Impact of rain interception by vegetation and mulch on the L-band emission of natural grass

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Abstract

This paper explores the effect of rain intercepted by vegetation and mulch on the L-band emission of natural grass. The study is based on radiometric, meteorological, and biophysical measurements obtained during the SMOSREX Experiment (Toulouse, France). Several approaches were followed to evaluate interception effects. Firstly, the analysis of microwave brightness temperature (TB) measurements at L-band indicated that interception increases vegetation emission at both polarisations. Secondly, the use of microwave indices to detect the presence/absence of interception was examined. In particular, a modified polarisation ratio at 50° was found to be well related to the interception status of the standing vegetation. Finally, the vegetation optical depth (τ), which parameterises the extinction across the vegetation layer, was retrieved from the TB observations. It was found that τ increases with the increase in the water content stored within the vegetation and mulch after rainfall. The study highlights the strong impact of intercepted water in otherwise weakly attenuating covers such as grasses. Interception might therefore be an issue to consider in order to improve soil moisture retrieval algorithms from L-band observations.

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1. Introduction

Several decades of research in the field of passive microwave remote sensing give evidence that surface soil moisture can be monitored from space (Schmugge et al., 2002; Wigneron et al., 2003). An optimal frequency for surface soil moisture studies is the L-band (1.4 GHz), as L-band radiation can propagate without significant interaction with the atmosphere. The rationale for this technique relies on the sensitivity of low frequency microwave radiation to free water (within the soil surface, plants, oceans, etc.). Free water in soils and free water in vegetation cause opposite effects on the flux of microwave radiation: while free water will enhance vegetation emission it will reduce soil emission (Ulaby et al., 1986). Many studies have investigated the L-band emission of different vegetation types. The results of these studies are included in the L-band Microwave Emission of the Biosphere model (L-MEB) (Wigneron et al., in press), which is a zero order radiative transfer model with parameters specific to each cover type. In addition to the vegetation type, the question of intercepted rainfall arises when we attempt to model the emission of soils covered by vegetation. Wigneron et al. (1996) measured the L- and C-band emission of a wheat field before, during, and after irrigation, and showed that intercepted water contributed to increase C-band emission at horizontal polarisation. In that study, the combination of the two microwave frequencies was used to estimate the vegetation water content during irrigation.

In addition, residual vegetation produces a layer of plant debris and mulch in forests and grasslands with a large water storage capacity. A layer of plant debris may be considered transparent to the soil microwave emission (Jackson &
but when filled with water it becomes an important microwave absorber and emitter (Schmugge et al., 1988; Wang et al., 1990). Putuhena & Cordery (1996) estimated the maximum interception by several types of forest floors and understory grasses as a function of the dry biomass, thickness, and fraction cover. The authors concluded that intercepted water represented between once and twice the dry vegetation biomass for leaf type litters and understory grasses, while the interception was lower for stem and branch litters.

This paper contributes to the development of methods to estimating surface products from L-band observations by addressing the following questions related to rain interception: i) How does the L-band emission of vegetated areas change as a consequence of rain interception?, ii) Can we flag the presence/absence of interception from microwave measurements only?, iii) Is the vegetation optical depth $a$, which parameterises the extinction across vegetation in the L-MEB model, sensitive to rain interception by mulch and vegetation? Our analysis is based on brightness temperature data series obtained by the radiometer LEWIS (Lemaître et al., 2004), designed for the SMOSREX Experiment (de Rosnay et al., submitted for publication). Since the end of January 2003, the experiment provides continuous measurements of the L-band emission of bare soil and natural grass grown in a field left fallow, as well as multispectral (visible and infrared), meteorological, and biophysical data. Over grass, the retrieval of surface soil moisture by forward inversion of L-MEB has not produced successful results due to the presence of wet mulch almost all year round, and wet vegetation after rainfall. In wet conditions the soil emission is reduced, and the overall emission can be dominated by the high emission of mulch and vegetation. These effects are difficult to decouple. Surface soil moisture retrievals in such conditions lead to a ‘dry soil effect’, meaning that the high surface emission is associated to the emission of dry soil.

2. Material and methods

2.1. The SMOSREX experiment site

The current study is based on data acquired between February 2003 and October 2004 during the SMOSREX experiment. SMOSREX (Surface Monitoring of the Soil Reservoir EXperiment) is located near the town of Toulouse (France), at the ONERA (Office National d’Etudes et Recherches Aérospatiales) test site at Fauga–Mauzac (43°23.12’N, 1°18.53’E, 188 m altitude). SMOSREX addresses issues relevant to the SMOS (Soil Moisture and Ocean Salinity mission, ESA) (Kerr et al., 2001) and HYDROS (Hydrosphere State mission, NASA) (Entekhabi et al., 2004) missions, with L-band radiometers onboard. Such issues include the improvement of surface soil moisture retrieval algorithms from L-band measurements, and the assimilation of microwave measurements to estimate soil moisture in the root zone (Calvet & Noilhan, 2000).

Fig. 1. SMOSREX experimental site. a) LEWIS radiometer, b) LEWIS rotation axis, parallel to the grass and bare soil border, c) detail of the vegetation in May, d) Detail of the mixed layer after removing the standing vegetation.
The study area at the SMOSREX site includes a bare soil field, and a field left fallow where natural grasses grow (Fig. 1). Both plots are continuously monitored by several radiometers operating at different frequencies: LEWIS (L-band radiometer for Estimating Water in Soils, (Lemaître et al., 2004), one pyrometer at each plot (8–14 μm, 40° observation angle), and two luminancemeters, one measuring solar irradiance, and the other one measuring the grass luminance at 40° incidence angle and at five spectral bands in the visible and in the infrared. In addition, a complete meteorological station installed in the grass field provides surface fluxes, visible and infrared net radiation, and basic meteorological data (2 m temperature, wind speed and direction, atmospheric pressure, air humidity, dew point). Soil monitoring includes a set of Delta-T moisture probes located at different depths in both plots, from the surface down to 90 cm deep. Surface soil moisture measurements are referred to in this work by the readings of Delta-T probes vertically inserted at the surface. These readings correspond, approximately, to the moisture content of the first 6 cm of soil. Finally, soil temperature sensors are displayed at 1, 5, 20, 50 and 90 cm deep.

Table 1 summarises the soil properties at the grass plot. The texture class down to 30 cm corresponds to a silt-loam to loam soil, while higher clay content is found at deeper layers. Measurements of the surface roughness were carried out by means of a needle profiler to obtain the surface height standard deviation σh [mm], and the roughness correlation length L [cm] (Table 1).

The climatic conditions in the study area result in significant soil moisture variations between dry summers and wet winters. Time series of the volumetric soil moisture w_s (0–6 cm) at the grass plot, precipitation, air temperature, and leaf area index(LAI) during the experiment are depicted in Fig. 2. Day of experiment (DoE) 1 corresponds to 1st of January 2003. The presence of cool season grasses explains the two peaks observed in the LAI cycle. At the end of the summer, or early fall, precipitation replenishes the soil moisture content and a second vegetation growth period starts. Grasses were cut at the end of January in 2003 and at the beginning of February 2004.

### Table 1

<table>
<thead>
<tr>
<th>Depth [cm]</th>
<th>Bulk density [kg m^{-3}]</th>
<th>Sand fraction</th>
<th>Clay fraction</th>
<th>Time</th>
<th>σh [mm]</th>
<th>L [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.5*</td>
<td>0.37</td>
<td>0.16</td>
<td>Oct. 2003</td>
<td>9.2</td>
<td>22.4</td>
</tr>
<tr>
<td>40</td>
<td>1.5</td>
<td>0.28</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>1.7</td>
<td>0.27</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

σ = Standard deviation.* measured at 10 cm.

2.2. The LEWIS radiometer

The radiometer LEWIS was specially designed and built by the ONERA for the SMOSREX campaign. After more than two years of measurements the instrument has demonstrated outstanding performance and reliability for a long-term

Fig. 2. SMOSREX climatic and vegetation characteristics. a) Surface soil moisture (0–6 cm) (thick line) and precipitation (thin line). b) Maximum (thick line) and minimum (thin line) air temperatures at 2 m height. c) LAI measurements (+) and interpolated LAI (line) at the grass plot.
campaign such as SMOSREX. LEWIS is a dual-polarisation Dicke type radiometer coupled to a conical horn antenna. A detailed technical description of the system and its performance can be found in Lemaître et al. (2004). The radiometer resolution, 0.2 K for a 4 s integration time, is optimal to monitor changes in the surface and vegetation water status due to, for example, rain interception, dew or frost. In addition, the quality of the antenna ensures a high-quality data set: the antenna diffraction pattern gives an aperture of 13.6° at half-power, as well as very low side lobes (−38 dB peak value). LEWIS performs continuous measurements of the L-band brightness temperature from a 13.7 m high structure as shown in Fig. 1. The antenna is able to rotate around an axis parallel to the border between the two experimental plots, so that each surface can be observed at different observation angles. LEWIS measures permanently the brightness temperature at 40° incidence angle (0° corresponds nadir) over grass, and it performs 8 automatic angular scans per day to obtain TB from both plots at 20°, 30°, 40°, 50° and 60°. During each scan over grass LEWIS observes the surface from 60° to 20° stopping at every angle, and back again from 20° to 60°. After that, LEWIS goes back to the fixed observation position at 40°. A whole angular scan over grass takes about 30 min. Other allowed positions are 0°, automatically reached if the wind speed exceeds 10 m s⁻¹, and the sky observation position for calibration operations.

2.3. Vegetation sampling

The vegetation sampling strategy was designed to characterise the biomass and water content of two main layers: (1) the standing vegetation layer, which includes green and dry standing vegetation (Figs. 1 and 2) a mixed layer between the mineral soil and the standing vegetation (Fig. 1). The mixed layer includes mulch (few mm), plant debris, and the tight layer of roots and stems found very close to the soil surface (few cm thick). The green vegetation LAI [m² m⁻²] was measured every week from 30 × 30 cm samples obtained at points located next to the radiometer field of view. A planimeter was used to determine the LAI. These samples were also weighted and oven dried to determine the dry biomass of the green and dry standing vegetation, and its water content. A good relationship was found between the LAI and the green standing vegetation water content GWC [kg m⁻²] as plotted in Fig. 3.

\[
\text{LAI} = 3.32\text{GWC} \quad R^2 = 0.84
\]

The LAI time variation given by Fig. 2 was obtained by fitting a logistic-type function (Eq. (2)) to the LAI measurements as in Wigneron et al. (1999):

\[
\text{LAI} = M(\text{G} - S) \quad G = \frac{1}{1 + \exp(-a_1(t-t_1))}S = \frac{1}{1 + \exp(-a_2(t-t_2))}
\]

RMSE = 0.43 m² m⁻² \( R^2 = 0.87 \) (2)

Best-fit function parameters \((M, a_1, a_2, t_1, \text{and } t_2)\) were obtained through a least-squares optimisation of the logistic function in Eq. (2) by comparison with LAI measurements. These are listed in Table 2. Sparser measurements of the standing vegetation water content and the mixed layer water content were acquired in 23 occasions between DoE 140 and DoE 540. Averaged measurements are shown in Fig. 3 for different dates. Values for the standing vegetation dry biomass up to 0.55 kg m⁻² were observed at the end of spring of 2004. Dots in Fig. 3 indicate wetness measurements, given by the ratio between the water content and the wet biomass. When vegetation was at its greenest state the standing vegetation wetness was usually over 70% in the absence of interception. We should note that no particular experiment was designed in this study to quantify rain interception by the standing vegetation, and the presence of interception is qualitatively inferred from meteorological data only. Measurements of

![Figure 3](image-url)

**Fig. 3.** Vegetation measurements. a) LAI vs green water content (GWC) and linear fit. b) Standing vegetation dry biomass \((S)\) [kg m⁻²] and wetness ratio \((G)\). c) Dry biomass of the mixed layer \((S)\) [kg m⁻²] and wetness ratio \((G)\).

<table>
<thead>
<tr>
<th>Time [DoE]</th>
<th>(M) [m² m⁻²]</th>
<th>(t_1) [DoE]</th>
<th>(t_2) [DoE]</th>
<th>(a_1) [DoE⁻¹]</th>
<th>(a_2) [DoE⁻¹]</th>
<th>(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 212</td>
<td>3.23</td>
<td>102.76</td>
<td>166.43</td>
<td>0.09</td>
<td>0.08</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>213 to 420</td>
<td>2.14</td>
<td>252.22</td>
<td>393.30</td>
<td>0.10</td>
<td>0.05</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>421 to 520</td>
<td>7.00</td>
<td>500.39</td>
<td>–</td>
<td>0.03</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>521 to 595</td>
<td>11.26</td>
<td>499.99</td>
<td>512.18</td>
<td>0.66</td>
<td>0.05</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>595 to 666</td>
<td>1.32</td>
<td>659.99</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>
the dry biomass in the mixed layer varied between 0.25 and 0.65 kg m\(^{-2}\). Here the wetness ratio is strongly linked to precipitation and soil wetness, therefore the wetness ratio in the mixed layer varied a lot during the experiment (between 15% and 70% as shown in Fig. 3, with higher values during the wettest months).

2.4. L-band emission model

Surface parameter estimates were performed by inversion of the L-MEB model (Wigneron et al., in press; Pellarin, Calvet et al., 2003), considering that both the standing vegetation and the mixed layer are part of a single vegetation layer. For a non-scattering medium (single scattering albedo is neglected) the brightness temperature \(TB_{\theta,\text{pol}}\) [K] is described by L-MEB as follows:

\[
TB_{\theta,\text{pol}} = (1 - \gamma_{\theta,\text{pol}}) (1 + \Gamma_{\theta,\text{pol}}) T_V + \gamma_{\theta,\text{pol}} \Gamma_{\theta,\text{pol}} T_E + TB_{\theta,\text{pol}}^{\text{SKY}} \gamma_{\theta,\text{pol}}^2
\]

The soil parameters in Eq. (3) are represented by the soil effective temperature \(T_E\) and the soil reflectivity \(\Gamma_{\theta,\text{pol}}\). The soil temperature \(T_E\) in Eq. (3) is an effective temperature assigned to the soil emitting layer according to the model in Eq. (4) proposed by Wigneron et al. (2001). The effective temperature is obtained from a measurement of the soil temperature close to the surface \(T_{\text{sfce}}\) (here at 1 cm deep), and the temperature in depth \(T_{S,s}\) (here at 50 cm deep).

\[
T_E = T_{S,s} + (T_{\text{sfce}} - T_{S,s}) \left( \frac{W_s}{W_0} \right)^c
\]

At the SMOSREX site the empirical parameters \(w_0\) and \(c\) in Eq. (4) are \(w_0 = 0.36\) and \(c = 0.71\) (de Rosnay et al., 2004).

The Fresnel equations relate the reflectivity of a smooth soil, \(\Gamma_{\theta,\text{pol}}\), to the soil dielectric constant, and the latter is a function of the moisture content at the surface amongst other soil properties. The Dobson model (Dobson et al., 1985) was used in this study to compute the soil dielectric constant. The reflectivity of a non-smooth surface, \(\Gamma_{\theta,\text{pol}}\), can be described by a semi-empirical approach based on three roughness parameters \(h_s, Q_s\) and \(N_s\) (Choudhury et al., 1979; Wigneron et al., 1995) calibrated from microwave measurements.

\[
\Gamma_{\theta,\text{pol}} = \left[ (1 - Q_s) \Gamma_{\theta,\text{pol}}^S + Q_s \Gamma_{\theta,\text{pol}}^S \right] e^{-h_s(\cos(\theta))^{Q_s}}
\]

These parameters account for the effects of i) surface scattering caused by the surface geometry in itself, ii) non-uniform emission due to the irregular distribution of water and temperature on the surface, and iii) volume scattering due to dielectric discontinuities near the surface. In agricultural soils Eq. (5) can be simplified by setting \(Q_s\) and \(N_s\) equal to zero (Wigneron et al., 2001; Wigneron & Shi, in press).

The vegetation parameters in Eq. (3) are given by the vegetation temperature \(T_V\) [K] (in this study the air temperature at 2 m was used), and the vegetation transmissivity \(\gamma_{\theta,\text{pol}}\). The vegetation transmissivity \(\gamma_{\theta,\text{pol}}\) is a function of the vegetation optical depth, \(\tau\), which characterises the extinction across the canopy.

\[
\gamma_{\theta,\text{pol}} = \exp(-\tau_{\theta,\text{pol}}/\cos(\theta))
\]

The vegetation optical depth has been related to the vegetation water content, \(VWC\) [kg m\(^{-2}\)] through an empirical parameter, \(b'\) (Jackson & Schmugge, 1991):

\[
\tau_{\theta,\text{pol}} = b_{\theta,\text{pol}}' \cdot VWC
\]

As a first approach the dependence of \(\tau\) on angle and polarisation will be assumed to be negligible to describe the optical depth of the green vegetation, residual vegetation and mulch layer.

Finally, the parameterisation of the atmospheric and galactic contribution \(TB^{\text{SKY}}\) developed by (Pellarin et al., 2003b) was used. Accordingly, the atmospheric contribution is computed from measurements of the air temperature and altitude.

2.5. Model inversion

In this study, estimates of vegetation attenuation and surface roughness effects will be computed through retrievals of, respectively, the optical depth \(\tau\) and the roughness parameter \(h_s\). Retrievals of \(\tau\) or \(h_s\) are based on the minimisation of the cost function \(C_F\) in Eq. (8), given by the sum of squared differences-weighted by the standard deviations \(\sigma\) of i) the N TB\(^\circ\) measurements obtained by LEWIS and simulated TB from L-MEB, and ii) first guess \(p_{\text{ini}}\) and retrieved values for each of the \(P\) surface parameters as in Pardé et al. (2004).

\[
C_F = \sum_{i=1}^{N} \frac{(TB_{\theta,\text{pol}}^i - TB_{\theta,\text{pol}}^\circ_i)^2}{\sigma_{TB}^i} + \sum_{j=1}^{P} \frac{(p_{j} - p_{j}^{\text{ini}})^2}{\sigma_{p}^j}
\]

For a given time \(t\), a set of ten TB\(^\circ\) measurements was available (five angles and two polarisations), from which a single parameter was retrieved (\(\tau\) or \(h_s\)). To determine the best fit parameters a numerical algorithm using a Levenberg–Marquadt type optimisation approach was used.

2.6. Calibration of soil emission

The calibration of the soil emission was supported by the results obtained at the adjacent bare soil plot by Escorihuela et al. (2004). One important result of that study was the observed dependence between the surface roughness parameter \(h_s\) and surface soil moisture \(w_s\). This relationship was already pointed out by (Wigneron et al., 2001) for an agricultural field. Both studies conclude that roughness effects are stronger for dry soils. The calibrated relationship \(h_s(w_s)\) developed by Escorihuela et al. (2004) for bare soil indicates that \(h_s\) is constant for low \(w_s\), then it decreases linearly with \(w_s\) and it remains constant for wet soil conditions \((w_s > 0.30\ m^3/m^3)\). The other estimated roughness parameters over bare soil were \(Q_s = 0, N_s = 1\) and \(N_s = 0\). This soil model will be referred to as the Bare Soil (BS) model.
Over grass, it was assumed that $Q_S=0$, $N_{S, H}=1$ and $N_S$, $V=0$ and the same slope $s$ ($s = -3$ m$^2$ m$^{-3}$) between $h_s$ and $w_s$ obtained for the BS model was maintained. Note that the roughness parameter $h_s$ may differ between both surfaces for a given moisture content due to different agricultural practices. Therefore, $h_s$ in dry soil conditions (referred to as $h_s^0$) was calibrated specifically for the soil emission at the grass plot. The calibration of $h_s^0$ was made when the effect of vegetation on the microwave emission was very low and could be easily neglected ($\tau=0$): i) in summer, so that VWC $\approx$ 0, ii) for $w_s$ under 0.10 m$^3$ m$^{-3}$ (so that the mixed layer was dry), iii) in the absence of rain interception (minimum three days after the last rain) and iv) in the afternoon (between 12 and 18 local solar time) to support the hypothesis that the standing vegetation and the mixed layer were completely dry. The best-fit $h_s$ parameters obtained under these conditions are given in Fig. 4 for several dates. Considering that lowest values of $w_s$ were obtained when the effect of vegetation was minimal (corresponding to best conditions for calibrating the soil emission), the lowest retrieved $h_s$ value was selected (i.e. $h_s^0=1.3$). Accordingly, the soil model used in this study to quantify the soil emission at the grass plot is given by Eq. (9), where $h_s=0.7$ is obtained by substitution of $w_s=0.30$ m$^3$ m$^{-3}$ in the relationship given for intermediate soil moisture values:

$$h_s = h_s^0 = 1.3 \text{ for } w_s \leq 0.1 \text{ m}^3 \text{ m}^{-3}$$
$$h_s = 1.6 - 3w_s \text{ for } 0.1 \text{ m}^3 \text{ m}^{-3} < w_s \leq 0.3 \text{ m}^3 \text{ m}^{-3}$$
$$h_s = 0.7 \text{ for } w_s > 0.3 \text{ m}^3 \text{ m}^{-3}$$

3. Results

3.1. The radiometric signature of rain interception

Two examples illustrating the response of TB to rainfall are given in Fig. 5. The first example corresponds to a very light rain on DoE 139, with 0.3 mm of accumulated rain during 1.7 h. The estimated LAI was equal to 2.7 m$^2$ m$^{-2}$. Soil moisture variations before and after the rain were almost negligible, showing that rain was fully intercepted. Note that the soil moisture probe accuracy is estimated around 0.01 m$^3$ m$^{-3}$. As a result increased due to vegetation wetting, and $T_{sfc}$ decreased following the soil temperature daily cycle. This is illustrated in Fig. 5 for the TB at H polarisation and 30° (TB$_{30,H}$). In addition, the polarisation ratio $PR_{50}$ given by Eq. (10) was also found to be sensitive to interception.

$$PR_{50} = \frac{(TB_{50,V} - TB_{50,H})}{(TB_{50,V} + TB_{50,H})} \tag{10}$$

The polarisation ratio $PR_{50}$ decreases with decreasing soil moisture and increasing vegetation. As the vegetation biomass increases two effects contribute to reduce $PR_{50}$: the strongly polarised soil emission (TB$_{50,V} \gg$ TB$_{50,H}$) is attenuated by the vegetation layer, while the depolarized vegetation emission increases (TB$_{50,V} \approx$ TB$_{50,H}$). The significant reduction observed in $PR_{50}$ as soon as the rain started reflected the attenuation of the soil emission caused by intercepted water by the standing vegetation. Conversely, the later increase in $PR_{50}$ was the result of the evaporation of intercepted rain. Therefore, while rainfall is expected to decrease the TB and increase the $PR_{50}$ over bare soils the opposite effect was observed over grass. Note that by interception we refer to wetness associated to rainfall. The distinction between interception by the standing vegetation and the mixed layer is made when necessary.

The second example shows two consecutive rain episodes (Fig. 5). Firstly, 7.3 mm were measured during a 1-h interval on the late evening of DoE 109 (LAI $\approx 2.1$ m$^2$ m$^{-2}$). Following that event, surface soil moisture varied from $w_s=0.18$ m$^3$ m$^{-3}$ to $w_s=0.30$ m$^3$ m$^{-3}$. Even though soil moisture responded quickly to precipitation, the global effect of rainfall was to increase TB$_{30,H}$ and to reduce $PR_{50}$ as a consequence of rain interception by the standing vegetation and the mixed layer. In the early morning of DoE 110, TB$_{30,H}$ was still high due to very light intermittent rains overnight. A number of less intense rains took place on DoE 110 from midday to midnight (4.7 mm), which increased soil moisture up to 0.34 m$^3$ m$^{-3}$. Interception effects could be clearly identified through variations in the polarisation ratio $PR_{50}$. $PR_{50}$ reached minimum values ($PR_{50}=0.011$) after the successive rainfalls that took place up to the early morning of DoE 111 as shown in Fig. 5. Note that at the end of DoE
the polarisation ratio is close to that of DoE 109 despite soils being wetter. This result highlights the role of the mixed layer in absorbing the soil emission when wet. Links between interception and microwave indices, which were illustrated through these two examples, will be investigated in detail in the following section.

Fig. 5. a) Radiometric signature of a light rainfall and b) a moderate rainfall.

Fig. 6. Polarisation index for the whole data set (dots) and for measurements taken at least 24 h after the last rainfall (+). The continuous dark line represents the LAI. Threshold values used in the definition of interception flags (PR<sub>50</sub>=0.02 and PR<sub>50</sub>=0.031) are also plotted (thin lines).
3.2. Microwave indices for rain interception by the standing vegetation

The relationship between a large number of microwave indices and interception was examined (not presented here). The microwave indices were based on simple combinations of TB measurements at H, V or both polarisations, and one or two angles, namely a small angle (20° or 30°), and a large angle (40° or 50°). Only best results, which were obtained using the PR\textsubscript{50} index (Eq. (10)), will be shown in this paper. The sensitivity of PR\textsubscript{50} to interception can be observed in Fig. 6, where measurements of PR\textsubscript{50} for the whole data set, and at least 24 h after the last rainfall are represented. A significant decrease in PR\textsubscript{50} associated to rain interception is observed for all vegetation and soil moisture conditions. Based on these observations, two interception flags based on PR\textsubscript{50} were developed, a flag for likely interception, and a flag for unlikely interception.

- The analysis of Fig. 6 indicated that 98% of measurements in which PR\textsubscript{50} ≤ 0.020 corresponded to rainfall events within the last 24 h. This feature can be associated to the interception by the standing vegetation mainly: PR\textsubscript{50} increased for measurements taken at least 24 h after the rain as a consequence of the evaporation of rain intercepted by the standing vegetation.
- It was observed that 90% of the measurements taken in the rain-free period in Fig. 6 corresponded to PR\textsubscript{50} ≥ 0.031. Water on the standing leaves is likely to have evaporated after 24 h, thus the condition PR\textsubscript{50} ≥ 0.031 could be used to flag unlikely interception by the standing vegetation.
- The interception flags PR\textsubscript{50} ≤ 0.020 and PR\textsubscript{50} ≥ 0.031 present some limitations. For example, in wet soil conditions and very low vegetation PR\textsubscript{50} is expected to be very high. This means that the index PR\textsubscript{50} might remain over 0.031 after rainfall. Also, PR\textsubscript{50} is very low when vegetation reaches the highest development. In that case some measurements would be discarded by the interception flags for non-interception conditions. Intermediate values of PR\textsubscript{50} between 0.02 and 0.031 are not classified as the vegetation and mixed layer wetness were not quantified in this experiment. Despite these limitations the use of the flags PR\textsubscript{50} ≤ 0.020 and PR\textsubscript{50} ≥ 0.031 covered 85% of the data set.

The use of interception flags at different time scales was evaluated further in detail. Table 3 summarises the results for times scales varying between 3 and 24 h. The columns in Table 3 provide a direct approach reading, while the rows give an inverse approach reading as explained next.

- Through the direct approach we could assess the effect of interception on the microwave signature represented by PR\textsubscript{30}. When rain was present within the last time \( t \), the probability of obtaining PR\textsubscript{50} ≤ 0.020 was highest for \( t = 3 \) h (65% of the cases, from the ratio 9.3% over 14.3% in Table 3). Note that this probability is significant but not very high as the percentage of measurements that remain unclassified is higher when rainfall is present. In the absence of rainfall within the last time \( t \), the probability of having PR\textsubscript{50} ≥ 0.031 was found to be very high for all time scales, particularly for \( t = 24 \) h where interception effects should be minimised.
- Through the inverse approach we examined the performance of the interception flags to determine the likelihood of interception. The correspondence between PR\textsubscript{50} ≤ 0.020 and rainfall improved with the time scale. For example, if PR\textsubscript{50} ≤ 0.020 then rainfall had occurred within the last 24 h for 98% of the cases as stated earlier (98% is obtained from 16.8% over 17.1% in Table 3). The probability of finding no rain when PR\textsubscript{50} ≥ 0.031 was very high, especially at short time scales.

3.3. Vegetation optical depth estimates

The possibility of estimating the vegetation optical depth \( \tau \) from low frequency microwave measurements has been shown in a large number of works (Wigneron et al., 1995; Van de Griend et al., 1996; Owe et al., 2001). This opens the possibility of obtaining a vegetation-related parameter from space measurements, which could be related to the vegetation biomass. We examined the relationship between optical depth estimates and rain interception over grass. Estimates of \( \tau \) were obtained from multi-angular and dual polarisation TB measurements at L-band, and the L-MEB model. The scenario observed by LEWIS can be described as a system where the following components contribute to TB: bare soil (soil emission was characterised in Section 2.6), standing green vegetation (including intercepted water just after rainfall), and the mixed layer. The contribution of these three main components to the TB signature was investigated from the analysis of observations made during time periods corresponding to different meteorological and vegetation conditions as described next.

### Table 3

<p>| Dual entry table for the interception flags based on PR\textsubscript{50} and rainfall events at different time scales |
|---|---|---|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Rain</th>
<th>No rain</th>
<th>Total</th>
<th>Rain</th>
<th>No rain</th>
<th>Total</th>
<th>Rain</th>
<th>No rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>− 3 h</td>
<td>− 3 h</td>
<td>Total</td>
<td>− 12 h</td>
<td>− 12 h</td>
<td>Total</td>
<td>− 24 h</td>
<td>− 24 h</td>
</tr>
<tr>
<td>PR\textsubscript{50} ≤ 0.020</td>
<td>9.3%</td>
<td>7.8%</td>
<td>17.1%</td>
<td>14.6%</td>
<td>2.5%</td>
<td>17.1%</td>
<td>16.8%</td>
</tr>
<tr>
<td>PR\textsubscript{50} ≤ 0.031</td>
<td>2.0%</td>
<td>66.1%</td>
<td>68.1%</td>
<td>6.9%</td>
<td>61.2%</td>
<td>68.1%</td>
<td>14.2%</td>
</tr>
<tr>
<td>Other</td>
<td>3.0%</td>
<td>11.8%</td>
<td>14.8%</td>
<td>6.0%</td>
<td>8.8%</td>
<td>14.8%</td>
<td>9.1%</td>
</tr>
<tr>
<td>Total</td>
<td>14.3%</td>
<td>85.7%</td>
<td>100%</td>
<td>27.5%</td>
<td>72.5%</td>
<td>100%</td>
<td>40.1%</td>
</tr>
</tbody>
</table>

Percentages (%) refer to the total number of measurements.
3.3.1. Green vegetation emission

In order to model the L-band emission of green vegetation we extracted a number of measurements made when the effects of interception could be considered as very low. We selected data three days ahead from the last rain to avoid interception in the standing vegetation, and \( w_s \) under 0.15 m \( \text{m}^3 \text{m}^{-3} \) to reduce the effect of wetness in the mixed layer. The optical depth estimates for measurements fulfilling this condition are represented by \( \tau_{gv} \) in Fig. 7. An approximation for the green vegetation optical depth, \( \tau_{gv} \), is given by the enveloping function \( \tau_{0}^{gv} \) given by Eq. (11) and represented in Fig. 7.

\[
\tau_{gv} = 0.03 \exp(\text{LAI}^{0.52}) - 1
\]  

Note that if \( w_s \) was limited to \( w_s = 0.20 \text{ m}^3 \text{m}^{-3} \) (results not shown) then LAI values over 4 m \( \text{m}^{-2} \) also followed the trend given by Eq. (11). The vegetation water content diurnal cycle was also found to produce a diurnal cycle in the optical depth. The average diurnal variation in the extracted dataset (120 days) was equal to \( \Delta \tau_{gv} = \max(\tau_{gv}) - \min(\tau_{gv}) = 0.045 \) \( \sigma = 0.27, \text{maximum} \Delta \tau_{gv} = 0.14 \). This variation could explain the scattering observed in Fig. 7 for a given LAI. Also, \( \tau_{gv} \) values were higher than expected for LAI values close to 0 m \( \text{m}^{-2} \). Nevertheless, the approximation given in Eq. (11) provides the minimum contribution of green vegetation to TB, and it is helpful to understand the effect of interception on the brightness temperature.

Table 4 summarises the errors obtained in the modelled TB for the conditions presented in this section (green vegetation). The RMSE between modeled and measured multi-angular and bi-polarizations brightness temperatures was computed for each time \( t \). The average RMSE for the whole period using best fit \( \tau_{gv} \) values was 3 K \( \sigma = 1.1 \text{ K} \). As expected, a lower accuracy was obtained when using the approximation given by Eq. (11) (namely substituting \( \tau_{gv} \) by \( \tau_{0}^{gv} \)): the average RMSE was 4.6 K and \( \sigma = 2.1 \text{ K} \).

3.3.2. Optical depth and interception

The effect of intercepted water on the retrieved \( \tau_{gv} \) values is illustrated in Fig. 8 for the two rain events shown in Fig. 5. The sensitivity of \( \tau_{gv} \) to interception can be clearly noted, even for the small rainfalls occurred in the afternoon of DoE 139 (0.3 mm): \( \tau \) increased from \( \tau = 0.15 \) before the rain to \( \tau = 0.28 \) right after the rain (Fig. 8). The 7.3 mm rainfall that occurred in the late evening of DoE 109 also produced a clear increase in \( \tau \) from \( \tau = 0.15 \) before the rain to \( \tau = 0.44 \) after the rain (Fig. 8). The intermittent rainfalls that followed between midday and midnight on DoE 110 also reflected on \( \tau \), that increased up to \( \tau = 0.5 \). The low values of PR 50 showed that interception could still be present at the beginning of the intermittent rains. Therefore it is likely that the plant was close to its maximum interception capacity, giving smaller \( \tau \) variations than the ones observed during the first rainfall.

Table 4

<table>
<thead>
<tr>
<th>Period</th>
<th>Parameters</th>
<th>Config.</th>
<th>No meas.</th>
<th>RMSE [K]</th>
<th>( \sigma ) (RMSE) [K]</th>
<th>Max RMSE [K]</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green vegetation</td>
<td>Best fit ( \tau_{gv} )</td>
<td>HV</td>
<td>1241</td>
<td>3.0</td>
<td>1.1</td>
<td>6.7</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>( \tau_{0}^{gv} = f(\text{LAI}) )</td>
<td>HV</td>
<td>1241</td>
<td>4.6</td>
<td>2.1</td>
<td>12.2</td>
<td>0.96</td>
</tr>
<tr>
<td>No interception</td>
<td>Best fit ( \tau )</td>
<td>HV</td>
<td>2620</td>
<td>4.4</td>
<td>2.3</td>
<td>12.6</td>
<td>0.89</td>
</tr>
<tr>
<td>Interception</td>
<td>Best fit ( \tau )</td>
<td>HV</td>
<td>2640</td>
<td>6.0</td>
<td>2.3</td>
<td>13.2</td>
<td>0.59</td>
</tr>
<tr>
<td>All cases</td>
<td>Best fit ( \tau )</td>
<td>HV</td>
<td>6578</td>
<td>5.4</td>
<td>2.5</td>
<td>13.2</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Fig. 7. Retrieved green vegetation optical \( \tau_{gv} \) depth as a function of the LAI. Solid line: enveloping function \( \tau_{0}^{gv} = 0.03(\exp(\text{LAI}^{0.52}) - 1) \).
A more general analysis of the \( \tau \) time variation for the whole period of study is given in Fig. 9. These time series include i) \( \tau_{gv}^0 \) obtained from Eq. (11) (thick line), ii) retrieved values for the optical depth at least 24 h after the last rainfall (\( \tau^0 \)) (i.e. no interception within the standing vegetation, black dots), and iii) \( \tau \) values retrieved for the whole data set (thin line). Maximum values of these parameters were \( \max(\tau_{gv}^0) = 0.25 \), \( \max(\tau^0) = 0.44 \) and \( \max(\tau) = 0.70 \). The contribution of green vegetation and interception to \( \tau \) can be analysed from these time series and most significant results are:

i) The difference \( \tau^0 - \tau_{gv}^0 \) corresponds to the contribution of the mixed layer to the optical depth and it can go up to 0.39. Note that the green vegetation optical depth variation from LAI=0 to LAI=5 m\(^2\) m\(^{-2}\) given by Eq. (11) was equal to 0.27. As expected, the difference \( \tau^0 - \tau_{gv}^0 \) was more significant outside the late spring and summer periods, where lower \( \nu_s \) and only a few rainfalls led to drier wetness in the mixed layer.

ii) The difference \( \tau - \tau_{gv}^0 \) can be related to the interception by the standing vegetation and the mixed layer. We observed...
that this difference went up to 0.56 from dry to wet conditions and high biomass.

Estimates of the optical depth difference $\tau - \tau_{gv}^0$ were related to different interception conditions. The approach is very similar to the one presented earlier in this paper for the interception flags based on the polarisation ratio. However, only the flags based on are proposed for satellite applications as they rely on observations only. First, the relationship between likely interception and the difference $\tau - \tau_{gv}^0$ 24 h after the last rainfall was examined. It was found that 95% of these measurements satisfied the relationship $\tau_{gv}^0 / c_{21} <= 0.25$. Second, in the absence of rainfall within the last 24 h the relationship $\tau - \tau_{gv}^0$ was accomplished by 90% of those measurements. In this way, two relationships based on the optical depth could be compared to interception: $\tau - \tau_{gv}^0$ for likely interception, and $\tau - \tau_{gv}^0$ for unlikely interception. Both the direct and inverse approaches (Table 5) were analysed as previously done for the PR50 flags, and very similar results were obtained.

- The direct approach indicated a good relationship between the absence of rainfall and the optical depth difference $\tau - \tau_{gv}^0$. This is, the probability of obtaining $\tau - \tau_{gv}^0$ was very low, while the probability of obtaining $\tau - \tau_{gv}^0$ was very high for all the time scales. As for the PR50 flags, the case that was worse represented was that of rainfall leading to optical depth values out of the likely interception flag.

- The inverse approach showed a good performance of the interception flags to detect the interception status. When the condition $\tau - \tau_{gv}^0$ was applied, the presence of rainfall within the last time increased as expected with the time scale. If $\tau - \tau_{gv}^0$ then rainfall had occurred within the last 24 h for 98% of the cases as stated earlier (from 18.1% over 19.1% in Table 5). Finally, the relationship $\tau - \tau_{gv}^0$ was well correlated to the absence of rainfall, especially at short scales. For $t = 24$ h the probability of no rainfall was 79% (from 54.0% over 68.3% in Table 5).

The presence of interception increased the error in the TB simulations, as shown in Table 4. The RMSE between measured and simulated TB was equal to 4.4 K ($\sigma = 2.3$ K) for observations corresponding to cases of no interception by the standing vegetation (No interception). Finally, potential

---

Table 5

<table>
<thead>
<tr>
<th></th>
<th>Rain</th>
<th>No rain</th>
<th>Total</th>
<th>Rain</th>
<th>No rain</th>
<th>Total</th>
<th>Rain</th>
<th>No rain</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau - \tau_{gv}^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 0.25$</td>
<td>9.5%</td>
<td>9.6%</td>
<td>19.1%</td>
<td>3.9%</td>
<td>19.1%</td>
<td>18.1%</td>
<td>1.0%</td>
<td>19.1%</td>
<td>19.1%</td>
</tr>
<tr>
<td>$\leq 0.18$</td>
<td>1.8%</td>
<td>66.6%</td>
<td>68.4%</td>
<td>6.7%</td>
<td>61.7%</td>
<td>68.4%</td>
<td>14.3%</td>
<td>54.1%</td>
<td>68.4%</td>
</tr>
<tr>
<td>Other</td>
<td>3.0%</td>
<td>9.6%</td>
<td>12.4%</td>
<td>5.6%</td>
<td>6.9%</td>
<td>12.4%</td>
<td>3.7%</td>
<td>4.9%</td>
<td>12.4%</td>
</tr>
<tr>
<td>Total</td>
<td>14.3%</td>
<td>85.7%</td>
<td>100%</td>
<td>27.5%</td>
<td>72.5%</td>
<td>100%</td>
<td>40.1%</td>
<td>59.9%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Percentages (%) refer to the total number of measurements.

---

Fig. 10. Mixed layer optical depth ($\tau - \tau_{gv}^0$) versus water content in the mixed layer (LWC).
interception by standing vegetation (Interception) increased the RMSE up to 6 K (σ=2.3 K).

3.3.3. Water content in the mixed layer and optical depth

The optical depth estimates obtained for wet conditions evidence that the contribution of the mixed layer needs to be incorporated into the TB emission model. As a first approach, a formulation relating the microwave optical depth to the water content in the mixed layer (LWC [kg m⁻³]) was used, in a similar fashion to the widely used relationship given by Eq. (7) for standing crops. Thus, LWC and the mixed layer optical depth ($\tau_L = \tau_b - \tau_V^0$) were related using $b_L$ the parameter according to:

$$\tau_{L,\text{pol}} = b_{L,\text{pol}} LWC$$

The structure parameter $b_L$ was calculated from i) estimates of $\tau_L$ computed as the difference $\tau_b - \tau_V^0$ (no interception by the standing vegetation), and ii) measurements of LWC in the same conditions. For the latter, the spatial variability was considerable, so average values of LWC were used. Results are shown in Fig. 10. The linear fit ($R^2=0.60$) plotted in Fig. 10 suggests that the classical formulation for the vegetation optical depth might also be suitable to describe the attenuation by the mixed layer. The slope of the fit represents the structure parameter $b_L=0.26$. This value is at least twice the $b'$ parameter found for grass in the literature. This result highlights the important role of intercepted water by the lower part of the plant, mulch and vegetation residues to the overall emission at L-band.

4. Summary and conclusion

The SMOSREX ground experiment brings together a number of relevant studies for L-band radiometry from space, such as modelling of the bare soil and grass emission at L-band, synergy between microwave and multispectral measurements, and assimilation of microwave data into soil–vegetation–atmosphere models. This study focused on the L-band emission of natural grass measured by the radiometer LEWIS during 22 months. The length of the experiment provided very contrasting soil moisture and vegetation conditions, including rain interception by the standing vegetation and by a mixed layer including mulch, vegetation residues and plant roots. Rain interception transforms the almost transparent grass canopy into a powerful absorber of microwave radiation. As a result, soil emission is significantly attenuated, while the vegetation and mixed layer emission increase. Two main issues were addressed to improve surface soil moisture ($\nu_s$) retrievals in these conditions. Firstly, the possibility to detect the presence/absence of interception from microwave indices was studied. Two flags based on the polarisation ratio at 50° were found to be suitable to report the absence of rainfall, especially at short time scales (3 to 12 h), and the presence of rainfall, particularly at long time scales (12 to 24 h). Secondly, we investigated the relationship between rain interception and the vegetation optical depth ($\tau$), that was estimated by inversion of a non-scattering radiative transfer model (single scattering albedo equal to zero) of the vegetation emission. Multi-angular and dual-polarisation TB measurements were used in the retrievals. A parameterisation for the green optical depth as a function of the LAI was established from $\tau$ estimates in the absence of interception. At the greenest stage (LAI = 4 m² m⁻²), the green vegetation optical depth was $\tau=0.25$ in dry conditions. When interception by the mixed layer was considered, an increase in the optical depth up to 0.39 was found respect to dry conditions. Finally, $\tau$ values reached $\tau=0.7$ after rainfall due to interception by the standing vegetation.

Interception flags can be of great interest for satellite applications. Here the interest is multiple, as flagging potential interception is necessary to assess the quality of soil moisture retrievals performed in the presence of interception. Also, knowledge on the presence of interception could be used to separate the contribution of green vegetation and intercepted water to $\tau$, when the latter will be simultaneously retrieved to soil moisture. A limitation of the flags based on PR₅₀ is that they are able to flag the interception by the standing vegetation only. New experiments should be conducted to monitor the mixed layer wetness in order to develop an interception flag for the mixed layer. In addition, further experimental data is needed to validate the threshold values proposed in this study and to establish threshold values for other cover types. Whether it will be possible to estimate soil moisture in fields covered by dense grass and mulch is still an open question of key importance. Modelling work is now crucial to address this problem. First results presented in this work suggest that the attenuation effects due to the water content in the vegetation material are higher in the mixed layer than in the standing vegetation ($b_L=0.26$ for the mixed layer, while $b'_L \approx 0.05–0.15$ from the results shown in this work). Also, scattering effects that were neglected in this study need to be examined. Finally, the interception flags presented in this study have been applied to soil moisture retrievals at SMOSREX (Saleh et al., in press). The retrievals make use of semi-empirical relationships between surface soil moisture and brightness temperature measurements at L-band.

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