Characterization of Microwave Polarimetric Backscattering from Grasslands Using the Radiative Transfer Theory

Yisok Oh and Jin-Won Lee
Department of Radio Engineering, Hong-Ik University, Seoul, Korea
e-mail: yisokoh@wow.hongik.ac.kr

Abstract

Microwave polarimetric backscattering from a various types of grassland canopies has been analyzed by using the first-order radiative transfer theory in this paper. Leaves in the grassland are modeled by rectangular resistive sheets, which sizes (widths and lengths) and orientations (elevation and azimuth angles) are randomly distributed. Surface roughness and soil moisture of the ground plane under the grass canopy is considered in this computation. The backscattering coefficients of grasslands are computed for different radar parameters (angles, frequencies and polarizations) as well as different canopy parameters (size and orientation distributions of leaves, canopy depth, moisture contents of leaves and soil, rms height and correlation length of soil surface). A radar system for 15GHz has been fabricated and used for measurement of the scattering coefficient from a grass canopy. The computation result obtained by the scattering model for the grass canopy is compared with the measurements.

1. Introduction

Use of imaging radar systems for remote sensing of the earth terrain has been an extensive interest. The primary purpose of the active microwave remote sensing might be retrieval of vegetation parameters from radar images. It is necessary to develop an accurate scattering model for vegetation canopy to relate the radar scatter to the radar and vegetation parameters. The radiative transfer(RT) theory has been commonly used to calculate radar backscattering coefficients from vegetation canopy and to interpret experimental measurements[1,2]. The radiative transfer model in vector form have been proposed for polarimetric analysis of radar scattering for layered vegetation canopy[3,4,5].

In this paper, the first-order vector radiative transfer model for backscattering from grassland is developed with considering rough soil surface below the vegetation canopy. A grass leaf is modeled by a rectangular-type resistive sheet, and the size and orientation of the leaf are considered randomly distributed. The scattering coefficients of the grassland for various parameters are computed and discussed. A 15GHz polarimetric radar system is used to measure the backscattering coefficients of a grass field and compared with computation results from the radiative transfer model.

2. Formulation of the Radiative Transfer Model

The radiative transfer theory deals with the transport of energy through a medium containing particles. The vector radiative transfer equation is formulated in terms of the specific intensity as follows;

$$\frac{d\bar{I}(\bar{r},\hat{s})}{ds} = -\bar{\bar{\kappa}}_e\, \bar{I}(\bar{r},\hat{s}) + \int_{4\pi} \bar{\bar{P}}(\hat{s},\hat{s}')\, \bar{I}(\bar{r},\hat{s})\, d\Omega, \tag{1}$$

where the vector specific intensity $\bar{I}$ is a 4×1 column matrix, $\bar{\bar{\kappa}}_e$ is a 4×4 extinction matrix, $\bar{\bar{P}}$ is a 4×4 phase matrix, $\bar{r}$ is a position vector, and $\hat{s}$ denotes the direction of propagation. Considering a single horizontal vegetation layer as shown in Fig. 1, the total backscattering intensity may be related to the incident intensity through the 4×4 transformation matrix $\bar{\bar{T}}$ as follows;

$$\bar{I}_t^s(\theta_0,\phi_0) = \left[\bar{\bar{T}}_c(\theta_0,\phi_0) + \bar{\bar{T}}_g(\theta_0,\phi_0)\right] \bar{I}_0(\pi-\theta_0,\phi_0) = \bar{\bar{T}}_t(\theta_0,\phi_0)\, \bar{I}_0(\pi-\theta_0,\phi_0) \tag{2}$$

The transformation matrices $\bar{\bar{T}}_c$ and $\bar{\bar{T}}_g$ are for backscatter from the vegetation layer interacted with ground surface and for direct backscatter from the ground, respectively.

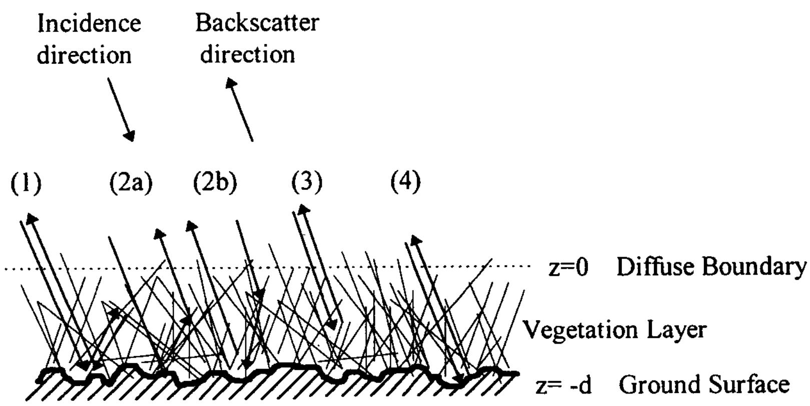

Fig. 1: Backscatter mechanisms for a single vegetation layer.

The transformation matrices can be formulated as follows;

$$\begin{aligned}\bar{\bar{T}}_c(\theta_0,\phi_0) = {} & \frac{1}{\mu_0} e^{-\bar{\bar{\kappa}}_e^+ d/\mu_0} \bar{\bar{R}}(\theta_0)\bar{\bar{E}}(\pi-\theta_0,\phi_0+\pi)\bar{\bar{A}}_1\, \bar{\bar{E}}^{-1}(\theta_0,\phi_0)\bar{\bar{R}}(\theta_0) e^{-\bar{\bar{\kappa}}_e^- d/\mu_0} \\ & + \frac{1}{\mu_0} \bar{\bar{E}}(\theta_0,\phi_0+\pi)\bar{\bar{A}}_{2a}\, \bar{\bar{E}}^{-1}(\theta_0,\phi_0)\bar{\bar{R}}(\theta_0) e^{-\bar{\bar{\kappa}}_e^- d/\mu_0} \\ & + \frac{1}{\mu_0} e^{-\bar{\bar{\kappa}}_e^+ d/\mu_0} \bar{\bar{R}}(\theta_0)\bar{\bar{E}}(\pi-\theta_0,\phi_0+\pi)\bar{\bar{A}}_{2b}\, \bar{\bar{E}}^{-1}(\theta_0,\phi_0) \\ & + \frac{1}{\mu_0} \bar{\bar{E}}(\theta_0,\phi_0+\pi)\bar{\bar{A}}_3\, \bar{\bar{E}}^{-1}(\pi-\theta_0,\phi_0),\end{aligned} \tag{3}$$

$$\bar{\bar{T}}_g(\theta_0,\phi_0) = e^{-\bar{\bar{\kappa}}_e^+ d/\mu_0}\, \bar{\bar{G}}_4(\theta_0)\, e^{-\bar{\bar{\kappa}}_e^- d/\mu_0}, \tag{4}$$

where $\mu_0 = \cos\theta_0$, $\bar{\bar{R}}$ is a reflection matrix, $\bar{\bar{E}}$ is an eigen matrix, and the matrices $\bar{\bar{A}}_m$ represent four scattering mechanisms (1, 2a, 2b, and 3 in Fig. 1), which can be computed from the phase matrix $\bar{\bar{P}}$. The ground backscattering matrix $\bar{\bar{G}}$ can be obtained from the modified Stokes scattering operator $\bar{\bar{M}}_m$, which is a function of scattering matrix S in an average sense (mechanism 4 in Fig. 1). From the total scattering transformation matrix, the polarimetric backscattering coefficients can be obtained as follows[1-3];

$$\begin{aligned}
\sigma_{vv}^{0} &= 4\pi \cos\theta_0 \left[\overline{\overline{T}}_t(\theta_0,\phi_0)\right]_{11} \\
\sigma_{hh}^{0} &= 4\pi \cos\theta_0 \left[\overline{\overline{T}}_t(\theta_0,\phi_0)\right]_{22} \\
\sigma_{hv}^{0} &= 4\pi \cos\theta_0 \left[\overline{\overline{T}}_t(\theta_0,\phi_0)\right]_{21} \\
\sigma_{vh}^{0} &= 4\pi \cos\theta_0 \left[\overline{\overline{T}}_t(\theta_0,\phi_0)\right]_{12}.
\end{aligned} \tag{5}$$

The phase matrix for the grassland may be computed as follows;

$$P(\theta_s,\phi_s;\theta_i,\phi_i) = \sum_{k=1}^{K} N_k \iiiint p_k(a,b;\theta_p,\phi_p)\overline{\overline{L}}_k(\theta_s,\phi_s;\theta_i,\phi_i;\theta_p,\phi_p)\,da\,db\,d\theta_p\,d\phi_p, \tag{6}$$

where k represents particle type (leaf, stem, grain etc.), p_k is the joint probability density function, and $\overline{\overline{L}}_k$ is the Mueller matrix (Stokes matrix) which can be obtained from the 2×2 scattering matrix $\overline{\overline{S}}$.

The scattering matrix of a single leaf in the grassland can be computed by approximating the leaf to a thin rectangular resistive sheet. It has been shown that a resistive sheet model in conjunction with the physical optics approximation accurately predict the backscattering cross section of a leaf [6]. In this case the reflection coefficients for horizontal and vertical polarizations are given, respectively, as follows;

$$\Gamma_h = \left(1 + \frac{2R}{Z_0}\cos\theta_0\right)^{-1}, \qquad \Gamma_v = \left(1 + \frac{2R}{Z_0}\sec\theta_0\right)^{-1} \tag{7}$$

with $R = \dfrac{iZ_0}{k_0\tau(\varepsilon-1)}$, where R is a complex resistivity representing a leaf, Z_0 is the intrinsic impedance of free space, k_0 is the wave number of free space, τ is thickness of a leaf, and ε is complex relative permittivity.

3. Computation Results

To obtain a relatively simple formulation for the radiative transfer model, it is assumed that the grassland consists of uniformly distributed leaves. The size and orientation of leaves, however, can have arbitrary distribution functions. As an example, a grassland is considered to have the following parameter set; mean width of leaves ($\overline{a}$) = 4 mm, mean length of leaves ($\overline{b}$) = 10 cm, number of leaves in unit volume(N) = 50,000 m^{-3}, canopy depth(d) = 10 cm, leaf moisture content (m_{gv}) = 0.5 g/cm^3, soil moisture content (m_{vs}) = 0.2 cm^3/cm^3. The dielectric constants of leaves and soil surface could get from empirical formulae. The soil surface underneath vegetation layer has an exponential correlation function having the rms height of 0.5 cm, the correlation length of 5 cm in this example. Fig. 2 shows the angular response of the polarimetric scattering coefficients computed by the model at 15 GHz. At larger incidence angle, the hh-polarized backscattering coefficients are higher than vv-polarized ones as shown in Fig. 2. Fig. 3(a) shows the contributions of the direct-ground scattering (mechanism 4) and the vegetation and vegetation-ground scattering (mechanism 1, 2, 3) to the total backscatter. Fig. 3(b) shows contributions of mechanisms 1, 2, 3 to the vegetation and vegetation-ground scattering.

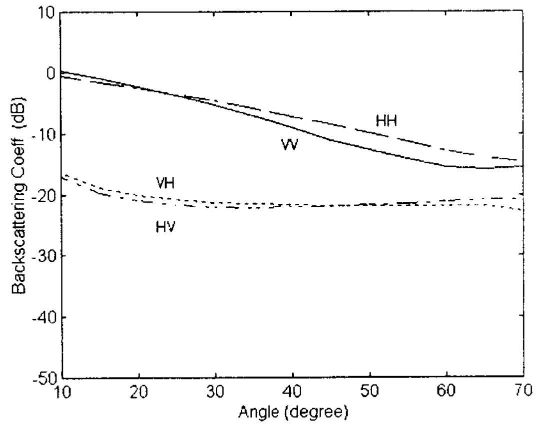

Fig. 2: Angular response of polarimetric backscattering coefficients.

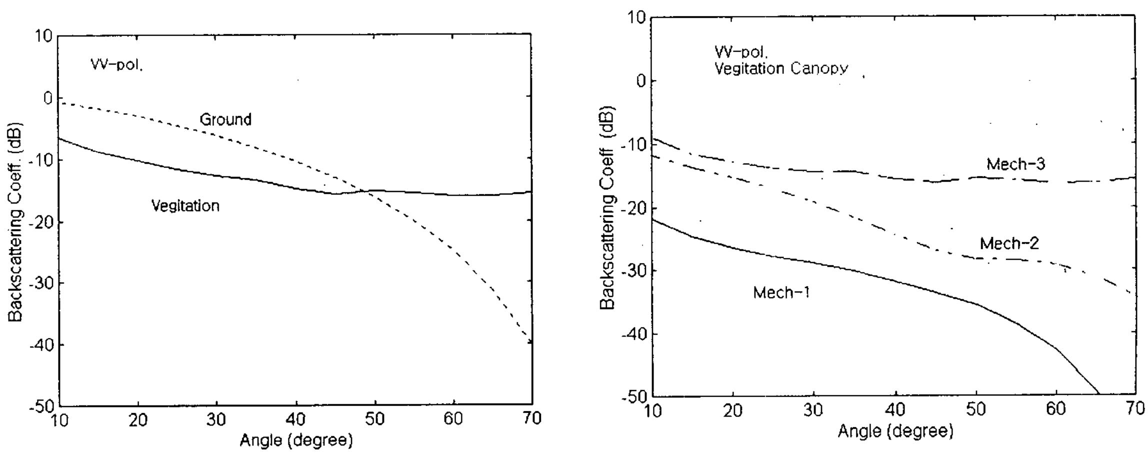

Fig. 3: Backscattering coefficient for vv-polarization; (a) comparison of ground and vegetation scattering, and (b) comparison of different scattering mechanisms.

4. Measurements

The backscattering coefficients from a patch of grassland were measured using Hong-Ik University's Ku-band indoor measurement facility. The radar system consists of an HP8510C vector network analyzer, an automatically controllable turn table, a Ku-band polarimetric antenna system and a computer. The radar has been calibrated accurately by the convenient calibration technique(CCT) using known targets; a sphere and a trihedral. Illumination integral for each angle was calculated by using three-dimensional antenna pattern and utilized to compute the backscattering coefficient accurately. At each incidence angle, 50 independent samples were measured to get enough statistics.

The ground truth data were also measured at the same time. At first, a small 15 cm × 15 cm patch was selected to measure statistics of size and orientation of leaves. The number of the leaf in the small patch was 150. The mean values of width, length, thickness, elevation angle, and azimuth angle of leaves are 3.28 mm, 8.1 cm, 0.22 mm, 46.1^0, and 135.2^0, respectively. The histogram of leaf length and leaf elevation angle of 150 samples are shown in Fig. 4(a) and (b).

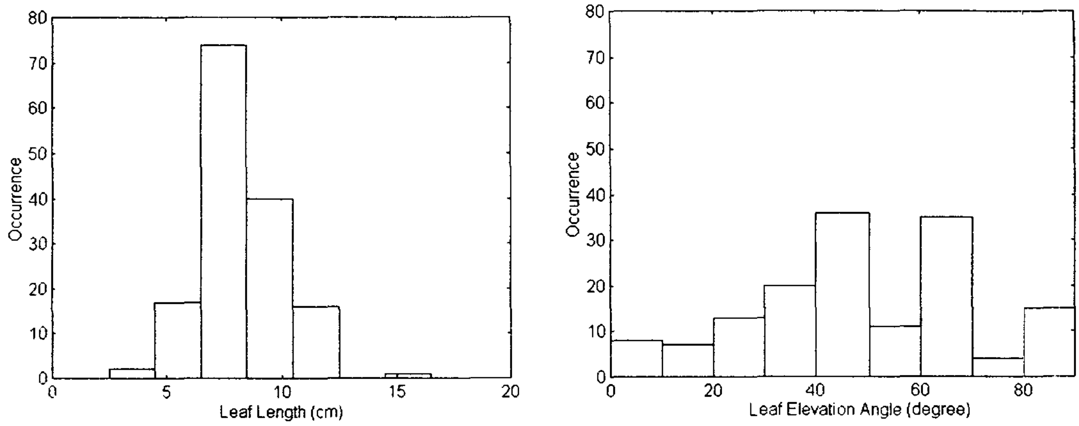

Fig. 4: Histograms for distributions of (a) leaf length (b) and (b) leaf elevation angle (θ).

Then, the roughness of soil surface was computed using four sets of measured surface height distributions. The measured rms height and the measured correlation length are 0.92 cm and 7.1 cm, respectively. The shape of the normalized correlation resembled more to an exponential function than a Gaussian function.

Figs. 5(a) and (b) show comparison of the measurement of polarimetric backscattering coefficients at 20^0 -70^0 angular range and the computation results by the radiative transfer model based on the measured ground truth.

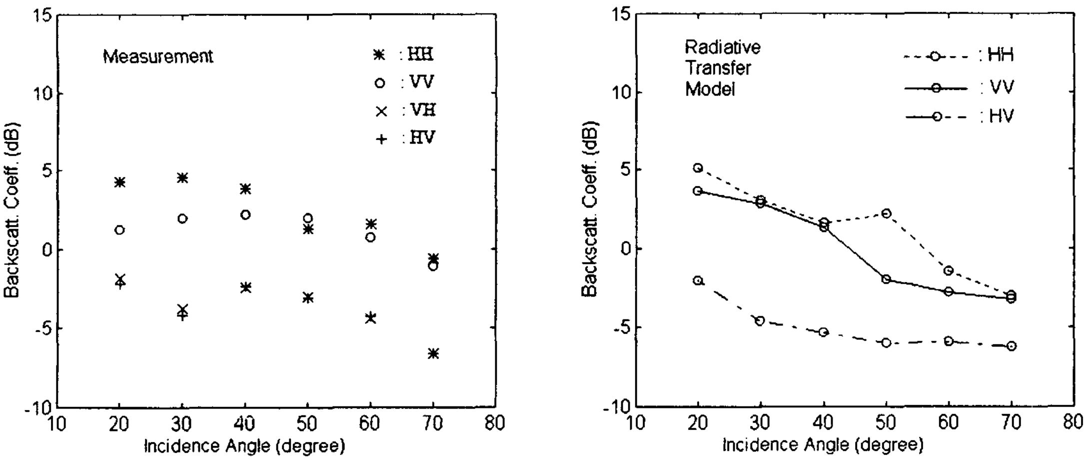

Fig. 5: Polarimetric backscattering coefficients obtained from (a) measurements and (b) radiative transfer model.

The radiative transfer model agrees with the measurements relatively well. The hh-polarized backscattering is higher than vv-polarization, and the ratio of hh-polarized and hv-polarized backscattering coefficients is 4 - 7 dB in both cases. The model, however, show deviations from the measurements at some angles, and the model might be improved in near future for better agreement with the measurements.

5. Conclusion

Microwave polarimetric backscattering coefficients of grassland canopies have been computed by using the first-order radiative transfer model. Leaves in the grassland are modeled by rectangular resistive sheets, which sizes and orientations are randomly distributed over a rough soil surface. A Ku-band indoor radar system were used for measurement of the backscattering coefficient of a grassland. The computation result obtained by the scattering model for the grass canopy agreed relatively well with the measurements.

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