Retrievals of soil moisture and optical depth from CAROLS

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Abstract— We propose in this paper to evaluate a method to retrieve soil moisture (SM) and vegetation optical thickness, in areas of unknown roughness and unknown vegetation water content in view of operational applications, by using airborne Tb measurements acquired in South-West of France. Results are compared to *in situ* measurements, manual and automatic ones included in SMOSmania network, in the South-West of France.

1. INTRODUCTION

The European Space Agency has launched the SMOS (Soil Moisture and Ocean Salinity) satellite during the spring of 2009. The generation of land products from SMOS brightness temperature (Tb) measurements relies on the inversion of the microwave forward model L-MEB (L-band Microwave model of the Biosphere) [7]. The L-MEB model assembles a set of equations describing the emission and scattering of the surface, vegetation and atmosphere at L-band (1.4 GHz). The calibration of L-MEB for different surfaces has been addressed by numerous studies over the last ten years, most of them based on the analysis of ground-based L-band data. The study presented here is base on results of the CAROLS study [8], designed in support of the CAL-VAL of SMOS and of the evaluation of the L-MEB model over land surfaces.

We propose in this paper to evaluate a method to retrieve soil moisture (SM) in areas of unknown roughness and unknown vegetation water content in view of operational applications, by using airborne Tb measurements acquired at two incidence angles and two polarizations. We made the assumption that the roughness parameter was dependent on SM; this roughness correction was used in the 2-Parameter retrievals of soil moisture and optical depth for all flights. Results are compared to *in situ* measurements, manual and automatic ones included in SMOSmania network, in the South-West of France. Very good agreement between these sources of SM estimation was optained which is very promising for future SMOS validation activities.

We will first present CAROLS data (II), the radiative transfert model (III) and finaly comparison between measurements and model inversion (IV).

2. CAROLS DATA PRESENTATION

In the context of the SMOS Cal/Val project, an airborn radiometer was developed and installed in an aircraft since 2007. Airborne campaigns were conducted in 2007, 2008 and 2009 for scientific and technical purposes and a final campaign was conducted in 2010 after the launch of the SMOS satellite. Details of the campaigns are available in the paper of Zribi et al. [8] and we summarize here the main informations about these campaigns.

2.1. CAROLS Radiometric Data

In 2007, we developped with the collaboration of TUD (Technical University of Denmark) a radiometer as a copy of EMIRAD [1]. This radiometer was tested onboard in 2007. Its main characteristics are:

- Frequency: 1400–1427 MHz at −3 dB, Digital I/Q demodulation and correlation for accurate estimation of the 3rd and 4th Stokes parameters,
- Data integrated for 1 ms, and recorded on a primary storage PC,
- The raw data pre-integrated to 1.8 μs is recorded on a dedicated PC.

Two antennas were installed in the plane, one nadir looking and one right side looking antenna (view angle around 33 degrees). The radiometer was programmed to switch on each antenna alternatively every 5 seconds.

The radiometer was calibrated using laboratory measurements, automatic calibration with two internal sources and additionnal losses are estimated using a well known ocean target. Far from the coast, salinity and temperature are stable during the campaign and we were able to compute Tb values with a sufficient accuracy. The radiometer performences were estimated in laboratory and we showed that stability and accuracy were arround 0.1 K during the whole 2009 campaign.

2.2. CAROLS 2009 Flights

In 2009 13 flights were conducted during Spring (23/04/2009–28/05/2009). The plane was taking off in Toulouse (France) and different sites were overligthed: Gulf of Biscay, South West of France and Valencia site (VAS).

In this paper we only used Tb measured in the South West of France, overflying the SMOSmania test sites operated by Meteo-France [2]. In Figure 1, we show the flight path and the location of the SMOSmania sites.

2.3. Brightness Temperature Preprocessing

Before estimating the soil moisture, different steps were applied to correct Tb.

- The first step is the projection of Tb measured from the antenna frame (X and Y polarization) into the earth frame (H and V polarization).
- Combination of Tb values measured with the nadir antenna with the more closed Tb values measured with the slant antenna.
- Filtering data that are poluated by Radio Frequency Interferences (RFI) was based on Kurtosis and Tb standard deviation thresholding [4].

Then radiative model inversion was applied to these corrected Tb data.

2.4. Ground Based Measurements

In the meantime of the flights, different automatic and manual measurements were done *in situ*:

- Soil moisture (SM) and soil temperature (ST) were estimated every 30 mn using TDR (Time Domain Reflectometry) measurements on the 12 sites within the SMOSmania network [2]. In this study, we used TDR measurements at 5 cm depth to evaluate the Tb inversion process.
- Specific fields were choosen in 2009 for in situ gravimetric SM measurements, temperature and theta probes measurements too. One part ot these fields are located near Bordeaux, on the Western part of the flight and the other part is located near Toulouse.

Location of the 12 SMOSmania ground stations are shown on Figure 1.

On this figure, we showed the flight path and we can see the distance between some of the stations and the flight path. To estimate the soil moiture values under the path, we had to extrapolate the values measured by the automatic stations.

All SM *in situ* measurements were used to evaluate the ability of the model inversion to estimate surface SM.

3. RADIATIVE TRANSFERT MODEL

The radiative model we used to compute surface Tb values is the L-Meb model [7] described and used in many studies. This model represents the soil as a surface in contact with the atmosphere, and the vegetation as a homogeneous layer. This model computes soil emission based on the Dobson [3] or Mironov model, vegetation contribution to the surface Tb is computed based on the τ-ω model where the ω parameter is supposed to be close to zero. Then the only vegetation parameter is the optical thickness τ which, in this study was supposed not to be independent on the view angle. The general equation describing the effect of soil and vegetation on the surface Tb is:

$$Tb(\theta, P) = (1 - \omega_{\theta,P})(1 - \gamma_{\theta,P})1 + \Gamma_{\theta,P}\gamma_{\theta,P} \cdot T_{veg} + (1 - \Gamma_{\theta,P})\gamma_{SM,P}T_{\mathit{eff}} \tag{1}$$

where T_{eff} and T_{veg} are the effective soil and vegetation temperatures, ω and γ are respectively the single scattering albedo and the transmissivity of the vegetation layer, varying with the polarization

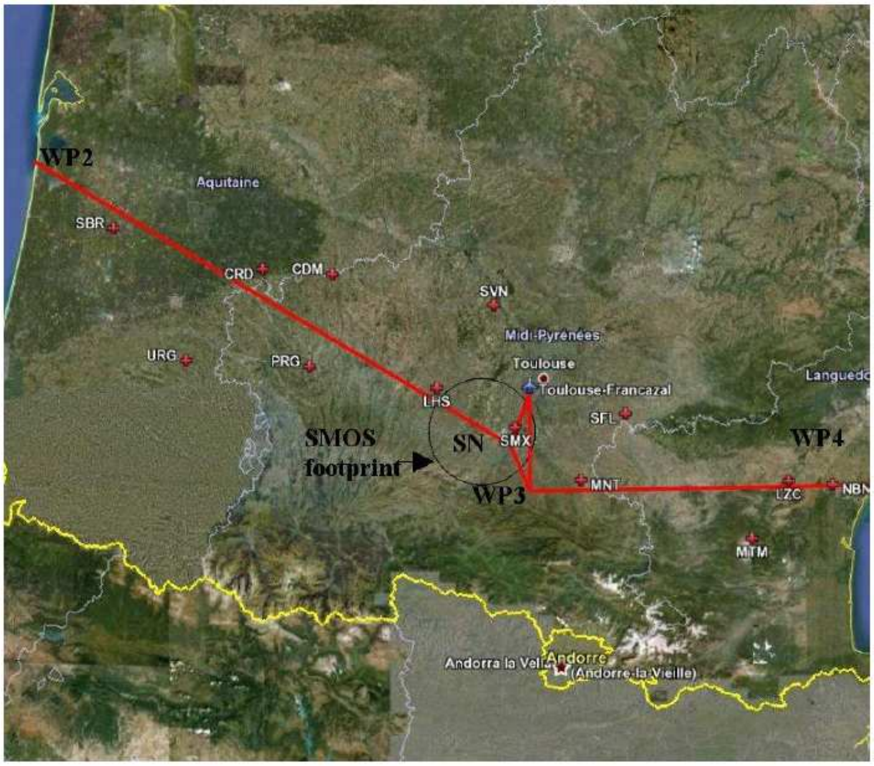


Figure 1: Position of the SMOSmania stations in the South-West of France. Red line show the position of the Flight path.

P and the view angle θ. The transmissivity is linked to the optical thickness:

$$\gamma_{\theta,P} = \exp - \frac{\tau_P}{\cos(\theta)} \tag{2}$$

The reflectivity of a rough soil, Γ is controlled by the soil roughness parameters. T_{eff} was estimated based on (i) the surface temperature (T_s) (ii) the in-depth physical temperature (T_{depth}), using the equation:

$$T_{\mathit{eff}} = T_{depth} + (T_s - T_{depth} \cdot (SM/xa))^{xb} \tag{3}$$

where $wa = 0.739$ and $wb = 0.2585$. We used airborne infra-red temperature measurements to estimate T_s. In-depth temperature were estimated using SMOSmania measurements at 50 cm depth extrapolated under the flight path (temperature variations are supposed to be weak).

Roughness parameter is also a major problem in the soil surface Tb modelisation. We made the assumption in this paper that the roughness parameter H depends on surface SM as described in [6]:

$$H = 1 - 1.13 \times SM \tag{4}$$

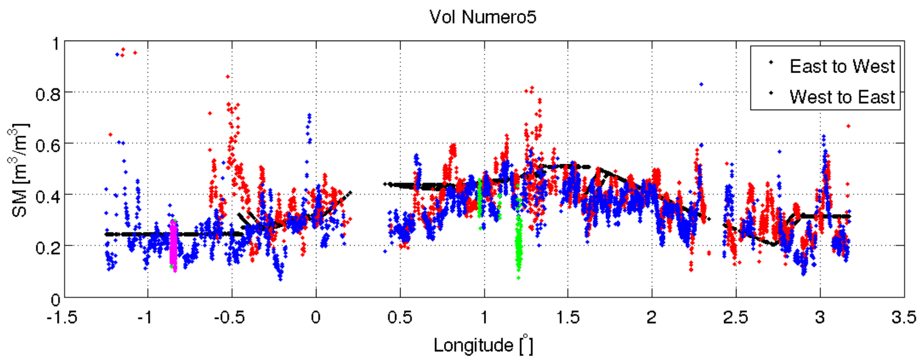
We finally have two unknown parameters to estimate: SM and the optical depth, τ. For that purpose we used non linear regression based on Gauss-Marquardt algorithm to minimizes a cost function between the 4 simulated Tb values and the 4 measured ones (the method is described in [5]).

4. RESULTS OF SURFACE SOIL MOISTURE ESTIMATION

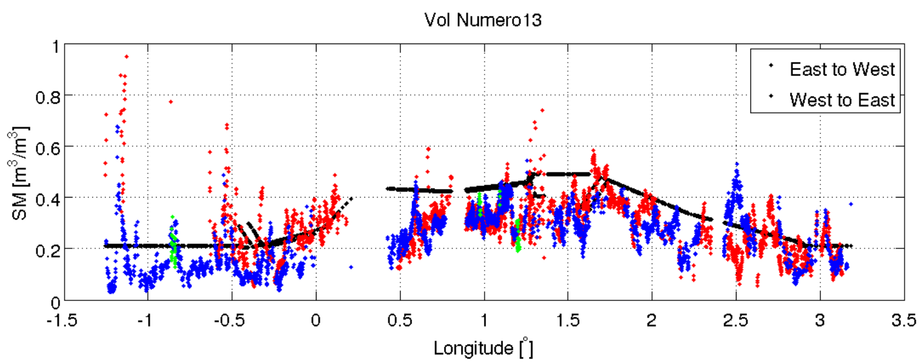
For each 4 Tb measurements we estimated the two SM and τ parameters. SM values were compared with two pools of *in situ* data: SM measured in SMOSmania stations and SM measured manualy under the flight path. SMOSmania SM measurements were spatial interpolations of measurements mad at each each CAROLS sites. These results are presented in the next 2 figures: Figures 2 and 3.

In Figures 2, we present SM spatial variations as estimated by CAROLS during two flights compared to *in situ* measurements. We show that despite some strong SM variations, probably due to heterogeneous landscapes, and a light underestimation in SM estimation, a general good agreement was found between these two ways of estimating SM. Temporal and Spatial variations are well mapped by CAROLS retrievals. In Figure 3, we compared local SM values to the mean remote-sensely retrieved SM value. Data concerning all flights where plotted on the same figure and good correlation is found: $R = 0.69$, the RMSE is $0.08\,\mathrm{m}^3/\mathrm{m}^3$.

Figure 4 shows estimated τ spatial variations for the flights 5 and 13. Values are between 0 and 0.2 in general, but in the Western part, it seems that this estimated value is larger, may be due to the presence of 'Les Landes' forest.



(a)



(b)

Figure 2: Comparison between SM spatial variation estimated with CAROLS and with in situ measurements, concerning flight 5 (a) and 13 (b). Red and Blue points are related to remote sensed SM, for out and home travel; Black points are interpolation of SMOSmania SM automatic measurements under the flight track; green and mauve are undertrack SM measurements.

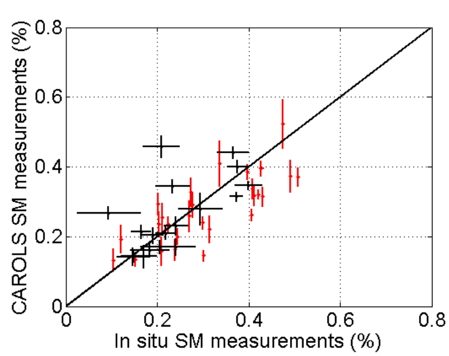


Figure 3: SM retrievals from CAROLS flight compared to local SM measurements. Black points concern SMOSmania measurements, red one concern handmade measurements under the flight track. Bars indicate the standard deviation of the field soil moisture and the retrieved soil moisture.

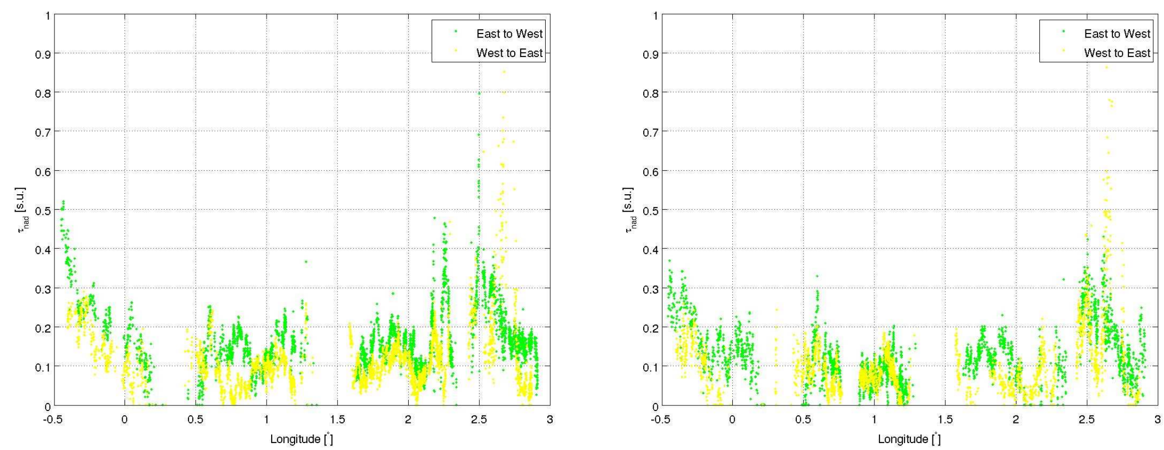


Figure 4: Vegetation optical thickness τ parameter variations with space for flight (a) 5 and (b) 13. The two colors are for the two parts of the flight (out and home).

5. DISCUSSION AND CONCLUSION

This paper investigated L-band measurements over forests and low crops obtained from oan airborne L-band radiometer (CAROLS) during the CAROLS'09 campaign in South-West France. The main objective of the study was to evaluate the performance of the microwave radiative transfer model which sits at the core of ESA's SMOS soil moisture algorithm. The approach developed here is based on a two-parameter inversion of the radiative transfer model (L-MEB) using non linear regression using 4 brightness temperature measurements: two view angles and two polarizations. We compared SM estimations with *in situ* SM measurements and we showed a very good agreement between these two data sets. The next steps of this study are (i) correction of Tb measurements using DEM (ii) comparison between τ and remotely sensed vegetation parameters like LAI or NDVI.

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