Improved Understanding of Soil Surface Roughness Parameterization for L-Band Passive Microwave Soil Moisture Retrieval

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***Abstract*—Surface roughness parameterization plays an important role in soil moisture retrieval from passive microwave observations. This letter investigates the parameterization of surface roughness in the retrieval algorithm adopted by the Soil Moisture and Ocean Salinity mission, making use of experimental airborne and ground data from the National Airborne Field Experiment held in Australia in 2005. The surface roughness parameter is retrieved from high-resolution (60 m) airborne data in different soil moisture conditions, using the ground soil moisture as input of the model. The effect of surface roughness on the emitted signal is found to change with the soil moisture conditions with a law different from that proposed in previous studies. The magnitude of this change is found to be related to soil textural properties: in clay soils, the effect of surface roughness is higher in intermediate wetness conditions (0.2–0.3 v/v) and decreases on both the dry and wet ends. Consequently, this letter calls for a rethink of surface roughness parameterization in microwave emission modeling.**

***Index Terms*—Microwave radiometry, National Airborne Field Experiments (NAFE), soil moisture, Soil Moisture and Ocean Salinity (SMOS), surface roughness.**

I. Introduction

PASSIVE microwave remote sensing is an increasingly utilized technique to monitor surface soil moisture over large areas due to its all-weather capabilities, limited noise induced by the vegetation canopy, and high sensitivity to the dielectric properties of the soil–water medium [1]. Year 2009 will see the launch of the first soil-moisture-specific passive microwave mission, the Soil Moisture and Ocean Salinity (SMOS) mission carrying an L-band interferometric radiometer. The soil moisture retrieval algorithm adopted by SMOS requires information on the land-surface characteristics which contribute to the microwave emission of the Earth's surface. At L-band frequencies, vegetation water content (VWC) and soil surface roughness have the highest impact on the surface emission for a given soil moisture condition. Therefore, the choice of the parameters used to model the effect of surface roughness on the emission is of primary importance.

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Surface roughness is generally parameterized with the semi-empirical model proposed by [2], which makes use of two parameters: H_R which is related to measurable geophysical characteristics of the soil surface, such as standard deviation (σ_S) and correlation length (L_C) of the surface height profiles, and a polarization mixing parameter Q_S that can be estimated from calibration to passive microwave measurements. While Q_S was found to have very low values at L-band [3], the dependence of H_R on the surface roughness characteristics is not well known. Moreover, the best geophysical parameters to describe H_R over agricultural fields were found to be the slope parameter ($m = \sigma_S/L_C$) and the surface soil moisture [3]. The dependence of H_R on soil moisture was explained by an effect of volume scattering: the spatial fluctuations of the dielectric constant within the soil volume are stronger during drying out, producing an important "dielectric" roughness effect in addition to the "physical roughness" effect linked to the soil surface height. Recent results obtained over bare and grassy surfaces at the European SMOSREX site have proposed a linear decay of H_R with increasing soil moisture between a transition soil moisture point and the field capacity, with constant values of H_R outside those limits [4], [5]. This letter extends the earlier tower-based results to scales more representative of future SMOS footprints using aircraft data at L-band, supported by detailed ground measurements of soil moisture, soil temperature, VWC, and surface roughness.

II. Data

The data used in this letter were collected during the National Airborne Field Experiment 2005 (NAFE'05). This was a large-scale airborne experiment conducted in Australia in November 2005 (full details about the experiment can be found in [6]). The four-week long campaign was conducted in the Goulburn river catchment (32° S, 150° E, Fig. 1), a semiarid area of grazing lands with native grass cover and some cropped areas (mainly wheat and barley). Heavy rainstorms delivered approximately 50 mm of cumulative rainfall during the first two weeks of the campaign, followed by a dry-down period until the end of the experiment. Aircraft L-band measurements were taken at 60-m resolution over eight experimental farms two times a week, with supporting ground monitoring of the top 5-cm soil moisture undertaken weekly at high-resolution site within each experimental farm (see Fig. 1). This letter focuses on the aircraft observations taken at the center of the high-resolution sites where ground soil moisture was monitored at 6–12-m spacing.

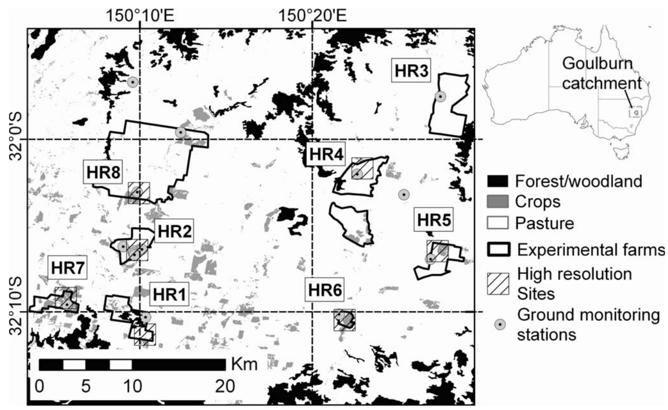

Fig. 1. NAFE'05 experiment ground-sampling layout with land-cover map. The high-resolution sites, focus of this letter, are labeled.

The high-resolution sites presented a variety of land-surface conditions and land covers. Stanley, Dales, and Roscommon were characterized by native pasture; Pembroke, Merriwa Park, Cullingral, and Illogan were cropped fields (a mix of wheat, barley, and oats); whereas Midlothian was split between a bare fallow field and a lucerne crop. Soil type was clay or clay loam for most sites, with the exception of Roscommon and Illogan (sandy loam and silt loam).

Soil moisture observations (0–5 cm) were made by means of the Hydraprobe Data Acquisition System, which integrates a GPS receiver with the Vitel HydraProbe in a portable geographic information system framework. Such observations were calibrated against gravimetric measurements (taken throughout the campaigns at different locations) and laboratory data, yielding an estimated accuracy of ± 3.5 %v/v [7]. VWC at each high-resolution site and its temporal variation were determined by means of biomass samples taken every week. Surface physical roughness was characterized with 1-m long pin profilers with two perpendicular sets of readings made at five locations within each experimental farm.

III. Surface-Roughness Retrieval

The radiative transfer model used in this letter to simulate the surface emission is the L-band Microwave Emission of the Biosphere (L-MEB) model, described in detail in [8]. The model will be the core of the soil moisture retrieval algorithm adopted for the SMOS mission. The effects of soil and vegetation on the surface brightness temperatures are described in L-MEB by the so-called "$\tau-\omega$ model"

$$TB(\vartheta, P) = (1-\omega_{\vartheta,P})(1-\gamma_{\vartheta,P})(1+\Gamma_{\vartheta,P}\gamma_{\vartheta,P})T_v + (1-\Gamma_{\vartheta,P})\gamma_{\vartheta,P}T_{\mathrm{EFF}} \quad (1)$$

where P represents the measured polarization (H or V), ϑ is the observation angle, ω and γ are, respectively, the vegetation scattering albedo and transmissivity, and the two T terms are the temperatures of the vegetation and the soil effective temperature. The vegetation transmissivity γ is calculated from the vegetation optical depth, $\tau(\gamma = \exp(\tau/\cos\vartheta)$, which can be linearly related to the VWC as $\tau = b^*\mathrm{VWC}$ through the experimental parameter b, which depends on the plant structure and the sensor frequency and incidence angle [9]. To account for this angular effect, the expression $\tau = b^*\mathrm{VWC}$ is used to calculate a NADIR-equivalent optical depth, which is then modulate with the incidence angle based on two polarization-dependent and vegetation-specific structure parameters, tt_h and tt_v. The reflectivity of a rough soil Γ, which is also sensitive to the observation angle and measured polarization, is derived from the smooth soil Fresnel reflectivity Γ^* as a function of the observation angle through the model soil parameters H_R and N_{RP}

$$\Gamma = \Gamma^* \exp\left[-H_R \cos(\vartheta)^{N_{RP}}\right]. \quad (2)$$

In this letter, the values for the model parameters used were those proposed for the soil moisture retrieval of the future SMOS mission for native grass and wheat crops (J.-P. Wigneron, personal communication). N_{RV} was set to -1 or 0 and N_{RH} to 0 or 1 (respectively for crop and grass). Vegetations scattering albedo was set to 0 (crops) and 0.05 (grass). VWC was determined from ground samples, whereas the effective soil temperature was determined using surface (2.5 cm) and deep (15 cm) soil temperature measurements from the local monitoring stations (see Fig. 1) at the time of the aircraft overpass using the formulation proposed in [3]. Vegetation temperature T_V was approximated with the soil temperature at 2.5 cm. Soil texture was determined from 5-cm samples taken nearby each high-resolution site.

The parameters with the highest impact on the soil moisture retrieval using the described model are b and H_R. The existing estimates of b and H_R ("SMOS default," Table I) were initially verified by using them to retrieve soil moisture and compare it with the ground soil moisture observations. "SMOS default"-retrieved soil moisture is shown in Fig. 2 against the ground soil moisture, and the mean absolute error of the retrieval (MAE) are listed for each site in Table I. It is shown that, by using "SMOS default" values for both b and H_R parameters, large retrieval errors (underestimation) are obtained, particularly for the crop sites (Pembroke, Merriwa Park, and Cullingral), whereas, for the grass sites, the errors are much smaller. Given the confounding influence of parameters H_R and b on the retrieved soil moisture, with an increase in H_R and b generally having the same effect of increasing the overall emission, these results indicate that the value of either or both parameters proposed for the SMOS retrieval are too low. It was therefore necessary to perform a site-specific calibration to separate the effect of the two parameters and to address the main objective of this letter, the surface roughness parameter.

Given the availability of five to eight daily bi-polarized aircraft observations at multiple angle for each high-resolution site, both parameters can be retrieved by taking advantage of the multi-angular capabilities of the L-MEB model and using the ground-measured soil moisture as input of the model. Two different calibration approaches were used. First, it was assumed that the "SMOS default" values for b were correct, and H_R was calibrated for each individual site. Second, b and H_R were alternatively calibrated at each site and each day through a sequence of iterations; at each step, the value of b used as input to calibrate H_R was the average of the values calibrated across all days in the previous step, whereas b was calibrated

TABLE I

VALUES OF PARAMETER b AND H_R AND MEAN ABSOLUTE ERRORS (MAE, [%v/v]) OF SOIL MOISTURE RETRIEVAL FOR SMOS DEFAULT AND THE TWO SITE-SPECIFIC CALIBRATION APPROACHES DISCUSSED IN THE TEXT. MEAN AND ± STANDARD DEVIATION IN TIME OF CALIBRATED PARAMETERS IS SHOWN. * = NATIVE GRASS; ** = MIX FALLOW/LUCERNE; *** = CROP

Site name	Range of angles	SMOS default			Calibration of only Hr b fixed to SMOS default		Iterative calibration of b and H_R		
		b	H_R	MAE	H_R	MAE	b	H_R	MAE
Roscommon*	17°	0.12	0.5	2.8	0.5+/-0.1	2.6	0.09+/-0.01	0.43+/-0.2	2.4
Stanley*	17°	0.12	0.5	13.4	0.9+/-0.1	3.5	0.36+/-0.01	0.79+/-0.1	2.7
Dales*	17°	0.12	0.5	16.0	1.1+/-0.2	5.6	0.73+/-0	0.52+/-0.4	14.9
Midlothian**	33°	0.12	0.5	24.6	1.2+/-0.3	5.2	1.2+/-0.05	0.87+/-0.3	4.5
Pembroke***	18°	0.08	0.2	32.4	1.0+/-0.1	2.7	0.14+/- 0	0.70+/-0.2	2.9
Illogan***	20°	0.08	0.2	7.5	0.4+/-0.1	6.1	0.11+/-0.01	0.38+/-0.1	6.4
MerriwaP.***	11°	0.08	0.2	19.2	0.9+/-0.2	7.4	0.1+/-0.01	0.79+/-0.2	8.1
Cullingral***	6°	0.08	0.2	24.7	1.3+/-0.2	4.6	0.59 +/-0.03	0.85+/-0.3	5.2

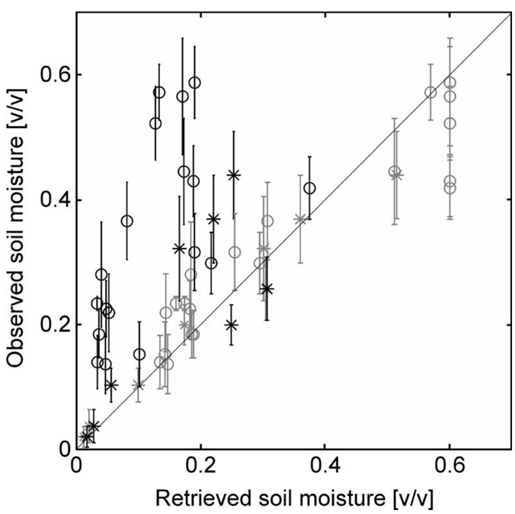

Fig. 2. Retrieved versus ground-observed soil moisture using (black symbols) SMOS default parameters and (gray symbols) NAFE'05 calibrated b and H_R. Asterix indicates native grass sites; circles indicate crop sites. Vertical error bars indicate ± of the standard deviation of observed soil moisture within each footprint.

using the calibrated values of H_R for each day in the previous step. The iterations were repeated until the mean values of both parameters would not change significantly between subsequent iterations. This process led to an adjustment of the values of both parameters to match the observed emission, while minimizing the temporal variation or retrieved parameters b, which is only dependent on the plant structure and is therefore not expected to change in time.

In both approaches, all the bi-polarized multi-angular observations available for each site on each observation day were used to retrieve one single value of the parameter for the site. Although the available range of incidence angles varied slightly between sites, due to differences in aircraft flight lines and attitude, on average each site was observed over a range of angles of 20°. This is indicated in the second column of Table I.

IV. RESULTS

The calibrated values of both the b and H_R parameters for the two approaches and the MAE of soil moisture retrieval are shown in Table I, together with the standard deviations of the retrieved values across the monitoring days to highlight the temporal variation of the parameters. Note that the MAE was calculated using the average values of the parameters for each site. Overall, the SMOS values of b were found to be suitable for crops in the study area, whereas the values of H_R had to be increased significantly from the SMOS default values in order to obtain an accurate soil moisture retrieval. This could be due to differences in agricultural practices between the NAFE'05 study area and the European sites typical of most SMOS studies which provided estimates of H_R. For the native grass sites, the SMOS values of H_R were found to be suitable, whereas values of b were somewhat too low.

It should be noted that the iterative calibration of b and H_R produced very high values for parameter b in some cases. In particular, the Midlothian, Dales, and Cullingral sites had unrealistically high b values (above ~0.5), which cannot be explained by the effect of the standing vegetation alone. This can be explained by very high surface roughness or some other sources of emission, like, for example, litter or rainfall intercepted on the plant, not explicitly modeled but implicitly accounted for in the high values of b. It should be noted that these sites also exhibited very high values of H_R in the first calibration approach (individual H_R calibration with b fixed), confirming the hypothesis of an actual deficit in the emission budget. The joint calibration of b and H_R at the Dales site did not improve the soil moisture retrieval. Analysis of the aircraft-observed surface emission at this site revealed very poor sensitivity to the ground-measured soil moisture, which could be explained by the presence of a litter layer that remained moist and, thus, saturated the signal. This effect has been observed also at some European sites [5]. The Dales site was therefore not considered further in this analysis.

It is interesting to note the lower values of H_R calibrated at the sites with more sandy soils (Roscommon and Illogan), which was not expected, as soil texture should not affect the physical roughness of the surface. This could be an effect of the dielectric model used by the L-MEB algorithm, the Dobson model [10], which is known to have poorer performance on sandy soils. It is also shown in Table I that similar soil moisture retrieval errors are obtained with the two calibration approaches (calibration of only H_R and calibration of both parameters). Nevertheless, the second approach guarantees that

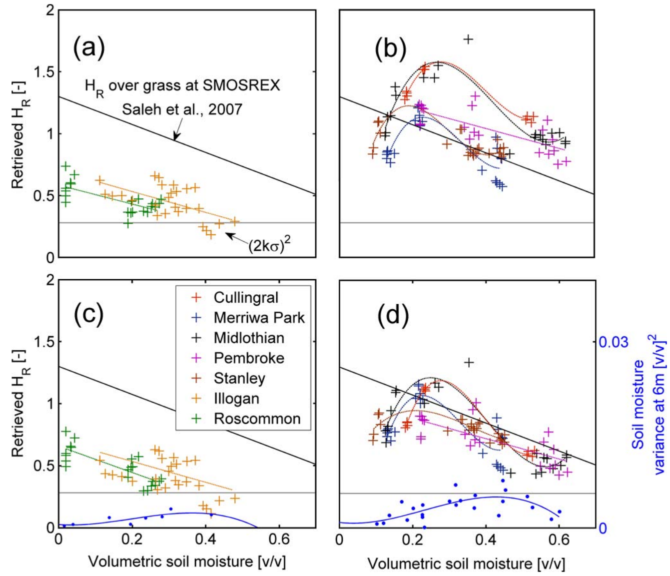

Fig. 3. Retrieved parameter H_R as a function of ground soil moisture for all the high-resolution sites; using SMOS values for parameter b for (a) sandy soils and (b) clayey soils, and using site-specific calibrated values of b for (c) sandy soils and (d) clay soils. Dashed colored lines are the best fit for each site. Solid gray lines show the value of the Choudhury parameter for physical roughness (average of all sites $= 0.25$), whereas solid black lines indicate the roughness–soil moisture relationship proposed by Saleh *et al.* [5]. (blue dots and solid lines) Soil moisture heterogeneity at 6-m spacing is also displayed for each high-resolution site and each date with cubic fit.

any vegetation effect be removed from the calibrated values of H_R, which makes it more suitable for the purpose of this letter. The soil moisture retrieved using these calibrated parameters is plotted against the ground soil moisture in Fig. 2 for comparison with SMOS default retrieval.

In order to investigate the dependence of H_R on soil moisture, H_R was retrieved for each bi-polarized observation of the high-resolution sites. This approach provides more data points at a wider range of soil moisture conditions than when using all the observations at once to retrieve on value of H_R for each day (as done thus far). The retrieved H_R as a function of the ground-observed soil moisture is shown in Fig. 3. In this plot the results obtained using both sets of values of parameter b (SMOS value and calibrated b) are presented, and the high-resolution sites are grouped by soil type, upon observing a strong soil-type dependence of retrieved values of parameter H_R in Table I.

It is observed that the values of H_R are not constant but rather change with respect to the soil moisture conditions. In the intermediate-to-wet range of soil moisture conditions (0.2 v/v to saturation), the general trend is that of a decrease of the parameter from higher value in intermediate wetness conditions to lower values in wet conditions. This is observed for all soil types and regardless of whether parameter b is calibrated or not. The trend is consistent with what were already observed in previous studies using a tower radiometer at the European SMOSREX site [4], [5]. The linear regression proposed in those studies (for natural grass) is shown in Fig. 3 for comparison. It is notable how, in the case where b is calibrated (bottom panels shown in Fig. 3), this trend is matched by the values of H_R retrieved in this letter for clay soils. On more sandy soils instead, the values of H_R are much lower, although the linear decrease with soil moisture conditions is maintained.

It is also notable in Fig. 3 that, for clay soils and when drier conditions are encountered, a negative trend between H_R and soil moisture seems to dominate, after a peak of H_R is reached at around 0.2–0.3 v/v soil moisture conditions. This is not visible for the Pembroke site, which nevertheless did not experience conditions drier then 0.2 v/v. The observed decrease of H_R on dry conditions is in contrast with previous studies which reported constant values of H_R in this range, as well as above the field capacity [4], [5]. This could have been due to the fact that the soil types in the sites analyzed by those studies were mainly sandy, whereas the decrease was observed here mainly for clays and clay loams.

In [4] and [5], it was suggested that the decrease of H_R with increasing soil moisture is associated with the presence of micro-scale heterogeneity in soil moisture during drying. This would add a component of dielectric roughness to the physical roughness of the soil surface which would instead dominate on wet conditions where soil moisture is more uniform at the microscale. On the same line of thought, the decrease of H_R observed in Fig. 3 in the dry end could be associated to the decrease in micro-scale dielectric heterogeneity that one would expect in drying clay soils due to lower limit imposed by the residual or wilting points. At the dry end, therefore, the physical-roughness component of H_R would become increasingly dominant, and the dielectric-roughness component would decrease.

In Fig. 3, the physical-roughness component is quantified through the classical Choudhury parameter $[11] = (2\ \mathrm{k}\sigma_S)^2$, function of the standard deviation of the surface heights and the wavenumber k. Here, the average between all the high-resolution sites (0.25) was taken as a reference, resulting from an average σ_S of 8.4 mm (2-mm standard deviation) across the eight sites. It is clear that, for clay soils and when calibrated values of b are used (lower left panels as shown in Fig. 3), the values of H_R approach the physical-roughness component toward both the dry and wet soil moisture ends. The range of H_R values between extreme and intermediate soil moisture conditions exhibited by clay soils in Fig. 3 is on the order of 0.3–0.5. On bare soil, this would correspond to an error in soil moisture retrieval of 15–20 %v/v. For many of the cases presented here, therefore, using a constant value or a simple linear decrease of H_R with soil moisture could lead to significant soil moisture retrieval errors.

The comparison between the relationship of H_R and soil moisture on sandy and clay soils shown in Fig. 3 further supports the hypothesis of dielectric roughness induced by micro-scale heterogeneity of soil moisture. One would in fact expect this heterogeneity to be higher in clay soils due to the highest water retention property of these. This was verified by analyzing the variance of the soil moisture measurement taken at 6- and 12-m spacing throughout each high-resolution site. This is shown in Fig. 3 (blue right axis in lower panels), where the soil moisture variance is plotted against the mean soil moisture for each area and each day. For clay soils, the soil moisture heterogeneity is in fact much higher (nearly double that of sandy sites) and achieves a maximum around

0.3–0.45 v/v with a rapid decrease below 0.3 v/v. For sandy soil, this heterogeneity is smaller, with corresponding lower values of H_R. The implicit assumption is made here that the soil moisture dependence of the heterogeneity at the 6-m scale is a good approximation of that of the micro-scale heterogeneity which would be observed on very small soil samples and which is expected to determine the dielectric roughness. The goodness of this assumption is difficult to verify, and therefore, the measure of heterogeneity adopted here is to be thought of only as an indication of the relative magnitude of soil moisture heterogeneity between soil types and its variation with wetness conditions. Further investigation is needed in order to understand what is the scale at which the soil moisture heterogeneity mostly affects the relationship between soil moisture and microwave emission and how this effect can be parameterized through H_R as a function of soil type or accounted for in a soil dielectric model. Moreover, it should be better understood whether the smaller value of H_R are not an artifact of the poor performance of the Dobson model on sandy soils.

V. Conclusion

Effective parameterization of surface roughness is important for passive microwave remote sensing of soil moisture. In this letter, the dependence of surface roughness on soil moisture microscale heterogeneity was investigated using aircraft and ground soil moisture observations. The surface roughness parameter was found to be not constant but rather variable, depending on soil moisture conditions and soil type. On clay soils, it exhibited a maximum at intermediate soil moisture conditions ($\sim$0.25 v/v) and a decrease toward both dry and wet conditions, whereas on sandy soils, it exhibited lower values and a monotonic decrease going from dry to wet conditions. In the intermediate wet soil moisture range (0.25 v/v to saturation), a soil moisture dependent linear relationship similar to that proposed by previous studies [4], [5] was found to apply well to the crops and native grasses on clay soils. However, the values of roughness approached the contribution of the surface physical roughness ($\sim$0.28) on both the wet and dry ends. This was explained as the effect of a dielectric component in the microwave roughness which is related to soil moisture microscale heterogeneity. It was shown that this effect might be higher in clay soils and maximum at intermediate soil moisture conditions when the water retention properties of clay determine high spatial variability. These results indicate the need to model the dielectric component of the surface roughness effect on the soil emission as a function of the soil textural properties and soil moisture. This letter also suggested that the values of H_R proposed for SMOS might be too low to provide accurate soil moisture estimates over crop sites, whereas they are suitable for native grass-covered sites.

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