# A Simple Microwave Backscattering Model for Vegetation Canopies

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## Abstract

A simple microwave backscattering model for vegetation canopies on earth surfaces is developed in this study. A natural earth surface is modeled as a two-layer structure comprising a vegetation layer and a ground layer. This scattering model includes various scattering mechanisms up to the first-order multiple scattering(double-bounce scattering). Radar backscatter from ground surface has been modeled by the polarimetric semi-empirical model (PSEM), while the backscatter from the vegetation layer modeled by the vector radiative transfer model. The vegetation layer is modeled by random distribution of mixed scattering particles, such as leaves, branches and trunks. The number of input parameters has been minimized to simplify the scattering model. The computation results are compared with the experimental measurements, which were obtained by ground-based scatterometers and NASA/JPL air-borne synthetic aperture radar(SAR) system. It was found that the scattering model agrees well with the experimental data, even though the model used only ten input parameters.


***Key words*** : Microwave Backscattering Model, Vegetation Canopy, Radiative Transfer Model.

## Ⅰ. Introduction

The radar scattering from natural earth surfaces involves complicated electromagnetic wave interactions, because of the randomly oriented complex geometries of the various scattering particles. Therefore, it is impossible to deal with all kinds of possible earth elements configurations and conditions in a polarimetric radar scattering model for a vegetation layer over earth surfaces. Hence, our attention is always focused on the development of approximate scattering models[1],[2]. However, the existing approximate scattering models are still complicated for use. For example, the Michigan microwave canopy scattering model(MIMICS) needs too many input parameters(more than 60 input parameters). Moreover, the models are not accurate enough because of using the inaccurate theoretical surface scattering models, such as the PO, the GO, and the SPM models.

In this study, we developed a new simple 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 including multiple scattering effects[3]. We modeled the vegetation canopy with two layers; a soil surface layer and a vegetation layer. The vegetation layer contains randomly oriented and positioned leaves, branches and trunks.

Existing scattering models for dielectric disks, spheroids and cylinders are examined, and their validity regions are determined. Validity regions of existing classical models for soil surfaces, such as the geometrical optics(GO) model, the physical optics(PO) model, and the small perturbation method(SPM) model, are also examined[4]. A new polarimetric semi-empirical model(PSEM) for bare soil surfaces has been developed [5]. The input parameters of the PSEM model are the soil moisture content $m_v$, the rms height $s$ and the correlation length $l$ of a surface. If the correlation length is not available, a modified form of the PSEM can be used[6]. In this study the modified simple model is used to reduce input parameters.

## Ⅱ. Radiative Transfer Model

The vector Radiative transfer theory is a common technique to compute polarimetric microwave scattering from randomly distributed scatterers[2]. Existing scattering models for vegetation canopy deal with three layered vegetation canopy, *i.e.*, crown layer, trunk layer and soil layer. However, the vegetation canopy is modeled by only two layers as shown in Fig. 1, because the natural vegetation canopies usually do not show clear cut between the crown layers and the trunk layers. In this scattering model, the radar backscattering from two-layered vegetation canopy comprises five main scattering mechanisms such as (1) ground-crown-ground scattering, (2) crown-ground scattering or ground-crown scattering, (3) crown scattering, (4) ground-trunk sca-

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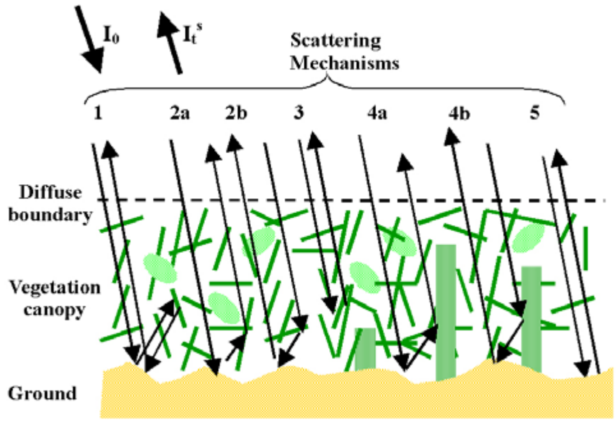



Fig. 1. Scattering mechanisms.

ttering, or trunk-ground scattering, and (5) ground scattering.

Fig. 1 shows a vegetation canopy consisting of a single horizontal vegetation layer of height $d$ over a dielectric ground surface. 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,

$$\overline{I}_t^s(\mu_0, \phi_0) = \overline{T}_t(\mu_0, \phi_0)\, \overline{I}_0(-\mu_0, \phi_0). \tag{1}$$

where $\mu_0 = \cos\Theta_0$, $\Theta_0$, and $\phi_0$ 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.

$$\sigma^0_{vv} = 4\pi\cos\Theta_0 [\, T_t(\mu_0, \phi_0)]_{11} \tag{2a}$$

$$\sigma^0_{hh} = 4\pi\cos\Theta_0 [\, T_t(\mu_0, \phi_0)]_{22} \tag{2b}$$

$$\sigma^0_{hv} = 4\pi\cos\Theta_0 [\, T_t(\mu_0, \phi_0)]_{21} \tag{2c}$$

$$\sigma^0_{vh} = 4\pi\cos\Theta_0 [\, T_t(\mu_0, \phi_0)]_{12} \tag{2d}$$

The transformation matrix comprises two components:

$$\overline{T}_t(\mu_0, \phi_0) = \overline{T}_c(\mu_0, \phi_0) = \overline{T}_g(\mu_0, \phi_0) \tag{3}$$

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

$$\overline{T}_g(\mu_0, \phi_0) = \exp(-\overline{k}_e^+ d/\mu_0)\overline{G}(\mu_0) \cdot \exp(-\overline{k}_e^- d/\mu_0), \tag{4}$$

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

$$\overline{G}(\mu_0) = \frac{1}{\cos\Theta_0}\overline{M}_m, \tag{5}$$

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]

$$\begin{aligned}\overline{T}_c =\ & 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0)\overline{\varepsilon}_c(-\mu_0, \phi_0+\pi) \\ & \cdot \overline{A}_1\, \overline{\varepsilon}_c^{-1}(\mu_0, \phi_0)\overline{R}(\mu_0)\exp(-\overline{k}_e^- d/\mu_0) \\ & + 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0) \\ & \cdot \overline{\varepsilon}_c(-\mu_0, \phi_0+\pi)\, \overline{A}_2\, \overline{\varepsilon}_c^{-1}(-\mu_0, \phi_0) \\ & + 1/\mu_0\, \overline{\varepsilon}_c(\mu_0, \phi_0+\pi)\, \overline{A}_3\, \overline{\varepsilon}_c^{-1}(\mu_0, \phi_0)\overline{R}(\mu_0) \\ & \cdot \exp(-\overline{k}_e^- d/\mu_0) \\ & + 1/\mu_0\, \overline{\varepsilon}_c(\mu_0, \phi_0+\pi)\, \overline{A}_4\, \overline{\varepsilon}_c^{-1}(-\mu_0, \phi_0) \\ & + 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0)\overline{R}(\mu_0) \\ & \cdot \overline{\varepsilon}_c(-\mu_0, \phi_0+\pi)\, \overline{A}_5\, \overline{\varepsilon}_c^{-1}(-\mu_0, \phi_0) \\ & \exp(-\overline{k}_e^- d/\mu_0) + 1/\mu_0 \exp(-\overline{k}_e^+ d/\mu_0) \\ & \cdot \overline{\varepsilon}_c(\mu_0, \phi_0+\pi)\, \overline{A}_6\, \overline{\varepsilon}_c^{-1}(\mu_0, \phi_0) \\ & \cdot \overline{R}(\mu_0)\exp(-\overline{k}_e^- d/\mu_0)\end{aligned} \tag{6}$$

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.

In the formulation, we also assumed that the scatterers are randomly and sparsely distributed and there is no correlation between them. The radar scattering characteristics of the scattering particles are obtained using the existing scattering models as in the next section.

## Ⅲ. Scattering from Particles

Natural leaves and branches usually have complicated shapes and sizes. Coniferous leaves can be modeled by spheroids for the computation purpose, while the deciduous leaves modeled by thin disks. 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].

The generalized Rayleigh-Gans(GRG), and the physical optics(PO) models are commonly used for calculation of scattering matrices of leaves[8]. The GRG model is same with the Rayleigh approximation except that the phase term is retained within the integral, and the phase interference function works as a modifying factor.

The scattered field vector is related to the incident field vector in terms of a dyadic scattering amplitude $\overline{\overline{S}}$ as follows:

$$\overline{E}^s(\overline{r}) = \frac{e^{ikr}}{r}\overline{\overline{S}}(\hat{k}_s, \hat{k}_i)\cdot \hat{q}iE_0 \tag{7}$$

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

$$S_{pq} \equiv \hat{p}_s \cdot \overline{\overline{s}}\{\hat{k}_s, \hat{k}_i)\cdot \hat{q}i \tag{8}$$

It was found that both of the GRG and the PO approximation can be applied for scattering from thin leaves at microwave frequencies[8]. 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

$$\overline{J}_s^R(\overline{r}') = \overline{J}_s^{pc}(\overline{r}')\Gamma_q \tag{9}$$

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 ($\Gamma_h$ and $\Gamma_v$) for a resistive sheet can be derived using the impedance boundary conditions.

$$\Gamma_h = \left[1 + \frac{2R\cos\Theta_0}{\eta_0}\right]^{-1} \text{and} \tag{10a}$$

$$\Gamma_v = \left[1 + \frac{2R}{\eta_0\cos\Theta_0}\right]^{-1}, \tag{10b}$$

with $R = \dfrac{i\eta_0}{k_0 t(\varepsilon_r - 1)}$, where $R$ is the resistivity of the leaf, $\Theta_0 = \pi - \Theta_i$, and $t$ is the leaf thickness.

The relative permittivity $\varepsilon_r$ for vegetation particles ($\varepsilon_v$) has been computed by the following empirical formula[9].

$$\varepsilon_v = \varepsilon_r + v_{fw}\left[4.9 + \frac{75.0}{1 + jf/18} - j\frac{18\sigma}{f}\right] + v_b\left[2.9 + \frac{55.0}{1 + (jf/0.18)^{0.5}}\right] \tag{11}$$

where $\varepsilon_r = 1.7 - 0.74\, M_g + 6.16\, M_g^2$(residual permittivity), $v_{fw} = M_g(0.55\, M_g - 0.076)$(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 $\sigma = 1.27$.

## Ⅳ. Scattering from Bare Soil Surfaces

It is well known that the classical theoretical surface scattering models, such as the PO, the GO, and the SPM models, are not accurate even in their validity regions. A semi-empirical polarimetric model(SEPM) was developed for random bare soil surfaces using a combination of truck-mounted scatterometer measurements and airborne SAR observations, both supported by extensive ground observation of the soil surface statistics and moisture content. The two distinguishing features of the model are that it not only agrees with experimental observations over a wide range of soil surface conditions, but it also agrees with the integral equation method(IEM) and geometrical optics model over their individual regions of validity, thereby encompassing the full range of surface roughness encountered under natural conditions[5].

The expression of the PSEM is

$$\sigma_{vh}^0 = 0.11 m_v^{0.7}(\cos\theta)^{2.2}\lfloor 1 - \exp(-0.32(ks)^{1.8})\rfloor, \tag{12}$$

$$\sigma_{vv}^0 = \sigma_{vh}^0/q, \tag{13}$$

$$\sigma_{hh}^0 = p\sigma_{vv}^0 = p\sigma_{vh}^0/q, \tag{14}$$

where

$$q = 0.1(s/l + \sin(1.3\theta))^{1.2}\{1 - \exp\lfloor -0.9(ks)^{0.8}\rfloor\}, \tag{15}$$

$$p = 1 - (\theta/90^\circ)^{0.35 m_v^{-0.65}}\cdot\exp(-0.4(ks)^{1.4}), \tag{16}$$

and the $vv$- and $hh$-polarized backscattering coefficients can be computed from the $vh$-polarized backscattering coefficient with the co-polarized ratio $p$, and the cross-polarized ratio $q$.

The input parameters of the SEPM are the incidence angle $\Theta$, the volumetric soil moisture content $Mv$, and the roughness parameters $ks$ and $kl$, where $s$ is the rms height, $l$ is the correlation length and $k$ is the wavenumber($k = 2\pi f/c$). The soil moisture content $Mv$ of the top 3 cm soil-surface layer is used at all frequencies because it was shown that the top 2∼3 cm soil layer exhibits the greatest influence on the radar backscatter response even though the wave may penetrate deeper into the soil for a dry surface at L-band. The model agrees with experimental observations over a wide range of soil surface conditions: $0.04 < Mv < 0.291$ m$^3$/m$^3$, $0.13 < ks < 6.98$ at $10^0 \le \Theta \le 70^0$.

## Ⅴ. Numerical Results and Verification

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.

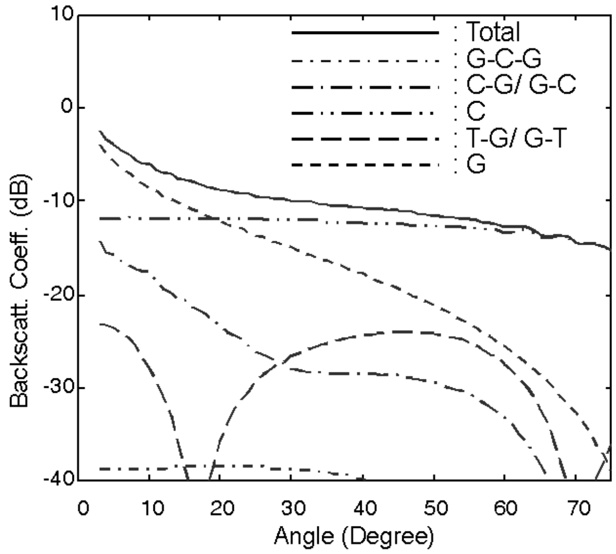
We tested the variation of the model on various each parameter values. As an example, the backscattering coefficients for a vegetation canopy with $m_v$=0.15 $cm^3/cm^3$, $s$=0.5 cm, $h$=5 m, $n_l$=100 $m^{-3}$, $l_l$ = 6 cm, $W_l$ = 3 cm, $n_b$ =10 $m^{-3}$, $l_b$=0.5 m, $n_t$=0.1 $m^{-3}$, and $l_t$=2.5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

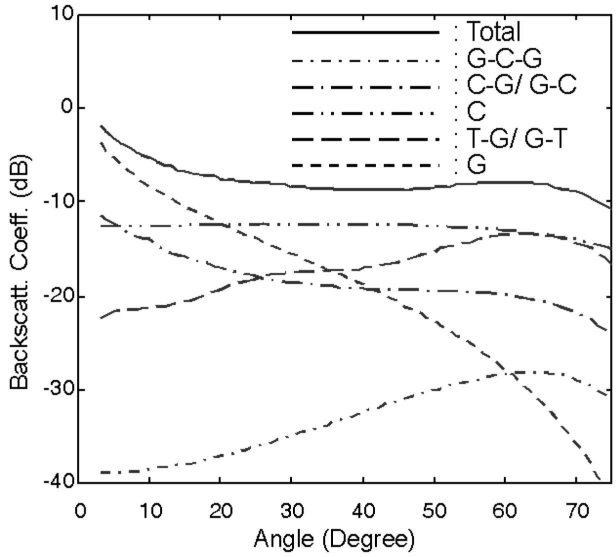
The backscattering coefficients are computed by the new scattering model and compared with the JPL/AirSAR measurements obtained at Non-San area for the PACRIM-2 campaign in Korea in 2000. The computation results are based on the ground truth data measured *in situ* at the same time.

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 2～3 dB 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.

It was shown that the computed cross-polarized backscattering coefficients are lower than the measurements. The reason of the deviation may be because the model includes only the first-order multiple scattering and ignores the higher-order multiple scattering terms.




(a) *vv*-polarizations

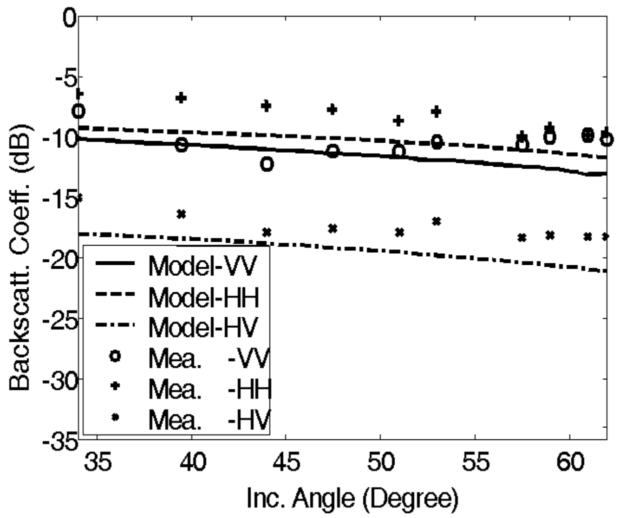



(b) *hh*-polarizations

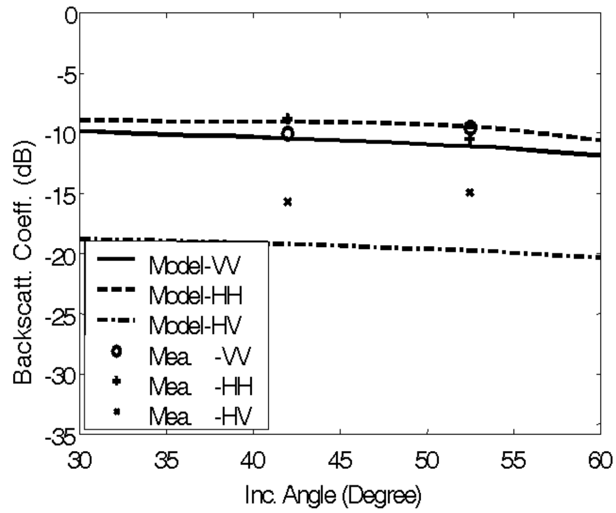
Fig. 2. Computation results for a typical forest at 5.3 GHz.

## Ⅵ. Concluding Remarks

A simple microwave backscattering model is developed for vegetation canopies. 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




(a) Rice fields




(b) Forests at 5.3 GHz

Fig. 3. The comparison with SAR measurement data and computation results.

the computed backscattering coefficients for the fields and the measurements. It was also found that the model predicts a lower cross-polarized response because of ignoring the higher-order multiple scattering.

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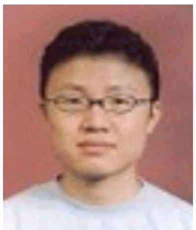

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