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Testing a New Model for the L-Band Radiation of Moist Leaf Litter

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Abstract—The crown vegetation of a deciduous forest is known to be semitransparent at low microwave frequencies, and leaf litter covering the forest soil has been recognized to have a significant impact on ground emission. The proposed approach for modeling the L-band radiative transfer through leaf litter consists of an isotropic effective medium approach for the litter permittivities, a coherent radiative transfer model for computing the coherent reflectivities from dielectric depth profiles, and an averaging procedure for computing the reflectivities determining the field-scale brightness temperatures. Evaluations were performed for the case of leaf litter on top of a conducting wire grid (litter-grid formation) and for litter on underlying soil (litter-soil formation). A model sensitivity analysis was performed with respect to parameters characterizing litter thickness variations and boundary roughness. For the litter-soil formation, the model was rather sensitive to local irregularities at the air-to-litter boundary. Modeled microwave signatures reproduced the major features of the measurements performed on a site comprising a litter-grid formation. Under dry conditions, the investigated litter layer was nearly “invisible.” When the same litter layer was wetted, it acted as an important radiation source to be taken into account for the quantitative remote soil moisture detection of forested areas. Under certain conditions, the simulations revealed an increasing brightness when the litter is wetted prior to the underlying soil. Further wetting of the litter-soil system then resulted in a decreasing brightness as expected for increased moisture. Such effects are important to know to avoid misleading interpretations of L-band signatures.

Index Terms—Leaf litter, microwave radiometry, radiative transfer, soil moisture.

I. INTRODUCTION

THE TERRESTRIAL surface layer is an important boundary for energy fluxes between the Earth and the atmosphere. It controls the climate at local, regional, and global scales. Techniques for monitoring the surface moisture are therefore of particular interest. Microwave radiometry at L-band (1–2 GHz) is a passive remote sensing technique that is applicable for soil moisture retrieval at large scales

[1]–[4]. The Soil Moisture and Ocean Salinity (SMOS) mission of the European Space Agency (ESA) aims at areal monitoring the land surface moisture and ocean salinity from a satellite equipped with an L-band radiometer [5], [6]. Global coverage will be obtained every three days with a spatial resolution of approximately $40 \times 40 \text{ km}^2$ and an expected soil moisture accuracy of 4% by volume.

As forested areas comprise approximately one third of the Earth’s land surface (excluding Antarctica and Greenland), in many cases, the observed footprint will partly or fully be covered by forests. To interpret the upcoming spaceborne brightness temperature data in terms of soil water content, it is therefore essential to know the radiation properties of the forest canopies and of the organic layer (litter) covering the mineral soils.

Several theoretical [7]–[9] and experimental studies [10]–[14] were performed with regard to deciduous and coniferous forests. The Forest Soil Moisture Experiment (FOSMEX) [12] performed at a deciduous forest site at the Research Center Jülich, Germany, showed the semitransparency of the forest canopy at L-band frequencies, allowing for sensing the forest ground radiation. Recently, litter has been recognized as a serious problem for quantitative soil moisture detection using L-band radiometry. From the one-year FOSMEX data set, consisting of dual- and single-polarized L- and X-band data simultaneously recorded with ground moisture and temperature, it was postulated that a large fraction of rainwater funnels through the litter layer to deeper soil horizons [12]. In particular, under wet conditions, litter acts as an absorber and as a significant source of radiation in addition to the underlying soil. The “Bray 2004” L-band radiometry campaign [15], which was conducted in the coniferous forest of Les Landes near Bordeaux, France, corroborated the semitransparency of the forest canopy. Although the horizontally polarized brightness was predominantly affected by the physical temperature, a marginal correlation with simultaneously measured soil and litter moisture was identified. The generally high scene emissivities were associated with the presence of a substantial litter layer. By virtue of the strong correlation found between soil and litter moisture, it was concluded that decoupling the effects of soil and litter on the above canopy brightness might be difficult.

Although the relevance of litter has been recognized for quantitative microwave radiometry, very little theoretical and experimental knowledge about the microwave radiative transfer through litter is available to date. This instance was the motivation for proposing a physically based model of the microwave radiation of leaf litter at different moisture conditions.

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The microwave measurements used to validate the model are performed with the ETH L-Band Radiometer (ELBARA) [16] installed above a footprint comprising an area with leaf litter on top of a conducting wire grid.

This paper contributes to the conceptual understanding of microwave radiative properties of leaf litter in deciduous forests. The findings might be useful for calibrating the parameters occurring in the so-called L-band Microwave Emission of the Biosphere model to be used in the SMOS Level 2 algorithm [17], [18].

II. FIELD EXPERIMENT

The L-band radiometer campaign performed to validate the developed leaf-litter model took place from August to September 2006 at the Institute of Plant Sciences, Eschikon (550 m a.s.l.), which is 15 km northeast of Zürich, Switzerland. L-band brightness temperatures were measured with a microwave radiometer deployed on a small tower and directed toward an artificially prepared area containing leaf litter. Auxiliary data, such as precipitation and *in situ* ground temperatures, were recorded every 15 min, simultaneously with the brightness temperatures for comparison and modeling purposes.

A. Remote Sensing System

The L-band radiometer ELBARA [16] was specifically designed for tower-based field-scale experiments. Since 2002, this instrument has been successfully deployed in numerous campaigns which provided information that is important for interpreting L-band radiance in terms of soil moisture and other scene parameters like roughness and vegetation covers [10]–[12], [19]–[23].

ELBARA is a Dicke-type radiometer operating at the frequency $f = 1.4$ GHz corresponding to the vacuum wavelength $\lambda = 21$ cm. Horizontally and vertically polarized brightness temperatures T_B^H and T_B^V are measured with an absolute accuracy better than ± 1 K and a sensitivity of < 0.1 K within the temperature range of 200–400 K. Radio-frequency interferences are distinguished from natural thermal radiance by measuring quasi-simultaneously at two channels of 18-MHz bandwidth and overlapping frequencies of 1.400–1.418 GHz and 1.409–1.427 GHz, respectively. Preceding each measurement, calibration is performed internally with cold (278 K) and hot (338 K) loads. Sky brightness $T_{B,sky}$ are measured frequently, exhibiting a standard deviation of less than 2 K, which indicated the stable operation of the instrument during the campaign. To confine the received radiance to a well-defined and narrow footprint area, a large dual-mode Picket horn antenna [24] (diameter $d = 1.4$ m; length $l = 2.7$ m) is used. The -3 -dB full beamwidth in the far field ($> 2 \cdot d^2/\lambda \cong 18.7$ m) is 12° around the antenna main direction for both polarizations.

B. Experimental Setup

The campaign conducted in 2006 was started on Day of Year (DoY) 237 (August 24) and ended two weeks later on

Fig. 1. Setup of the experiment showing the elliptic area ($A = 2.3$ m and $B = 1.5$ m) comprising the stratified litter-grid formation prepared for measuring the litter radiative transfer properties with the L-band radiometer ELBARA mounted on the tower.

DoY 250 (September 6). A small tower was installed to deploy the ELBARA radiometer so that the antenna aperture was approximately 5 m apart from the center of the footprint area (Fig. 1). The measurements were performed at the fixed observation angle $\alpha = 50^\circ$ relative to the vertical direction.

The artificially prepared central area of the observed site was made up of a highly reflecting wire grid laid on the ground and covered with dead leaf material representing litter that is present in deciduous forests. The mesh size of the wire grid was 2 mm, which is both small enough to shield the upwelling soil radiation and large enough for almost unhampered water drainage. Fig. 1 shows the elliptic area with half axes $A = 2.3$ m and $B = 1.5$ m comprising the stratified litter-grid formation used for inferring radiative properties of leaf litter. The view angle associated with the prepared area is significantly larger than the -3 -dB full beamwidth (12°) of the antenna directivity in the far field, which means that the received radiance is predominantly emitted from the prepared area. Furthermore, the observed scene at the distance of approximately 5 m is still within the antenna near field, implying that the actual antenna directivity is even more confined than the -3 -dB full beamwidth of 12° in the far field. However, the fractional contribution to the total antenna sensitivity, resulting from the solid angle comprising the elliptic area, has been determined to be $\mu \approx 0.9$ from measurements taken with and without the wire grid (Section III-B).

Furthermore, ground temperatures were recorded with thermistors (Campbell S-TL107) installed 30 mm below the aluminum wire grid at five different locations. The neighboring area was turned into bare soil by sprinkling the leaf herbicide ROUNDUP Ultra (glyphosate).

C. Litter Preparation

The leaf material was collected during the preceding defoliation period 2005, and stored under a cover outdoors, to maintain the leaf moisture as well as possible without promoting

decomposition. The dry-matter fraction m_d (in kilograms per kilogram), which is defined as the ratio between the oven-dry leaf mass and the mass of the moist leaf material, was measured to be $m_d \approx 0.5 \text{ kg} \cdot \text{kg}^{-1}$. The same value was found for the leaves immediately after the defoliation of the forest site in Jülich, where the FOSMEX campaign was performed [11], [12]. This indicates that the measures taken to avoid drying the leaves during storage were effective. However, compared with fresh green leaves (with typically $m_d = 0.15 \text{ kg} \cdot \text{kg}^{-1}$ [22]), the water contained in the dead leaves of a litter layer is considerably lower.

The dead leaves were spread on top of the aluminum wire grid as uniformly as possible and prevented from being blown off by covering with a nylon mesh that was tested to have no influence on the radiometric measurements. The deployed gravimetric column density $\rho_L = 1.2 \text{ kg} \cdot \text{m}^{-2}$ of leaves corresponds to the typical amount accumulated on the ground of a dense deciduous forest during one year [11], [25]. The mean thickness of the resulting leaf-litter layer was approximately $\langle D_L \rangle \approx 20 \text{ mm}$. For modeling reflectivities of the artificially prepared area (Section III), variations in the litter layer thickness D_L are relevant. Thereby, it is important to note that variations in D_L on lateral scales below and above the resolution limit affect the ground reflectivity differently. The dimension Λ of an object that can just be resolved at the wavelength λ and the observation angle α can be estimated from the Bragg limit (see [26, Sec. 4.7.2])

$$\Lambda \cong \frac{\lambda}{2 \sin \alpha}. \quad (1)$$

Evaluating for $\lambda = 21 \text{ cm}$ and $\alpha = 50^\circ$ yields the resolution limit $\Lambda \approx 14 \text{ cm}$ relevant for our setup. The standard deviations of D_L on lateral scales below ($< \Lambda$) and above ($> \Lambda$) the Bragg limit were estimated from visible inspection to be approximately $\pm 2.5 \text{ mm}$.

The characteristic litter drainage time τ_L is used to model the temporal dynamics of the litter moisture. The time τ_L is estimated from volumetric column densities ρ_{wL} (in cubic meters per square meter) of water retained in the litter layer, which is measured before and after irrigating for 1 h at a rate of $10 \text{ mm} \cdot \text{h}^{-1}$. Litter samples were taken immediately after the irrigation ($t = 0$), as well as 1 h ($t = 1 \text{ h}$) and 3 h ($t = 3 \text{ h}$) later. From the weights of the taken samples in comparison with the corresponding weight of the same litter area taken before the irrigation, the following values were found: $\rho_{wL}(t = 0) = 3.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$, $\rho_{wL}(t = 1 \text{ h}) = 1.2 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$, and $\rho_{wL}(t = 3 \text{ h}) \approx 0.0$. Fitting these values with an exponentially decaying model yields $\tau_L = 1 \text{ h}$. This relatively fast drainage of the leaf litter indicates the abundance of preferential flow paths through the litter and is in accordance with litter-percolation and -retention measurements performed under laboratory conditions [27]. Indeed, the microwave measurements presented in Section IV-D reveal fast responses to the rain events, followed by signatures indicating delayed litter drying. However, after the gravity-driven water flow (drainage) subsides, further drying of the litter may be delayed due to condensation [28], particularly for wet underlying soils and litter temperatures below the soil temperature.

The fact that the dry-matter fraction m_d of the leaves was unchanged before and after the storage, and considering the short litter drainage time τ_L , it is reasonable to assume that the leaf internal moisture, and thus m_d , does not vary significantly during the dry and wet periods of the campaign. However, this assumption might be false for other types of litter, leading to significantly slower drying, as observed for the litter present on the ground of coniferous forests [15].

III. MODELING APPROACH

Approaches applicable for modeling microwave radiative properties of a leaf-litter layer are presented in this section. First, a simple empirical model for relating rain intensity with litter moisture is proposed. The radiative transfer model [29] that is used to derive reflectivities from measured brightness is revisited in Section III-B. In Sections III-C and D, the modeling of reflectivities of litter on top of a wire grid (litter-grid formation) and on underlying soil (litter-soil formation) is described. These sections present the effective medium approach used for litter layer permittivities, and the model applied for computing reflectivities associated with empirical dielectric profiles, representative of the litter-grid and the litter-soil formation.

A. Litter-Water Interaction

For the comparison between modeled and measured time series of L-band signatures (Section IV-D), the temporal evolution $\rho_{wL}(t)$ of the water column density wetting the litter is required. It is proposed to express $\rho_{wL}(t)$ as the exponentially weighted moving average of measured time series $P(t)$ of precipitation rate (rain intensity in millimeters per hour)

$$\rho_{wL}(t) = \int_{t-\infty}^t \exp \frac{-(t-t')}{\tau_L} P(t') dt'. \quad (2)$$

Thereby, the experimentally determined characteristic drainage time $\tau_L = 1 \text{ h}$ of the litter layer is considered (see Section II-B). The approach (2) is numerically evaluated by using rain intensities $P(t)$ in units of $[\text{millimeters} (0.25 \text{ h})^{-1}]$ measured every 0.25 h. Furthermore, $t - 5 \cdot \tau_L$ is used for the lower integration limit in (2), which is a good approximation in view of the exponential decaying weighting with time constant τ_L .

B. Microwave Radiative Transfer

The remotely sensed scene consists of a central elliptic area of leaf litter on an underlying wire grid (litter-grid formation), and the area outside was mainly bare soil (Fig. 1). Brightness temperatures T_B^H and T_B^V at horizontal and vertical polarizations are modeled with radiative transfer comprising these two surface types with corresponding fractional amounts μ and $(1 - \mu)$ of which they contribute to the total radiances T_B^p ($p = H, V$). Reflectivities R^p and R_{out}^p inside and outside the elliptic area are distinguished, whereas uniform ground

Fig. 2. Dielectric inclusion used in the effective medium approach for modeling the leaf-litter permittivities ε_L . (a) Oblate ellipsoid representing a leaf. (b) Cross section of the oblate ellipsoid ($a, b \gg c$) coated with free water of thickness d_w used to represent the wetting of the leaf surface. The water content within the leaf affects $\varepsilon_{\text{leaf}}$ via (7).

temperature T is assumed. With $T_{\text{B,sky}}$ being the sky brightness temperature, the expression for T_{B}^p ($p = \text{H, V}$) reads

$$T_{\text{B}}^p = \mu [T(1 - R^p) + T_{\text{B,sky}} R^p] + (1 - \mu) [T(1 - R_{\text{out}}^p) + T_{\text{B,sky}} R_{\text{out}}^p]. \quad (3)$$

This equation fulfills Kirchhoff's law and describes T_{B}^p as the linear combination of radiances emitted by the two surface types with emissivities $(1 - R^p)$ and $(1 - R_{\text{out}}^p)$, respectively. The weighting μ was determined from the brightness temperatures $T_{\text{B,grid}}^p$ and $T_{\text{B,no grid}}^p$ measured with and without the highly reflecting wire grid laid on the elliptic area. Using $T_{\text{B,no grid}}^p$ in (3) with $\mu = 0$ yields R_{out}^p , and inserting these reflectivities with measured $T_{\text{B,grid}}^p$ and $R^p = 1$ in (3) again yields

$$\mu^p = \frac{T_{\text{B,no grid}}^p - T_{\text{B,grid}}^p}{T_{\text{B,no grid}}^p - T_{\text{B,sky}}^p}. \quad (4)$$

The measured fractional amounts μ^p were slightly different for the two polarizations $p = \text{H}$ or V . However, as μ^{H} and μ^{V} were very similar, the polarization averaged value $\mu = (\mu^{\text{H}} + \mu^{\text{V}})/2 = 0.90$ is used in the further evaluations.

C. Effective Medium Approach for the Litter Permittivity

The highly complex morphology of a litter layer cannot easily be represented by an anisotropic effective medium approach used for modeling effective leaf-litter permittivities $\varepsilon_L = \varepsilon'_L + i \varepsilon''_L$. Therefore, an isotropic mixture of oblate ellipsoids with permittivity $\varepsilon_{\text{leaf}}$, semiaxis $a, b \gg c$, and number density n (per cubic meters) embedded in air with $\varepsilon_A = 1$ is used for modeling ε_L [Fig. 2(a)]. This approach at least accounts for the general shape of the leaves constituting the litter. Different litter moisture states ρ_{wL} are considered by means of shells with thickness d_w coating each ellipsoid [Fig. 2(b)]. Thereby, the total volume of these shells with permittivity ε_w of free water is used to represent the water volume ρ_{wL} retained in the litter per ground area.

The number density n is calculated from the gravimetric leaf-litter column density ρ_L in its drained state, the mass density

ρ_{leaf} of the bulk leaf material, the mean thickness $\langle D_L \rangle$ of the litter layer, and the ellipsoid volume $V^{\text{leaf}} = 4\pi abc/3$

$$n = \frac{\rho_L}{V^{\text{leaf}} \rho_{\text{leaf}} \langle D_L \rangle}. \quad (5)$$

The representative thickness d_w of the water shells encompassing the oblate ellipsoids (the leaves) with approximated surface area $2\pi ab$ is

$$d_w = \frac{\rho_{\text{wL}}}{2\pi ab n \langle D_L \rangle}. \quad (6)$$

The complex permittivity $\varepsilon_{\text{leaf}}$ of a single leaf with dry-matter fraction m_d is modeled by using the approach proposed in [30]

$$\varepsilon_{\text{leaf}} = 0.522(1 - 1.32m_d)\varepsilon_{\text{sw}} + 0.51 + 3.84m_d. \quad (7)$$

Thereby, the permittivity ε_{sw} of saline water within the bulk leaf material is calculated by using the multiparameter fit described in [31], requiring temperature T , frequency f , and salinity S as the parameters. Formula (7) is applicable in the frequency range 1–100 GHz for leaves with $0.1 \leq m_d \leq 0.5 \text{ kg} \cdot \text{kg}^{-1}$ and $S \leq 10$ ppt (parts per thousand by weight, which, at low concentrations, is approximately equal to grams of salt per liter of water).

The directional dependent polarizabilities Π_a , Π_b , and Π_c of the water-coated ellipsoids, which are required in the effective medium approach, are averaged in accordance with the assumed isotropy. Applying a generalized Maxwell–Garnett mixing rule valid for depleted dielectric mixtures [26], [32] reveals the isotropic effective litter permittivity ε_L

$$\varepsilon_L = \varepsilon_A + n \frac{(\Pi_a + \Pi_b + \Pi_c)}{3}. \quad (8)$$

An analytical expression for the polarizabilities Π_i , ($i = a, b, c$), of multilayered dielectric ellipsoids was derived in [33]. The specialization for the case of an ellipsoid with core permittivity $\varepsilon_{\text{leaf}}$ coated with a single layer of permittivity ε_w reads

$$\begin{aligned} \Pi_a = \varepsilon_A V_w \{ & (\varepsilon_w - \varepsilon_A) + [\varepsilon_w + N_a^w(\varepsilon_A - \varepsilon_w)] \Psi \} / \\ & \{ [\varepsilon_A + N_a^w(\varepsilon_w - \varepsilon_A)] + N_a^w(1 - N_a^w)(\varepsilon_w - \varepsilon_A) \Psi \} \end{aligned} \quad (9)$$

with

$$\begin{aligned} \Psi = \left\{ & (\varepsilon_{\text{leaf}} - \varepsilon_w) \frac{V^{\text{leaf}}}{V_w} + \varepsilon_{\text{leaf}} + N_a^{\text{leaf}}(\varepsilon_{\text{leaf}} - \varepsilon_w) \right\} / \\ & \{ \varepsilon_w + N_a^{\text{leaf}}(\varepsilon_{\text{leaf}} - \varepsilon_w) - N_a^{\text{leaf}}(1 - N_a^{\text{leaf}})(\varepsilon_{\text{leaf}} - \varepsilon_w) \}. \end{aligned}$$

$V^{\text{leaf}} = 4\pi abc/3$ in (9) is the volume of the leaf ellipsoid, and $V_w = 4\pi(a + d_w)(b + d_w)(c + d_w)/3$ is the corresponding volume of the water ellipsoid with semiaxis $a + d_w$, $b + d_w$, and $c + d_w$. Accordingly, the depolarization factors N_a^{leaf} and

N_a^w in (9) are the factors of the leaf and water ellipsoids, respectively, computed as (N_a^w accordingly)

$$N_a^{\text{leaf}} = \frac{abc}{2} \int_0^\infty \frac{ds}{(s+a^2)\sqrt{(s+a^2)(s+b^2)(s+c^2)}}. \quad (10)$$

Likewise, Π_b and Π_c in (8) are calculated by replacing $N_a^{\text{leaf}}(N_a^w)$ with $N_b^{\text{leaf}}(N_b^w)$ or $N_c^{\text{leaf}}(N_c^w)$ in (9), which are obtained by interchanging b and a (or c and a) in (10).

D. Reflectivities

A coherent model for the reflectivities R^p ($p = H, V$) of the litter–soil and litter–grid formations will be described in the following. To this end, dielectric profiles $\varepsilon(z)$, where z is the downward vertical direction, are required.

1) *Litter–Grid Formation*: Dielectric depth profiles $\varepsilon(z)$ that are used to model reflectivities of the litter–grid formation are represented by Fermi and step functions

$$\varepsilon(z) = \begin{cases} \varepsilon_A + \frac{\varepsilon_L - \varepsilon_A}{1 + \exp\left(-\frac{z - z_{AL}}{k_{AL}}\right)}, & z < z_G \\ \varepsilon_G, & z \geq z_G. \end{cases} \quad (11)$$

This is a two-stage transition from the air permittivity $\varepsilon_A = 1$ to the litter permittivity ε_L , followed by the abrupt increase to the absolute value ε_G being the grid permittivity. The depths z_{AL} and $z_G = z_{AL} + \langle D_L \rangle$ are the z -values of the Air-to-Litter (AL) and the Litter-to-Grid (LG) transitions, where $\langle D_L \rangle$ is the mean thickness of the litter layer. The parameter k_{AL} in (11) is related to the vertical extent $2 \cdot \Delta_{AL}$ of the AL transition, which is defined as the difference in z from 10% to 90% of the permittivity difference $\varepsilon'_L - \varepsilon_A$

$$\Delta_{AL} = \ln 9 \, k_{AL} \cong 2.197 \, k_{AL}. \quad (12)$$

Accordingly, Δ_{AL} can be identified by twice the standard deviation of the litter layer thickness on lateral scales smaller than the Bragg limit if D_L is Gaussian distributed with mean $\langle D_L \rangle$. Generally, Δ_{AL} determines the sharpness of the dielectric AL transition associated with the upper boundary of the litter layer. Besides these local thickness variations, spatially varying moisture on scales below the Bragg limit may also affect the value of Δ_{AL} (see [26, pp. 287–290]).

The grid permittivity ε_G in (11) is estimated from the electrical conductivity $\sigma_G = 5.7 \cdot 10^6 \, \text{S} \cdot \text{m}^{-1}$ of the aluminum wire grid used in the relation $\varepsilon''_G = \sigma_G (2\pi\varepsilon_0)^{-1} (\varepsilon_0 = 8.85 \cdot 10^{-12} \, \text{C}^2 \cdot \text{J}^{-1} \cdot \text{m}^{-1})$, yielding $\varepsilon_G \approx \varepsilon''_G = 7.3 \cdot 10^7$. The resulting almost infinite dielectric gradient at the depth $z = z_G$ leads to an almost perfect reflection at the LG interface.

As an example, the real part $\varepsilon'(z)$ of a permittivity profile (11) is shown in Fig. 3(a) for $\varepsilon_L = 2.30 + i 0.17$ corresponding to the modeled permittivity of the fully drained litter layer ($\rho_{wL} = 0 \, \text{m}^3 \cdot \text{m}^{-2}$). The mean litter layer thickness $\langle D_L \rangle = z_{AL} - z_G = 20 \, \text{mm}$ is considered by choosing $z_{AL} = 50 \, \text{mm}$ and $z_G = 70 \, \text{mm}$. The depth z_{AL} of the AL transition is chosen arbitrarily, but it is large enough such that $\varepsilon(z=0) \approx \varepsilon_A$, and consequently, the reflectivity deduced from the profile $\varepsilon(z)$ becomes independent of z_{AL} . Furthermore, $k_{AL} = 2.3 \, \text{mm}$ is

Fig. 3. (a) Example of a dielectric profile $\varepsilon'(z)$ for the litter–grid formation (11) with $\varepsilon_L = 2.30 + i 0.17$, $\varepsilon_G = 7.3 \cdot 10^7$, $z_{AL} = 50 \, \text{mm}$, $z_G = 70 \, \text{mm}$, $k_{AL} = 2.3 \, \text{mm}$ [small-scale variation $\Delta_{AL} = 5 \, \text{mm}$ according to (12)], and $D_L = \langle D_L \rangle = 20 \, \text{mm}$. (b) Coherent reflectivities $R_{\text{coh}}^H(D_L)$ for $\alpha = 50^\circ$ modeled from $\varepsilon(z)$ for $0 \leq D_L \leq 90 \, \text{mm}$ and (solid line) $\varepsilon_L = 2.30 + i 0.17$ and (dashed line) $\varepsilon_L = 9.27 + i 0.55$; $R^H = 0.95$ is the linear average of $R_{\text{coh}}^H(D_L)$ in the range $15 \leq D_L \leq 25 \, \text{mm}$ for representing the large-scale variation $\Delta D_L = 5 \, \text{mm}$ of $\langle D_L \rangle$.

used to take into account the estimated value $\Delta_{AL} = 5 \, \text{mm}$ (12) representing the extent of the AL transition associated with the estimated standard deviation of $\pm 2.5 \, \text{mm}$ of $\langle D_L \rangle$ on lateral scales below the Bragg limit.

The model used for the coherent reflectivities R_{coh}^p ($p = H, V$) associated with $\varepsilon(z)$ is based on a matrix formulation of the boundary conditions at dielectric discontinuities derived from Maxwell's equations [34]. The expected inputs are two profile vectors $\mathbf{d}$ and $\boldsymbol{\varepsilon}$ containing thickness d_i and complex permittivities ε_i of the layers $i = 1, \dots, N$, of the stack. Furthermore, the permittivities of the media comprising the incidence and the transmitted wave, the wavelength λ , the polarization $p = H$ or V , and the observation angle α are required inputs. The discrete permittivities ε_i of the vector $\boldsymbol{\varepsilon}$ are computed from (11) for $0 \leq z_i \leq z_G$ with increment $d_i = 0.1 \, \text{mm}$ corresponding to a small fraction of λ .

Fig. 3(b) shows $R_{\text{coh}}^H(D_L)$ for $\alpha = 50^\circ$ derived from $\varepsilon(z)$ representing the litter layers with thickness in the range of $0 \leq D_L \leq 90 \, \text{mm}$. The solid line is computed for drained litter with $\varepsilon_L = 2.30 + i 0.17$ [as in panel Fig. 3(a)], and the dashed line shows $R_{\text{coh}}^H(D_L)$ for $\varepsilon_L = 9.27 + i 0.55$ corresponding to the permittivity modeled for the wettest observed litter ($\rho_{wL} = 5.0 \cdot 10^{-3} \, \text{m}^3 \cdot \text{m}^{-2}$). Due to alternating constructive and destructive interferences between waves reflected at the AL interface and at the grid, $R_{\text{coh}}^H(D_L)$ exhibits several local extrema. Furthermore, $R_{\text{coh}}^H(D_L)$ shows a decreasing trend with increasing D_L , as the consequence of increasing absorption within the litter layer covering the reflecting wire grid.

In contrast to Δ_{AL} , the variation ΔD_L of $\langle D_L \rangle$ on lateral scales above the Bragg limit determines the cancellation of coherent effects in the reflectivities R^p . This cancellation is considered by linearly averaging $R_{\text{coh}}^p(D_L)$ over $(\langle D_L \rangle - \Delta D_L) \leq D_L \leq (\langle D_L \rangle + \Delta D_L)$, representing the thickness range of the litter layer. The resulting reflectivities R^p affect the L-band signature used in the radiative transfer model (3). Consequently, the R^p 's expected for experimental conditions with $\langle D_L \rangle = 20 \, \text{mm}$ and $\Delta D_L = 5 \, \text{mm}$ are computed as

Fig. 4. (a) Example of a dielectric profile $\varepsilon'(z)$ for the litter–soil formation (13) with $\varepsilon_L = 2.30 + i 0.17$, $\varepsilon_S = 10$, $z_{AL} = 50$ mm, $z_{LS} = 70$ mm, $k_{AL} = k_{LS} = 2.3$ mm, $\langle D_L \rangle = 20$ mm, and $2 \cdot \Delta_{AL} = 2 \cdot \Delta_{LS} = 10$ mm. (b) Coherent reflectivities $R^H_{coh}(D_L)$ for $\alpha = 50^\circ$ modeled from $\varepsilon(z)$; $R^H = 0.25$ to be used in (3) is derived from averaging $R^H_{coh}(D_L)$ over $15 \leq D_L \leq 25$ mm.

$R^p_{coh}(D_L)$ averaged over the range $15 \leq D_L \leq 25$ mm. For the example shown in Fig. 3(b) (solid line), the resulting reflectivities or the fully drained ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$) and wettest observed ($\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$) litters are $R^H = 0.95$ and $R^H = 0.60$, respectively. By means of the shown coherent reflectivities $R^H_{coh}(D_L)$, it is noted that increasing ΔD_L can either increase or decrease R^H depending on the run of $R^H_{coh}(D_L)$ in the range of averaging. This adoption might be useful for understanding the effect of ΔD_L on R^p discussed later (Section IV-B).

2) *Litter–Soil Formation*: Reflectivities R^p affecting the L-band signatures of a soil covered with leaf litter are modeled accordingly on the basis of adapted dielectric profiles $\varepsilon(z)$. The chosen approach for $\varepsilon(z)$ is a combination of two Fermi functions for imitating the AL transition and the underlying dielectric transition from Litter-to-Soil (LS)

$$\varepsilon(z) = \varepsilon_A + \frac{\varepsilon_L - \varepsilon_A}{1 + \exp\left(-\frac{z - z_{AL}}{k_{AL}}\right)} + \frac{\varepsilon_S - \varepsilon_L}{1 + \exp\left(-\frac{z - z_{LS}}{k_{LS}}\right)}. \quad (13)$$

As many soils are isotropic in the dielectric sense, the soil dielectric constant ε_S is a scalar. The depths z_{AL} and $z_{LS} = z_{AL} + \langle D_L \rangle$ are the z -values of the AL and the LS horizons, which are separated by the mean litter layer thickness $\langle D_L \rangle$. As aforementioned, the vertical extent $2 \cdot \Delta_{LS}$ of the LS transition is related to the corresponding parameter k_{LS} by (12) by replacing $AL \rightarrow LS$.

Fig. 4(a) shows an example of $\varepsilon(z)$ computed with (13) for the fully drained litter ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$) with $\varepsilon_L = 2.30 + i 0.17$ and the underlying soil with $\varepsilon_S = 10$ corresponding to the volumetric moisture $\theta_S = 0.2 \text{ m}^3 \cdot \text{m}^{-3}$ if the empirical mixing formula [35] is considered. The estimated small-scale variations $\Delta_{AL} = \Delta_{LS} = 5$ mm of the litter layer interfaces are considered by $k_{AL} = k_{LS} = 2.3$ mm.

The resulting coherent reflectivities $R^p_{coh}(D_L)$ are computed by using the coherent radiative transfer model applied to $\varepsilon(z)$ given by (13). Averaging $R^p_{coh}(D_L)$ over $(\langle D_L \rangle - \Delta D_L) \leq$

$D_L \leq (\langle D_L \rangle + \Delta D_L)$ yields R^p to be used in the radiative transfer (3).

For the example shown in Fig. 4(a), the resulting $R^H_{coh}(D_L)$ shown in Fig. 4(b) reveals a damped oscillating behavior with D_L , as expected for lossy litter. For $\langle D_L \rangle = 20$ mm and $\Delta D_L = 5$ mm, the reflectivity $R^H = 0.25$ is computed from averaging $R^H_{coh}(D_L)$ over $15 \leq D_L \leq 25$ mm.

IV. RESULTS AND DISCUSSION

Effective permittivities ε_L of the litter layer computed for different moisture conditions ρ_{wL} are given in Section IV-A. Sections IV-B and C present calculated reflectivities R^p ($p = H, V$) of the stratified litter–grid and litter–soil formations. Thereby, the dielectric depth profiles $\varepsilon(z)$ expressed either by (11) or (13) are used in the coherent radiative transfer model. In Section IV-D, $R^p(t)$ values modeled for the litter–grid formation are used in (3) to be compared with the measured L-band signatures.

A. Modeled Effective Litter Permittivities

The parameters of the model described in Section III-C and used for computing the effective litter permittivity ε_L are listed in the left section of Table I together with the example values (first two columns). Corresponding intermediate results of the model and the final litter permittivity $\varepsilon_L = 9.27 + i 0.55$ computed for $\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$ (bold dots in Fig. 5) are listed in the right section of Table I (last two columns).

Fig. 5 shows (solid lines) real and (dashed lines) imaginary parts of $\varepsilon_L(\rho_{wL}) = \varepsilon'_L + i \varepsilon''_L$ computed for the range $0 \leq \rho_{wL} \leq 6 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$ and the temperatures (bold lines) $T = 290$ K and (thin lines) $T = 303$ K, respectively. The remaining parameters are the same as listed in Table I. The hollow dots indicate $\varepsilon_L(\rho_{wL})$ computed for $T = 290$ K and fully drained litter ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$), and the bold dots for the litter in its wettest observed state ($\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$) are also shown in Table I.

The similarity of the values of ε_L computed for $T = 290$ K and $T = 303$ K indicates the marginal sensitivity of the effective medium approach with respect to the temperature T . The diminishing positive temperature responses of ε'_L and ε''_L are due to the negative temperature gradient $d\varepsilon_w/dT \approx -0.3 \text{ K}^{-1}$ of the real water permittivity which dominates the effect of increased losses within the saline water phase at higher T .

B. Modeled Reflectivities of the Litter–Grid Formation

The reflectivities R^H and R^V of the litter–grid formation shown in Fig. 6(a) and (b) are computed from $\varepsilon(z)$ of the form (11), considering that $\alpha = 50^\circ$. The thin solid lines show R^p ($\varepsilon'_L, \varepsilon''_L$) ($p = H, V$) for the range $1 \leq \varepsilon'_L \leq 10$ of the real parts of litter permittivities $\varepsilon_L = \varepsilon'_L + i \varepsilon''_L$ and the reasonable imaginary parts $\varepsilon''_L = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$. According to the isotropic effective medium approach, ε'_L and ε''_L are related to each other. The corresponding relation $\varepsilon''_L(\varepsilon'_L)$ is deduced from the data shown in Fig. 5 (bold lines) computed for $T = 290$ K. This allows for expressing $R^p(\varepsilon'_L)$ as a function

TABLE I
(LEFT SECTION) MODEL PARAMETERS USED FOR COMPUTING THE LEAF-LITTER PERMITTIVITY ϵ_L AND
(RIGHT SECTION) MODEL RESULTS CALCULATED FOR MOIST LITTER WITH $\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$

	model parameters	values	eq. / ref.	model outputs	values
leaf	a, b, c [m]	$5 \cdot 10^{-2}, 4 \cdot 10^{-2}, 10^{-4}$	(5)	n [m ³]	$7.5 \cdot 10^4$
			(6)	d_w [mm]	0.264
	ρ_{leaf} [kg m ⁻³]	950	[31]	$\epsilon_{\text{sw}} [-]$ $\epsilon_w [-]$	$80.0 + i 12.7$ $80.8 + i 6.9$
	m_d [kg kg ⁻¹]	0.5	(7), [30]	$\epsilon_{\text{leaf}} [-]$	$16.6 + i 2.3$
litter	$\langle D_L \rangle$ [m]	$2 \cdot 10^{-2}$	(10)	$N_a^{\text{leaf}}, N_b^{\text{leaf}}, N_c^{\text{leaf}} [-]$	$1.5 \cdot 10^{-3}, 2.1 \cdot 10^{-3}, 1$
	ρ_L [kg m ⁻²]	1.2		$N_a^w, N_b^w, N_c^w [-]$	$3.8 \cdot 10^{-3}, 5.3 \cdot 10^{-3}, 1$
	ρ_{wL} [m ³ m ⁻²]	$5.0 \cdot 10^{-3}$	(9), [33]	Π_a [m ³]	$1.7 \cdot 10^{-4} + i 1.2 \cdot 10^{-5}$
others	T [K]	290		Π_b [m ³]	$1.5 \cdot 10^{-4} + i 9.7 \cdot 10^{-6}$
	f [GHz]	1.4		Π_c [m ³]	$2.9 \cdot 10^{-6} + i 3.0 \cdot 10^{-8}$
	S [ppt]	3	[22]	$\epsilon_L [-]$	$9.27 + i 0.55$

Fig. 5. (Solid lines) Real and (dashed lines) imaginary parts $\epsilon'_L(\rho_{wL})$ and $\epsilon''_L(\rho_{wL})$ of effective complex litter layer permittivities $\epsilon_L(\rho_{wL})$ computed for litter moisture column densities $0 \leq \rho_{wL} \leq 6 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$. The bold lines are modeled for $T = 290 \text{ K}$, and the thin lines are modeled for $T = 303 \text{ K}$; the remaining parameters are the same as listed in Table I (left section). Permittivity values for the fully drained ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$) and wettest observed ($\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$) litter conditions are marked by the hollow and the bold dots, respectively.

of ϵ'_L only [solid bold lines in Fig. 6(a) and (b)]. Furthermore, litter water column densities ρ_{wL} , in accordance with $\epsilon'_L(\rho_{wL})$ taken from Fig. 5 (bold lines), are indicated on the top axis, illustrating the reflectivity dependence $R^p(\rho_{wL})$.

$R^H(\epsilon'_L, \epsilon''_L)$ and $R^V(\epsilon'_L, \epsilon''_L)$ generally decrease with increasing imaginary part ϵ''_L , which is directly related to the absorption in the litter. The simulations performed for horizontal polarization predict $R^H(\rho_{wL})$ to generally decrease with ρ_{wL} as the consequence of both, increasing ϵ'_L and ϵ''_L . The corresponding $R^V(\rho_{wL})$ is less sensitive with respect to ϵ'_L but monotonically decreases due to the absorption (correlated with ϵ''_L) in the litter layer. The values $R^H = 0.95$ [Fig. 3(b)] and $R^V = 0.89$ computed for the litter layer in its fully drained state ($\rho_{wL} = 0.0 \text{ m}^3 \cdot \text{m}^{-2}$, $\epsilon_L = 2.30 + i 0.17$) and $R^H = 0.60$ and $R^V = 0.68$ for the wettest observed litter state ($\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$, $\epsilon_L = 9.27 + i 0.55$) are indicated by the hollow and the bold dots, respectively. Furthermore, independent of ϵ'_L , the overall litter-grid formation becomes an ideal reflector ($R^p = 1$) for a lossless litter layer ($\epsilon''_L = 0$), which is manda-

tory by virtue of the energy conservation and the total reflection at the wire grid.

The impact of the small-scale and large-scale variations Δ_{AL} and ΔD_L of the mean litter thickness $\langle D_L \rangle$ on the modeled R^H and R^V is shown in Fig. 7 by means of comparisons with reference reflectivities computed for $\Delta_{AL} = \Delta D_L = 5 \text{ mm}$ (bold lines). The calculations are performed for $\langle D_L \rangle = 20 \text{ mm}$, $\alpha = 50^\circ$, $T = 290 \text{ K}$, and with the remaining model parameters from Table I. The upper panels of Fig. 7 show $R^p(\epsilon'_L)$ computed for the constant large-scale thickness variation $\Delta D_L = 5 \text{ mm}$ and three different values $\Delta_{AL} = 0, 5, 10 \text{ mm}$ of variations below the Bragg limit. The bottom panels show $R^p(\epsilon'_L)$ at constant small-scale and variable large-scale variations $\Delta_{AL} = 5 \text{ mm}$ and $\Delta D_L = 0, 5, 10 \text{ mm}$, respectively.

Increasing Δ_{AL} , corresponding to broader vertical extents of the AL transition, decreases R^H for $\epsilon'_L < 7.5$, whereas higher reflectivities R^H are predicted for $\epsilon'_L > 7.5$ corresponding to $\rho_{wL} > 3.4 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$. For the almost drained litter with $\rho_{wL} = 1.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$, the reflectivity $R^H = 0.85$ computed for the steplike AL transition ($\Delta_{AL} = 0 \text{ mm}$) is reduced to $R^H = 0.80$ for $\Delta_{AL} = 10 \text{ mm}$ associated with an AL transition zone expanded over 20 mm. This corresponds to a relative change in R^H of approximately 6%. At vertical polarization, the model sensitivity with respect to Δ_{AL} is less pronounced.

The impact of the large-scale variations ΔD_L of $\langle D_L \rangle$ shown in the bottom panels of Fig. 7 clearly exceeds the effect of the small-scale variation Δ_{AL} shown in the top panels. For $\epsilon'_L \approx 7.5$ (corresponding to $\rho_{wL} \approx 3.4 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$), R^H is increased by the factor of ≈ 1.6 from $R^H = 0.44$ to 0.72 if ΔD_L is increased from 0 to 10 mm. The corresponding sensitivity of R^V is less pronounced, but it is still significant particularly for the moist litter with $\rho_{wL} > 3.4 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$ corresponding to $\epsilon'_L > 7.5$.

C. Modeled Reflectivities of the Litter-Soil Formation

Fig. 8 shows $R^H(\epsilon'_L, \epsilon_S)$ and $R^V(\epsilon'_L, \epsilon_S)$ of the litter-soil formation computed from the profiles $\epsilon(z)$ of the form (13) comprising the parameters Δ_{AL} , Δ_{LS} , and ϵ_S . In the same manner as the computations performed for the litter-grid

Fig. 6. Reflectivities $R^p(\varepsilon'_L, \varepsilon''_L)$ of the litter-grid formation computed for $\alpha = 50^\circ$, $T = 290$ K, the litter permittivity real parts $2 \leq \varepsilon'_L \leq 10$, and the imaginary parts $\varepsilon''_L = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$ for (a) $p = H$ and (b) $p = V$. The remaining model parameters were the same as used in Fig. 3(b), yielding $R^H = 0.95$ [hollow dot in (a)]. The bold lines showing $R^p(\varepsilon'_L)$ are computed by using $\varepsilon''_L(\varepsilon'_L)$ according to ε_L derived from the effective medium approach (Fig. 5). R^p for $\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$ and $\rho_{wL} = 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$ are indicated by the hollow and the bold dots, respectively.

Fig. 7. Sensitivity of the model for computing (a) $R^H(\varepsilon'_L)$ and (b) $R^V(\varepsilon'_L)$ of the litter-grid formation with $\langle D_L \rangle = 20$ mm, $\alpha = 50^\circ$, and $T = 290$ K. Small-scale variations $\Delta_{AL} = 0, 5$, and 10 mm of $\langle D_L \rangle$ are varied in the upper panels, whereas the variation $\Delta_{DL} = 5$ mm above the Bragg limit is kept constant. The bottom panels show the evaluations for variable $\Delta_{DL} = 0, 5, 10$ mm and constant $\Delta_{AL} = 5$ mm.

Fig. 8. Reflectivities $R^p(\varepsilon'_L, \varepsilon_s)$ of a litter-soil formation computed for $0 \leq \rho_{wL} \leq 6 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$, $\alpha = 50^\circ$, and $T = 290$ K. Data are shown for (a) $p = H$ and (b) $p = V$ and $\varepsilon_s = 5, 10, 17, 25$ ($\theta_s = 0.1, 0.2, 0.3, 0.4 \text{ m}^3 \cdot \text{m}^{-3}$). The crosses and the hollow and the bold dots are R^p 's for the bare soil, the drained litter condition ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$), and the wettest observed litter condition ($\rho_{wL} = 5 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$), respectively.

formation, the values of the parameters shown in Table I were used with $0 \leq \rho_{wL} \leq 6.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$. Furthermore, $\langle D_L \rangle = 20 \text{ mm}$, $\alpha = 50^\circ$, and four soil water contents $\theta_S = 0.1, 0.2, 0.3, 0.4 \text{ m}^3 \cdot \text{m}^{-3}$ corresponding to the soil permittivities $\varepsilon_S \approx 5, 10, 17, 25$ shown in Fig. 8 were considered. The hollow and the bold dots label R^p ($p=H, V$) for the fully drained ($\rho_{wL}=0 \text{ m}^3 \cdot \text{m}^{-2}$) and the wettest ($\rho_{wL}=5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$) litter conditions. Results for $\varepsilon_L = \varepsilon_A = 1$ yielding R^p of the bare soils (no litter) with ε_S are marked with crosses.

For $\varepsilon_S = 5, 10, 17, 25$ and for low values of ε'_L , the model predicts decreasing $R^p(\varepsilon'_L, \varepsilon_S)$ with increasing ε'_L . This is the result of an impedance match between air and bulk soil permittivity ε_S , as caused by an intermediate litter layer with $\varepsilon_A < \varepsilon'_L < \varepsilon_S$ corresponding to a relatively dry litter. Expressed by means of soil water contents, this implies that the reflectivity of a relatively moist soil ($\theta_S \approx 0.4 \text{ m}^3 \cdot \text{m}^{-3}$) covered with drained litter ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$) can be decreased by wetting the litter layer.

The changeover between the negative and positive gradients $dR^p(\varepsilon'_L, \varepsilon_S)/d\varepsilon'_L$ clearly depends on ε_S . The modeled $R^p(\varepsilon'_L, \varepsilon_S)$ of the litter–soil formation reveals that the reflectivities are not necessarily related to an unambiguous set of soil and litter permittivities ε_S and ε'_L . Low ε_S , in combination with high ε'_L , may yield the same $R^p(\varepsilon'_L, \varepsilon_S)$ as certain combinations of low ε'_L and high ε_S . This model prediction is of practical relevance for interpreting the L-band signatures observed in the course of a precipitation-induced wetting sequence of soils covered by litter. Assume a soil with $\theta_S = 0.2 \text{ m}^3 \cdot \text{m}^{-3}$ ($\varepsilon_S \approx 10$) below the fully drained litter ($\rho_{wL} = 0 \text{ m}^3 \cdot \text{m}^{-2}$, $\varepsilon_L = 2.30 + i 0.17$) preceding a precipitation event. During rainfall events, litter moisture ρ_{wL} increases prior to the soil water content θ_S , and consequently, reflectivities R^p are expected to decrease during the first phase of the wetting sequence. In a later phase, when the litter approaches the water saturated state and θ_S is raised, the R^p values increase with further precipitation as is the case for bare soils with increasing moisture. However, a corresponding L-band signature has been observed over an artificially prepared litter–soil formation.

As per the model sensitivity study performed for the litter–grid formation (Fig. 7), the effect of the parameters Δ_{AL} , Δ_{LS} , and ΔD_L on the reflectivities R^H and R^V is shown in Fig. 9. The calculations are performed for $\langle D_L \rangle = 20 \text{ mm}$ and $\theta_S = 0.2 \text{ m}^3 \cdot \text{m}^{-3}$ corresponding to $\varepsilon_S \approx 10$ and $T = 290 \text{ K}$. The impact of individually varied parameters taking the values $\Delta_{AL} = 0, 5, 10 \text{ mm}$, $\Delta_{LS} = 0, 5, 10 \text{ mm}$, and $\Delta D_L = 0, 5, 10 \text{ mm}$ was investigated by comparison with reference reflectivities computed for $\Delta_{AL} = \Delta_{LS} = \Delta D_L = 5 \text{ mm}$ (bold lines and identical with the one in Fig. 8 for $\varepsilon_S = 10$). The resulting model sensitivities with respect to the small-scale thickness variations Δ_{AL} and Δ_{LS} of the litter layer associated with the AL and the LS transitions are shown in the top and the middle panels of Fig. 9. The sensitivity with respect to the variation $\Delta D_L = 0, 5, 10 \text{ mm}$ of the litter thickness above the Bragg limit is presented in the bottom panels. Furthermore, the crosses mark the R^p computed for bare soils (no litter $\varepsilon_L = 1$).

As can be seen in the top left panel of Fig. 9, R^H is rather sensitive to the changes in Δ_{AL} . For the moist litter with $\rho_{wL} = 5.0 \text{ m}^3 \cdot \text{m}^{-2}$, R^H is reduced by $\approx 35\%$ from $R^H \approx 0.40$

Fig. 9. Sensitivity study of the model used for computing (a) $R^H(\varepsilon'_L, \varepsilon_S)$ and (b) $R^V(\varepsilon'_L, \varepsilon_S)$ of the litter–soil formation with $\langle D_L \rangle = 20 \text{ mm}$, $\varepsilon_S \approx 10$ ($\theta_S = 0.1 \text{ m}^3 \cdot \text{m}^{-3}$), $\alpha = 50^\circ$, and $T = 290 \text{ K}$. Small-scale variations $\Delta_{AL} = 0, 5, 10 \text{ mm}$ and $\Delta_{LS} = 0, 5, 10 \text{ mm}$ of $\langle D_L \rangle$ are varied in the upper and the middle panels, whereas $\Delta D_L = \Delta_{LS} = 5 \text{ mm}$ or $\Delta D_L = \Delta_{AL} = 5 \text{ mm}$ are kept constant. The bottom panels show the evaluations for variable $\Delta D_L = 0, 5, 10 \text{ mm}$ and constant $\Delta_{AL} = \Delta_{LS} = 5 \text{ mm}$.

to $R^H \approx 0.26$ if the extension of the AL interface is increased from a steplike ($\Delta_{AL} = 0 \text{ mm}$) to a gradual transition with $\Delta_{AL} = 10 \text{ mm}$. In addition, the small-scale thickness variation Δ_{LS} representing the irregularities at the lower boundary of the litter layer (LS transition) is predicted to be relevant for the reflectivities. In contrast to the sensitivities of R^p of the litter–grid formation (Fig. 7), the reflectivities computed for the litter–soil formation are less affected by the changes in large-scale thickness variations ΔD_L . This can be explained by the fact that ΔD_L determines the cancellation of coherence, which is generally less distinct in the litter–soil formation than in the litter–grid formation. Coherence is more important for the litter–grid formation, as the dielectric contrast between the litter and the grid permittivity is clearly more distinct than the contrast between the permittivities of litter and soil layers.

The analysis of the parameter sensitivity shows that R^p is generally sensitive to the litter layer irregularities Δ_{AL} , Δ_{LS} , and ΔD_L . It is noticed that litter layers covering soils cannot be accurately modeled with a single homogeneous dielectric slab with the true effective litter permittivity. The impact of the extent $2 \Delta_{AL}$ of the AL transition on R^H is identified as the most prominent.

D. Comparison With Measurements on the Litter–Grid Formation

Hereafter, microwave signatures are simulated by using the models presented in Section III, which are fed with time series of ground temperature $T(t)$ and rain intensities $P(t)$ [Fig. 10(a) and (b)] to be compared with the simultaneously measured

Fig. 10. (a) Ground temperatures $T(t)$ and (b) hourly cumulated precipitation $P(t)$ in millimeters per hour computed from rates measured every 0.25 h in units of [millimeters (0.25 h)^{−1}]. The time series cover the two-week period of the field experiment performed on the site comprising the litter-grid formation.

L-band signatures (Fig. 11). The shown precipitation data $P(t)$ in millimeters per hour are the hourly cumulated precipitation computed from rates measured every 0.25 h in units of [millimeters (0.25 h)^{−1}]. The microwave brightness temperatures $T_B^p(t)$ ($p = H, V$) were measured above the site comprising the litter-grid formation for the period of two weeks ($237 < \text{DoY} < 250$) and at $\alpha = 50^\circ$.

Average ground temperature during the campaign was $\langle T \rangle = 290$ K. Due to the near-surface installation of the sensors (30 mm below the wire grid), rather pronounced diurnal variations of up to 5 K were observed. During the first week, frequent and intense rainfall occurred, reaching the maximum intensity of $P = 3.6 \text{ mm} \cdot \text{h}^{-1}$, whereas the second week of the campaign was rainless.

The temporal evolution of the litter moisture $\rho_{wL}(t)$ shown in Fig. 11(a) is derived from $P(t)$ [Fig. 10(b)] using (2) with the experimentally determined drainage (discharge) time $\tau_L = 1$ h of the litter layer. The maximum value $\rho_{wL} \approx 5.0 \cdot 10^{-3} \text{ m}^3 \cdot \text{m}^{-2}$ is computed for the most intense rain with $P = 3.6 \text{ mm} \cdot \text{h}^{-1}$ occurring on DoY 238.5.

The chronological sequence $\varepsilon_L(t)$ arising from the litter-water and temperature dynamics $\rho_{wL}(t)$ and $T(t)$ is computed by using the isotropic effective medium approach described in Section III-C. In accordance with the experimental conditions, the simulations are performed for a litter layer with mean thickness $\langle D_L \rangle = 20$ mm and gravimetric column density $\rho_L = 1.2 \text{ kg} \cdot \text{m}^{-2}$ on top of the wire grid. The remaining model parameters are the same as listed in the left section of Table I. Computed real and imaginary parts $\varepsilon'_L(t)$ and $\varepsilon''_L(t)$ are shown in Fig. 11(b). As our approach assumes isotropy, the simulated $\varepsilon_L(t) = \varepsilon'_L(t) + i \varepsilon''_L(t)$ are polarization independent.

Fig. 11(c) and (d) shows the comparisons between (black) measured and (gray) modeled microwave signatures by means of reflectivities R^p and brightness temperatures T_B^p for (left) $p = H$ and (right) $p = V$. Reflectivities $R^p(t)$ of the litter-grid formation are simulated on the basis of $\varepsilon_L(t)$ [Fig. 11(b)] using the models from Section III-D with estimated small- and large-scale irregularities $\Delta_{AL} = \Delta_{DL} = 5$ mm.

Equation (3), with $T(t)$ [Fig. 10(a)], sky brightness $T_{B,\text{sky}} = 6.3$ K [36], and modeled $R^p(t)$, is used to derive $T_B^p(t)$ (Fig. 11(d), gray) to be compared with measurements

(Fig. 11(d), black). Thereby, the typical values $R_{\text{out}}^H = 0.40$ and $R_{\text{out}}^V = 0.25$ for a smooth bare soil at medium moisture are considered for the area outside the litter-grid formation. In consideration of the small fractional amount $1 - \mu \approx 0.1$ of which the outer area contributes to the total radiance, this choice is not expected to be critical. Vice versa, the measurement-based $R^p(t)$'s (Fig. 11(c), black) are derived from the L-band measurements $T_B^p(t)$ by using (3) solved for $R^p(t)$.

When the litter was drained during the second week of the campaign ($244 \leq \text{DoY} \leq 250$), the measured $T_B^p(t)$'s (Fig. 11(d), black) reveal generally low values with diurnal variations. The corresponding means $\langle T_B^H \rangle = 39.8 \pm 2.6$ K and $\langle T_B^V \rangle = 52.5 \pm 4.1$ K are close to the values $T_{B,\text{grid}}^H = 25.4$ K and $T_{B,\text{grid}}^V = 30.3$ K measured for the bare wire grid (Fig. 11(d), dashed lines), indicating the high microwave transparency of the drained litter layer ($\rho_{wL} \approx 0 \text{ m}^3 \cdot \text{m}^{-2}$). By contrast, the measured $T_B^p(t)$'s are increased significantly by the precipitation events taking place during the first week ($237 \leq \text{DoY} \leq 242$). The measured maximum T_B^p 's are comparable with the brightness typically emitted by moist soils, revealing the pronounced litter emission under wet conditions. After the individual rain events, the measured $T_B^p(t)$'s decrease rapidly, followed by retarded decreases reaching similar values as during the rainless period. The fast responses immediately after the rain events indicate the limited water retention capability of the litter layer in accordance with the estimated litter discharge time $\tau_L \approx 1$ h (Section II-B). The subsequent slower responses are supposed to be associated with drying of the litter due to the evaporation after gravimetric water flow (drainage) is subsided. This drying process is expected to be slow compared with the drainage and might even be delayed due to condensation [28] for wet underlying soils.

In consequence of the low $T_B^p(t)$ measured under dry conditions, the measurement-based $R^p(t)$'s (Fig. 11(c), black) have high mean values $\langle R^H \rangle = 0.94$ and $\langle R^V \rangle = 0.91$ for $244 \leq \text{DoY} \leq 250$. These values are only slightly smaller than one, being the reflectivity of the bare wire grid (Fig. 11(c), dashed lines). Most of the oscillations identified in the measurement-based $R^p(t)$'s are supposed to be artifacts. These variations are most likely produced by the pronounced diurnal temperature dynamics of the litter, which is underestimated by the measured subsurface temperatures $T(t)$ used in (3). During the rain events ($237 \leq \text{DoY} \leq 242$), the measured $R^p(t)$'s drop significantly, taking values typically for bare soil sites. Furthermore, the fast and the slow responses preceding the precipitations are observed.

The simulated $R^p(t)$'s (Fig. 11(c), gray) reproduce the main features of the measured $R^p(t)$'s (Fig. 11(c), black). For the dry period $244 \leq \text{DoY} \leq 250$, the computed means $\langle R^H \rangle = 0.95$ and $\langle R^V \rangle = 0.89$ match the mean measured reflectivities $\langle R^H \rangle = 0.94$ and $\langle R^V \rangle = 0.91$ well. The almost perfect agreement of $\langle R^H \rangle$ for drained litter is achieved by evaluating the model for the salinity $S = 3$ ppt of the intracellular water mainly determining the litter absorption for $\rho_{wL} \approx 0 \text{ m}^3 \cdot \text{m}^{-2}$ and, thus, R^p (Fig. 6).

Along with the rain events associated with increased $\rho_{wL}(t)$, the measured and simulated $R^p(t)$'s reveal distinct dips. The fast responses immediately after the rain events are well

Fig. 11. Comparison between (gray) simulated and (black) measured L-band signatures of the site comprising the litter-grid formation at $\alpha = 50^\circ$ for the (left) H- and (right) V-polarizations. (a) Litter moisture column density $\rho_{wL}(t)$ derived from the precipitation rate $P(t)$ [Fig. 10(a)] using (2). (b) Real and imaginary parts of litter permittivities $\varepsilon_L(t) = \varepsilon'_L + i\varepsilon''_L$ computed with the effective medium approach (Section III-C). (c) Reflectivities (black) $R^p(t)$ based on measured brightness $T_B^p(t)$ ($p = H, V$) using (3); (gray) $R^p(t)$ is computed by using the models from Section III-D and $\varepsilon_L(t)$. (d) Measured (black) $T_B^p(t)$ and (gray) $T_B^p(t)$ derived from the simulated $R^p(t)$ using (3).

reproduced by the model, corroborating the postulated litter drying due to drainage with time constant $\tau_L \approx 1$ h (2) preceding the rain. As litter drying due to evaporation is not considered in the model, the subsequent retarded responses are not grasped by the calculated $R^p(t)$. However, by adding a second time scale to the kernel function in (2), the observed slow responses associated with evaporation and retarded due to water vapor escaping from the underlying soil (compare Section II-C) may be reproduced.

For H-polarization, the dynamics of $R^H(t)$ is in good agreement with the measurements, whereas the modeled $R^V(t)$'s generally underestimate the observed precipitation-induced signatures. The even larger amplitudes measured for V- than for H-polarization indicate that the true litter permittivity ε_L is not a scalar as modeled with the isotropic effective medium approach but a tensor with larger values in the vertical direction (compare Section III-C).

Following the well-reproduced values of $R^H(t)$, the agreement between the measured and simulated $T_B^H(t)$'s is also relatively good. Generally, the modeled signatures at V-polarization are less accurate than at H-polarization, which is attributed to anisotropic properties of the litter permittivity which is not considered here.

Further measurements, with higher gravimetric column densities ρ_L of dead leaves on top of the conducting wire grid, were performed. Up to $\rho_L = 2.4 \text{ kg} \cdot \text{m}^{-2}$, the litter layer was

still almost transparent under drained conditions, but for $\rho_L > 8 \text{ kg} \cdot \text{m}^{-2}$, the layer was totally opaque and dominated the radiance of the underlying wire grid at any moisture condition.

V. SUMMARY AND CONCLUSION

Quantitative soil moisture retrieval from remotely sensed L-band radiance requires sophisticated radiative transfer models that are able to elucidate the major sources and sinks of radiation. L-band brightness temperatures $T_B^p(t)$ ($p = H, V$) measured above forested sites comprise the radiation contributions emitted, absorbed, and scattered within the crown and the understory vegetations, as well as the contributions from the forest ground. Although the constitution of the ground is rather delicate in deciduous forests, their structure can roughly be represented by mineral soil covered with a litter layer mainly consisting of dead leaves.

As the presence of litter is affecting the above canopy L-band radiance, the radiative transfer properties of leaf litter are important to know for the quantitative soil moisture retrieval. This task has been tackled by evolving a physically based model and comparing simulations with L-band measurements taken above a site comprising leaf litter on an underlying wire grid.

The experimental setup consisted of the L-band radiometer ELBARA mounted on a 5-m-high tower directed at the

observation angle $\alpha = 50^\circ$. The artificially prepared litter layer was made up of $\rho_L = 1.2 \text{ kg} \cdot \text{m}^{-2}$ of leaves corresponding to the mean layer thickness $\langle D_L \rangle = 20 \text{ mm}$, which is a typical amount for a deciduous forest. In addition to $T_B^p(t)$, precipitation $P(t)$ and ground temperatures $T(t)$ were recorded. Litter moisture was measured gravimetrically to fit an exponential model (2) for the relation between $P(t)$ and column densities $\rho_{wL}(t)$ of water retained in the litter.

Reflectivities $R^p(\rho_{wL})$ of the litter-grid and the litter-soil formations are computed for $0 \leq \rho_{wL} \leq 6 \text{ m}^3 \cdot \text{m}^{-2}$. Depending on the soil water content θ_S below the litter layer, negative or positive gradients $dR^p/d\rho_{wL}$ are predicted. This implies that R^p observed during the initial phase of a rain event can be decreased as the litter moisture ρ_{wL} increases prior to θ_S . Furthermore, the developed approaches were rather sensitive to the absorption within the litter (related to ε_L'') and with respect to litter layer thickness variations Δ_{AL} , Δ_{LS} , and Δ_{DL} on lateral scales below and above the Bragg limit (resolution limit). The present sensitivity study shows the importance of small-scale irregularities at the litter boundaries, revealing that a litter layer covering a soil cannot be adequately modeled with a single homogeneous dielectric slab exhibiting the true effective permittivity of the litter.

Brightness temperatures $T^p(t)$ were computed from the modeled $R^p(\rho_{wL})$ to be compared with the remotely sensed $T^p(t)$, yielding a fairly good agreement if the model is evaluated for reasonable parameters.

By taking the aforementioned aspects into consideration, it can be concluded that the typical amount of dead leaves on the ground of comparable deciduous forests might be nearly "invisible" at L-band wavelengths if not wetted by ongoing or recent rain. In the latter cases, the same amount of leaf litter can act as an important radiation source to be taken into account for the quantitative remote soil moisture detection. The present investigation indicates anisotropic effective litter permittivities with higher values in the vertical direction than within the litter plane. Vertical preferential flow paths of water through the leaf litter were postulated to be the reason for this observation. However, considering the large dissimilarities between litter types present in different forests under different climatic conditions, further investigations on litter-water interactions are required for assessing the generality of the presented results.

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