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Observations and Modeling of a Pine Forest Floor at L-Band

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Abstract—Recent studies of passive L-band observations over forests have shown that the average canopy transmissivity in temperate coniferous and deciduous forests is on the order of 0.4–0.5. Although the canopy would therefore be expected to transmit a reasonable amount of ground emission, the total emission observed above the canopy shows very little variation with varying soil moisture content. Moist litter present on the forest floor is known to obscure the soil emission. Therefore, more knowledge on the L-band radiative properties of litter and understory layers is needed to better understand the emission of the whole forest system. In order to contribute toward this issue, a field experiment was conducted in a pine forest in southwest France. Radiometric observations were done on the canopy and on different configurations of the forest floor, following sequential stripping of each forest floor layer. In combination with a long-term data set of above-canopy observations, this resulted in emissivity values of bare soil, soil–litter, soil–litter–grass, and soil–litter–grass–canopy configurations for a range of soil and litter moisture values. Calculations involved the use of the Wilheit and L-MEB models. The sensitivity to soil moisture was found to be substantially suppressed by the presence of a grass understory and litter. This corroborates the low correlation between soil moisture and L-band brightness temperature measured above the canopy. Several results of recent modeling and laboratory studies are also confirmed by this paper, which is, to our knowledge, the first to use *in situ* experimental data in this context.

Index Terms—Forest, L-band, litter, microwave radiometry, understory.

I. INTRODUCTION

IN VIEW of the European Space Agency's (ESA) upcoming Soil Moisture and Ocean Salinity (SMOS) satellite mission, a better understanding of L-band forest emission is certainly

needed, as many pixels over land will contain at least partial forest cover and thus complicate soil moisture retrievals. Over the past few years, several studies have focused on passive L-band (1.4 GHz; $\lambda \approx 21$ cm) observations of forests [1]–[5]. Results consistently revealed that it is crucial to know the L-band radiative properties of litter and understory in order to fully understand the microwave signatures. Until recently, the high L-band emissivity found over forests [3], [6] was mainly attributed to the influence of the tree canopy. However, canopy transmissivity was subsequently shown to be higher than first assumed—typical average values for coniferous and deciduous forests being in the range of 0.4–0.5 [4], [7]. This implies that it might be possible to obtain information on forest floor emission transmitted through the canopy. Furthermore, the generally high emissivity values found over forests might not be predominantly due to a high opacity of the tree canopy but could also be due to the litter and/or understory layers.

Ten years ago, a study over prairie grass [8] was the first to note that the thatched layer of dead vegetation in unburned grass areas has a considerable impact on L-band emission when wet. The issue was taken up again recently [9] to confirm that, compared to a living grass layer, a mixed layer of dead grass and mulch shows an increased optical depth with higher moisture. Concerning forest litter, Guglielmetti *et al.* [5] hypothesized that the below-canopy contribution to the L-band signal observed over forests might even be completely dominated by the litter layer, due to its high opacity and attenuation of soil emission. However, simulations at L-band [10], [11] found that above-canopy emission still showed a certain sensitivity to soil moisture, although the latter could be reduced by the presence of litter. Dielectric mixing models for litter have been developed by Della Vecchia *et al.* [12] and Kleshchenko *et al.* [13] for pine forest and needle litter, respectively, and lately by Schwank *et al.* [14] for deciduous leaf litter. The latter study found that a deciduous litter layer is nearly transparent at L-band for dry conditions, but when wetted, it acts as an important source of emission. Laboratory observations [15] have shown that the emission of a soil–litter (SL) system is quite complex, depending on litter layer thickness and the moisture contents of both the soil and litter layers. The three studies [5], [14], [15] consistently noted a transitional period just after wetting the litter, due to drainage and uptake/repartitioning of the water by the litter layer. However, none of the forest litter studies mentioned above were based on *in situ* field observations with the forest floor layers in their undisturbed state. This paper aims to fill this gap in the available information by performing forest floor observations in an experimental setting within the forest.

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TABLE I
SUMMARY OF DATA SETS AND OBSERVING CONFIGURATIONS USED IN THIS PAPER. OBSERVED SURFACE: S = Soil, L = Litter, G = Grass, C = Tree Canopy, Sky = Sky. VARIABLES: T = Temperature, SM = Soil Moisture, LM = Litter Moisture

configuration	year	direction	θ [°]	ϕ [°]	P	duration	varying parameters
S	2007	down	30-60, per 5	180	H,V	15 mins.	-
SL	2007	down	30-60, per 5	180	H,V	15 mins.	-
SLG	2007	down	30-60, per 5	180	H,V	15 mins.	-
SLGC	2004	down	45	65	H	3-6 months	T, SM, LM
Sky	2007	up	150	0	H,V	5 mins.	-
CSky	2007	up	120-180, per 5-10	75, 53 and 0	H,V	50, 45 and 30 mins.	-

In a previous study calibrating the L-band microwave emission of the biosphere (L-MEB) model [16] over forests [7], the effect of the understory and litter was indirectly taken into account through the soil roughness parameter H_R . This paper takes a more physically based approach by using the coherent Wilheit model [17] to simulate the emissivity of an SL forest floor configuration. In general, the forest floor is modeled as a composition of soil, litter, and grass layers. L-band observations were obtained of the tree canopy and of the forest floor in three different configurations [soil–litter–grass (SLG), soil–litter (SL), and bare soil (S)]. In order to investigate the behavior of the various forest layers with varying ground moisture conditions, the emissivity of each configuration and the thermal sampling depth of the SL configuration were related to varying soil moisture content. The main focus of this paper is to obtain a better insight into the relative contribution of each forest layer to the overall L-band emission.

II. MATERIALS

This paper uses data from two experiments both performed at the “Bray” site, the most recent having taken place in 2007 and a previous one in 2004 [3]. In 2007, L-band observations were performed below the canopy, whereas in 2004, this was done above the canopy. Throughout this paper, the two experiments will be named the “below-canopy” and the “above-canopy” experiments, respectively.

A. Site Description

The “Bray” site lies within the production forest of Les Landes, at approximately 20 km southwest of Bordeaux, France (latitude 44°42' N, longitude 0°46' W, altitude 61 m). Sole tree species at the experimental site is the Maritime Pine (*Pinus pinaster* Ait), with an age of 37 years in 2007 and an average height of 22 m during both experiments. The trees are planted in parallel rows along a northeast–southwest axis with an interrow spacing of 4 m. The value of canopy Leaf (needle) Area Index (LAI) is around $2.15 \text{ m}^2 \cdot \text{m}^{-2}$ in summer and $1.95 \text{ m}^2 \cdot \text{m}^{-2}$ in winter. Corresponding total column biomasses (trunks, branches, and needles) are approximately 11.28 and $10.58 \text{ kg} \cdot \text{m}^{-2}$ which are typical values for a “medium dense” forest and thus indicate the sheltered character of the forest floor. The understory includes a few scattered shrubs and young trees but consists mostly of grass (mainly *Molinia caerulea* L. Moench). Green grass LAI is $\approx 1.55 \text{ m}^2 \cdot \text{m}^{-2}$ in summer and not applicable during winter. At the time of the below-canopy experiment, the grass was completely senescent, whereas the

above-canopy experiment took place from July to December and therefore covered a range of grass phenological stages.

The soils at the Bray site are sandy and hydromorphic podzols, with dark organic matter in the first 60 cm. Percentages of sand and clay are around 80% and 3%, respectively. The average soil bulk density at the site is around $1.25 \text{ g} \cdot \text{cm}^{-3}$. The soil is covered by a dense litter layer of spatially varying thickness (average of 3 cm, with thicknesses up to 10 cm [15]), consisting of decomposing grass and pine needles, cones, and branches. The percentage of organic matter in this layer was determined to be around 85%.

B. Data Sets

Both experiments were conducted with the L-band polarimetric radiometer EMIRAD built at the Technical University of Denmark [18]. Table I summarizes the different data sets and observing configurations used in this paper, whereby the observed surface configurations can consist of various combinations of soil (“S”), litter (“L”), grass (“G”), tree canopy (“C”), and sky (“Sky”).

The above-canopy experiment was performed between July and December 2004 and is described in more detail in [3]. The radiometer was mounted on a 40-m tower over the forest, and downward-looking observations were done at horizontal polarization ($P = H$) and angles $\theta = 25^\circ$ to 60° relative to nadir. A thermal infrared (IR) radiometer (Heitronics KT 15.85D; $9.6\text{--}11.5 \mu\text{m}$) was mounted next to the microwave radiometer to provide measurements of surface temperature T_{IR} over approximately the same footprint. At a fixed location, ground measurements of soil and litter moisture were taken every 10 s with ThetaProbes connected to a CS21X data logger, and averaged to half-hourly values. Half-hourly precipitation totals were also recorded every 30 min. The L-band brightness temperatures $T_B^{\text{H},45^\circ}$ used from this experiment were those observed at $\theta = 45^\circ$ (cf. Table I: configuration “SLGC”). Moreover, only observations for which no rainfall had taken place in the past 24 h were included in the analysis. As this concerned a long-term experiment, observations were done for a variation of temperatures and soil and litter moisture contents.

The below-canopy observations were made at the “Bray” site on February 15–19, 2007 and consisted of two parts: 1) downward observations of the forest floor from below the tree canopy, and 2) upward observations of the tree canopy in the direction of the sky. Fig. 1 shows a photograph of the experimental setup during the below-canopy downward observations and sketches of the setups for both the downward [Fig. 1(a)] and the upward [Fig. 1(b)] observations.

Fig. 1. Experimental setup of the radiometric observations during the below-canopy experiment using the EMIRAD L-band (1.4 GHz) radiometer. (Top) Photograph. (a) Sketch of downward observations of the forest floor. (b) Sketch of upward observations of the tree canopy.

An internal calibration of the radiometer was done automatically for each observation using internal hot and cold loads with respective noise temperatures of 320 and 120 K as described in [18]. An additional “external calibration” was carried out in the same way as described for the above-canopy experiment in [3], in order to correct for losses in the antenna and cables. For the latter calibration, sky brightness $T_{B, \text{Sky}}$ was measured at 30° from zenith before, during, and after the experiment (cf. Table I: configuration “Sky”). The measured values were then adjusted to the theoretical value $T_{B, \text{Sky}} = 4.6$ K [19], and this correction was subsequently applied to all observations.

No precipitation occurred during any of the below-canopy observations; moreover, no precipitation occurred during the 24 h before the upward observations of the canopy.

For the downward observations, the instrument was mounted on a 4.5-m high tower below the tree canopy. Full (−3 dB) antenna beamwidth was 25°, resulting in a footprint area ≈ 10 m² at $\theta = 40^\circ$. Three forest floor configurations were observed: 1) “SLG,” 2) “SL,” and 3) “S” (cf. Table I). Layers were manually removed between each of the three series, and observations were done at horizontal ($P = H$) and vertical ($P = V$) polarization and angles $\theta = 30^\circ$ to 60° with 5° increments. The experiment was intended to study how the emission properties of the different ground configurations change with the removal of each layer, not to obtain temporal information on layer properties. Therefore, each configuration (i.e., each angular series) was only observed for a short period of time (15 min, cf. Table I).

It should be noted that in all cases, some tree trunks partly covered the edges of the footprints, particularly at higher observation angles. Furthermore, some grass tufts (cut off at the surface) and roots remained in the footprints of the “S” and “SL” configurations, as it was impossible to remove these without severely influencing surface roughness. However, as tree trunks and grass tufts/roots were present in all configurations, the relative differences in emissivity between the different configurations can be assumed to be correct. Finally, the “S” configuration probably still contained some organic material in the topsoil as the depth of the litter layer was highly variable.

Directly before and after the radiometric observations, *in situ* measurements of temperature and moisture were performed. Soil temperatures were measured with a standard lab-calibrated digital thermometer, yielding the average temperature of the top 7 cm of the forest floor. Soil moisture was obtained with a time-domain reflectometer probe (TRIME FM2 (IMKO), type P2) and by gravimetric sampling. Furthermore, grass and litter samples were taken for determining the moisture of the litter and grass layers. Finally, air temperature within the canopy at 20-m height was obtained from ongoing meteorological measurements at the Bray site. As vertical temperature gradients in such a forest system are expected to be relatively small (see, e.g., [3]), the air temperature was used in the model as an approximation for grass and tree canopy temperatures.

The upward radiometric observations through the canopy were done at a slightly different location forest-inward, in order to avoid an overly high contribution of sky emission at the forest edge. However, canopy conditions at the locations of the downward and upward observations were very similar. For the upward observations, the radiometer was mounted on a 1.5-m structure and directed upward in order to obtain canopy observations analogous to those described in [7]. Three series of observations were done at angles between 120° and 180° relative to the downward vertical direction (nadir) [see Fig. 1(b)]. Each series was taken at a different azimuth angle φ , i.e., at 75°, 53°, and 0° (parallel) relative to the row direction of the trees (cf. Table I: configuration “CSky”).

III. METHODS

A. L-MEB Model (SLGC Configuration)

In this paper, the L-MEB model [16] was used to model the emission of the whole forest system (i.e., a

soil–litter–grass–canopy (SLGC) configuration) from above-canopy observations. The model is based on the zero-order radiative transfer approach shown in (1), which considers the upwelling radiation emitted by the forest floor (first term) and the combination of up- and downwelling canopy radiation (second term). The downwelling canopy radiation is reflected at the forest floor and subsequently transmitted back upward through the canopy. The third term of the equation considers the sky radiation reflected by the canopy, the sky radiation reflected by the forest floor, and an additional sky term which represents an approximation of multiple scattering between the forest floor and the canopy in order to satisfy Kirchhoff's law [20]. In L-MEB, the latter contribution is neglected, as both scattering within the canopy and sky radiation are low. Although, in consequence, L-MEB does not fulfill Kirchhoff's law, the error is insignificant and the numerical results are very similar to those of a physically correct expression

$$T_B^{P,\theta} = T_F \cdot \left(1 - R_F^{P,\theta}\right) \cdot \gamma_C^{P,\theta} + \left(1 - \omega_C^P\right) \cdot \left(1 - \gamma_C^{P,\theta}\right) \cdot T_C \cdot \left(1 + R_F^{P,\theta} \cdot \gamma_C^{P,\theta}\right) + \left[\omega_C^P \cdot \left(1 - \gamma_C^{P,\theta}\right) \cdot \left(1 + \left(R_F^{P,\theta} \cdot \gamma_C^{P,\theta}\right)^2\right) + R_F^{P,\theta} \cdot \left(\gamma_C^{P,\theta}\right)^2\right] \cdot T_{B,\text{Sky}}. \quad (1)$$

In (1), the subscript F denotes the forest floor, while the variables T_F and T_C indicate the thermodynamic temperatures of the forest floor and the tree canopy, respectively. The forest floor reflectivity $R_F^{P,\theta}$ is related to forest floor emissivity $e_F^{P,\theta}$ through $R_F^{P,\theta} = 1 - e_F^{P,\theta}$. Depending on the observed configuration (Section II-B), $e_F^{P,\theta}$ can be either the S emissivity $e_F^{P,\theta} = e_S^{P,\theta}$, the emissivity of the SL configuration $e_F^{P,\theta} = e_{SL}^{P,\theta}$, or the emissivity of the SLG configuration $e_F^{P,\theta} = e_{SLG}^{P,\theta}$. The sky brightness temperature $T_{B,\text{Sky}}$ was calculated according to the method outlined in [19].

The variable ω_C^P is the effective single scattering albedo of the tree canopy, and the variable $\gamma_C^{P,\theta}$ describes canopy transmissivity, which is related to the canopy optical depth $\tau_C^{P,\theta}$

$$\gamma_C^{P,\theta} = \exp\left(-\tau_C^{P,\theta} / \cos\theta\right). \quad (2)$$

The optical depth $\tau_C^{P,\theta}$ is derived from brightness temperatures measured at angles θ 's in upward direction. Dividing by the cosine corrects for the difference in physical path length through the canopy layer at different angles but does not take into account the effects of uniaxial canopy anisotropy with a vertical axis of symmetry. Such effects are taken into account by the parameter tt_C^P used in the L-MEB model [16]. This results in $\tau_{C,\text{NAD}}$, with the subscript "NAD" denoting theoretical nadir values

$$\tau_C^{P,\theta} = \tau_{C,\text{NAD}} \left(\sin^2(\theta) \cdot tt_C^P + \cos^2(\theta)\right). \quad (3)$$

In this paper, all L-MEB-related retrievals were done using the cost function CF [21] as a minimization criterion for model

inversion

$$CF = \sum_{i=1}^n \frac{(T_{B,i}^0 - T_{B,i})^2}{\sigma_{T_B}^2} + \frac{(p_i - p_i^{\text{ini}})^2}{\sigma_p^2}. \quad (4)$$

The error computed by this cost function represents the sum of the squared differences $T_{B,i}^0 - T_{B,i}$ in observed and simulated brightness temperatures plus the squared differences $p_i - p_i^{\text{ini}}$ in retrieved and initial parameter values. The parameters $\sigma_{T_B}^2$ and σ_p^2 are the corresponding variances. In this paper, all retrievals were done without constraints. In addition, several initial values were always tested.

B. Canopy and Forest Floor Emissivities

The procedure used to obtain the forest floor emissivities was the following: First, the upward canopy observations were analyzed to obtain values of the canopy parameters $\tau_{C,\text{NAD}}$ and tt_C^P . Subsequently, these were used to account for canopy emission reflected by the forest floor in the downward observations.

1) *Canopy Emission (CSky Configuration)*: The upward-observed (i.e., downwelling) brightness temperatures $T_B^{P,\theta}$ comprise the contributions of the following: 1) upwelling forest floor radiation reflected by the tree canopy; 2) downwelling radiation from the tree canopy; and 3) downwelling sky radiation. The zero-order radiative transfer model used for the analysis of the upward canopy observations [4], [7], [22] is shown as

$$T_B^{P,\theta} = T_F \cdot \left(1 - R_F^{P,\theta}\right) \cdot \omega_C^P \cdot \left(1 - \gamma_C^{P,\theta}\right) + \left(1 - \omega_C^P\right) \cdot \left(1 - \gamma_C^{P,\theta}\right) \cdot T_C + T_{B,\text{Sky}} \cdot \gamma_C^{P,\theta}. \quad (5)$$

In the equation [see (5)], multiple interactions between the forest floor and the canopy have been neglected, as the product of the canopy and forest floor (SLG configuration) reflectivities is $\ll 1$. The equation fulfills Kirchhoff's law.

Following a previous study over the same forest [7], the single scattering albedo was set to $\omega_C = 0.07$. Canopy temperature T_C was taken from the air temperature at 20 m, as explained in Section II-B, and T_F was taken from an IR temperature measurement of the forest floor during the upward observations. $R_F^{P,\theta}$ was set to 0.05 in accordance with an estimation of $e_F^{P,\theta} = 0.95$ in [22], which was based on experimental data covering a range of moisture conditions and frequencies [23]. The precision of this parameter is not very critical at this point because of its small impact on $T_B^{P,\theta}$.

By combining (5) with (2) and (3), it was then possible to simultaneously retrieve the parameters $\tau_{C,\text{NAD}}$ and tt_C^P , using the cost function CF defined in (4) as a minimization criterion.

2) *Forest Floor Emission (S, SL, and SLG Configurations)*: Because the downward observations were performed below the tree canopy, the forest floor emissivities ($e_S^{P,\theta}$, $e_{SL}^{P,\theta}$, or $e_{SLG}^{P,\theta}$) were obtained from the measured brightness temperatures $T_B^{P,\theta}$ using an adapted zero-order radiative transfer approach

$$T_B^{P,\theta} = T_F \cdot \left(1 - R_F^{P,\theta}\right) + \left(1 - \omega_F^P\right) \cdot \left(1 - \gamma_C^{P,\theta}\right) \cdot T_C \cdot R_F^{P,\theta} + R_F^{P,\theta} \cdot T_{B,\text{Sky}} \cdot \gamma_C^{P,\theta}. \quad (6)$$

As with the previous equation [see (5)], (6) fulfills Kirchhoff's law and neglects multiple interactions. With T_C , ω_C^P , and $\gamma_C^{P,\theta}$ obtained from the upward canopy observations (Section III-B-1) and T_F from ground measurements ($T_F = T_{\text{soil}}$ in the case of a soil or litter layer; $T_F = T_{\text{air}}$ in the case of a grass layer), it was then possible to calculate the forest floor emissivity $e_F^{P,\theta} = 1 - R_F^{P,\theta}$.

C. Modeling of SL Emissivity

1) *Footprint Emissivity*: Previously, the L-MEB model has been used to model a litter layer using the $\tau - \omega$ approach [9]. However, the τ and ω parameters in L-MEB, representing volume effects such as extinction and scattering, are relevant for a vegetation layer but potentially less so for litter due to its higher volume density. Therefore, this paper uses a more physically based approach.

The emissivity $e_F^{P,\theta} = e_{\text{SL}}^{P,\theta}$ of the SL forest floor configuration was simulated following the method proposed in [14]. The basic ideas behind this approach are as follows: 1) The dielectric depth profile $\varepsilon(z)$ of a specific ground configuration is represented by an empirical approach which describes gradual transitions between the dielectric regimes; 2) coherent reflectivities $R_{\text{coh}}^{P,\theta}$ associated with $\varepsilon(z)$ are computed with a coherent radiative transfer model. $R_{\text{coh}}^{P,\theta}$ accounts for roughness with lateral dimensions below the resolution limit (Bragg limit); and 3) $R_{\text{coh}}^{P,\theta}$ is averaged over the thickness range of the considered dielectric layers (e.g., litter) in order to model the partial cancellation of coherence due to variations at lateral scales above the resolution limit. The resulting reflectivity $R_F^{P,\theta}$ is then used to model the measured $T_B^{P,\theta}$.

In this paper, two modifications were applied to the approach used in [14]: 1) instead of a matrix formulation of Maxwell's boundary conditions at dielectric discontinuities, the Wilheit model [17] was used to compute $R_{\text{coh}}^{P,\theta}$, and 2) a more realistic averaging approach was used to derive $R_F^{P,\theta}$ from $R_{\text{coh}}^{P,\theta}$.

As in [14], Fermi functions were used to represent the dielectric profile $\varepsilon_{\text{ALS}}(z)$ of the litter-soil (LS) configuration

$$\varepsilon_{\text{ALS}}(z) = \varepsilon_A + \frac{\varepsilon_L - \varepsilon_A}{1 + \exp\left(-2.197 \cdot \frac{z - z_{\text{AL}}}{\Delta_{\text{AL}}}\right)} + \frac{\varepsilon_S - \varepsilon_L}{1 + \exp\left(-2.197 \cdot \frac{z - z_{\text{LS}}}{\Delta_{\text{LS}}}\right)}. \quad (7)$$

The parameters ε_L and ε_S are the effective litter and soil permittivities, respectively, and z is the downward vertical direction. The mean depths of the dielectric transitions between air and litter (AL) and LS are z_{AL} and z_{LS} , respectively. Consequently, the litter layer thickness is $D_L = z_{\text{LS}} - z_{\text{AL}}$. The sharpness of the dielectric transitions is parameterized by $2 \cdot \Delta_{\text{AL}}$ and $2 \cdot \Delta_{\text{LS}}$, defined as the differences in z from 10% to 90% of the corresponding permittivity differences.

An example of a permittivity profile $\varepsilon_{\text{ALS}}(z)$ of the LS configuration is shown in Fig. 2, using parameter values typical for the Bray forest floor. Given $\varepsilon_{\text{ALS}}(z)$, the Wilheit modeling procedure was performed for a total depth of 30 cm with the

Fig. 2. Example of a dielectric profile $\varepsilon'_{\text{ALS}}(z)$ according to (7) representative for the SL configuration. $\theta = 45^\circ$, $D_L = 3$ cm, $2 \cdot \Delta_{\text{AL}} = 1.39$ cm, $2 \cdot \Delta_{\text{LS}} = 1.25$ cm, and $\varepsilon_S = 16.428 + 2.977i$ and $\varepsilon_L = 4.613 + 0.104i$, corresponding to soil and litter moistures of $0.205 \text{ m}^3 \cdot \text{m}^{-3}$ and $0.453 \text{ kg} \cdot \text{kg}^{-1}$. These values are typical for the Bray forest floor.

thickness of each of the $N = 300$ homogeneous layers set to 0.1 cm, which is less than one-tenth of the wavelength in the medium. No temperature gradients were considered over the total depth. This procedure resulted in the coherent reflectivities $R_{\text{coh}}^{P,\theta}$.

As mentioned earlier, compared with [14], an improved averaging approach was used in this paper to compute the experimentally relevant footprint reflectivities $R_F^{P,\theta}$ from the coherent reflectivities $R_{\text{coh}}^{P,\theta}$. Instead of linearly averaging $R_{\text{coh}}^{P,\theta}$ over the range of the litter layer thickness D_L within the footprint, a normalized gamma probability distribution $P(D_L)$ was used, as shown in (8) (with $\Gamma = \text{Gamma function}$). This is a more realistic approach as the spatial variability of D_L is accounted for and weighed

$$R_F^{P,\theta} = \int_0^\infty P(D_L) \cdot R_{\text{coh}}^{P,\theta}(D_L) dD_L \quad \text{with} \quad P(D_L) = \frac{1}{b^a \Gamma(a)} \cdot D_L^{a-1} \cdot \exp\left(\frac{-D_L}{b}\right). \quad (8)$$

The distribution $P(D_L)$ with $a = 3.85$ and $b = 1.05$ cm shown in Fig. 3 was based on the distribution of D_L observed in the field [15]. Combining the coherent reflectivities $R_{\text{coh}}^{P,\theta}$ with $P(D_L)$ yielded the footprint reflectivities $R_F^{P,\theta}$.

The general procedure for model calibration of the below-canopy observations of the SL configuration was to simultaneously retrieve the parameters Δ_{AL} and Δ_{LS} [see (7)] using an unconstrained nonlinear optimization procedure, in which several initial values were tested.

2) *Soil and Litter Permittivity*: For the calibration of the Wilheit model with the below-canopy observations of $e_{\text{SL}}^{P,\theta}$, gravimetric litter moisture $LM[\text{kg} \cdot \text{kg}^{-1}]$ was estimated from volumetric soil moisture $SM[\text{m}^3 \cdot \text{m}^{-3}]$ using the site-specific empirical relation observed during a period of six months in 2004 [3]

$$LM = 3.0971 \cdot SM - 0.1816 \quad (R^2 = 0.84). \quad (9)$$

Fig. 3. Normalized gamma probability distribution $P(D_L)$ [see (8)] with $a = 3.85$ and $b = 1.05$ cm used for modeling the distribution of litter layer thickness D_L .

Effective soil and litter permittivities ε_S and ε_L are represented in the empirical dielectric profile $\varepsilon_{ALS}(z)$ [see (7)]. The Dobson dielectric mixing model [24] was used to compute ε_S as a function of the volumetric soil moisture $SM[m^3 \cdot m^{-3}]$ with soil parameters as given in Section II-A and Table II (Section IV-A). Estimates of $\varepsilon_L = \varepsilon'_L + i \varepsilon''_L$ were taken from laboratory measurements relating LM to litter permittivity, for litter samples with bulk density of $0.1 \text{ g} \cdot \text{cm}^{-3}$ taken from the Bray site [15]

$$\varepsilon'_L = 2.3 \cdot \tanh(8 \cdot (LM - 0.65)) + 5.8 \cdot LM + 4.1 \quad (10a)$$

$$\varepsilon''_L = 1.25 \cdot \tanh(18 \cdot (LM - 0.63)) + 1.35. \quad (10b)$$

IV. RESULTS AND DISCUSSION

A. Ground Measurements During the Below-Canopy Experiment

Results of the ground measurements during the below-canopy experiment are shown in Table II. Temperature and soil moisture values in this table are averages of measurements done before and after each series of radiometric observations of a given configuration (S, SL, or SLG, see Section II-B). Gravimetric litter moisture is obtained from soil moisture according to the empirical relation given by (9).

B. Canopy Observations

Fig. 4 shows values of the forest canopy transmissivity $\gamma_C^{P,\theta}$ derived from the three different azimuthal observation series, plotted against observation angle θ . The lines in the figure trace the polarization-averaged values of $\gamma_C^{P,\theta}$ for each of the three azimuthal series. The figure shows a general increase in $\gamma_C^{P,\theta}$ for $\theta = 120^\circ - 180^\circ$, which illustrates the effect of difference in path length through the canopy at different angles [cf. the $1/\cos \theta$ term in (2)]. Depending on θ , the observed dispersion between azimuth series can amount up to 0.10. This is due to the fact that, particularly at shallower incidence angles, each azimuthal measurement series observed a different part of the

TABLE II
TEMPERATURE AND MOISTURE VALUES OBTAINED FROM GROUND MEASUREMENTS DONE BEFORE AND AFTER EACH RADIOMETRIC OBSERVATION SERIES OF THE THREE DIFFERENT CONFIGURATIONS S, SL, AND SLG

	Soil-litter-grass	Soil-litter	Bare soil
Date	15/02/07	15/02/07	16/02/07
$T_{\text{soil } 0-7 \text{ cm}}$ [K]	281.55	282.75	283.53
$T_{\text{air at } 20 \text{ m}}$ [K]	284.05	287.6	288.41
Soil moisture 0-5 cm [$m^3 \cdot m^{-3}$]	0.194	0.205	0.220
Litter moisture [$kg \cdot kg^{-1}$] (from eq. 9)	0.450	0.481	-
Litter fresh biomass [$kg \cdot m^{-2}$]	-	6.74	-
Grass moisture [$kg \cdot kg^{-1}$]	0.67	-	-
Grass fresh biomass [$kg \cdot m^{-2}$]	2.58	-	-

canopy and the dispersion in $\gamma_C^{P,\theta}$ thus reflects the canopy heterogeneity. Furthermore, the figure shows that the differences in $\gamma_C^{P,\theta}$ for each pair of H and V polarizations are very small at the lower angles but increase at observation angles $\geq 150^\circ$. This might be due to the tree structure, which shows a more horizontal orientation of the branches close to the trunk but a more vertical one toward the outer ends, as reported in [25]. At the lower observation angles, the footprint will predominantly contain the more central parts of the trees, which consist of both horizontal and vertical elements, whereas at the higher observation angles, it mainly covers the more vertical branch ends. This may explain the fact that the vertically polarized transmissivity $\gamma_C^{V,\theta}$ is lower at the higher observation angles. At $\theta = 180^\circ$, the antenna plane of incidence is horizontal and perpendicular to the ground. Differences in $\gamma_C^{P,\theta}$ for each pair of H and V signals must therefore be interpreted as azimuthal differences rather than actual horizontal and vertical differences. As Fig. 4 shows, none of the three observation series shows a difference between the paired H and V values at $\theta \approx 180^\circ$. Moreover, values of $\gamma_C^{P,\theta}$ for each of the three azimuth observation series are very similar at this observation angle. This indicates that at $\theta \approx 180^\circ$, as can be expected from the tree structure described earlier, the influence of row structure disappears and the tree canopy is isotropic.

Following the procedure explained in Sections III-A and III-B1, values of the canopy parameters $\tau_{C,NAD}$ and tt_C^P were retrieved from observations at angles $120^\circ - 180^\circ$. The results are shown in Table III for each of the three azimuth observation series, together with the resulting root mean square (rms) error in $T_B^{P,\theta}$. Average values were used as model inputs in all further parts of this paper.

The differences in $\tau_{C,NAD}$ for each azimuthal series show the spatial variability of the canopy optical depth. This will, of course, have some impact on the derivation of ground emissivities and, thus, on the modeling results.

It should be noted that the values given in Table III differ slightly from those found in a previous study concerning an experiment made in 2006 [7]. The reason for this lies in the fact that the 2006 observations were done at the edge of the forest, and consequently, only observations at angles between 120° and 150° were used in the analysis in order to minimize sky influence. Furthermore, the model used previously in [7] neglected the ground radiation reflected by the canopy. This

Fig. 4. Forest canopy transmissivity $\gamma_C^{P,\theta}$ [see (5)] plotted against observation angle θ for three different azimuth angles (75°, 53°, and 0°) relative to the row direction of the trees. Dotted, dashed, and solid lines trace the polarization-averaged values of $\gamma_C^{P,\theta}$ for the 75°, 53°, and 0° azimuth angles, respectively.

TABLE III

VALUES OF TREE CANOPY PARAMETERS $\tau_{C,NAD}$ AND tt_C^P RETRIEVED FROM OBSERVATIONS AT ANGLES 120°–180° FOR EACH OF THE THREE AZIMUTH OBSERVATION SERIES, TOGETHER WITH THE RESULTING RMS ERROR IN $T_B^{P,\theta}$

	$\tau_{C,NAD}$	tt_C^H	tt_C^V	RMS error [K]
75° azimuth	0.43	1.08	1.14	5.450
53° azimuth	0.46	1.18	1.16	13.035
0° azimuth (// to rows)	0.41	1.44	1.44	7.878
average $\pm$ stdev.	0.43 $\pm$ 0.03	1.23 $\pm$ 0.19	1.25 $\pm$ 0.17	

paper has extended on the previous results by using a more complete model [see (5)], together with observations done within the forest, and a greater range of angles (120°–180°) to obtain more realistic values of $\tau_{C,NAD}$ and tt_C^P .

C. Forest Floor Emissivities

The forest floor emissivities $e_F^{P,\theta}$ for H and V polarizations derived using (6) are shown in Fig. 5 for each of the three observed forest floor configurations [S, SL, and SLG].

Two aspects of this figure are noticeable. First, emissivities are high, particularly those of the SLG system, which are slightly over 1 for V polarization. The latter result is nonphysical. Although forest floor emission is expected to be high, particularly when litter and grass layers are involved, in this case, the experimental setup probably has an additional effect. Because these observations were done below the canopy and inside the forest, the situation is, in fact, quite similar to being inside a black box. As the forest floor emission is already high, it is easy to overestimate $e_{SLG}^{P,\theta}$ unless all other contributions to the observed $T_B^{P,\theta}$ are exactly known. However, the setup was specifically chosen in order to obtain *in situ* measurements with the forest floor layers in their undisturbed state and, as said previously (Section II-B), to better understand the relative layer contributions to emissivity.

A second noticeable aspect in Fig. 5 is that it clearly shows that the contributions of both the litter and the grass layers

Fig. 5. Forest floor emissivities $e_F^{P,\theta}$ corrected for the contributions of the reflected downwelling canopy and sky radiation [see (6)] plotted against observation angle θ for each of the three observed forest floor configurations (S, SL, and SLG).

to overall radiance are important. In a previous study [8], the thatch structure of an unburned grass cover was found to result in very high emissivities and low sensitivity to moisture status of the underlying soil. A later study over grass [9] found a similar effect for a “mixed layer” consisting of mulch, plant debris, and a tight layer of grass roots and stems, particularly when wet; however, the respective contributions of these components could not be separated. Finally, Schwank *et al.* [14] found that a layer of dead leaves on the ground of deciduous forests is almost transparent at L-band if dry, but an important radiation source when wet. Fig. 5 shows that, although the effect of the litter layer on overall radiance is certainly not negligible, a layer of moist senescent grass can have an additional important effect. This could contribute to the low sensitivity to soil moisture found for above-canopy radiometric observations at the Bray site [3], an effect which, until now, was attributed mainly to the litter layer.

D. Model Calibration

The model calibration for the SL configuration was done, as described in Section III-C, by retrieving parameter values Δ_{AL} and Δ_{LS} which describe the vertical extents of the AL and LS transitions. Because (9), (10a), and (10b) were all based on experimental data obtained from the Bray site, it should be kept in mind that in this procedure, ε_S and ε_L were not independent.

The values resulting from the retrievals were $\Delta_{AL} = 0.695$ cm and $\Delta_{LS} = 0.624$ cm, associated with rms errors in emissivity $e_{SL}^{P,\theta}$ of 0.036 (V) and 0.029 (H), respectively. These values of Δ_{AL} and Δ_{LS} resulted in the dielectric profile $\varepsilon'_{ALS}(z)$ shown previously in Fig. 2, for $\theta = 45^\circ$, $D_L = 3$ cm, $SM = 0.205 \text{ m}^3 \cdot \text{m}^{-3}$ (cf. Table II), and $LM = 0.453 \text{ kg} \cdot \text{kg}^{-1}$ [see (9)]. The corresponding soil and litter permittivities are $\varepsilon_S = 16.428 + 2.977i$ and $\varepsilon_L = 4.613 + 0.104i$, respectively. The coherent reflectivities resulting from this profile are $R_{coh}^{H,45^\circ} = 0.083$ and $R_{coh}^{V,45^\circ} = 0.06$. Subsequently, accounting for the distribution $P(D_L)$ yields the values $R_F^{H,45^\circ} = 0.213$ and $R_F^{V,45^\circ} = 0.077$ for the footprint reflectivities.

Fig. 6. Comparison between values of forest floor emissivity for an SL configuration $e_{SL}^{P,\theta}$ derived from below-canopy observations and simulations. The latter were done using the Wilheit model with AL and LS dielectric transitions.

Fig. 7. Horizontally polarized surface emissivities derived from above-canopy observations ($e_{SLGC,obs}^{H,45^\circ}$ and $e_{SLG,obs'}^{H,45^\circ}$; black) and simulations ($e_{SL,sim}^{H,45^\circ}$ and $e_{S,sim}^{H,45^\circ}$; gray), plotted against volumetric soil moisture content.

Fig. 6 shows the simulated footprint emissivities (dotted lines) compared with the SL emissivities derived from the below-canopy observations (solid lines) for observation angles 35° – 60° .

The fact that the emissivities derived from observations show different angular dependences to the simulated values could be due to various causes: The first one is an imperfect calculation of forest canopy radiance, in which the spatial variability of $\tau_{C,NAD}$ (Section IV-B), i.e., the effect of canopy heterogeneity, is not completely accounted for. The second one is the neglected effect of grass tufts and trunks in the footprint, and the third is the large beamwidth of the antenna. Finally, an incorrect probability distribution and/or an (as yet unknown) angular dependence of litter emissivity could be important. The errors are larger at vertical polarization, where the slope orientation of the observations is opposite to that of the simulations. In a study concerning deciduous leaf litter [14], larger modeling errors at vertical polarization were attributed to possible anisotropic properties of the observed litter type. The results found in this

paper suggest that anisotropy might also occur in the case of coniferous litter.

E. Emissivity and Soil Moisture

A compilation was made of the results of both the above- and below-canopy experiments in order to present a comprehensive image of the emission of each layer of the forest system as a function of *SM* conditions. This was done for the H polarization only, as only this polarization was available during the above-canopy experiment (Section II-B).

Fig. 7 shows four different emissivities plotted against soil moisture content: 1) above-canopy observed emissivity $e_{SLGC,obs}^{H,45^\circ}$ (published previously in [3]); 2) below-canopy emissivity of the SLG system $e_{SLG,obs'}^{H,45^\circ}$, derived from the above-canopy observations; 3) simulated values of SL emissivity $e_{SL,sim}^{H,45^\circ}$; and 4) simulated values of smooth S emissivity $e_{S,sim}^{H,45^\circ}$.

It should be noted that in all observed and simulated results shown in Fig. 7, values of *SM* and *LM* were taken from the ground measurements made during the above-canopy experiment (Section II-B), and not from (9), which was used for model calibration only (Sections III-C2 and IV-D).

The observed emissivities of the SLGC ($e_{SLGC,obs}^{H,45^\circ}$) were obtained from the above-canopy data set by calculating $T_B^{H,45^\circ}/T_{gc}$ with T_{gc} being the effective ground-canopy temperature [3]. Then, SLG emissivity $e_{SLG,obs'}^{H,45^\circ}$ was calculated from these measurements by removing the contribution of the tree layer from the above-canopy observations [see (1)], using the canopy parameters obtained from the below-canopy upward observations [see (5)]. It was assumed that significant changes in the tree canopy would not have taken place in the period between the two experiments. The suffix “obs” in the subscript indicates that values of $e_{SLG,obs'}^{H,45^\circ}$ are not the actual observations themselves, but have been derived from observations. T_{gc} was used for both the tree canopy temperature and for the temperature of the SLG system.

The SL emissivities ($e_{SL,sim}^{H,45^\circ}$) were simulated with the Wilheit model (Section III-C1) using the calibrated values of Δ_{AL} and Δ_{LS} and the probability distribution shown in Fig. 3. SL temperatures T_{SL} were approximated by the effective soil temperatures $T_{S,eff}$ [3] obtained during the above-canopy experiment. In the simulations, it was assumed that the parameters Δ_{AL} and Δ_{LS} do not depend on moisture conditions.

Finally, a time series of smooth S emissivity ($e_{S,sim}^{H,45^\circ}$) was obtained with the Fresnel equations, the Dobson dielectric mixing model [24], $T_{S,eff}$ [3], and soil parameter values as given in Section II-A.

The respective decreases in gradient de_F/dSM from $e_{SL,sim}^{H,45^\circ}$ through $e_{SLG,obs'}^{H,45^\circ}$ to $e_{SLGC,obs}^{H,45^\circ}$ show that the sensitivity to soil moisture is already substantially suppressed by the presence of a grass layer. This corroborates the low above-canopy sensitivity of emissivity with respect to ground moisture conditions found in [3], even though the average transmissivity of the tree canopy lies around 0.55 (cf. Fig. 4). This sensitivity loss is clearly due to the effect of the grass understory as well as that of the tree canopy.

The scatter in $e_{\text{SLG},\text{'obs'}}^{\text{H},45^\circ}$ values can be explained by temperature variations between subsequent observations. When deriving these below-canopy emissivities, the effective temperature T_{gc} was used for both the tree canopy and the SLG system. However, it is very well possible that the latter case particularly is a rather coarse approximation. The variation inherent in the above-canopy data set is for a great deal due to the changing phenological conditions of the grass understory from summer to winter. Furthermore, some variation, particularly such as seen around $SM \approx 0.21 - 0.26 \text{ m}^3 \cdot \text{m}^{-3}$, could also be the result of different LM conditions for a given SM .

Under dry conditions, the grass layer is almost transparent and emission originates mainly from the SL system ($e_{\text{SLG},\text{'obs'}}^{\text{H},45^\circ} \approx e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ for $SM \leq 0.16 \text{ m}^3 \cdot \text{m}^{-3}$). This transparency of dry grass is similar to the behavior of a dry litter layer found in [14]; therefore, under dry conditions, the overall forest floor emission will, in fact, mainly originate in the soil layer.

For $SM \approx 0.21 - 0.26 \text{ m}^3 \cdot \text{m}^{-3}$, multiple emissivity values $e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ can sometimes be seen, which result from periods with differing litter moisture LM at the same SM . For a given value of SM , emissivity becomes lower for increasing LM .

Finally, Fig. 7 includes the simulated $e_{\text{S},\text{sim}}^{\text{H},45^\circ}$ for a smooth S of the Bray type in order to provide a reference against which to view the other three emissivities. It can be seen when comparing the gradients of $e_{\text{S},\text{sim}}^{\text{H},45^\circ}$ and $e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ that the addition of a litter layer does not change the sensitivity to soil moisture but merely increases emissivity values. This suggests that the effective roughness H_R [26] of the SL configuration does not change with changing soil moisture. A previous study [27] over grass covers found that the relationship $H_R(SM)$ became less pronounced with increased litter cover, and was nonexistent in the case of a sandy soil, both of which conditions apply to the Bray site. However, the physical behavior of the “effective” soil roughness parameter is not yet understood well enough to conclude whether this is a general or a site-specific result.

F. Thermal Sampling Depth

The thermal sampling depth of a medium is defined as the depth δ_T above which $\sim 63\%(1 - e^{-1})$ of the upwelling thermal radiation originates [17]. Consequently, δ_T is determined by both the real and imaginary parts of the dielectric constant [28]. In this paper, δ_T (measured from the top of the litter layer) was obtained from simulations performed for the SL configuration using the Wilheit model (Section IV-E). These simulations were run for the soil and litter moisture contents measured during the above-canopy experiment, and for three different litter layer thicknesses D_L , in order to give an insight into the relative contribution of each layer to the total emission in the case of an SL system.

In the results, the litter layer thickness D_L was subtracted from the thermal sampling depth ($\delta_T - D_L$), i.e., the thermal sampling depth was defined relative to the LS interface. The advantage of this approach is the fact that it gives the depth *within the soil layer* at which 63% of the total upwelling emission originates, as a function of D_L .

Fig. 8. (Top) and (bottom): Values of $\delta_T - D_L$ (average of H and V polarizations) of $e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ emissivities plotted against volumetric soil moisture content SM for three different values of D_L . (a) Arrows indicate values of LM for $SM = 0.25 \text{ m}^3 \cdot \text{m}^{-3}$. (b) Corresponding $e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ plotted against SM for three different litter layer thicknesses D_L .

Values of $\delta_T - D_L$ are plotted against SM in Fig. 8(a) for $\theta = 45^\circ$ and three different values $D_L = 1, 3, 10$ cm. Values of δ_T were almost identical for H and V polarizations; therefore, polarization-averaged values are shown. It should be repeated here that temperature gradients within the SL system were ignored (Section III-C1).

Fig. 8(b) shows the corresponding $e_{\text{SL},\text{sim}}^{\text{H},45^\circ}$ plotted against SM for each value of D_L .

In Fig. 8(a), it can be seen that for a given SM and D_L , various values of $\delta_T - D_L$ are visible between $SM \approx 0.21 - 0.26 \text{ m}^3 \cdot \text{m}^{-3}$, which reflect different conditions of LM as indicated by the arrows in the figure (values of LM given for $SM = 0.25 \text{ m}^3 \cdot \text{m}^{-3}$). This effect of LM , of course, increases with increasing thickness D_L . It can be seen that the thermal sampling depth increases with decreasing LM for a given value of SM .

The depth $\delta_T - D_L$ below the SL interface will, of course, increase with decreasing litter cover; however, the magnitude of this increase depends on the moisture conditions present. In general, low SM conditions were associated with low LM conditions. The fact that the differences between $\delta_T - D_L$ for $D_L = 1$ cm and $D_L = 10$ cm are very small for low SM confirms that the litter layer is rather transparent in dry LM conditions (cf. Fig. 7).

For higher moisture (i.e., SM and LM) conditions, litter layer emission becomes more important, resulting in a changeover in δ_T (observed here at $SM \approx 0.2 \text{ m}^3 \cdot \text{m}^{-3}$) and subsequent decreasing $\delta_T - D_L$ with increasing moisture content for $D_L = 3$ cm and $D_L = 10$ cm. The positive gradients in $\delta_T - D_L$ with increasing SM in certain cases, such as for $D_L = 1$ cm and for $D_L = 3$ cm and $D_L = 10$ cm at $SM < 0.2 \text{ m}^3 \cdot \text{m}^{-3}$, are in accordance with the results of a recent modeling study [14], which predicted that both negative and positive gradients of reflectivity can occur with changing soil moisture. This behavior was explained by coherent effects becoming relevant for particular combinations of litter and soil permittivities, ϵ_L and ϵ_S , present in the ground system. Due to

such coherent effects, even a litter layer much thinner than the wavelength λ (e.g., $D_L = 1$ cm) can affect the ground emission significantly.

This figure [Fig. 8(a)] shows that only when the litter layer is very thick and very wet does the emission originate predominantly in the litter layer, resulting in negative values of $\delta_T - D_L$. In all other cases, the radiometric signal still contains a certain contribution of soil emission.

The patterns in emissivity shown in Fig. 8(b) are similar to those found previously from simulations in [12] and [15] and show the effect of coherence occurring in the presence of a litter layer, as a function of D_L . The unexpected patterns in the case of $D_L = 1$ cm, such as the positive gradient $d(\delta_T - D_L)/dSM$ in Fig. 8(a) and the shallow slope in corresponding $e_{SL, \text{sim}}^{H, 45^\circ}$ in Fig. 8(b), can be explained by the fact that coherent effects can occur even for layer thicknesses much smaller than the observation wavelength (see, e.g., [29]). In field observations, these effects will cancel each other out to a certain degree because of the spatial variation in D_L within a footprint and will therefore not necessarily be visible.

V. SUMMARY AND CONCLUSION

The main objective of this paper was to better understand the L-band emission properties of the different layers of a forest system as a function of varying ground moisture conditions. This paper involved the combined use of two unique data sets and two well-established models (L-MEB and Wilheit).

L-band radiometric observations were made *in situ* below the canopy over three different configurations of a forest floor: 1) an SLG configuration; 2) an SL configuration; and 3) an S configuration. Layers were manually removed between each of the three series of observations. Upward-looking observations were made of the tree canopy in order to derive the radiative transfer properties of the crown vegetation. Above-canopy observations of SLGC emission were available from a long-term data set previously obtained at the same site. The emissivities of S, SL, SLG, and SLGC configurations were related to varying soil moisture contents.

The emissivities of the smooth S and the SL configuration showed a similar sensitivity to variations in soil moisture content. As expected, this sensitivity then decreased with each additional vegetation layer.

Under dry conditions, the grass layer was almost transparent, as is also the case for a dry litter layer. Therefore, in such conditions, the below-canopy emission originates almost entirely in the soil layer. However, under wetter conditions, the L-band sensitivity to soil moisture is substantially suppressed by the presence of a wet grass understory, whether living or senescent. This explains why such low above-canopy sensitivity to ground moisture conditions was found previously over forests, even though the tree canopy was rather transparent.

The thermal sampling depth of the SL forest floor configuration was investigated for a range of soil moisture values. It was found that the thermal sampling depth generally exceeded the thickness of the litter layer, indicating that the radiometric signal still contained a certain contribution of soil emissivity.

Only in the case of a rather thick and wet litter layer was the soil emission almost completely obscured.

Altogether, this paper gives a comprehensive image of the L-band emission of the various forest layers (soil, litter, grass, and tree canopy) with varying ground moisture conditions. This paper is the first on this subject to use undisturbed *in situ* experimental data, and it confirms several results of recent modeling and/or laboratory-based studies. This knowledge can help to improve the analysis of above-canopy forest observations at L-band, an important issue in the context of spaceborne sensors such as SMOS.

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