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Evaluation of multi-frequency bare soil microwave reflectivity models

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ABSTRACT

Passive microwave remote sensing is commonly used to monitor the hydrological processes of the earth's surface (soil moisture) as well as key surface environmental processes (vegetation dynamics, snow cover, etc.). For many applications, it is important to model the effects of surface roughness. This study focuses on the unique PORTOS-93 measurement campaign that covered a wide range of bare soil conditions in terms of moisture, temperature and surface roughness. The PORTOS-93 campaign covers a frequency range from 1.41 to 90 GHz. In this study, based on the PORTOS-93 dataset, we compare the Wegmüller & Mätzler (1999) model (referred to as WM99) with the Wang & Choudhury (1981) model (referred to as QHN) and evaluate their abilities to simulate the soil surface brightness temperature (T_B). We show that improved results were obtained by tuning the parameters of the two models to the entire PORTOS-93 dataset for each frequency separately compared to the model tuned independently of frequency. In addition we found that the Mironov et al. (2009) soil permittivity model is slightly more accurate at lower frequencies (<11 GHz) for simulating soil permittivity than the Dobson et al. (1985) soil permittivity model for the PORTOS-93 site. We also found that both of these permittivity models need to be tuned at higher frequencies (>20 GHz) and that using the Wang & Schmugge (1980) model tuned using parameters derived by Calvet et al. (1995a) at higher frequencies for the PORTOS-93 dataset gives best results. Using the proposed tuned reflectivity models for each frequency separately, we obtained an overall bias of −0.20 K and 0.21 K for the WM99 and QHN models respectively between the measured and modelled brightness temperatures. This corresponds to a significant improvement in comparison to the use of the tuned WM99 model independently of the frequency (bias = −38.08 K).

1. Introduction

Passive microwave remote sensing is commonly used to monitor hydrological processes as in the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001) and the National Aeronautics and Space Administration's (NASA) upcoming Soil Moisture Active and Passive (SMAP) mission (Brown et al., 2013). These missions mainly concentrate on L-band (1.41 GHz) microwave brightness temperatures (T_B) to retrieve the soil moisture (*SM*). In order to extract *SM*, the contribution from the soil to the overall T_B has to be isolated from other contributions such as the atmosphere (Kerr & Njoku, 1990), the vegetation (Wigneron et al., 2003) and the snow cover (Rautiainen et al., 2012). This signal also needs to take into account the soil surface properties such as surface roughness (Escorihuela et al., 2007; Wigneron et al., 2011) and soil texture (Njoku & Entekhabi, 1996; Wigneron et al., 2003).

The NASA National Snow and Ice Data Center (NSIDC) and the Japan Aerospace Exploration Agency (JAXA) provide standard soil moisture products from the Advanced Microwave Scanning Radiometer—Earth Observing System (AMSR-E) (Njoku, Jackson, Lakshmi, Chan, & Nghiem, 2003; Shibata, Imaoka, & Koike, 2003). The NSIDC AMSR-E Level 3 soil moisture product (Njoku et al., 2003) is based on an inversion algorithm from the 10.7 GHz and 18.7 GHz brightness temperature data using the empirical soil permittivity model of Wang and Schmugge (1980) and semi-empirical equations based on the Wang and Choudhury (1981) roughness model with three free parameters (hereinafter referred to as the QHN model): the roughness height (H_R), a polarisation mixing parameter (Q_R) and a parameter accounting for the angular dependency of the reflectivity (N_R). The JAXA product is based on the discrete ordinate method proposed by Tsang and Kong (1977) and the soil permittivity model of Dobson, Ulaby, Hallikainen, and El-Rayes (1985), hereafter referred to as the Soil Moisture Dielectric Mixing (SMDM) model. Validation studies show that the algorithms currently in use by JAXA and NASA still need improvements (see Jackson et al., 2010).

Studies for other environmental applications (land surface parameter retrieval such as vegetation and snow cover dynamics, or vegetation

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water content) based on higher frequencies (from 6 to 90 GHz) need accurate estimates of the soil signal under the canopy or the snow (e.g. Mätzler, 2006). In most of these studies, the soil contribution brings uncertainties that must be taken into account to improve the retrievals (see for example Calvet et al., 2011; Prigent, Wigneron, Rossow, & Pardo-Carrion, 2000).

Ground-based microwave experiments in combination with ground-truth measurements have been conducted to elaborate methods to relate *SM* to the L-band T_B such as PORTOS (Wigneron, Laguerre, & Kerr, 2001), SMOSREX (de Rosnay et al., 2006) and also airborne campaigns such as SMEX03 (Jackson et al., 2005), CanEx-SM10 (Magagi et al., 2013) and SMAPEx (Panciera et al., 2014). These studies have mainly proposed soil surface roughness corrections to the L-band T_B (Escorihuela et al., 2007; Schwank et al., 2010; Shi et al., 2002; Wang & Choudhury, 1981; Wigneron et al., 2011) but only a few studies have tried to apply these corrections to T_B at higher frequencies (>1.4 GHz, Calvet, Wigneron, Chanzy, & Haboudane, 1995; Prigent et al., 2000; Wang, O'Neill, Jackson, & Engman, 1983; Wegmüller & Mätzler, 1999).

For example the PORTOS-93 (Wigneron et al., 2011) and SMOSREX (Escorihuela et al., 2007) campaigns were conducted to relate the bare soil geophysical parameters (soil moisture, temperature, surface roughness, textural composition, etc.) to the simulated soil reflectivity at L-band using the QHN roughness model. Analysis of the PORTOS-93 data showed that the last two parameters could be neglected ($N_R = Q_R = 0$) with a low impact on the accuracy of the *SM* retrievals (Lawrence, Wigneron, Demontoux, Mialon, & Kerr, 2013). The SMOSREX study also showed that Q_R could be neglected but suggested that N_R had to be specific for a given polarisation and found that $N_{RV} = -1$ and $N_{RH} = 1$ (Escorihuela et al., 2007). Nonetheless, the values of N_{RV} and N_{RH} at L-band are not yet well established (Lawrence et al., 2013; Wigneron et al., 2007). Prigent et al. (2000) have shown that for higher frequencies (23.8 GHz and higher), to use such a QHN approach, all three parameters (H_R, Q_R and N_R) had to be considered. They have also shown that all three parameters were dependent upon the surface properties and type (smooth soil, rough soil or covered with vegetation) meaning that these parameters needed to be tuned for each area and can vary in time depending on the surface type (texture, roughness, etc.). Goodberlet and Mead (2014) suggested that to model the effects of soil surface roughness at L-band, the Q_R parameter should be considered and that it is related empirically to the surface roughness. Also, they suggested that H_R depended not only on the surface roughness but also on the Fresnel reflectivity (based on the soil surface permittivity which depends on soil moisture). This last result differs from previous studies. Finally, they showed that $N_{RV} = -2$ and $N_{RH} = 1$ which is similar to what Escorihuela et al. (2007) suggested. These different studies showed that there is a need to further investigate the effects of surface roughness on the soil reflectivity since there are still many questions concerning the calibration of the surface roughness parameters.

Other studies focusing mainly on vegetated areas used a similar approach to extract soil surface parameters from passive microwave T_B at higher frequencies. Calvet, Wigneron, Chanzy, and Haboudane (1995) showed that it is possible to retrieve Q_R and H_R at 23.8, 36.5 and 90 GHz for fields covered by sorghum and wheat canopies and estimate the soil contribution to the measured T_B. The latter study also showed that the soil dielectric properties could be modelled for silt–loam soils using the model of Wang and Schmugge (1980) (hereafter referred to as WS80), provided that it has been calibrated to the specific conditions of the fields. In this study, the three frequencies had to be treated separately.

Pellarin, Kerr, and Wigneron (2006) simulated T_B at C- (6.6 GHz) and X-bands (10.7 GHz) at global scale using the QHN model and have evaluated these simulations with the Scanning Multichannel Microwave Radiometer (SMMR) satellite T_B. They showed that the QHN model was able to reproduce realistic values of T_B at a global scale. Roy et al. (2012) showed that an optimization of the reflectivity model on the AMSR-E T_B converged to specific values of H_R and Q_R at 19 and 37 GHz over Canadian boreal forest sites. These last studies were conducted over vegetated areas where the soil contribution to the measured satellite T_B is attenuated by the overlaying canopy making the retrieval of soil parameters more complex.

The most complete study at higher frequencies (>10 GHz) was done by Wegmüller and Mätzler (1999) who developed a reflectivity model (hereinafter referred to as the WM99 model) that is based on the Mo and Schmugge (1987) parameterization for the frequency range of 1 to 100 GHz and incidence angle range of 20 to 70° for rough bare soils. They showed that the vertical (V-Pol) and horizontal polarisation (H-Pol) reflectivities were strongly correlated and that only one polarisation had to be modelled (either V or H) as a function of the soil variables, while the other could be derived from the former. Mo and Schmugge (1987) and Wegmüller and Mätzler (1999) found that it is preferable to model the H-Pol reflectivity as a function of the soil variables (soil roughness, moisture and temperature) and, in a second step, the V-Pol reflectivity can be computed from the modelled H-Pol reflectivity. Contrary to what was discussed by Calvet, Wigneron, Chanzy, Raju, and Laguerre (1995), they did not consider the reflectivities at different frequencies separately. This is mainly due to the fact that Wegmüller and Mätzler (1999) used the SMDM soil dielectric model (Dobson et al., 1985), whereas Calvet, Wigneron, Chanzy, Raju, and Laguerre (1995) used an empirical soil dielectric permittivity mixing model (Wang & Schmugge, 1980). More recently, a new soil permittivity model, referred to as the Generalized Refractive Mixing Dielectric Model (GRMDM), was developed (Mironov, Kerr, Wigneron, Kosolapova, & Demontoux, 2012; Mironov, Kosolapova, & Fomin, 2009). Recent studies (Goodberlet & Mead, 2014; Mialon et al., 2014; Wigneron et al., 2011, 2012) found that this new model provides accurate simulations of the soil dielectric constant in comparison to the SMDM model at L-band.

Here, we propose to evaluate the WM99 and QHN models using the unique PORTOS-93 multi-angular, bi-polarisation and multi-frequency dataset. To do so, 1) an evaluation of the permittivity modelling based on the SMDM, GRMDM and WS80 models was made in the 1–90 GHz range of frequencies, 2) then, we evaluated and compared the two semi-empirical soil reflectivity models (WM99 and QHN) and 3) finally a comparison between different tuned approaches of the WM99 and QHN models was made.

2. Materials and methods

2.1. Experimental dataset

The PORTOS-93 dataset is thoroughly described in Wigneron et al. (2001) and only a short description of the measurements will be given here. The measurements were taken over seven bare fields at the Institut National de la Recherche Agronomique (INRA) Avignon Remote Sensing test site during the period of April 20th to July 10th, 1993 (Table 1). The sites are silty clay loam fields with a textural

Table 1
Measured surface roughness parameter (σ), soil moisture (*SM*) and effective soil temperature (T_{soil}) over the different fields for the entire measurement campaign. The mean and standard deviation of the measurements over each field are given.

Field no.	Std deviation of height σ (mm)		Soil moisture *SM* ($m^3\ m^{-3}$)		Soil temperature T_{soil} (K)	
	Mean	Std	Mean	Std	Mean	Std
6	59.37	13.77	0.15	0.09	298.68	2.01
9	4.76	1.89	0.19	0.07	298.15	3.67
11	8.39	1.24	0.20	0.04	297.71	3.43
15	8.96	2.84	0.18	0.11	299.36	3.25
16	47.43	4.76	0.15	0.16	302.94	6.85
17	4.57	1.98	0.14	0.10	300.50	6.44
18	19.15	5.08	0.15	0.16	305.75	7.27