# Multi-layer model simulations of backscattering and emission from snow covered soils

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## Abstract

In this paper an overview of experimental and theoretical investigations concerning snow cover by using both active and passive microwave sensors will be presented. In particular, the effects of multi-layer structure of snowpack and its temporal evolution on backscattering and emission have been investigated by model simulations based on the Dense Medium Radiative Transfer (DMRT).

The implemented model has been validated using both X- band Cosmo SkyMed acquisitions and multi-frequency microwave radiometric data collected in the winters between 2007 and 2011 on a test area located in the Eastern part of the Italian Alps, and corresponding direct measurements of the main snow parameters.

The effect of snow parameters on microwave backscattering at X- band and emission at X-, Ku- and Ka-bands has been analyzed by comparing experimental data and model simulations performed with a multi-layer version of the DMRT-QCA model. The study has been focused on the effect of layering structure of snowpack typical of the Alpine regions.

It has been observed that the multi-layer model is generally able to account for the effects of complex stratigraphy, reproducing the measured backscattering and emission with a higher accuracy than the single layer one.

## 1. Introduction

Microwave sensors are sensitive to snow properties and are able to give information on snow depth (SD) and snow water equivalent (SWE) as demonstrated by the pioneering works of the teams of Univ. of Berne and Univ. of Kansas [1, 2]. The key frequency channels in detecting the presence of snow were found to be at Ku- and Ka- bands, and most algorithms to retrieve snow parameters by using passive sensors are based on the difference between the brightness temperature (Tb) at these bands (i.e. 19 and 37 GHz). These frequencies are not available from the present in orbit Synthetic Aperture Radars (SAR), which operate at C- or X- band where wave penetration is quite high in dry snow and very low in wet snow.

Recent investigations showed a noticeable sensitivity of X-band backscattering and SWE when SD is higher than 50-60 cm [3]. The case of emission from layered snow has been theoretically studied by Liang et al. [4]. In this paper, the effects of multilayer structure of snowpack on emission and backscattering have been investigated by using a physical model and experimental data collected on the Italian Alps.

The model simulates snowpack by means of a stratified medium composed by spherical ice scatterers embedded in air, overlying a rough homogeneous half-infinite medium. Volume scattering/emission from snow is computed by using a multi-layer version of the Dense Medium Radiative Transfer Theory in the Quasi Crystalline Approximation (DMRT-QCA) with sticky particles [5]. Soil contribution is simulated by using the AIEM for the co-polar components and the semi-empirical approach by Oh for the cross-polar terms.

Radiometric data were collected from C to Ka bands with ground based instruments in winter seasons from 2007 to 2009 on a site selected in NE Italy. More recently, X-band SAR images of a wide area surrounding the radiometer station were obtained from the Cosmo Skymed mission. Also snow profiles were obtained with conventional methods at convenient temporal and spatial sampling. In addition to the measured profiles, and in order to make this study as general as possible, a few "synthetic" snow profiles, representative of typical cases of dry snow cover in the Alps were realized. The parameters taken into consideration were: grain size, snow density and layer thickness.

These "synthetic" profiles, that summarize the main characteristics for each period of the season, were obtained by analyzing 26 real snow profiles obtained in winter 2010-2011, when the snow depth was frequently greater than 60 cm. The performed sensitivity analysis carried out considering all the major parameters that affect emission and backscattering confirmed the high sensitivity of the model to grain size and pointed out the contribution of the layering structure of snowpack in particular to the polarized emission.

## 2. Experimental data

IFAC ground based radiometric system at C-, X-, Ku-, and Ka-band, in V and H polarizations, was installed in a shelter on a test area on the Cherz Plateau. This site is located in the Dolomites mountains, inside the Cordevole watershed (a few $Km^2$ extension). In the area, snow is usually present from mid-November to mid-April, and the

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beginning of melting/refreezing usually occurs in March. Maximum snow depth on the area ranged between 100 and 130 cm, with a peak of 180 cm in the winter 2008-2009 that was characterized by exceptional snowfalls.

A long-term experiment was carried out from winters between 2007 and 2009. Continuous acquisitions 24 h/day were carried out through a window, sealed by a sheet of polystyrene, whose attenuating properties were known. The relative wide-antenna beams guaranteed data collection from a significant average portion of snow.

On the same area a series of Cosmo-SkyMed images at X-band in VV polarization have been collected during winter 2010-2011.

Direct measurements of the snow parameters (grain shape and size, number and thickness of snow layers, liquid water content, density, water equivalent, surface roughness and hardness) have been collected once a week by the Avalanche Center of Arabba.

Experimental investigations confirmed that radiometric measurements collected during the accumulation of dry snow, especially at Ku- and Ka- bands, are sensitive to the snow parameters, and in particular the snow water equivalent (SWE), showing a general decreasing trend of brightness temperature, although with some fluctuations at SWE values higher than 100mm. On the other hand, microwave indexes (i.e. Polarization Index: PI=(TbV-TbH)/ ½(TbH+TbV), and the Frequency Index: FI=(TbKuV-TbKaV)+(TbKuH-TbKaH)]/2) have different behaviors, which in case of polarization index is significantly influenced by the snow layering.

As we can see in diagrams of Figs.1, PI at different frequencies (X-, Ku-, and Ka-bands), represented as a function of SD, seems to be sensitive to snow presence and changes rapidly from bare to snow-covered soils. However, the characteristics of snow cover significantly affect this behavior, and PI shows an increase as snow depth (SD) increases, similar to that one of FI, for stratified snow (1a) and a decreasing trend for not stratified snow (1b).

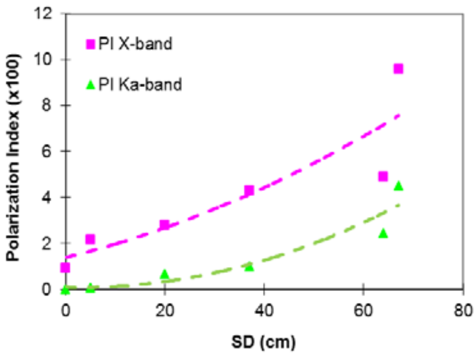


Fig. 1a – PI at X and Ka bands vs. SD for stratified snow cover

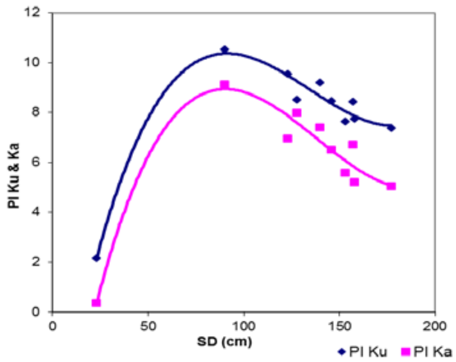


Fig. 1b – PI at Ku and Ka bands vs. SD for not stratified snow cover

The analysis of temporal backscattering (σ°) behavior at X-band is instead shown in Fig. 2 and compared with the trend of SWE. We can note that until SWE is lower than 150 mm the backscattering remains almost constant, whereas when SWE increases the backscattering increases as well. As soon as snow cover becomes wet, the two parameters are no more related to each other and, even if SWE continues to increases, the backscattering decreases sharply.

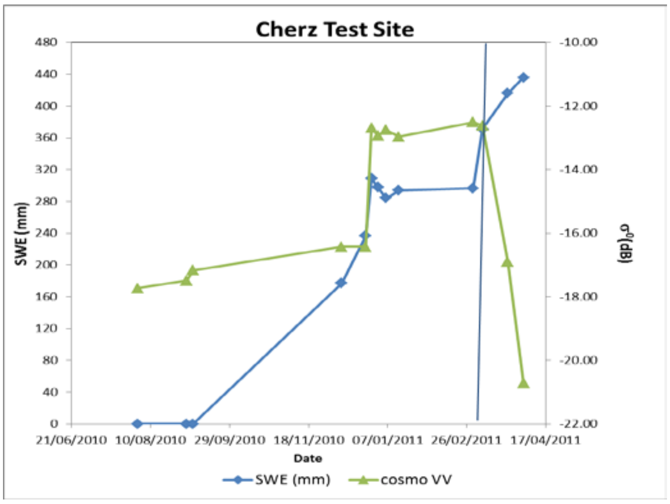


Fig. 2 – Temporal trends of SWE and σ° during winter season 2010-2011

## 3. Modeling

We know that snow is a complicated medium due to its layered structure: snow emission and scattering are affected by stratigraphy. Electromagnetic models represent an important tool for understanding the mechanisms that drive the microwave emission and for interpreting the experimental data.

In this case, we considered a multilayer implementation of the dense-medium radiative transfer theory (DMRT) that accounts for the effects of snow layers on the emission/scattering of dry snow. Model simulations have been compared with ground based radiometric measurements and satellite SAR acquisitions at X- band, collected on the Cherz plateau. This comparison has the twofold purpose of validating the model and interpreting some particular aspects of snow microwave emission.

The simulations have been carried out for each available set of snow parameters, disregarding the data collected at the beginning and at the end of each winter season. Soil contribution has been accounted for by using the AIEM model with a Gaussian 2D autocorrelation function and the dielectric constant of soil has been assumed equal to the one of frozen soil or the one of quite wet soil (SMC=20-25%) depending on the subsurface temperature values measured by the temperature probe. The equivalent grain radius for the model input has been scaled according to the relationship by Kontu and Pulliainen [6]. The snow stickiness has been set to a fixed value of 0.2.

An example of simulations and comparison with experimental data is shown in Fig. 3 for FI (a) and σ° (b) vs. SD. In the diagrams experimental data (points and regression lines) and model simulations for both single-layer (SL) and multi-layer (ML) simulations (only regression lines) are shown. As expected, SL is not able to simulate experimental data, whereas ML approximates rather well the real situation, although with some overestimations, especially for backscattering data and for low values of SD where the effect of soil is significant.

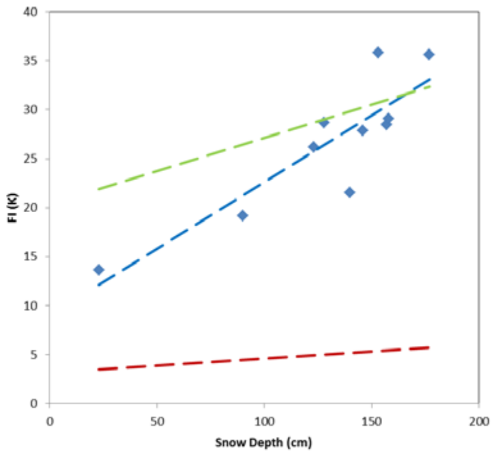


Fig. 3a – measured and simulated FI data vs. SD (rhombs: measured data, red line: SL model, green line: ML model)

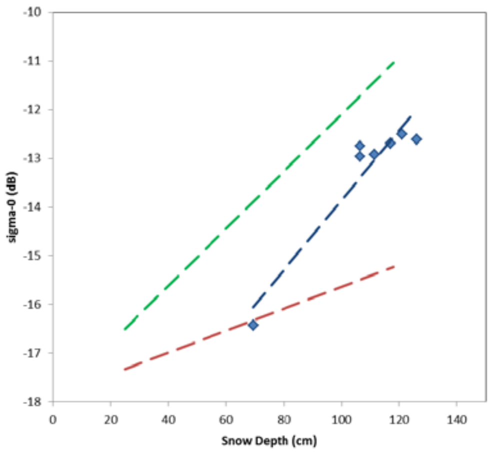


Fig. 3b - measured and simulated σ° data vs. SD (rhombs: measured data, red line: SL model, green line: ML model)

## 4. Summary

The effects of multi-layer structure of snowpack and its temporal evolution on both microwave emission and backscattering have been investigated by using a multilayer version of the Dense Medium Radiative Transfer model in the QCA approximation. The study has been focused on the effect of layering structure of snowpack typical of the Alpine regions.

The comparison between simulated and measured data (at Ku- and Ka-bands for radiometers, and X-band for SAR) showed a quite satisfactory agreement, considering the complicated snow layering and the difficulties in measuring accurately the various snow parameters.

As expected, the multilayer model is in general able to account for the effects of complex stratigraphy (up to 15 layers), reproducing the measured microwave emission and backscattering with a higher accuracy than the single layer one.

Model simulation confirmed the sensitivity of PI at Ku and Ka bands to the snow stratigraphy and of FI and σ° to the SD that can be successfully considered for the retrieval of the latter parameter.

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