Polarimetric Emissivity of Vegetation-Covered Soils: Simulation Results

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Abstract: Soil moisture can be determined by L-band radiometry. Because of the long electromagnetic wavelength -21 cm- surface roughness effects are small. In principle, vegetation effects are also small, but they cannot be neglected if the observation angle is large and/or the vegetation cover is thick or dense. In addition, coherent effects may appear because the distance between scatterers becomes comparable to the electromagnetic wavelength. In this paper we investigate the effect on the four Stokes elements (T_v, T_h, U and V) of a vegetation cover consisting of individual trunks over a tilted rough surface. Simulated results show the known trends for T_v and T_h: higher brightness temperatures for dry soils than for moist soils, and lower difference T_v - T_h for vegetation covered soils than for bare soils. The third and fourth Stokes parameters (U, V) show a more erratic behavior highly dependent on the vegetation geometry (orientation of scatterers), increasing at large observation angles and with peak amplitudes of a fraction of a Kelvin.

I. INTRODUCTION

Several models describing vegetated surfaces from the electromagnetic point of view have appeared: uniform layer, continuous medium and discrete medium characterized by scatterers [1]. It has been shown [2] that the backscattering from a typical forest canopy at low microwave frequencies and/or when the crown layer is tenuous is dominated by the ground trunk interaction. Therefore, a simplified and accurate model should only include the tree trunks and the ground.

Individual trunks are modeled by a set of randomly oriented finite-length, stratified cylinders with an external corrugated bark layer that are randomly distributed over an elliptic illuminated area (circular at nadir), whose lengths follow a Gaussian distribution. Ground is modeled by a dielectric half space underneath the cylinders, with a slightly rough Gaussian surface, characterized by its rms height and correlation length, and an arbitrary tilt.

Multiple scattering from cylinders overlaying a dielectric half space is highly dominated by the first-order solution (coherent sum of scattered fields by each cylinder). The interaction among cylinders producing higher order solutions is only of significance when they are very close.

Finally, the emissivity of the Stokes vector (e_v, e_h, e_U, and e_V) is evaluated from the scattering coefficients computed considering the summation of all the scattered fields from the trunk-ground sets to the incident field.

II. DESCRIPTION OF THE METHOD

The characterization of an individual trunk-ground set is performed by means of the scattering matrix S that relates the incident and scattered fields [3]. All fields are decomposed into vertical and horizontal polarization by employing the forward scattering alignment convention (FSA) (Fig. 1).

The scattering matrix S relates the incident and scattered fields in the following way

\[ \begin{bmatrix} E'_v \\ E'_h \end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E''_v \\ E''_h \end{bmatrix}. \]  

(1)

The scattering produced by a cylinder can be computed with several models, such as physical optics and harmonic expansions (semi-exact solution) [3]. Assuming that the cylinder and the ground plane are in the far-field region, the effect of the ground plane interface is taken into account by including only the mirror image contributions. Thus, the trunk-ground response can be decomposed into four main contributions: direct scattering from the trunk S_t, scattering from the trunk reflected later from the ground S_gt, scattering from the ground reflected later from the trunk S tg, and scattering with ground-trunk-ground path S NTN (Fig.2).

Hence:

\[ S = S_t + S_{gt} + S_{tg} + S_{NTN}. \]  

(2)
The multiple scattering problem consists of \( N \) trunks. Once all scattering matrices \( S_l \) corresponding to each trunk-ground set have been computed, the first order solution is given by
\[
\begin{bmatrix}
    E_l' \\
    E_n' \\
    E_m' \\
    E_s'
\end{bmatrix} =
\begin{bmatrix}
    \mathbf{v}_l \\
    \mathbf{v}_n \\
    \mathbf{v}_m \\
    \mathbf{v}_s
\end{bmatrix}
\begin{bmatrix}
    S^l_l \\
    S^l_n \\
    S^l_m \\
    S^l_s
\end{bmatrix}
\begin{bmatrix}
    \mathbf{r}_l \\
    \mathbf{r}_n \\
    \mathbf{r}_m \\
    \mathbf{r}_s
\end{bmatrix} e^{j \mathbf{k} \cdot \mathbf{r}'} e^{j \alpha_i \cdot r'}
\]
\( i = 1, 2, 3 \).

From (3) polarimetric bistatic scattering coefficients \( \gamma_{pq} \) are computed. \( \gamma_{pq} \) represents the cross-correlation of the scattered waves at \( m \) and \( p \) polarizations due to incident waves at \( n \) and \( q \) polarizations respectively. Then, the Stokes emission vector can be computed straightforwardly [5]:
\[
e_{\theta, \phi} = \frac{1}{4\pi \cos(\theta)} \int_{0}^{\pi} \cos(\theta) \left( (\gamma_{1111} + \gamma_{1111}) d\Omega, \right.
\]
\[
e_{\theta, \phi} = \frac{1}{4\pi \cos(\phi)} \int_{0}^{\pi} \cos(\phi) \left( \Re m (\gamma_{1111} + \gamma_{1111}) d\Omega. \right.
\]

It should be pointed out that in (4) the forward scattering contribution is dominant. Results computed using the physical optics solution are not different from those computed using the semi-exact solution.

The model for the ground surface alone is similar, but in (4) the polarimetric bistatic coefficients are computed for a Gaussian surface characterized by its rms height and correlation length (\( \sigma_{Z\text{rms}} = 2\sigma_{Z\text{angle}} f_{\text{corr}} \)).

Vegetation attenuation is computed from the scattered fields in the forward direction [6, eqn. 22]. At nadir, since tree trunks offer a negligible section, the computed attenuation is one and increases at larger incidence angles.

### III. Simulation Results

Table I summarizes the simulation parameters used in this study. Only the trunk density and the soil moisture content have been modified. Ground rms height is set to 0.5 cm, and results are very similar to a flat ground.

Fig. 3 shows two random realizations of the trunks over the surface, corresponding to 0.25\% and 0.5 \% density. Fig. 4 shows the corresponding gain (equal to minus attenuation) due to the vegetation cover versus the observation angle. The attenuation increases proportionally to the trunk density, and counteracts the extra scattering resulting in a net increase of the emissivity.

Fig. 5 shows the emissivity at vertical and horizontal polarizations for trunk densities 0.25\% and 0.5 \% and soil moisture 0 and 0.25. As it is known, the higher the soil moisture, the lower the emissivity, and vice-versa. For higher trunk densities, the effect of vegetation scattering (dotted line) is more pronounced (dotted lines are more separated from the dashed ones), as expected. In general, the increased vegetation attenuation is responsible of a higher emissivity for higher than for lower densities. This effect is more pronounced if the attenuation presents higher values than those plotted in Fig. 4.

The behavior of the emissivities for the third and fourth Stokes parameters is quite erratic, and the peak amplitudes for \( d=0.25\% \) and 0.5 \% are similar. Fig. 6 shows a representative result at \( W=0.25 \) and 0.25 \%. It should be pointed out that for the simulation parameters in Table I, ground contribution is negligible and all the contributions are coming from the vegetation scattering.

### TABLE I: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.4 GHz</td>
</tr>
<tr>
<td>Antenna footprint</td>
<td>40 m x 40 m</td>
</tr>
<tr>
<td>Trunks: Density</td>
<td>0.25 – 0.5 %</td>
</tr>
<tr>
<td>Height</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Inner layer: radius</td>
<td>13 cm</td>
</tr>
<tr>
<td>( \varepsilon_1 )</td>
<td>4 – j 1</td>
</tr>
<tr>
<td>Outer layer: radius</td>
<td>15 cm</td>
</tr>
<tr>
<td>( \varepsilon_2 )</td>
<td>20 – j 3</td>
</tr>
<tr>
<td>Corrugation: period dL</td>
<td>0.7</td>
</tr>
<tr>
<td>Depth</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>Ground: Local slope</td>
<td>0°</td>
</tr>
<tr>
<td>Water content: W</td>
<td>0 – 0.25</td>
</tr>
<tr>
<td>RMS height</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Correlation length</td>
<td>7 cm</td>
</tr>
</tbody>
</table>

### IV. Experimental Results

The experiment consisted of pointing a small pine tree with an X-band polarimetric radiometer so that it occupies most of the antenna beam (\( ~ 20° \)) (Fig. 7a). The radiometer was pointed at 80° incidence angle and the pine tree was rotated in 10° steps and the first three Stokes parameters (\( T_v, T_h \) and \( U \)) were recorded. Since pine leaves were approximately half wavelength (\( ~ 1.5 \) cm) and were randomly oriented we expected a non-negligible \( U \).
From Fig. 7 $T_v$ and $T_h$ have a very similar average value, with random fluctuations due to the different orientation of the pine leaves. The behavior of $U$ is also fluctuating, but since the density of randomly distributed and oriented scatterers (pine leaves) is very high, its amplitude is also much higher than what would be expected from Fig. 6, about $300 \ K \cdot 1.5 \times 10^{-3} \sim 0.45 \ K$.

**CONCLUSIONS**

In this paper a model to compute the emissivity of a set of tree trunks randomly distributed and oriented over the ground is presented. The model, although in its present stage too simple to model a realistic forest, correctly predicts the trends of $T_v$ and $T_h$, with regard to soil moisture content and vegetation density. It also predicts a very small third Stokes parameter, less than half a Kelvin. However, this value may increase significantly if trunks are allowed to have random orientation -which increases significantly the computation time- and when branches and leaves be incorporated to the model. Values of $U$ about 2 K have been measured with a simple experiment at X-band with a rotating pine tree.

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**REFERENCES**


