Remote Sensing of Environment 114 (2010) 995–1001

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Effective soil moisture sampling depth of L-band radiometry: A case study

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ARTICLE INFO

Article history:
Received 19 September 2009
Received in revised form 9 December 2009
Accepted 12 December 2009

Keywords:
Soil moisture
Passive microwave
SMOS
Roughness
Sampling depth

ABSTRACT

The aim of this study is to analyze the influence of the soil moisture sampling depth in the parameterization of soil emission in microwave radiometry at L-band. The analysis is based on brightness temperature, soil moisture and temperature measurements acquired over a bare soil during the SMOSREX experiment. A more detailed profile of surface soil moisture was obtained with a soil heat and water flows mechanistic model. It was found that (1) the soil moisture sampling depth depends on soil moisture conditions, (2) the effective soil moisture sampling depth is shallower than provided by widely used field moisture sensors, and (3) the soil moisture sampling depth has an impact on the calibration of soil roughness model parameters. These conclusions are crucial for the calibration and validation of remote sensing data at L-band.

1. Introduction

Soil moisture plays a key role in hydrological cycle. It is consequently a key variable for weather forecasting, climate studies, water resources and crop management, and forecasting extreme events. L-band (21 cm, 1.4 GHz) microwave radiometry has a high sensitivity to soil moisture and is among the best ways to estimate soil moisture by remote sensing. Other means (higher frequency radiometry, optical domain, active remote sensing) have a larger vulnerability to cloud cover and/or various perturbing factors such as roughness or vegetation cover (Kerr, 2007). As a consequence of recent technical developments, two new satellite missions, the Soil Moisture and Ocean Salinity (SMOS) and the Soil Moisture Active Passive (SMAP), will be providing for the first time global mapping of surface soil moisture based on radiometric measurements at L-band.

The radiative transfer models that simulate soil emission could be roughly divided between the coherent models and non-coherent model approaches. In coherent models approaches, the soil is seen as a layered medium and each layer is characterized by its dielectric constant and temperature. The contribution of each layer to the total soil microwave emission is determined by computing the propagation of a coherent electromagnetic wave, through the layered medium. In the non-coherent models, the soil is usually seen as a single layer with an effective soil moisture and effective temperature.

For operational applications involving microwave radiometry, soil moisture is generally estimated by inverting a simple non-coherent model of soil microwave emission. Raju et al. (1995) compared both approaches of soil modeling and they found that both accurately model soil emission provided that the non-coherent approach uses an appropriate soil moisture depth. They found that for L-band radiometers pertinent soil moisture depth was close to 2.5 cm.

In the framework of the SMOS mission preparation, several sites have been instrumented to calibrate and validate SMOS data when it becomes available. Field and airborne campaigns have been carried out to test, validate and understand better the radiative transfer models at L-band. Some of them have shown that, in order to accurately model soil emission, it was necessary to adjust a roughness parameter as a function of soil moisture. In this way, a linear dependency of soil roughness with soil moisture was found by Escorihuela et al. (2007b) over a bare soil on the SMOSREX site. Similarly, over vegetated areas, it was found that the calibration of the soil emission was essential to retrieve accurate estimates of soil moisture. The soil roughness parameters from field and airborne L-band microwave data over vegetated areas were found to be sensitive to soil moisture during the SMOSREX, the COSMOS and NAFE campaigns (Panciera et al., 2009; Saleh et al., 2006, 2009).

In these sites, surface soil moisture was monitored with sensors that provide an integrated measurement over the 0–5 cm surface layer. Although the L-band soil moisture sampling depth is expected to be somewhat shallower than 5 cm, this type of sensors are widely used to validate remote sensing data at L-band (Calvet et al., 2007;

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doi:10.1016/j.rse.2009.12.011

Merlin et al., 2008). This choice is dictated by the geometry of existing moisture sensors, which are difficult to install and maintain near the surface.

Our objective in this paper is to determine whether the parameterization of soil emission was affected by the depth of field soil moisture measurements. In particular, we investigated the relationship between soil roughness model parameters and soil moisture found in several studies (Escorihuela et al., 2007b; Panciera et al., 2009; Saleh et al., 2006, 2009).

2. Materials and methods

The SMOSREX experimental site is located in the South of France. The site is equipped with a complete meteorological station that measures precipitation, air temperature, atmospheric pressure, wind speed and direction, infrared and solar radiation and specific humidity. The site consists of two plots a bare soil and natural grass grown in a field left fallow, in this paper only measurements over the bare soil are considered. Soil moisture and temperature profiles were monitored every 30 min for the whole experiment. Soil moisture is measured by impedance probes installed at different depths between the soil surface and every 10 cm down to 90 cm deep. In addition, a set of thermistors was installed at the surface and along the soil profile down to a depth of 90 cm. Local Solar Time (LST) is used as time reference for SMOSREX data. The soil is texturally a loamy soil, with a composition of 17% clay, 36% sand, and 47% silt, a bulk density of 1.4 g cm^3 and a porosity of 40% at the surface. Further details concerning the SMOSREX experiment are given in de Rosnay et al. (2006).

In this paper, the data set extending from DOY 133 to DOY 366 in 2004 will be used. This data set has been already used to model soil emission; roughness parameters were found to be dependent on soil moisture (Escorihuela, et al., 2007b).

2.1. Surface soil moisture profile

Surface soil moisture was monitored using a set of impedance moisture sensors Delta-T Theta Probe ML2 (mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors). Surface sensors were vertically installed in the soil, providing an integrated measurement of the soil dielectric constant (K_{TP}) between 0 and 5 cm depth. In order to address the soil moisture spatial variability, there were four replicas of surface probes that were about 2 m apart. The relationship between K_{TP} and soil moisture (Θ_{TP}) was established by using field calibration. For that purpose, six soil samples were regularly randomly taken from the experimental field for a wide range of soil moisture conditions. Soil moisture was determined by gravimetry for each sample. The average for the six samples was used to estimate the volumetric soil moisture content at the LEWIS footprint scale. Temperature effects on moisture probes were corrected as in Escorihuela et al. (2007a).

In addition, for this experiment a more detailed profile of soil moisture was obtained with the TEC (Transfert Eau Chaleur) model, a soil heat and water flows mechanistic model (Chanzy & Bruckler, 1993). This model is based on the Philip and De Vries partial differential equations. These equations account for energy and water flows in partially saturated porous media and account for the liquid and vapor phases of the water reduced to the case of vertical flows. The nonlinear partial differential equations of the soil model are solved by a Galerkin finite element method. At the surface, the boundary conditions are obtained by solving the energy balance using climatic data (air temperature, vapor pressure and wind velocity at a height of 2 m and short-wave incoming solar radiation). Consequently, moisture and temperature dynamics are driven by the climate conditions. This mechanistic model simulates the changes of water content and temperature profiles under given climatic conditions.

The thermal conductivity was estimated using the De Vries equations (de Vries, 1963) whereas the parameters of the hydraulic functions (retention curve and unsaturated hydraulic conductivity) were fitted to match soil moisture and temperature measurements in the top 10 cm soil layer.

The model thus allows to obtain a finer description of the surface soil moisture. Surface soil moisture was calculated between 0 to 1 cm ($\Theta_{0\text{–}1\ \mathrm{cm}}$), 0 to 2 cm ($\Theta_{0\text{–}2\ \mathrm{cm}}$), 0 to 3 cm ($\Theta_{0\text{–}3\ \mathrm{cm}}$) and 0 to 5 cm ($\Theta_{0\text{–}5\ \mathrm{cm}}$) deep and could be computed at any depth down to 90 cm.

2.2. Surface roughness measurements

Before the experiment (in November 2003), the soil was slightly randomly ploughed; this work did not produce lines that could be visually observed. Basic roughness parameters were measured on the 4th of February 2004 and on the 2nd of April 2004. Roughness measurements were performed also after the experiment on 13th January 2006.

Soil roughness was characterized by means of a 2-m needle board. The board has 201 needles, 1-cm spacing, which are free to move vertically following the soil elevation profile. Roughness measurements were performed in the along and across directions of the radiometer field of view and replicated six times at each measurement date. The results from these measurements did not show any correlation with the measurement direction. Consequently, the roughness properties are considered to be randomly distributed, and the average value of all replications is considered hereafter. Results from the roughness measurements are shown in Table 1.

A power-curve was fitted with measurements in order to estimate the standard deviation of height (σ) during the experiment:

$$\sigma\,[\mathrm{mm}] = -26.11DOY^{0.06046} + 43.46. \tag{1}$$

According to this estimation, during the experiment σ would slightly decrease from about 8.4 mm to 6.1 mm. These measurements indicate that the soil is still evolving after ploughing due to meteorological phenomena (rain and wind). The σ ratio to the wavelength ($\lambda = 21.4$ cm) is quite small, which characterizes a rather smooth soil at this frequency.

Table 1

Results from roughness measurements over the SMOSREX field. The standard deviation height (σ) and correlation length (Lc) are given in mm. Six measurements were performed at each date, the standard deviation of measurements is given between brackets.

	4 Feb 04	2 Apr 04	13 Jan 06
σ	11.09 (3.6)	9.12 (2.1)	4.52 (1.2)
Lc	101.22 (42.2)	70.70 (33.7)	93.52 (37.5)

2.3. Radiometric measurements

Radiometric measurements were obtained by the L-band radiometer for Estimating Water In Soils (LEWIS). LEWIS is a L-band dual-polarization Dicke type radiometer and was specifically designed for the SMOSREX experiment. It is equipped with a Potter horn antenna of 1.3-m diameter, its beam-width at −3 dB is 13.6°, and the first side lobes are as low as −38 dB. The calculated beam efficiency is greater than 98%. The radiometer is thermally regulated at 0.02 K. The instrument resolution is 0.2 K for a 4 s integration time, and the estimated absolute calibration accuracy of the instrument is 0.5 K. The instrument is mounted on a 15-m-high structure. The radiometer features an automatic scan every 3 h to look at the bare soil at incidence angles from 20° to 60° (nadir = 0°), and at H and V