A Simple and Accurate Model for Radar Backscattering from Vegetation-covered Surfaces

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Abstract- A simple and accurate microwave backscattering model for vegetation-covered soil surfaces is developed in this study. A vegetated surface is modeled as a two-layer structure comprising a vegetation layer and an underlying ground layer. This scattering model includes five main scattering mechanisms including the first-order multiple scattering. The vegetation layer is modeled by random distribution of mixed scattering particles, such as leaves, branches and trunks, and its radar backscatter is computed using the first-order vector Radiative Transfer model. The number of input parameters has been minimized to simplify the scattering model, and its accuracy has been improved by comparing with the experimental measurements.

I. INTRODUCTION

Radar backscattering from vegetated surfaces involves complicated electromagnetic wave interactions, because of the randomly oriented complex geometries of the various scattering particles. Therefore, it is very difficult to develop an accurate polarimetric radar scattering model for a vegetation layer over an underlying soil surface. Moreover, a scattering model will get many input parameters to increase the computation accuracy, which leads to a very complicate model for a practical usage [1-2].

In this study, we developed a simple and accurate scattering model, which has only ten input parameters and shows a reasonably good accuracy. This model employs the iterative vector Radiative transfer theory to compute the backscattering coefficients of a vegetation canopy over an underlying soil surface [3]. We modeled the vegetation canopy with randomly oriented and positioned leaves, branches and trunks having random size distributions. Existing scattering models for dielectric disks, spheroids and cylinders are examined, and their validity regions are determined. A polarimetric semi-empirical model (PSEM) for bare soil surfaces in [4] was used for this model development.

II. SCATTERING MATRICES FOR PARTICLES

A. Lossy Dielectric Cylinders Disks

Deciduous leaves can be modeled by thin disks. The generalized Rayleigh-Gans (GRG), and the physical optics (PO) models are commonly used for calculation of scattering matrices of leaves [5]. The scattered field vector is related to the incident field vector in terms of a dyadic scattering amplitude $\overline{\overline{S}}$ as follows:

$$\overline{E}^{s}(\overline{r}) = \frac{e^{ikr}}{r}\overline{\overline{S}}\left(\hat{k}_s, \hat{k}_i\right)\cdot \hat{q}_i E_0 \tag{1}$$

where the scattering amplitude S_{pq} for a q-polarized incident wave and a p-polarized scattered wave can be written by

$$S_{pq} \equiv \hat{p}_s \cdot \overline{\overline{S}}\left(\hat{k}_s, \hat{k}_i\right)\cdot \hat{q}_i \,. \tag{2}$$

It was found that both of the GRG and the PO approximation can be applied for scattering from thin leaves at microwave frequencies [5]. In this paper, the PO model is used. For the PO model, the leaf is assumed as a resistive sheet. Then, the equivalent current $\overline{J}(\overline{r}')$ can be approximated to a surface current distribution $\overline{J}_s^R(\overline{r}')$ on the resistive sheet lying on *x-y* plane as

$$\overline{J}_s^R(\overline{r}') = \overline{J}_s^{pc}(\overline{r}')\Gamma_q \,. \tag{3}$$

The PO surface current on a perfect conductor $\overline{J}_s^{pc}(\overline{r}')$ can be obtained using the equivalence principle. The horizontal and vertical reflection coefficients (Γ_h and Γ_v) for a resistive sheet can be derived using the impedance boundary conditions.

$$\Gamma_h = \left[1 + \frac{2R\cos\theta_0}{\eta_0}\right]^{-1} \text{ and} \tag{4a}$$

$$\Gamma_v = \left[1 + \frac{2R}{\eta_0 \cos\theta_0}\right]^{-1}, \tag{4b}$$

with $R = \frac{i\eta_0}{k_0 t(\varepsilon_r - 1)}$, where R is the resistivity of the leaf, $\theta_0 = \pi - \theta_i$, and t is the leaf thickness.

The relative permittivity ε_r for vegetation particles (ε_v) has been computed by the following empirical formula [6].

$$\begin{aligned}\varepsilon_v = \varepsilon_r + v_{fw}[4.9 + \frac{75.0}{1 + jf/18} - j\frac{18\sigma}{f}] \\ + v_b[2.9 + \frac{55.0}{1 + (jf/0.18)^{0.5}}]\end{aligned} \tag{5}$$

where $\varepsilon_r = 1.7 - 0.74M_g + 6.16M_g{}^2$ (residual permittivity), $v_{fw} = M_g(0.55M_g - 0.076)$ (volume fraction of free water),

$v_b = 4.64 M_g{}^2 \,/(1+7.63 M_g{}^2)$ (volume fraction of the bulk vegetation bound water mixture), and $\sigma = 1.27$.

B. *Lossy Dielectric Cylinders*

Branches and trunks usually have cylindrical shapes. The physical optics model is used for scattered field of a finite cylinder with arbitrary cross section and orientation [3]. For a single branch, the scattered matrix can be computed for a arbitrarily oriented cylinder.

$$\overline{\overline{S}} = Q \begin{bmatrix} (\hat{v}_s^c \cdot v_s) & (\hat{h}_s^c \cdot v_s) \\ (\hat{v}_s^c \cdot \hat{h}_s) & (h_s^c \cdot h_s) \end{bmatrix} \cdot \begin{bmatrix} T'_{vv} & T'_{vh} \\ T'_{hv} & T'_{hh} \end{bmatrix} \cdot \begin{bmatrix} (\hat{v}_i \cdot v_i^c) & (\hat{h}_i \cdot v_i^c) \\ (\hat{v}_i \cdot \hat{h}_i^c) & (h_i \cdot h_i^c) \end{bmatrix} \quad (6)$$

where

$$Q = \frac{-i l_c \cos\phi_s}{\pi \cos\phi_i} \left\{ \frac{\sin\left[k_0 (\sin\phi_i + \sin\phi_s) l_c/2\right]}{\left[k_0 (\sin\phi_i + \sin\phi_s) l_c/2\right]} \right\} \quad (7)$$

with

$$T'_{vv} = \sum_{n=-\infty}^{\infty} (-1)^n C_n^{TM} e^{in\phi'} \quad (8a)$$

$$T'_{vh} = \sum_{n=-\infty}^{\infty} (-1)^n \overline{C}_n e^{in\phi'} \quad (8b)$$

$$T'_{hv} = -\sum_{n=-\infty}^{\infty} (-1)^n \overline{C}_n e^{in\phi'} \quad (8c)$$

$$T'_{hh} = \sum_{n=-\infty}^{\infty} (-1)^n C_n^{TE} e^{in\phi'} . \quad (8d)$$

The coefficients in above equations are given in [7].

III. FIRST-ORDER RADIATIVE TRANSFER MODEL

In the 1st-order RTM, the backscattering coefficients can be computed from five scattering mechanisms in the ground and vegetation layers of a vegetation field as shown in Fig. 1.

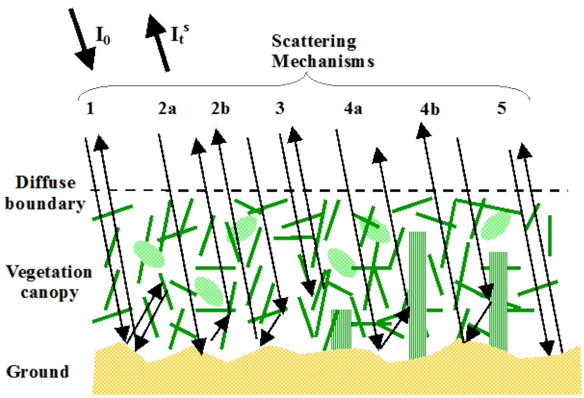


Fig 1. Scattering mechanisms.

Five scattering mechanisms consist of (1) ground forward, vegetation backward, and ground forward scattering, (2) vegetation and ground forward scattering, (3) direct vegetation backscattering, (d) ground and trunk forward scattering, and (5) direct ground backscattering, as shown in Fig. 1. The ground backscattering is calculated using Oh et al.'s model which is one of the most well-known empirical scattering model for bare soil surfaces [8].

The total backscattered intensity $\overline{I}_t^s(\mu_0,\phi_0)$ is related to the intensity I_0 incident upon the canopy through the transformation matrix $\overline{T}_t(\mu_0,\phi_0)$ by the equation,

$$\overline{I}_t^s(\mu_0,\phi_0) = \overline{T}_t(\mu_0,\phi_0)\overline{I}_0(-\mu_0,\phi_0) . \quad (9)$$

where $\mu_0 = \cos\theta_0$, θ_0 and ϕ_0 are the vertical and horizontal incidence angles. The transformation matrix $\overline{T}_t(\mu_0,\phi_0)$ is a 4×4 matrix which the elements have the following relationships with the scattering coefficients.

$$\sigma_{vv}^0 = 4\pi\cos\theta_0 [T_t(\mu_0,\phi_0)]_{11} \quad (10a)$$

$$\sigma_{hh}^0 = 4\pi\cos\theta_0 [T_t(\mu_0,\phi_0)]_{22} \quad (10b)$$

$$\sigma_{hv}^0 = 4\pi\cos\theta_0 [T_t(\mu_0,\phi_0)]_{21} \quad (10c)$$

$$\sigma_{vh}^0 = 4\pi\cos\theta_0 [T_t(\mu_0,\phi_0)]_{12} \quad (10d)$$

The transformation matrix comprises two components:

$$\overline{T}_t(\mu_0,\phi_0) = \overline{T}_c(\mu_0,\phi_0) + \overline{T}_g(\mu_0,\phi_0) \quad (11)$$

where $\overline{T}_c(\mu_0,\phi_0)$ and $\overline{T}_g(\mu_0,\phi_0)$ are the vegetation canopy and ground backscattering transformation matrices, respectively. The expression for $\overline{T}_g$ is given by

$$\overline{T}_g(\mu_0,\phi_0) = \exp(-\overline{k}_e^+ d/\mu_0)\overline{G}(\mu_0) \cdot \exp(-\overline{k}_e^- d/\mu_0) , \quad (12)$$

where $\overline{k}_e^+$ and $\overline{k}_e^-$ are the 4×4 extinction matrices of the vegetation layer for upward and downward propagation, respectively. $\overline{G}(\mu_0)$ is the ground backscattering matrix given by

$$\overline{G}(\mu_0) = \frac{1}{\cos\theta_0}\overline{M}_m , \quad (13)$$

where $\overline{M}_m$ is the modified Stokes scattering operator, which describes ground backscatter [3].

The expression for $\overline{T}_c$ is given by [3, 7].

$$\begin{aligned}
\overline{T}_c &= 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0)\overline{\varepsilon}_c(-\mu_0,\phi_0+\pi) \\
&\quad \cdot \overline{A}_1\, \overline{\varepsilon}_c^{-1}(\mu_0,\phi_0)\overline{R}(\mu_0)\exp(-\overline{k}_e^- d/\mu_0) \\
&+ 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0) \\
&\quad \cdot \overline{\varepsilon}_c(-\mu_0,\phi_0+\pi)\, \overline{A}_2 \overline{\varepsilon}_c^{-1}(-\mu_0,\phi_0) \\
&+ 1/\mu_0\, \overline{\varepsilon}_c(\mu_0,\phi_0+\pi)\overline{A}_3\, \overline{\varepsilon}_c^{-1}(\mu_0,\phi_0)\overline{R}(\mu_0) \\
&\quad \cdot \exp(-\overline{k}_e^- d/\mu_0) \quad + 1/\mu_0\, \overline{\varepsilon}_c(\mu_0,\phi_0+\pi)\overline{A}_4\, \overline{\varepsilon}_c^{-1}(-\mu_0,\phi_0) \\
&+ 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0) \\
&\quad \cdot \overline{\varepsilon}_c(-\mu_0,\phi_0+\pi)\overline{A}_5 \overline{\varepsilon}_c^{-1}(-\mu_0,\phi_0)\exp(-\overline{k}_e^- d/\mu_0) \\
&+ 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{\varepsilon}_c(\mu_0,\phi_0+\pi)\overline{A}_6 \overline{\varepsilon}_c^{-1}(\mu_0,\phi_0) \\
&\quad \cdot \overline{R}(\mu_0)\exp(-\overline{k}_e^- d/\mu_0)
\end{aligned} \quad (14)$$

where the matrices A_1, A_2, A_3, A_4, A_5, A_6 corresponding the scattering mechanisms 1, 2a, 2b, 3, 4a and 4b, respectively, can be obtained by integration of a function of the phase matrices and the extinction matrices. $\overline{R}(u)$ is the reflectivity matrix of the ground surface. The matrix $\overline{\varepsilon}_c$ is the 4×4 eigen-matrix of the vegetation layers [3]. The phase matrix can be computed by integration of the Mueller matrix multiplied with the distribution function of the particles. The

Mueller matrix functions are calculated using the scattering matrices of scatterers.

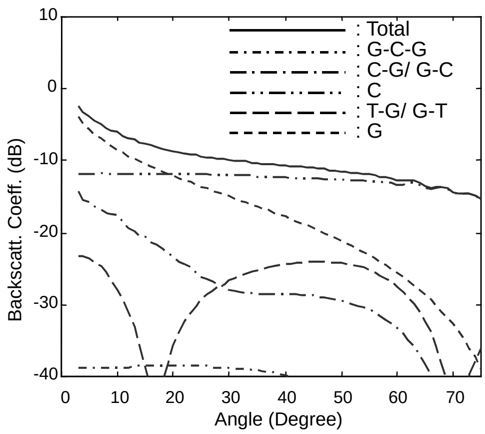
IV. Numerical Results

At first, we tried to examine the sensitivities of the scattering coefficients on each input parameters. Then, we selected only ten most important input parameters, which are (1) the volumetric moisture content m_v (cm^3/cm^3) and (2) the rms surface height s (cm) of the ground surface, (3) the height h (m) of the vegetation layer, (4) leaf density n_l (m^{-3}), (5) leaf length l_l (cm), (6) leaf width W_l (cm), (7) branch density n_b (m^{-3}), (8) branch length l_b (cm), (9) trunk density n_t (m^{-3}), and (10) trunk length l_t (m).

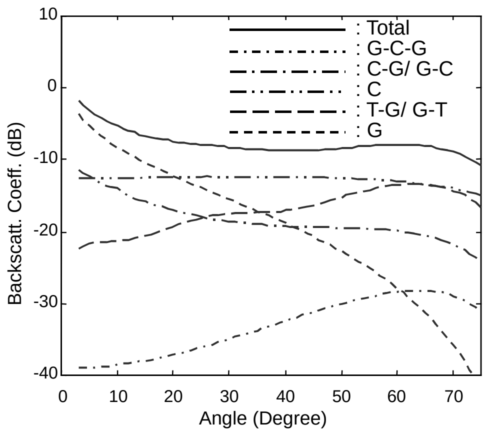
Other input parameters are appropriately induced from the ten major input parameters. For example, all of the probability distribution functions for particle (leaf, branch and trunk) are assumed to be uniform for simplicity. The minimum and maximum boundaries of the particles are computed from the given mean values. The trunk diameter is assumed to be 0.015 times of the trunk length. These assumptions are based on the experimental observations.

We tested the variation of the model on various each parameter values. As an example, the backscattering coefficients for a vegetation canopy with m_v = 0.15 cm^3/cm^3, s = 0.5 cm, h = 5 m, n_l = 100 m^{-3}, l_l = 6 cm, W_l = 3 cm, n_b =10 m^{-3}, l_b = 0.5 m, n_t = 0.1 m^{-3}, and l_t =2.5 m, are computed at 5.3 GHz at vv- and hh-polarizations.

Fig. 2 shows the computation results. The letters G, C, and T in Fig. 2 denote ground, crown and trunk, respectively. It was found that the backscattering coefficient is dominated by the ground scattering at low incidence angles, and by the crown-direct scattering at higher incidence angles for both polarizations at 5.3 GHz as shown in Figs. 2 (a) and (b).



(a)



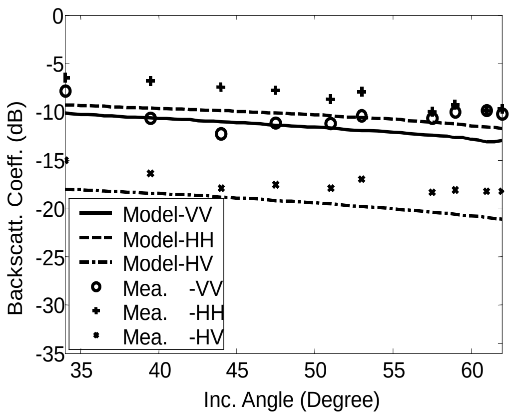
(b)

Fig. 2. Computation results for a typical forest at 5.3 GHz: (a) *vv*- and (b) *hh*-polarizations.

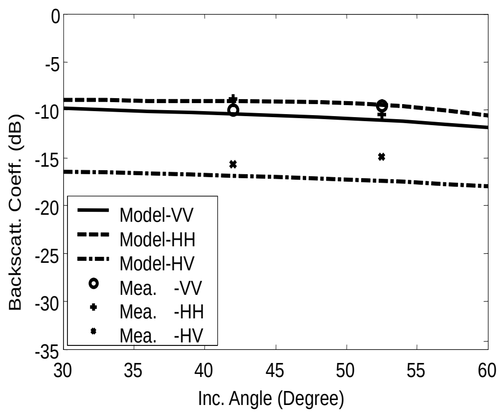
V. Comparison with Measurements

The backscattering coefficients are computed by the new scattering model and compared with the JPL/AirSAR measurements obtained at Non-San area for the PACRIM-2 campaign in Korea in 2000. The computation results are based on the ground truth data measured *in situ* at the same time.

Fig. 3 (a) shows the comparison between the computations and the measurements of the backscattering coefficients of ten rice fields at 5.3 GHz. The estimated backscattering fields were computed using the ground truth data measured *in situ*. A good agreement is shown in Figs. 3 (a) and (b) with only ten input parameters. The discrepancy of about 2~3dB may be from the errors of the radar calibration, the ground data measurements, and/or the scattering model. Fig. 3 (b) shows the comparison between the computations and the measurements for three forest areas.



(a)



(b)

Fig. 3. The comparison with SAR measurement data and computation results for (a) rice fields and (b) forests at 5.3GHz.

VI. CONCLUDING REMARKS

A simple and accurate model was developed for microwave backscattering from a vegetation canopy over an underlying soil surface. The vegetation canopy was modeled with randomly distributed and oriented particles having random size distributions. The model was tested for many kinds of vegetation canopies, and verified with the JPL/AirSAR measurement data sets for rice fields and forest areas. Good agreements are shown between the computed backscattering coefficients for the fields and the measurements.

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