Effective dielectric constant model of electromagnetic backscattering from stratified air–sea surface film–sea water medium*

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Studies of surface film medium on the sea surface are carried out in this paper for developing the technology to automatically detect and classify sea surface films, and an effective dielectric constant model of electromagnetic backscattering from a stratified air–ocean interface. Numerical results of the new model show the characteristics of effective dielectric constants for the air–sea surface film–sea water medium as follows. The effective dielectric constants decrease with increasing relative dielectric constants of the sea surface films. The effective dielectric constants decrease in horizontal polarization (abbr. HH polarization) and increase in VV vertical polarization (abbr. VV polarization) with increasing radar incident angle. Effective dielectric constants vary with relative sea surface film thickness as a cosinusoidal function of sea surface film thickness. Effective dielectric constant of VV polarization is larger than that of HH polarization. Two potential applications are found with our model, i.e., the retrieval of dielectric constants from the sea surface film, and the film thickness retrieval with our model. Our model has a highly significant influence on improving the technology related to the remote sensing of sea surface films.

Keywords: dielectric constant, sea surface film, electromagnetic backscattering, Bragg scattering, multiple scattering

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1. Introduction

To reduce or even avoid oil pollution of the ocean surface especially in coastal waters, a real time, effective oil spill surveillance capability is necessary. Nowadays, space-borne radar is an efficient remote sensing tool to detect ocean surface films, especially oil spills. One of the best methods for oil detection is to use a synthetic aperture radar (SAR) for capturing the SAR images of the sea surface.[1]

Because the dielectric constant of ocean surface film is lower than that of sea water, the ocean surface film area appears darker than the clean water area in the SAR image.[2] Many ocean surface films detecting algorithms have been developed based on the differences in reduction of the normalized radar cross section (NRCS) and other features.[3–16] Wind wave tank measurements of wave damping and the NRCS in the presence of monomolecular surface film show that the measured polarization ratio between NRCS in vertical polarization (abbr. VV polarization) and that in horizontal polarization (abbr. HH polarization) is higher in magnitude than that predicted by simple Bragg (SB) scattering theory at low wind. Gade *et al.*[6] explained this phenomenon with a three-scale model,[7] i.e., besides short Bragg waves and long waves, short-scale and intermediate-scale waves are separately regarded as a composite three-scale surface wave model. The observed results of biogenic and anthropogenic ocean surface films in SAR images show that the damping behavior of the NRCS for the same film is dependent on wind speed. The damping ratio at high wind speed, i.e., the ratio between NRCS from a slick-free water surface and that from a slick-covered water surface is smaller than at low-to-moderate wind speeds. Comparing the damping ratios among surface films consisting of heavy fuel (IFO 180), oleyl alcohol (OLA), oleic acid methyl ester (OLME), and triolein (TOLG) with each other, the damping behaviors of these different ocean surface films especially for L band SAR images, vary with the biogenic surface film (OLA), exhibiting large damping characteristics.[8] Recently, an automatic multi-polarization method of discriminating the main types of thin crude oil films from natural oil films by SAR images was presented.[9] The thickness of ocean surface film is confined to be less than the radar wave skin depth, which excludes the dependence of the technique on the dielectric constant of oil.

Besides trying to discriminate among different ocean surface films, other algorithms have focused on oil spill detec-

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tion by SAR. For example, the co-polarized phase difference (CPD) was presented and used to characterize the scattering return from oil spills and biogenic slicks.[10,11] The conformity coefficient is used to map sea surface oil slicks with using the Radarsat-2 quad-polarization SAR images.[12] Polarimetric SAR decomposition parameters, average alpha angle, and entropy are estimated for oil-slick contaminated sea surfaces.[13–15] A genetic algorithm is applied to the automatic detection of oi spills.[16]

In brief, it is still difficult to automatically detect all ocean surface films by remote sensing radar, although there are many algorithms available that can automatically identify some oil spills. Actually, there is no effective method to identify all types of ocean surface slicks. The main reason is that the existing algorithms are based on the backscattering NRCS which cannot physically explain all the mechanisms for the differences between ocean surface slicks and clean ocean water, nor all the different types of ocean surface slicks.

It is mentioned in a recent study on methods of discriminating the main types of thin oil films from natural ones by SAR images,[9] that the dependence of the technique on the dielectric constant of oil should be excluded. However, the dielectric constant of material is a property of the physical characteristics and it should be an essential factor for discriminating different types of ocean surface slicks. Previous research results show that the predicted NRCS of ocean surface film is underestimated by using simple Bragg scattering theory. These two problems limit our ability to improve the discrimination technology of ocean surface films by SAR.

Here, an effective dielectric constant model is presented to solve the above two problems. Firstly, in contrast to the limitations in Ref. [9], we hope that the model is dependent on the dielectric constant of ocean surface film, thus our model is not restrained by the thickness of ocean surface film. Secondly, a multi-layer backscattering (ML) model is used to build an effective dielectric constant model which is ignored by previous studies. Owing to the occurrence of film, the electromagnetic (EM) backscattering problem becomes a problem related to EM scattering from three-layer medium. One cannot simply use the Bragg scattering model in two-layer medium. Finally, an effective dielectric constant of ocean surface film is used to correct the NRCS derived from the SB scattering model so that it is equal to the NRCS predicted by a multiple-layer Bragg scattering model. In our model, the NRCS distributed by sea water is considered and compensates for the NRCS predicted by the SB model.

The rest of this paper is arranged as follows. The multiple-layer Bragg backscattering formulae for sea surface films are derived in Section 2. An effective dielectric constant model for a stratified air–ocean surface film–sea water medium is presented in Section 3. Numerical results are given in Section 4. The conclusions drawn from the present study are given in Section 5.

2. Multiple layered Bragg backscattering from ocean surface film

2.1. EM backscattering model for sea surface

Bragg scattering is a dominant mechanism of radar backscattering from a rough surface. A composite surface scattering model was presented by Wright[17] as a formulation of a composite surface scattering model for the ocean. Based on this model, the backscattering cross section per unit area (i.e., NRCS) has the following form:

$$\sigma_{\mathrm{p}}^{0} = 4\pi k^{4}\cos^{4}\theta_{\mathrm{l}}\left|F_{\mathrm{p}}\right|^{2} W\left(2k\sin\theta_{\mathrm{l}}\right), \tag{1}$$

where p denotes the polarization mode HH or VV, $k = 2\pi/\lambda$ is the radio wave number, λ is the radio wavelength, $W(\cdot)$ is the two-dimensional wave-number spectral density of the surface roughness, θ_{l} is the local incident angle which is a function of radar incident angle θ_{i}, a is the slope in the azimuth direction, and b is the slope in the range direction. The relation for θ_{l} is

$$\theta_{\mathrm{l}} = \mathrm{acos}\left(\cos\left(\theta_{\mathrm{i}} + \mathrm{atan}(b)\right)\cos\left(\mathrm{atan}(a)\right)\right). \tag{2}$$

Scattering coefficients of a flat scattering surface in VV and HH polarization are

$$F_{\mathrm{HH}} = \frac{\cos\theta_{\mathrm{i}} - \left(\varepsilon_{\mathrm{r}} - \sin^{2}\theta_{\mathrm{i}}\right)^{1/2}}{\cos\theta_{\mathrm{i}} + \left(\varepsilon_{\mathrm{r}} - \sin^{2}\theta_{\mathrm{i}}\right)^{1/2}}, \tag{3}$$

and

$$F_{\mathrm{VV}} = \frac{\left(\varepsilon_{\mathrm{r}} - 1\right)\left[\sin^{2}\theta_{\mathrm{i}} - \varepsilon_{\mathrm{r}}\left(1 + \sin^{2}\theta_{\mathrm{i}}\right)\right]}{\left[\varepsilon_{\mathrm{r}}\cos\theta_{\mathrm{i}} + \left(\varepsilon_{\mathrm{r}} - \sin^{2}\theta_{\mathrm{i}}\right)^{1/2}\right]^{2}}, \tag{4}$$

respectively. ε_{r} is the relative dielectric constant of the ocean surface.

2.2. EM backscattering from stratified air–sea surface film–sea water media

At the ocean surface, an air–ocean surface film–sea water medium is defined as the flat-boundaries layered medium structure which is shown in Fig. 1(a). The $z = 0$ is the interface between air and the ocean surface film. Let the thickness of ocean surface film be h, then the position of the interface between the ocean surface film and the water will lie at $z = -h$. The dielectric constants and magnetic conductivities of air, the film and sea water are ε_0, μ_0, ε_1, μ_1, and ε_2, μ_2, respectively. Generally speaking, except for ferromagnetic bodies, the magnetic conductivities of other media may be approximately equal to that of free space. Thus, we have $\mu_1 = \mu_2 = \mu_0 = 4\pi\times10^{-7}$ H/m and $\varepsilon_0 = 8.85419\times10^{-12}$ F/m. The angle between x and the projection of the incident wavenumber vector $\boldsymbol{k}_{\mathrm{i}}$ on the (x,y) plane is φ_{i} (not shown in Fig. 1). One can obtain

$$\boldsymbol{k}_{\mathrm{i}} = k\boldsymbol{k}_0 = k_x\boldsymbol{x}_0 + k_y\boldsymbol{y}_0 + k_z\boldsymbol{z}_0$$

$$= k\left(\sin\theta_{\rm i}\cos\varphi_{\rm i}x_0 + \sin\theta_{\rm i}\sin\varphi_{\rm i}y_0 - \cos\theta_{\rm i}z_0\right). \quad (5)$$

The incident field may be decomposed into TE and TM components. The corresponding reflected and transmitted field components can be computed through the reflection and transmission coefficients. We obtain the Fresnel reflection coefficients (F) and transmission coefficients (T) at $z=0$ for HH and VV polarization as follows:

$$F_{\rm HH}^{01} = \frac{k_{z0}-k_{z1}}{k_{z0}+k_{z1}}, \quad (6)$$

$$F_{\rm VV}^{01} = \frac{\varepsilon_1 k_{z0}-\varepsilon_0 k_{z1}}{\varepsilon_1 k_{z0}+\varepsilon_0 k_{z1}}, \quad (7)$$

$$T_{\rm HH}^{01} = \frac{2k_{z0}}{k_{z0}+k_{z1}}, \quad (8)$$

$$T_{\rm VV}^{01} = \frac{2\varepsilon_1 k_{z0}}{\varepsilon_1 k_{z0}+\varepsilon_0 k_{z1}}, \quad (9)$$

and at $z=-h$

$$F_{\rm HH}^{12} = \frac{k_{z1}-k_{z2}}{k_{z1}+k_{z2}}, \quad (10)$$

$$F_{\rm VV}^{12} = \frac{\varepsilon_2 k_{z1}-\varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1}+\varepsilon_1 k_{z2}}, \quad (11)$$

$$T_{\rm HH}^{12} = \frac{2k_{z1}}{k_{z1}+k_{z2}}, \quad (12)$$

$$T_{\rm VV}^{12} = \frac{2\varepsilon_2 k_{z1}}{\varepsilon_2 k_{z1}+\varepsilon_1 k_{z2}}, \quad (13)$$

where $k_{z0,z1,z2} = k\sqrt{\mu_0\varepsilon_{0,1,2}}\cos\theta_{i,1,2}$, $\theta_1 = \text{asin}\left(\sqrt{\varepsilon_0/\varepsilon_1}\sin\theta_i\right)$, and $\theta_2 = \text{asin}\left(\sqrt{\varepsilon_0/\varepsilon_2}\sin\theta_i\right)$.

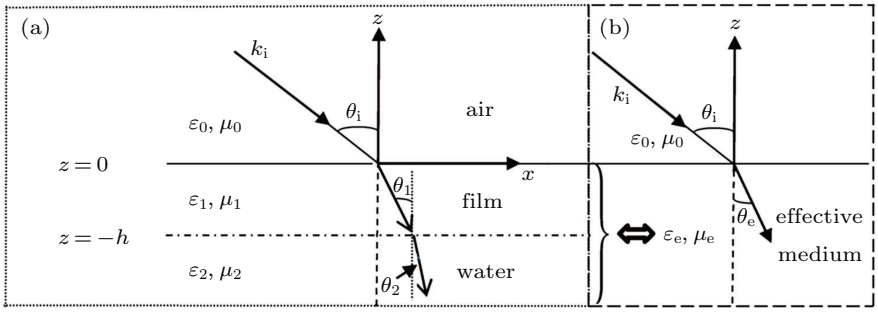


Fig. 1. Geometries for the air–ocean surface film–sea water media represented as a flat boundaries layered structure: (a) three-layer structure of air, film, and water; (b) effective two-layer structure of air and the effective medium corresponding to the scenario in panel (a).

According to Refs. [18] and [19], taking into account the multiple reflection in the film layer, one can obtain the reflection coefficients of the air–sea surface film–sea water medium in HH polarization and VV polarization at $z=0$

$$R_{\rm p} = \frac{F_{\rm p}^{01} + F_{\rm p}^{12}\,{\rm e}^{{\rm j}(2k_{z1}h)}}{1 + F_{\rm p}^{01}F_{\rm p}^{12}\,{\rm e}^{{\rm j}(2k_{z1}h)}}, \quad (14)$$

where $R_{\rm p}$ is the generalized reflection coefficient of the air–sea surface film–sea water medium.

According to the SB model (Eq. (1)), the NRCS of the air–sea surface film–sea water medium becomes

$$\sigma_{\rm p}^0 = 4\pi k^4\cos^4\theta_{\rm l}\left|R_{\rm p}\right|^2 W\left(2k\sin\theta_{\rm l}\right). \quad (15)$$

3. Effective dielectric constant model for stratified air–sea surface film–sea water medium

For classifying the films on the ocean surface, the dielectric constant of a substance is the best discrimination factor to be retrieved from any given multiple-layer medium.

The effective dielectric constant of a multiple-layer medium is presented here. The geometry for the stratified air–sea surface film–sea water medium is shown in Fig. 1(a). Figure 1(b) shows the effective two-layer structure of air and the effective medium corresponding to Fig. 1(a). The sea surface film–sea water medium is regarded as an effective medium with an effective dielectric constant and magnetic conductivity of $\varepsilon_{\rm e}$ and $\mu_{\rm e}$, respectively, where $\mu_{\rm e} = \mu_1 = \mu_2 = \mu_0$ and $\theta_{\rm e}$ is the effective transmission angle. Thus, the scattering problem of stratified air–sea surface film–sea water medium is simplified into being a scattering problem of two-layer medium, i.e., air-effective medium (Fig. 1(b)). Following the Bragg backscattering theory, the NRCS of the air-effective medium has a similar form to Eq. (1) as shown below.

$$\sigma_{\rm p} = 4\pi k^4\cos^4\theta_{\rm l}\left|F_{\rm p}^{\rm e}\right|^2 W\left(2k\sin\theta_{\rm l}\right) \quad (16)$$

where $F_{\rm p}^{\rm e}$ in HH and VV polarizations are respectively

$$F_{\rm HH}^{\rm e} = \frac{\cos\theta_{\rm i} - \left(\varepsilon_{\rm e} - \sin^2\theta_{\rm i}\right)^{1/2}}{\cos\theta_{\rm i} + \left(\varepsilon_{\rm e} - \sin^2\theta_{\rm i}\right)^{1/2}}, \quad (17)$$

$$F_{\rm VV}^{\rm e} = \frac{\varepsilon_{\rm e}\cos\theta_{\rm i} - \left(\varepsilon_{\rm e} - \sin^2\theta_{\rm i}\right)^{1/2}}{\varepsilon_{\rm e}\cos\theta_{\rm i} + \left(\varepsilon_{\rm e} - \sin^2\theta_{\rm i}\right)^{1/2}}. \quad (18)$$

According to the concept of the equivalence hypothesis of effective dielectric constant, the NRCS of air–sea surface film–sea water medium should be equivalent to that of the air-effective medium, i.e., $\sigma_{\rm p}^{\rm e} = \sigma_{\rm p}^0$. Then we have

$$F_{\rm p}^{\rm e}\left(\varepsilon_{\rm e}\right) = R_{\rm p}\left(\varepsilon_0, \varepsilon_1, \varepsilon_2\right) \quad (19)$$

Equation (19) is our effective dielectric constant model for stratified air–sea surface film–sea water medium. The value of $\varepsilon_{\rm e}$ can be calculated with the model.

4. Results and discussion

4.1. Case study to retrieve effective dielectric constants in HH and VV polarization

A case analysis is given to show the detailed process of calculating the effective dielectric constant for air–sea surface film–sea water medium.

Radarsat-2 SAR is employed to capture the backscattering NRSC images of the air–sea surface film–sea water medium. Its frequency is 5.04×10^9 Hz. The EM-wave propagation velocity is 3×10^8 m·s^{-1}. Thus, the incident radio wavelength is 5.95 cm. Let the incident angle be 30°. The thickness of the film is 0.01 m. Relative dielectric constants of film and sea water are 2 and 80, respectively. To retrieve the effective dielectric constant ε_{e0}, let the effective dielectric constant ε_e vary from 0 to 100 (which covers all substance dielectric constants). The values of reflection coefficient R_p of the air–sea surface film–sea water medium in HH polarization and VV polarization at $z = 0$ can be calculated from Eq. (14). The reflection coefficients $F_p^e(\varepsilon_e)$ of the air-effective medium can be obtained from Eqs. (17) and (18). Following our model (Eq. (19)), one can obtain ε_p^e from the following equation:

$$F_p^e\left(\varepsilon_p^e\right) = R_p(\varepsilon_0, \varepsilon_1, \varepsilon_2). \tag{20}$$

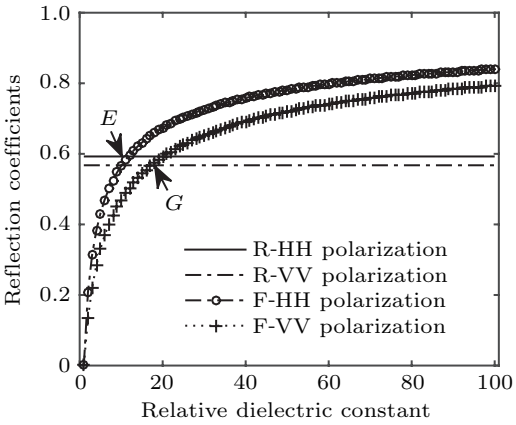


Fig. 2. Plots of reflection coeeficient versus relative dielectric constant for the cases of HH polarization and VV polarization.

The numerical results for determining the reflection coefficients in HH and VV polarization, each as a function of corresponding relative dielectric constants, are shown in Fig. 2. Let us denote the point where R_{HH} cuts F_{HH} as E, and where R_{VV} cuts F_{VV} as G, with $R_{HH} = 0.59$ and $R_{VV} = 0.57$. Combining the effective coefficient functions F_p^e and $\varepsilon_p^e$of relative dielectric constants, varying from 0 to 100 with R_p in E and G, one can retrieve the effective dielectric constants ε_{HH}^e= 11.72 and $\varepsilon_{VV}^e = 17.28$ at points E and G, respectively. This implies that the air–sea surface film–sea water medium with a dielectric constant of film 2, can be regarded as an air-effective medium with effective dielectric constants ε_{HH}^e= 11.72 and $\varepsilon_{VV}^e = 17.28$ in HH polarization and VV polarization, respectively.

4.2. Characteristics of effective dielectric constants for air–sea surface film–sea water media

Based on our effective dielectric constant model for the stratified air–sea surface film–sea water medium, the characteristics of an effective dielectric constant for the stratified air–sea surface film–sea water medium are studied here.

Firstly, according to our model, the relative dielectric constant of the film has an effect on the effective dielectric constant. Let the thickness of the sea surface film be 0.01 m. Figure 3 shows that the effective dielectric constants decrease with increasing values of the relative dielectric constants of the film. Effective dielectric constant in VV polarization is larger than that of HH polarization. The discrepancy in effective dielectric constant between VV polarization and HH polarization increases with the increase of relative dielectric constant of the sea surface film.

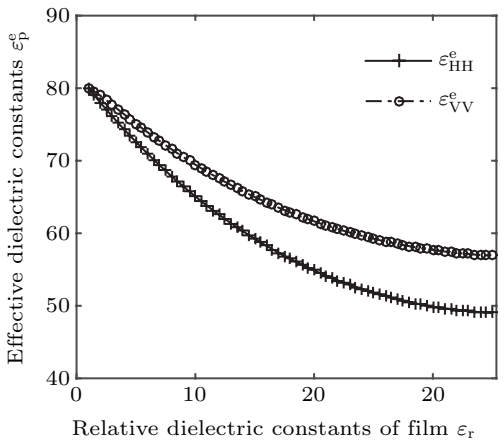


Fig. 3. Effective dielectric constants varying with relative dielectric constant of the sea surface film for the cases of HH polarization and VV polarization.

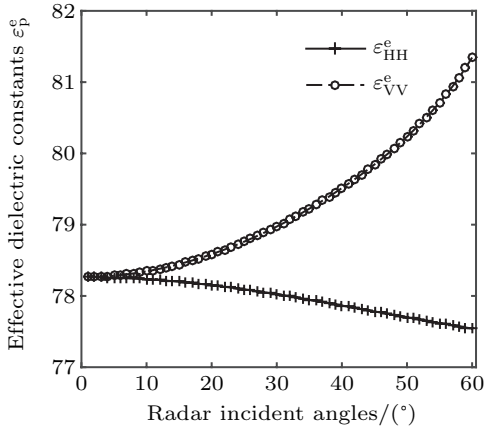


Fig. 4. Effective dielectric constants varying with radar incident angle for the cases of HH polarization and VV polarization.

Secondly, the effect of radar incident angle on effective dielectric constant is shown in Fig. 4. Comparing the results

in Fig. 4 with those in Fig. 3, one can find that the radar incident angle has less effect than the effect of the relative dielectric constant of film on the effective dielectric constant. Figure 4 shows the effects of radar incident angle on effective dielectric constants for HH polarization and VV polarization are quite different from each other. As the radar incident angle increases from 0° to 60°, the effective dielectric constant decreases in HH polarization but increasaes in VV polarization. Furthermore, the changing rate of the effective dielectric constant with radar incident angle in VV polarization is larger than that corresponding to HH polarization.

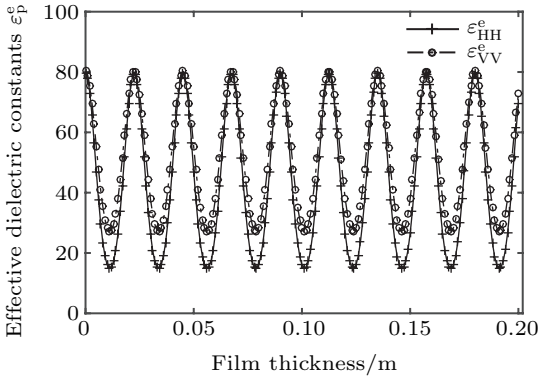


Fig. 5. Effective dielectric constants varying with relative sea surface film thickness.

Finally, sea surface film thickness can affect the effective dielectric constant. From Fig. 5, it is clearly seen that the effective dielectric constant varies with relative sea surface film thickness as a cosinusoidal function of sea surface film thickness. Like the results shown in Figs. 3 and 4, the effective dielectric constant of HH polarization is less than that of VV polarization, which holds true for all film thickness values (0–0.2 m here).

To sum up, there exist mainly three parameters of the sea surface film, i.e., thickness, relative dielectric constant of the film and the radar incident angle, and these parameters are sensitive to effective dielectric constant. Among them, thickness is the most significant factor influencing retrieval results of effective dielectric constant, whereas the radar incident angle has the least effect on the effective dielectric constant.

As for the application, there are two potential applications for our model results in Figs. 3–5. One is to retrieve the dielectric constant from sea surface film because the effective dielectric constant monotonically decreases with relative dielectric constant of the sea surface film (Fig. 3). The other is likely to retrieve the film thickness with using our model, although the problem of thickness ambiguity remains to be solved (suggested by Fig. 5).

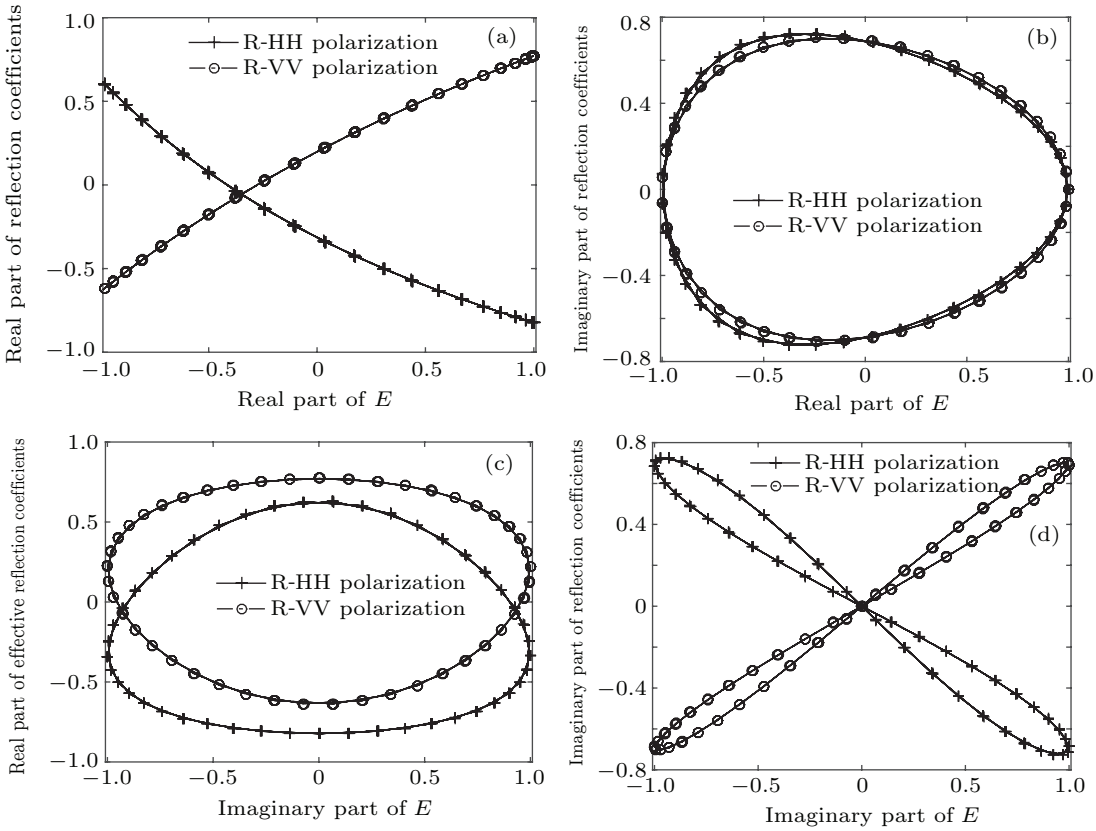


Fig. 6. Relationships between reflection coefficients and phase term $E = e^{j(2k_{z1}h)}$ for the cases of HH polarization and VV polarization, showing the plots of (a) the real part of reflection coefficient versus the real part of phase E, (b) the imaginary part of reflection coefficient versus the real part of phase E, (c) the real part of reflection coefficient versus the imaginary part of phase E, and (d) the imaginary part of reflection coefficient versus the imaginary part of phase E.

Here, we discuss how to find the monotonic relationship between the effective dielectric constant and possible relevant parameters. Starting from the relationship between reflection coefficient and phase term $E = e^{j(2k_{z1}h)}$ in our model, four relationships are determined in Fig. 6. Here, relationships between the real part of the reflection coefficients and the real part of phase E, the imaginary part of the reflection coefficient and the real part of phase E, the real part of the reflection coefficient and the imaginary part of phase E, and the imaginary part of the reflection coefficient and the imaginary part of phase E are shown in Figs. 6(a)–6(d), respectively. One can find that the only monotonic relationship in Fig. 6 is shown in Fig. 6(a), i.e., the real part of the reflection coefficient is a monotonic function of the real component of the phase term E.

According to results shown in Fig. 6, the monotonic relationships between the effective constant and the real parts of the cases of HH polarization and VV polarization are shown in Fig. 7. The results show that the effective constant increases with increasing value of the real component of E in the cases of HH polarization and VV polarization. Moreover, the effective constant in VV polarization is larger than that in HH polarization. Based on the results shown in Fig. 7, our model may be a potential tool for the retrieval of film thickness.

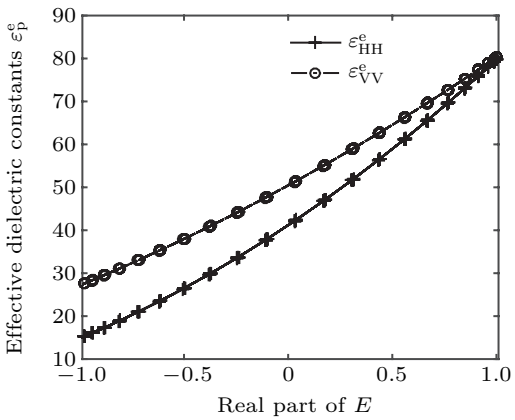


Fig. 7. Effective dielectric constants varying with the real part of the phase term $E = e^{j(2k_{z1}h)}$ for the cases of HH polarizayion and VV polarization.

5. Conclusions

It is a difficult task to automatically detect and classify sea surface films by remote sensors such as SAR, needless to say, the retrieval of film thickness values. For finding the potential of developing this technology to solve these problems, an effective dielectric constant model of electromagnetic backscattering from a stratified air–ocean surface film–sea water medium is presented in this paper.

Starting from the EM backscattering theory of multiple-layer medium and the Bragg backscattering model of EM backscattering from a rough surface, the concept of the effective dielectric constant of the air–ice–sea water medium is presented to study the characteristics of the effective dielectric constant for air–sea surface film–sea water medium.

Numerical results of our model show characteristics of the effective dielectric constant for air–sea surface film–sea water medium. This is regarded as an effective medium as follows: (i) Effective dielectric constant decreases with increasing the value of the relative dielectric constant of a sea surface film; (ii) effective dielectric constant decreases in HH polarization while increases in VV polarization, with increasing the value of the radar incident angle; (iii) effective dielectric constant varies with relative sea surface film thickness as a cosinusoidal function of sea surface film thickness; and (iv) effective dielectric constant in VV polarization is larger than that in HH polarization.

There are two potential applications suggested for our model. One is to retrieve the dielectric constant from sea surface film, because the effective dielectric constant monotonically decreases with increasing the relative dielectric constant of sea surface film. The other is to likely retrieve the film thickness with using our model, although there exists the problem of thickness ambiguity that needs to be solved.

In brief, in this paper, the concept of an effective dielectric constant is presented to develop an effective dielectric constant model. With our model, the potential to retrieve the dielectric constant and thickness from a sea surface film is presented. Our model has highly significant potential for improving sea surface film remote sensing technology.

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