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In-situ passive microwave emission model parameterization of sub-arctic frozen organic soils

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ABSTRACT

Many passive microwave remote sensing applications such as land surface temperature, snow water equivalent and soil moisture retrievals need to take into account a soil parameterization to the overall surface signal emission. Soil emission modeling presents large uncertainties when the soil is frozen. In this paper, an empirical retrieval method is presented, specifically for rough frozen soil permittivity estimates at 10.7, 19 and 37 GHz. The method was tested and validated using in-situ passive microwave measurements at incidence angles from 0 to 60° of sub-arctic frozen organic soils in Northeastern Canada. The retrieved permittivity values give an overall RMSE between the measured and simulated brightness temperatures of 4.6 K for all frequencies combined. A sensitivity analysis was conducted on the different soil parameters optimized in this study. This analysis suggests that the accuracy of the retrieved parameters, using the method given here, is of ± 1.00 for the permittivity and ± 0.12 cm for surface roughness. Also, a comparison was conducted between the parameterization used in this study and the one of Wegmüller and Mätzler (1999) to estimate the soil contribution to the emitted brightness temperature of snowpacks. An improvement of 66% of the RMSE between the modeled and measured snow brightness temperatures was observed when using the approach of this study compared to the previous work. The method shows great potential to improve the estimation of the frozen soil contribution to the measured passive microwave brightness temperature.

1. Introduction

For many years, scientists have studied bare soil reflectivity modeling (Wang and Choudhury, 1981; Choudhury et al., 1979; Wegmüller and Mätzler, 1999; Schwank et al., 2010; Wigneron et al., 2011), partly motivated by the ability to retrieve soil moisture from satellite data, such with the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001, see also the review by Wigneron et al., 2017). The Soil Moisture Active and Passive (SMAP) mission (Brown et al., 2013) also studies soil moisture from satellite-based data, as well as the soil state (frozen/thawed) in northern regions (Spencer et al., 2013; Derksen et al., 2017). The majority of these studies mainly focus on L-band rather than higher frequencies (Kerr et al., 2012, Mialon et al., 2012, Wigneron et al., 2011, Lawrence et al., 2013, Shi et al., 2002), given the ability of such wavelengths to penetrate vegetation and snow. Some soil moisture products retrieved from higher frequencies such as the Advanced Microwave Scanning Radiometer for Earth Observation (AMSR-E) (Njoku, 2004; Zeng et al., 2014) and soil state products (frozen, thawed) using the Special Sensor Microwave Imager (SSM/I) exist (Kim et al., 2012). Nonetheless, these products are limited to areas where there is no dense vegetation, no snow cover and where the soil is not frozen. Also, they do not parameterize the soil properties.

For cryospheric studies, frequencies up to 37 GHz are commonly used (Dietz et al., 2012) and some studies have shown that, even at these high frequencies, the soil contribution to the emitted signal at the surface of the snowpack has to be considered (Montpetit et al., 2013; Roy et al., 2013). A major issue with the estimation of the soil contribution to the emitted signal at the surface is the estimation of frozen soil permittivity. Different models exist such as the one developed by Zhang et al. (2010) but still need further validation and information on soil characteristics (soil bulk density, volumetric moisture, temperature, etc.) that are complex to extract in remote arctic soils. Previous studies have tried to parameterize the soil using passive microwave measurements acquired at the surface of the snowpack using optimization schemes to limit the soil emission modeling errors (Montpetit et al., 2013; Roy et al., 2013; Pulliainen, 2006). No study has properly parameterized the frozen soils using passive microwave measurements of bare frozen soils at higher frequencies. This study aims to retrieve

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empirical parameters of a sub-arctic frozen organic soil using a simple model to account for passive microwave soil emission at frequencies commonly used in cryospheric studies (10.7, 19 and 37 GHz) and characterize its impact on results of studies using passive microwaves to retrieve snow properties.

In this paper, we present a simple method to retrieve effective passive microwave soil properties from brightness temperature measurements using the semi-empirical model developed by Wegmüller and Mätzler (1999) (hereafter referred to as WM99) and validate these properties using an independent dataset taken at different sites in northern Québec (see Section 2). We first describe the study sites and the geophysical and radiometric measurements. Then, the models and the optimization method will be detailed. The optimization and validation results will then be presented and discussed. Finally the importance of a proper frozen soil parameterization will be discussed for passive microwave snow studies.

2. Data and methods

2.1. Study sites and field measurements

The soil and radiometric data for this study were first collected in the James Bay area, Québec (53°26′N, 76°46′W, 186 m a.s.l.) during three intensive measurement periods (IMP) in January (8th to 12th, IMP1), February (12th to 17th, IMP2) and March (19th to 23rd, IMP3) of 2013. More data was also acquired near Umiujaq, Québec (56°33′N, 76°30′W, 74 m a.s.l.) during one intensive period in January (21st to 28th of 2014). The bare soil measurements were done in clearings with minimal influence from the environment (topography, vegetation, etc.) to the measured microwave brightness temperature (T_B). Fig. 1 shows an example of the soil measurement sites where the snow was removed to acquire the soil T_B measurements. A total of 8 sites were selected in this study where the soil composition mainly consisted of organic matter.

The soil T_B measurements were acquired using surface-based radiometers on a mobile sled at 10.7 (hereafter referred as 11 GHz), 19 and 37 GHz in both horizontal (H-Pol) and vertical (V-Pol) polarizations. Calibrations were done on a regular basis throughout the winter season using a warm and cold target as described by Asmus and Grant (1999). The downwelling $T_{B,sky}$ were estimated with an atmospheric absorption microwave model (Liebe, 1989) implemented in the Helsinki University of Technology (HUT, Pulliainen et al., 1999) model, using the 29 atmospheric layers above surface of the North American Regional Reanalysis (NARR Mesinger et al., 2006) data (see Roy et al., 2012). The measured T_B at frequency f and polarization p can then be described by:

Fig. 1. Example of bare soil site and the surface-based radiometers on a mobile sled.

$$T_{B,soil}(f,p) = e_{f,p} T_{soil}^{eff} + (1 - e_{f,p}) T_{B,sky}(f,p) \tag{1}$$

where $e_{f,p}$ is the rough soil emissivity at polarization p and $T_{soil}{}^{eff}$ is the effective soil physical temperature. Temperature profiles were taken using a Traceable 2000 digital temperature probe with an accuracy of 0.1 °C for depths of 0 to 10 cm with an interval of 2 cm. Since the soil is considered a homogeneous medium for this study, the effective soil temperature was estimated to be the averaged temperature over the first 5 cm. Other soil geophysical parameters such as soil roughness were not measured due to logistic challenges of working in remote sub-arctic environments.

Among the 8 sites analyzed, one James Bay site, measured on February 13th 2013, was considered for model calibration purposes (hereafter referred to as the BJcal site) since it was the only site where a wide range of incidence angle (0° to 60°) was measured with the surface-based radiometers. The site consisted of a bare soil area where the snow was removed (20 m long by 5 m wide) to eliminate any possible contribution coming from the snow walls around the bare soil surface. The BJcal site was revisited during the winter IMPs and other sites were measured during the 2013 winter campaign for validation purposes (hereafter referred to as BJval sites). The BJval sites are thus considered independent from the BJcal site since the soil properties were not the same ($T_{soil}{}^{eff}$ for example). The BJval sites were also clearings and soil temperatures varied from − 13 °C to − 5 °C. Three other validation sites were measured during the 2014 winter campaign in Umiujaq (hereafter referred to as UMIval sites). The UMIval sites were clearings and soil temperatures varied from − 17 °C to − 10 °C. Table 1 shows the mean $T_{B,soil}$, $T_{soil}{}^{eff}$ measurements and the measured incidence angles for the 2013 and 2014 winter campaigns.

2.2. Modeling and optimization framework

The WM99 model describes the rough soil reflectivity at a frequency f and polarization p ($\Gamma_{f,p}$) by its smooth Fresnel reflectivity in H-Pol ($\Gamma_{f,H}{}^{Fresnel}$), which depends on the incidence angle (θ) and the permittivity of the soil (ε_f), weighted by an attenuation factor that depends on the standard deviation in height of the surface (soil roughness, σ), the measured wavenumber (k) and a polarization ratio dependency factor (β_f). Semi-empirical equations (Eqs. (2) and (3)) were determined by Wegmüller and Mätzler (1999) using a large set of soil T_B measurements with a frequency range of 1–100 GHz and incidence angles of 20° to 70°. As shown in Montpetit et al. (2013, 2015), a modification to this model was applied for this study using a β_f factor (β_f = 0.655 in the original WM99 model) in Eq. (3) to take into account the frequency dependency of the polarization reflectivity ratio. This model was chosen over other soil reflectivity models because of the fewer parameters to optimize (7 parameters total) compared to other models tested in Montpetit et al. (2015). The WM99 model for incidence angle lower than 60° is therefore described by:

$$[1 - e_{f,H}(\theta,\varepsilon_f,\sigma)] = \Gamma_{f,H}(\theta,\varepsilon_f,\sigma) = \Gamma_{f,H}^{Fresnel}(\theta,\varepsilon_f)\exp(-(k\sigma)^{\sqrt{-0.1\cos\theta}}) \tag{2}$$

$$[1 - e_{f,V}(\theta,\varepsilon_f,\sigma)] = \Gamma_{f,V}(\theta,\varepsilon_f,\sigma) = \Gamma_{f,H}(\theta,\varepsilon_f,\sigma)\cos\theta^{\beta_f} \tag{3}$$

Using Eq. (1), for a given frequency and polarization, it is possible to derive the soil surface reflectivity using the measured soil temperature, the estimated downwelling $T_B{}^{sky}$ and the measured $T_B{}^{soil}$ at the soil surface.

The first part of the optimization process consisted in obtaining the two unknowns of Eq. (2), the soil permittivity (ε_f) and surface roughness (σ). Since the permittivity is frequency dependent and the surface roughness is a geophysical property of the soil surface considered frequency independent, four parameters (one permittivity per frequency and one soil roughness for all frequencies) were derived by minimizing