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Evaluating the L-MEB model from long term microwave measurements over a rough field, SMOSREX 2006

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***Abstract*—The present study analyses the effects of the roughness on the surface emission at L-band based on observations acquired during a long term experiment. At the SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment) site near Toulouse, France, a bare soil was ploughed and monitored over more than a year by means of a L-band radiometer, profile soil moisture and temperature sensors as well as a local weather station, accompanied by 12 roughness campaigns. The aim of this study is (1) to present this unique database, and (2) to use this dataset to investigate the semi-empirical parameters for the roughness in L-MEB (L-Band Microwave Emission of the Biosphere), that is the forward model used in the SMOS (Soil Moisture and Ocean Salinity) soil moisture retrieval algorithm. In particular, we studied the link between these semi empirical parameters and the soil roughness characteristics expressed in terms of standard deviation of surface height (σ) and the correlation length (LC). The dataset verifies that roughness effects decrease the sensitivity of surface emission to soil moisture, an effect which is most pronounced at high incidence angles and soil moisture and at horizontal polarization. Contradictory to previous studies, the semi-empirical parameter Qr was not found to be equal to 0 for rough conditions. A linear relationship between the semi-empirical parameters N and σ was established, while N_H and N_V appeared to be lower for a rough ($N_H \sim 0.59$ and $N_V \sim -0.3$) than for a quasi-smooth surface. This study reveals the complexity of roughness effects and demonstrates the great value of a sound long-term dataset of rough L-band surface emissions to improve our understanding on the matter.**

***Index Terms*—SMOS, Roughness, Passive Microwave, L-band, L-MEB model.**

I. INTRODUCTION

SOIL moisture is a key parameter controlling air-land interface exchanges. Although very important in many applications (climate models, agriculture, water resources management), it is difficult to monitor this variable at a global scale. The SMOS (Soil Moisture and Ocean Salinity) satellite mission [1; 2], successfully launched in November 2009, is the first mission to deliver global surface soil moisture fields at a high temporal resolution of 3 days. The retrieval scheme to derive soil moisture [3] is based on multi-angular passive microwave brightness temperatures (f=1.4 GHz) as measured by the instrument [4] and on surface emission models at L-band (L-MEB, L-band Microwave Emission of the Biosphere [5; 6; 7]).

Land surface emission at this wavelength is mainly controlled by soil moisture but important issues are still to be tackled [8] such as roughness, which is the focus of this paper. Roughness influence on surface emission is complex as it implies 3-D geometric soil surface features as well as soil moisture heterogeneity, in particular between peaks and hollows. Its major effect is to decrease the sensitivity of L-band brightness temperatures to soil moisture [9; 10]. Shi et al. [11] found by the use of an Integral Equation Model (IEM) that roughness influence is more significant at high incidence angles and high soil moisture content as well as a function of polarization. They noted an increase in emissivity with roughness at the horizontal polarization at low incidence angles. For dry soil, the emissivity of the vertical polarization (typically higher than ~0.8) shows a decrease compared with that of a flat surface, whereas for wet soil (emissivity lower than ~0.8) an increase is observed.

Using complex models as the IEM approach to compute the surface emissivity is not possible in the SMOS soil moisture algorithm as it needs many inputs and its computation is time demanding. Instead the SMOS level2 retrieval algorithm [3] uses semi-empirical approaches [7; 8] to compute the emission of the surface. The correction for a rough surface [9; 10; 12; 13]

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is based on empirical parameters (Hr, N_V, N_H, Qr) that have to be calibrated with in-situ data reflecting local surface characteristics (soil texture, level of roughness). Most recent studies on L-band emission [14; 15; 16] have retrieved these parameters to best fit the observations, but more investigations are needed on roughness to relate the soil L-MEB parameters to the surface roughness characteristics.

The roughness analyses conducted so far have all been either restricted to short investigation periods [17; 13] or to almost flat surface conditions [18] only. These have motivated the present study which for the first time focuses on a rough soil observed over a long time period at the SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment) site in 2006/07. A bare soil was ploughed creating a very rough surface and its roughness evolved for over more than a year naturally due to climatic events (rainfalls, wind).

The aim of this study is twofold. First, this unique database (referred to as SMOSREX-2006) is presented and the L-band observations over the rough surface covering a wide range of soil moisture conditions (from very wet to very dry) are analysed over a long period of time (14 months). Second, the SMOSREX-2006 is used to evaluate the roughness parameters of the semi empirical model used in the L-MEB model. Qr, Hr and N_p (p for the polarization horizontal or vertical) are retrieved in this evaluation and compared with the surface roughness characteristics.

II. MATERIAL

A. Database and experimental site

In preparation of the SMOS mission, the experimental site of SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment [19]) has been set up near Toulouse in the Southwest of France. Operating since 2003, the database has been used to improve the models implemented in the SMOS soil moisture retrieval [3; 20; 18].
It is equipped with the LEWIS (L-band radiometer for Estimating Water in Soil) radiometer [21] which has been continuously monitoring the emission of the surface. The instrument, placed on a 15m high tower can monitor two fields, one with grasscover and a bare soil. It acquires brightness temperatures at vertical and horizontal polarizations (commonly referred to as V and H) at the same frequency as SMOS, i.e. 1.4 GHz, at several incidence angles (i.e. 20, 30, 40, 50 and 60^o) every 3 hours (i.e. 2h30, 5h30, 8h30, 11h30, 14h30, 17h30, 20h30, 23h30 UTC).
Additionally, ground measurements are available. Soil texture was analysed and the bare soil was found to be 17% clay , 36% sand and 47% silt [19]. The SMOSREX site is equipped with a weather station, which has been monitoring meteorological data (air temperature, pressure, precipitation, wind) and soil moisture and temperature profiles are measured on each field every 30 minutes. Temperatures measured at different depths, i.e. at 1cm, 5cm, 20cm, 50cm and 90cm with one probe per depth, at the same location as the soil moisture probes, are used to compute the soil temperature. Surface soil moisture is obtained by averaging data from 5 probes placed at the surface (top 0-6 cm layer) on the bare soil field. Soil moisture probes are calibrated from gravimetric measurements [22], from which soil density is estimated.
It is important to note that obtaining an accurate estimation of soil moisture is difficult and can be slightly different from what contributes to the brightness temperatures measured by the radiometer. Due to surface heterogeneity, some differences can occur between the surface covered by the probes ($\sim$4m^2) and LEWIS field of view that covers a wider surface [19]. Moreover, peaks and hollows imply strong heterogeneity in the surface soil moisture conditions, as soil water content is generally higher in hollows than on peaks. Finally, soil moisture probes measure the dielectric constant over the 0-6 cm top soil layer, whereas the surface emission in L-band is expected to be correlated to the soil moisture of the top 2-3 cm soil layer [23].

B. Roughness measurements

The roughness experiment took place on the bare soil field. On January 13th, 2006 the field was ploughed in a deep manner to ensure a distinct row structure parallel to LEWIS plane of incidence. Thereafter, surface roughness changed naturally over time in response to climatic events, mainly rainfalls and wind.

Surface roughness is measured by means of a two meter long needle board with 201 needles at 1 cm spacing. The needles move freely in the vertical direction and were allowed to fall til they touched the surface reproducing surface variations. Twelve measurement campaigns were conducted over the following 14 months (see Table I), each consisting in the acquisition of several roughness profiles (up to 6), in both directions, i.e. parallel and perpendicular to the plane of incidence of the LEWIS instrument. Pictures of each vertical profiles were taken with a digital camera to obtain the corresponding numerical profiles of the height variation. These were then used to derive two statistical parameters describing the surface, the standard deviation of heights -σ- and the correlation length -LC [24]. The daily σ are obtained by averaging the variance, i.e. σ^2, of the different samples acquired in both directions. LC was derived from the auto-correlation function C(x), Eq. 1 [24; 25], which measures the correlation between two heights separated by a distance x:

$$C(x) = \frac{\sum_{i=1}^{N+1-j} z_i \cdot z_{j+1-i}}{\sum_{i=1}^{N} z_i^2} \tag{1}$$

where z(i) is the height of the needles; j an integer ≥ 1; the spatial displacement x=(j-1).δx; δx being the distance between 2 needles, i.e. 1 cm; N the number of needles N=201. The LC corresponds to the distance x where the correlation function (Eq. 1) has decreased to 1/e, i.e. beyond which two heights are no longer statistically correlated [24]. The auto-correlation function is commonly approximated by the function $C(x)=\exp\frac{(-|x|^n}{LC^n})$, where n=1 for the Exponential model or n=2 for the Gaussian model [26; 25; 27]. For each day of measurement LC is simply the average of the different profiles, mixing both directions. For example, a flat surface is characterized by a low σ and a high LC.

Data acquired before this campaign, i.e. in February and April 2004 [18] and in January 13th just before ploughing the soil, are also used as they provide additionnal information concerning a quasi-smooth surface. Roughness was also measured in 2010 so that the soil roughness temporal variation could be estimated at interannual scale.

III. METHODOLOGY

A. *Observations*

The first part of our study is dedicated to surface emission at L-band as observed by the LEWIS radiometer. All cases such as freezing, snow (snow storm on January 28-30 2006) that may introduce artefacts are excluded from the dataset. It is more pertinent to study surface emissivity than brightness temperature as the latter is also influenced by the soil temperature. The emissivity ε of a bare soil is obtained from the measured brightness temperatures by removing surface temperature and the sky contributions by applying the following ε_p =(TB$_p$ - TB$_{sky}$) / (Teff - TB$_{sky}$), where the subscript p stands for the polarization (H or V), and Teff is the effective soil temperature [28] as computed from measured temperatures at all depths based on [19; 29]. The sky contribution T$_{sky}$ is quite low at L-band and set to a constant value of 3.7 K according to [21; 30].

To study the effect of surface roughness on the measured signal, the prevailing surface conditions are divided into four classes of differing σ. Ranges of σ are defined from a trend of measured σ (Eq. 5) to better emphasize the effect of roughness on the signal. The evolution of σ with time (Table I and Fig. 1) suggests the following ranges : $\sigma < 16$ mm relative to smooth surface, i.e. before the campaign ; σ belonging to the range 16-20 mm characterizing the steady state reached by the surface at the end of the campaign, from the end of April 2006 to March 2007 ; σ between 20 and 24 mm for the transition between very rough and steady state surface, from February to April 2006 ; and a last case concerning a very rough surface characterized by a σ higher than 24 mm, just after ploughing.

B. *Surface modeling*

This database is also used to retrieve and study the semi-empirical parameters in the L-MEB that account for the effect of a rough surface [3; 7]. The emission of a flat surface is obtained by computing its dielectric constant from soil conditions, i.e. texture, temperature and surface soil moisture. The model developed by Mironov et al. [31; 32] is used as it has been shown to be more relevant for our experiment site [23] than the Dobson's model [33; 34]. The reflectivity Γ = 1-ε, is then derived using Fresnel's law for a flat soil. The surface emission, or reflectivity, must then be corrected to take into account a rough air-soil interface. This roughness contribution is estimated by the following semi-empirical approach [10; 17; 18]:

$$\Gamma_p(\theta) = [(1-Qr).\Gamma_p^o(\theta) + Qr.\Gamma_q^o(\theta)].e^{-Hr.cos^{N_p}(\theta)} \tag{2}$$

where Γ is the reflectivity with the subscripts p and q = V or H for the Horizontal and Vertical polarizations; the index 0 stands for reflectivity of a flat surface computed from the Fresnel's law; θ being the incidence angle; Qr, Hr, N$_p$ are the roughness parameters to be calibrated [10; 17]. Qr is a mixing factor that allows us to take into account the polarization mixing caused by the rough surface, N$_p$ allows us to account for the incidence angle [35] and depends on the polarisation [18] and Hr is the effective roughness parameter.

A first attempt to relate these empirical parameters to surface roughness suggested that Hr = $(2k\sigma)^2$ [9]. Hr was also found to depend on soil moisture [17; 18; 14] but as it has not been confirmed [23], it is not considered in the present study. This dependence could be partially explained by a mismatch between sampling depth of soil moisture sensors and the actual depth of the surface emission layer in L-band [23]. N$_p$ (p = H or V for horizontal and vertical polarization) was found to be different for the two polarizations and N$_H$=1 and N$_V$=-1 were found for our SMOSREX site [18]. Qr is generally considered to be negligible [14; 15; 13; 18] at L-band but in reality a rough surface implies a mixing in polarization [10; 26] that can only be simulated by setting Qr > 0 [11].

Parameter retrieval:
4 parameters are unknown in Eq. 2, that are Qr, Hr, N$_H$ and N$_V$. The retrieval is done in two steps. The first one is based on a relationship between N$_H$ and N$_V$ [18]. Indeed, both theory using Fresnel's law and observations over a flat surface show that the reflectivity at H and V polarizations are related by the following approximate equation (see [18]):

$$\Gamma_H(\theta) = [\Gamma_V(\theta)]^{cos^{\Delta N}(\theta)} \qquad (3)$$

For a smooth surface, ΔN (Eq. 3), i.e. the difference (N$_H$ - N$_V$), was found to be equal to 2 [18] which is not relevant for a rough surface [11]. $\Gamma_H(\theta)$ and $\Gamma_V(\theta)$ are extracted from our database (i.e. LEWIS measurements) for each day of the roughness campaign (see Table I, left hand column) allowing us to compute ΔN for rough conditions. The second step uses Eq. 2 from Lewis brightness temperatures, where N$_H$ - N$_V$ are linked together as a results of the first step.
The retrieval consists of minimizing a cost function that computes the quadratic differences between measured emissivities (ε_{lewis} at incidence angles of θ = 20, 30, 40, 50^o and both polarizations) and simulated emissivities (ε_{model}). This sets the best values of parameters (Eq. 2) that fit the observations [3] [5]. The cost function to be minimized is:

$$CF = \frac{\sum(\varepsilon_{lewis} - \varepsilon_{model})^2}{\delta(\varepsilon_{lewis})^2} + \sum_i \frac{\sum(P_i^{init} - P_i)^2}{\delta(P_i^2)} \qquad (4)$$

where ε_{lewis} at all angles and polarizations are used; $\delta(\varepsilon_{lewis})$ being the error in emissivity measured by LEWIS instrument [21]; P$_i$ are the retrieved parameters (Qr, Hr, and N$_p$), P$_i^{init}$ the initial values of the retrieved parameters (respectively Qr^{init} = 0.1, Hr^{init} = 0.75, N$_p{}^{init}$ = 1); and $\delta(P_i)$ the standard deviation of the retrieved parameters (δQr = 1, δHr = 2, δN$_H$ = 1).

As Qr was found to be = 0 [13], two cases are considered here: A) where Qr = 0 and Hr, N$_H$ and N$_V$ are retrieved and B) all the 4 parameters Qr, Hr, N$_H$ and N$_V$ are retrieved.

IV. RESULTS AND DISCUSSION

This section presents the results obtained from the SMOSREX-2006 campaign. Firstly, roughness measurements are presented for 14 months and secondly, the emissivities measured by the LEWIS instrument are analyzed to better understand the effect of roughness on the L-band surface emission. Finally, this database is used to study the semi empirical model that accounts for roughness in L-MEB. The parameters of the semi-empirical model are derived and related to surface roughness conditions.

A. *Measured roughness*

Table I presents the means and standard deviations of σ and LC as well as the ratio σ/LC acquired during each day of the campaign. Mean values are obtained considering samples at both orientations, i.e. parallel and perpendicular to LEWIS plane of incidence. Before ploughing, the surface was almost flat characterized by σ=4.73±1.31 mm and a correlation length LC = 94.11 ± 38.81 mm. As a comparison, previous measurements of the SMOSREX site [18] reported σ = 11.09 mm in February 2004 and σ = 9.12 mm in April 2004, indicating a smooth surface. After ploughing, the surface was characterized by a standard deviation height σ of 34.58 mm ± 10.29 mm and a correlation length of 62.42±26.68 mm. The auto-correlation functions (Eq. 1) suggest that the surface is closer to an exponential one than a gaussian one [26; 27].

The time variations of σ (top panel), the correlation length (2nd panel from the top), the soil moisture (3rd panel from the top) from the end of 2005 to March 2007 and the emissivity monitored at an incidence angle of 40 at both polarizations (bottom panel) are given in Fig. 1. The effects of the soil ploughing can be clearly distinguished on January 13th (top panel) and is characterized

TABLE I

STANDARD DEVIATION OF HEIGHTS, σ, AND THE CORRELATION LENGTH, LC, FOR EACH DAY OF THE CAMPAIGN. σ AND LC ARE AVERAGED FROM EVERY SAMPLES ACQUIRED AT BOTH DIRECTIONS. THE RIGHT-HAND COLUMN IS THE RATIO σ/LC

date	Roughness Characteristics		
Year mm/dd/yy	Standard Deviation of surface height σ (mm)	correlation length LC (mm)	σ/LC (mm)
02-07-03*	11.51* ± 2.72	59.56* ± 35.90	0.19*
02-04-04*	11.09* ± 3.59	101.22* ± 42.20	0.11*
04-02-04*	9.12* ± 2.18	70.67* ± 33.70	0.13*
01-13-06*	4.73* ± 1.31	94.11* ± 38.81	0.05*
01-13-06	34.58 ± 10.29	62.42 ± 26.68	0.55
01-20-06	29.67 ± 9.66	70.21 ± 29.55	0.42
02-01-06	26.85 ± 11.17	60.99 ± 16.90	0.44
02-20-06	25.58 ± 5.86	65.26 ± 22.88	0.39
03-16-06	23.10 ± 6.61	76.06 ± 33.78	0.30
04-03-06	25.44 ± 6.76	87.78 ± 34.97	0.29
05-04-06	20.93 ± 7.05	96.08 ± 56.66	0.22
05-30-06	20.32 ± 7.22	82.39 ± 31.60	0.25
06-29-06	18.05 ± 4.84	105.19 ± 43.16	0.17
11-24-06	19.25 ± 5.99	118.21 ± 33.12	0.16
03-12-07	17.43 ± 5.72	115.32 ± 42.66	0.15
10-06-10	12.31 ± 3.19	122.68 ± 62.42	0.10

* *Measurements before ploughing*

by a sharp increase in σ followed by a noticeable decrease in σ from January to May. Then σ decreases more slowly, reaching a quasi-constant value by July 2006. After 14 months σ was about 17.4 mm. In June 2010 the soil roughness was measured (Table I) and presented a level of roughness comparable with the value measured in April 2004, as σ=12.31±3.19 mm and LC=122.68±62.42 mm. This trend is well reproduced using an exponential fit function (dashed line top panel Fig. 1) as:

$$\sigma = 38.35xDOE^{-0.126} \qquad (5)$$

with DOE being the Day of the Experiment (dashed line top panel Fig. 1). The correlation length - LC- presents an opposite behaviour, showing a low value after ploughing and increasing with time as the surface becomes less and less rough. A fit function was used to represent its trend (dashed line, 2nd panel from top Fig. 1) and is defined as:

$$LC = 48.67xDOE^{0.132} \qquad (6)$$

The effect of ploughing leads to a decrease in soil moisture as shown in Fig. 1 (2^{nd} Fig. from the bottom) in January 2006. This effect could be explained by a redistribution of the water content within the soil. Consequently, the emissivity (bottom panel of Fig. 1) increases whereas the difference of polarization, ε_V-ε_H, decreases. It should be noted that ploughing changes also the bulk density: the soil density decreasing from 1.5 kg/m^3 in 2005, to 1.39 kg/m^3 in February 20th, 2006. Weather conditions then compact the surface, decreasing σ and increasing the density to 1.57 kg/m^3 in November 2006. Thus, ploughing the surface modifies the soil properties (bulk density, soil moisture redistribution) impacting the dielectric constant and so the surface emissivity [17].

σ and LC are correlated as seen in Fig. 2, which reports the relation existing between LC, σ/LC and σ^2/LC as a function of σ. Estimating LC from field measurements is difficult (i.e. the measurements are noisy) but a modeling study [36] has shown that it has a very low influence on brightness temperature, especially at H polarization. The results of σ and LC are slightly different to what was obtained with the same database [26] as their methodology to compute σ and LC is different.

B. Observations of surface emissivities

Fig. 3 presents the emissivity calculated from LEWIS measurements as a function of soil moisture at 4 incidence angles, from θ=20^o (top row) to θ=50^o (bottom row) and for both polarizations (V black dots and H grey dots). The different columns correspond to the four roughness classes from quasi-smooth on the right to rough surfaces on the left. Emissivity computed from Fresnel's law is plotted (grey and black lines Fig. 3) characterizing the emission of a perfectly smooth surface with identical surface conditions (i.e. with the same soil moisture, density, temperatures). As expected, emissivity decreases with increasing soil moisture at both polarizations and all angles. The effect of roughness is to decrease the sensitivity of surface emission to soil moisture. This can be observed especially at wet conditions (i.e. > 0.25m^3/m^3), where the emissivity increases with roughness. The

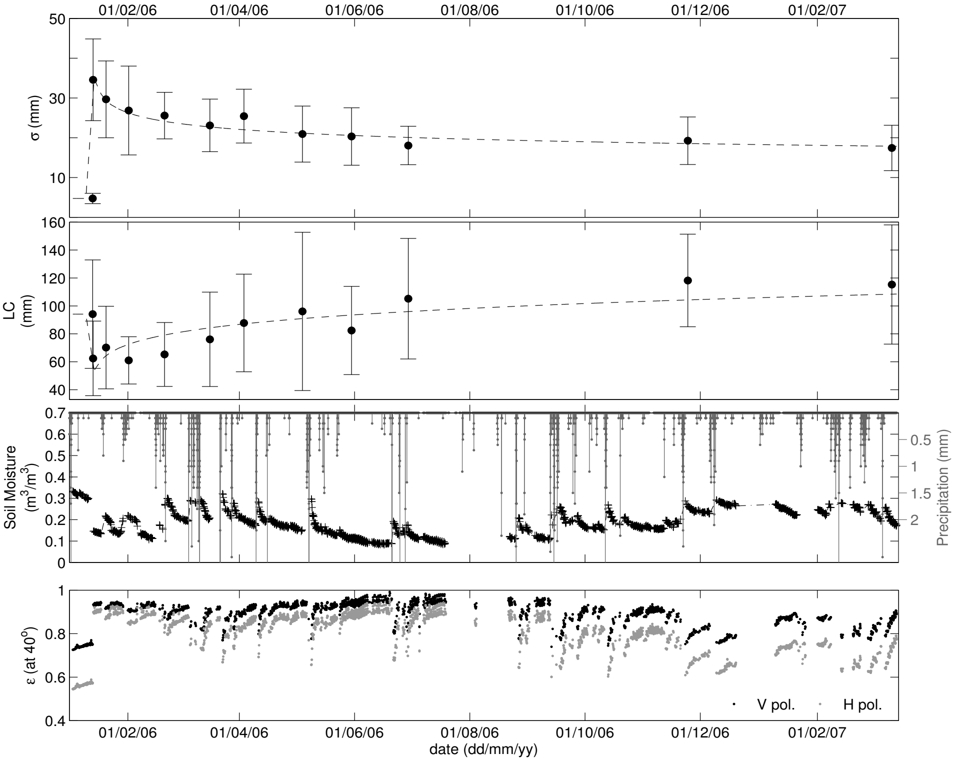

Fig. 1. Time series of surface parameters from December 2005 to March 2007. Top Fig. is σ (in mm) and its standard deviation ; The surface was ploughed the 13th of January 2006. 2nd from the top: the correlation length ; 3rd panel: soil moisture (black x, left hand y-axis) and precipitation (grey sticks, right hand y-axis, note that it is inversed for graphical convenience) ; Bottom figure is the emissivities at V (black dots) and H (grey dots) polarizations monitored by Lewis radiomater at an incidence angle of 40^o.

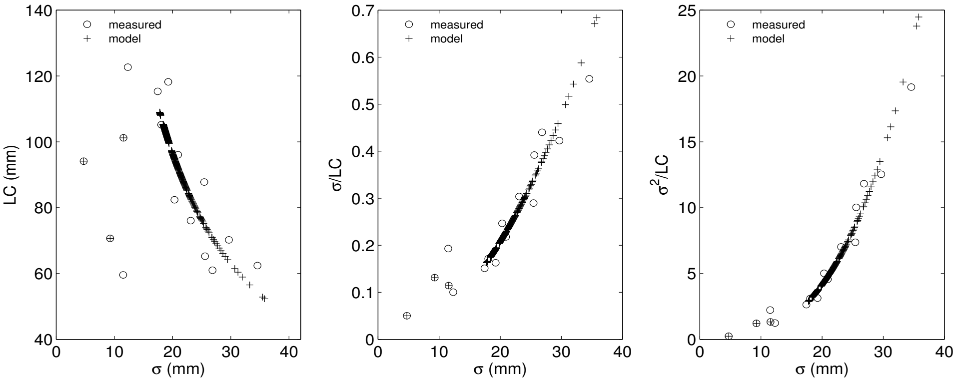

Fig. 2. LC, σ/LC and σ^2/LC as a function of σ. For each case are displayed: the measured σ and LC (Table I), “o” symbols and referred to as “ measured ” in the legends; σ and LC obtained from Eq. 5 and 6,“ +” symbols and referred to as “modeled” in the legends. Measured and model data are similar for data acquired before ploughing the surface.

difference between the emissivities at H and V polarization increases with increasing incidence angle for each wetness conditions but is decreased with roughness. Furthermore, the impact of roughness on the emissivity is more pronounced at H than V polarization. At the incidence angle of 40^o, the emissivity at H pol. is $\sim$ 0.56 at a soil moisture content of $0.3m^3/m^3$ and for a smooth surface (3rd line, right hand side Fig. 3) whereas it is $\sim$ 0.8 for a rough surface (left hand side Fig. 3). It corresponds to an increase in the emissivity of 0.24, whereas for the V polarization this increase is $\sim$ 0.145, from an emissivity of $\sim$ 0.72 for flat condition to $\sim$0.865 for a rough surface. The decrease in the emissivity with soil moisture has a linear trend for rough conditions and for each incidence angle (left-hand columns Fig. 3), the effect being again more pronounced at H polarization than at V polarization.

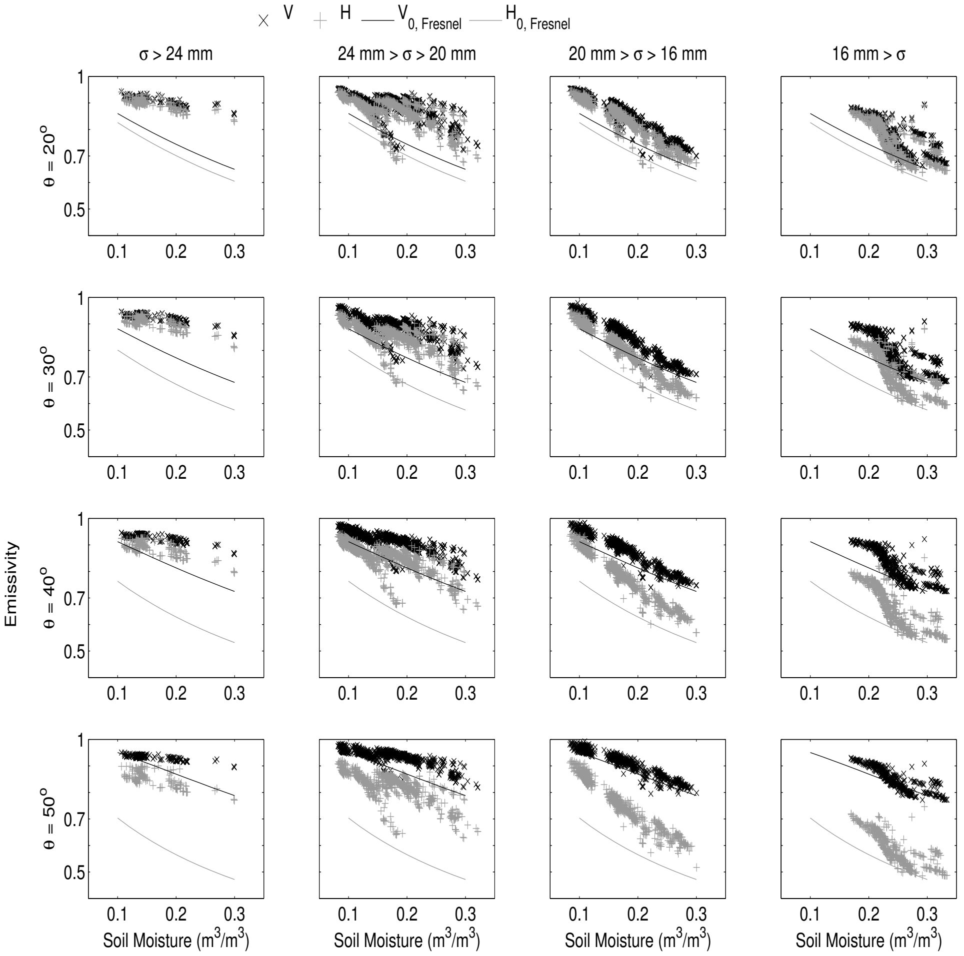

Fig. 3. Emissivity at V (black x) and H (grey +) polarizations, monitored at 4 incidence angles as a function of soil moisture : 20^o (top row figures), 30^o (2nd row), 40^o (3rd row) and 50 ^{o} (bottom row). The 4 columns correspond to roughness conditions, from a very rough surface -1st column from the left- to quasi-smooth condition (right hand side column). Emissivity computed from Fresnel's law (flat surface) is shown as black (V pol.) and grey (H pol.) continuous lines.

C. L-Meb model calibration

The second objective of this paper is to use the database to study the roughness parameters (Qr, Hr, N_H and N_V) as defined in Eq. 2.

1) Relation between N_H and N_V: ΔN is derived from Eq. 3 and presented in Fig. 4 as a function of σ values estimated by the fit function (Eq. 5 and grey dashed line Fig. 1). The use of the fit instead of actual values is done to limit errors caused by sampling limits in characterizing the field (2m board and $\sim$ 8 samples per day). Fig. 4 clearly shows a decreasing trend of ΔN with σ, well represented by the linear function defined as ΔN = N_H-N_V = -0.049 . σ + 2.188 (R = 0.90, RMSE = 0.16, bias=0). Smoother surface, i.e. σ < 16 mm, is characterized by a ΔN of $\sim$ 1.8, which is in agreement with ΔN = 2 found previously [18], whereas it is $\sim$0.5 for very rough surface, i.e. σ> 35mm. This trend is close to that obtained in [13] (ΔN = -0.036 x σ+2.24) over another agricultural site.

2) Retrieved parameters: N_p (p= H or V), Qr and Hr (Eq. 2) were derived from Eq. 4, for every day over the period November 2005-April 2007. The emissivity computed using these parameters, leads to an RMSE=0.022 (R^2=0.95) when compared to LEWIS emissivity, whereas an RMSE = 0.053 (R^2=0.69) is encountered when applying the parameters found by Escorihuela et al. [18] over a flat surface. Fig. 5 presents the retrieved roughness parameters Qr (top Fig.), Hr (middle Fig.) and N_H and N_V (bottom Fig.) for case B as a function of time. The time variation in σ and its best fit trend (Eq. 5) are also showed for comparison. Hr presents a high variability, but in general it decreases as σ decreases.

The high variability in the retrieved values of Hr could be linked to the fact that this parameter

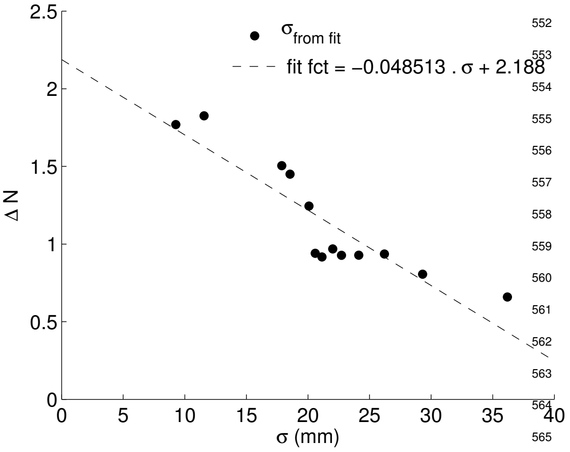

Fig. 4. σ estimated from roughness measurements plotted against ΔN (black •) calculated from LEWIS data, including the linear fit function (dashed line).

tends to compensate for the difference between the sampling depth [23] [37] of the in-situ soil moisture sensors (∼ 0-6 cm top soil layer), and of the LEWIS observations (∼ 0-2/3 cm). For example after a rain event following dry soil moisture conditions, the LEWIS observations immediately show a clear decrease in the monitored brightness temperatures whereas the in-situ probe still measures a low water content. Whilst LEWIS is sensitive to the first 0-2/3 cm, which is wet after a rain event, the probe integrates the soil moisture between the surface layer which is wet and a deeper layer which is dryer. In this case, the soil moisture estimated by the probe is underestimated in comparison to the soil moisture seen by LEWIS. The L-MEB model uses this underestimated soil moisture and compensates this effect by adjusting Hr to fit the LEWIS observations. Such effects may explain the high variability in the retrieved values of Hr obtained in May, July, September 2006. The opposite situation is also observed (dry surface over the 0-2/3 cm surface layer and rather wet conditions over the 0-6 cm surface layer) and could explain high retrieved values of Hr obtained in March 2004 and November 2005.

The results of the retrieval are presented as a function of the estimated σ (Eq. 5, dashed line top Fig. 1) and LC (Eq. 6) in Fig. 6 and Fig. 7 (grey markers for the case A with Qr=0 and black markers for the case B where Qr is retrieved). We also studied the derived parameters with the quantity σ/LC (not shown here), but the results are very similar to the results presented in Fig. 6. Qr (case B, it is retrieved, black • Top left Fig. 6) increases significantly from values around 0.05 for a flat surface to 0.3 for a rough surface. A Low Qr value for a quasi-smooth surface is in agreement with both theory (no polarization mixing, [11]) and observations [13] [18]. It confirms also that Qr is not equal to 0 for rough surface and needs to be taken into account to model the signature of rough soils. Retrieved values of Hr (Top right Fig. 6) show more variability as mentioned earlier. They evolve on average from ∼ 0.2-0.3 for a smooth surface to ∼ 1 for a rough surface. The relation Hr=f(σ) obtained in [13] is represented by the dashed line, fitting the results of the presented study. It is interesting to note that this relationship obtained for different conditions over a different site and a variety of soil roughness conditions provide a good general fit to the results obtained in this study. These results confirm that the empirical relationship Hr = $(2k\sigma)^2$ [9] (dotted line Fig. 6) is not applicable, also found in [13]. Retrieved values of Hr when Qr, Hr and Np (p = H or V) are retrieved are higher than when Qr is set equal to 0. Qr and Hr variations seem to be correlated to variations in σ whereas no clear correlation with σ could be found for N_V and N_H (bottom left Fig. 6) confirming the observations of [13]. N_H and N_V are found on average to be equal to 2.8 and 1 respectively for a smooth surface whereas the authors of [18] set them to lower values of 1 and -1. For rough surface however, N_H and N_V do not vary and can clearly be set to N_H= 0.59 and N_V=-0.30. Q seems related to Hr (bottom right Fig. 6) by the relation H=2.69*Q (R=0.71). Eq. 2 imposes the conditions Q=0 for H=0, meaning the emissivity of a flat surface is that from Fresnel's law.

The retrieved parameters show the opposite behavior when studied as a function of LC (Fig. 7) with Hr and Q decreasing with increasing LC. N_V and N_H present less variations for a rough surface (low LC) than in Fig. 6.

V. CONCLUSIONS AND PERSPECTIVES

Roughness effects at L-band are complex and need more investigations to be fully understood and modeled [13; 38]. This paper presents the unique SMOSREX-2006 experimental database dedicated to study the effect of roughness at L-band over 14 months. A bare soil has been significantly ploughed at the SMOSREX site and continuously monitored by LEWIS L-band radiometer. It has been found that the influence of roughness is more important at high incidence angles (about 40 to 50^o), high soil moisture values and at H polarization.

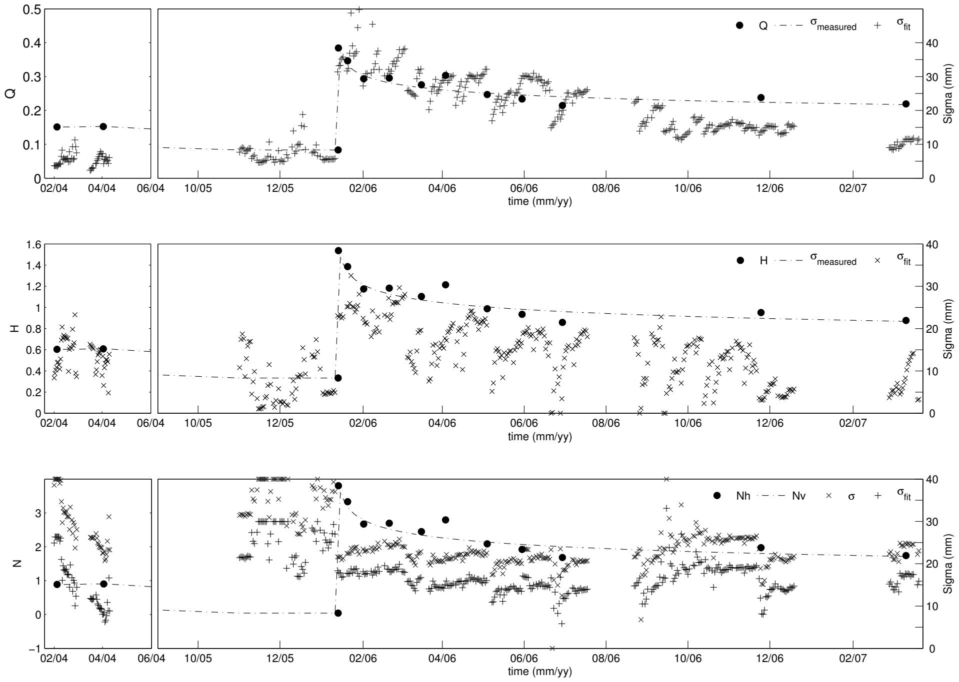

Fig. 5. Time series of the roughness parameters of Eq. 2. Top figure shows Qr, middle figure shows Hr and the bottom figure presents N_H (x) and N_V (+). σ and its fit trend (Eq. 5) are also depicted (with right hand side y-axis). The time series are split in two panels (left and right hand columns) as the time series are not continuous (no roughness measurement in 2005).

The soil moisture derived from the SMOS mission is based on a semi-empirical approach [8] and the roughness effect is taken into account by the Q-H model [9; 13; 18]. The presented database is also used to study the semi-empirical parameters of the L-MEB emission model as a function of surface characteristics represented by σ and LC. The results of this study suggest that for a rough surface Qr=0.3, Hr∼=1, N_H= 0.59 and N_V =-0.30, whereas a smooth surface is characterized by Qr∼0.05, Hr∼0.2/0.3, N_H ∼2.8 and N_V ∼1. It is different from most of the previous works on the subject which set Q=0 even for rough conditions. A simple model can not have been found to represent the dependence of the semi-empirical parameters with σ and LC due to their high variability, especially in case of Hr. However, it is interesting to note that the σ-Hr relation proposed by [13] seems to be applicable here over SMOSREX conditions. A linear relationship between N_H and N_V is also found, with the difference N_H-N_V decreasing with σ. The variations of these semi-empirical parameters can be explained by the difference in sampling depth between the sensors that are not sensitive to the same surface layer. This difference can be reduced by selecting some certain weather and soil moisture conditions. After an important rainfall the soil reaches its field capacity and is more homogeneous in terms of soil moisture content as both the 0-2/3 cm top layer (as monitored by LEWIS) and the top 0-6cm (as monitored by the probes) should have the same soil moisture content. After a drying period, the soil reaches its lower soil moisture content and both the probes and LEWIS monitor the same amount of soil moisture. By extracting those specific periods, it is expected to reduce the variability of the derived parameters.

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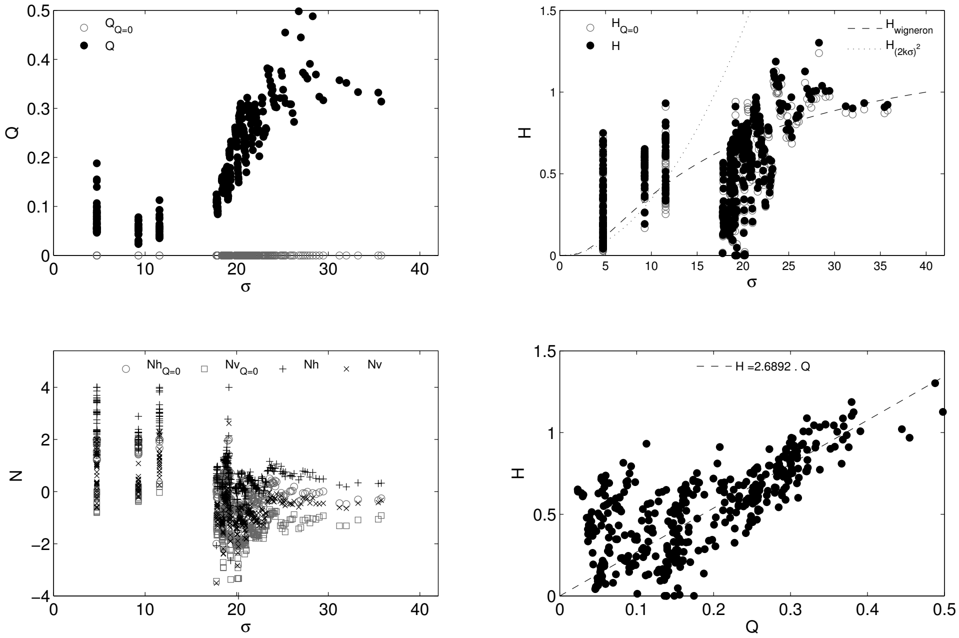

Fig. 6. Retrieved Qr, Hr and N_p (p= V or H) as a function of estimated σ (i.e. Eq. 5). Two cases considered : A) Qr=0, Hr and N_p (p= V or H) are derived (grey markers on all Figure); B) Qr is derived (black markers). In the top right figure are also depicted H functions as found in i) Wigneron et al. 2011 [13] (dashed line) and ii) Hr = $(2k\sigma)^2$ [9] (dotted line).

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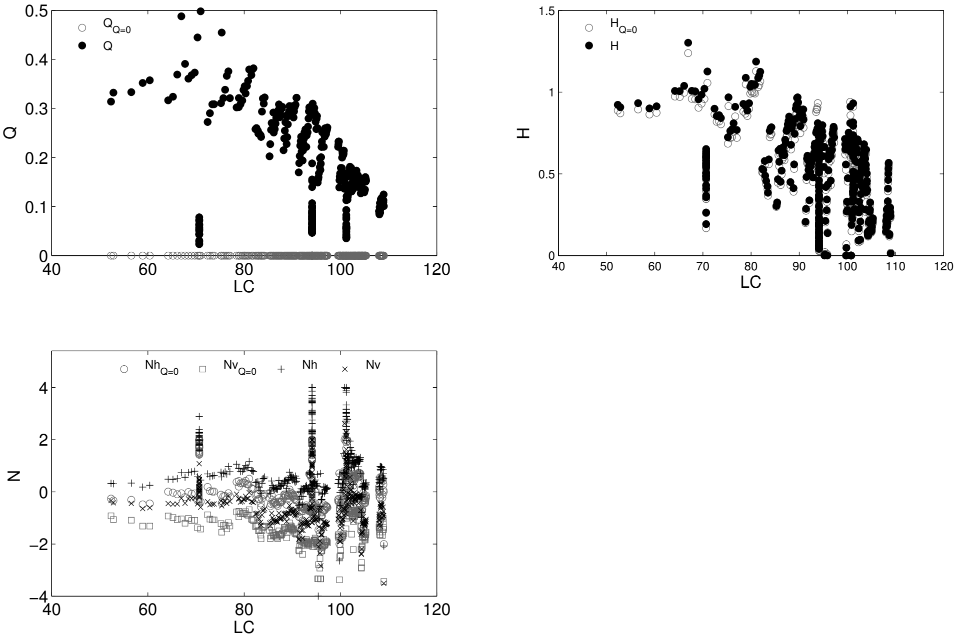

Fig. 7. Retrieved Qr, Hr and N_p (p= V or H) as a function of estimated LC (i.e. Eq. 6). Two cases considered : A) Qr=0, Hr and N_p (p= V or H) are derived (grey markers) B) Qr is derived (black markers on all Fig.).

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