Remote Sensing of Environment 199 (2017) 63–77

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

# Reappraisal of the roughness effect parameterization schemes for L-band radiometry over bare soil

Bin Peng [a,b,*], Tianjie Zhao [a,*], Jiancheng Shi [a], Hui Lu [c], Arnaud Mialon [d], Yann H. Kerr [d], Xu Liang [e], Kaiyu Guan [b]

[a] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[b] National Center for Supercomputing Applications and Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana 61801, IL, USA
[c] Ministry of Education Key Laboratory for Earth System Modeling and Department of Earth System Science, Tsinghua University, Beijing 100084, China
[d] CESBIO, Université de Toulouse, CNES/CNRS/IRD/UPS, Toulouse 31400, France
[e] Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh 15261, PA, USA

## ARTICLE INFO

*Article history:*
Received 1 December 2015
Received in revised form 13 June 2017
Accepted 8 July 2017
Available online xxxx

*Keywords:*
Soil moisture
Brightness temperature
Roughness effect
Emission
Uncertainty
L-band radiometry

## ABSTRACT

Roughness effect parameterization is critical to accurately simulate brightness temperature (Tb) signals observed by a radiometer over bare soil surface. However, current roughness parameterization schemes usually suffer from severe error, which dominates the error budget in current Tb modeling over bare soil surface. In this study, uncertainty of soil roughness parameterization schemes is comprehensively assessed using data set collected during 2004 to 2006 at the Surface Monitoring Of the Soil Reservoir Experiment (SMOSREX) bare soil experimental site. To reduce uncertainty from sampling depth mismatch, the soil moisture profile with a 1 cm thickness from a calibrated Hydus-1D (H1D) model is utilized to determine the optimal soil moisture inputs to soil emission model. Uncertainties of 15 literature-based roughness effect parameterization schemes developed for L-band Tb modeling are inter-compared. The "$Q/H$" model is further calibrated against multi-angle and dual-polarization Tb observations at the SMOSREX bare soil site under different roughness conditions. Our results show that: (1) soil moisture sampling depth varies with soil moisture content and roughness condition. When soil is drier and rougher, the soil moisture sampling depth gets deeper. (2) The 15 roughness schemes generally perform better at vertical polarization than at horizontal polarization and better when soil surface is relative smooth than when soil surface gets rougher. The 15 roughness correction schemes have their own advantages and disadvantages with diverse error and bias characteristics. None of them has a superior performance at all conditions in terms of roughness, polarizations and incident angles. (3) A non-zero $Q$ configuration is preferred in parameter retrieval experiments and the observed linear relationship between $\Delta N$ and root-mean-square height ($\sigma$) or $\sigma^2/L_C$ can only be reproduced when $Q$ is non-zero in parameter retrieval. (4) The effective roughness parameters ($Q$, $N_p$ and $h$) generally increase when soil get rougher. The calibrated $Q$, $N_h$ and $N_v$ show exponential dependence on the effective parameter $h$. The calibrated $h$ still shows dependence on surface soil moisture after accounting the impact from soil sampling depth and also shows strong power-law dependence on Tb at incident angle of 40°. The non-zero-$Q$ fitting models have comparable performance in Tb modeling with zero-$Q$ models but may be more physically realistic.

## 1. Introduction

Soil moisture is an important storage component of the global water cycle (Koster et al., 2004; Koster and Suarez, 2001; Seneviratne et al., 2010) and has been endorsed as one of the Essential Climate Variables (ECVs) by the World Meteorological Organization (WMO). Soil moisture can be observed across different scales. In-situ observations using traditional gravimetric method (weighting and drying soil samples) or many indirect ways (Dobriyal et al., 2012) have pleasing accuracy at point scale. However, these in-situ measurements are insufficient for applications in larger scales due to the great spatial heterogeneity of soil moisture caused by inhomogeneous soil texture, landscape, vegetation cover, precipitation pattern, as well as agricultural management. Remote sensing technique is proper for regional/global surface soil moisture mapping. Up to present, L-band microwave remote sensing has been proved to be the most promising way to provide distributed surface soil moisture information at large scales (Njoku and Entekhabi, 1996). The Soil Moisture and Ocean Salinity mission (SMOS, launched in November 2009) (Kerr et al., 2010; Kerr et al., 2001) was the first L-band spaceborne radiometer for global soil moisture mapping, followed by the Aquarius/SAC-D mission (launched in June 2011 and ended in June 2015) (Le Vine et al., 2010; Le Vine et al., 2007) which was mainly

---

* Corresponding authors at: State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China.
*E-mail addresses:* binpeng@illinois.edu (B. Peng), zhaotj@radi.ac.cn (T. Zhao).

http://dx.doi.org/10.1016/j.rse.2017.07.006
0034-4257/

developed for oceanic applications but could be also utilized for global soil moisture monitoring (Bindlish et al., 2015). The newly launched Soil Moisture Active and Passive mission (SMAP, launched in January 2015) (Entekhabi et al., 2010a) radiometer is currently orbiting in space and providing valuable global soil moisture products to the community. The proposed SMOS-next (Soldo et al., 2013) and Water Cycle Observation Mission (WCOM) (Shi et al., 2014) projects with L-band radiometers are also expected to come into space soon in the near future.

Great efforts have been made in the last 30 years to retrieve soil moisture information from L-band brightness temperature (Tb) with promising accuracy (Chan et al., 2016; Chen et al., 2017; Chen et al., 2010; Colliander et al., 2017; Cui et al., 2016; Guo et al., 2013; Zhao et al., 2015). In the operational SMOS retrieval algorithm (Kerr et al., 2012), the soil moisture and vegetation optical depth (VOD) at nadir are simultaneously retrieved through the inversion of L-MEB (L-band Microwave Emission of the Biosphere) model (Wigneron et al., 2007) using SMOS multi-angle and dual polarization Tb observations. For SMAP level 2 soil moisture product from passive radiometer, five different but highly related algorithms, i.e. the Single Channel Algorithm using horizontal and vertical polarization observations (SCA-H and SCA-V), the Dual Channel Algorithm (DCA), the Microwave Polarization Ratio Algorithm (MPRA) based on the land parameter retrieval model and the extended DCA, are utilized to retrieve soil moisture from Tb at mono-incident angle of 40°. All of these algorithms are based on the inversion of a zero-order radiative transfer model (RTM), commonly known as tau-omega ($\tau$-$\omega$) model, which is also the basis of L-MEB model in SMOS algorithm. Any uncertainties in the RTM would lead to errors in the retrieved soil moisture products and accurately modeling Tb is therefore most critical in these retrieval algorithms. Moreover, L-band Tb assimilation has been recently shown to be more effective than soil moisture product assimilation (De Lannoy and Reichle, 2016a) as the inconsistency issues of model parameters (e.g. soil texture) and model variables (e.g. soil temperature profile) in satellite soil moisture assimilation can be avoided and satellite Tb product is a more straightforward geophysical observation and has less time latency than retrieved soil moisture product (De Lannoy and Reichle, 2016b; Lievens et al., 2015). Tb assimilation approach is also utilized in SMAP mission to provide operational level 4 surface and root-zone soil moisture product with high spatial (9 km) and temporal (3-hourly) resolutions (Reichle et al., 2014; Reichle et al., 2016). However, previous studies (De Lannoy et al., 2013; De Lannoy et al., 2014; Lievens et al., 2015) implied that significant discrepancy exists between the simulated Tb and SMOS observations and parameter calibration needs to be conducted globally such that the climatology of modeled Tb can match with that from satellite observations before Tb assimilation. Though this kind of parameter calibration is definitely appreciated and the prerequisite for a climatology-consistent Tb modeling system for L-band Tb assimilation, any changes to the land surface model structures, parameters or forcing inputs as well as the RTM itself would require a re-calibration (De Lannoy et al., 2013). Thus, more efforts are still needed to reduce the errors in RTM for both soil moisture retrieval and Tb assimilation applications. Presently, L-band Tb modeling is still hampered by the vegetation cover and soil roughness issues (Wigneron et al., 2017). For satellite missions aimed at soil moisture monitoring, it is essential to contend with the effects of vegetation cover over the soil surface. However, accurately modeling the signal from bare soil surface is an important first step. Here we focus on the soil roughness modeling for bare soil emission at L-band in this study.

Compared with physical based numerical models (Huang and Tsang, 2012; Huang et al., 2010; Li et al., 2000; Tsang et al., 2013a) and analytical models (Chen et al., 2003; Wu et al., 2001), semi-empirical models are preferred in soil moisture retrieval and Tb assimilation due to their relative simple model structures and high computation efficiency. The parameterization can be achieved through theoretical-based and experimental-based approaches (also see Table 1). The former approach is to parameterize the surface reflectivity/emissivity through Monte-Carlo runs of the theoretical models under a wide range of surface characteristics. Representative works of this approach at L-band utilize the analytical models, IEM (Integral Equation Model) (Shi et al., 2002) or AIEM (Advanced IEM) (Chen et al., 2010; Cui et al., 2016; Zhao et al., 2015), or numerical models, such as the NMM-3D (Numerical Maxwell Model-3 Dimensional) (Huang et al., 2010; Tsang et al., 2013b), as the their theoretical basis. As these schemes are parameterized from the database simulated by theoretical models, they are believed to be applicable for a wide range of surface conditions with good accuracy. However, they may also suffer from the issues related to volumetric scattering of dry soil particles (Lu et al., 2009; Lu et al., 2015) and they are not very tractable for interpreting spaceborne observations as they requires the geometric roughness parameters (root-mean-square height, autocorrelation length as well as autocorrelation function type) which are hard to measure or calibrate at satellite footprint scale (Wigneron et al., 2007).

The experimental-based semi-empirical models adopt totally different philosophy for parameterization and mainly are represented by the $Q/H$ type models (Choudhury et al., 1979; Escorihuela et al., 2007; Wang and Choudhury, 1981; Wang et al., 1983; Wigneron et al., 2011; Wigneron et al., 2001). Challenges in these $Q/H$ type models are to obtain effective roughness parameters through calibration and to build empirical relationships between the calibrated and measured roughness parameters. We are still struggling to have a consistent structure and parameter values in $Q/H$ models (Wigneron et al., 2017). For L-band, the polarization mixing factor $Q$ is widely believed to be not important and set to be zero in many literatures (Lawrence et al., 2013). This assumption has been proved to a good approximation when compared to experimental data (Escorihuela et al., 2007; Mo and Schmugge, 1987; Wegmüller and Mätzler, 1999; Wigneron et al., 2011; Wigneron et al., 2001). However, $Q$'s effect seems not to be neglectable and may become dominant at higher frequencies (Shi et al., 2005) or larger incident angles (Goodberlet and Mead, 2014) or when the effective roughness gets larger. Recent optimization studies using PORTOS-93 dataset (Montpetit et al., 2015) and SMOSREX06 dataset (Mialon et al., 2012) also implied a non-zero $Q$. Therefore, whether a non-zero $Q$ is needed in L-band Tb modeling still seems to be whirling. The physical relationship between $H_p$ or $h$ and the measured roughness parameters is still unclear (Lawrence et al., 2013). The originally proposed $h=(2k\sigma)^2$ by Choudhury et al. (1979) is a common choice in surface reflectivity/emissivity simulation (Wang and Choudhury, 1981). However, this might be too high for rough soil surface (Wigneron et al., 2011). Some other simple formula are also developed (Wigneron et al., 2011; Wigneron et al., 2001) to relate $h$ with root-mean-square height ($\sigma$) or slope ($m=\sigma/L_c$). Many studies show that $h$ may also be related with soil moisture (Escorihuela et al., 2007; Kerr et al., 2011; Kerr et al., 2012; Parrens et al., 2014; Saleh et al., 2007; Wigneron et al., 2001). However, the physical interpretation of this argument needs to be further studied. The angle dependence function $G(\theta)=\cos^{N_p}(\theta)$ also has significant effect on the simulated surface reflectivity. $N_p$ generally varies in the range of $[-2,2]$. In the complete coherent representation by Choudhury et al. (1979) and Wang and Choudhury (1981), $N_p$ was set to be 2.0 for both polarizations. Later study by Wang et al. (1983) shown that the $\cos^2\theta$ dependence would be too strong and set $N_p=0$. This assumption was also hold in studies by Wigneron et al. (2001) and Wigneron et al. (2011) for both polarizations and in SMOS algorithm for vertical polarization. Earlier calibration study over relative smooth bare soil surface over SMOSREX during 2004–2005 showed that $N_p=1.0$ for horizontal polarization while $N_p=-1$ for vertical polarization (Escorihuela et al., 2007). Later calibration over the same SMOSREX site during 2006 showed that $N_h$ and $N_v$ were 2.8 and 1.0, respectively for relative smooth condition, while were 0.59 and $-0.30$ for rough condition (Mialon et al., 2012).

As discussed above and also in a recent review by Wigneron et al. (2017), a variety of parameterization schemes holding different theoretical assumptions and calibrated under different soil moisture and roughness conditions were developed in previous studies. A