Effective tree scattering and opacity at L-band☆

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A B S T R A C T

This paper investigates vegetation effects at L-band by using a first-order radiative transfer (RT) model and truck-based microwave measurements over natural conifer stands to assess the applicability of the \( \tau - \omega \) (tau-omega) model over trees. The tau-omega model is a zero-order RT solution that accounts for vegetation effects with two vegetation parameters (vegetation opacity and single-scattering albedo), which represent the canopy as a whole. This approach inherently ignores multiple-scattering effects and, therefore, has a limited validity depending on the level of scattering within the canopy. The fact that the scattering from large forest components such as branches and trunks is significant at L-band requires that zero-order vegetation parameters be evaluated (compared) along with their theoretical definitions to provide a better understanding of these parameters in the retrieval algorithms as applied to trees. This paper compares the effective vegetation opacities, computed from multi-angular pine tree brightness temperature data, against the results of two independent approaches that provide theoretical and measured optical depths. These two techniques are based on forward scattering theory and radar corner reflector measurements, respectively. The results indicate that the effective vegetation opacity values are smaller than but of similar magnitude to both radar and theoretical estimates. The effective opacity of the zero-order model is thus set equal to the theoretical opacity and an explicit expression for the effective albedo is then obtained from the zero- and first-order RT model comparison. The resultant albedo is found to have a similar magnitude as the effective albedo value obtained from brightness temperature measurements. However, both are less than half of the single-scattering albedo estimated using the theoretical calculations (0.5–0.6 for tree canopies at L-band). This lower observed effective albedo balances the scattering darkening effect of the large theoretical single-scattering albedo with a first-order multiple-scattering contribution. The retrieved effective albedo is different from theoretical definitions and not the albedo of single forest elements anymore, but it becomes a global parameter, which depends on all the processes taking place within the canopy, including multiple-scattering and canopy ground interaction.

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1. Introduction

Soil moisture (SM) state is a key variable of the terrestrial water cycle. Global SM observations are of value in applications involving land–atmosphere interaction studies such as climate prediction, weather forecasting, water management, agricultural productivity estimation, and flood and drought hazards monitoring (Entekhabi et al., 1999). Microwave radiometry at low frequencies, such as L-band (1–2 GHz), has a great potential to sense to surface SM even if the soil is covered with vegetation. Several microwave space missions, such as ESA’s Soil Moisture Ocean Salinity (SMOS) mission and NASA’s Soil Moisture Active Passive (SMAP) mission (to be launched 2014), include an L-band radiometer and aim to provide the global measurements of the Earth’s surface SM with an accuracy of 0.04 cm³/cm³ for those areas of the Earth’s land surface where vegetation water content (VWC) does not exceed 5 kg/m² (Entekhabi et al., 2010; Kerr et al., 2010).

For routine SM retrievals over vegetated terrain, the spaceborne baseline algorithms use the tau-omega model (Mo et al., 1982), a zero-order Radiative Transfer (RT) solution, due to its simplicity, and ease of inversion and implementation (Jackson, 1993; NJoku et al., 2003; Owe et al., 2001; Wigneron et al., 2007). This model links terrain geophysical variables to the observed brightness temperature through ground reflectivity and two vegetation parameters, the
optical depth or opacity $\tau$, and the single-scattering albedo $\omega$. It has extensive heritage and has been effectively used in SM field campaigns (Jackson, 1993; Jackson et al., 1999; Wigneron et al., 1995) that cover grasslands, agricultural crops, and generally light to moderate vegetation. Forested areas have commonly been excluded from operational SM retrieval plans. There is some experimental and modeling evidence that microwave radiometry could be able to resolve the changes in SM state for some moderately dense forest types (Della Vecchia et al., 2006; Kurum et al., 2011; Lang et al., 2001; Santi et al., 2009). However, when the canopy gets denser, and/or the litter and understory layers get thicker, sensitivity to SM is degraded significantly (Della Vecchia et al. 2007; Grant et al., 2007, 2009; Guglielmetti et al., 2008; Kurum et al., in press). Knowledge of vegetation features at L-band appears to be of great importance for either correcting for the vegetation effects on SM retrievals or determining vegetation wet biomass itself. This paper is concerned with vegetation parameterization of the tau–omega model when applied over trees.

The tau–omega model loses its validity when there is dense vegetation (i.e. forest, mature corn, etc.) with scatterers, such as branches and trunks (or stalks in the case of corn), which are large with respect to the wavelength. More scattering terms (at least up to a first-order at L-band) should be included in the RT solutions for forest canopies if these are expected to be accurate. A recent study by Kurum et al., 2011, proposed an additional first-order multiple-scattering term to the tau–omega model to correct for large tree scattering. This additional term represents emission by particles in the vegetation layer and emission by the ground that is scattered once by particles in the layer. The resulting model represents an improvement over the standard zero-order solution since it accounts for the scattered vegetation and ground radiation that can have a pronounced effect on the observed emissivity and subsequent SM retrieval. On the other hand, a zero-order approach might be still applied to vegetation canopies with large scatterers, using equivalent or effective vegetation parameters (Ferrazolli et al., 2002). This approach requires that the retrieved vegetation values (vegetation opacity and single-scattering albedo) be evaluated (compared) with theoretical definitions of these parameters for forest canopies. The purpose of this paper is to assess the applicability of the tau–omega model for tree canopies recognizing that there is increased scatter from trees as compared to grasses and crops, and to determine the effective values for tau and omega for trees and how these parameters are related to their theoretical definitions.

Only a limited number of theoretical and experimental studies have addressed the topic of effective tree parameterization (Ferrazolli et al., 2002; Grant et al., 2008; Guglielmetti et al., 2007, 2008; Saleh et al., 2002; Santi et al., 2009). Moreover, effective and theoretical values of vegetation parameters that are found in the literature are often limited to agricultural crop data. These values are not consistent with each other, and difficult to compare due to the variety of methods and procedures employed (Van de Griend and Wigneron, 2004). As a result, there is a need to establish a direct physical link between the effective vegetation parameterization and the theoretical description of absorption and scattering within the canopy. This paper uses a first-order RT model and truck-based microwave measurements over natural conifer stands to investigate this relationship by performing a physical analysis of the scattered and emitted radiation from vegetated terrain. The microwave data used in this investigation were collected over natural conifer stands located in Maryland in 2008 and 2009 (Kurum et al., in press). Physical measurements of the canopy and soil conditions were also made.

Vegetation opacity of coniferous trees was obtained using three independent approaches that provide effective, measured, and theoretical estimates. Results indicate that the effective optical depth values are smaller than but of similar magnitude to both the theoretical and measured values. The effective vegetation opacity was then set equal to the theoretical opacity in the zero-order model, and an explicit expression for the effective albedo was obtained using the first-order model. The resultant albedo was found to be comparable to the effective albedo determined as a best-fit parameter that minimizes the difference between the microwave observation and that value computed from the tau–omega model. The effective omega values were less than half of the theoretical single-scattering albedos [0.5–0.6 for tree canopies at L-band] (Ferrazolli et al., 2002; Kurum et al., 2011). This effective albedo implicitly accounts for multiple-scattering effects by balancing the scattering darkening of single-scattering albedo with the first-order scattering contribution.

2. Material and method

2.1. Basic radiative transfer modeling of vegetation

The commonly used approach to simulating the brightness temperature of vegetated terrain is to apply Radiative Transfer (RT) theory. The RT approach is a heuristic method based on the law of energy conservation that starts with the RT equation, which governs the transport of specific intensity through a random medium (Chandrasekhar, 1960). The theory assumes independent scattering and ignores coherent effects. The RT equation can be formulated for a continuous medium (Fung, 1982; Ishimaru, 1978; Wigneron et al., 1993) or a discrete medium (Chauhan et al., 1994; Ferrazzoli and Guerriero, 1996; Karam, 1997; Kurum et al., 2011; Saatchi et al., 1994; Tsang et al., 1985). The discrete modeling is more appropriate for a medium such as vegetation in which the individual scatterers have discrete configurations and have a dielectric constant that is distinct from the background (air). In the discrete approach, the vegetation layer is represented as an ensemble of scatterers. The scatterers are described by specified orientation, size, and position statistics. The layer is situated over a homogenous dielectric half-space representing the ground. The interface between the ground and canopy can be assumed to be rough. The different types of scatterers are usually assumed to be uniformly located within the vegetation layer, and to have canonical shapes. Leaves are modeled as dielectric disks (Le Vine et al., 1983, 1985). Branches and trunks are modeled as finite length dielectric cylinders of commensurate dimensions (Karam et al., 1988; Seker and Schneider, 1988). The single-scattering characteristics of these constituents, when averaged, determine the attenuation and scattering properties of the canopy. The advantage of the discrete approach is that the results are expressed in terms of quantities (plant geometry and orientation statistics) that are related to the biophysical properties of individual plants.

RT theory can treat single and multiple-scattering in a medium consisting of random discrete scatterers. There are a number of approaches that can be used to calculate the multiple-scattering. This includes combining scattering contributions through exact numerical solutions (Tsang et al., 1985), a matrix doubling algorithm (Ferrazolli and Guerriero, 1996), and iterative methods (Karam, 1997; Kurum et al., 2011; Tsang et al., 1985). An RT-based model in conjunction with the matrix-doubling algorithm was implemented by Ferrazolli and Guerriero, 1996, and validated with various vegetation canopy data including forest. This model considers the multiple-scattering effects associated with the volume scattering and the interactions between multiple-layers in the vegetation canopy and the underlying ground surface. Karam, 1997, modeled the vegetation as a multi-layer random medium above a rough surface. This multi-layer model is based on an iterative solution of the RT equations using single-scattering albedo as a perturbation (small) parameter. The model was validated with experimental data acquired over corn and soybean crops and also used to simulate emission from a walnut canopy. Alternatively, Peake’s emissivity formula (Peake, 1959) in conjunction with a single-scattering approximation (Lang, 1981), which is called distorted Born approximation, was implemented by Saatchi.
et al., 1994, and Chauhan et al., 1994 for a variety of land covers including grass and corn. Later, the same model was used to simulate emission from a forest canopy (Lang et al., 2001, 2006). Recently, Kurum et al., 2011, developed a new microwave radiometry model that considers first-order scattering at L-band. The model was first validated against experimental data acquired over deciduous trees. It was then adapted to conifer trees which included a new representation of the forest floor (Kurum et al., in press). The model is based on an iterative solution of the RT equations by implementing the method of successive orders of scattering (Lenoble, 1985). The approach provides explicit expressions for the zero- and first-order scattering and emission processes that occur within the canopy. The zero- and first-order RT solutions of this approach are summarized below.

2.1.1. Zero-order solution

The zero-order RT solution represents the solution to the non-scattering RT equations, where scattering is largely ignored by setting the scattering source functions to zero (Kurum et al., 2011). This solution is also known as the tau–omega model (Mo et al., 1982). In this approximation, the vegetation canopy is treated as a bulk attenuating layer and scattering effects are introduced by means of a single-scattering albedo. The tau–omega model is given by

\[
\epsilon_p^{(0)}(\theta) = \left[1 - \gamma_p(\theta) R_{ggp}(\theta)\right] - \omega_p(\theta) \left[1 + \gamma_p(\theta) R_{ggp}(\theta)\right] \left[1 - \gamma_p(\theta)\right]
\]

(1.a)

where the ambient soil and vegetation temperatures are assumed approximately equal, the subscript \(p\) denotes vertical or horizontal polarization, i.e., \(p = h\) or \(v\). The first term represents the non-scattering (independent of single-scattering albedo) and is also equivalent to the zero-order solution of the albedo expansion for canopies having uniform physical temperature profiles (Karam, 1997). The second term represents scattering darkening due to albedo. The combination of the first two terms represents the zero-order solution.

In (1.a), the quantity \(\gamma_p(\theta)\) is the vegetation transmissivity, which is parameterized as

\[
\gamma_p(\theta) = e^{-\tau_p \sec \theta}
\]

(1.b)

where \(\tau_p(\theta)\) is the vegetation opacity or optical thickness and is given by

\[
\tau_p(\theta) = \kappa_{sp}(\theta) d
\]

(1.c)

where \(\theta\) is the observation angle from the nadir, \(d\) is thickness of the vegetation layer, and the volume extinction coefficient is defined by (Tsang et al., 1985):

\[
\kappa_{sp}(\theta) = \frac{4\pi}{\kappa_0} \sum \rho_{\alpha} \text{Im} \left\{ f_{fgg}^{(\alpha)} \right\}
\]

(1.d)

where \(f_{fgg}^{(\alpha)}\) is the forward scattering amplitude of the \(\alpha\)-th type of scatterer and each scatterer type \(\alpha\) can be branch, leaf/needle, or trunk. The number density of each scatterer type \(\alpha\) is denoted by \(\rho_{\alpha}\), and \(\kappa_0 = 2\pi/\lambda_0\) is the wave number where \(\lambda_0\) is the free space wavelength. The sum is over all types of particles of which the vegetation is comprised. The angular brackets in this formula denote ensemble average over the angular and size statistics of particles. The tree site considered in this paper (refer to Section 2.2) is composed of natural Virginia pine (Pinus virginiana) trees. The pine needles are represented by average-size circular cylinders; hence, the averaging is done for orientation angles only. The trunks are vertical and for the stand studied here have a typical size. No averaging is therefore performed on trunks. The branch sizes are divided into several groups having an average length and diameter. An average orientation is then determined for each branch group.

An alternative empirical method widely used in the literature in determining the vegetation attenuation (Jackson and O’Neill, 1990; Jackson and Schmugge, 1991) is to relate the nadir optical depth to the vegetation water content (VWC) by

\[
\tau_p(\theta = 0^\circ) = b_p \times \text{VWC}
\]

(1.e)

where \(b_p\) is an empirically determined constant based on vegetation type and polarization. Le Vine and Karam, 1996, have showed that for canopies whose structure (i.e., branches, trunks, etc.) are large compared to wavelength, the linear relation between attenuation and VWC does not hold and the \(b_p\)-parameter becomes a complex function of frequency, VWC, and architecture. In addition, branch water content gets more correlated with optical depth than total VWC does due to the dominance of branch effects in scattering/extinction within the canopy (Ferrazzoli et al., 2002). As a result, the approach given in Eq. (1.e) is more appropriate for agricultural crops at L-band.

In Eq. (1.a), the single-scattering albedo is denoted by \(\omega_p(\theta)\) and is defined by (Tsang et al., 1985):

\[
\omega_p(\theta) = \frac{\kappa_{sp}}{\kappa_{sp} + \kappa_{ap}}
\]

(1.f)

where \(\kappa_{sp}\) is the scattering coefficient of the layer while \(\kappa_{ap}\) represents the total absorption coefficient. This is the albedo of the average scatterer in the canopy since the canopy is composed of more than one scatterer type. It represents the fractional power scattered from the average particle. In the case of a forest canopy, the scattering from large vegetation components such as branches and trunks is significant. The values of the composite albedos for both polarizations are generally in the range of 0.5–0.6 (Ferrazzoli et al., 2002; Kurum et al., 2011). This large albedo of a tree canopy leads to scatter-induced reduction in brightness temperature, and this scattering darkening effect for vegetation canopies (with large scatterers) should be balanced with a multiple-scattering contribution, which is missing in the tau–omega model.

Finally, \(R_{ggp}(\theta)\) is the microwave reflectivity of the forest floor. The ground under the tree canopy being considered here (refer to Section 2.2) was relatively smooth, where the surface rms height was on the order of 0.0–0.5 cm. Thus surface variation is rather low compared to the wavelength at L-band. As a result, only the coherent component of the surface roughness is important, and the diffuse component is ignored. It is also assumed that the rough surface under the forest follows Kirchhoff’s approximation and has a Gaussian height distribution (Choudhury et al., 1979); therefore, the reflectivity of the rough surface is expressed as

\[
R_{ggp}(\theta) = \Gamma_{ggp}(\theta) e^{-h \cos^2 \theta}
\]

(1.g)

where \(\Gamma_{ggp}(\theta)\) is the \(p\)-polarized Fresnel reflectivity of the average dielectric surface and the roughness height parameter is given by \(h = 4\alpha^2 k_0^2\) in terms of surface rms height, \(\alpha\) and the wave number \(k_0\). In addition to roughness, for the study site used here, a moist organic litter layer needs to be considered. A litter layer can alter surface reflectivity significantly as verified by recent theoretical and experimental studies (Della Vecchia et al., 2007; Grant et al., 2007, 2009; Guglielmetti et al., 2008; Kurum et al., in press). In this paper, the ground reflectivity, \(\Gamma_{ggp}(0)\), is calculated using a recently developed three-layer soil model that includes a litter layer, an organic transition layer, and mineral soil (Kurum et al., in press). Ground observations collected approximately coincident with microwave measurements are utilized in this calculation.

2.1.2. First-order solution

The first-order solution of the RT equation with respect to the scattering source function is obtained by using the zero-order RT
brightness temperature as an exciting source (Kurum et al., 2011). This formulation adds a new scattering term to the tau-omega model. The improved model has an advantage over the conventional tau-omega model because the first-order solution accounts for scattering of the radiated emission from the ground and the vegetation layer. The first-order solution from the forest canopy leads to the following expression:

$$
\Theta_p^{(1)}(\theta) = \Theta_p^{(0)}(\theta) + \Omega_p(\theta)
$$

(2.a)

where the ambient temperatures of the vegetation layer and the ground are assumed to be the same, the polarization $p$ can be horizontal ($h$) or vertical ($v$), and the quantity $\Theta_p^{(0)}(\theta)$ is the zero-order solution given in Eq. (1.a). The parameter $\Omega_p(\theta)$ denotes the additional scattering contribution to the zero-order model. It represents the emission from the ground and the vegetation layer that is single-scattered from tree trunks, branches, and needles. The scattering component $\Omega_p(\theta)$ is composed of eight terms representing different scattering-mechanisms, which are given by:

$$
\Omega_p(\theta) = \sum_{j} \left\{ \Omega_p^{(0)}(\theta) + \Omega_p^{(1)}(\theta) \right\}
$$

(2.b)

where the summation index $j \in \{G, U, D, DG\}$ denotes the scattering-mechanism types, i.e., the subscripts $G, U, D, and DG$ refer to the scattered radiation contributions due to ground emission, up-welling emission, down-welling emission, and down-welling emission followed by ground reflection, respectively. The scattered radiation from each mechanism arrives at the receiver either directly (denoted by $s1$) or through reflection from the ground (denoted by $s1r$). The pictorial illustration of the scattering processes and the explicit expressions for each scattering term are given in Kurum et al., 2011.

2.2.2. Experiment

The Virginia pine forest stand under investigation has an average height of 12-m, an average basal area of 34 m$^2$.ha$^{-1}$, and an average diameter at breast height of 12.6-m. Virginia pine is a medium sized evergreen conifer and is native to North America. The bark is thin, dark reddish-brown and is broken into shallow plates. The short needles (4 cm to 8 cm) of Virginia pine range from dark green to gray green to yellow-green and are usually twisted and in pairs. These trees have a tendency to maintain a substructure of needleless branches (dead). The average leaf area index (LAI) was measured 2.66 with a standard deviation of 0.16, which indicates a very homogeneous vegetation canopy. The forest floor has a distinct needle litter layer (undergone little or no decomposition) over an organic humus transition layer (partially and fully decomposed organic materials) lying on a well drained mineral soil. The average thickness of the litter layer was 0.8 cm. The organic humus layer thickness was 2.2 cm. The soils were loamy sand, with textures varying from 57% sand, 13.6% clay to 87% sand, 3.4% clay depending on location within the site. Surface roughness was very small, with an rms roughness height < 0.5 cm. A summary of the site characteristics are given in Table 1.

2.2.4. Ground-truth

Coincident with the microwave measurements, ambient canopy temperatures were obtained at approximately the same look angle
as the microwave instruments using an Apogee\textsuperscript{2} thermal infrared radiometer (8–14 μm) mounted on the ComRAD instrument platform. After the microwave measurements were completed at each incidence angle, Dynamax ML2x\textsuperscript{3} Theta Probes (TOPs) and handheld infrared thermometers were used to obtain volumetric moisture content and surface soil temperature, respectively. Ground measurements were taken at four arbitrary locations within each field of view (generally 20 samples in each plot), and subsequently averaged for each incidence angle. A wide range of ground moisture (the site-calibrated TP readings varied 0.05–0.30 cm\textsuperscript{3} cm\textsuperscript{-3}) under the pine trees was encountered during the entire campaign. Average ambient temperatures and TP readings over plot A are provided in Table 2. More information on the ground and vegetation characteristics can be found in Kurum et al., in press.

### 3. Results and discussion

#### 3.1. Fitting a zero-order model

Rigorous models with many input variables, such as the first-order RT model summarized in Section 2.1.2, require a detailed knowledge of the vegetation and ground characteristics. These complex models are useful for understanding the sensitivity of the microwave sensor response to the forest canopy and underlying ground. On the other hand, simple models that require fewer parameters and \textit{a priori} information, such as the tau–omega model, are necessary as they are to be implemented operationally in relative inversion algorithms for sensors with a limited number of observations. There are a number of approaches that can be used to retrieve SM from low frequency passive microwave observations (Jackson, 1993; Njoku et al., 2003; Owe et al., 2001; Wigneron et al., 2007). Almost all of these are founded on the same zero-order RT solution (tau–omega model) due to its simplicity, ease of inversion and implementation, and its extensive validation over light to moderate vegetation.

Although it is not really suitable for forests, given the increased scatter from trees compared to grasses and crops, Ferrazzoli et al. (2002), proposed that the same zero-order approach might be applied to vegetation canopies with large scatterers, and that equivalent or effective parameters could be used. The basis of this approach lies in exploiting multi-angular and dual-polarization emissivity data in order to simultaneously retrieve geophysical products such as vegetation characteristics. The retrieved vegetation parameters are calibrated by means of a theoretical multiple-scattering model. Recently, this approach was tested using L-band microwave measurements over a coniferous (pine) and deciduous forest Grant et al., 2008.

### Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>NASA GSFC’s Goddard Geophysical and Astronomical Observatory (GGAO) campus in Greenbelt, Maryland, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest type</td>
<td>Natural Virginia pine trees (\textit{Pinus virginiana})</td>
</tr>
<tr>
<td>Tree height</td>
<td>12 m</td>
</tr>
<tr>
<td>Diameters at breast height</td>
<td>Varying 2–34 cm with an average of 12.6 cm</td>
</tr>
<tr>
<td>Basal area</td>
<td>340 m\textsuperscript{2} ha\textsuperscript{-1}</td>
</tr>
<tr>
<td>Woody volume</td>
<td>310.9 m\textsuperscript{2} ha\textsuperscript{-1}</td>
</tr>
<tr>
<td>Bulk densities</td>
<td>1.11 g cm\textsuperscript{-3} (mineral soil), 0.15 g cm\textsuperscript{-3} (organic humus layer), 0.10 g cm\textsuperscript{-3} (surface litter layer)</td>
</tr>
<tr>
<td>Mineral soil</td>
<td>Loamy sand — varying from 57% sand, 14% clay to 87% sand, 3% clay depending on location within the site.</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>RMS roughness height 0.5 cm</td>
</tr>
<tr>
<td>TP Readings range</td>
<td>0.05–0.30 cm\textsuperscript{3} cm\textsuperscript{-3}</td>
</tr>
</tbody>
</table>

#### Table 2

<table>
<thead>
<tr>
<th>Measurement dates</th>
<th>Ambient temperature [°C]</th>
<th>TP readings [cm\textsuperscript{3} cm\textsuperscript{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Aug-08</td>
<td>29.1</td>
<td>0.12</td>
</tr>
<tr>
<td>04-Aug-08</td>
<td>24.1</td>
<td>0.11</td>
</tr>
<tr>
<td>18-Aug-08</td>
<td>21.4</td>
<td>0.07</td>
</tr>
<tr>
<td>16-Aug-08</td>
<td>21.8</td>
<td>0.14</td>
</tr>
<tr>
<td>8-Sep-08</td>
<td>23.3</td>
<td>0.15</td>
</tr>
<tr>
<td>20-Sep-08</td>
<td>3.2</td>
<td>0.17</td>
</tr>
<tr>
<td>8-Apr-09</td>
<td>4.8</td>
<td>0.24</td>
</tr>
<tr>
<td>23-Apr-09</td>
<td>9.6</td>
<td>0.27</td>
</tr>
<tr>
<td>15-Sep-09</td>
<td>19.6</td>
<td>0.14</td>
</tr>
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</table>

The values of the effective vegetation optical depth $\tau_v$ and albedo $\omega_\alpha$ are calculated by minimizing the following merit function:

$$
\min \left[ \sum_{i=1}^{N} \sum_{p=1}^{h} \left[ e_p(\tau_v, \omega_\alpha, \theta_i) - e_{mp}(\theta_i) \right]^2 \right]
$$

where $\tau_v$ and $\omega_\alpha$ act as free parameters and are defined as independent of polarization and angle, $\theta_i$ is the observation angle from the nadir, $N$ is the number of available incidence angles, $e_{mp}$ is the measured $p$-polarized emissivity (the ratio of the measured brightness and the ambient temperatures), and $e_p(0)$ is the modeled $p$-polarized zero-order RT solution given in Eq. (1.a). The subscript $p$ denotes polarization [horizontal (h) or vertical (v)]. In this minimization, it is assumed that surface reflectivities are known $a$ priori. The ground parameters collected approximately coincident with microwave measurements are utilized in conjunction with a three-layer dielectric forest floor model given in Kurum et al., in press.

The minimization procedure is applied to the multi-angular and dual-polarized microwave data collected at the Virginia Pine forest site at different days (from August 1, 2008 to April 23, 2009). Fig. 2 shows the plot of the measured emissivity data (collected on September 8, 2008) over the observation angles from 15° to 55° along with the results of the fitted zero-order tau–omega model. As seen from this example plot, the zero-order fit curve captures the angular and polarization behavior of the data well. The polarization and angular dependence of the best-fit zero-order emissivity stems from the polarization and angle discrimination in the surface reflectivities only since the opacity and albedo values in Eq. (3) were assumed to be independent of both polarization and angle of incidence. Fig. 3 shows the retrieved vegetation opacities and albedo values for each day. The average effective vegetation optical depth for all measurements was 0.91 ± 0.10 and the average effective albedo value was 0.29 ± 0.10.

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**Table 1**

**Experiment site information.**

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<td>1.11 g cm\textsuperscript{-3} (mineral soil), 0.15 g cm\textsuperscript{-3} (organic humus layer), 0.10 g cm\textsuperscript{-3} (surface litter layer)</td>
</tr>
<tr>
<td>Mineral soil</td>
<td>Loamy sand — varying from 57% sand, 14% clay to 87% sand, 3% clay depending on location within the site.</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>RMS roughness height 0.5 cm</td>
</tr>
<tr>
<td>TP Readings range</td>
<td>0.05–0.30 cm\textsuperscript{3} cm\textsuperscript{-3}</td>
</tr>
</tbody>
</table>

---

**Table 2**

**Average ambient temperatures and TP readings over plot A.**

<table>
<thead>
<tr>
<th>Measurement dates</th>
<th>Ambient temperature [°C]</th>
<th>TP readings [cm\textsuperscript{3} cm\textsuperscript{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Aug-08</td>
<td>29.1</td>
<td>0.12</td>
</tr>
<tr>
<td>04-Aug-08</td>
<td>24.1</td>
<td>0.11</td>
</tr>
<tr>
<td>18-Aug-08</td>
<td>21.4</td>
<td>0.07</td>
</tr>
<tr>
<td>16-Aug-08</td>
<td>21.8</td>
<td>0.14</td>
</tr>
<tr>
<td>8-Sep-08</td>
<td>23.3</td>
<td>0.15</td>
</tr>
<tr>
<td>20-Sep-08</td>
<td>3.2</td>
<td>0.17</td>
</tr>
<tr>
<td>8-Apr-09</td>
<td>4.8</td>
<td>0.24</td>
</tr>
<tr>
<td>23-Apr-09</td>
<td>9.6</td>
<td>0.27</td>
</tr>
<tr>
<td>15-Sep-09</td>
<td>19.6</td>
<td>0.14</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Radiometer angular response from Virginia pine forest and the fitted zero-order model for data collected on September 08, 2008.
These results need to be evaluated in the context of their theoretical definitions in order to provide a better understanding of these parameters in the retrieval algorithms over trees. Here, the effective vegetation opacities will be compared against the results of two independent approaches that provide optical depths, theoretical and measured. The theoretical technique is based on the forward scattering theory and the measured on the radar corner reflector observations. Following this analysis, an explicit expression for the effective albedo is then obtained from the zero- and first-order RT model comparison.

3.2. Opacity estimates

3.2.1. Direct measurement using a corner reflector

The forest opacity can be measured directly by means of radar measurements with trihedral corner reflectors. The corner reflectors are widely used for external radar calibration since they yield large backscattering radar cross sections over wide azimuth and elevation angular ranges (Ulaby and Elachi, 1990). This approach is based on the expected strong return from a corner reflector under trees. It assumes that coupling between the corner reflector and the surrounding background and trees is small.

In this paper, amplitude-only response of the radar is considered and the technique involves microwave measurements over an open area and over a canopy from above at several spatial locations. First, backscatter from trihedral corner is characterized by two sets of measurements in an open area; one with the trihedral reflector present on the ground, which is denoted by $\sigma_{\text{flppm2}}^{0}$, and another without the trihedral reflector (background measurement), which is denoted by $\sigma_{\text{ppm1}}^{0}$. The backscatter from trihedral corner only is obtained by a background subtraction (i.e., $\sigma_{\text{flppm2}}^{0} - \sigma_{\text{flppm1}}^{0}$). Then, measurements of backscatter from the canopy alone (denoted by $\sigma_{\text{ppm3}}^{0}$) and from a trihedral corner reflector placed underneath the canopy (denoted by $\sigma_{\text{flppm4}}^{0}$) are made with the antenna above forest crown at each of several locations. The latter measurement is given by

$$\alpha_{\text{flppm4}}^{0} = \alpha_{\text{flppm3}}^{0} - e^{-2\tau_{\text{mp}} \text{sec} \theta} \left( \alpha_{\text{flppm2}}^{0} - \alpha_{\text{ppm1}}^{0} \right) \quad (4.\text{a})$$

where the second term represents the backscatter from the trihedral attenuated by the canopy. Measured loss in propagation through trees is obtained upon solving Eq. (4.\text{a}) for the optical depth, which yields

$$\tau_{\text{mp}} = -\frac{\cos \theta}{2} \ln \left( \frac{\alpha_{\text{flppm4}}^{0} - \alpha_{\text{flppm3}}^{0}}{\alpha_{\text{flppm2}}^{0} - \alpha_{\text{ppm1}}^{0}} \right) \quad (4.\text{b})$$

This technique is applied to the microwave data, which were collected at a 45° incidence angle only and at 19 different azimuth locations (from 0° to 90° with 5° increments) over forest and one over an open area next to trees. Note that calibrated backscatter coefficients are not required in Eq. (4.\text{b}) since the ratio cancels the calibration coefficients out. The pictures of the trihedral taken from front and behind during the radar measurement are given in Fig. 1. The measured vegetation opacity values obtained at an angle of incidence of 45° are plotted as a function of azimuth locations in Fig. 4. This plot clearly indicates that canopy attenuation varies depending on where the antenna is pointing due to the possible variations of vegetation structure in each illuminated volume. The measured vegetation optical depths for each polarization are averaged and the outliers such as those when the reflector was blocked by a tree, are discarded from the results before averaging. The $h$-polarized optical depth is found to be $1.33 \pm 0.39$ while the $v$-polarized one is $1.12 \pm 0.38$.

3.2.2. Theoretical simulation using the forward scattering theorem

The vegetation propagation constant can also be determined by using the theoretical definition given in Eqs. (1.c) and (1.d) that involves the forward scattering amplitudes of each of the tree constituents, averaged over all particle sizes and angle orientations. Since the forward scattering amplitude of an arbitrary particle is a complex quantity, this medium will attenuate the wave. This technique requires detailed measurements of size/angle distributions and dielectric constants of the tree constituents (trunk, branches, and needles). These vegetation characteristics were obtained by destructive tree sampling; details are described in *Kurum et al., in press*. The calculated forest parameters derived using this technique represent theoretical values.

3.2.3. Comparison

The angular and polarization dependences of the theoretical vegetation optical depth are plotted. The figure also includes the measured $h$- and $v$-polarized average vegetation opacity at an incidence angle of 45° and the polarization independent average effective opacity obtained through minimization of Eq. (3), for comparison purposes. Based on these plots, the followings can be concluded:

a) The theoretical opacity depends weakly on angle and polarization. This can be attributed to the combined effect of vertical trunks and the near-horizontal orientation of primary branches that are the main source of scattering and extinction. There are two competing factors for this result: 1) vertical trunks are coupled more with vertically polarized waves, and 2) near-horizontally oriented primary branches interact more with horizontal polarization. Both of these effects seem to be canceled each other for the trees considered in this investigation. This result provides a basis to

![Fig. 4. Measured vegetation optical thicknesses from trihedral experiment at incidence angle of 45° on September 15, 2009.](Image 328x74 to 527x235)
In Eq. (6), the theoretical single-scattering albedo, shown to be suf-
range of 0.5 e 0.6 for both polarizations and depends weakly on angle of incidence and polarization because of the combined effect of vertical trunks and horizontal orientation of the primary branches. The simulated effective albedo values are in the range of 0.2–0.3, which are less than half of the single-scattering albedo and are higher than the SMOS default effective albedo value of 0.1 for forest canopies (Grant et al., 2008). This reduced albedo becomes a global parameter for the whole canopy including the ground and accounts for multiple-scattering effects by balancing the scattering darkening effects of single-scattering albedo with the first-order scattering contribution as seen from the last term in Eq. (6). The plot also indicates that effective albedo values decrease monotonically with increasing angle. This is due to the increase in the contribution of the first-order scattering with increasing angle (Kurum et al., 2011).

Fig. 6 shows results from both the theoretical single-scattering albedo using Eq. (1.f) and the simulated effective albedo using Eq. (6) for the conifer forest as a function of incidence angle for both polarizations. As seen from the plot, the single-scattering albedo is around 0.6 for both polarizations and depends weakly on angle of incidence and polarization because of the combined effect of vertical trunks and horizontal orientation of the primary branches. The simulated effective albedo values are in the range of 0.2–0.3, which are less than half of the single-scattering albedo and are higher than the SMOS default effective albedo value of 0.1 for forest canopies (Grant et al., 2008). This reduced albedo becomes a global parameter for the whole canopy including the ground and accounts for multiple-scattering effects by balancing the scattering darkening effects of single-scattering albedo with the first-order scattering contribution as seen from the last term in Eq. (6). The plot also indicates that effective albedo values decrease monotonically with increasing angle. This is due to the increase in the contribution of the first-order scattering with increasing angle (Kurum et al., 2011).

Fig. 7 shows the effect of ground moisture on the simulated and fitted effective albedo. In the plot, the effective albedo values of Eq. (3) are obtained from measured data as a best-fit parameter that mini-
mizes the difference between measured data and the zero-order RT model results for all available incidence angles while the simulated albedos are calculated using Eq. (6) at incidence angles of 15° and 45°. In the calculation of the best-fit effective albedo, vegetation parameters are taken to be independent of polarization and angle while horizontal (solid lines) and vertical (dashed lines) polarizations are considered in calculation of simulated effective albedos. The results represent the albedo values over a wide range of ground conditions, where ground moisture varied between 0.05 and 0.30 cm³.cm⁻³ (see Table 2). The simulation results indicate a slight increase in the effective albedo with the increase in ground moisture content. On the other hand, the zero-order RT model-fitted effective values seem to be independent of the moisture content of the ground but have a magnitude similar to the simulated ones.

It can be concluded that the definition of the retrieved effective albedo differs from that of the single-scattering albedo. While the single-scattering albedo represents single-scattering properties of vegetation transmissivity, γₚ(θ), are calculated using the canopy parameters derived by destructive sampling in the scattering model. The ground reflectivity, Rₚ, is calculated by the three-layer soil model, where the ground observations collected approximately coincident with microwave measurements are utilized. Calculation of the first-order scattering term, Ωₚ(θ), requires both vegetation and ground parameters.

3.3 Albedo estimates

As previously mentioned, the scattering from large vegetation components such as branches and trunks is significant. The values of the composite albedos for both polarizations are generally in range of 0.5–0.6. This large albedo of a tree canopy leads to scatter-
induced reduction in brightness temperature, and this scattering darkening effect should be balanced with a multiple-scattering con-
tribution, which is missing in Eq. (1.a). The first-order RT solution is shown to be sufficient for describing emission and scattering processes within the forest canopy at L-band (Kurum et al., 2011). Under the assumption that effective vegetation opacity in the tau–omega model is the same as the theoretical opacity for tree canopies (given the increased scatter from trees compared to grasses and crops), one can relate the zero-order solution given in Eq. (1.a) with an effective albedo to the first-order solution given in Eq. (2.a) with the theoretical single-scattering albedo i.e.,

\[ ε_p^{(0)}(θ_p, γ_p, R_p) = ε_p^{(1)}(θ_p, γ_p, R_p) \]

Upon solving Eq. (5) for the effective albedo yields:

\[ Ω_p(θ) = \frac{Ω_p(θ)}{1 + γ_p(θ)R_p(θ)} \]

Due to the last term in Eq. (6), the effective albedo, Ω_p, depends on all the processes taking place within the canopy and ground. In Eq. (6), the theoretical single-scattering albedo, ω_p, and

![Image](image_url)
vegetation elements only, and is independent of ground properties, the effective albedo takes into account of all the processes taking place within the canopy, including multiple-scattering and canopy ground interaction.

4. Summary and conclusions

Inversion of the tau–omega model requires effective or equivalent values for the whole canopy. There is a need to establish a direct physical link between these effective vegetation parameters and their formal definitions. This paper used a first-order RT model and truck-based microwave measurements over a natural conifer stand to investigate this relationship. Physical analysis of the scattered and emitted radiation from vegetated terrain were performed using microwave data collected over a natural conifer stand located in Maryland in 2008 and 2009.

Vegetation opacity of coniferous trees was obtained using three independent approaches that provide effective, measured, and theoretical estimates. The effective values were found to be smaller than but of similar magnitude to both measured and theoretical values. This implies that the opacity values retrieved by the tau–omega model could be approximated by the theoretical values while preserving their physical meaning. An explicit expression was provided for the effective albedo by relating the zero-order model to the first-order RT model with an effective albedo after setting the vegetation opacity of the zero-order approach equal to the theoretical opacity. The effective albedo was also determined as a best-fit parameter that minimizes the difference between microwave observation and the parametric model. The resulting simulated and fitted effective albedos were found similar magnitude but less than half of the single-scattering albedo estimated using the theoretical definition. This reduced albedo accounts for multiple-scattering effects by balancing the scattering darkening of single-scattering albedo with the first-order scattering contribution. The retrieved effective albedo is different from theoretical definitions and not the albedo of single forest elements anymore, but it becomes a global parameter, which depends on all the processes taking place within the canopy, including multiple-scattering and canopy ground interaction.

References


