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Analyzing and modeling the SMOS spatial variations in the East Antarctic Plateau

Giovanni Macelloni [a,*], Marion Leduc-Leballeur [b,c], Marco Brogioni [a], Catherine Ritz [b,c], Ghislain Picard [b,c]

[a] Institute of Applied Physics "Nello Carrara" — National Council of Research, Via Madonna del Piano, 10, 50019 Sesto Fiorentino, Italy
[b] University Grenoble Alpes, LGGE (UMR5183), Grenoble, France
[c] CNRS, LGGE (UMR5183), Grenoble, France

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ABSTRACT

The SMOS brightness temperature (T_B) collected on the East Antarctic Plateau revealed spatial signatures at L-band that have never before been observed when only higher-frequency passive microwave observations were available, and this has opened up a new field of research. Because of the much greater penetration depth, modeling the microwave ice sheet emission requires taking into account not only snow conditions on the surface, but should also include glaciological information. Even if the penetration depth of the L-band is not well known due to the uncertainty on the imaginary part of the ice permittivity, it is likely to be of the order of several hundreds of meters, which means that the temperature of the ice over a depth of nearly 1000 m influences the emission. Over such a depth, the temperature is related to both the surface conditions and to the ice sheet thickness, which in turn depends on the bedrock topography and on other glaciological variables. The present paper aims to provide a thorough theoretical explanation of the observed T_B spatial variation close to the Brewster angle at vertical polarization, in order to limit the effect of surface and vertical density variability in the firn. In order to provide reliable inputs to the microwave emission models used for simulating T_B data, an in-depth analysis of the temperature profiles was performed by means of glaciological models. The comparison between simulated and observed data over three transects totalling 2000 km in East Antarctica pointed out that, whereas the emission models are capable of explaining the T_B spatial variations of several kelvins (0.7 and 2.9 K), they are unable to predict its absolute value correctly. This study also shows that the main limiting factor in simulating low-frequency microwave data is the uncertainty in the currently available imaginary part of the ice permittivity.

1. Introduction

In the past decade, space agencies have promoted microwave radiometry missions in the L-band (1.4 GHz) with the main aim of investigating soil moisture and ocean salinity. Three missions have been launched: the European Space Agency (ESA)'s Soil Moisture and Ocean Salinity (SMOS) in 2009 (Kerr et al., 2010), the National Aeronautical and Space Agency (NASA)'s Aquarius in 2011 (Le Vine, Lagerloef, & Torrusio, 2010) which ceased operations in June 2015, and NASA's Soil Moisture Active Passive (SMAP), launched in 2015 (Entekhabi et al., 2010). In addition to the missions' primary objectives, the global scale availability of long-term, all-weather time-series of calibrated L-band data has opened up additional research topics, including that of the cryosphere. The interest of the L-band for snow and ice applications relies on the very low absorption of ice at L-band (imaginary part of the permittivity 10^{-4}, e.g. Nyfors, 1982), about one order of magnitude lower than for the higher frequencies, and the low scattering by particles (grain size, bubbles in ice), which are very small compared to the wavelength. Consequently, in dry snow and ice the extinction is low and the penetration depth is very high (hundreds of meters), and these facts open up new opportunities for probing the soil or water under the ice or the internal layers of the ice-sheet.

Indeed, Antarctica is covered by a vast ice sheet that contains about 90% of all the ice on Earth, and has an average thickness of 1.6 km. Characterized by a high surface albedo, the surface of the ice sheet reflects 80–90% of the incoming solar radiation, thus leaving little energy to heat the surface in summer. Coupled interactions between the ice sheet, atmosphere and ocean strongly influence climate on both a regional and a global scale, and in fact the study of this region is particular important for a better knowledge of past climate (e.g. EPICA project, Augustin et al., 2004) and for predicting possible future changes. Due to Antarctica's extent, extreme weather conditions (with temperatures reaching minima of between −85 °C and −90 °C in winter) and remoteness, satellite remote sensing constitutes a unique tool for studying this region of the Earth. Several sensors and missions have been used to study this area from the beginning of the remote sensing era (Zwally,

* Corresponding author.
E-mail addresses: g.macelloni@ifac.cnr.it (G. Macelloni), marion.leduc-leballeur@ujf-grenoble.fr (M. Leduc-Leballeur), m.brogioni@ifac.cnr.it (M. Brogioni), catherine.ritz@ujf-grenoble.fr (C. Ritz), ghislain.picard@ujf-grenoble.fr (G. Picard).

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1977) and now include also L-band passive radiometers. One point of interest in using these sensors in Antarctica was for calibrating and validating data (e.g. Macelloni et al., 2013). Among the possible areas, the East Antarctic Plateau, in particular the area of Dome C near the Italian-French base of Concordia (located at the top of the dome at 75.06°S, 123.21° E), is being investigated as one of possible the long-term test sites for a variety of different satellite sensors. The snow characteristics of this site are almost homogeneous on a one-hundred kilometer scale, and offer extremely limited surface slopes (less than 0.4%). Moreover, the atmospheric conditions are very clear for most of the year, and precipitation is limited. Lastly, the site offers other interesting characteristics that make this area very attractive for the external calibration of remote sensing missions: due to its position, the Dome C site make it possible to observe the area several times a day using polar-orbiting satellite instruments (depending on sensor characteristics such as orbit, observation mode, swath, and observation angle). Detailed information has been obtained from several past campaigns (e.g. bedrock and snow topography, and snow accumulation rate), and several instruments have been installed in-situ for continuous atmospheric and snow measurements. At L-band ground-based (Macelloni, Pampaloni, Brogioni, Cagnati, & Drinkwater, 2006; Macelloni et al., 2013) and airborne (Skou, Kristensen, Sobjaerg, & Balling, 2015) experiments, supported by ESA, have been conducted in that area within the framework of SMOS calibration and validation activities. On the one hand, these experiments have demonstrated the temporal stability of the brightness temperature (T_B) in a restricted area at vertical polarization (lower than 1 K in one year); on the other hand they have shown a significant spatial variability (i.e. some Kelvins over tens of km) when the ice sheet is observed at high resolution spatial scale (Skou et al., 2015). SMOS analyses conducted over the East Antarctic Plateau also confirm that, whereas the T_B is temporarily stable (showing an annual standard deviation of 1–4 K depending on the location) and locally homogeneous (i.e. showing a variation < 1 K over a 50-km scale) it changes smoothly by several kelvins on a larger spatial scale (i.e. 500 km) (Macelloni et al., 2014). Spatial analyses have also revealed some well-known glaciological features in the T_B over the East Antarctica Plateau, such as the presence of Lake Vostok (Jezek et al., 2015). Moreover, it is worth mentioning that the T_B temporal stability is much higher at vertical (V) than at horizontal (H) polarization (Brucker, Dinnat, Picard, & Champollion, 2014), due to the fact that H polarization is more sensitive to changes in surface properties, thus resulting in a varying reflection coefficient at the air-snow interface.

This is confirmed in Brucker et al. (2014) and in Macelloni et al. (2013), in which it was found that different surface properties (e.g. the presence of hoar in the surface or of a strong wind capable of modifying the surface density) are able to modify the L-band observations at H polarization from both satellite and ground-based radiometers. This phenomenon is well-known at higher frequencies (Champollion, Picard, Arnaud, Lefebvre, & Fily, 2013; Shuman, Alley, & Anandakrishnan, 1993; Shuman & Alley, 1993). The higher T_B temporal stability at V polarization can also be explained by the different sensitivity of H and V polarizations to surface and layer roughness, as suggested in Schwank et al. (2014). In this particular paper, the roughness was treated by using the concept of impedance matching, as suggested by Mätzler et al. (2006), and it was demonstrated that a modification of a surface roughness of 50 mm, as a standard deviation of height, produces negligible effects at V polarization, while it can impact H polarization by 2.5 K at a surface temperature of 273.15 K.

The T_B spatial variability at L-band shows similarity with the higher frequencies, with distinctly different types of behavior in dry and wet zones (Picard, Brucker, Fily, Gallée, & Krinner, 2009) and a clear dependence on the surface temperature in the dry zone (e.g. Schneider & Steig, 2002; Picard et al., 2009), thus resulting in a general decrease of T_B from the coast to the interior. The pattern due to grain size (Brucker et al., 2014) that is visible from 5 GHz to 89 GHz is absent at L-band. In contrast, recent studies (Jezek et al., 2015; Pablos, Piles, González-Gambau, Camps, & Vall-llossera, 2015) have pointed out that the T_B variations are related to the thickness of the ice sheet. In particular in Jezek et al. (2015), it was shown that, for the region near Lake Vostok (77°S–105°E), where variations in the surface temperature are weak, the SMOS T_B variation (up to 8 K) over certain transects is clearly related to ice sheet thickness. Pablos et al. (2015) extended the analysis to the entire Antarctic Plateau: using Aquarius data, they demonstrated that there is a fairly good agreement between T_B and ice thickness variations over selected transects in East Antarctica, except for the case of spatially-rapid variations, which have not been resolved due to the coarse resolution (about 100 km) of Aquarius. In the same paper, it was verified that, because of a penetration depth of hundreds of meters and an ice thickness greater than 2000 m, no correlation was observed between Aquarius T_B and the bedrock elevation.

Again in Jezek et al. (2015) and using a relatively simple electromagnetic first-order radiative transfer model, a first attempt was made to relate the T_B variation observed by SMOS to the modification in the temperature profile of the ice sheet, which in turns depends on various glaciological parameters (i.e. thickness, surface temperature, geothermal flux, etc.).

In Brogioni, Macelloni, Montomoli, and Jezek (2015), it was found that multi-frequency microwave data collected at L- and C-bands at Dome C using a ground-based radiometer can be reproduced by using the Dense Media Radiative Transfer-MultiLayer incoherent model (DMRT-ML, Picard et al., 2013). In particular, the study points out that, apart from the Brewster angle and V polarization, the variations in the vertical density profile of the firn play a major role in determining the microwave emission signature at both considered frequencies. This is due to the significant role of the interface reflections, as opposed to the scattering by snow grain, which dominates at high frequencies. At C-band, the emission also has an appreciable sensitivity to the grain size and its vertical profile. Conversely, at V polarization close to the Brewster incidence angle (~60°), the surface and internal reflections vanish. This suggests that when the details of the density profile are unknown, as is the case with most of the Antarctica ice sheet, only simulations at an incidence angle close to Brewster and V polarization are possible.

More sophisticated models have been developed for the simulation of T_B at low frequencies. In Leduc-Leballeur et al. (2015) the results show that a coherent microwave emission model based on the wave approach is able to simulate SMOS data at Dome C, by using specifically measured ground data, with a better accuracy than with the incoherent model DMRT-ML, especially at H polarization. A refinement is required in theory, because the length scale of the density variations is the same as the wavelength (or sub-wavelength, 5-20 cm), which affects the efficiency of the internal interface reflections. Nevertheless, it is worth noting that the best agreement between the measured and the simulated data was mainly due to the appropriate selection of the ice permittivity model, instead of the coherency effect. In this latter case, the formulation proposed in Tiuri, Sihvola, Nyfors, and Hallikaiken (1984) was used, and an estimate of the penetration depth, i.e. 67% of the signal, was obtained at a depth of 250 m, and 99% of the signal emanated from the top 900 m. The simulations confirmed that T_B is only slightly affected by seasonal variations in surface temperature (less than 0.2 K), thus confirming the high temporal stability of snow emission at L-band. In Tan et al. (2015), an inter-comparison between several microwave emission models (i.e. first order model, incoherent and coherent models) was performed in the 0.5–2 GHz frequency range. The results demonstrated that incoherent models such as DMRT-ML (Picard et al., 2013; Tsang, Kong, & Ding, 2000) and MEMLS (Wiesmann & Mätzler, 1999; Mätzler & Wiesmann, 1999) provide almost identical results at all frequencies, but that the agreement between coherent and incoherent models greatly depends on the medium representation and in particular on the thickness of the layers and on the density variability between the layers. Indeed, if it is assumed that the density of the layers that compose the ice sheet are correlated, quite a good agreement is obtained between coherent and incoherent models for a correlation length greater than the