Modeling Forest Emissivity at L-Band and a Comparison With Multitemporal Measurements

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***Abstract*—This letter describes recent advances in modeling forest emissivity at L-band. The formulation is based on a previously developed discrete model and includes a new representation of forest litter. Comparisons with multitemporal radiometric data collected in the framework of the "Bray 2004" experiment, which was carried out within Les Landes forest, are shown and discussed. Input variables are given by using detailed ground measurements. In general, the model reproduces both absolute values and temporal variations of measured brightness temperature. The contribution of the litter to overall emission was found to be important.**

***Index Terms*—Forests, litter, microwave radiometry, soil moisture.**

I. Introduction

IMPORTANT space projects, such as SMOS [1], are undergoing development, with the purpose of monitoring soil-moisture and land properties by means of spaceborne L-band radiometers. In view of these projects, it is important to estimate the emissivity of various kinds of surface covers, including forests. In fact, forests cover a large fraction of land, so that several pixels will be affected, partially or even totally, by their presence.

Some experimental and theoretical studies, which are aimed at investigating the emission properties of forests, have been done in the recent years, and results are summarized in [2]. However, results are still scarce, particularly at L-band, and include only a limited set of forest covers and radiometric configurations. New efforts are required to estimate the emission due to forest components and the attenuation introduced over soil emission, which are important to fully exploit the potential of future L-band radiometers.

A theoretical model, which is based on the radiative-transfer theory and a discrete approach, was developed at "Tor Vergata" University of Rome [3], [4]. The model was run at several microwave frequencies, but only a few tests were possible at L-band, due to the scarce availability of experimental data. A reasonable agreement between model simulations and emissivity data collected by an L-band airborne radiometer over Les Landes forest was found, and results were illustrated in [5]. However, the test was somewhat limited since measurements covered a single flight. Further efforts are needed to test the model over various soil-moisture conditions. Moreover, the same model needs to be refined in order to include litter effects.

This letter shows some recent advances in forest modeling. First, it describes some refinements applied to the electromagnetic model in order to include litter effects. Then, the results of a new test are presented. Model outputs are compared against multitemporal brightness temperatures collected by an L-band radiometer located over a tower at the Bray site, within Les Landes coniferous forest [6].

Section II summarizes the experimental data set and the electromagnetic model used for standing vegetation and describes the method adopted to represent the emission of soil and litter. Comparisons between the model simulations and the experimental data of "Bray 2004" experiment are shown in Section III.

II. Materials and Methods

A. Experiment

A multitemporal set of brightness temperatures was collected during the "Bray 2004" experiment in Les Landes forest [6]. Measurements were carried out by the EMIRAD radiometer, which is operating at 1.41 GHz and horizontal polarization, between July and December 2004. The radiometer antenna had a full beamwidth of 25° and looked downward from a 40-m tower toward a 34-year-old Maritime Pine forest, with an average tree height of 22 m. Measurements were averaged to half-hourly values for the final data analysis. Details about the EMIRAD radiometer are given in [7].

A thermal IR radiometer (Heitronics KT 15.85D; 9.6–11.5 μm) was fixed next to the microwave instrument to give measurements of canopy temperature over approximately the same footprint. The soil temperature was measured at depths of 1, 2, 4, 8, 16, 64, and 100 cm below the soil surface, using thermocouples made by INRA and a CR21X Campbell Scientific data logger.

During the radiometric measurements, the volumetric soil moisture, at 0–5-cm depth, and the litter moisture were measured with a sampling time of 10 s and averaged to half-hourly values. The volumetric soil moisture varied between about 10% and 30% during the experimental period. Details about moisture measurements are given in [6].

For the litter, a measurement of fresh biomass was also done. The value was equal to about 10 kg/m^2, and the average thickness of the litter layer at this site was about 5 cm.

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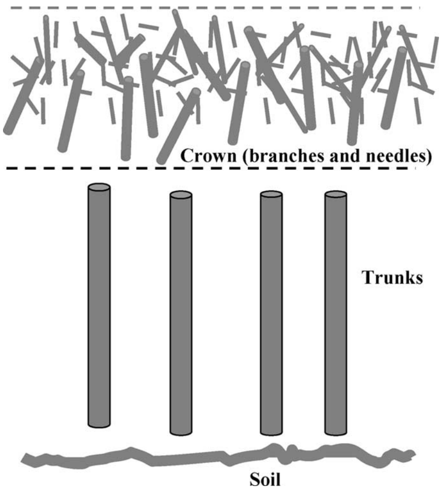

Fig. 1. Sketch of model representation.

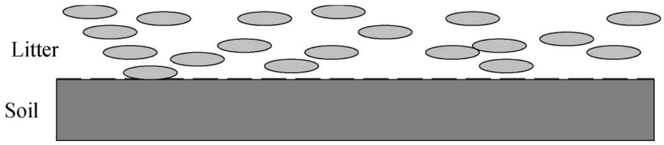

Fig. 2. Sketch of litter model.

Forest geometric parameters have been estimated using the results of previous detailed studies [8]. Further details about the experiment and the ground measurements are given in [6].

B. Electromagnetic Model

1) Standing Vegetation: The emission model is based on the radiative-transfer theory and adopts a discrete approach. Vegetation elements, such as trunk, branch, and needle, are represented by means of cylinders of various dimensions. Extinction cross sections and bistatic-scattering cross sections are computed using suitable electromagnetic theories (i.e., "infinite-length" cylinder or Rayleigh–Gans approximation), depending on cylinder dimensions and wavelength. Contributions of single elements are then combined by using a multiple-scattering algorithm. The same algorithm is used to combine vegetation scattering with soil scattering. Finally, the emissivity of the whole medium is computed by using the energy-conservation law. Details of the procedure are given in [3] and [4] and are not repeated here.

A general sketch of the model is shown in Fig. 1.

2) Soil and Litter: In the previous model version (see, e.g., [3]), the soil was described as a simple homogeneous half-space with a rough interface, and its permittivity was computed using the semiempirical formula given in [9]. In the new version, the model has been refined in order to include the litter effects. The procedure may be subdivided into various steps.

At first, the soil is assumed to have a flat interface and to be overlaid by a dielectric layer, representing the litter. In this first stage, the layer interfaces are also assumed to be flat. The layer is a mixture of air and dielectric material (Fig. 2), representing dry needles or other kinds of litter fall. The fresh biomass of the dielectric material D_F (kilograms per square meter) may be roughly estimated by using the litter-fall data available in the literature (see, e.g., [10]). During the Bray 2004 experiment, a direct measurement of the fresh biomass and the thickness was done, as stated in Section II-A.

The gravimetric moisture of the dielectric material DMC (in kilograms per kilogram) is related to the volumetric soil moisture SMC (in cubic meters per cubic meter) by an empirical linear relationship based on ground measurements [6]. Measurements were made during the same Bray 2004 experiment, by taking half-hourly averages of soil and litter moistures from July to December 2004. During the measurements, the SMC ranged from about 10% to 35%, while the DMC ranged from about 10% to 90% [6]. The simple formula is

$$\begin{aligned} &\text{DMC} = \text{SMC} \quad \text{for } 0 \leq \text{SMC} < 0.1 \\ &\text{DMC} = 3.0971^{*}\text{SMC} - 0.1817 \quad \text{for } 0.1 \leq \text{SMC} \leq 0.35 \\ &\text{DMC} = 0.90 \quad \text{for SMC} > 0.35. \end{aligned} \tag{1}$$

The correlation coefficient for this relationship, over the whole ranges of SMC and DMC, is $R^2 = 0.84$.

The permittivity of the dielectric material is computed as a function of the moisture, using the same empirical formula adopted for vegetation [11].

The volume fraction of the dielectric material may be computed as a function of its weight and moisture and of the litter-layer thickness, as indicated next.

The dry biomass of the dielectric material is given by

$$D_D = D_F(1 - \text{DMC}). \tag{2}$$

The volume of the dry part of the dielectric material per unit area (in cubic meters per square meter) is given by

$$\text{VD}_s = D_D/\rho_s \tag{3}$$

where ρ_s is the density of dry matter (0.3 g/cm^3).

The volume of the wet part of the dielectric material per unit area (in cubic meters per square meter) is given by

$$\text{VD}_w = (D_F - D_D)/\rho_w \tag{4}$$

where ρ_w is the density of water (1 g/cm^3).

The volume fraction of the dielectric material within the litter layer is

$$V_F = (\text{VD}_w + \text{VD}_s)/T_L \tag{5}$$

where T_L is the litter thickness.

For the case of the Bray site, since a litter fresh biomass of 10 kg/m^2 was measured with an SMC of about 0.25, the corresponding litter dry biomass is 4.07 kg/m^2. The volume fraction of the dielectric material within the layer is spread into the interval [0.64–0.30], for litter-moisture values corresponding to a range of volumetric soil-moisture values of [0.05–0.30].

At this point, the permittivity of the layer mixture is computed by means of the quadratic "refractive model" for mixtures given in [9]. For soil permittivity, the dielectric model proposed in [12] is used.

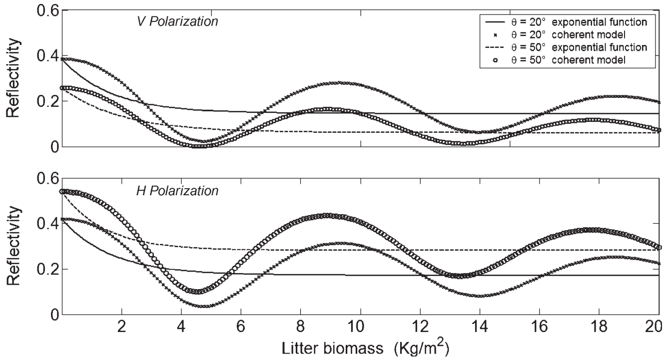

Fig. 3. Simulated reflectivity of soil/litter as a function of litter biomass. Volumetric soil moisture = 20%. (Top) Vertical polarization. (Bottom) Horizontal polarization.

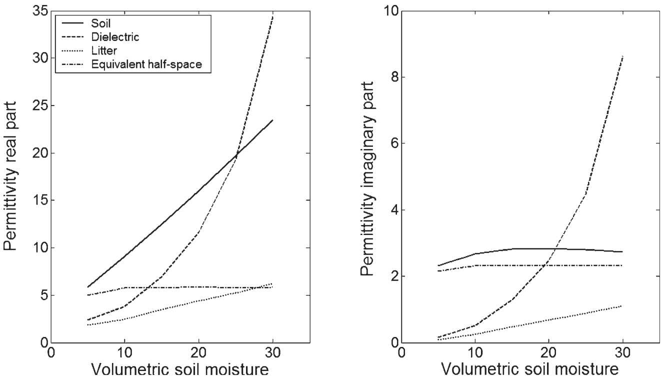

Fig. 4. (Left) Real and (right) imaginary parts of the dielectric constants as a function of the soil moisture. Litter dry biomass: 1.3 kg/m^2. Continuous line: soil ($\varepsilon_{\mathrm{rs}}$). Dashed line: Dielectric material ($\varepsilon_{\mathrm{rd}}$). Dotted line: Litter mixture ($\varepsilon_{\mathrm{rl}}$). Dash-dotted line: Equivalent half-space ($\varepsilon_{\mathrm{re}}$).

TABLE I
MAIN PROPERTIES OF FOREST SITE

	Unit	**32 years site**
Branch volume	(m^3/Ha)	Upper level: 9.13
		Lower level: 18.22
Branch permittivity		22.9 - j 5.4
Needle volume	(m^3/Ha)	59.45
Needle permittivity		18.3 – j 4.2
Trunk volume	(m^3/Ha)	160.21
Trunk height	(m)	18.1
Trunk diameter	(cm)	17.5
Trunk permittivity		17.1 – j 3.3
Trunk density	(#/Ha)	368

The previously described procedure allows us to evaluate the dielectric and geometrical parameters of a composite medium consisting of a dielectric half-space with a flat interface overlaid by a dielectric layer of given permittivity and thickness. At this point, the overall reflectivity of this composite medium is computed, at all required angles and both horizontal (H) and vertical (V) polarizations, using the coherent multiple-reflection model described in [13]. This coherent model predicts a trend of reflectivity as a function of the layer thickness, which is characterized by enhanced oscillations, due to coherent interactions among multiple reflected waves. In reality, this process is smoothed by the natural variations of the layer thickness around its average value. In order to account for this, the trend of reflectivity versus the layer thickness is modified, in such a way as to eliminate the oscillations and keep the asymptotic values. To this aim, the parameters of an exponential function, giving the minimum rms difference with coherent model outputs, are estimated.

In order to illustrate the procedure, we have considered the case of a flat soil with a volumetric moisture SMC equal to 20% overlaid by a litter layer of various values of biomass D_F and thickness T_L. We have assumed a ratio between T_L and D_F equal to 0.5 cm/(kg/m^2), which fits the Bray measurements. Based on (1), the moisture of the litter dielectric material is equal to 0.46. We have considered two angles (20° and 50°). Fig. 3 shows the reflectivity as a function of the litter biomass computed after the two steps of the procedure: 1) as a result of the coherent multiple-reflection model and 2) after averaging to account for the natural variations of the layer thickness.

In the next step, an equivalent homogeneous half-space is considered, and its permittivity is computed by minimizing a "cost function" proportional to the rms difference between the set of reflectivity values computed for the composite medium and the one computed for this homogeneous "equivalent" medium. The latter set is generated by applying the well-established Fresnel formulas for flat half-spaces and considering all angles in the range from 0° to 60°, with a 10° step, and both polarizations. Thus, the whole soil–litter medium is reduced to a unique homogeneous half-space of given permittivity.

As an example, we have considered a soil overlaid by a litter layer with a dry biomass of 1.3 kg/m^2. First of all, we have estimated the rms error in reflectivity due the previously described reduction to a unique half-space. The error varies with the soil moisture and the angle. When the soil moisture is low (i.e., 5%) or higher than 20%, the error is lower than 0.01 at an angle of 15° and lower than 0.02 at an angle of 45°. The worst situation is for the SMC in the range between 10% and 20%. In this range, the differences may be high, up to 0.035, for angles higher than 45°. However, it must be considered that this error is for the reflectivity of a bare and flat surface. Surface roughness and forest cover reduce its effect in the computation of the overall reflectivity (and, hence, emissivity) to values lower than 0.01, even in the worst cases. Then, we have computed the real and imaginary part of the dielectric constants obtained in the various steps, as a function of the soil moisture: soil ($\varepsilon_{\mathrm{rs}}$), dielectric material ($\varepsilon_{\mathrm{rd}}$), litter mixture (i.e., dielectric material + air) ($\varepsilon_{\mathrm{rl}}$), and equivalent half-space ($\varepsilon_{\mathrm{re}}$). It is intended that the moisture of the dielectric material is related to the soil moisture by (1). Results are shown in Fig. 4 for both real and imaginary parts. Due to the relatively low values of the litter volume fraction, $\varepsilon_{\mathrm{rl}}$ is appreciably lower than $\varepsilon_{\mathrm{rs}}$, in the whole range of the soil-moisture values. The litter behaves similarly to a matching layer, which reduces the dielectric discontinuity between the air and the soil. As a consequence, the permittivity of the equivalent half-space $\varepsilon_{\mathrm{re}}$ is lower than the soil permittivity, and also its variations, with respect to the moisture, are moderate. Permittivity differences between

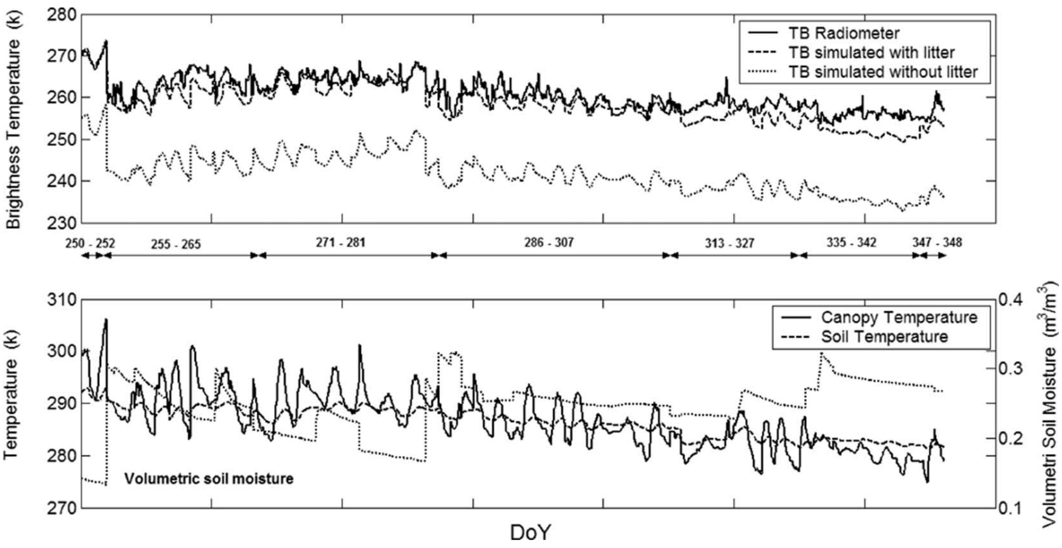

Fig. 5. Multitemporal trends versus day of the year at Bray site. (Top) Brightness temperature (measured, simulated including litter, and simulated without litter) at 45°, H polarization. (Bottom) Soil moisture, soil temperature, and canopy temperature.

the soil and the equivalent half-space are mostly evident in the real part, which is also the part that most influences the overall reflectivity and, thus, the numerical algorithm.

Finally, the roughness at the interface between the air and the previously defined homogeneous half-space is introduced and described by well-established parameters, such as height standard deviation and correlation length. The bistatic-scattering coefficient is computed by means of the integral-equation method [14] and is used to combine the soil scattering with the vegetation scattering.

III. COMPARISON BETWEEN SIMULATIONS AND EXPERIMENTAL DATA

In order to simulate the brightness temperatures measured over the Bray site by the EMIRAD radiometer, the model was run by using as input the forest variables previously estimated for Les Landes stands with an age as close as possible to the age of Bray stand. In particular, we considered the data published in [8] for the Berganton site, which was 32 years old. Corresponding values of geometrical and physical parameters used as input were given after subdividing the forest crown into two levels. The most significant variables are summarized in Table I. Permittivity values were obtained with moisture values equal to 60% for needles and branches, 50% for trunks, dry-matter density values equal to 0.3 g/cm^3 for needles, and 0.4 g/cm^3 for branches and trunks.

For soil and litter variables, the values measured on site and given in Section II-A were adopted. The litter moisture was derived by the empirical formula (1).

The model computes the single-component emissivity due to soil, canopy, and canopy–soil multiple interactions. In order to evaluate the emitted brightness temperature, the simulated soil emissivity was multiplied by the soil temperature, while the other components were multiplied by the canopy temperature, according to standard models (see, e.g., [15]). The three terms were finally added to each other. The canopy temperature was assumed to be equal to the measured infrared temperature, while the soil temperature was derived by direct measurements at 1-cm depth. Comparisons were done at a 45° angle and horizontal polarization.

Results are shown in Fig. 5. Four time intervals with almost continuous measurements have been considered. Days of the year are as follows: 250–252, 257–265, 271–281, 286–307, 313–327, 335–342, and 347–348. The trends of brightness temperature measured by the radiometer and simulated by the model are shown in the upper plots. In addition, the trend obtained by neglecting the litter is reported for comparison. The lower plot shows the trends of the canopy temperature, soil temperature, and soil moisture.

It may be observed that the measured brightness temperature shows daily variations, mostly related to the variations of the canopy and the surface temperature, and long-term variations, related to the seasonal effect of temperature decrease and soil-moisture increase. The model reproduces well both the absolute values of the brightness temperature and its variations, although with a slight underestimation in the last days. If litter is not considered $(T_L = 0)$, an evident underestimation is observed. Litter removal does not influence the sensitivity of simulated T_B to the variations of the canopy and soil temperature but produces a slight increase in the sensitivity to the variations of SMC (e.g., by about 2 K for the SMC variation between day 252 and day 257).

The overall standard error between the measured and the simulated brightness temperatures is equal to 2.56 K and would increase up to 17.98 K if litter was not included in the model.

IV. CONCLUDING REMARKS

A discrete radiative-transfer model, which is developed to simulate microwave emission from forests, was refined to include litter effects. The model was tested with multitemporal L-band measurements carried out in the framework of "Bray 2004" campaign. The forest was coniferous (Maritime Pine), and the forest floor was characterized by a thick litter layer. The model reproduces both the absolute values and the temporal variations of the measured brightness temperature. The overall rms error is equal to 2.56 K. The presence of the litter produces an appreciable increase of the overall emissivity. Future ground and remote measurements will allow us to test the model more extensively and eventually apply refinements.

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