MULTI-FREQUENCY PASSIVE REMOTE SENSING OF ICE SHEETS FROM L-BAND TO W-BAND

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ABSTRACT

Multi-frequency microwave radiometer measurements can reveal important subsurface characteristics of ice sheets such as internal temperature, density, grain size and ice thickness, which are critical to understand ice sheet dynamics. This study explores the sensitivity of electromagnetic radiation from ice sheets to these properties across the microwave spectrum, from L-band to W-band. The results indicate that (*i*) the maximum depth for which surface radiations provide information decreases from >2000 m in L-band to ~3 m in W-band, (*ii*) seasonal variations in internal temperatures are reflected mostly at frequencies in K_a-band and above, (*iii*) impact of the geothermal heat flux can be observed mainly in L- and S-bands, and (*iv*) changes in density and grain size properties affect the electromagnetic penetration depth, thus, may influence surface emissions across the entire microwave spectrum.

Index Terms— Ice Sheets, Microwave Radiometry, Remote Sensing

1. INTRODUCTION

Accurate measurements of certain properties of ice sheets such as thickness, internal physical temperature, density and grain size are critical to characterize ice dynamics, mass balance, and polar climate. Recent studies have demonstrated that some of these subsurface features can be profiled using wideband radiometers operating in L-, K- and K_a-bands by combining electromagnetic forward emission models with models of depth-dependent physical properties [1-2]. On the other hand, a complete analysis across the entire microwave spectrum from L-band to W-band to investigate specific frequencies sensitive to particular ice sheet characteristics is missing in the literature. This study, in the following sections, provides a simple microwave radiation model to describe surface emissions from, i.e., surface brightness temperatures of, ice sheets and discusses changes in them in different microwave frequency bands as specific features of ice sheets vary. The goal is to provide an insight for future designs of remote sensing missions that will target ice sheets by determining the optimum frequencies of operation to retrieve desired ice characteristics.

2. PHYSICAL AND THERMAL PROPERTIES OF ICE SHEETS

This study assumes ice sheets to be layered planar media where each layer is 1 cm thick and characterized by its uniform physical temperature, density and grain size. These properties can be modeled with variable parameters as explained in the following subsections:

2.1. Physical Temperature

Physical temperature of ice sheets as a function of depth, $T(z)$ (in K), can be estimated as the solution of a heat conduction equation. However, in-situ measurements at the Concordia Station in Antarctica [3] has been utilized in this study for the temperatures of ice layers close to the surface (top 21 meters), and the temperature of deep ice is assumed to increase linearly with depth as:

$$T(z \leq 21m) = \text{In-situ measurements at Concordia}$$
$$T(z > 21m) = T(z = 21\text{m}) + Q \times (z - 21m) \quad (1)$$

where the linear increase in deep ice temperature is governed by the variable Q (in K/m) related to the geothermal heat flux.

2.2. Density

Density of ice sheets versus depth, $\rho(z)$ (in kg/m^3), can be expressed as the sum of a smooth exponential increase with depth and a zero-mean damped Gaussian noise representing density fluctuations due to internal layerings as described in [4]. The exponential increase can be defined with the densification parameter H (in m^{-1}), and the damped Gaussian noise can be described by its standard deviation σ (in kg/m^3) and damping factor α (in m^{-1}) as follows:

$$\rho(z) = \rho_\infty - (\rho_\infty - \rho_0)e^{-zH} + N(0, \sigma)e^{-z\alpha} \quad (2)$$

where ρ_0 and ρ_∞ are the near surface and compacted deep ice density (in kg/m^3), respectively. These values are accepted to be 922 and 336 kg/m^3, respectively in this work.

2.3. Grain Size

Under the assumption of constant accumulation and negligible densification, the grain size of ice crystals (in µm) can be considered to increase with depth as follows [5]:

$$r(z)^2 = r_{surface}^2 + gz \quad (3)$$

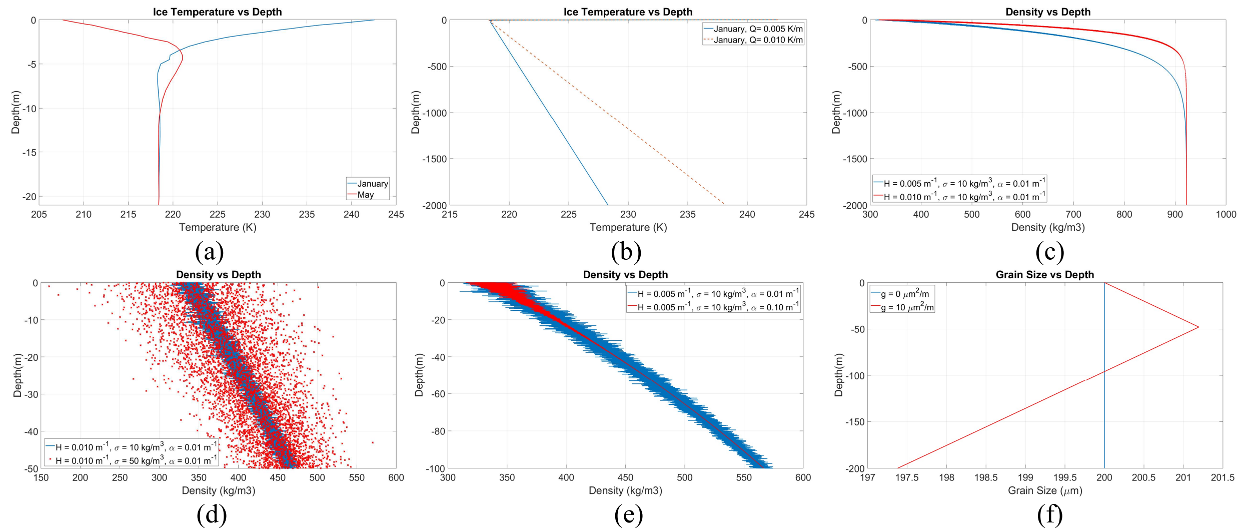


Figure 1: Simulation Inputs: (a) Average ice temperatures measured at Concordia station during January 2010 and May 2009, (b) ice temperature models for $Q = 0.005$ and 0.010 K/m for January 2010, ice density vs depth for (c) $H = 0.005$ and 0.01 m^{-1} when $\sigma = 10$ kg/m^3 and $\alpha = 0.01$ m^{-1}, (d) $\sigma = 10$ and 50 kg/m^3 when $H = 0.005$ m^{-1} and $\alpha = 0.01$ m^{-1}, (e) $\alpha = 0.01$ and 0.1 m^{-1} when $H = 0.005$ m^{-1} and $\sigma = 10$ kg/m^3, (f) grain size models for $g = 0$ and 10 μm^2/m.

where $r_{surface}$ (in μm) is the near surface grain size and the parameter g (in μm^2/m) is the grain size gradient. On the other hand, in deep ice, i.e. where the bulk density of ice layers are larger than the half of the compacted deep ice density, air bubbles in ice should be considered as scatterers; thus, the grain size is described by their radius which decreases with depth as:

$$r(z > z_{critical})^2 = r_{critical}^2 - g \times (z - z_{critical}) \qquad (4)$$

where $z_{critical}$ and $r_{critical}$ are the depth and grain size, respectively, where the bulk ice density exceeds the half of the compacted deep ice density, i.e., 461 kg/m^3.

3. RADIATION SIMULATIONS

Once the temperature, density and grain size of an ice layer is known, the electromagnetic extinction coefficient, κ_e, associated with that layer at a particular frequency can be computed as described in [6]. Consequently, nadir surface brightness temperatures, $T_B(z = 0, f)$, can be calculated as a function of frequency as follows:

$$T_B(z = 0, f) = \int_{z_{deep}}^{z=0} \left[\prod_{z'=z}^{z'=0} \Gamma(z')\right] \kappa_e(f, z) T(z) e^{-\int_{z'=z}^{z'=0} \kappa_e(z', f) dz'} dz \qquad (5)$$

where $\Gamma(z')$ and $T(z)$ are the amplitude squared of the Fresnel transmission coefficient at the ice layer interface at depth z' and the physical ice temperature at depth z, respectively.

For this study, surface brightness temperatures vs z_{deep}, i.e., cumulative brightness temperatures, are calculated at 1.5, 3, 6, 10, 15, 22.5, 33.5, 57.5 and 87.5 GHz representing L-, S-, C-, X-, K$_u$-, K-, K$_a$, V- and W-bands according to equation (5) using:

(*i*) four different temperature profiles generated using two in-situ near surface temperature measurements and two Q values in equation (1),

(*ii*) eight different density profiles generated using two H, two σ, and two α values in equation (2), and,

(*iii*) two different grain size profiles generated with two g values in equations (3) and (4), as shown in Figure 1.

4. RESULTS

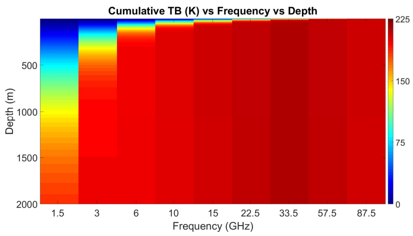
The sensitivity of surface brightness temperatures to changes in internal ice temperature, ice density and grain size has been evaluated at frequencies from L-band to W-band using the radiation simulations mentioned in section 3. Radiations calculated using January in-situ measurements, $Q = 0.005$ K/m, $H = 0.005$ m^{-1}, $\sigma = 10$ kg/m^3, $\alpha = 0.01$ m^{-1} and $g = 0$ μm^2/m (shown in Figure 2) are considered as reference, and changes in cumulative brightness temperatures are plotted versus depth and frequency as these parameters vary.

4.1. Emission Sensitivity to Ice Thickness

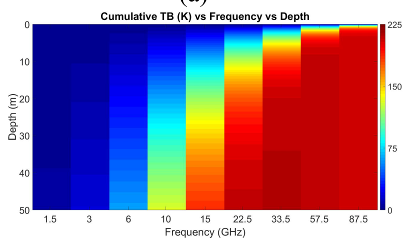
As seen from Figure 2, microwave emissions provide information regarding ice layers down to ~3 m in W-band, ~8 m in V-band, ~20 m in K$_a$-band, ~45 m in K-band, ~70 m in K$_u$-band, ~125 m in X-band, ~300 m in C-band, ~1500 m in S-band and >2000 m in L-band. Decreasing electromagnetic penetration depth with frequency results in lower sensitivity to deep ice layers in higher frequency bands.

4.2. Emission Sensitivity to Internal Temperatures

Figure 3 demonstrates that the seasonal temperature variations in shallow ice from January to May have a

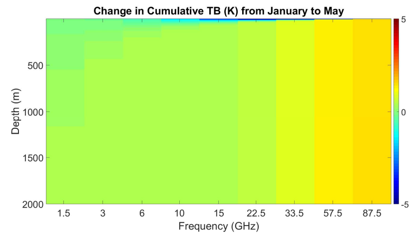


(a)



(b)

Figure 2: Cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m for reference parameters given in section 4.



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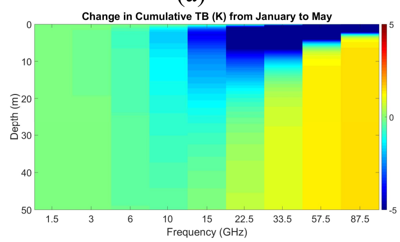
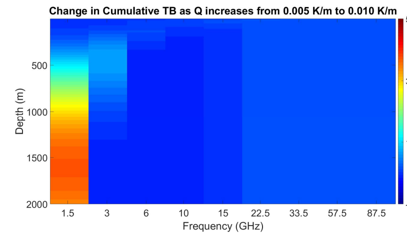


(b)

Figure 3: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m when Concordia ice temperature measurement during May 2009 are used instead of January 2010.



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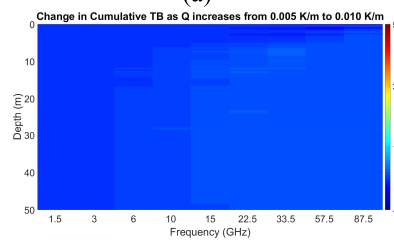
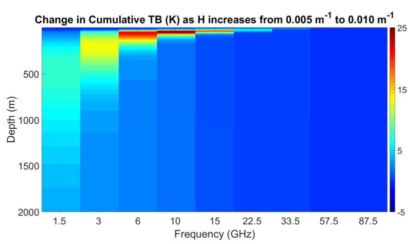


(b)

Figure 4: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m as Q is increased from 0.005 to 0.010 K/m.



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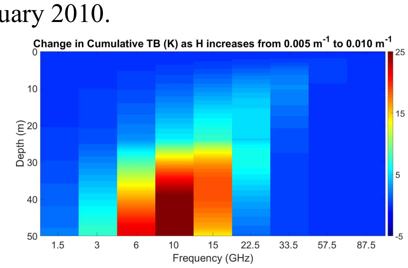


(b)

Figure 5: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m as H is increased from 0.005 to 0.010 m^{-1}.

considerable impact on the surface brightness temperatures mostly in K_a-band and above. In case of very thin ice (<20 m), however, frequencies as low as X-band may also be sensitive to seasonal effects. On the other hand, the influence of a change in geothermal heat flux from 0.005 to 0.01 K/m is visible only in L- and S-bands as depicted in Figure 4. These observations can be explained by the fact that only at low frequencies the electromagnetic penetration depth is large enough so that the warmer deep ice layers due to higher heat flux can influence surface emissions. Contrarily, the major contribution at higher frequencies comes from shallow ice where the seasonal temperature variations are dominant.

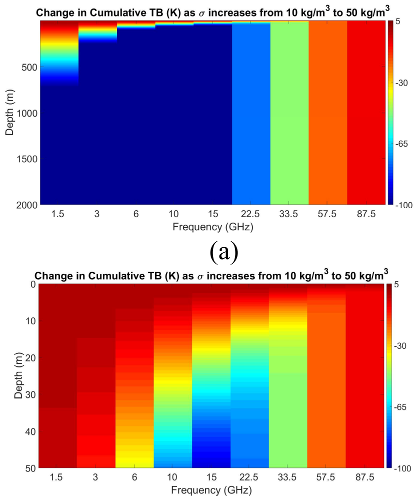
4.3. Emission Sensitivity to Density Characteristics

4.3.1. Densification Rate

Increasing the densification parameter H from 0.005 to 0.01 m^{-1} results in less dense ice, specifically down to 500 m depth as shown in Figure 1, layers of which have lower extinction coefficients. Lower extinction coefficients lead to reduced radiation from individual layers but increase the penetration depth as attenuation in each layer is also decreased. While the first leads to lower brightness temperatures, the latter causes higher emissions as the impact of deeper layers with higher temperatures grows. Figure 5 demonstrates these opposing effects on brightness temperature variations as H increases. Brightness temperatures decrease in general; however, significant increases can be seen as well in all frequency bands near their maximum depths of sensitivity mentioned in section 4.1 due to increased electromagnetic penetration.

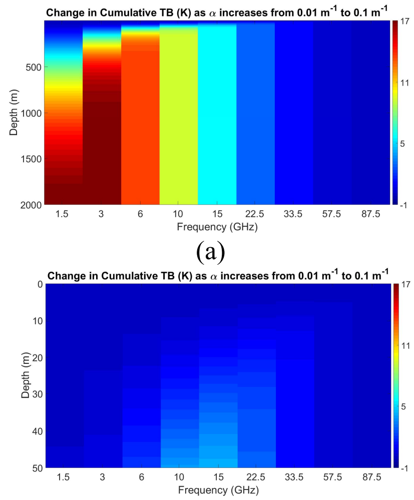
4.3.2. Density Fluctuations

Higher standard deviations in density fluctuations lead to larger internal reflections between ice layers, thus reduce the electromagnetic penetration depth. At low frequencies, such as L- to K_u-bands, where even deep layers contribute to the surface emission, this leads to a significant drop in the brightness temperatures as seen in Figure 6. At high frequencies and for thin ice, however, such contributions do not exist; thus, the surface emissions can even rise due to the



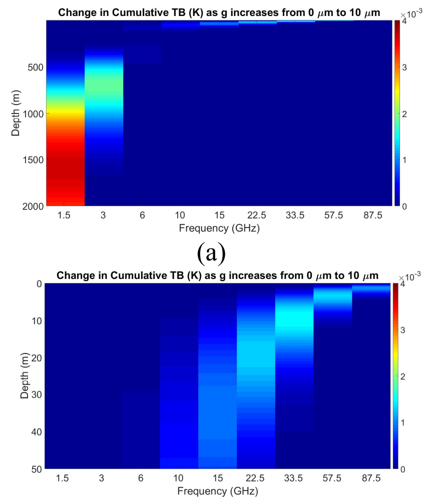
(a) (b)

Figure 6: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m as σ is increased from 10 to 50 kg/m^3.



(a) (b)

Figure 7: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m as α is increased from 0.01 to 0.10 m^{-1}.



(a) (b)

Figure 8: Changes in cumulative brightness temperatures versus depth down to (a) 2000 m and (b) 50 m as g is increased from 0 to 10 μm^2/m.

increased influence of the warmer near-surface layers. The impact of an increased damping factor in the density fluctuations, on the other hand, is opposite as illustrated in Figure 7 since the internal reflections disappear quickly with depth and electromagnetic penetration depth increases.

4.4. Emission Sensitivity to Grain Size

Based on the grain size model discussed in section 2.3, increased grain size gradient leads to larger ice crystals near surface, but smaller air bubbles in deep ice. Thus, scattering and extinction coefficients increase near surface and decrease in deep ice. It is observed in Figure 8 that, as g increases from 0 to 10 μm, these effects almost cancel each another and brightness temperatures do not change considerably.

5. CONCLUSIONS

This study demonstrates the frequency bands in which ice sheet surface brightness temperatures are sensitive to ice temperature, density and grain size. It is important to note that the models representing ice sheet properties used in this initial study may not reflect the actual ice conditions everywhere; thus, as future work, similar studies will be performed for specific areas using actual in-situ information for more accurate investigations.

6. ACKNOWLEDGMENT

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