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A review of recent developments in low-frequency ultra-wideband microwave radiometry for studies of the cryosphere

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Over the past decade, a series of airborne experiments in the Arctic and Antarctica explored microwave emission from sea ice and ice sheets at frequencies from 0.5 to 2 GHz. The experiments were motivated by the fact that lower frequencies penetrate deeper into a frozen surface, thus offering the possibility to measure physical temperatures at great depths in ice sheets and, subsequently, other unique geophysical observables including sea ice salinity. These experiments were made feasible by recent engineering advances in electronics, antenna design, and noise removal algorithms when operating outside of protected bands in the electromagnetic spectrum. These technical advances permit a new type of radiometer that not only operates at low frequency, but also obtains continuous spectral information over the band from 0.5 to 2 GHz. Spectral measurements facilitate an understanding of the physical processes controlling emission and also support the interpretation of results from single frequency instruments. This paper reviews the development of low-frequency, wide band radiometry and its application to cryosphere science over the past 10 years. The paper summarizes the engineering design of an airborne instrument and the associated algorithms to mitigate radio frequency interference. Theoretical models of emission built around the morphologic and electrical properties of cryospheric components are also described that identify the dominant physical processes contributing to emission spectra. New inversion techniques for geophysical parameter retrieval are summarized for both Arctic and Antarctic scenarios. Examples that illustrate how the measurements are used to inform on glaciological problems are presented. The paper concludes with a description of new

instrument concepts that are foreseen to extend the technology into operation from space.

KEYWORDS

ice sheets, sea ice, remote sensing, radiometry, microwave

1 Introduction

Earth's cold regions are integral to the global energy, water and bio-geochemical cycles. The continuing rapid retreat of Arctic sea ice, ice sheet mass loss and warming of permafrost in these regions contribute to changes in the atmosphere and ocean that in turn are affecting human activities at all latitudes. These global teleconnections between Earth's icy regions and lower latitudes remain incompletely understood limiting the predictability of climate variability and change.

The modern constellation of spaceborne remote sensing instruments monitor several of the cryospheric variables necessary to understand changes in polar sea ice extent and ice sheet dynamics, and to predict future changes. Radars for measuring the thickness of the ice sheets and the thickness of the snow cover on sea ice are routinely deployed on aircraft (Gogineni et al., 2004; Gogineni et al., 2007). Synthetic aperture radars operated as imagers and as interferometers reveal details about ice sheet morphology and surface velocity required for estimating changes in ice sheet mass balance (Rignot & Kanagaratnam, 2006). Spaceborne altimeters and gravimeters are yielding long time series of changes in ice sheet volume and mass (Zwally et al., 2021). Airborne and spaceborne microwave radiometers have further proved essential for developing long term records of cryospheric variables and for probing into the volume of the icy cover.

The radiometric emission from snow and ice in particular is a thermodynamically controlled process that is directly related to the snow and ice physical temperature and is modulated by the electrical properties of the ice. The strong differences in electrical properties between relatively saline sea ice and open ocean, for example, have long been exploited to study the extent, concentration and age of sea ice (Parkinson, 2019). Similarly, the microwave emission from the dry snow covering polar ice sheets or terrestrial land cover changes dramatically when small amounts of liquid water are dispersed amongst the ice grains (Hallikainen and Winebrenner, 1992). Free water changes the relative importance of scattering and increases absorption resulting in the observed brightness temperature of the slightly wet snow behaving almost as a black body. This sudden change in brightness temperature is a useful and important indicator of melt extent, duration and intensity on the polar ice sheets, and allows monitoring the onset of melt across the terrestrial seasonal snow cover.

Earth orbiting satellite observations of microwave emission began in the late 1960's with the Soviet launch of the radiometer

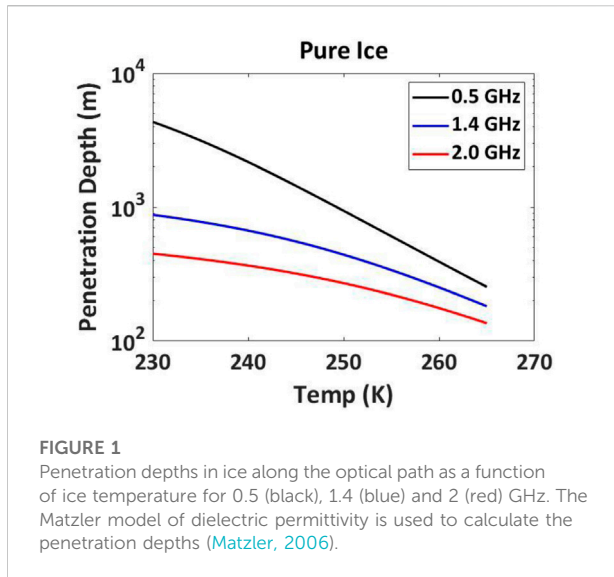
equipped Cosmos 243 satellite. Routine observations continued with the deployment of the NASA Electrically Scanning Microwave Radiometer (ESMR) on the Nimbus V satellite. The 19 GHz, horizontally polarized ESMR data were used to estimate sea ice concentration but were limited in the range of sea ice properties that could be addressed due to the use of a single frequency. Successor instruments including the multichannel Scanning Multifrequency Microwave Radiometer (SMMR) and the Special Sensor Microwave Imaging Radiometer (SSM/I) have successfully provided operational products by overcoming many of these challenges (Parkinson, 2019). SMMR, SSM/I and later the Advanced Multichannel Scanning Radiometer (AMSR) (Maeda et al., 2016) instruments along with the forthcoming Copernicus Imaging Microwave Radiometer (CIMR) incorporate several frequency and polarization channels but with frequencies spaced at intervals that significantly exceed the bandwidth of any individual channel. The multiple frequency channels used enable development of more sophisticated algorithms to infer better information about melt intensity on ice sheets, concentration of thin sea ice and sea ice age. Although the spatial resolution achieved in spaceborne microwave radiometer measurements is relatively coarse (10s of km), the wide swath (over 1,000 km), frequent repeat coverage, and relatively simple to use brightness temperatures result in products that are highly useful for hemispheric-scale studies of the Earth's cold regions. Table 1 lists the suite of spaceborne radiometers and their capabilities.

Most earlier radiometers operated at frequencies in the range 6.9 GHz–89 GHz. Scientific interest in mapping and monitoring sea surface salinity motivated the development of lower frequency 1.4 GHz (L-band) radiometers that are particularly sensitive to salinity-controlled emission from the ocean. NASA's Aquarius satellite (launched 2011) provided global observations of sea surface salinity necessary to understand the role of the ocean in the Earth's water cycle and oceanic circulation (Bindlish et al., 2014). The Soil Moisture Active Passive satellite (Entekhabi et al., 2010; launch 2015) and the Soil Moisture Ocean Salinity mission (Kerr et al., 2010, launch 2009) also deployed L-band radiometers that proved useful not only for terrestrial and open ocean studies but also for studies of the cryosphere. L-band brightness temperature data from SMOS are now used routinely to estimate thin sea ice thickness in the Arctic (Kaleschke et al., 2012). More recently, unique time-series signatures have been observed in SMAP data that are associated with the presence of subsurface aquifers in the permeable firn cover of the polar ice

TABLE 1 Instrument Parameters of spaceborne radiometers.

Instrument	Frequency (GHz)	Bandwidth	Polarization	Incidence angle	Footprint size	Operation
SMOS	1.41	19 MHz	H, V	0° to 55°	35–50 km	2009–Present
SMAP	1.41	22 MHz	Full	40°	40 km	2015–Present
Aquarius	1.41	25 MHz	H, V, 3 rd Stokes	28.7° 37.8° 45.6°	76x94 km 84x120 km 96x156 km	2011–2015
ESMR (Nimbus 5)	19.35	250 MHz	Single	0°	25 km	1972–1983
ESMR (Nimbus 6)	37	250 MHz	H, V	45°	20x45 km	1975–1983
SSMR	6.63 10.69 18 21 37	250 MHz (All channels)	H, V	50.2°	95x160 km 60x100 km 35x60 km 30x50 km 17x29 km	1978–1987
SSM/I	19.35 22.235 37 85	400 MHz 400 MHz 1,500 MHz 3,000 MHz	H, V (Only V for 22.235 GHz)	53.1°	45x68 km 40x60 km 24x36 km 11x16 km	1987–1997
SSMIS*	19.35 22.235 37 91.655	356 MHz 407 MHz 1,580 MHz 2,829 MHz	H, V (Only V for 22.235 GHz)	53.1°	42x70 km 42x70 km 27x44 km 13x14 km	2003–Present
AMSR*	6.925 10.65 18.7 23.8 36.5 89	350 MHz 100 MHz 200 MHz 400 MHz 1,000 MHz 3,000 MHz	H, V	55°	40x70 km 26x46 km 15x26 km 12x20 km 8x13 km 3x5 km	2002–2003
AMSR-E	6.925 10.65 18.7 23.8 36.5 89	350 MHz 100 MHz 200 MHz 400 MHz 1,000 MHz 3,000 MHz	H, V	55°	43x75 km 29x51 km 16x27 km 14x21 km 9x14 km 4x6 km	2002–2011
AMSR2	6.925 7.3 10.65 18.7 23.8 36.5 89	350 MHz 350 MHz 100 MHz 200 MHz 400 MHz 1,000 MHz 3,000 MHz	H, V	55°	35x62 km 35x62 km 24x42 km 14x22 km 11x19 km 7x12 km 3x5 km	2012–Present

Frequency channels between 50 and 63.3 GHz, and higher than 91.655 GHz, are omitted.



sheets (Miller et al., 2022). Table 1 lists the suite of spaceborne radiometers and their capabilities.

Encouraged by the successful application of L-band radiometers to cryospheric research, a series of airborne experiments over the past decade explored emission from the cryosphere at still lower frequencies from 0.5 to 2 GHz (Johnson et al., 2021). These experiments were motivated by the fact that lower frequencies penetrate deeper into a frozen surface, thus offering the possibility to measure physical temperatures at great depths in the ice sheets and, subsequently, other unique geophysical observables including sea ice salinity and distributions of free water beneath the ice sheets. These experiments were made feasible by recent engineering advances in electronics, antenna design, and noise removal algorithms when operating outside of protected bands in the electromagnetic spectrum (see Section 2). Those technical advances permit a new type of radiometer that not only operates at low frequency, but also obtains continuous spectral information from 0.5 to 2 GHz. Spectral measurements such as these facilitate an understanding of the physical processes controlling emission and also support the interpretation of results from single frequency instruments.

This paper discusses the development of low-frequency, wide band radiometry over the past 10 years. The paper reviews the engineering design of an airborne instrument and algorithms to mitigate radio frequency interference in Section 2. Theoretical models of emission built around the morphologic and electrical properties of cryospheric components are then described that identify the dominant physical processes contributing to the emission spectra (Section 3). New techniques for geophysical parameter retrieval for both Arctic and Antarctic scenarios are

summarized in Section 4 and applications of the measurements to glaciological problems are addressed in Section 5. The paper concludes with a discussion in Section 6 of new instrument concepts that are foreseen to extend the technology to space.

2 Development of UWBRAD

The initial impetus for low-frequency wide band measurements came about from concepts that rely on the deep penetration of low-frequency microwaves into glacial ice necessary to infer intraglacial temperature (Jezek et al., 2015). Intra-glacial temperature remains one of the most elusive of the various parameters required to understand and predict the behavior of the polar ice sheets. Temperature is an important factor that moderates ice rheology and hence the rate at which ice flows over the bed. Knowledge of the temperature thus influences mass continuity calculations of ice flux through a volume and the prediction of ice flow rates under changing climate conditions. By observing brightness temperatures (T_B) over a wide band of microwave frequencies, the variations in penetration depth over the band enable inversion of the measured T_B spectra into the physical temperature depth profile. Penetration depths derived using the Matzler (2006) model of ice permittivity for a typical range of temperatures are presented in Figure 1. The figure illustrates that emission arises from depths of kilometers or more in the ice sheet at low frequencies. The use of several frequencies that probe varying depths then enables estimates of temperature higher in the ice column.

2.1 UWBRAD radiometer design

Based on proof-of-concept calculations of low frequency radiative transfer through polar ice (Jezek et al., 2015), The Ohio State University developed the Ultra-Wide Band Software-Defined Microwave RADiometer (UWBRAD) (Johnson et al., 2021). This section discusses the design and the engineering challenges associated with 0.5–2 GHz measurements.

UWBRAD was designed to provide nadiral brightness temperature observations from 0.5 to 2 GHz using multiple frequency channels (Johnson et al., 2021). Because this frequency range is not a protected portion of the spectrum, UWBRAD must allow for brightness temperature measurements in the presence of other, man-made, radio frequency interference (RFI). The goal is achieved by sampling 0.5–2 GHz frequency range into 12 channels each of ~88-MHz bandwidth so that advanced RFI detection and mitigation methods can be applied in real time. The 88-MHz

TABLE 2 UWBRAD instrument Parameters.

Freq (GHz)	0.5–2, 12 x ~ 88 MHz (3 dB bandwidth) channels
Polarization	Single (Right-hand circular)
Observation angle	Nadir
Spatial Resolution	1.2 km x 1.2 km (for 1 km platform altitude)
Integration time	100 msec
Ant Gain (dB)/ Beamwidth	11 dB 60°
Calibration (Internal)	Reference load and Noise diode sources
Calibration (External)	Ocean Measurements
Noise equiv dT	1 K in 100 msec (each 88 MHz channel)
Interference	Full sampling of bandwidth in 16 bits resolution each channel; real time “software defined”
Management	RFI detection and mitigation

channel is contained within a measured 125-MHz bandwidth that is resolved into 512 subchannels, with ~360 of these subchannels comprising the 88-MHz channel. Brightness temperatures within each 88-MHz bandwidth channel are further resolved at a frequency resolution of 0.24 MHz, allowing both the detection and filtering of interference and use as a “hyperspectral” radiometer for specific applications. This process enables UWBRAD to identify open portions of the spectrum that can be used for radiometric observations even in the presence of other transmitting sources. UWBRAD instrument specifications are listed in Table 2 and can be contrasted with the frequency, bandwidth and polarization

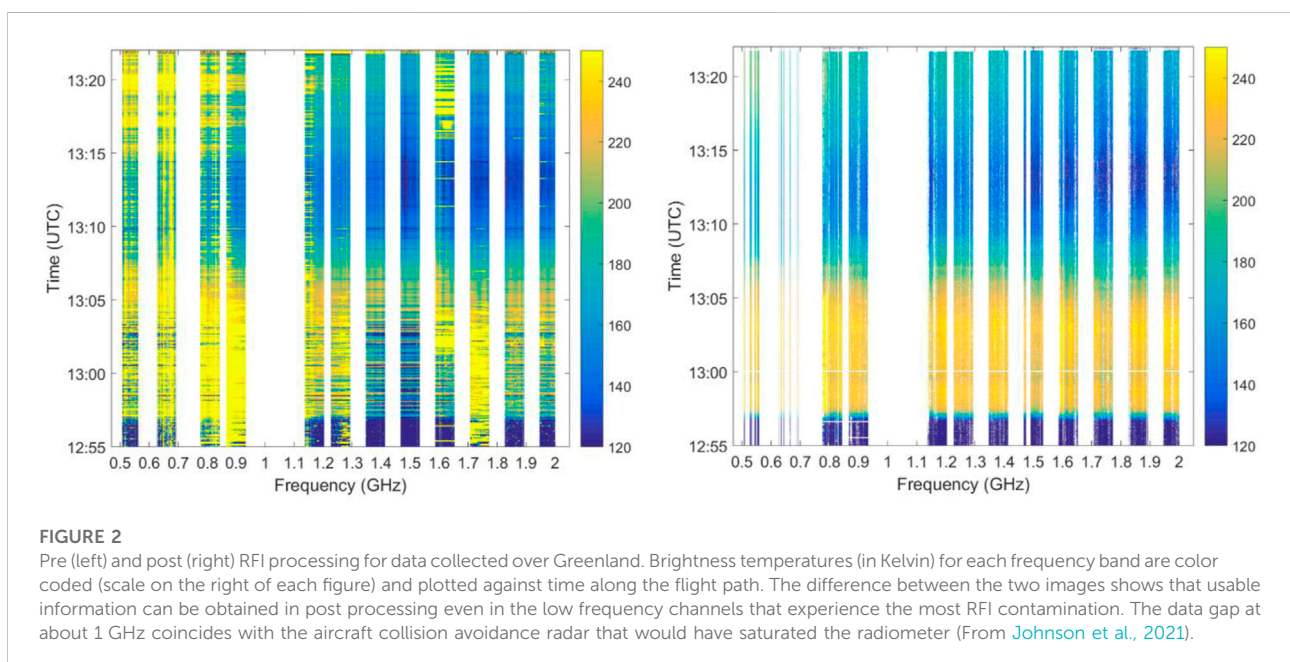
parameters of the spaceborne sensors listed in Table 1. The unique feature of UWBRAD compared to other sensor designs is the capability to obtain spectral data over the wide frequency range.

The UWBRAD antenna subsystem adopts a 2-arm conical log spiral design which provided a single circular-polarization port output for 0.5–2 GHz observations. The antenna was designed to provide a gain pattern that was approximately frequency independent, ensuring that all radiometer channels view the same scene and thereby reducing the impact of any spatial inhomogeneity on the brightness temperature *versus* frequency.

2.2 RFI removal and observations

Details on the RFI detection and removal algorithms are described in Andrews et al., 2018 and Andrews et al., 2021a. Post-campaign algorithms include pulse, spectral kurtosis, and cross-frequency methods to discard time/frequency sub-channels believed to contain RFI from the measured spectrogram of each sub-channel. The data undergo a final manual RFI analysis to identify any remaining frequency sub-channels showing anomalous behaviors over longer time scales. These frequencies are also flagged and discarded from the final integration over frequency to report a single brightness temperature value for each of the 12 x 88 MHz UWBRAD channels.

Example UWBRAD spectrograms acquired over the Greenland Ice Sheet near Thule Airbase before and after RFI processing are shown in Figure 2. RFI is severe at lower



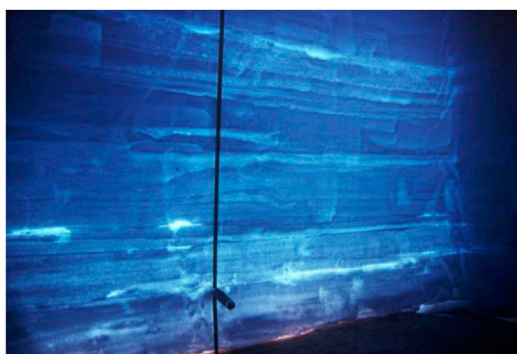


FIGURE 3
Stratigraphy revealed in a back lit 2 m deep snow pit wall located excavated in west central Greenland. The layering is primarily a result of annual snow deposition and densification. Bright objects are ice lens formed by the downward trickle of summer melt until interrupted by less permeable layers (Photo courtesy of M. Anderson).

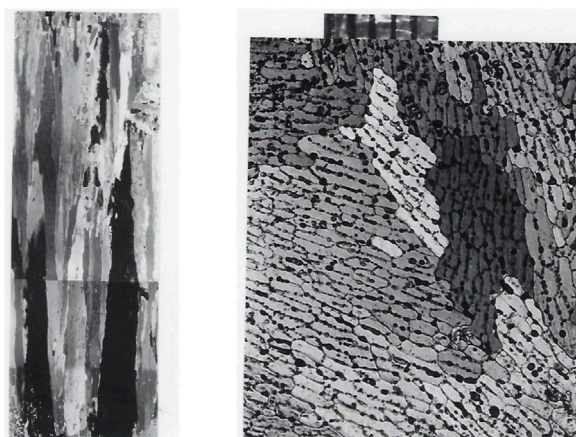


FIGURE 4
Thin section of sea ice along the vertical direction (17.5 cm long) and horizontal direction (16 cm on a side). Markers at top of the horizontal section are 1 mm. Individual vertical crystals are made visible by observation under polarized light. Small brine pockets appear along grain boundaries in the horizontal section (Photo courtesy of A. Gow and K. Jezek).

frequencies reducing the amount of usable data in the lower two bands. Fortunately, the 360 subchannels in each band allows viable thermal noise data to be recovered in each of the 12 UWBRAD frequency channels.

The results over both Greenland and Antarctica indicate that complete data loss in a single band is virtually nonexistent. The channel bandwidth loss due to the algorithms varied with frequency but remained within acceptable limits for all channels (Andrews, 2021).

3 Wide band emission theory

Forward models of brightness temperature incorporate the important morphologic and electrical properties for each component of the cryosphere. Ice sheets can be described as a layered medium that includes near surface firn layer that is 10s–100s of m thick. The stratigraphic layers from brief wind, episodic melt events and annual snow deposits are identifiable as changes in firn density that in turn diminish the transmission of energy upwelling from deeper in the ice sheet (Figure 3). Surface melt water can percolate down through the upper firn and refreeze in the form of ice lenses, ice pipes and rough layers that scatter the upwelling energy. Temperature gradients through the ice sheet are modulated by surface temperature, accumulation rates, ice sheet motion and basal heat fluxes, and the base of the ice sheet may overlies water or a frozen rocky bed.

In contrast to ice sheets, seasonal changes in sea ice are dramatic and cause physical differences between sea ice types that impact the microwave signature (Tucker et al., 1992). Young sea ice is highly saline with entrapped brine pockets distributed along the boundaries of elongated ice crystals that extend downward along the direction of ice growth (Figure 4). Snow cover deposited on the surface during winter wicks brine upwards resulting in a saline surface layer. Summer melt drains through multiyear, reduced salinity ice and leaves behind air filled channels and air pockets that also can cause microwave scattering.

On the one hand, the complexities of the snow and ice present challenges to the interpretation of the wide band radiometry. On the other hand, added information present in wide band data offers the possibility overcome those obstacles and to capture information on several glaciological properties.

3.1 Electrical properties of glacier ice

The electrical properties of glacier and sea ice are reported in numerous publications (e.g. Hobbs, 2010). The complex permittivity of glacier ice at microwave frequencies is the consequence of several dispersion processes that become temperature dependent as frequencies approach the microwave portion of the spectrum. This temperature dependence makes remote sensing studies of the thermal properties of glacier ice possible.

Mätzler (2006) models the lossy part of the permittivity as the sum of two temperature-dependent terms, one inversely proportional to frequency and a second term proportional to frequency. Tiuri et al. (1984) offers a different model that also includes two temperature terms with one varying inversely with frequency and the second varying with square root of frequency. However studies by Macelloni et al. (2016) suggest that the Matzler model yields better comparison with measurements at L-band for ice on the East Antarctic Plateau. The Matzler model is used to interpret data from ice sheet experiments though out this paper.

3.2 Brightness temperature model

Initial theoretical work determined the feasibility of using low frequency wide band radiometry to estimate physical temperature at depth in the polar ice sheets. Given the largely homogeneous structure of the interior ice sheets and the small size of snow grains to the operational wavelengths, a simple model that integrates the upwelling energy through the ice column was used:

$$T_B^{cloud}(z = H) = \int_0^H (\kappa_a + \kappa_s) T(z) e^{-\int_z^H (\kappa_a + \kappa_s) \sec(\theta_i) dz'} \sec(\theta_i) dz + T_B(z = 0) e^{-\int_0^H (\kappa_a + \kappa_s) \sec(\theta_i) dz} \quad (1)$$

Here, $T_B^{cloud}(z=H)$ is the brightness temperature at the ice sheet surface just prior to transmission through the firn “cap” and $T_B(z=0)$ is the upwelling emission from the sub ice rock or water after transmission into the ice. The absorption and scattering coefficients are given by κ_a and κ_s respectively. The physical temperature with depth is $T(z)$. The propagation angle off vertical in the ice (θ_i) was taken as normal to the surface (i.e. $\theta_i=0^\circ$). The model is derivable from the radiative transfer equation when higher order scattering effects are ignored. The model proved useful in demonstrating that a wide band radiometer could provide important glaciological information but was lacking when field data collected over different glaciological regimes showed that the model generally overestimates the T_B (Jezeq et al., 2015; Jezeq et al., 2018).

3.3 Incoherent and coherent radiative transfer models

Several models are available that describe emission through a layered medium and have been applied to investigations of wide band emission from polar ice (Tan et al., 2015). The Dense Media Radiative Transfer Model–Multiple Layers (DMRT-ML) (Picard et al., 2013) and Microwave Emission Model of Layered Snowpack (MEMLS) (Wiesmann and Matzler, 1999) are based on radiative transfer theory and account for intermediate reflection between adjacent layers and volume scattering effects. The propagation is modeled as incoherent so that any interference processes are ignored. MEMLS treats thin layers as coherent but this feature was not included in UWBRAD analyses (Tan et al., 2015). When volume scattering is ignored, emission through a stratified medium can also be described by an exact solution to the coherent problem (Tsang and Kong, 2000). The coherent model treats all the wave propagation and reflections in a fully coherent manner and is subject to strong wave interference.

For the case where the bulk of the upwelling energy comes from the lower, more homogeneous region of the ice sheet, Tan (see Jezeq et al., 2018) proposed a hybrid model to investigate

situations where layering and scattering in the upper firn are important. The model was formalized by Xu et al. (2020). In this description, the emission and the firn layer transmission and scattering processes are decoupled so that they can each be evaluated separately. The model is formulated as

$$T_B = T_B^{cloud} \Gamma \exp(-\tau_s) \quad (2)$$

where T_B is the predicted brightness temperature, T_b^{cloud} is the incoherent cloud model predicted brightness temperatures for the lower portions of the ice sheet (which ignores density fluctuations as in Eq. 1), and Γ is the bulk transmissivity through the upper firn layer and is computed by the partially coherent model. The attenuation factor τ_s is also included to account for any additional loss caused by scatterers in the upper firn layers. The model as written above was used to obtain scattering properties of ice lens scatters in the percolation zone of the Greenland Ice Sheet. Comparisons between the coherent model including scattering, the incoherent model including scattering and UWBRAD data are shown in Figure 5 for the dry snow zone where scattering is negligible and for the percolation zone where scattering from ice lenses is dominant. Undulations in the measured and coherently modeled T_B are indicative of interference effects within and between firn layers. The firn is modeled with stochastically varying densities and layer thicknesses (Brogioni et al., 2015).

A variety of meteorological and glaciological processes determine firn stratigraphy at various scales (Figure 3). Overburden pressure thins layers as they are successively buried by seasonal accumulation. Thin, hard crusts form during wind and melt events. Low density layers are formed by temperature gradients through the firn that drive vapor transport. An important conclusion of the emission models is that many, closely spaced layers (cm scale) are required to match the measured T_B . This seems counterintuitive because transmission through individual thin layers is high when the thickness is much less than a wavelength (as is the case for UWBRAD frequencies). However, many small reductions in transmission can be sufficient to mute the upwelling radiation.

3.4 A partially coherent radiative transfer model of layered ice

The fully coherent model based on solving Maxwell’s equations for thousands of layers throughout the entire ice sheet is computationally intensive. The “partially coherent” implementation of the coherent model was developed explicitly for the ice sheet case to capture the impact of variations in ice density on predicted brightness temperatures while improving computational efficiency (Tan et al., 2021). The partially coherent model divides the ice sheet into blocks. Within each block, the

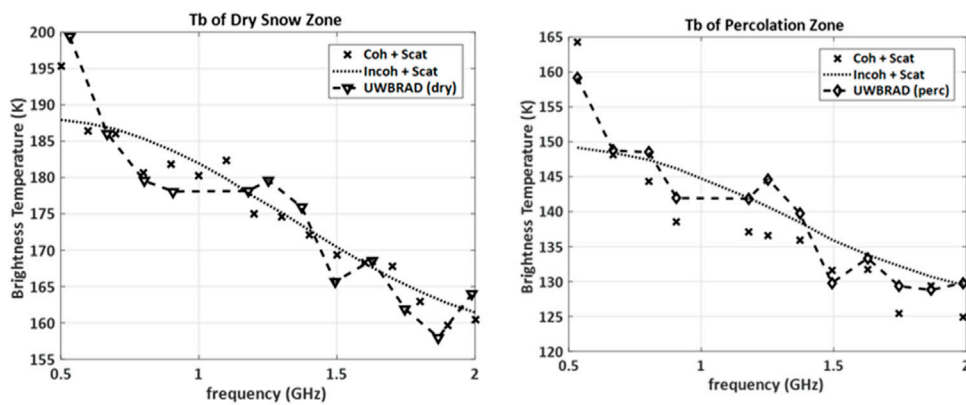


FIGURE 5

Coherent and incoherent T_B models for the Greenland dry snow zone along with wide band data (left). The same models for the percolation zone and UWBRAD data on the right. The coherent model better captures some of the fluctuations in the wide band data and also the increase in T_B at the lowest frequencies (From Jezeek et al., 2018).

coherent model is applied to take into account coherence among the contributions of closely spaced layers. The model is based on the physical reasoning that coherent interactions occur primarily within spatial scales of a few wavelengths.

A Monte Carlo procedure is used to calculate the average block reflection and transmission parameters. Between adjacent blocks, interactions are assumed to be incoherent, and the radiative transfer theory is used to incoherently cascade block parameters. Results of the partially coherent model are in good agreement with the fully coherent model.

3.5 Combined active and passive remote sensing of ice sheets

A potential solution to the problem of characterizing the firn is to use a radar operating at the same frequencies as the radiometers (Xu et al., 2020). The integrated backscattered signal over some depth can be used to infer the firn cap reflectivity and hence the transmissivity to be applied to the T_B spectra. A coherent reflectivity model was developed for both ice sheet thermal emission and backscattering. Maxwell equations were used to calculate the coherent reflections from the cap layers, and the Wentzel-Kramers-Brillouin (WKB) approximation was used to calculate the transmission for the slowly varying profile below the cap layers. Numerical simulations using typical values for Antarctic temperatures and firn densities demonstrate the use of radar measurements to compensate reflection effects on brightness temperatures. The reflections corrected brightness temperature is then directly related to the physical temperature and absorption profile making possible the retrieval of subsurface temperature profile with multi-frequency measurements.

3.6 Sea ice

The electrical properties of sea ice are dynamic and vary as the brine and air distributions in the ice changes over the seasons (Figure 4). Sea ice permittivity studies are summarized by Hallikainen and Winebrenner (1992). The work by Vant et al. (1978) remains the benchmark study relevant to the frequencies utilized here.

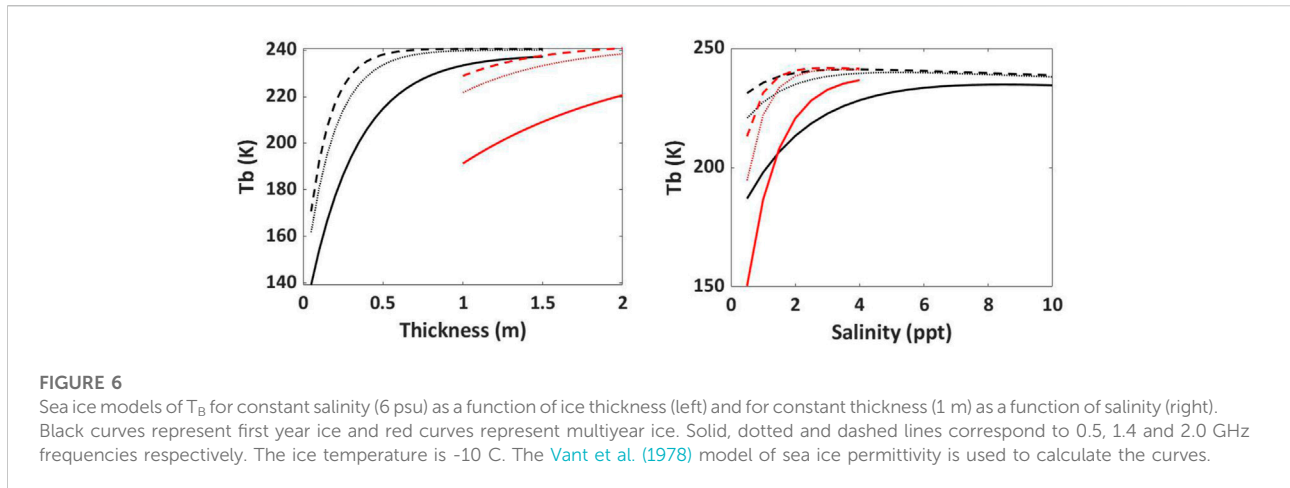
Standard, forward models of emission from sea ice were adopted from the literature. Based on environmental conditions during the experiments described later, a 3-layer model consisting of ocean, ice and air was suitable for sea ice at the start of the fall season (Jezeek et al., 2019). The radiative transfer model assumes incoherent contributions of up and down-welling radiation (Ulaby and Fung, 1981, p. 243). The model implementation assumes that scattering is small compared to absorption, ice physical properties are constant with depth, emission is normal to the surface, there is no antenna pattern correction, and there is only a single ice type in the scene which is completely covered in that ice type. The relationship between brightness temperature and model parameters is then given as:

$$T_b(\text{surface}) = \frac{1 - R_{ice/air}}{1 - (R_{ice/air}R_{ice/water})/L^2} \left[\left(1 + \frac{R_{ice/water}}{L} \right) \times \left(1 - \frac{1}{L} \right) T_{ice} + \frac{1 - R_{ice/water}}{L} T_{water} \right] \quad (3)$$

where

$$L = e^{k_a H},$$

$R_{ice/air}$ and $R_{ice/water}$ are the power reflection coefficients at the ice/air and ice/water boundaries, T_{water} and T_{ice} are the physical temperatures of the sea water and ice, respectively, H is the ice



thickness, and k_a is the absorption coefficient in the sea ice medium which is related to the electromagnetic wavenumber k_0 and the real and imaginary parts of the ice relative permittivity $\epsilon = \epsilon' - j\epsilon''$. Figure 6 shows the sensitivity of the resulting normal incidence T_B to frequency and changing ice thickness and salinity (salinity and thickness are held fixed for each figure respectively). For first year ice, T_B saturates at about 0.5 m thickness and 3 ppt salinity at 2 GHz and about 1 m thickness and 6 ppt salinity at 0.5 GHz and for ice at -10 C. For the typically thicker and less saline multiyear ice, T_B saturates at more than 2 m thickness and 2 ppt salinity at 2 GHz and more than 2 m and about 4 ppt salinity at 0.5 GHz again at -10 C. The analysis shows that T_B over this frequency range is sensitive to both parameters and moreover the spectral information can help sort out ambiguities that might confound a single frequency, for example distinguishing between first year and multiyear ice.

Later experiments recursively added additional layers including snow and sea ice of different properties (Demir et al., 2022a). The volume of snow plays a minor role in the emission but serves to more efficiently couple the upwelling radiation into the air. Adding layers to the model to capture temperature and salinity gradients in the ice reveals more complex behavior. As discussed later in Section 5.4, the accretion of new sea ice growth on the base of thick ice that has survived one or more seasons warms the emission because of the slightly increased transmission across the ocean ice boundary and the increased emission from the electrically lossy new ice growth.

4 Geophysical parameter estimation

The forward models discussed in Section 3 predict T_B as a function of frequency for different glacial and sea ice conditions. For sea ice, the forward model described by Eq. 3 was fit to the measured T_B in a least squares sense to deduce the geophysical parameters of interest (Jezeq et al., 2018; Demir et al., 2022a) (Eq. 4). The modeled brightness temperatures (T_{b_model}) given by Eq. 3 are parameterized over a range of sea ice thicknesses and salinities. The ice temperature

is taken from ancillary data. The root mean square difference between the twelve measured and modeled brightness temperatures is minimized from which the salinity and thickness are inferred. The retrieved parameters are discussed in Section 5.

$$\Delta = \sqrt{\frac{1}{12} \sum_{ch=1}^{12} (T_{b_measured}(ch) - T_{b_model}(ch))^2} \quad (4)$$

4.1 Bayesian inversion for ice sheet temperature

In this section, we review a Bayesian inversion approach to calculate glacial ice physical temperatures inferred from spectral, brightness temperature data. The inversion also relies on forward radiative transfer models along with models of ice sheet thermodynamics.

Bayesian inversion estimates the probabilities of realizing a particular geophysical parameter given data. The first step is to assign prior estimates of the parameter distributions such as ice thickness, surface temperature and snow accumulation rate. Second a model is chosen that relates T_B to the glaciological parameters. Finally, the glaciological parameters are used to solve an analytic expression for ice sheet temperature at depth (Duan et al., 2022; Yardim et al., 2022).

The hybrid microwave emission model discussed above is adopted as the forward radiative transfer model. T_B measured by the UWBRAD is modeled using vertical ice sheet temperature and density profiles. A 3-parameter Robin (1977) and a two-scale firn density variation (Brogioli et al., 2015) models are used to characterize temperature and density profiles, respectively. Because both temperature parameters and density variation parameters affect T_B , they

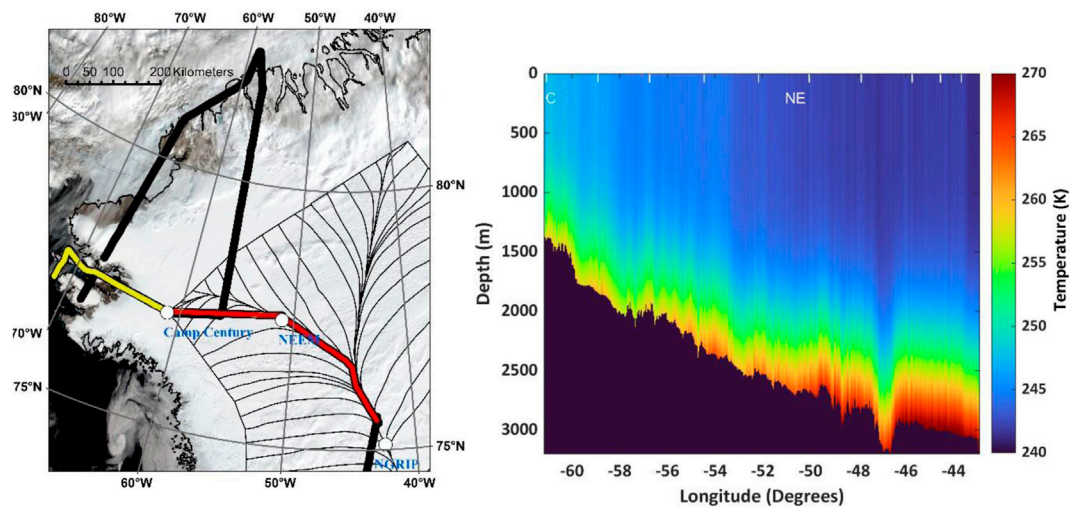


FIGURE 7

UWBRAD transects across Greenland (left). The 2016 Greenland flight is shown in yellow. The 2017 Greenland Flight is shown in black. The portion of the 2017 line along which intraglacial temperatures (right) were estimated is shown in red. Slope-derived ice-flow lines extending from the ice divides are shown by thin black lines. Derived temperature profiles along the survey line from Camp Century (C), to NEEM (NE) to NGRIP (near end-of-line) Greenland (right) (From [Yardim et al., 2022](#)).

need to be solved simultaneously. A sequential Bayesian framework is developed for retrieving the ice sheet internal temperature from UWBRAD brightness temperature measurements in the presence of the nuisance density parameters ([Yardim et al., 2022](#)).

4.2 Greenland ice sheet temperatures

The Bayesian inversion retrieves glaciological parameters used in the Robin model to calculate the temperature at depth. These are the mean annual surface temperature, average accumulation rate and geothermal heat flux. The retrieved parameters agree favorably with other model and measured estimates of mean annual surface accumulation and surface temperature ([Yardim et al., 2022](#)). Geothermal heat flux at the base is retrieved and represents one of the first remote sensing estimates of this variable which is an important control on basal sliding.

The glaciological parameters are inserted into the Robin model to calculate the physical temperature at depth. Temperatures are computed along the Greenland Ice divide ([Figure 7](#) left) where the Robin model is valid. Temperature profiles along the line are shown in [Figure 7](#) (right). Temperature uncertainties are less than 1 K near the surface and increase to about 3 K at the bed ([Yardim et al., 2022](#)). The temperature profile is the first continuous measurement of ice temperature through the ice column. Previous measurements relied on the few and widely spaced boreholes through the ice.

5 Scientific studies

Airborne experiments were carried out across the Greenland Ice Sheet, the Lincoln Sea, Terra Nova Bay Antarctica and from the coast of Northern Victoria Land to Concordia Station located on the East Antarctica Plateau. In addition to acquisitions over these primary objectives, data-of-opportunity were acquired over Arctic lakes, the boreal forest, permafrost and the Davis Strait during transits to and from the primary sites ([Andrews, 2021](#)). In this section we review the unique spectral signatures identified for ice sheets and sea ice. We go on to discuss the scientific information gleaned from the application of the concept.

5.1 Greenland ice sheet spectra

[Benson \(1962\)](#) showed that the upper surface of the ice sheet is partitionable into four melt zones. The annual snow and some upwelling ice melts from the surface in the ablation zone. Melt streams dissect the icy surface that can be cluttered with patches of rocky debris. Surface lakes dominate the wet snow zone and the firn stratigraphy can be interrupted by thick layers of superimposed ice. Seasonal melt drains through ice pipes and forms ice layers and ice lenses in the percolation zone. Melt is generally absent in the dry snow zone but recent climate change compromises a strict definition of dry snow across the ice sheet.

An airborne experiment in 2016 traversed the melt zones along a line starting from the margin of the northwestern ice

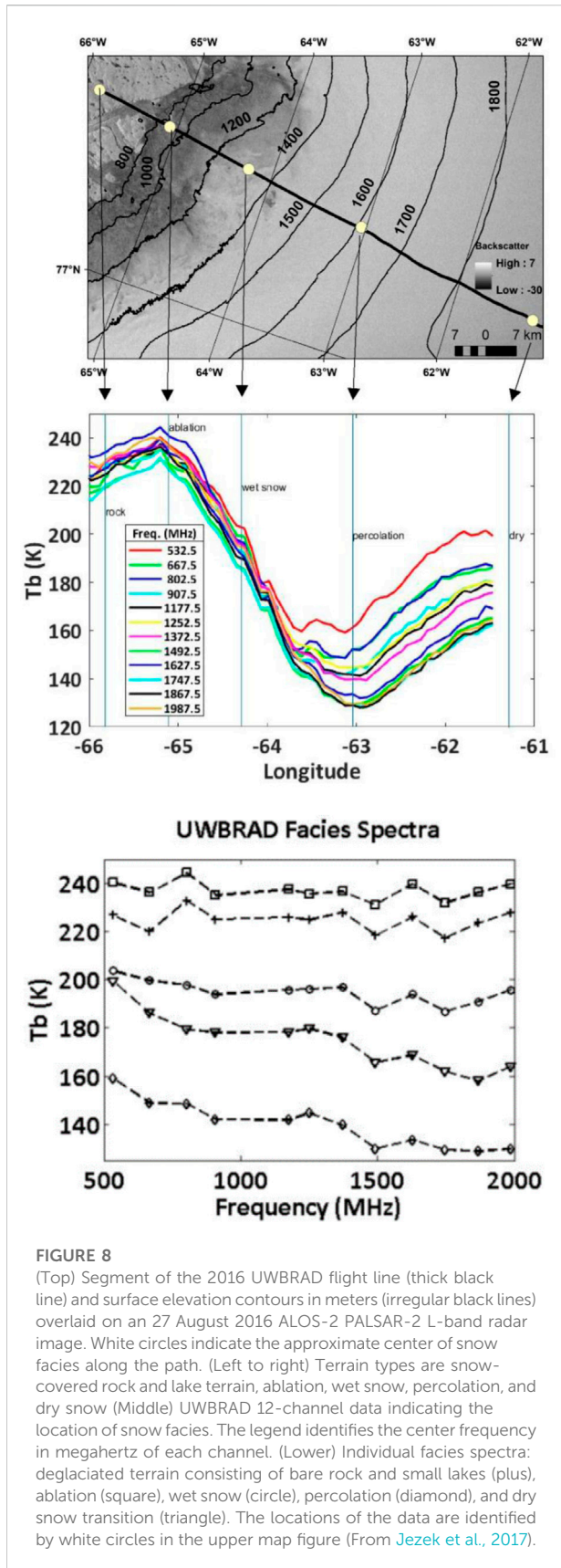


FIGURE 8
 (Top) Segment of the 2016 UWBRAD flight line (thick black line) and surface elevation contours in meters (irregular black lines) overlaid on an 27 August 2016 ALOS-2 PALSAR-2 L-band radar image. White circles indicate the approximate center of snow facies along the path. (Left to right) Terrain types are snow-covered rock and lake terrain, ablation, wet snow, percolation, and dry snow (Middle) UWBRAD 12-channel data indicating the location of snow facies. The legend identifies the center frequency in megahertz of each channel. (Lower) Individual facies spectra: deglaciated terrain consisting of bare rock and small lakes (plus), ablation (square), wet snow (circle), percolation (diamond), and dry snow transition (triangle). The locations of the data are identified by white circles in the upper map figure (From Jezek et al., 2017).

sheet at about 800 m and reaching eastward to about Camp Century at a surface elevation of about 1900 m (yellow line in Figure 7 and Figure 8 top) (Jezek et al., 2017). The UWBRAD-measured T_B spectra vary with intensity and spectral gradient as each melt zone is encountered (Figure 8 middle). T_B brightens by about 10 K on the approach from the rocky margin to the ablation zone. Thereafter the T_b drops precipitously in the wet snow zone before reaching a minimum intensity and a broadening of the spectral gradient in the percolation zone. Spectra warm by almost 30 K during the transition from the percolation zone to the dry zone. The spectral gradient increases as the radiometer becomes less affected by scattering and more influenced by ice thermal properties at depth. Spectra for individual snow facies are shown in Figure 14 (bottom). The different melt facies are distinguishable based on the intensity and the slope of the spectra.

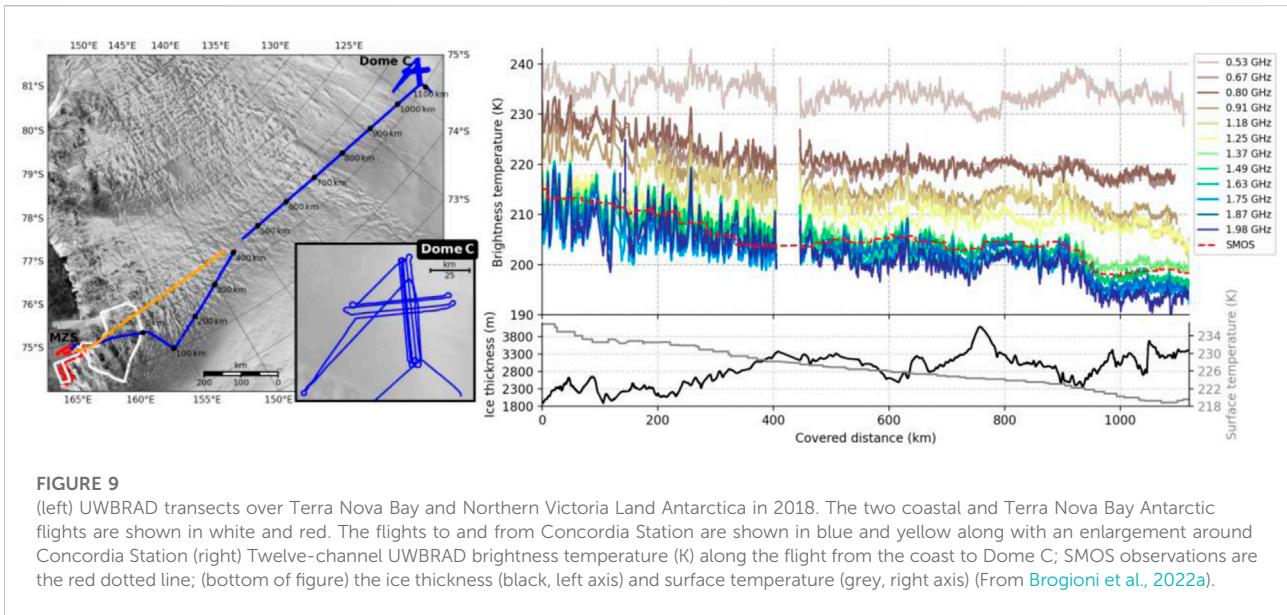
5.2 Antarctic Ice Sheet spectra

The Ice Sheet and Sea Ice Ultrawideband Microwave Airborne experiment (ISSIUMAX) project was conducted between October 30th and December 8th, 2018 (Brogioni et al., 2022a). The airborne campaign was hosted at the Italian Antarctic base (Mario Zucchelli Station) on the Ross Sea and extended from Terra Nova Bay to Concordia Station in East Antarctica. The project goals were (i) to demonstrate the use of 500–2000 MHz brightness temperature spectra for deriving vertical ice sheet temperature profiles of the inland Antarctic ice sheet, and (ii) to explore the capability to infer glaciological information in coastal regions of Antarctica, including sea ice. An additional goal as to demonstrate that microwave radiometry is feasible in the heavily used 500–2000 MHz spectral range in remote regions such as Antarctica.

UWBRAD T_B spectra along the transect from Mario Zucchelli Station to Concordia Station on the East Antarctic plateau are shown in Figure 9 (Brogioni et al., 2022a). T_B decreases linearly from the coast to Dome C dimming between 7 and 16 K depending on the frequency. The lowest frequency channel decreases by only about 5 K. SMOS observations decrease by 13.7K (Figure 9), comparable to the 1370-MHz UWBRAD decrease of 14.1 K. Brightness temperatures over the UWBRAD frequency band vary by more than 30 K, which is similar to the spectra observed over the interior dry snow zone of the Greenland ice sheet (Figure 8).

5.3 Lincoln Sea and Arctic Ocean sea ice spectra

Arctic multiyear and thin sea ice covering the Lincoln Sea (northern apex of the 2017 campaign in Figure 7 left) was

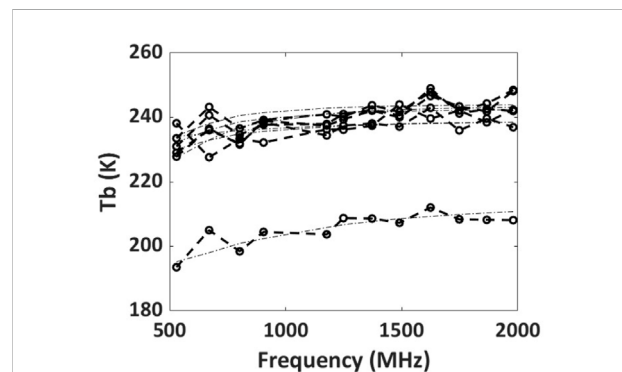


sampled in the early fall (September 2017) after melt had ended. Surface temperatures remained below about -10 C for the period of observations. Spectral signatures for consolidated multiyear ice are about 30 K warmer than the thin sea ice growing in recently opened leads (Figure 10) (Jezeek et al., 2018). The spectra warm with frequency as the contribution from nearer the surface dominates the gradually reducing contribution from the radiometrically cold ocean. Models fit to the data using Eq. 3 show good agreement with the data.

5.4 Multiyear ice signatures during the winter

A 4-channel (540, 900, 1380, and 1740 MHz) version of the UWBRAD instrument was deployed during the international MOSAIC campaign for operation on the sea ice surface (Demir et al., 2022b). The German research vessel Polarstern served as the base of operations and was moored to a multiyear floe in October 2019. The instrument began data collection in December near 86° N latitude and 120° E longitude in the Arctic Ocean.

The study site was situated on a more than 2 m thick sea ice floe that included undeformed desalinated second-year ice (potentially with refrozen melt ponds). Observed brightness temperatures from this site were compared with the sea ice emission model using *in situ* data of ice salinity and temperature (Figure 11). *In situ* observations showed that new ice growth of about 8 cm was inferred from temperature profiles recorded from December 4 to December 13. Growth trends correlated with a gradual increase in the brightness temperatures by about 10 K (Demir, 2021; Demir et al., 2022a). Because the exact thickness of the basal layer was limited by the



measurement interval, bottom layer thickness values between 0–15 cm were tested to compare the simulated and observed T_B over the time period of December 8–13 (at fixed 35° pointing angle). The best fit values were determined as 8.7 cm on December 9 and 13.5 cm on December 13, both of which are in the range of basal layer thicknesses detected in ice core samples taken from representative sites. Figure 11 compares measured and modeled brightness temperature time series during this time interval. New ice growth under the older ice raises T_B as emission from the radiometrically warm new ice contributes to the net upwelling energy. Of particular importance is the observation that a relatively thin layer of new ice growth at the base of the multiyear flow changes the emission by almost 10 K. The implication is that

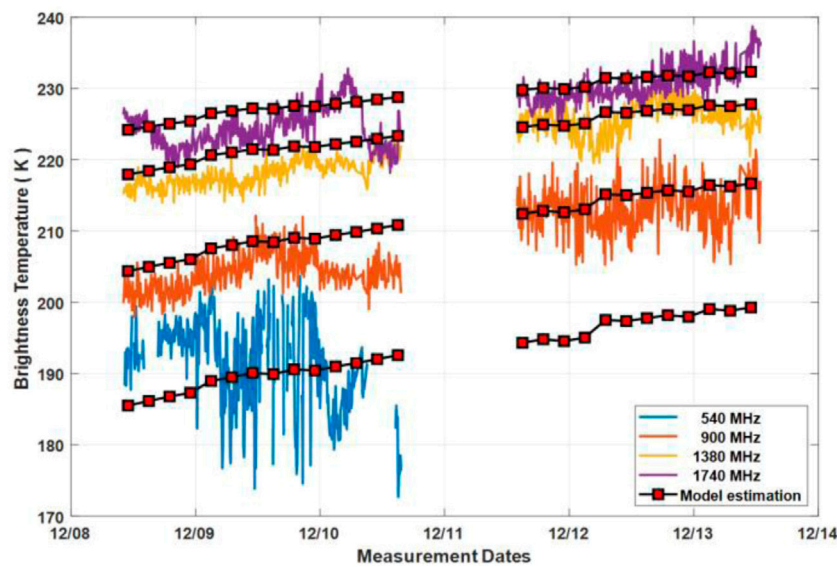


FIGURE 11

T_B for the four-channel, modified UWBRAD instrument operated on a thick multiyear ice floe in December 2019. Model estimate shows that the slow accretion of new sea ice at the base gradually increases the brightness temperature at all frequencies (From Demir et al., 2022a).

passive microwave emission algorithms for estimating the thickness of multiyear ice must consider basal accretion (Demir et al., 2022a).

5.5 Terra Nova Bay Antarctica sea ice spectra

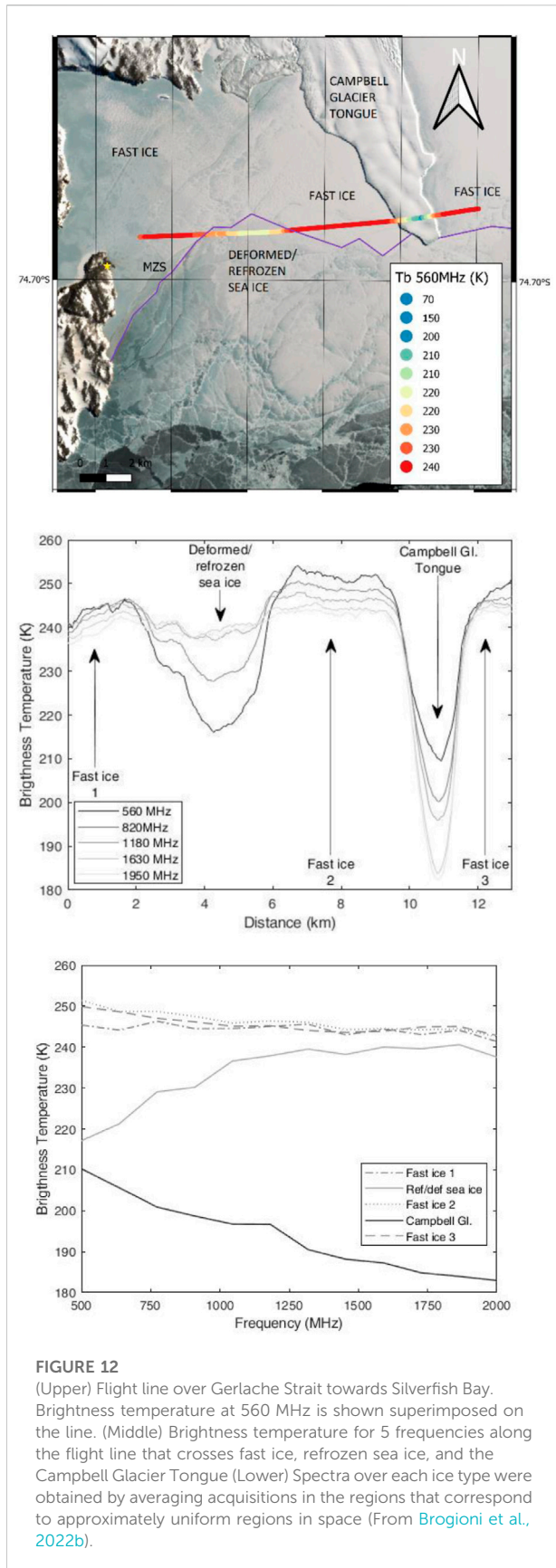
The sea ice covering Terra Nova Bay is complex (Ackley et al., 2020; Rack et al., 2021). Substantial amounts of frazil ice can form into thick rafts. Platelet ice can form beneath the sea ice. The sea ice routinely breaks out in summer and is rarely less than 2-years old. New ice forms in open leads and older, thicker fast ice is found along the coast. Unlike the arctic, pancake ice is common as is flooding at the interface between snow and sea ice.

Wide band microwave data were collected over the Terra Nova Bay sea ice cover in December 2018 (Brogioni et al., 2022b). An example from Gerlache Inlet to Silverfish Bay highlights the spectral behavior of different Antarctic sea ice types (Figure 12). Brogioni and others (2022b) determined that the nearly 2 m thick near-coastal sea ice (or “fast ice”) at sites 1, 2, and 3 formed in March–April 2018. Katabatic winds near site 1 cause ablation/sublimation of the fast ice and result in almost no snow coverage, while the fast ice at sites 2 and 3 was covered by snow of less than 45 cm thickness. The roughly 1.5 m thick sea ice at site 2 in contrast was the product of multiple breakup processes. The site 4 freshwater ice of the Campbell Glacier Tongue (Site 4) has a much greater thickness (~ 400 m landward)

UWBRAD brightness temperature spectra at the five labeled sites are shown in the lower plot of Figure 12. As expected from theory (Johnson et al., 2021; Demir et al., 2022b), the thicker sea ice at sites 1, 2, and 3 shows a “flatter” spectrum having brightness temperatures in the 240–250 K range. This is due to the sensitivity of brightness temperature to ice thickness: for a salinity of 6 ppt (as measured *in situ*) the electromagnetic signal saturates for thicknesses higher than 1.5–2 m even at 500 MHz. The flattest spectrum occurs for the bare ice at site 1, while the spectra of sites 2 and 3 show a slight decreasing trend with frequency possibly due to surface roughening of the snow to sea ice interface. Over the more dynamic, deformed and thinner ice between sites 1 and 2, brightness temperatures are cooler by almost 40 K compared to the thick ice at sites 1, 2 and 3. Moreover there is a positive gradient with frequency as was also observed in Lincoln Sea campaign where the ice was typically thinner than 2 m (Figure 10). Brightness temperatures over the Campbell Glacier tongue decrease uniformly with frequency from 210 K (560 MHz) to 182 K (1950 MHz). This behavior is typical of continental ice as illustrated in Figures 8, 9.

5.6 Ice shelves

Ice shelves are a unique feature of the modern Antarctic Ice Sheet. Ice shelves form as glacier ice from the interior spreads and thins onto the ocean. To date only a limited amount of wide band data have been collected on floating ice. Though not an ice shelf, Enigma Lake is a small, supraglacial body of water located near



Mario Zucchelli Station. The overlying ice varies from a few centimeters to 15 m thickness. The brightness temperature spectra decreases over the lake relative to the surrounding rocky surfaces because of the cold brightness temperature contributed by the underlying water into the ice (Figure 13). Also shown are individual spectra for Enigma lake and rocky terrain. The Enigma Lake spectrum warms with frequency as the water contribution is attenuated and in a fashion more similar to sea ice rather than ice on the polar plateau (Brogioni et al., 2022b).

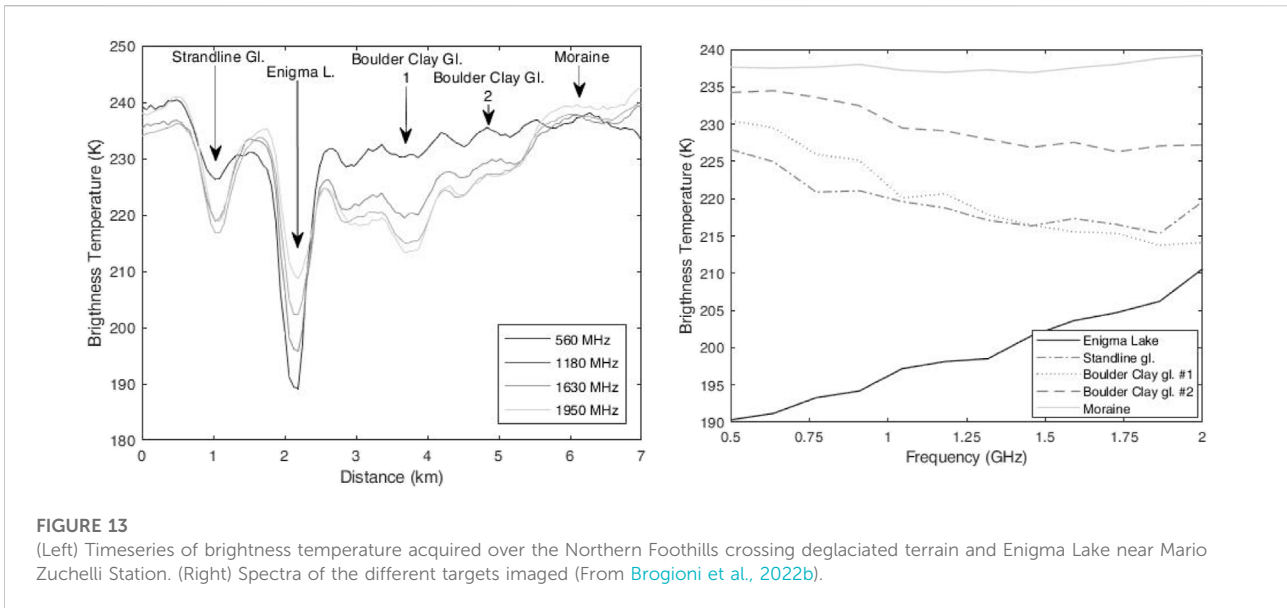
The Nansen Ice Shelf was also sampled but the ice shelf structure is particularly complex because of converging glacier flows feeding the ice shelf, debris on the surface, and substantial melt. Nevertheless, initial results suggest that the wide band T_B spectral gradients increase as do brightness temperature magnitudes as the ice crosses the grounding line (Brogioni et al., 2022b).

6 Cryospheric science results

In this section we review applications of low-frequency wide band emission data to sea ice and ice sheet science. Wide-band nearly continuous spectra enable new ways to explore the ice sheet and sea ice geophysical properties.

6.1 Polar firn studies

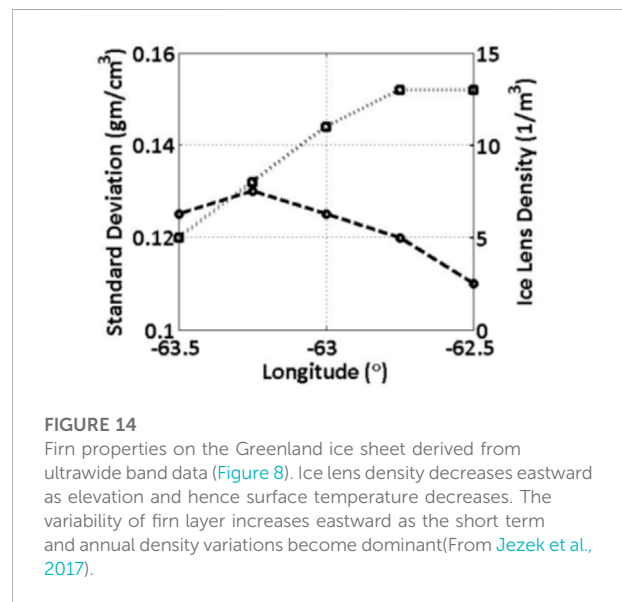
Firn in the Greenland Ice Sheet percolation zone is punctuated by ice lenses formed by refrozen melt (Figure 3). Melt descends through the permeable upper layers of varying density until an impermeable layer is reached at which point either an ice lens is formed or an ice layer if there is sufficient melt over an area. The hybrid brightness temperature model (Eq. 2) was used to estimate scattering from ice lenses and layers in the percolation zone. Frequency dependencies inherent in wide band data are used to derive the number densities of the embedded icy disks and to estimate the variability of firn density. Modeling applied to the spectra in Figure 8 shows that the density fluctuations raise or lower the brightness temperatures nearly uniformly over the entire spectrum (excepting coherent layer effects), while the scattering losses from the embedded ice lenses affect more the brightness temperatures at higher frequencies, creating an added frequency dependence (Jezeek et al., 2017). The interplay between density fluctuations and ice lens density as the data move from west to east produces the unique spectral responses. Consistent with expectations, Figure 14 shows that the calculated density of ice lenses decreases from west to east with increasing ice sheet elevation and decreasing surface temperature. The variability of firn density also increases as the gradual reduction of melt enables fine scale firn stratigraphy to develop. The result is significant given the need to understand situations in which melt water drains off of the ice sheet resulting in mass loss and where melt percolates vertically and refreezes.



Densification of polar firn across the ice sheets is of interest for use in correcting satellite altimeter measurements of ice sheet mass balance. The partially coherent model discussed above is implemented to explain the UWBRAD microwave brightness temperatures by modeling Greenland firn as a 3-D continuous random medium with finite vertical and horizontal correlation lengths (Xu et al., 2022). Refrozen layers are described as deterministic sheets with planar interfaces. The number of refrozen layer interfaces is determined from coincident Operation IceBridge radar observations. The forward model matches measured 0.5–2 GHz brightness temperatures with firn density and correlation length parameters that in turn are consistent with similar parameters in firn densification models. Firn parameters so estimated are also in good agreement with multi-angle 1.4 GHz vertically and horizontally polarized brightness temperature measured by the SMOS satellite at DOME C, Antarctica (Xu et al., 2022).

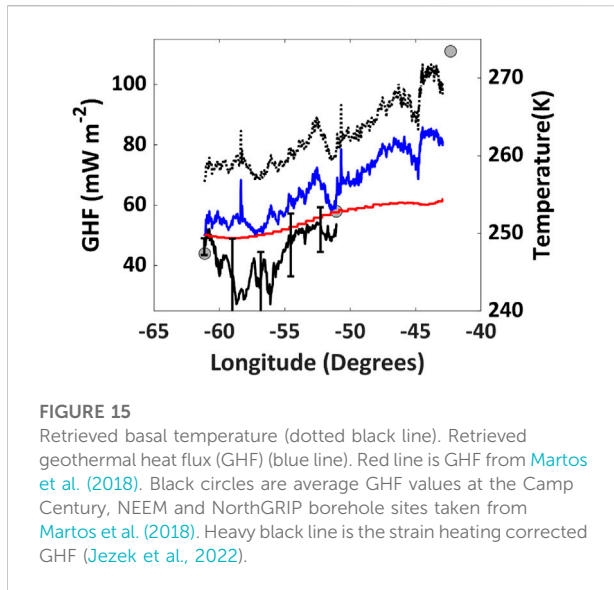
6.2 Greenland ice sheet intraglacial temperature and glacier flow

Ice internal temperature was obtained from 2017 brightness-temperature spectra (Figure 7). Temperatures vary slowly through the upper ice sheet and more rapidly near the base increasing from about 259 K near Camp Century to values near the melting point near NGRIP. As the temperature increases the ice softens, which can be described by a deformation rate factor that relates stress to strain rate. The basal-ice rate-factor increases from about



$1 \times 10^{-8} \text{ kPa}^{-3} \text{ a}^{-1}$ to $8 \times 10^{-8} \text{ kPa}^{-3} \text{ a}^{-1}$ along the line, which when adjusted for enhancements from crystalline fabrics and grain size results in increased lateral motion of the ice and shearing across the bed (Jezeek et al., 2022).

Geothermal heat flux imposes a boundary condition on glacier thermodynamics and is one of the parameters obtained by the inversion (Section 4.1). Geothermal heat flux values retrieved from the brightness temperature spectra increase from about 55 mW m^{-2} – 84 mW m^{-2} from Camp Century to NGRIP. A strain heating correction using an enhancement on

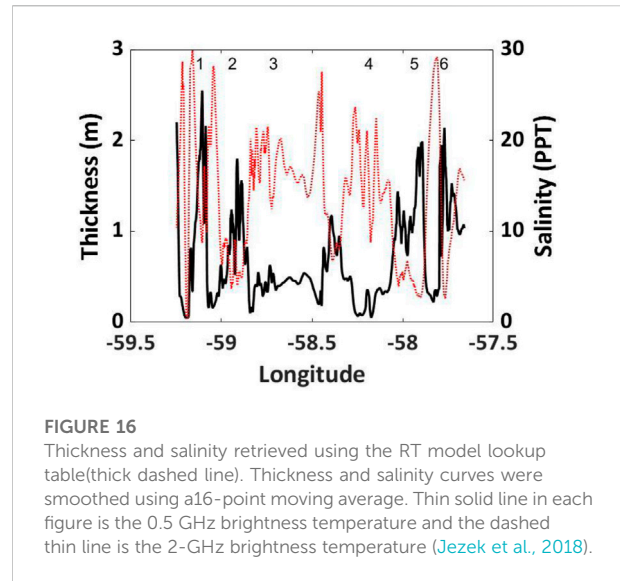


the rate factor improves agreement with other geophysical data sets ([Martos et al., 2018](#)) near Camp Century and NEEM but differ by about 15 mW m^{-2} in the central portion of the profile ([Figure 15](#)) ([Jezek et al., 2022](#)).

6.3 Lincoln Sea ice thickness and salinity

The Lincoln Sea sea-ice emission spectra ([Figure 10](#)) enables estimation of both the ice thickness and ice salinity by fitting the forward model ([Eq. 3](#)) to the microwave spectral data ([Figure 16](#)). Estimated thicknesses range between about 0.2 and 2 m for most of the profile which is not unexpected for the ice pack north of Greenland. Estimated salinities vary from about 5 ppt to over 20 ppt. Generally, thin ice is associated with high salinities whereas thick ice is associated with low salinities. It is noted that salinities are too high for both multiyear and new ice. The discrepancy may be the result of neglecting important effects including physical property gradients through the sea ice, the interface roughness, and/or the presence of snow along with uncertainties in the electrical properties of the sea ice ([Jezek et al., 2018](#)).

To explore arctic basin-wide sensitivity of wide band data for retrieving sea ice thickness and salinity, [Demir \(2021; Demir et al., 2022b\)](#) simulated brightness temperature for Arctic sea ice for the period October 2020–March 2021 using sea-ice thicknesses from the SMOS-CryoSat-2 algorithm. The simulations assumed first year and second year ice along with allowing for snow cover. Compared to existing sea-ice thickness retrievals obtained from 1.4-GHz microwave radiometers, the results demonstrate that 0.5–2-GHz radiometry can achieve higher sensitivity to a sea-ice thickness within the range 0.5–1.5 m for first year sea ice and enable the retrieval of



multiple sea-ice parameters (thickness and salinity) simultaneously ([Demir et al., 2022b](#)).

7 Spaceborne concepts

The successful engineering and scientific demonstrations of airborne low-frequency wide band radiometry lead naturally to concepts for the implementation of spaceborne systems. Thus far, two similar concepts have been proposed. CryoRad under consideration by ESA consists of a single satellite hosting a single payload: a wideband, low-frequency microwave radiometer that observes from 0.4 GHz to 2 GHz with continuous frequency sampling specifically designed to address scientific challenges in polar regions. The instrument observes at nadir and in circular polarization to avoid Faraday rotation effects. The CryoRad swath is 120 km, with a spatial resolution on the ground that varies from 45 km at 0.4 GHz to 8 km at 2 GHz. The average revisit time is 3 days at latitudes higher than 60° and about 10 days at the equator. ([Macelloni et al., 2018](#)). The PolarRad mission concept being developed in the United States is similar in that a wideband microwave radiometer is planned to measure Earth brightness temperatures from 500 to 2000 MHz ([Andrews et al., 2021b](#)).

8 Summary

Over the past 10 years, ultra wide band, low-frequency radiometry has evolved from a concept and into a new tool for exploring the cryosphere. Advances in electronics, instrument design, and procedures for isolating radio frequency interference permitted the development of a new class of radiometer capable of acquiring high quality brightness temperatures in the 0.5–2 GHz

range that includes many regions outside the protected bands of the electromagnetic spectrum. Surface and airborne experiments in the Arctic and Antarctica, on ice sheets and on sea ice, and over rocky terrain reveal unique spectral signatures associated with each scene—a unique feature of the wide band radiometer. More information is contained in the wide bandwidth enabling more geophysical parameters to be gleaned from the data including temperatures deep within the ice sheets and both the thickness and salinity of sea ice. To date, airborne experiments have been restricted by the usual limitations of season and range. In the near future, there is the possibility that those limitations will be overcome by the deployment of similar instruments in space.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Author OD was employed by the company Skyworks Solutions Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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