3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Multi-Frequency Microwave Radiometry for Retrieving Antarctic Firn Subsurface Temperatures

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Abstract

This paper discusses the retrieval of Antarctic firn subsurface temperatures as a function of depth via multi-frequency microwave radiometer measurements focusing on the Concordia station. To demonstrate the feasibility of the retrieval, we investigated the correlation between the brightness temperatures measured by the GPM (Global precipitation Measurement) constellation radiometers at various frequencies and the subsurface temperatures of the Antarctic firn at various depths near the Concordia station.

1. Introduction

In a previous study, we demonstrated how the Global Precipitation Measurement Constellation (GPM) can be used as a multi-frequency (11 frequency channels at 6.9 GHz, 7.3 GHz, 10.65 GHz, 18.7 GHz, 19.35 GHz, 22.235 GHz, 23.8 GHz, 36.5 GHz, 37 GHz, 89 GHz, and 91.665 GHz) microwave radiometer system to characterize the Antarctic firn in terms of its physical and thermal properties using a simple microwave radiation model to calculate the firn surface brightness temperatures [1]. And the radiation model has been validated by matching satellite measurements to simulated brightness temperatures. This paper uses this model to highlight the correlations between GPM brightness temperature measurements at various frequencies and subsurface physical firn temperatures at various depths to reveal the potential of multi frequency microwave radiometer measurements to retrieve critical thermal properties of the Antarctic firn versus depth.

Intercalibrated brightness temperatures measured by AMSR2 and SSMIS radiometers in the GPM constellation and the 6.9 GHz and 7.3 GHz brightness temperature measurements of AMSR2 collected over a year between January 2020 (Month 1) and December 2020 (Month 12) were processed and averaged monthly over a 0.25°x0.25° degree latitude-longitude grid cell centered around the Concordia (75°05′59″S 123°19′56″E) station in Antarctica. Figure 1 depicts these brightness temperatures in horizontal polarization versus month at all above-mentioned AMSR2 and SSMIS frequencies (except 22.235 GHz since only vertically polarized brightness temperatures are available at this frequency).

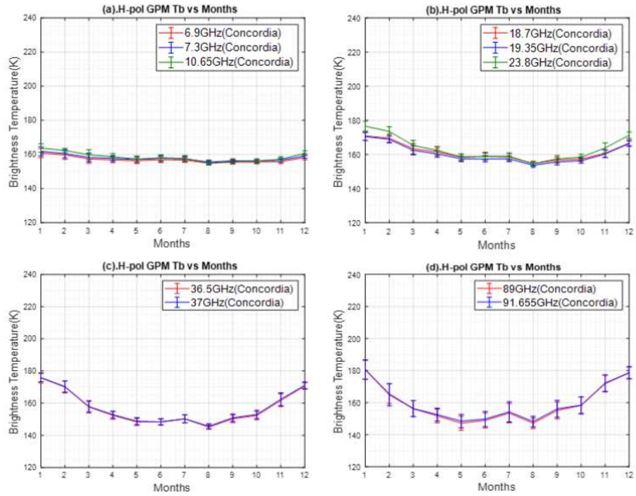


Figure 1: Horizontally polarized brightness temperatures over the Concordia station in Antarctica vs months at frequencies (a) 6.9, 7.3 and 10.65 GHz; (b) 18.7, 19.35 and 23.8 GHz; (c) 36.5 and 37 GHz; (d) 89 and 91.655 GHz.

2. Firn Temperature

Monthly averaged physical temperature profiles measured at the Concordia station in Antarctica between 2006 and 2010 up to a depth of 21 meters [2] as shown in Figure 2 were considered to be ground truth firn temperature data in this study. After 21 meters, the deep ice was considered to be isothermal with no temperature variations.

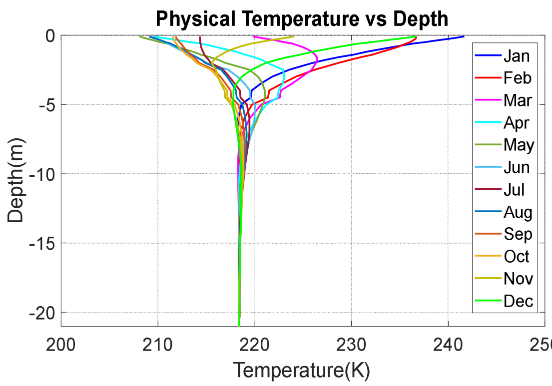


Figure 2. Monthly averaged in-situ temperature measurements versus depth at the Concordia station between 2006 and 2010[2].

3. Average Depths of Sensitivity

The microwave radiation model given in [1] to calculate the firn surface brightness temperatures, can be re-written as:

$$T_B(z=0, f, \theta_i, p) = \int_{z_{deep}}^{z=0} W(f,\theta,p,z) T(z) dz \quad (1)$$

where, $W(f,\theta,p,z)$ is the weight function as a function of depth for frequency f, incidence angle θ_i, and polarization p, and it includes the impacts of internal reflections and absorptions of the electromagnetic waves within the firn.

To calculate the contributions of Antarctic firn layers at different depths to the surface brightness at GPM frequencies, normalized weight functions were defined as:

$$W_n(f,\theta,p,z) = W(f,\theta,p,z) / \int_{z_{deep}}^{z=0} W(f,\theta,p,z) dz \quad (2)$$

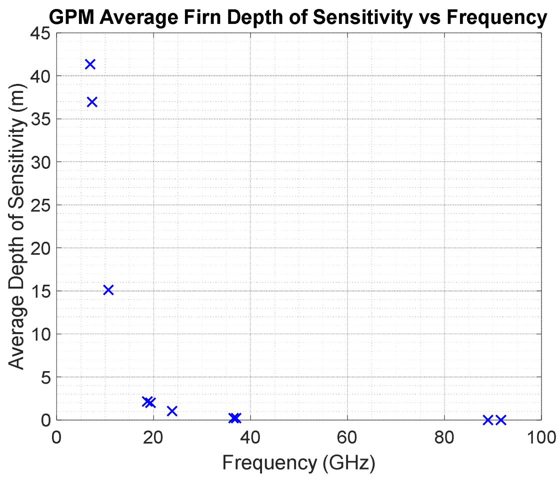
Finally, the depths where the firn layers above and below that point are both responsible for half of the surface emission were called the average depths of sensitivity, $z_{avg}(f,\theta,p)$, and calculated as:

$$0.5 = \int_{z_{deep}}^{z=z_{avg}(f,\theta,p)} W_n(f,\theta,p,z) dz \quad (3)$$

for each GPM frequency. Average depths of sensitivities for horizontally polarized GPM measurements and GPM incidence angles are shown in Figure 3.

Frequency (GHz)	6.9	7.3	10.65	18.7	19.35	23.8	36.5 – 37	89 – 91.65
z_{avg} (m)	~ 41.4	~ 37.0	~ 15.1	~ 2.1	~ 2.0	~ 1.0	~ 0.2	~ 0

(a)



(b)

Figure 3. Average firn depths of sensitivity at GPM frequencies and incidence angles. (a) Table illustrating depth of sensitivity values and (b) Plot of the average depths of sensitivity versus GPM frequencies.

Note the average depths of sensitivity decrease from tens of meters to a few centimeters as the frequency increases from 6.9 GHz to 91.65 GHz. This is expected as the electromagnetic penetration depth decreases in ice with increasing frequency [3].

4. Discussions

To investigate the correlations between the physical firn temperatures at the depths of sensitivity for GPM frequencies and the brightness temperatures measured by GPM, we first normalized both temperatures by subtracting their annual mean from the individual monthly averages. Figure 4 depicts these normalized temperatures. As mentioned in section 2, deep firn was considered to be isothermal. Therefore, for the depths of 41.4, 37 and 15 m, i.e., the depths of sensitivity for 6.9, 7.3 and 10.65 GHz, we observe a constant pattern throughout the year in both physical and brightness temperature measurements showing a high correlation. For frequencies higher than 10.65 GHz seasonal physical temperature variations in the shallow firn can be seen. Brightness temperatures, sensitive to the same portion of the firn, similarly vary with high correlation with the physical temperatures. For the highest frequencies, both physical temperatures near surface and the measured brightness temperatures vary significantly, about 35K, between summer and winter months as the deviation from annual means ranges from 25 to -10 K.

5. Conclusion

High correlation observed in this study between GPM brightness temperatures measurements at different frequencies and physical firn temperatures at the associated depths of sensitivity demonstrate the potential forretrieving Antarctic firn subsurface temperatures as a function of depth using the GPM constellation or any other multi-frequency microwave radiometer measurements.

6. Acknowledgements

This material is based on the work supported by the National Science Foundation under Grant no.1844793.

The AMSR2 and SSMIS data were obtained from the NASA Goddard Space Flight Center's Precipitation Processing System (PPS) [4] and the Globe Portal System (G-Portal) of JAXA [5].

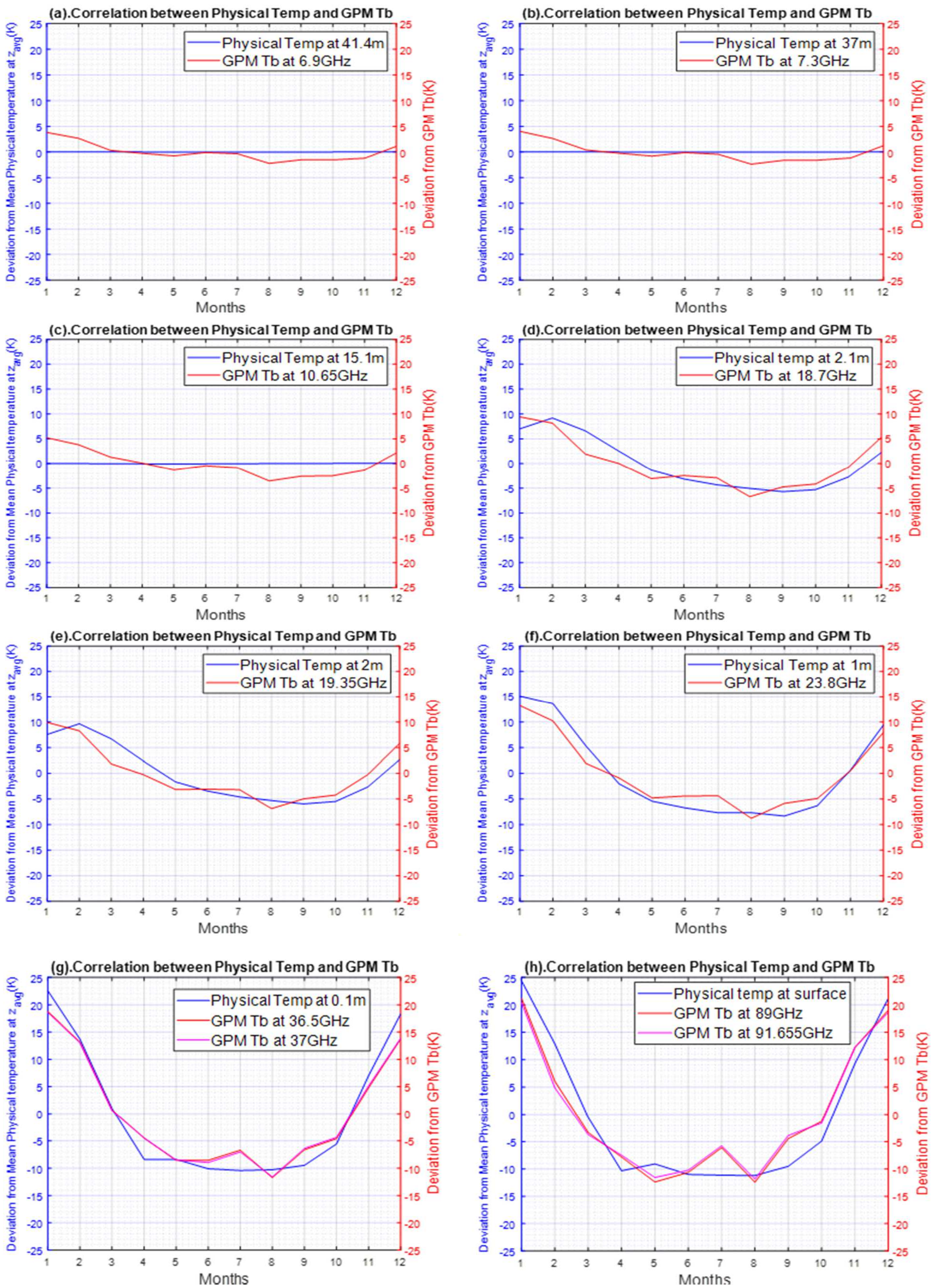


Figure 4. Correlation between GPM measured brightness temperatures at (a) 6.9 GHz, (b) 7.3 GHz, (c) 10.65 GHz, (d) 18.7 GHz, (e) 19.35 GHz, (f) 23.8 GHz, (g) 36.5-37 GHz and (h) 89-91.65 GHz and physical firn temperatures at the associated average depths of sensitivity at (a) 41.4 m, (b) 37 m, (c) 15.1 m, (d) 2.1 m, (e) 2 m, (f) 1 m, (g) 0.2 m and (h) firn surface.

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