THE IMPACT OF FIRN MODELS ON ULTRAWIDEBAND BRIGHTNESS TEMPERATURES IN THE PARTIALLY COHERENT MODEL

Haokui Xu[1], *Brooke Medley*[2],*Leung Tsang*[1], *Joel.T. Johnson*[3], *and Kennth.C.Jezek*[4]

1. Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA
2. Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
3. ElectroScience Laboratory, The Ohio State University, Columbus, OH 43210 USA
4. School of Earth Sciences, Byrd Polar Research Center, The Ohio State University, Columbus,OH,43210 USA

ABSTRACT

The density profile of a polar ice sheet is an important parameter for the estimation of ice mass balance. Wave reflections caused by density variations are also a key uncertainty in the retrieval of ice sheet temperature profiles in Ultra-Wide band radiometry. In this paper, we examine different firn density profile models and analyze the subsurface reflections they cause using an analytical partially coherent approach. We also examine firn density profiles obtained from borehole measurements, from past UWBRAD modeling studies, from a community firn model, and from snow radar echo measurements. In previous studies, the ice sheet has been model as a 1D random medium with density variations in depth. However, horizontal density variations also exist, so that the ice sheet is a 3D random medium. Analyses using the partially coherent model show that in the presence of horizontal fluctuations, contributions from short scale variations vanish as the horizontal correlation length decreases due to the diffraction of waves.

Index Terms— Polar ice sheet density models, subsurface reflecitons, Polar ice sheet, 3D random media,UWBRAD

1. INTRODUCTION

When snow accumulates on the surface of the ice sheet, it slowly densifies into the solid ice at depth. The transitional material in this process is referred to as firn. Active and passive microwave sensors inform us about the scattering and emission properties of firn over large scales [1] that are ultimately related to the physical properties of the material (e.g., grain size, density, temperature, roughness, phase, stratigraphy). Several studies have used active microwave remote sensing to track the internal stratigraphy of the firn column to infer spatiotemporal variations in snow accumulation rates [2]. This same stratigraphy, however, complicates interpretation of data from passive sensors, especially at lower frequencies (i.e., P and L band, <1–2 GHz) where penetration extends much deeper into the ice sheet. The Ultra-Wideband Software-Defined Microwave Radiometer (UWBRAD) use 12 channels between 0.5 -2GHz to retrieve the vertical temperature profile of polar ice sheets [3]. The brightness temperature measured is impacted by the temperature of the ice, but density fluctuations also modulate the emissions. Thus passive measurements have the potential to extract the properties of firn density in addition to providing information on temperature profiles.

To study the density profile of polar firn, the community firn model (CFM, [4]) can be applied to simulate firn properties. Snow radar data [5] can also be used to study near surface density changes. Other previous studies have modeled polar firn as a 1D random medium having variations only in depth. In this paper, a partially coherent model is used to study subsurface reflections in the firn using a 3D random medium description of polar firn. We show that in the presence of horizontal variations, short scale density fluctuations in the polar firn do not contribute to subsurface reflections.

This paper is organized as follows. In Section 2, we examine the density models and the snow radar data used for the study of ice sheet density profiles. In Section 3, we use the partially coherent model to study the effects of horizontal variations, and conclusions are provided in Section 4.

2. FIRN DENSITY MODELS

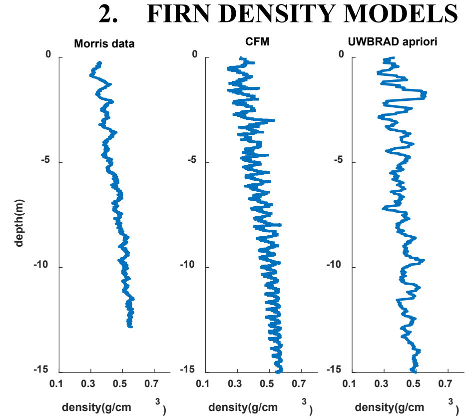

Figure 1 Density profiles from Morris borehole, CFM modelling and UWBRAD match up profile.

Figure 1 plots example firn density profiles from borehole measurements (left), from the CFM (middle), and from previous stochastic models (right). These density profiles are described as functions of depth only. The stochastic model description is obtained from [6] and includes "short" and "long" scale fluctuations having correlation lengths of ~ 2 and ~ 18 cm respectively and density variations of 1 and 0.06 g/cm^3 respectively.

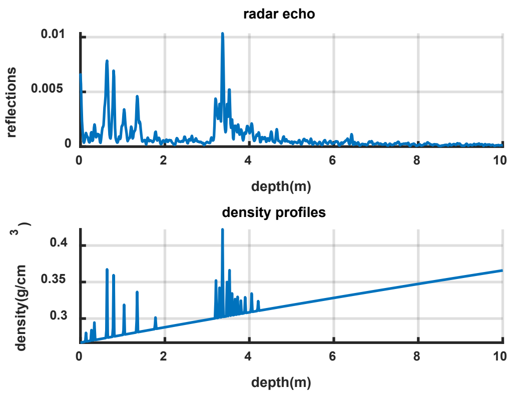

Figure 2 Snow radar echos and propsed profile for radar echos

Although the three descriptions show basic properties that are similar, their differences cause significant changes in modeled radar echo returns. Figure 2 illustrates measured (upper plot) snow radar echo returns over the NEEM borehole. The strong echoes obtained can be reproduced in a radar echo simulation model only by including discrete refrozen layers in the density profile (Figure 2 lower), which are not typically obtained in the existing firn density modeling approaches.

3. PARTIALLY COHERENT MODEL ANALYSIS

Radar reflections from the polar firn for nadir observations can be described using [7]:

$$ref_{vol} = \int_{-d}^{0} dz \exp(2(k_1'' + k_{1sz}'')z) \frac{1}{4} \int_0^{\frac{\pi}{2}} d\theta_s \sin\theta_s \left|X_{01i}\right|^2 \left\{ \left|\frac{k_{zs}}{k_{1zs}}\right|^2 \left|X_{10s}\right|^2 + \left|\frac{k_{zs}}{k}\right|^2 \left|Y_{10s}\right|^2 \right\} \frac{\delta k_1'^4}{2} \frac{l_z}{1+(k_1'+k_{1sz}')^2 l_z^2} l_\rho^2 \exp\left(-\frac{1}{4} k^2 l_\rho^2 \sin^2\theta_s\right) \quad (1)$$

Where X_{01} and X_{10} are the wave transmission coefficient for h pol for incident and scattering. Y_{10} is the transmission coefficient for scattering in v pol. δ is the variance of permittivity normalized by the mean permittivity. The last 2 terms are the spectrum density in z and horizontal directions respectively. The integration is over the thickness of the firn layer considered and the impact of angular spreading is included. Eqn (1) applies a random medium description of the firn medium that is extended in three dimensions through the inclusion of the angular integration. As an illustration of these differences, examples of 1D (i.e. permittivity fluctuates in depth only as assumed in past studies) and 3D (permittivity fluctuates both horizontally and vertically) random media are shown in Figure 3.

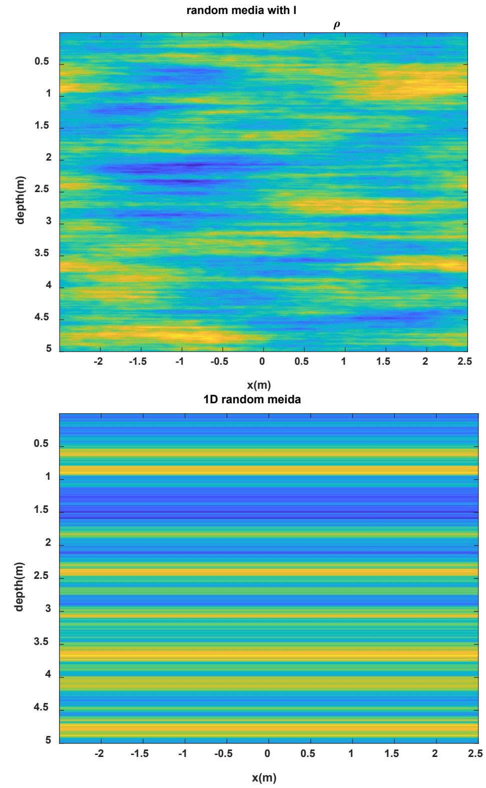

Figure 3 3D random media (up) and 1D random media (down). The short scale has $\delta = 0.01g/cm^3$ and the long scale has $\delta = 0.04g/cm^3$ The vertical correlation length is 2cm and 20cm. The horizontal correlation lengths are 10cm and 1m respectively

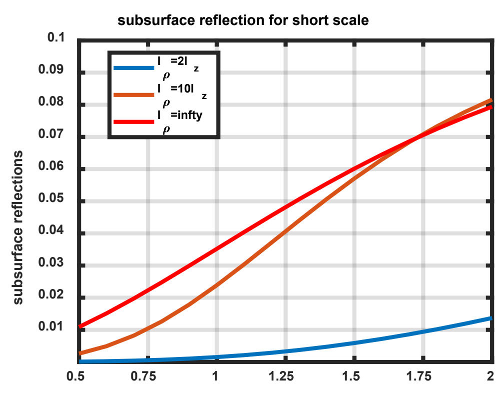

Figure 4 Subsurface reflections by short scale with different l_p/l_z with parameters Δρ=0.02g/cm^3, lz=1cm. The subsurface reflection decreases as the horizontal correlation length decreases.

Figure 4 plots quantity proportional to the total strength of reflections computed using the partially coherent model.The results show the impact of the horizontal correlation length on the reflections observed In particular, as the horizontal correlation length decreases, reflections decrease due to the diffraction of EM waves.

4. CONCLUSIONS

The results of this analysis confirm the importance of using realistic descriptions of firn density profiles when attempting to simulate the microwave sensor response to ice sheets. A profile consistent with snow radar echos was proposed by introducing discrete refrozen layers into the profile. A partially coherent model analysis extended to three dimensions also that firn reflections decrease due to diffraction as the horizontal correlation length is decreased.

5. REFERENCES

[1] Medley, B., Ligtenberg, S. R. M., Joughin, I., Van den Broeke, M. R., Gogineni, S., & Nowicki, S. (2015). Antarctic firn compaction rates from repeat-track airborne radar data: I. Methods. Annals of Glaciology, 56(70), 155-166.

[2] Medley, B., Joughin, I., Das, S. B., Steig, E. J., Conway, H., Gogineni, S., ... & Lenaerts, J. T. (2013). Airborne-radar and ice-core observations of annual snow accumulation over Thwaites Glacier, West Antarctica confirm the spatiotemporal variability of global and regional atmospheric models. Geophysical Research Letters, 40(14), 3649-3654.

[3] J. T. Johnson et al., “The Ultra-wideband Software-Defined Radiometer (UWBRAD) for ice sheet internal temperature sensing:Results from recent observations,” in Proc. IGARSS, Milan, Italy,Jul. 2015, pp. 7085–7087

[4] Stevens, C. M., Verjans, V., Lundin, J., Kahle, E. C., Horlings, A. N., Horlings, B. I., & Waddington, E. D. (2020). The Community Firn Model (CFM) v1. 0. Geoscientific Model Development Discussions, 1-37.

[5] Rodriguez-Morales, F., P. Gogineni, C. Leuschen, C. T. Allen,C. Lewis, A. Patel, L. Shi, W. Blake, B. Panzer, K. Byers, R. Crowe, L. Smith, and C. Gifford, Development of aMulti-Frequency Airborne Radar Instrumentation Package for Ice Sheet Mapping and Imaging, Proc. 2010 IEEE Int. Microwave Symp., Anaheim, CA, May 2010, pp. 157 – 160.

[6] S. Tan *et al.*, "A Partially Coherent Approach for Modeling Polar Ice Sheet 0.5–2-GHz Thermal Emission," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 10, pp. 8062-8072, Oct. 2021, doi: 10.1109/TGRS.2020.3039057

[6] Tsang, L., and Kong, J. A. (1976), Thermal microwave emission from half-space random media, Radio Sci., 11(7), 599– 609, doi:10.1029/RS011i007p00599.