. In this study, we develop a dynamic scattering model of snowcover, with a more realistic snow microstructure, based on DMRT and SNTHERM. This coupled model is then applied to enable the simulation of temporal radar response of snowcover under changing environmental conditions.

2. MODELING OF SNOWCOVER

The snowcover considered here is modeled as a stack of horizontal layers assuming planar boundaries between air-snow, snow-snow, and snow-soil interfaces. The complexities of rough interfaces in the snow structure are ignored in this study. Figure 1 shows the layered geometry used. The uppermost medium ($z > 0$) is air with permittivity ϵ_0 , the layer of thickness d_N represents a stratified snow medium, and the lower half space ($z < -d_N$) is soil with a complex permittivity ϵ_g . Within the l -th snow layer, snow grains are modeled as random clusters of small primary spherical ice particles of radius a_l and with a complex permittivity ϵ_s which totally occupy a volume fraction f_{vl} . A stickiness parameter τ_l [17] is applied to parameterize the clustering behavior of snow grains. The clustered ice particles are randomly distributed within the background medium of complex permittivity ϵ_{bl} . For dry snow, the background is air with permittivity ϵ_0 . For the case of wet snow, the water inclusions are incorporated as part of the background medium whose dielectric constant is calculated using Polder-van Santen mixing formula.

The DMRT equations bear a similar form to the conventional radiative transfer equations. Thus the same discrete-ordinate method [12] can be ap-

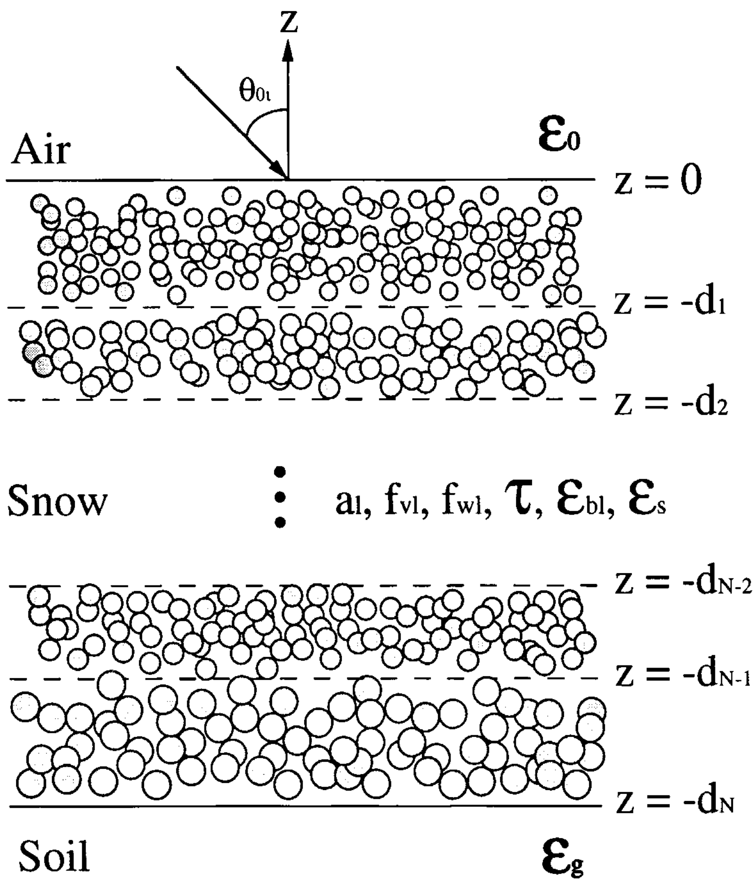

Figure 1. Configuration of an N-layer snowcover.

plied to solve the DMRT equations. We use a Gaussian quadrature weighted sum, and then transform the differential-integral equation into a system of coupled first-order differential equations, which is thus solved using the eigenanalysis technique. The reflection and refraction of radiation at the snow-snow interface are calculated according to the stratigraphy of snow, which shows the depth-dependent snow properties. Appropriate boundary conditions are chosen to ensure energy conservation at each interface. To take into account the refraction across the boundary, the qudarture rule of Tanaka and Nakajima [18] is applied to connect the radiation paths across the interface between two media.

SNTHERM is a mass and energy balance model of snow physics [11], where the snowcover is modeled as a one-dimensional (vertical coordinate z)

layered system consisting of dry air, ice, liquid water and water vapor. Each layer assumes a horizontally infinite control volume which is subjected to the governing equations for energy and mass balance [11]. To accommodate the compaction of snowcover, the control volume thickness is allowed to change over time. The mass of ice and water is assumed to be conserved under contraction of the control volume, whereas the displaced portion of air and water vapor are expelled. Governing sets of equations are linearized with respect to the unknown variables and solved by the tridiagonal matrix algorithm [11]. Boundary conditions at the air-snow interface are prescribed by meteorologicaly-determined fluxes of mass and energy. SNTHERM requires initial vertical profiles of temperature, water content, grain size, and density for the snowpack. These physical characteristics for the selected strata are usually supplied from real measurements. With the subsequent meteorological conditions (air temperature and humidity, wind speed, precipitation, solar and infrared radiation), SNTHERM provides various outputs including depth profiles of snow properties, surface energy flux, and water infiltration. Among them, the stratified structure of snow layers, grain size, bulk snow density and liquid density are the required parameters for DMRT scattering model.

3. COMPARISON OF MODEL AND MEASUREMENTS

A series of millimeter wave backscatter experiments on snowcover were conducted by the University of Massachusetts at Amherst [9]. Three radar systems operating at 35, 95, and 225 GHz were used in the experiment, where the 95 and 225 GHz radars are fully polarimetric, while the 35 GHz one was only capable of vv polarization observations. Besides the radar signatures, meteorological data and snow ground truth were also recorded.

We perform the backscatter simulations of snowcover at 35 and 95 GHz with the snow parameters, density, grain size, wetness, and layer thickness, as provided by SNTHERM or ground truth measurements. Typical values of ice permittivity $\epsilon_s = (3.2+i0.002)\epsilon_0$ and soil permittivity $\epsilon_g = (6.0+i0.6)\epsilon_0$ are assumed; however, the stickiness parameter is chosen to be $\tau = 0.2$, throughout the whole simulation.

Figure 2 presents the model and the measured backscatter of σ_{vv} at 35 GHz and 60° incident angle for the whole period of data collection. The snow parameters are supplied by the SNTHERM simulations. The observed strong diurnal variation of radar response is correlated with the liquid water content within the snowpack. The backscatter drops during daytime periods when liquid water content increases, while in cold nights, the backscatter rises back again because of the refreezing of the snow. Both

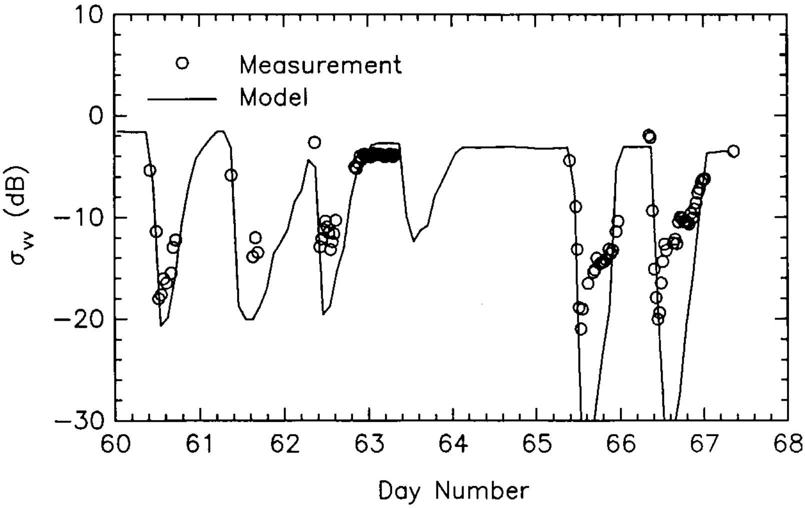

Figure 2. Temporal variations of backscatter in *vv* polarization at 35 GHz and 60° incident angle. Circles are measured data from Reference [9] and solid curve is DMRT simulation with snow parameters provided by SNTHERM model.

measured and model radar responses show a quick drop at the onset of melting as a result of the presence of liquid water during the warm daytime. Due to water infiltration, the liquid water has a nonuniform distribution in the snowpack. As refreezing occurs in the cold night, the good insulation property of snow slows down the refreezing process in deeper layers, thus causing a slow recovery of the backscatter.

4. SUMMARY

In this work we present a millimeter wave backscatter model of time-varying snowcover. This model is developed based on the multilayer DMRT theory with a one-dimensional snowpack physics model named SNTHERM. The electromagnetic sensor response of snowcover is calculated by solving the multilayer DMRT equations, where the cohesive spherical particles are used to model the metamorphosed snow grains, and the effects of reflection and refraction at the snow-snow interface are taken into account. The SNTHERM model is applied to study the influence of surface energy exchange under varying meteorological conditions on the snow metamorphosis process. It supplies important snow model parameters, and in this case was used to interpolate in time the snow property measurements made in the field and laboratory. We demonstrated that SNTHERM can provide the linkage between the snow metamorphosis and the electromagnetic properties of snowcovers. The resulting backscatter from coupled multilayer DMRT and SNTHERM model is compared with experimental data and good agreements are obtained. It indicates this coupled multilayer DMRT and SNTHERM model can be useful in predicting the multi-temporal radar response of snowcovers and in retrieving snow parameters for remote sensing applications.

ACKNOWLEDGMENT

The research in this paper was supported by the U.S. Army Cold Regions Research and Engineering Laboratory Contract No. DACA89-95-K-0014, the Office of Naval Research Contract No. N00014-92-J-4098, and US Army Project 4A762784AT42.

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