Bidirectional reflectance distribution function modeling of one-dimensional rough surface in the microwave band*

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In this study, the bidirectional reflectance distribution function (BRDF) of a one-dimensional conducting rough surface and a dielectric rough surface are calculated with different frequencies and roughness values in the microwave band by using the method of moments, and the relationship between the bistatic scattering coefficient and the BRDF of a rough surface is expressed. From the theory of the parameters of the rough surface BRDF, the parameters of the BRDF are obtained using a genetic algorithm. The BRDF of a rough surface is calculated using the obtained parameter values. Further, the fitting values and theoretical calculations of the BRDF are compared, and the optimization results are in agreement with the theoretical calculation results. Finally, a reference for BRDF modeling of a Gaussian rough surface in the microwave band is provided by the proposed method.

Keywords: bidirectional reflectance distribution function, rough surface, genetic algorithm, microwave band

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1. Introduction

The definition of the bidirectional reflectance distribution function (BRDF) was formally proposed in 1970 by Nicodemus.[1,2] The BRDF is the ratio between the surface irradiance micro-increment from a direction and the reflected radiation brightness increment from the direction caused by the direction. It can describe the space reflectance distribution characteristics and spectral characteristics of various surfaces; it is also suitable for obtaining scattering characteristics in laser, infrared, and microwave bands, which has a wide range of applications in fields such as target scattering characteristics,[3] ground-based remote sensing,[4] and computer image processing.[5] Theoretically, the light-scattering properties[6] of a rough surface were studied by the Kirchhoff approximation,[7] the perturbation,[8] and corresponding mixed methods. The relationship[9] between BRDF and unit radar cross section[10] has also been obtained, and BRDF can be calculated using the scattering coefficient of rough surface. BDRF is generally obtained with experiments and theoretical calculations. However, these two methods are complex and time consuming. Therefore, BRDF models based on the experimental data, such as the Cook–Torrance model,[4] Wolf model,[11] complex reflectance model,[12] and five-parameter models,[13] are used. The studies on BRDF of rough and target surfaces focus largely on the laser and infrared bands. However, to our knowledge, few papers about the BRDF of a rough surface in the microwave band have been reported in the published literature. In this paper, the modeling of BRDF in the microwave band is discussed.

A genetic algorithm[14–16] is an optimization algorithm that imitates biological genetics, the natural selection mechanism and constructs artificially. It is an optimization consisting of selection, crossover, mutation, and other basic operators. The algorithm is widely used, simple and effective. A genetic algorithm can seek the optimal solution for a problem using random probability, which is proved in theory. It has strong global optimization search capabilities and robustness without relying on a specific problem. A genetic algorithm is random, iterative and evolutionary, based on natural selection and population genetics, and has strong global optimization search capabilities. The algorithm requires variables that are expressed as binary strings. According to the principle of survival of the fittest, it chooses the binary string to copy that adapts exactly to the environment. Moreover, through crossover and mutation of two genes, a new generation string, which is more adaptive to the environment, is produced. After changing generations, the algorithm finally converges to one string that is the most adaptive to the environment. Finally, the optimal solution of the desired variable can be obtained by decoding the above binary string.

In this study, the BRDF is modeled for one-dimensional (1D) Gaussian conducting and dielectric rough surfaces using a genetic algorithm combined with the five-parameter model. The parameter values of the five-parameter model of a rough surface for different frequencies and roughness values are obtained in the microwave band. To verify the validity of the model, the model fitting values and calculated values obtained by the method of moments are compared. The BRDF of a rough surface at an incident angle of 40°, not included in the

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model for optimization, is also compared. The results illustrate the feasibility and reliability of BRDF modeling of 1D Gaussian conducting and dielectric rough surfaces in the microwave band.

2. Five-parameter model of BRDF

The BRDF is defined as the ratio of specific direction radiance and incident radiance of a rough surface scattering. A rough surface can be regarded as being composed of many small surface elements. The normal direction of each facet is in the upper hemisphere space. In this case, the phenomenon of diffraction and multiple reflections of the microscopic plane are not considered. The light scattering of the rough surface is the sum of the mirror reflections of the microscopic plane. In Fig. 1, BRDF can be expressed by the following equation when the uniform electromagnetic radiation to a surface is sufficiently large and isotropic:[17–19]

$$\begin{aligned} f_{\mathrm{r}} &= (\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}; \theta_{\mathrm{r}}, \varphi_{\mathrm{r}}) \\ &= \mathrm{d}L_{\mathrm{r}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}; \theta_{\mathrm{r}}, \varphi_{\mathrm{r}}) / \mathrm{d}E_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}) \\ &= \mathrm{d}L_{\mathrm{r}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}; \theta_{\mathrm{r}}, \varphi_{\mathrm{r}}) / [\mathrm{d}L_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}) \cos\theta_{\mathrm{i}} d\omega_{\mathrm{i}}], \end{aligned} \quad (1)$$

where θ_{i} and φ_{i} denote the incident angle and azimuth, and θ_{r} and φ_{r} denote the reflective angle and azimuth, respectively. Here, $\mathrm{d}L_{\mathrm{r}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}; \theta_{\mathrm{r}}, \varphi_{\mathrm{r}})$ is the reflective brightness in the direction of $(\theta_{\mathrm{r}}, \varphi_{\mathrm{r}})$, and $\mathrm{d}L_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}})$ is the incident brightness in the direction of $(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}})$. Further, $\mathrm{d}E_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}) = \mathrm{d}L_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}) \cos\theta_{\mathrm{i}} d\omega_{\mathrm{i}}$ is the illumination and $d\omega_{\mathrm{i}}$ is the radiation solid angle of the incident brightness $\mathrm{d}L_{\mathrm{i}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}})$.

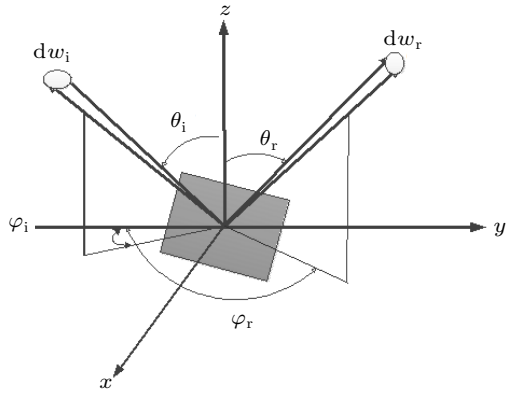


Fig. 1. Three-dimensional scattering model.

To more intuitively describe the scattering of the rough surface, the 1D geometric model is introduced in Fig. 2. Here, $\theta_{\mathrm{p}}^{\mathrm{i}}$, $\theta_{\mathrm{p}}^{\mathrm{r}}$, and γ_{p} are the projections of θ_{i}, θ_{r}, and γ, respectively, and α is the angle between the z axis and $\hat{n}$, which is the normal direction of the tiny plane. Referring to the above rough surface model, the five-parameter semi-empirical model of the BRDF can be expressed as[3]

$$f_{\mathrm{r}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}; \theta_{\mathrm{r}}, \varphi_{\mathrm{r}}) = k_{\mathrm{b}} \frac{k_{\mathrm{r}}^2 \cos\alpha}{1 + (k_{\mathrm{r}}^2 - 1)\cos\alpha} \exp[b(1 - \cos\gamma)^a] \times \frac{G(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}, \theta_{\mathrm{r}}, \varphi_{\mathrm{r}})}{\cos\theta_{\mathrm{r}} \cos\theta_{\mathrm{i}}} + \frac{k_{\mathrm{d}}}{\cos\theta_{\mathrm{i}}}, \quad (2)$$

where

$$\cos\alpha = \frac{\cos\theta_{\mathrm{i}} + \cos\theta_{\mathrm{r}}}{2\cos\gamma},$$

and

$$\cos^2\gamma = \frac{1}{2}(\cos\theta_{\mathrm{i}} \cos\theta_{\mathrm{r}} + \sin\theta_{\mathrm{i}} \sin\theta_{\mathrm{r}} \cos\varphi_{\mathrm{r}} + 1).$$

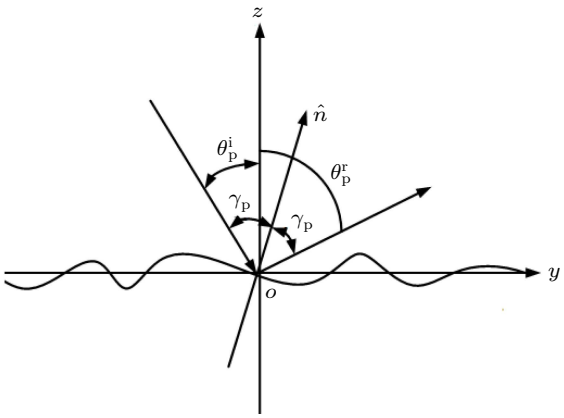


Fig. 2. One-dimensional geometric model of BRDF.

The model is divided into two parts: the first represents the mirror reflection (coherent scattering component), and the second represents the diffuse reflection component (incoherent scattering component). Here, γ is the incident angle of the local coordinate system at the micro-plane, k_{b}, k_{d}, k_{r}, a, and b are the parameters to be determined, and $G(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}, \theta_{\mathrm{r}}, \varphi_{\mathrm{r}})$ is the shadowing function, which can be calculated by the following equations:

$$G(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}, \theta_{\mathrm{r}}, \varphi_{\mathrm{r}}) = \frac{1 + \dfrac{\omega_{\mathrm{p}} \left| \tan\theta_{\mathrm{p}}^{\mathrm{i}} \tan\theta_{\mathrm{p}}^{\mathrm{r}} \right|}{1 + \sigma_{\mathrm{r}} \tan\gamma_{\mathrm{p}}}}{(1 + \omega_{\mathrm{p}} \tan^2\theta_{\mathrm{p}}^{\mathrm{i}})(1 + \omega_{\mathrm{p}} \tan^2\theta_{\mathrm{p}}^{\mathrm{r}})}, \quad (3)$$

$$\omega_{\mathrm{p}}(\alpha) = \sigma_{\mathrm{p}}\left(1 + \frac{u_{\mathrm{p}} \sin\alpha}{\sin\alpha + v_{\mathrm{p}} \cos\alpha}\right), \quad (4)$$

$$\tan\theta_{\mathrm{p}}^{\mathrm{i}} = \tan\theta_{\mathrm{i}} \frac{\sin\theta_{\mathrm{i}} + \sin\theta_{\mathrm{r}} \cos\varphi_{\mathrm{r}}}{2\sin\alpha\cos\gamma}, \quad (5)$$

$$\tan\theta_{\mathrm{p}}^{\mathrm{r}} = \tan\theta_{\mathrm{r}} \frac{\sin\theta_{\mathrm{r}} + \sin\theta_{\mathrm{i}} \cos\varphi_{\mathrm{r}}}{2\sin\alpha\cos\gamma}, \quad (6)$$

$$\tan\gamma_{\mathrm{p}} = \frac{\left|\cos\theta_{\mathrm{i}} - \cos\gamma\right|}{2\sin\alpha\cos\gamma}, \quad (7)$$

where σ_{r}, σ_{p}, u_{p}, and v_{p} are experience functions, generally taken to be $\sigma_{\mathrm{p}} = \sigma_{\mathrm{r}} = 0.0136$, $u_{\mathrm{p}} = 9.0$, and $v_{\mathrm{p}} = 1.0$. The best standard of model parameter selection is the minimum mean square error of the experimental data. The minimum mean square error can be calculated using the following formula:

$$E(x) = \frac{\sum_{\theta_{\mathrm{i}}} \sum_{\theta_{\mathrm{r}}} g_1(\theta_{\mathrm{i}}) g_2(\theta_{\mathrm{r}}) [f_{\mathrm{r}} \cos\theta_{\mathrm{r}} - f_{\mathrm{r}}^0 \cos\theta_{\mathrm{r}}]^2}{\sum_{\theta_{\mathrm{i}}} \sum_{\theta_{\mathrm{r}}} g_1(\theta_{\mathrm{i}}) g_2(\theta_{\mathrm{r}}) [f_{\mathrm{r}}^0 \cos\theta_{\mathrm{r}}]^2}, \quad (8)$$

where x is the column vector of the model parameters, f_r denotes the calculated values obtained with the BRDF models, f_r^0 represents experimental measurements or theoretically calculated values, and $g_1(\theta_i)$ and $g_2(\theta_r)$ are the weighting functions, which are used to adjust the influence of individual error on the total error when the measurement interval is uneven. Here, the data are measured in equal intervals; therefore, the weighting function is assumed to be unity. Further, the reflection coefficient direction is obtained with $R_s = f_r \cos\theta_r$. Hence, this form is chosen to optimize the empirical parameters.

3. Relationship between radar cross section per unit area and BRDF

The bistatic radar cross section (BRCS) can be defined as[20]

$$\sigma_{r,t}(\theta_i, \varphi_i; \theta_r, \varphi_r) = \lim_{R\to\infty} 4\pi R^2 \frac{E_s^r(\theta_r, \varphi_r)^2}{E_i^t(\theta_i, \varphi_i)^2}, \tag{9}$$

where $E_s^r(\theta_r, \varphi_r)$ is the scattering field of the polarization state of r. Here, $E_i^t(\theta_i, \varphi_i)$ denotes the incident field of the polarization state of t. The obtained BRCS should be the average of two orthogonal polarization states when transmitting and receiving using an unpolarized laser. The radar cross section per unit area of a rough surface can be defined as

$$\sigma^0 = \lim_{R\to\infty} 4\pi R^2 \frac{\langle E_s E_s^* \rangle}{A E_i^2}, \tag{10}$$

where A is the irradiation area and $\langle\rangle$ represents the statistical average of scattering intensity of the rough surface. When the receiving aperture is A_r, the ratio of scattering power received (ΔP_s) and incident power can be expressed as

$$\frac{\Delta P_s}{P_i} = \frac{A_r \langle E_s E_s^* \rangle}{A \cos\theta E_i^2}. \tag{11}$$

The following equation can be derived from Eqs. (10) and (11):

$$\sigma^0 = \lim_{R\to\infty} \frac{4\pi R^2}{A_r} \frac{\Delta P_s}{P_i} \cos\theta_i = 4\pi \cos\theta_i \frac{dP_s}{P_i\, d\Omega}, \tag{12}$$

where $d\Omega = \lim_{R\to\infty} A_r/R^2$. From the definition of the BRDF,

$$f_r = (\theta_i, \varphi_i; \theta_r, \varphi_r) = dL_r(\theta_i, \varphi_i; \theta_r, \varphi_r)/dE_i(\theta_i, \varphi_i). \tag{13}$$

Irradiance (E_i) is expressed as the exposure irradiating per unit area, i.e.

$$E_i = \frac{d\phi_i}{dA}. \tag{14}$$

For the extended surface, the radiation brightness (L_r) of the (θ_r, φ_r) direction is defined as the ratio of radiation of given surface element (dA) and the element orthogonal projection area on the plane in the direction perpendicular to (θ_r, φ_r); namely, the radiant flux per unit area and solid angle in the direction of radiation as

$$L_r = \frac{d^2\phi_s}{d\Omega\, dA \cos\theta_r} = \frac{dI_s}{dA\cos\theta_r}. \tag{15}$$

The second formula of Eq. (15) indicates that the radiation intensity in any direction is equal to the radiation intensity of unit orthographic projection area in that direction. For a fully diffused surface (Lambert surface), the radiation intensity obeys the cosine theorem $I_s = I_n \cos\theta_r$, and the brightness in the direction of leaving normal for the θ_r angle obeys the following equation:

$$L_r = \frac{dI_n \cos\theta_r}{dA\cos\theta_r} = \frac{dI_n}{dA}, \tag{16}$$

which does not depend on the observation direction. Here, I_n is the radiation intensity in the direction of the normal. From Eqs. (13)–(15), the BRDF of the rough surface can be obtained as

$$f_r = \frac{d^2\phi_s}{d\Omega\, dA\cos\theta_r} \Big/ \frac{d\phi_i}{dA} = \frac{d^2\phi_s}{d\phi_i\, d\Omega\cos\theta_r}. \tag{17}$$

The concept of BRDF above can be applied to the electromagnetic (optical) scattering from the rough surface. For an expanded uniform surface element, $d\phi_i/dA$ and $d\phi_s/dA$ can be the incident power (P_i) and scattered power (P_s) irradiating unit area, respectively. The radiation flux and power are actually the same. Therefore, the above equation can be rewritten as

$$f_r = \frac{dP_s}{P_i\, d\Omega\cos\theta_r}. \tag{18}$$

Substituting Eq. (18) into Eq. (12), we have

$$\sigma^0 = 4\pi f_r \cos\theta_i \cos\theta_r, \tag{19}$$

and the above equation shows the relationship[21] between BRDF (f_r) and unit radar cross section (σ^0).

4. BRDF modeling of rough surface

4.1. BRDF modeling of 1D conducting rough surface

Using the relationship between the BRDF (f_r) and scattering coefficient (σ^0) of a rough surface and the method of moments,[21] the direction reflection function of a 1D conducting rough surface is calculated for different incident frequencies and roughness values in the microwave band, as shown in Figs. 3 and 4.

Figure 3 illustrates the distribution of the direction reflection function of a 1D conducting rough surface under different incident angles for both polarizations at 6 GHz. The root mean square (RMS) and correlation length (CL) of the rough surface are set to be $\sigma = 0.32\lambda$ and $l = 1.4\lambda$. The spectral distribution of the rough surface is Gaussian.[22]

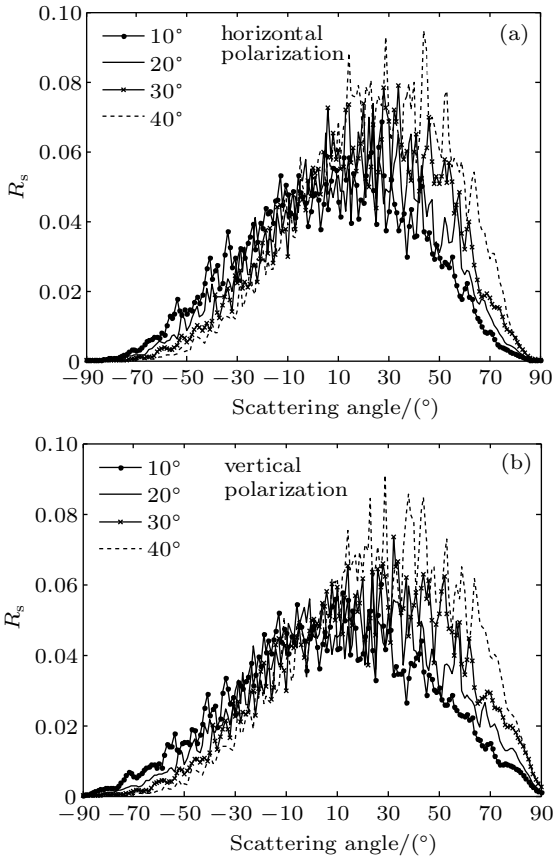


Fig. 3. Direction reflection function of 1D ideal conducting rough surface at 6 GHz. (a) Horizontal polarization; (b) vertical polarization.

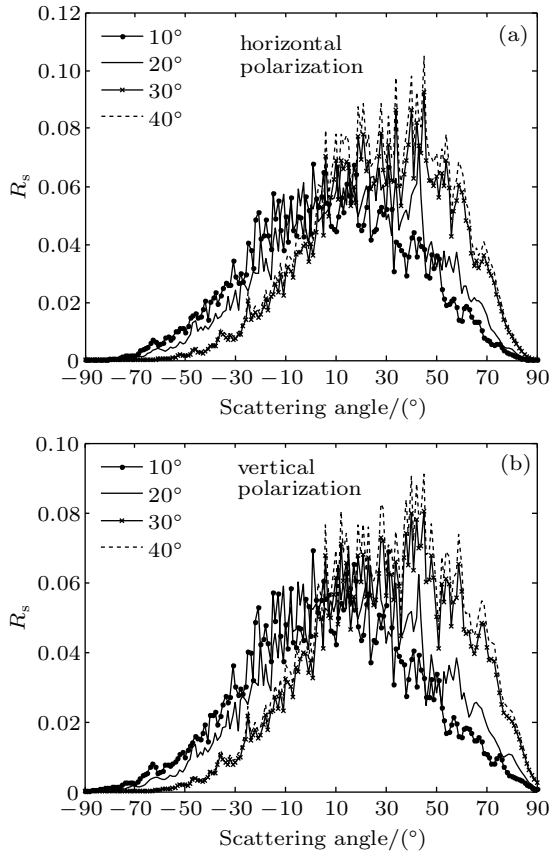


Fig. 4. Direction reflection function of 1D perfect conducting rough surface at 9 GHz. (a) Horizontal polarization; (b) vertical polarization.

Figure 4 presents the distribution of the direction reflection function of a 1D conducting surface under different incident angles for both polarizations at 9 GHz. RMS and CL are set to be $\sigma = 0.4\lambda$ and $l = 2.0\lambda$. From Figs. 3 and 4, it is found that the peak of the direction reflection function occurred in the mirror reflection direction. The reason for this phenomenon is found by considering the coherent component: the smaller the roughness of the rough surface, the more obviously the coherent component is observed.

The direction reflection functions of a 1D conducting rough surface for different frequencies and roughness values in the microwave band are obtained through calculations, and then some values must be uniformly selected to optimize the parameter values. The results of the five-parameter model of a 1D conducting rough surface and a dielectric rough surface are given in Figs. 5–8.

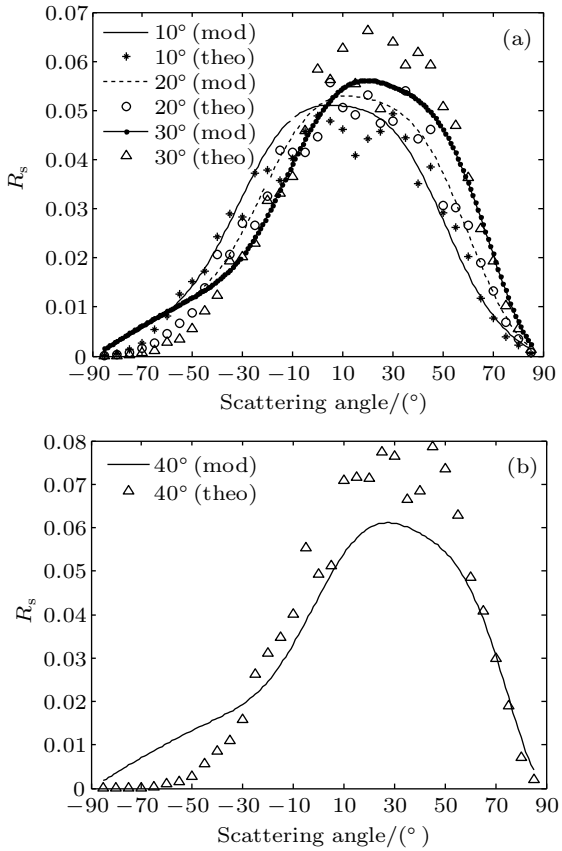


Fig. 5. Comparison of BRDF calculated with model (mod) and theory (theo) of conducting rough surface at 6 GHz with horizontal polarization. (a) Calculated data included in optimization; (b) data excluded from optimization.

The scattering above a Gaussian conducting rough surface with an incident frequency of 6 GHz for the horizontal polarization and vertical polarization is shown in Figs. 5 and 6, respectively, in which RMS and CL are set to be $\sigma = 0.32\lambda$ and $l = 1.4\lambda$. The incident angle is varied from 10° to 30° in increments of 10° and a comparison figure for an incident angle of 40° without optimization is also shown. From the results of Figs. 5(a) and 6(a), it is observed that the data calculated using the five-parameter model (the curves marked by

"mod") show good consistency with the theoretical data (the curves marked by "theo") for different incident angles. It is pointed out that, because the error considered is the minimum mean square error of all data (which is included in the optimization), the error is visibly large just in some scattering direction. However, the fitting degree of data calculated using the five-parameter model in Figs. 5(b) and 6(b) is not better than that in Figs. 5(a) and 6(a); we attribute this result to the fact that the data in Figs. 5(b) and 6(b) are excluded from optimization, and the error of these data is not considered.

To fully illustrate that the five-parameter model can be used to obtain the BRDF of a 1D conducting rough surface in the microwave band, different examples are selected, as depicted in Figs. 7 and 8 for the horizontal and vertical polarizations, respectively, where the incident frequency of scattering is set to be 9 GHz, and RMS and CL are set to be $\sigma = 0.4\lambda$ and $l = 2.0\lambda$. It is seen that the data calculated using the five-parameter model (the curves marked by "mod") in Figs. 7(a) and 8(a) show better agreement with the theoretical data (the curves marked by "theo") for the different incident angles than those of Figs. 7(b) and 8(b). On the basis of BRDF modeling of the 1D conducting rough surface shown in Figs. 5–8, the unknown parameters in each five-parameter model are presented in Table 1.

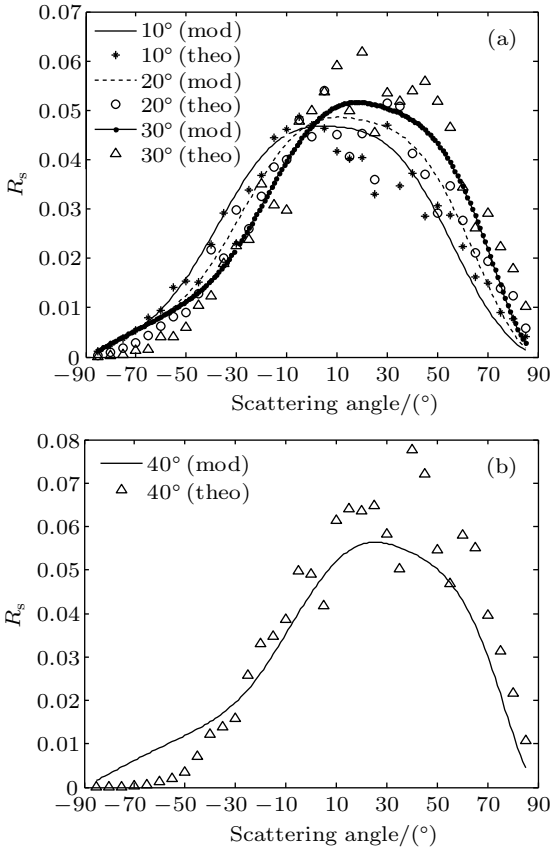


Fig. 6. Comparison of BRDF calculated with model (mod) and theory (theo) of conducting rough surface at 6 GHz with vertical polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

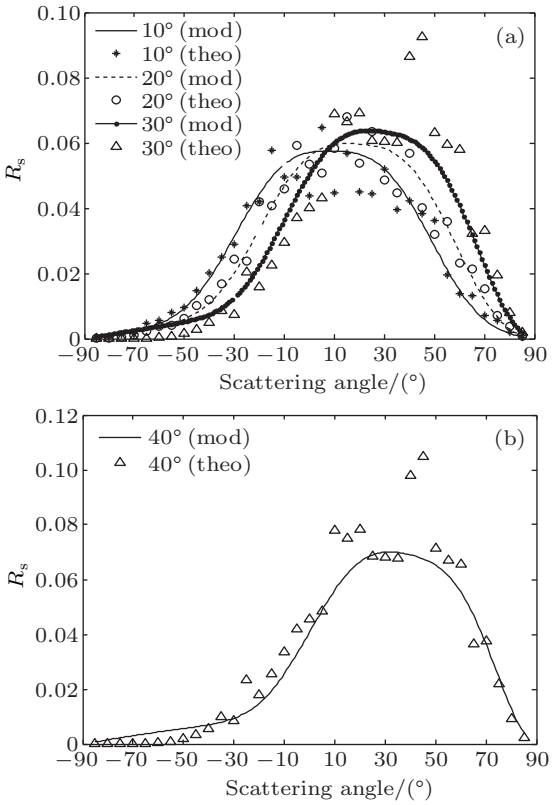


Fig. 7. Comparison of BRDF calculated with model (mod) and theory (theo) of conducting rough surface at 9 GHz with horizontal polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

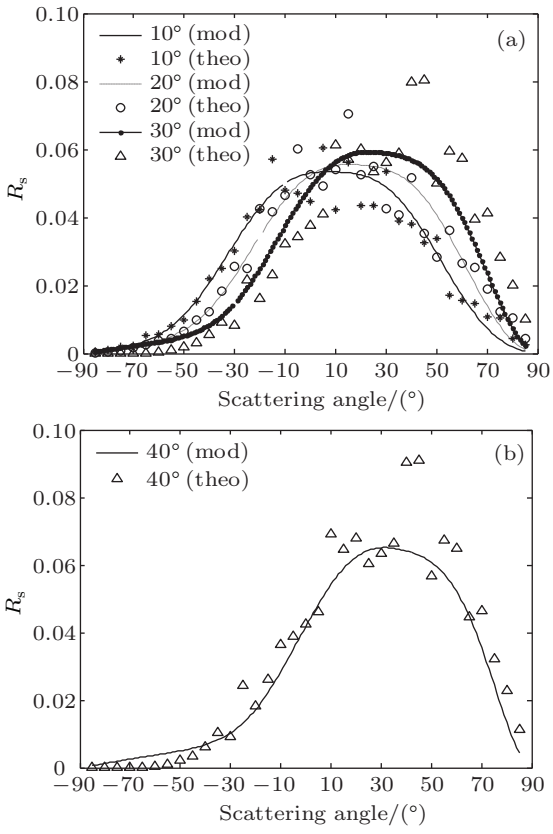


Fig. 8. Comparison of BRDF calculated with model (mod) and theory (theo) of conducting rough surface at 9 GHz with vertical polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

Table 1. Optimized results of BRDF parameters for one-dimensional conducting rough surface.

Frequency	RMS/λ	CL/λ	Polarization	E(error)/%	k_b	k_d	k_r	a	b
6 GHz	0.32	1.4	HH (Fig. 5)	1.51	0.0346	0.0158	14.89	1.533	−46.42
			VV (Fig. 6)	2.11	0.0323	0.0139	15.01	1.557	−34.39
9 GHz	0.4	2.0	HH (Fig. 7)	3.99	0.050	0.0067	37.18	1.510	−47.36
			VV (Fig. 8)	4.40	0.047	0.0057	39.84	1.474	−34.14

From comparison of the BRDF of the 1D conducting rough surface, it is found that the data calculated using the five-parameter model are in good agreement with the theoretical data for the different incident angles. Because the scattering at the mirror point of the rough surface in the examples increases faster than others, the errors are relatively large. In addition, several data sets are included in optimization modeling, and the optimization parameters must consider the error of each set. Therefore, the error increases with an increase in the optimized set of data. The optimized parameters for each case of the 1D conducting rough surface are shown in Table 1. The comparison shows that calculated results fit with the model results when the calculated data are included in the optimization as well as for calculated data excluded from optimization, thus proving the correctness and reliability of the modeling results. Therefore, the five-parameter model can be used to obtain the BRDF of a 1D conducting rough surface.

4.2. BRDF modeling of 1D dielectric rough surface

In this section, BRDF modeling of a 1D dielectric rough surface by the five-parameter model will be introduced. The direction reflection function of a 1D dielectric rough surface is calculated for different incident frequencies and roughness values in the microwave band, as shown in Figs. 9 and 10 for both horizontal polarization and vertical polarization.

Figure 9 illustrates the distribution of the direction reflection function of a 1D dielectric rough surface for an incident frequency of 6 GHz, where RMS and CL are set to be $\sigma = 0.3\lambda$ and $l = 1.3\lambda$; the dielectric constant of the dielectric rough surface is (2.5, 0.18). The distribution of the direction reflection function of the 1D dielectric rough surface for an incident frequency of 9 GHz is shown in Fig. 10. Here, RMS and CL are set to be $\sigma = 0.2\lambda$ and $l = 1.5\lambda$, and the dielectric constant of the dielectric rough surface is (2.5, 0.18). From Figs. 9 and 10, it is also found that the peak of the direction reflection function occurred in the mirror reflection direction, which is just like the conducting rough surface case, and when the roughness of the rough surface is smaller, a more obvious coherent component is observed in the specular direction.

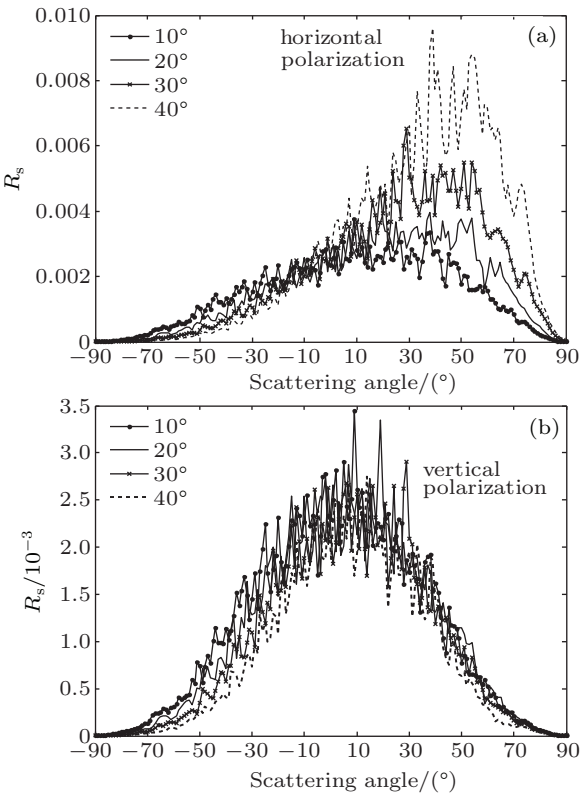


Fig. 9. Direction reflection function of 1D dielectric rough surface at 6 GHz. (a) Horizontal polarization; (b) vertical polarization.

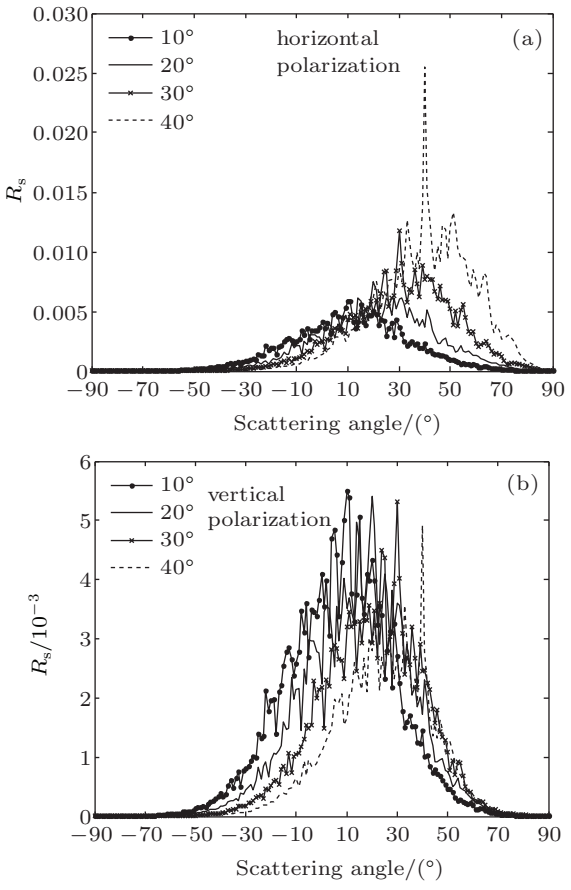


Fig. 10. Direction reflection function of 1D dielectric rough surface at 9 GHz. (a) Horizontal polarization; (b) vertical polarization.

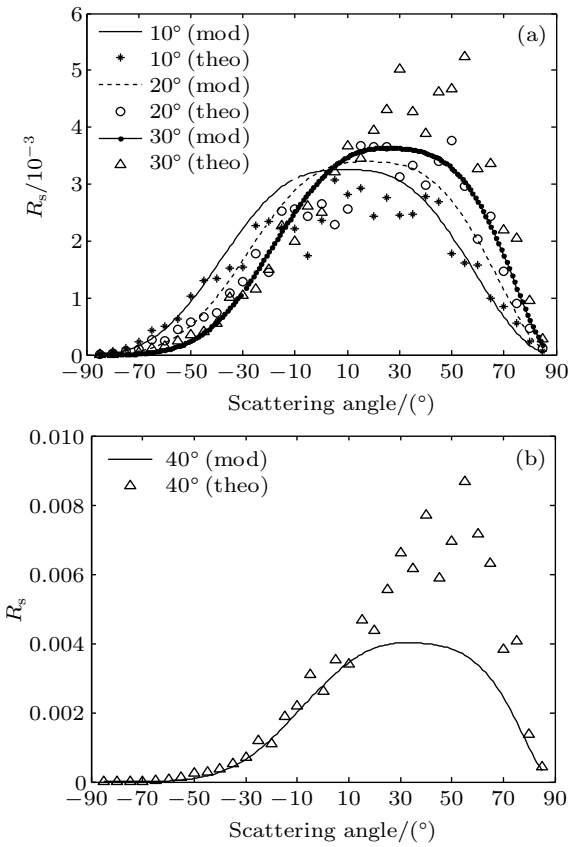


Fig. 11. Comparison of BRDF calculated with model (mod) and theory (theo) of dielectric rough surface at 6 GHz with horizontal polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

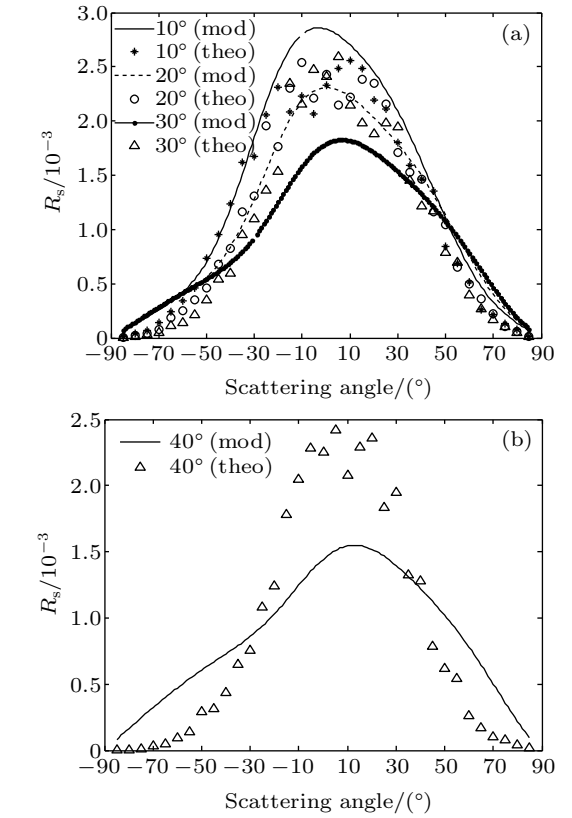


Fig. 12. Comparison of BRDF calculated with model (mod) and theory (theo) of dielectric rough surface at 6 GHz with vertical polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

The direction reflection functions of a 1D dielectric rough surface for different frequencies and roughness values in the microwave band are obtained through calculation, and some values must be uniformly selected to optimize the parameter values. The results of the five-parameter model of a 1D dielectric rough surface are presented in Figs. 11–14.

The scattering above a dielectric rough surface for an incident frequency of 6 GHz is depicted in Figs. 11 and 12, in which RMS and CL are $\sigma = 0.3\lambda$ and $l = 1.3\lambda$. The horizontal polarization case of the BRDF of a 1D dielectric rough surface is shown in Fig. 11, whereas the vertical polarization case is shown in Fig. 12. For different incident angles, the data using the five-parameter model (the curves marked by "mod") are in good agreement with the theoretical data (the curves marked by "theo") in Figs. 11(a) and 12(a), and the difference between the two curves increases in Figs. 11(b) and 12(b).

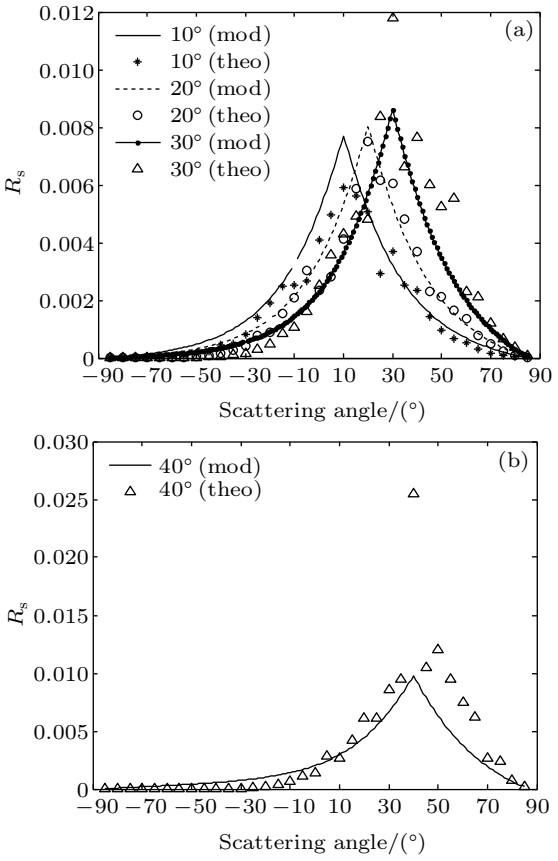


Fig. 13. Comparison of BRDF calculated with model (mod) and theory (theo) of dielectric rough surface at 9 GHz with horizontal polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

To fully illustrate the efficiency of the five-parameter model, which can be used to model the scattering pattern of a 1D dielectric rough surface in the microwave band, the scattering of a rough surface at 9 GHz is also shown. The results of the five-parameter model of a 1D dielectric rough surface for horizontal and vertical polarizations are shown in Figs. 13 and 14, respectively, where the incident frequency is 9 GHz, and RMS and CL are $\sigma = 0.2\lambda$ and $l = 1.5\lambda$. From Figs. 13

and 14, the calculated data involved in optimization are more accurate than those excluded from optimization for different incident angles.

Based on the BRDF modeling of the 1D dielectric rough surface in Figs. 11–14, the unknown parameters in the each five-parameter model are shown in Table 2.

From the modeling results and the table of optimization parameters, the modeling results are found to be in good agreement with the theoretical calculations. The error, mainly due to the model parameters, should fit all angles of incidence of optimized data. At some of the scattering angles, the scattering has a sharp increase, which can also cause an error. It can be seen from the figures of the BRDF of a dielectric rough surface that, irrespective of the data included in or excluded from optimization modeling, the result of the five-parameter model is satisfactory, which shows the validity and feasibility of using the five-parameter model for BRDF modeling of a 1D dielectric rough surface.

Table 2. Optimized results of BRDF parameters for one-dimensional dielectric rough surface.

Frequency/GHz	RMS/λ	CL/λ	Polarization	E(error)/%	k_b	k_d	k_r	a	b
6	0.3	1.3	HH (Fig. 11)	5.42	0.0032	0.0000019	29.06	1.454	−22.21
			VV (Fig. 12)	2.23	0.0019	0.00072	0.380	1.691	−55.40
9	0.2	1.5	HH (Fig. 13)	3.99	0.050	0.0067	37.18	1.510	−47.36
			VV (Fig. 14)	4.40	0.047	0.0057	39.84	1.474	−34.14

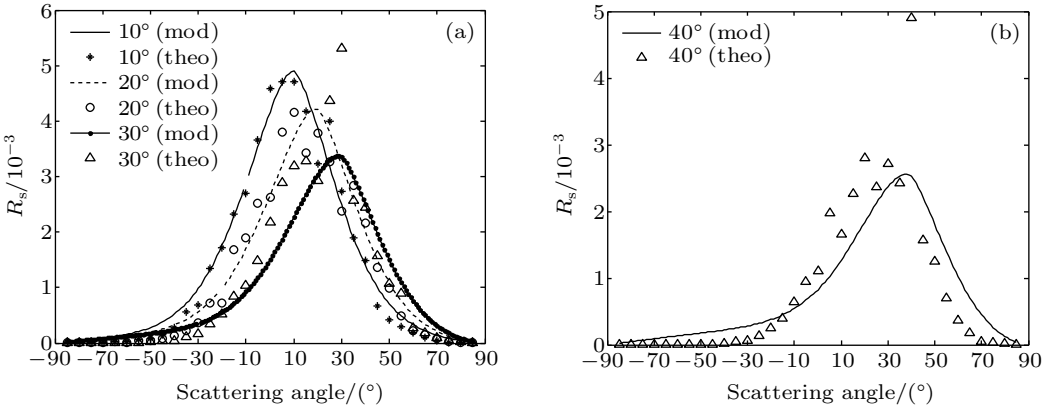


Fig. 14. Comparison of BRDF calculated with model (mod) and theory (theo) of dielectric rough surface at 9 GHz with vertical polarization. (a) Calculated data involved in optimization; (b) data excluded from optimization.

5. Conclusion

In this work, the theoretical value of the BRDF of a rough surface is compared with that of the five-parameter statistical model. Further, the optimization models of the BRDF of 1D conducting and dielectric rough surfaces for different incident frequencies and roughness values are given. By comparison, the theoretical values are in agreement with the modeling values, which proves the correctness and feasibility of optimizing the five-parameter model of the BRDF of 1D conducting and dielectric rough surfaces in the microwave band by using genetic algorithms. When compared with the theoretical calculations, the proposed method of modeling has no complex calculation process and the BRDF of the rough surface can be described more concisely. This modeling method overcomes the problem of experimental measurements that cannot obtain the BRDF of a rough surface for any incident and observation angles. Moreover, the modeling method provides some reference for the study of the BRDF of a rough surface in the microwave band. It should be noted that only the BRDF modeling of one-dimensional rough surface is investigated in this work. Future research will include the BRDF modeling of a two-dimensional conducting or dielectric rough surface for different dielectric constants and BRDF modeling of a layered rough surface.

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