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Total number of authors:
11

Published in:
Proceedings of 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS

Link to article, DOI:
10.1109/IGARSS47720.2021.9553580

Publication date:
2021

Document Version
Peer reviewed version

Citation (APA):
Sandells, M., Picard, G., Lowe, H., Maass, N., Winstrup, M., Brucker, L., Leduc-Leballeur, M., Larue, F., Aublanc, J., Thibaut, P., & Murfitt, J. (2021). Community Development of the Snow Microwave Radiative Transfer Model for Passive, Active and Altimetry Observations of the Cryosphere. In *Proceedings of 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 852-855). IEEE. https://doi.org/10.1109/IGARSS47720.2021.9553580

COMMUNITY DEVELOPMENT OF THE SNOW MICROWAVE RADIATIVE TRANSFER MODEL FOR PASSIVE, ACTIVE AND ALTIMETRY OBSERVATIONS OF THE CRYOSPHERE

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ABSTRACT

The Snow Microwave Radiative Transfer (SMRT) model was initially developed to explore the sensitivity of microwave scattering to snow microstructure for active and passive remote sensing applications. Here, we discuss the modular design of SMRT that has enabled its rapid extension by the community. SMRT can now represent a layered medium consisting of snow, land ice, lake ice and/or sea ice overlying a substrate of soil, water or parameterized by reflectivity. A time-dependent radiative transfer solution method has also been added to allow for low resolution mode altimetry applications. We illustrate the use of SMRT to simulate brightness temperature for snow on lake ice, backscatter for snow on soil and altimeter waveforms for snow on sea ice.

***Index Terms*—** SMRT, radiative transfer, altimetry, snow, ice

1. INTRODUCTION

Snow is a vital component of the cryosphere including as a water resource, as an insulating layer and due to its impact on the climate [1, 2]. There is a rich history of efforts to monitor snow with microwave remote sensing, including the development and use of snow emission models [3, 4, 5, 6]. One drawback of passive remote sensing of snow is the footprint size, which at tens of kilometers is too large for water resource management. Active microwave sensors are capable of much higher resolution observations, of the order of hundreds of metres [7] so there has been increased interest in the development of microwave backscatter models for snow [8, 9].

Microwave radiation, emitted by the snowpack or received from the radar, is scattered at air-ice boundaries of the snow crystals, which means that it is sensitive to the microstructure [10]. The method used to parameterise snow microstructure is the predominant difference between Dense Media Radiative Transfer electromagnetic theory and the Improved Born Approximation theory [11]. The Snow Microwave Radiative Transfer (SMRT) model [12] was developed to separate differences in the microstructure from differences in the electromagnetic model and any other model component, thereby allowing comparisons between different modelling assumptions.

Modularity has enabled SMRT to be adopted more widely. Building on the architecture used to construct a layered snowpack, the functionality to define sea ice layers was added. A range of salinity-dependent permittivity functions were incorporated for snow and ice. First year sea ice is modelled as brine scatterers within an ice background whereas multiyear sea ice is modelled as air bubbles in a saline ice background. For frozen lakes, fresh ice is represented by air bubbles within pure ice.

Retrievals of sea ice thickness from radar altimetry (e.g., at Ku and C bands) commonly assume reflection occurs at the snow-sea ice interface. The effects of snow on the signal were assumed to be limited to a delay to signal return due to refection. Yet scattering within snow rather than at the snow-ice interface could account for a 1.4m bias in multiyear sea ice thickness retrievals [13]. A time-dependent radiative transfer solution method has been implemented in SMRT to help

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Thanks to ESA for funding.

understand the impact of snow on altimeter waveform shape and develop more accurate sea ice thickness retrievals. SMRT modularity and extensions to [12] are described in the following section.

2. SMRT

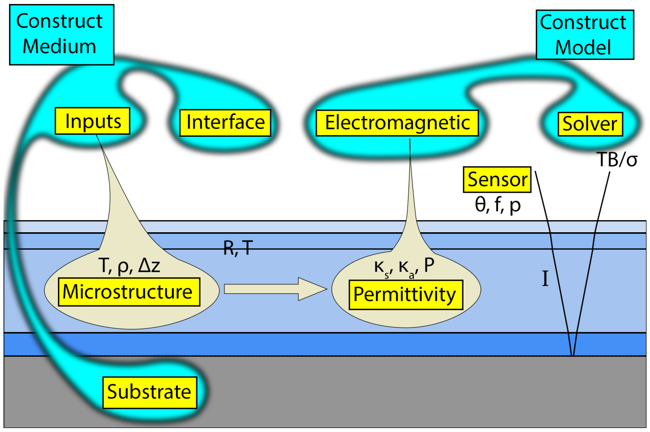


Fig. 1. Illustration of SMRT modularity. Module choices that can be made are shown in yellow. Stacking of the layers and interfaces to construct the medium are hidden from the user, as is the infrastructure to create the model.

SMRT separates the electromagnetic modelling into distinct components, as illustrated in Figure 1. Layer inputs are temperature T, thickness Δz and density ρ with microstructure parameters that depend on the chosen microstructure model. Interfaces between layers defining the reflectivity and transmissivity (R and T) can be represented by rough surface scattering models or by plain parallel interfaces. Using Fresnel coefficients is the default if unspecified. Different layer types are then stacked (e.g. snow layers on top of ice layers) and together with the interfaces and substrate form the column to be simulated.

Different sensor types can be defined given the incidence angles, frequencies and operating mode (active, passive, altimeter). Dual polarisation is simulated for passive. Both co- and cross-polarisation are simulated for active. The scattering model is constructed from the electromagnetic model and radiative transfer solver. Once the model is run, the electromagnetic properties for each layer (permittivity, Phase function P, scattering and absorption coefficients κ_s and κ_a) are calculated for the specified sensor frequencies.

Active and passive radiative transfer solution methods use a discrete ordinates approach. The radiation intensity I is calculated in multiple directions (64 is the default), with Snell's Law stream connection between layers. A time-dependent radiative transfer equation and radar equation based on [14] have been implemented for Low Resolution Mode (LRM) altimeter simulations. The altimeter mode in SMRT is currently limited to nadir observations over a horizontal or slightly tilted planar surface. SMRT outputs brightness temperature T_B for passive simulations, total backscatter σ_0 for active or time-dependent backscatter $\sigma(t)$ for LRM altimeter simulations. SMRT is written in python with an object oriented programming approach. It is freely available on GitHub at `https://github.com/smrt-model/smrt`.

The following sections demonstrate (i) a passive application for a snow on lake ice case, (ii) an active application for snow on soil and (iii) an altimeter application for snow on sea ice. The simple model setup is described and sensitivity results presented.

3. PASSIVE MODE

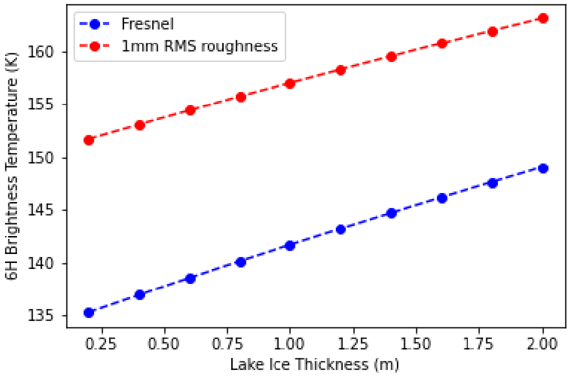


Fig. 2. SMRT sensitivity to lake ice thickness at 6 GHz in horizontal polarization.

SMRT was used to simulate brightness temperature at 6 GHz and incidence angle of 53^o for a layer of snow on a layer of lake ice. Snow parameters within the measurements of [15] were Δz=0.3m, snow sphere radius of 1mm and T=260 K. A sticky hard sphere microstructure model was assumed, with stickiness of 1.0. The sensitivity of brightness temperature to lake ice thickness was simulated, based on spherical air bubbles within the ice with 1mm radius, ice porosity of 1% and T=260 K. The sensitivity study distinguishes between a flat water substrate and a rough ice-water interface with reflectivity given by [16] (rms roughness = 1mm and water temperature of 273 K). Results in Figure 2 show a small increase in T_B with lake ice thickness. A rough interface between the lake ice and unfrozen water resulted in a 15 K increase in T_B. The rough substrate simulations compare well with airborne observations in Figure 6 of [15].

4. ACTIVE MODE

Microstructure parameters fitted to correlation functions from NoSREx III [17] micro-CT samples were used to construct 80 cm deep snowpacks, illustrated for the snowpack with Exponential microstructure in Figure 3. Whilst density varied with layer, the temperature of all layers was assumed to be 265 K. Reflectivity of the snow-soil interface was specified by soil backscatter from -5 to -20 dB. Figure 3 shows the total backscatter increases and influence of microstructure model decreases as the soil backscatter increases. For the microstructural parameters derived from this micro-CT profile the Sticky Hard Sphere Model shows the highest sensitivity. Exponential, Teubner Strey and Gaussian Random Field give similar results. This similarity can be explained from the micro-CT-derived (large) values for the second microstructural parameter for Teubner Strey and Gaussian Random Field in all but the near surface layer, under which the latter models tend to pure exponential functions.

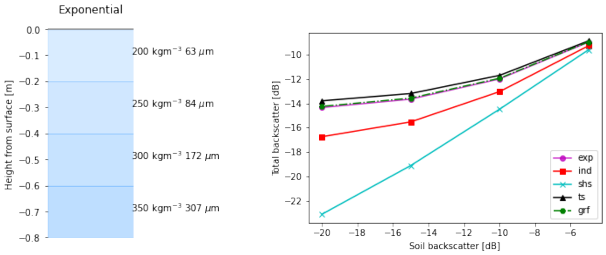
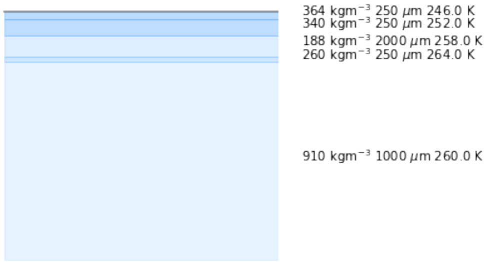


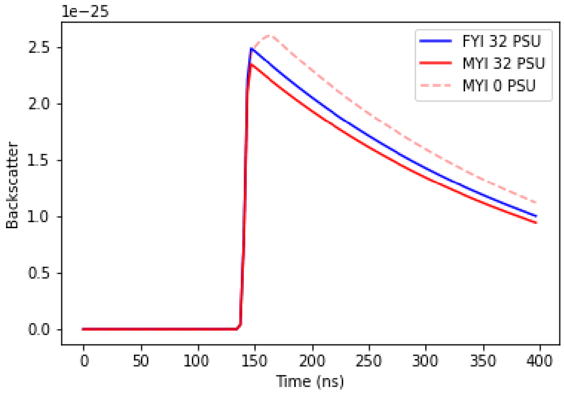
Fig. 3. Exponential microstructure snowpack stratigraphy and SMRT sensitivity 16.7 GHz VV backscatter sensitivity to soil backscatter and snow microstructure model (EXP: Exponential, IND: Independent Sphere, SHS: Sticky Hard Sphere, TS: Teubner Strey, GRF: Gaussian Random Field

5. ALTIMETER MODE

In-situ data from the CryoVex 2014 field campaign [18] were used to parameterize a four layer snowpack on top of a sea ice layer, with a water substrate underneath. Only subjective visual grain sizes were available, and the minimum grain extent was assumed to be representative of the sticky hard sphere radius. A stickiness value of 2.1 was used in the simulations. Mean ice thickness from transect drill measurements were used to define the ice layer thickness (1.52m for first year ice and 1.88m for multiyear ice). Ice density, spherical scatterer radius and salinity were assumed to be 910 kg m^{-3}, 1 mm and 32 PSU respectively for both first year and multiyear sea ice. First year sea ice is modelled as brine scatterers in a pure ice background, whereas multiyear ice is modelled as air bubble scatters in a saline ice background (three phase constituent modelling is not currently possible in SMRT). The difference in waveforms shown in Figure 4 between first year ice and multiyear ice (both with salinity of 32 PSU) mostly reflects this difference in modelling strategy. For multiyear ice, the simulated waveform has a smoother peak if the ice is considered pure.



(a) Snowpack and sea ice parameters



(b) Simulated altimeter waveform

Fig. 4. Difference between simulated Ku-band altimeter waveforms for first year (FYI) and multiyear (MYI) ice, and impact of multiyear ice salinity.

6. CONCLUDING REMARKS

Here, the extensive capabilities of SMRT have been demonstrated through its application to passive, active and altimeter simulations of snow, lake ice and sea ice. SMRT has already been evaluated against ground-based passive field observations [19] and other papers are currently in review. Results presented here are sensitivity studies and further work is needed to evaluate SMRT particularly for active and altimeter applications. Future field campaigns should match the required parameters needed for SMRT to enable greatest insight. SMRT can be used to define data collection priorities e.g. where interlayer roughness observations are needed, or where micro-CT is needed to determine microstructure parameters accurately. As a multi-application tool, SMRT offers the potential to interpret existing satellite observations and to help design new missions.

7. ACKNOWLEDGEMENTS

SMRT development was thanks to ESA funding under grant ESTEC:4000112698/14/NL/LvH.

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