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Research Article

Electromagnetic Scattering of Rough Ground Surface Covered by Multilayers Vegetation

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A microwave scattering model is proposed for the ground surface covered with multilayers vegetation. The vegetation leaves are simulated with the discrete elliptical particles in layers, which are randomly distributed above the randomly rough surface. The finite element method is applied to solve the scattering magnetic field equation based on the Dirichlet boundary, and the relationship between the radar cross section and bidirectional reflectance distribution function is deduced with the coherent scattering field. The internal mechanism of microwave scattering of multilayers vegetation is explored with the numerical results, and the relationship of vegetation growing parameter with scattering characteristic is established.

1. Introduction

The research on composite electromagnetic scattering of random rough surface covered by vegetation is significant for soil moisture retrieval, inversion model of vegetation parameter, and crop monitoring [1]. Due to the complexity of scattering mechanism in land surface environment, there are many problems about modelling methods and measurement technologies that remained to be solved recently. Although the empirical model is explicitly expressed with measured data, the definite physical meaning and phase of scattering field cannot be provided by statistical formula. On the other hand, the physical models are reasonably accurate, which needs massive iterations or matrix calculations.

Considering the vegetation canopy as a continuous random medium or ensemble of discrete scatters, kinds of bidirectional reflectance distribution function (BRDF) models have been developed for evaluation of remote sensing data. In the geometrical optic (GO) model, the leaves and branches of vegetation were taken as typical discrete scattering source, such as cylinders, disks, cones, and so on, and the scattering matrix was established for multiple scattering [2, 3]. Based on the law of energy conservation, the radiative transfer (RT) models predicted the scattering coefficients of continuously distributed scatters, which evolve as the famous MIMICS model, SAIL model, and GeoSAIL model for BRDF modelling of vegetation canopies [4–6].

Since the sizes of leaves and branches are much larger than the wavelength of radar wave in the light wave band, the coupling effect of each scattering component could be neglected in the BRDF models mentioned above. The total scattering field can be assumed as the linear combination of several components based on the optical approximation, which is calculated with semi-empirical shadowing function [7]. Nevertheless, the complex coupling scattering relationship is difficult to be analytically expressed in the microwave band because of resonance scattering in the vegetation layers, and the optical approximation could lead to uncontrollable errors in the scattering model and vegetation parameter retrieval.

According to analysis of half-space Green Function, the electromagnetic backscattering model for earth ground is developed based on the integral equation methods, which are more advantaged for the open domain problems [8]. The numerical approach of the finite element method (FEM) cooperated with the perfectly matched layer (PML) is extended to analyse the scattering properties of an arbitrary dielectric target above the dielectric rough surface. As the outward wave is absorbed with PML, the calculation accuracy of scattering field is promoted [9, 10]. Moreover, the domain decomposition method is used for finite difference time domain (FDTD) method, and the coherent scattering field is obtained based on the reciprocity theorem. The FDTD method is also used to predict the three-dimensional radiation fields of the entire tree, by combining the effects of the single elements forming the tree [11, 12].

Meanwhile, the composite scattering problem of electrically large rough surface covered with discrete particles is analysed with high frequency methods, and the graphics processing unit (GPU)-based massively parallel approach is also widely developed for efficient computation of electromagnetic scattering [13, 14]. By adding the average deviation of leaf angle distribution to accurately estimate the backscattering coefficients with the angular effect of scattering particles in a vegetation canopy, the water-cloud model is modified, and the results agree with the radar measurements of vegetation fields at C- and X-bands [15]. The energy conservation in scattering from layered random rough surfaces is studied with the second-order small perturbation method (SPM2), which includes both first-order incoherent scattering and a second-order correction to the coherent fields [16]. The coherent branching model of soybean shows that HH scattering has a significant difference up to 3 dB from that of the independent scattering [17].

This paper presents a composite scattering model of rough ground surface covered by multilayers vegetation in microwave band, which is derived from the realistic radar wave scattering observation. The internal mechanism of interaction between the vegetation canopies with the electromagnetic wave is analysed to establish relationship of vegetation growing parameter and radar echo. The complex physical scenario consists of vegetation and ground surface is simulated with horizontally random and vertically stratified discrete leaves and Gaussian rough surface. The full wave scattering field is calculated based on the Helmholtz equations with the FEM method, and the radar cross section (RCS) of land surface is deduced with the bidirectional reflectance distribution function (BRDF). The relationship of scattering field and vegetation parameters is discussed based on the simulated numerical results.

2. Geometry Model of Rough Ground Surface Covered with Vegetation

The reasonable geometry model is the important foundation of solution to electromagnetic calculation problem. Since it is difficult to apply the three-dimensional realistic geometric model of land ground covered by vegetation in numerical calculation, the simplified multilayers vegetation scattering model is shown in Figure 1, which is derived from the observation of realistic scattering phenomenon. While the two-dimensional Gaussian rough surface is used to simulate ground fluctuation, the typical leaves of layered vegetation are modelled with discrete elliptical particles, which are randomly distributed above the ground surface. Although this geometry model is obtained based on the observation of growth characteristics of corn, it can be applied for the similar vegetation.

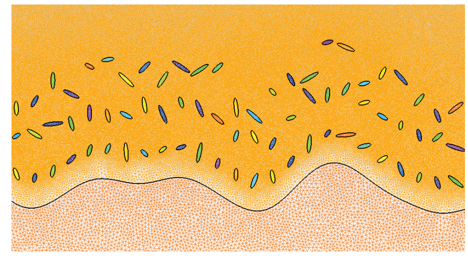

FIGURE 1: Schematic representations of geometric model for ground surface covered with multilayers vegetation. The typical leaves are modelled with discrete elliptical particles.

2.1. Model of Rough Ground Surface. The rough ground is taken as a kind of random rough surface with Gaussian distribution, which is simulated with the linear superposition method (LSM) [18].

$$f(x_n) = \frac{1}{L} \sum_{m=-N/2}^{N/2-1} F(K_m) \exp(-jK_m x_n) \tag{1}$$

where L is the length of the rough surface which is subdivided into N sections. The length of each section is Δx, and the surface is discretized as $x_n = n\Delta x (n = 1, 2, \cdots N)$. Equation (1) can be calculated with the Fast Fourier Transform (FFT).

$$F(K_m) = \sqrt{2\pi L W(K_m)} \begin{cases} \left(\frac{1}{\sqrt{2}}\right)[N(0,1) - jN(0,1)] & 1 \le m \le \frac{N}{2} - 1 \\ N(0,1) & m = 0, \frac{N}{2} \end{cases} \tag{2}$$

where $K_m = 2\pi m/L$, and $N(0,1)$ is a Gaussian distributed random number. The spectra function of Gaussian rough surface is given as

$$W(K_m) = \frac{h^2 l}{2\pi} \exp\left(\frac{K_m^2 l}{4}\right) \tag{3}$$

where h is the root mean square height and l is the correlation length.

2.2. Model of Multilayers Vegetation. The vegetation layers consist of leaves, stems, and branches, of which size, shape, and inclination angle are the significant parameters for microwave scattering. According to the observation of vegetation growing seasons, the leaves and stems are commonly simplified as elliptical model. Various kinds of vegetation are characterized with the axial ratio, inclination angle, and probability distribution density of elliptical particles. Considering that the vegetation is distributed with the rough ground surface fluctuation, the two-dimensional random distribution characteristics of single vegetation layer are expressed with distribution function $g(x, \phi)$ of elliptical model

$$g(x, \phi) = g_w(x, y) + g_l(\phi) \tag{4}$$

where $g_w(x, y)$ is the location distribution function [19], which is realized as Poisson distribution. $g_l(\rho)$ is the distribution function of inclination angle

$$g_l(\phi) = h(\phi)\sin(\phi) \tag{5}$$

$$h(\phi) = \frac{\beta}{\sqrt{1 - \rho^2\cos^2(\phi - \phi_m)}} \tag{6}$$

where ϕ and ρ are the inclination angle and ellipse eccentricity of leaves, respectively, and ϕ_m is the model inclination angle. β is determined by the normalization conditions [20]. Due to the changing shape of vegetation in different growing periods, the elliptical particles are vertically stratified, of which the sizes are also uniformly random.

3. Composite Scattering Model Based on Numerical Methods

Based on the composite geometric model of rough ground covered with multilayers vegetation, the scattering field is evaluated with numerical methods. Considering the transverse electric field case, the corresponding Helmholtz equation of scattering magnetic field is given as

$$\nabla^2 H_z(x, y) + k_0^2 H_z(x, y) = 0 \tag{7}$$

According to the Green Theorem, the integral of scattering field H_z and Green Function G are given on the domain D and ∂D

$$\iint\limits_D \left(G\nabla^2 H_z - H_z\nabla^2 G\right) dD = \int\limits_{\partial D} \left(G\frac{\partial H_z}{\partial n} - H_z\frac{\partial G}{\partial n}\right) dr \tag{8}$$

where D is the two-dimensional domain with boundaries ∂D. $\hat{n}$ is the normal unit vector of the boundary and the partial derivative is expressed as $\partial/\partial n = \hat{n}\nabla^2$. Then (8) is simplified with (7)

$$\iint\limits_D H_z\left(\nabla^2 G + k^2 G\right) dD = \int\limits_{\partial D} \left(H_z\frac{\partial G}{\partial n} - G\frac{\partial H_z}{\partial n}\right) dr \tag{9}$$

According to the wave equation of Green Function, the left part of (9) can be simplified as

$$H_z = -\int\limits_{\partial D} \left(H_z\frac{\partial G}{\partial n} - G\frac{\partial H_z}{\partial n}\right) dr \tag{10}$$

Since the two-dimensional Green Function can be expressed with the Hankel Function $H_0^{(1)}(k\mathbf{r})$, the equation of scattering field is derived as

$$\begin{aligned} &H_z(x, y) \\ &= \frac{i}{4}\int_{-\alpha}^{\alpha} \left(H_z(x)\frac{\partial H_0^{(1)}(k\mathbf{r})}{\partial y} - H_0^{(1)}(k\mathbf{r})\frac{\partial H_z(x)}{\partial y}\right) dx \end{aligned} \tag{11}$$

where the interval $[-\alpha, \alpha]$ is the two-dimensional boundary of rough surface at x axis.

The far field approximation should be included in the calculation of scattering field; thus the asymptotic development of Hankel Function is obtained for the far field case

$$H_0^{(1)}(kr) \approx \sqrt{\frac{2}{\pi kr}} e^{i(kr - \pi/4)} \tag{12}$$

Inserting (12) into (11), the scattering magnetic field is given as

$$H_z = C(d) K(\theta) \tag{13}$$

$$C(d) = \frac{i}{4}\sqrt{\frac{2}{\pi kd}} \exp\left[i\left(kd - \frac{\pi}{4}\right)\right] \tag{14}$$

$$\begin{aligned} K(\theta) = &\int_{-\alpha}^{\alpha} \left[-H_z(x)\, ik\sin\theta - \frac{\partial H_z(x)}{\partial y}\right] \\ &\cdot \exp(-ikx\cos\theta)\, dx \end{aligned} \tag{15}$$

where θ is the scattering angle and d is the distance from the scatter to the observation point. It is noted that $C(d)$ is the complex factor which depends on d, and the angular distribution of scattering magnetic field is determined by the important factor $K(\theta)$.

The scattering magnetic field in the differential Helmholtz equation shown in (7) is numerically calculated with FEM. The technology of PML is utilized to eliminate the artificial reflections caused by the boundaries. Moreover, the initial PML domain is separated into smaller regions for the increase of efficiency. Using the incident field as weighted function, the Galerkin method is applied for the numerical solutions. Then the value of $K(\theta)$ in (15) is obtained with the scattering magnetic field H_z, which is to be applied for the following evaluation of BRDF and RCS.

Reflectance properties of vegetation can be represented by BRDF, which illustrates the scattering of materials as a function of incidence and scattering angles and wavelength [21]. BRDF of scatter is defined as

$$f_r = \frac{L_r(\theta_i, \varphi_i; \theta_r, \varphi_r)}{E_i(\theta_i, \varphi_i)} \tag{16}$$

where $L_r(\theta_i, \varphi_i; \theta_r, \varphi_r)$ is the reflective brightness in the direction (θ_r, φ_r) and $E_i(\theta_i, \varphi_i)$ is the incident irradiance. For the electromagnetic scattering of expanded surface, the reflective brightness and incident irradiance can be substituted with the incident power P_i and scattered power P_s, respectively. Then (16) is rewritten as

$$f_r = \frac{dP_s}{P_i d\Omega\cos\theta_r} \tag{17}$$

where Ω is the solid angle. The power P_s is commonly evaluated with the Poynting vector $\mathbf{S}$, which is derived with (13) based on the assumption of plane wave

$$\mathbf{S} = \frac{1}{2}\mathbf{E} \times \mathbf{H}^* = \frac{1}{2} z_0 \frac{1}{8\pi kd} |K(\theta)|^2 \tag{18}$$

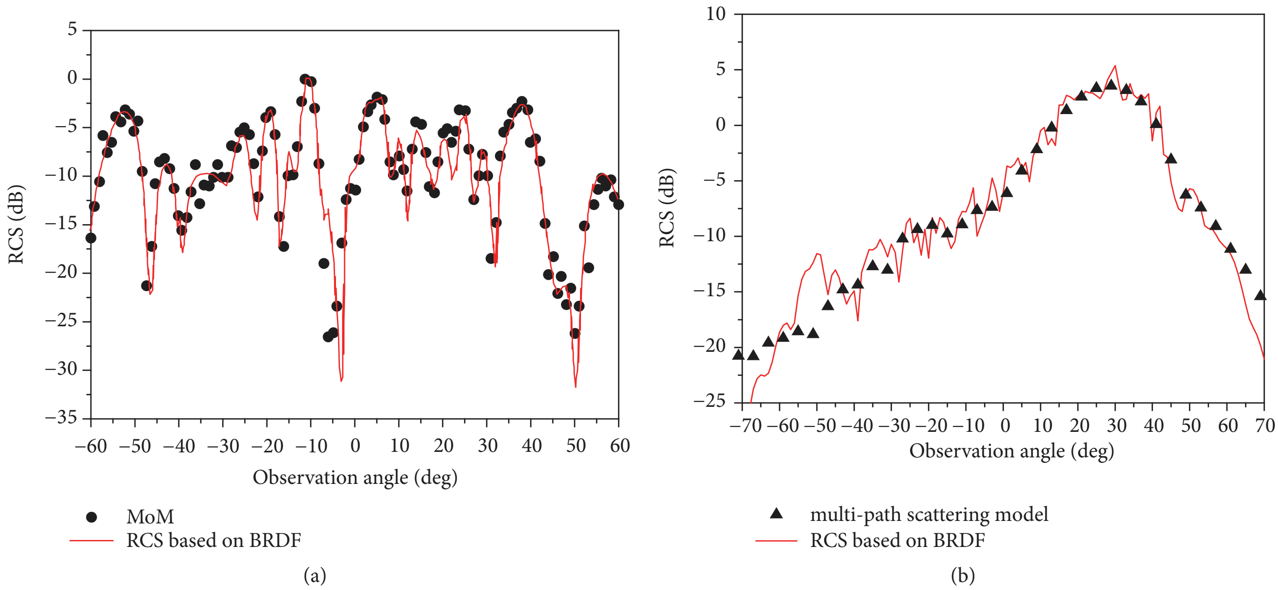

FIGURE 2: Validation of the presented method with the numerical methods. (a) The presented method is compared with MoM based on the rough land surface. (b) The presented method is compared with multipath scattering model based on the rough land surface covered by vegetation layers.

where z_0 is the wave impedance and $K(\theta)$ is obtained with (15). Thus, the BRDF f_r is calculated with the scattering magnetic field H_z. Meanwhile the scattering intensity of land surface can also commonly be analysed with scattering coefficient, which is defined as

$$\sigma = \lim_{d\longrightarrow\infty} 2\pi d \frac{|E_r|^2}{A_i |E_i|^2} \tag{19}$$

A_i is the illuminated area of surface. E_r and E_i are the scattering and incident electric fields, respectively. When A_r is noted as the receiving aperture, the ratio of received scattering power ΔP_s and incident power P_i is given as

$$\frac{\Delta P_s}{P_i} = \frac{A_r |E_r|^2}{A_i \cos\theta_i |E_i|^2} \tag{20}$$

Including (20), the scattering coefficient σ in (19) is rewritten with the power

$$\sigma = \lim_{d\longrightarrow\infty} 2\pi d \cos\theta_i \frac{\Delta P_s}{A_r P_i} = 2\pi \cos\theta_i \frac{dP_s}{P_i d\Omega} \tag{21}$$

where the solid angle is defined as $d\Omega = \lim_{d\longrightarrow\infty} A_r/d$. Comparing (17) and (21), the relationship of BRDF and scattering coefficient is expressed as

$$\sigma = 2\pi \cos\theta_i \cos\theta_r f_r \tag{22}$$

Consequently, the RCS of scatter is obtained with the integral on the surface of scatter

$$\text{RCS} = \int_A 2\pi f_r \cos\theta_i \cos\theta_r dA \tag{23}$$

Different from the classic GO model, the multiple scattering and shadowing effect are solved with full wave numerical algorithm. The calculation of each scattering component is unnecessary, and the errors caused by the manual setting ratio coefficient are intrinsically eliminated.

Due to the random distribution of vegetation leaves and stems in realistic environment, the scattering field of single geometric model of ground covered with vegetation could only be used to explore the scattering mechanism. In order to analyse the statistical characteristics of composite scattering, the Monte Carlo method is utilized to calculate the scattering intensity. The inclination angles and positions of the vegetation leaves are set with random number generator based on Poisson distribution, and the random roughness of ground is simulated with the Gaussian distributed random number. The statistical numerical results are obtained with the ensemble average of scattering field samples, and 50 samples are taken for each calculation case of BRDF and RCS.

4. Numerical Results and Discussion

4.1. Accuracy Validation of Scattering Model. Due to the advance in open domain problem, integral equation method (IEM) is widely used for the numerical calculation of land surface scattering, which is commonly realized with the method of moment (MoM) [22]. In order to validate the accuracy of the presented composite scattering model, the numerical results are compared with the mature MoM model in Figure 2(a). A dielectric rough surface is illuminated by a plane wave. The wavelength of the incident wave is 1 m and incidence angle is 0°. The calculation region is $8\lambda \times 8\lambda$ along both x- and y-directions. The root mean square (RMS) height and the correlation length of two different random rough

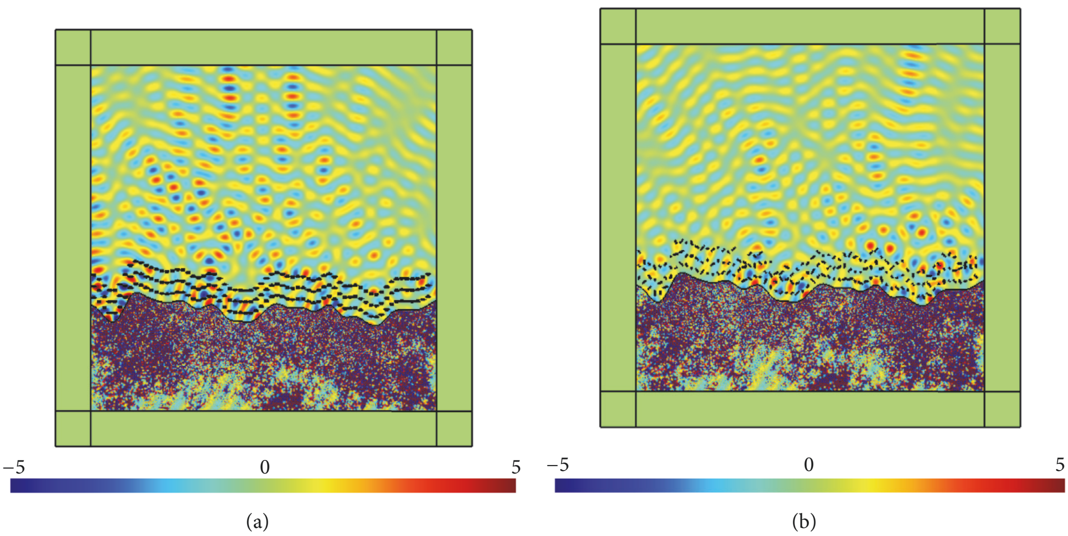

Figure 3: Near scattering field from the multilayers vegetation. (a) Uniformly distributed vegetation. (b) Randomly distributed vegetation.

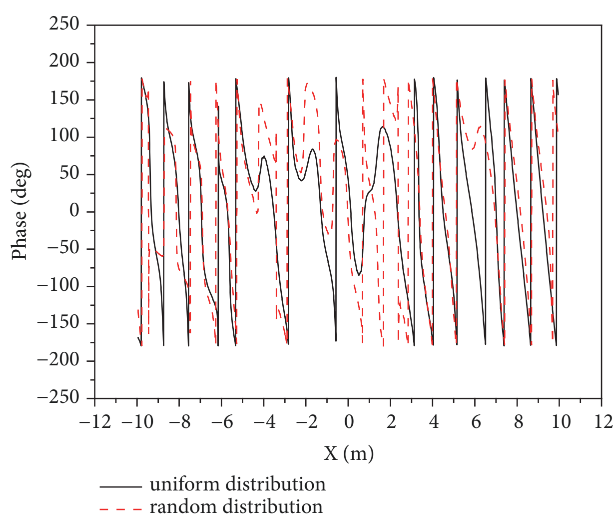

Figure 4: Phase of near scattering field from the multilayers vegetation with uniform distribution and random distribution.

surfaces are 0.5λ and 1λ, respectively. Figure 2 shows that the RCS which is transformed from BRDF matches well with the one obtained from MoM at most of the observation angles. The numerical results prove that the BRDF method could describe the electromagnetic field efficiently and straightforwardly. Due to the dielectric characteristics of leaves, the BRDF method is much more suitable for the electromagnetic scattering of vegetation, which is derived from differential equations.

The multipath scattering model has been widely applied for the calculation of electromagnetic scattering from ground covered with vegetation and obtains accordance with the measurement data [23]. Thus, the presented composite scattering model is also compared with the multipath scattering model. There are 3 layers vegetation leaves, and the geometric parameters of the rough surface are the same as the ones in Figure 2(a). The incidence angle is 30°, and the electromagnetic wavelength is 0.2 m. The results of bistatic RCS are shown in Figure 2(b). It is found that the general agreement appears between the results data of two models with scattering angle. The differences between solution methods of the coherent scattering of the two models lead to the discrepancies of RCS value at specular direction. The scattering intensity is also enhanced by the vegetation layers compared with the one in Figure 2(a). Considering the advantage of FEM on the accuracy of calculation of coupling scattering, the result of presented model is more reasonable for the two-dimensional geometric model.

4.2. Comparison of Vegetation Distribution Models. Considering the multiple scattering of vegetation leaves, the influence of vegetation distribution on near scattering field is discussed based on the simulated results. The uniform distribution and random distribution are compared in Figures 3 and 4. The wavelength of incident TM wave is 1 m, and the incidence angle is 60°. While the vegetation elements are uniformly distributed in single layer, the apparent speckles are found in the spatial distribution of scattering intensity. The regular stripes of field intensity are brought by the strong coherent scattering, which depends on the roughness of ground surface. Due to the diffuse scattering caused by the multiple scattering of randomly distributed leaves, the electromagnetic modulation effect is eliminated by the anisotropic positions of volume scatters. The phase of scattering field is extracted from the plane above the ground as shown in Figure 4, which is significant for the radar image and vegetation parameter retrieval.

The phase curves periodically vary along the x axis, of which slopes are related to the incidence angle in Figure 4. The oscillation of phase slope is caused by the composite scattering vegetation and rough ground, which is apparently influenced by the randomness of leaves distribution.

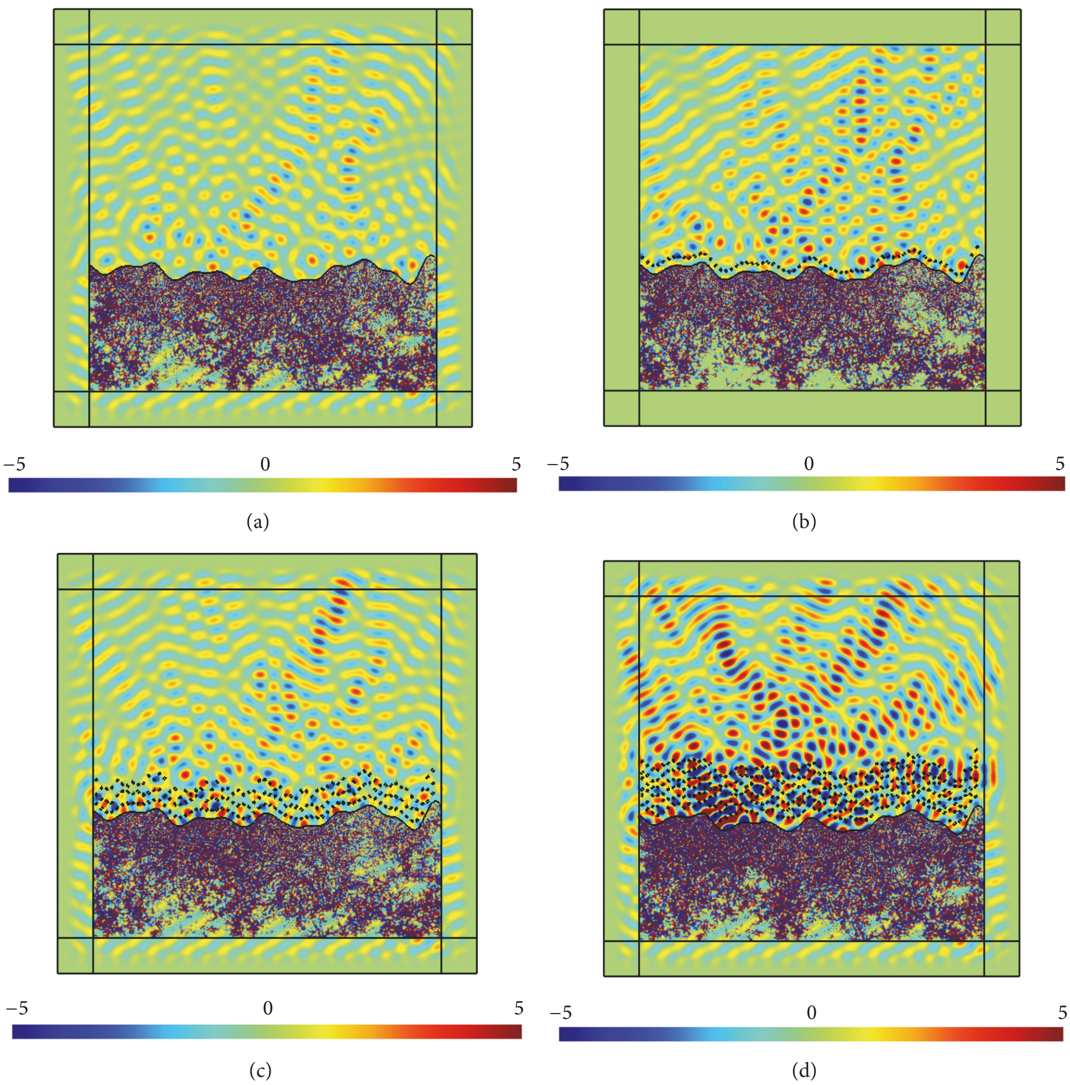

FIGURE 5: Near scattering field of ground surface with different layers of vegetation. (a) Scattering field without vegetation, (b) scattering field with 1 layer of vegetation, (c) scattering field with 3 layers of vegetation, and (d) scattering field with 6 layers of vegetation.

In consideration of the growth characteristics of common vegetation, the random distribution model of vegetation leaves is used in this paper.

4.3. Influence of Vegetation Layers Number on Composite Scattering. According to the remote sensing experimental data, the number of layers, water content, and density of leaves are key parameter of vegetation model for scattering analysis, which are closely related with the grow season of vegetation [17]. The near scattering field of ground surface covered by different layers of vegetation is shown in Figure 5. The relative permittivity of vegetation layer is $\varepsilon_r = 5 + j8$, and the distance between the layers is 0.3 m. The incident angle is 30°. It is found that the near field of composite scattering is apparently enhanced by the volume scattering from the vegetation layers, and the spatial distribution of field intensity exhibits coherent effect. The bright spots between the vegetation layers also indicate the strong multiple scattering between the leaves.

The far field scattering is evaluated with BRDF and RCS based on the field transformation, as shown in Figures 6 and 7. According to the intensity distribution of near field, the BRDF and RCS increase with the number of vegetation layers. While specular peaks of scattering intensities are obvious for the ground without leaves and with 3 layers of leaves, the peak of RCS in specular direction vanishes due to the strong multiple scattering between layers and the roughness of ground surface. Figure 7 shows that the increase of RCS from the bare soil surface to the one covered with 6 layers is more than 5 dB in the vertical direction, which is in accordance with [17]. Meanwhile it is found that the backscatter enhancement is caused by the volume scattering of leaves.

4.4. Influence of Leaves Features on Composite Scattering. The moisture of vegetation dramatically changes during different growing seasons, which is related to water content of leaves.

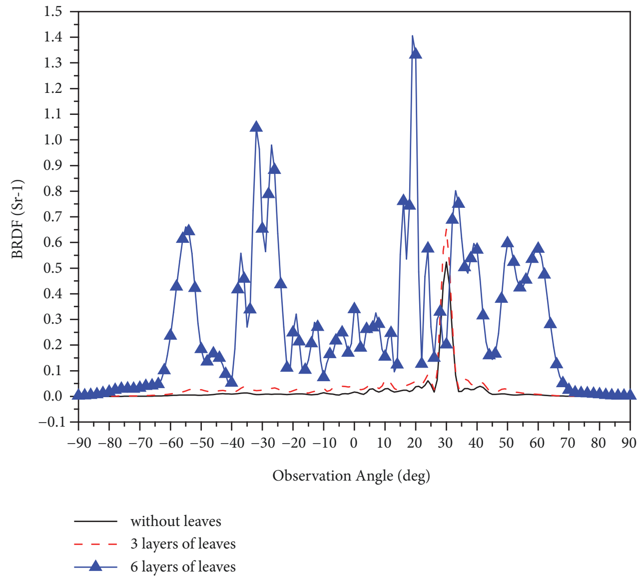

FIGURE 6: BRDF with different layers of leaves.

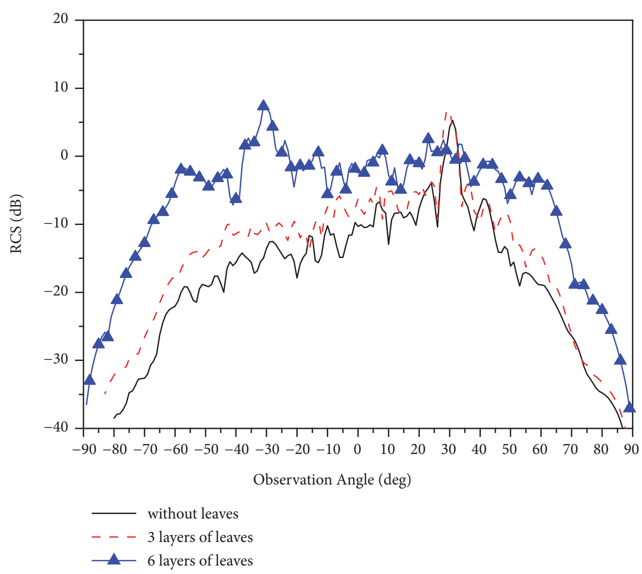

FIGURE 7: RCS with different layers of leaves.

Although the water content of vegetation is difficult to quantitatively examined, the semi-empirical relationship of water content and dielectric constant was established for corn leaves with the experiments data [24]. The complex dielectric constants of various vegetation are numerically evaluated with different water content of vegetation leaf as shown in Table 1.

Figure 8 shows that the enhancement of near scattering field is caused by the water content. It is indicated that the local reflectance of electromagnetic wave on the vegetation element is enhanced by the bound water in the leaves. Accompanying with the increasing water content, the strong scattering sources are transferred from vertically flat area to drastically undulating area, which are jointly influenced by the multiple scattering effect and vegetation moisture.

Figure 9 shows that the BRDF is extremely sensitive to the dielectric properties of vegetation. The nonlinear relationship of BRDF with water content shows that strong scattering appears associated with high moisture of vegetation.

The relationship of electromagnetic scattering with the leaf's shapes is examined with RCS in Figure 10. Since the leaves are simulated with elliptical particles, the shape of leaf is characterised with major axis a and minor axis b. RCS increases apparently with the size of leaves, which indicates that the vegetation layers are significant source of scattering. Moreover, the axial ratio of leaf seems to be a factor of

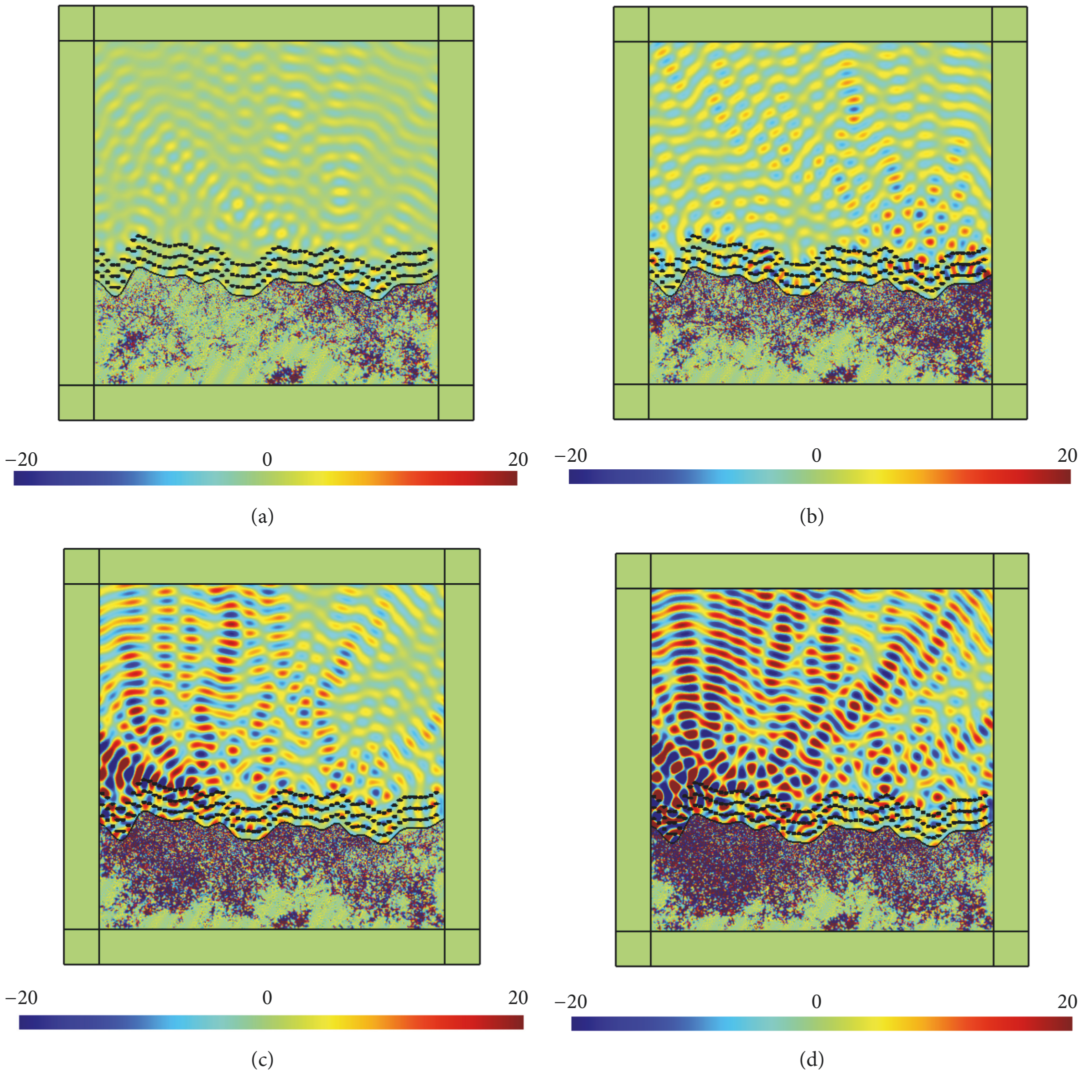

FIGURE 8: Near scattering field of ground surface with different water content of leaves. (a) Water content is 38.36%. (b) Water content is 51.42%. (c) Water content is 66.96%. (d) Water content is 68.61%.

TABLE 1: Relationship of complex dielectric constant with water content for corn leaf.

Water content	Real part of complex dielectric constant	Imaginary part of complex dielectric constant
38.36%	8	2.5
51.42%	12	3.8
66.96%	18	5.5
68.61%	19.5	5.5

scattering, and the thin leaves lead to stronger scattering intensity in the back direction.

4.5. Influence of Vegetation Density on Composite Scattering. Due to the absorption and multiscattering of electromagnetic wave in leaves, the scattering field is related to the density of discrete vegetation elements, which is discussed with RCS and BRDF. While the number of vegetation layers is three, the horizontal intervals of particles are 0.3 m, 0.5 m, and 0.7 m, respectively. The influence of vegetation density on BRDF and RCS is discussed in Figure 11. Since the coherent scattering of the leaves is enhanced by the increasement of vegetation density, the BRDF and RCS of internal 0.3 m are obviously higher than the ones of internal 0.7 m. Moreover, the peaks of BRDF in special angles indicate the directivity selection for ground remote sensing.

4.6. Influence of Ground Roughness on Composite Scattering. The influence of ground surface on the scattering intensity is analysed in Figure 12. The land ground is covered with 3 layers

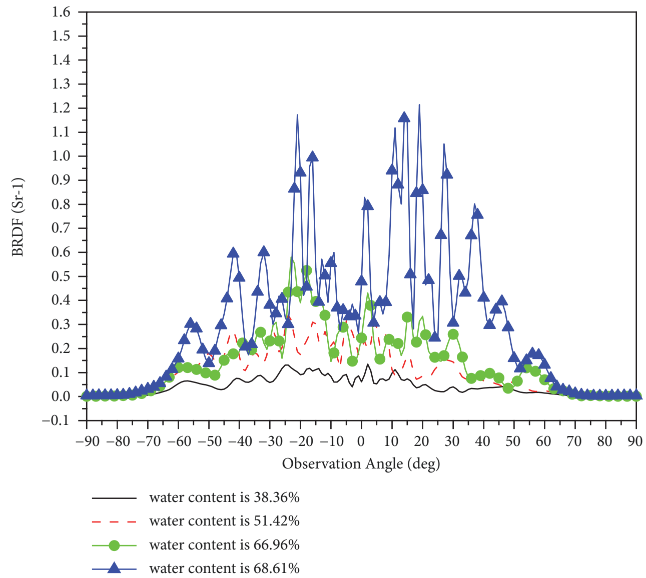

Figure 9: BRDF with different water contents of leaves.

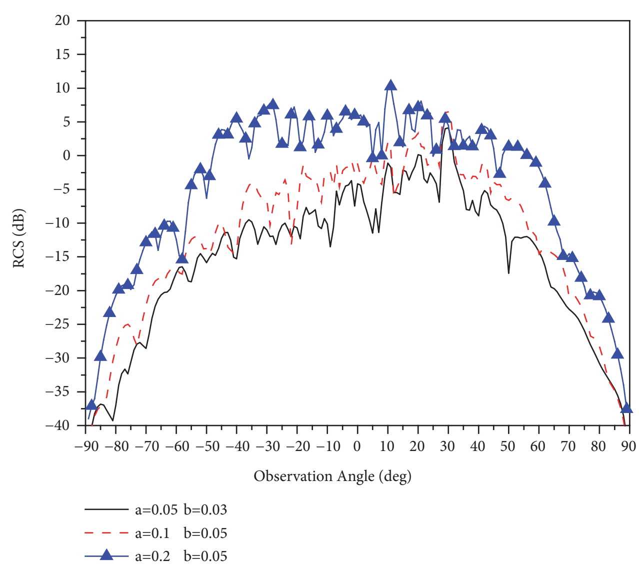

Figure 10: RCS with different shapes of leaves.

of vegetation, and the incidence angle is 30°. The roughness of surface is characterized with RMS and correlation length. It is shown that the scattering intensity increases with the RMS, and the smaller correlation length leads to strong backward scattering. The roughness of ground surface is a significant factor of diffuse field. Combining with Figures 7 and 10, it seems that the influence of ground surface roughness is less than the one of the vegetation layers. Therefore, the multiple scattering of vegetation should be carefully considered for the scattering field estimation and process of radar wave.

4.7. Influence of Incidence Angle on Composite Scattering. The scattering feature of vegetation layers is related to the incidence angle, as shown in Figure 13. When the incidence angle is 30°, the obvious peak of RCS is found in the specular direction. If the incidence angle increases to 60°, peak value decreases about 5 dB caused by the diffusing reflection. The scattering in the back direction is obviously enhanced with the large incidence angle, and the peak cannot be found. It is concluded that the electromagnetic scattering of vegetation layers is different from the one of bare oil ground. The regular angular distribution of scattering intensity is interfered by the multiple scattering of the leaves. In other words, the roughness of scatter increases by the vegetation cover.

5. Conclusions

The electromagnetic scattering of rough ground surface covered with multilayers vegetation is numerically investigated

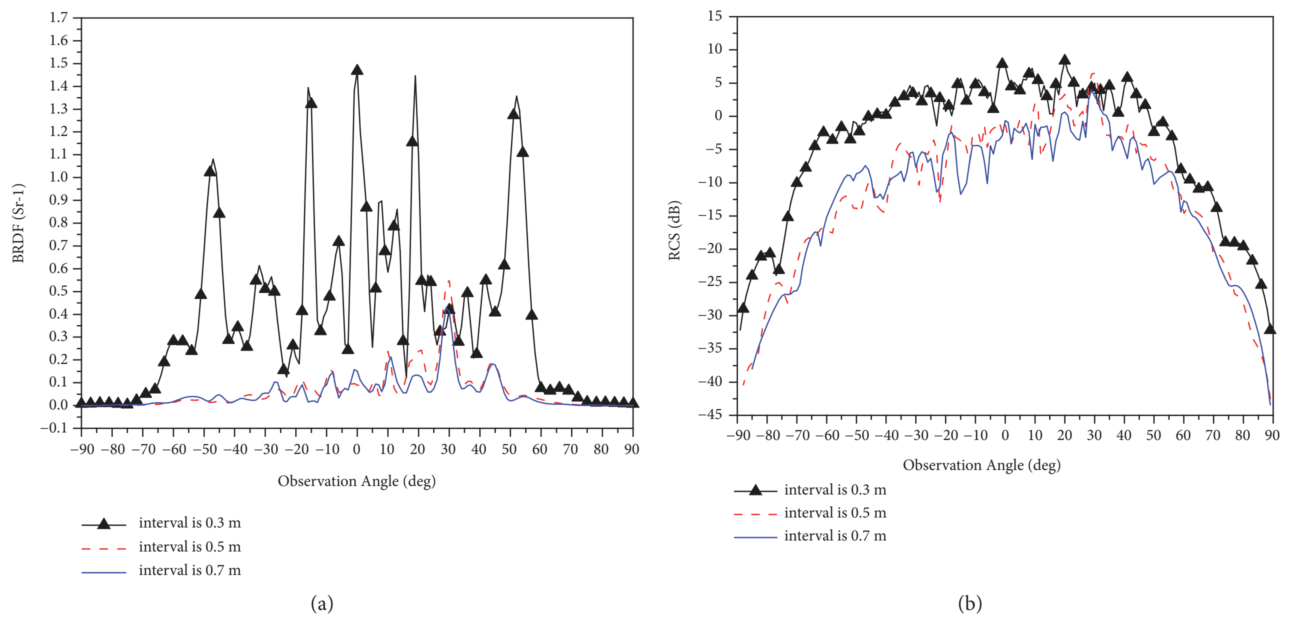

Figure 11: Relationship between scattering intensity and density of vegetation leaves. (a) BRDF with different intervals of leaves. (b) RCS with different intervals of leaves.

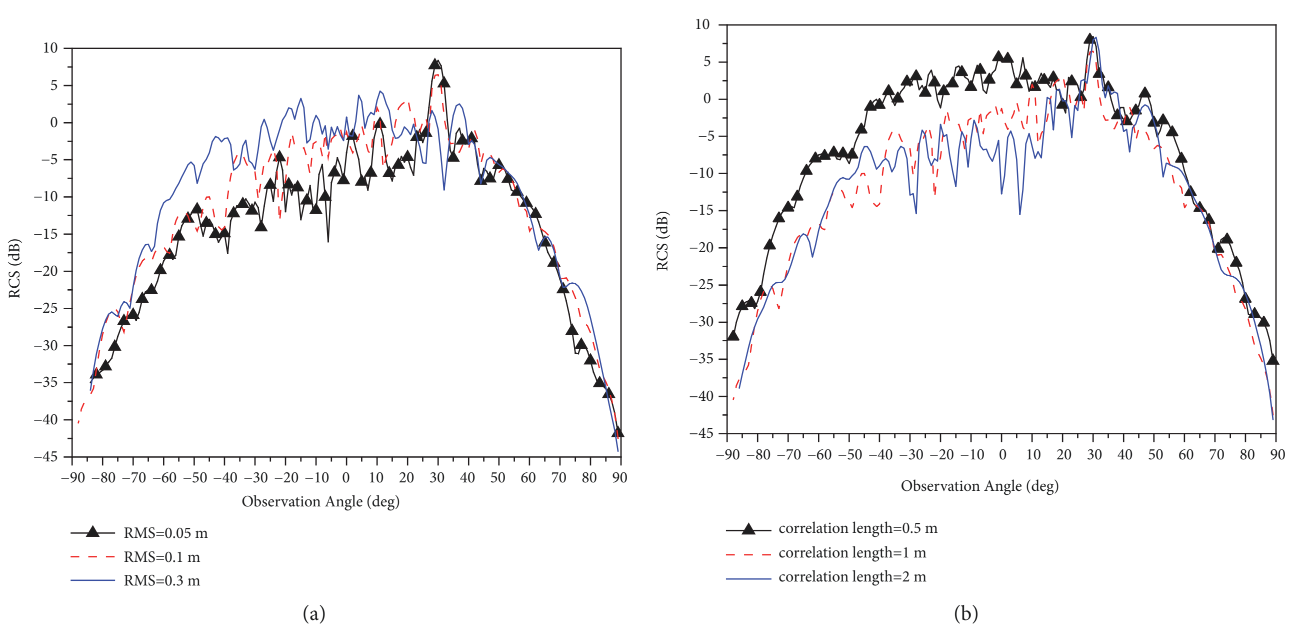

Figure 12: Relationship between the ground roughness and RCS. (a) RCS with different RMS of ground surface. (b) RCS with different correlation length of ground surface.

with the two-dimensional composite scattering model, which is established with discrete elliptic elements and Gaussian rough surface. Based on the solution to scattering magnetic field equation, the near scattering field, BRDF and RCS are examined under various conditions of vegetation distribution. Although the geometry model of ground surface and vegetation layers is two-dimensional, the basic principle of multiple scattering is presented with numerical solution. This composite scattering model is suitable for various crops, of which geometry model should be modified accordingly.

The phase of scattering field is apparently influenced by the spatial distribution pattern of vegetation elements in single layer, which indicates that I/Q channel information of radar echo contains significant feature of vegetation structure. Meanwhile the phase of scattering field could be used for the radar imaging. It is obvious that the coherent

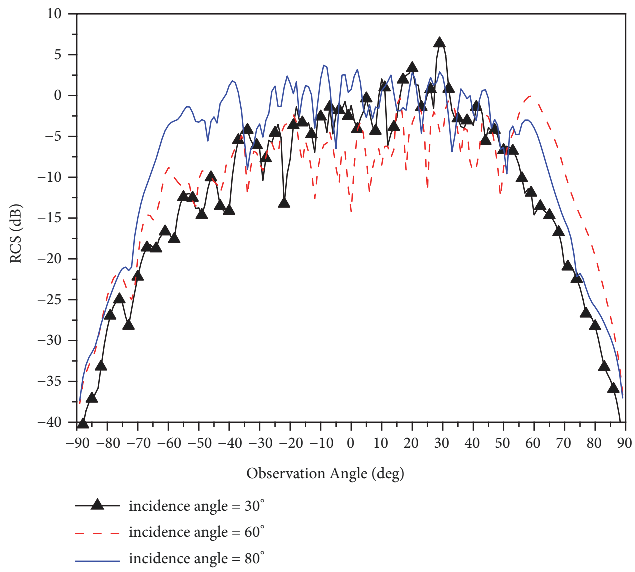

FIGURE 13: Simulations of the angular variation of RCS for different incidence angles.

scattering is enhanced by the number of vegetation layers and the density of leaves. Moreover, the influence of vegetation on the multiple scattering is distinguished in the BRDF and RCS simulation results. Since the water content, number of layers, and leaves density are key growing parameters of crops, the growth process of crops could be monitored with the relationship between growing parameters and microwave scattering intensity. BRDF of vegetation is found to be very sensitive to the water content, which is the basic data for the crop yield prediction. Consequently, a novel electromagnetic scattering numerical model of ground with multilayers vegetation is provided for the remote sensing in land surface environment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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