Brightness Temperatures of Snow Melting/Refreezing Cycles: Observations and Modeling Using a Multilayer Dense Medium Theory-Based Model

Marco Tedesco, *Member, IEEE*, Edward J. Kim, *Senior Member, IEEE*, Anthony W. England, *Fellow, IEEE*, Roger D. De Roo, *Member, IEEE*, and Janet P. Hardy

***Abstract*—The ability of electromagnetic models to accurately predict microwave emission of a snowpack is complicated by the need to account for, among other things, nonindependent scattering by closely packed snow grains, stratigraphic variations, and the occurrence of wet snow. A multilayer dense medium model can account for the first two effects. While microwave remote sensing is well known to be capable of binary wet/dry discrimination, the ability to model brightness as a function of wetness opens up the possibility of ultimately retrieving a percentage wetness value during such hydrologically significant melting conditions. In this paper, the first application of a multilayer dense medium radiative transfer theory (DMRT) model is proposed to simulate emission from both wet and dry snow during melting and refreezing cycles. Wet snow is modeled as a mixture of ice particles surrounded by a thin film of water embedded in an air background. Melting/refreezing cycles are studied by means of brightness temperatures at 6.7, 19, and 37 GHz recorded by the University of Michigan Truck-Mounted Radiometer System at the Local Scale Observation Site during the Cold Land Processes Experiment-1 in March 2003. Input parameters to the DMRT model are obtained from snow pit measurements carried out in conjunction with the microwave observations. The comparisons between simulated and measured brightness temperatures show that the electromagnetic model is able to reproduce the brightness temperatures with an average percentage error of 3% (∼8 K) and a maximum relative percentage error of around 8% (∼20 K).**

***Index Terms*—Cold Land Processes Experiment (CLPX), dense medium theory, microwave emission, microwave radiometry, remote sensing, snow, wet snow.**

I. Introduction

SNOW is a fundamental component of the Earth's water and energy cycles, acting as a major seasonal water reservoir as well as modulating the surface energy balance. Seasonal snow covers over 30% of the Earth's total land surface and more than half of the Northern Hemisphere land surface (∼60%) in midwinter [1]. At high latitudes and altitudes, where snowfall is the dominant type of precipitation [2], melting snow is responsible for the majority of the total annual streamflow. Microwaves are sensitive to snow properties (e.g., phase of water, mean grain size, fractional volume, and snow depth), and many studies have been conducted on the relationships between snow parameters and electromagnetic signatures (e.g., [3] and [4]) as well as for retrieving snow parameters from satellite remotely sensed data (e.g., [5]–[7]). While visible and near-infrared sensors cannot see through clouds, microwave measurements are largely insensitive to weather conditions and do not require solar illumination. The microwave signal can also provide information on the internal properties of the snowpack, such as snow water equivalent, while visible and infrared sensors cannot.

Melting and refreezing cycles of snow generally occur near the beginning and the end of the snow-covered season. In dry snow, which can be represented for microwave modeling purposes as ice particles embedded in an air background, the volumetric scattering due to ice particles attenuates the microwave emission signal coming from the soil. In the case of wet snow, the snowpack can be modeled as a mixture of ice, liquid water, and air. Here, volumetric scattering is reduced while absorption increases. As the liquid water content (LWC) increases, the brightness temperature increases until a threshold value for the LWC is reached, after which an increase in the LWC is not followed by an increase in the brightness temperature. When snow refreezes, brightness decreases as a consequence of the decrease of LWC and temperature.

Analysis of the relationships between snowpack characteristics undergoing melting and refreezing cycles and the corresponding microwave brightness signatures can provide insight into the physical processes involved and improve retrievals of snow properties from spaceborne radiometric data. We also note that these insights will be critical for future snow-related radiance-based assimilation schemes. In this study, we use a multilayer electromagnetic model based on dense medium radiative transfer theory (DMRT) under the quasi-crystalline approximation with coherent potential (QCA-CP) [8], [9] to simulate the brightness temperatures recorded by the University of Michigan Truck-Mounted Radiometer System (TMRS) [10] of snow melting/refreezing cycles. The use of a multilayer model is crucial to account for the vertical distribution of snow parameters, such as wetness and mean grain size. It has

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M. Tedesco is with the University of Maryland, Baltimore County, Goddard Earth Sciences and Technology Center, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: mtedesco@umbc.edu).

E. J. Kim is with the Laboratory of Hydrospheric and Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

A. W. England and R. D. De Roo are with the University of Michigan, Ann Arbor, MI 48109 USA.

J. P. Hardy is with the Cold Regions Research and Engineering Laboratory, Hanover, NH 03755-1290 USA.

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been demonstrated (e.g., [11]–[13]) that the use of a multilayer model improves the capabilities of the model to reproduce the observed brightness temperatures. Shih *et al.* [14] used a multilayer DMRT model to model the temporal signature of the millimeter-wave backscattering coefficient of snow undergoing melting and refreezing cycles with the support of the SNTHERM model, while Cagnati *et al.* [11] used an approach based on the combination of strong fluctuation theory and a hydrological model to simulate recorded brightness temperatures of melting/refreezing cycles in the Italian Alps. However, we found no examples in the literature of a multilayer DMRT model applied to the case of passive measurements (radiometry) of wet and dry snow conditions during melting/refreezing cycles. In this sense, the results reported in this study are based on a novel approach.

This paper is structured as follows. In Section II, the test site is described and the temperature profiles recorded by the meteorological station, and the snow pit data are presented and discussed. In Section III, the characteristics of the TMRS system are reported together with the temporal behavior of the recorded brightness temperatures. In Section IV, we describe the multilayer DMRT-based electromagnetic model. In Section V, we compare the modeled and observed brightness temperatures. We dedicate Section VI to the conclusions.

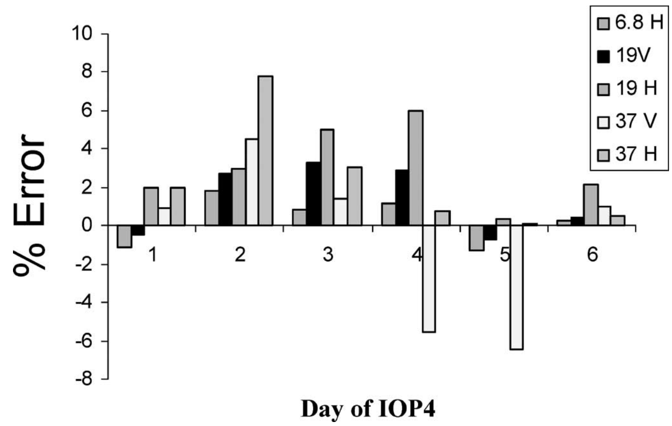

Fig. 11. Percentage error between measured and simulated brightness temperatures at 6.7 GHz (horizontal polarization) and at 19 and 37 GHz (vertical and horizontal polarizations).

VI. Conclusion

Microwave brightness temperatures of snow melting/refreezing cycles were recorded in Colorado at 6.7, 19, and 37 GHz by the University of Michigan Tower-mounted Radiometer System (TMRS) on March 2004 within the framework of the Cold Land Processes Experiment-1. Snow conditions and meteorological data were also collected. Collected data confirm that the 37-GHz channel is the most sensitive to melting and refreezing cycles. Sensitivity decreases as frequency decreases. The greater penetration depth at low frequencies is the main cause of the reduced sensitivity.

A novel approach based on a multilayer electromagnetic model using dense medium theory was used to simulate the observed brightness temperatures with the inputs derived from snow pit data and temperature profiles. In the model, wet snow was treated as a mixture of ice particles surrounded by a film of water embedded in a background of air. Three different classes of mean grain size were measured (Small, Medium and Large classes). As no information on the grain size distribution was available, different combinations of the values of the three classes were explored as inputs to the model (e.g., combination of Small, Medium, and Large, combination of Medium and Large, and only Large particles).

Simulated brightness temperatures were compared with those acquired by the TMRS. Results show that the model was able to reproduce measured brightness temperatures with good accuracy although the choice of particle size class used to derive inputs to the model strongly influences the model's performance. When all three classes of particle size were considered, the model overestimated the brightness temperatures (maximum percentage error $\sim$15%). This suggests that the derived mean particle size was too small. When only the Large particle sizes were used, the model strongly underestimated the brightness temperatures with a maximum percentage error of $\sim$28%. This suggests that the derived mean particle size was too large. The best match between modeled and measured brightness temperatures was achieved using values from the Medium and Large classes to derive the mean grain size as input to the model. In this case, the maximum percentage error equals 7.73% (19.8 K) for 37-GHz vertical polarization, and the average percentage error for all frequencies and dates is 3% ($\sim$8 K). However, with this choice, we observed that the model tended to underestimate the brightness temperatures. Disregarding the contribution of the Small class particles may be the cause of the observed underestimation. Collecting information on the distribution of the grain size (i.e., how many particles belonging to each of the three classes) would greatly improve our capabilities to resolve the differences between simulated and observed brightness temperatures.

The capabilities of the electromagnetic model to reproduce the observed brightness temperatures might also be improved by modifying the modeling of wetness itself. In our model, all ice particles are assumed to be surrounded by a thin film of water. This is not always true in nature, but our choice was dictated by the fact that the relationship between wetness and fractional volume of free water in snow is practically unknown. Experiments aimed at describing such relationship might provide useful information for future studies.