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Theoretical Study on Microwave Scattering Mechanisms of Sea Surfaces Covered With and Without Oil Film for Incidence Angle Smaller Than 30°

Honglei Zheng, Jie Zhang, Yanmin Zhang, Ali Khenchaf, *Member, IEEE*, and Yunhua Wang

Abstract—This article is devoted to investigating the microwave scattering mechanisms of oil-free and oil-covered sea surfaces for an incidence angle smaller than 30° in a backscattering configuration. The Elfouhaily spectrum is used to simulate an oil-free sea surface, whereas the Elfouhaily spectrum combined with the Jenkins damping model is applied to the simulation of an oil-covered sea surface. Then, the Kirchhoff approximation-stationary phase approximation (KA-SP) and the first order of small-slope approximation (SSA-1) are employed to simulate the scattering coefficients induced by specular scattering and total scattering, respectively. Importantly, a new parameter defined as specular scattering to total scattering ratio (STR) is proposed in this article, which can be used to measure the ratio of specular backscattered power to total backscattered power. The dependencies of the scattering coefficient and the STR on incidence angles, wind speeds, wind directions, oil thicknesses, and so on, are investigated. This article provides new insights for a better understanding of the evolution of microwave scattering mechanisms from oil-free and oil-covered sea surfaces in the transition region of incidence angles (from about 15° to 30°).

Index Terms—Kirchhoff approximation (KA), microwave scattering, ocean remote sensing, oil spill, small-slope approximation (SSA).

I. INTRODUCTION

OIL spilled on the sea surface causes considerable damage and threat to the environment and life in the ocean. In the past few decades, many researchers have made great efforts to monitor the oil pollution on the sea surface. It is well known that synthetic aperture radar (SAR) has been one useful tool for detecting and monitoring oil spills due to its effective measurement in almost all atmospheric conditions

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[1]–[3]. The basic principle of an SAR in probing oil films is based on the different remarkable scattering mechanisms between the polluted and clean sea surfaces [4].

Microwave scattering from the sea surface has been extensively studied [5]–[11]. For small incidence angles (from 0° to 15°), the scattering mechanism is dominated by the specular scattering [10], where the scattering coefficient, σ_0 , or normalized radar cross-section (NRCS) decreases rapidly with an increasing incidence angle. For moderate incidence angles (from about 30° to 70°), the Bragg resonance dominates and the scattering coefficient decreases slowly as the incidence angle increases [12]. In this range, the microwave backscatter is predominantly produced by the presence of small-scale waves superimposed on large gravity waves. As for the transition region (from about 15° to 30°), both specular scattering and Bragg scattering contribute to the scattered energy. Once the oil film spreads on the sea surface, short-gravity and capillary waves are suppressed, leading to a smaller sea surface roughness. Meanwhile, the specular scattering becomes more pronounced, resulting in more electromagnetic (EM) energy scattered in the forward direction. At the same time, the backscattered energy related to Bragg scattering is also reduced because the small-scale waves resonating with the incident radar signal have been damped. Consequently, the intensity of the backscattered field from oil-covered sea surface is remarkably reduced, resulting in “dark pitches” in SAR images. Apart from the intensity, the presence of oil film also influences the phase and polarimetric characteristics of the scattering field. For instance, the standard deviation of the co-polarized phase difference for oil-covered sea surfaces is obviously larger than that of the clean sea surfaces [13]. The polarimetric entropy, as a measurement of the randomness of scattering mechanisms, exhibits quite different properties for oil-free and oil-covered sea surfaces [14]. Other polarimetric characteristics widely employed in oil spill detection, such as the average scattering angle [14], the pedestal height [15], the degree of polarization [16], and so on, also directly relate to the scattering mechanism.

At present, most of the work in the previous literature 22focus on analyzing the measured SAR images by resorting to image processing and classification methods [3], [13], [17], [18]. In order to take full advantage of an SAR to probe an oil spill, it is necessary to study the scattering mechanisms of oil-free and oil-covered sea surfaces, theoretically

as well as experimentally. Although the radar backscattering cross-section has been widely applied for studying scattering mechanisms theoretically and experimentally, it cannot provide an estimation of the contribution of each mechanism to the backscattered signal [19]–[24]. Since most spaceborne or airborne radars operate under moderate incidence angles, most studies of microwave scatterings are conducted at moderate incidence angles. However, the operating region of some spaceborne SAR systems covers a small incidence angle and transition region, for example, the incidence angle of the precipitation radar (PR) on the Tropical Rainfall Mapping Mission (TRMM) is 0° – 18° , the incidence angles of the Ku-band PR and the Ka-band PR on the Global Precipitation Mission (GPM) satellite are, respectively, $\pm 17^\circ$ and $\pm 8.5^\circ$, the incidence angle of the Radarsat-2 ultrafine model is 20° – 54° , and so on. Therefore, it is of practical significance to study the microwave scattering at the incidence angles lower than 30° . In this regard, theoretical analyses are performed to study the dominant microwave scattering mechanisms from oil-free and oil-covered sea surfaces at incidence angles smaller than 30° , especially in the transition region. It is important to note that the responses of the scattering coefficient to oil films and the changes in the scattering mechanism caused by oil films under different oil film thickness, fractional filling factor, incidence angles, wind speeds, and wind directions are investigated. In addition, a novel parameter, specular scattering to total scattering ratio (STR), is proposed for the first time, which can directly reflect the evolution of scattering mechanisms on the sea surface from low-to-moderate incident angles. By quantitatively analyzing the proportion of two kinds of scattering (specular scattering and Bragg scattering) under various conditions, the changing trend of STR will be concluded.

This article is organized as follows: the modeling of oil-free and oil-covered sea surfaces, as well as the scattering model, is briefly introduced in Section II. Numerical simulations are presented and discussed in Section III. A conclusion is drawn in Section IV.

II. THEORY AND METHODOLOGY

A. Descriptions of Clean and Polluted Sea Surfaces

Simulating the sea waves accurately is the basis for studying the microwave scattering from the sea surface. The sea spectrum describes the distribution of each harmonic component of the sea surface as a function of the spatial wavenumber and wind direction, which is commonly used to model the sea waves. In the past few decades, many sea spectrum models have been proposed and developed, for example, the Apel spectrum [25], the Fung spectrum [12], the Elfouhaily spectrum [26], the Hwang spectrum [27], [28], and so on. Among these models, the sea spectrum proposed by Elfouhaily *et al.* is one of the most widely used because it not only matches well with the experimental result of Cox and Munk but also simultaneously describes large-scale and small-scale waves. Therefore, in this article, the Elfouhaily spectrum is employed to model a clean sea.

When oil films cover the sea surface, the short-gravity and capillary waves are dampened. At present, two damping

models are often used to simulate this damping effect. One model proposed by Lombardini *et al.* [29] is suitable for modeling the damping effect induced by the monomolecular film, and the other one is developed by Jenkins and Jacobs [30] which can be used to simulate the damping effect induced by oil films with finite thickness. In general, the thickness of a mineral oil spill is much larger than that of the monomolecular film. Thus, the damping model given by Jenkins and Jacobs is adopted in this article and the damping ratio can be written as

$$y(k_w) = \frac{\text{Re}(\zeta)}{2\nu} \quad (1)$$

where k_w is the spatial sea wavenumber, and ζ and ν are two interim parameters during the calculation of the damping ratio. More details about the damping model can be found in the appendix. The physical parameters of the oil film used in this article refer to the work of Sergievskaya *et al.* [31]. Notably, since numerous field experiments have demonstrated that the damping effect is independent of the wind direction [23], [32]–[35], the damping ratio disassociates from the wind direction in this model. In addition, in our simulations, the damping ratio induced by the oil film under various wind speeds are assumed to be the same, which is the same as that reported in [22] and [23].

Moreover, given that the slick film may be partially dispersed by winds and sea waves, a fractional filling factor (F) is introduced to modify the damping ratio. Therefore, the damping ratio can be rewritten as follows [20]:

$$y_F(k_w) = \frac{1}{1 - F + F/y(k_w)}. \quad (2)$$

Due to the small-scale waves of the slick-covered surface being damped, the roughness of the surface is reduced, resulting in a decrease in friction velocity. This phenomenon has been observed in field experiments. The friction velocity of an oil-covered sea surface u_{*c} can be calculated by an empirical equation [33]

$$u_{*c} = \beta u_{*f} \quad (3)$$

where u_{*f} denotes the friction velocity of the oil-free sea surface and $\beta = 0.7$. Therefore, the sea spectrum of the oil-covered sea surface can be expressed as

$$S_c(k_w, u_{*c}) = \frac{S_f(k_w, u_{*c})}{y_F(k_w)} \quad (4)$$

where $S_c(k_w, u_{*c})$ denotes the sea spectrum of the oil-covered sea and $S_f(k_w, u_{*c})$ denotes the sea spectrum of the clean sea.

Fig. 1 shows the damping ratio as a function of the spatial wavenumbers for different oil film thicknesses (d) and fractional filling factors (F). For real situations, the thickness of an oil film is typically very thin, about several to dozens of micrometers. Here, we take 10, 40, 70, and 100 μm as examples to evaluate the impact of oil film thickness. As shown in Fig. 1, the damping ratio increases with F . While d increases, the damping ratio decreases for $k_w < 70$ rad/m and increases for $k_w > 70$ rad/m. Similar to the case for Ku-band (14.6 GHz), which is discussed in detail later, the Bragg scattering wave range which resonates with Ku-band incident wave when the incidence angle is from 10° to 30° is

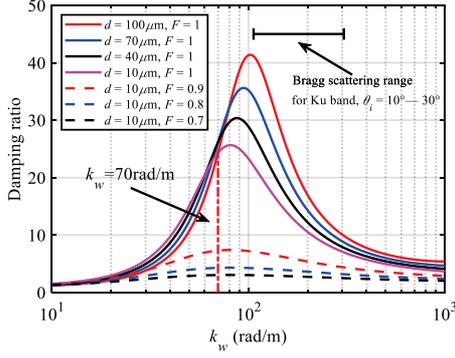


Fig. 1. Damping ratio as a function of the spatial wavenumber for different d and F .

shown in Fig. 1. The damping effect in this range becomes more significant with increasing d and F .

Fig. 2 shows the simulated root mean square (rms) slopes of clean and polluted sea surfaces versus wind speed at 10-m height (U_{10}). The corresponding rms slopes can be derived by [36]

$$\text{Upwind: } \sigma_u = \sqrt{\int_0^\infty \int_{-\pi}^\pi (k_w \cos \phi)^2 S_{c/f}(k_w, \phi) d\phi dk_w} \quad (5)$$

$$\text{Crosswind: } \sigma_c = \sqrt{\int_0^\infty \int_{-\pi}^\pi (k_w \sin \phi)^2 S_{c/f}(k_w, \phi) d\phi dk_w} \quad (6)$$

where $S_{c/f}(k_w, \phi)$ denotes the sea spectrum of oil-free or oil-covered sea surfaces and ϕ stands for wind direction. In Fig. 2, “E” denotes the results simulated using the Elfouhaily spectrum, “CM” denotes those simulated with the Cox and Munk model, “sea” denotes the clean sea, “oil” denotes the oil-covered sea surface, “u” denotes the upwind, and “c” corresponds to the crosswind. In Fig. 2(a), the simulated rms slopes of oil-free and oil-covered sea surfaces in upwind and crosswind directions are compared with those obtained by Cox and Munk [37]. The accuracy of the simulated rms slopes is acceptable. Notably, the impact on the rms slope by different d is small. Meanwhile, the corresponding simulated rms slopes for different F are shown in Fig. 2(b). We observed that F makes a larger impact on the rms slope.

B. Modeling of Microwave Scattering From Sea Surface

The problem of microwave scattering from the sea surface has been widely investigated [8], [10], [12], [38], [39]. Typically, the scattering mechanism from the sea surface includes two kinds of scattering mechanisms, namely the specular scattering (which dominates at small incidence angles) and the Bragg scattering (which dominates at moderate incidence angles)

$$E_s^t = E_s^{\text{sp}} + E_s^{\text{Br}} \quad (7)$$

where E_s^t denotes the total scattering field, and E_s^{sp} and E_s^{Br} denote scattering fields induced by specular scattering and Bragg scattering, respectively. Considering that the scattering

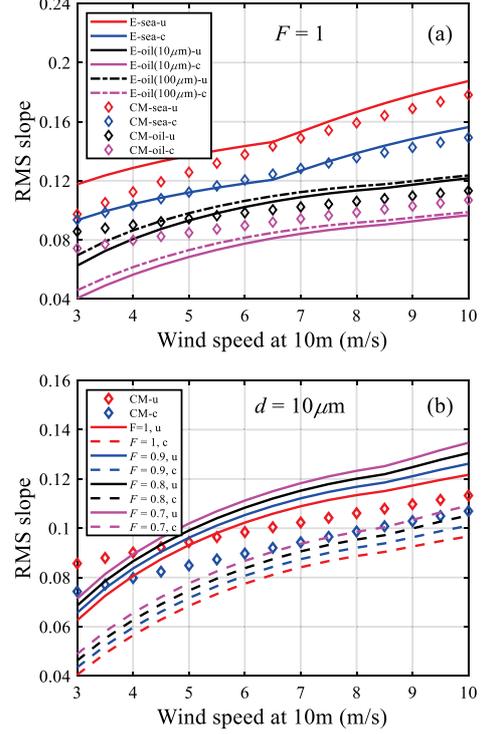


Fig. 2. Simulated rms slopes versus wind speed at 10 m: (a) with respect to d ; (b) with respect to F .

coefficient is proportional to the power of the scattering field (i.e., $\sigma_0 \propto |E_s|^2$), we propose the STR parameter to measure the proportion of specular scattered energy in total scattered energy, which is expressed as

$$\text{STR} = \frac{\sigma_0^{\text{sp}}}{\sigma_0^t} \quad (8)$$

where σ_0^t denotes the scattering coefficient of total scattering, and σ_0^{sp} denotes the scattering coefficient of specular scattering. When the incidence angle is small, the specular scattering dominates and the value of STR is close to 1. For moderate incidence angles, the Bragg scattering dominates and the value of STR tends to 0. While in the transition region, the value of STR varies from 1 to 0 with the increase in the incidence angle. The dependence of STR on the incidence angle can be easily concluded. However, the dependence of STR on wind speed, wind direction, and oil film is not clear. The following content is devoted to investigating this issue.

C. Simulation of the Specular Scattering

The Kirchhoff approximation (KA, or the tangent plane approximation) is an effective method for simulating the specular scattering [5], [10], [40], [41]. According to the KA, the scattered field at any point within a source-free region bounded by a closed surface can be expressed in terms of the tangential fields on the surface. The Kirchhoff approximation-stationary phase approximation (KA-SP) can be obtained by further applying the SP after the tangent plane approximation. Furthermore, to obtain the analytical solution of the scattering coefficient, the value of $q_z^2 \delta^2$ is often assumed to be large enough that the autocorrelation function is approximately

expressed as a Taylor expansion. The so-called Kirchhoff approximation–geometric optics approximation (KA-GO) can be obtained in case the autocorrelation function is approximately expressed as a second-order Taylor expansion. The result of GO4 can be obtained in case the autocorrelation function is approximately expressed as a fourth-order Taylor expansion [10], [42]. However, the KA-GO and GO4 are further approximations of KA-SP, which indicates that the results of KA-GO and GO4 may be less accurate. Therefore, in this article, the scattering coefficient of KA-SP in a backscattering configuration is derived and used for calculating the specular scattering coefficient, which can be expressed as

$$\sigma_{0,aa_0}^{\text{KA-SP}} = \frac{q^2 |k_i U_{aa_0}|^2}{2q_z^2} \exp[-q_z^2 \delta^2] \cdot \int_0^r \exp(q_z^2 W_0) \cdot \sum_m J_{-2m}(r q_{xy}) J_m(q_z^2 W_2) \exp[2jm\chi] r dr. \quad (9)$$

The appendix provides more details about the derivation and parameters.

D. Simulation of the Total Scattering

The small-slope approximation (SSA) proposed by Voronovich [43] and Voronovich and Zavorotny [44] has been proven to be effective by incorporating the specular scattering and Bragg scattering. Therefore, the scattering coefficient of total scattering is simulated by using the first-order SSA (SSA-1), which can be expressed as [44]

$$\sigma_{0,aa_0}^{\text{SSA-1}} = \frac{1}{\pi} \left| \frac{2k_{sv} k_{iv}}{k_{sv} + k_{iv}} B_{aa_0} \right|^2 \exp[-(k_{sv} + k_{iv})^2 \delta^2] \cdot \int \{\exp[(k_{sv} + k_{iv})^2 \rho(\mathbf{r})] - 1\} \cdot \exp[-i(\mathbf{k}_{sh} - \mathbf{k}_{ih}) \cdot \mathbf{r}] d\mathbf{r} \quad (10)$$

where \mathbf{k}_{ih} and \mathbf{k}_{sh} denote the horizontal components of the incidence wave and scattering wave, respectively; k_{iv} and k_{sv} denote the vertical components of the incidence wave and scattering wave, respectively; and B_{aa_0} is the polarization-dependent coefficient which can be found in [44].

Since the EM scattering can be influenced by the medium dielectric constant, the Debye equation is employed to model the dielectric constant of seawater [45], where the temperature equals 20 °C and salinity equals 35 ppt. Moreover, it should be noted that the dielectric constant of oil is quite small compared to seawater for the range of microwave frequencies. For instance, biogenic slicks and mineral oils have real components in the range of 2.2–2.35 and imaginary components less than 0.02, while seawater is about $60 + 40j$ [14]. Hence, microwaves can penetrate the oil film easily, which indicates that the impact caused by oil films on the scattered field can be neglected [33]. Except for the dielectric constant, other physical properties of the oil, such as surface tension, viscosity, density, and so on, also can affect the characteristics of the sea surface. However, the impacts induced by these properties are not discussed in this article due to the limited experimental data. Therefore, the impacts of the oil thickness and fractional filling factor are discussed in this article.

III. NUMERICAL SIMULATION AND DISCUSSION

A. Assessment of the Simulation Method

The KA and the SSA have been frequently applied for simulating the microwave scattering from the oil-free sea surface for several years. However, the utilization of these two methods for the relative study of the oil-covered sea surface is rare in previous articles. To assess the performance of the SSA-1 and KA-SP used in this article, the scattering coefficients simulated by these two methods under different conditions are compared with the measurements obtained from this section. Fig. 3(a)–(c) shows the comparison of the scattering coefficient simulated by the KA-SP and the SSA-1 with that of KA-GO and the geophysical model function (GMF) SASS-II [46] under various incidence angles, wind speeds, wind directions, and polarizations. Note that the scattering coefficients of hh-polarization and vv-polarization are the same for KA-GO and KA-SP. The frequency of the incident wave is set as 14.6 GHz. The wind directions at 0° and 90° correspond to the upwind and crosswind directions, respectively. From Fig. 3(a), it can be observed that the discrepancies among the KA-SP, SSA-1, and the KA-GO are quite small (about 1 dB) when the incidence angle is smaller than 15°. The discrepancy between KA-SP and KA-GO becomes significant when the incidence angle is larger than 15°. The reason for such a phenomenon is because the autocorrelation function of KA-GO is not exactly the same as KA-SP after the large $q_z^2 \delta^2$ approximation process. In addition, the differences among the KA-GO, the KA-SP, and the SSA-1 change slightly with wind speed and wind direction. The difference between the scattering coefficients predicted using the SSA-1 and the SASS is within 3 dB. In Fig. 3(c), the difference of the scattering coefficient between upwind and crosswind is less than 1 dB for the SASS, whereas it is almost 2 dB for the KA-SP, the KA-GO, and the SSA-1. The differences between the simulated results and measurements come from the semiempirical sea waves model (the sea spectrum) and the analytical approximate EM scattering model. At present, neither the sea spectrum nor the scattering model is accurate enough. For example, Voronovich and Zavorotny [44] pointed out that the accuracy of the Elfouhaily spectrum in the crosswind direction is questioned.

Fig. 3(d) shows the comparison between the simulated and measured oil–water contrasts for various incidence angles. Notably, the value of the oil–water contrast is defined as the ratio of scattering coefficients from the oil-covered surface and from the clean surface. The simulated value is obtained by using the SSA-1, while the measured value was calculated by Panfilova *et al.* [47] based on the measured data acquired by the Ku-band PR. In Fig. 3(d), σ_{oc} and σ_{of} denote the scattering coefficients of oil-covered and oil-free sea surface, respectively. The comparison results illustrate that the discrepancy is within the acceptable level. Thus, the simulation method introduced earlier can be used to study the microwave scattering mechanisms qualitatively.

For a real sea, the slopes of the sea surface in the upwind direction are steeper than that in the downwind direction, resulting in the differences between the corresponding

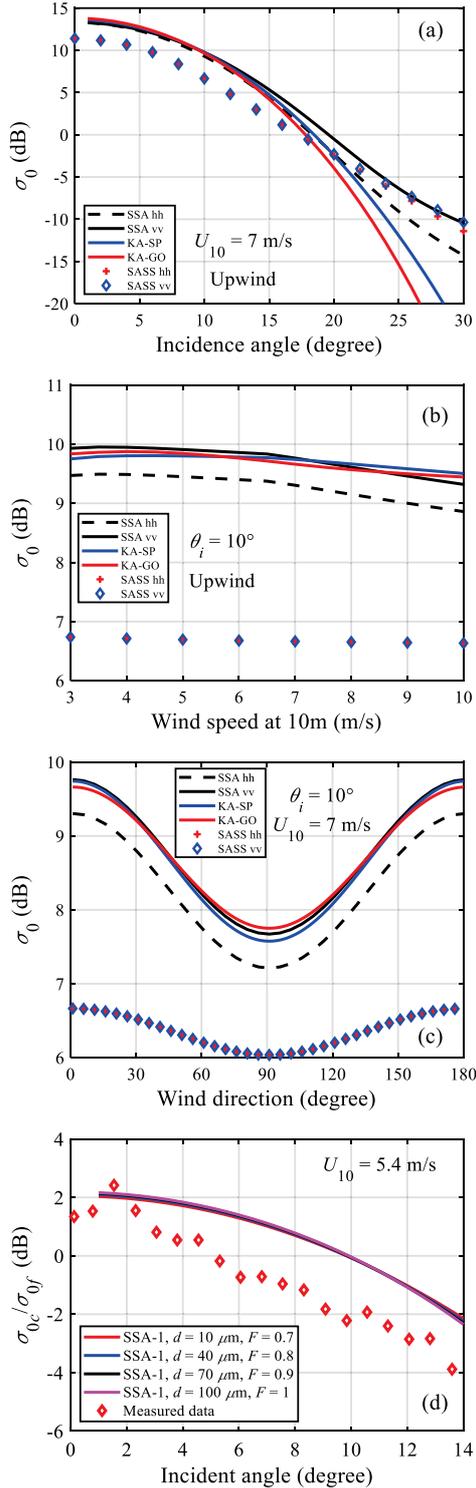


Fig. 3. Scattering coefficients simulated with SSA-1 and KA-SP are compared with those obtained using the KA-GO and the GMF SASS-II under various conditions: (a) incidence angles, (b) wind speeds, and (c) wind directions, respectively. (d) The comparison of scattering coefficients between the simulated and measured oil–water contrasts for various incidence angles.

scattering coefficients. But the discrepancies of scattering coefficients between upwind and downwind directions are very small, especially for small incidence angles, which have been well studied in [38] and [48]. Therefore, the impacts on the scattering coefficients induced by the upwind/downwind asymmetry of sea waves have been ignored in this article,

which is dealt with as in [22] and [49]. Moreover, since the difference of scattering coefficients between hh-polarization and vv-polarization is not remarkable in small incidence angles, henceforth, only the case for vv-polarization is presented and discussed in detail in the sequel.

B. Analysis of the Scattering Coefficients Under Various Conditions

In general, the ocean surface can be divided into two types of scale structures according to the two-scale model: the small-scale structure ruled by capillary waves and the large-scale structure ruled by gravity waves, wherein the large-scale structure can be approximately regarded as being composed of numerous small facets [5]. The Bragg scattering and specular scattering are induced by the small-scale structure and large-scale structure, respectively. By using the SSA-1 (which corresponds to total scattering) and the KA-SP (which corresponds to specular scattering), the scattering coefficients of clean and polluted sea surfaces are simulated for various incidence angles, wind speeds, and wind directions, as shown in Fig. 4. For an incidence angle smaller than 15° , the scattering coefficients of polluted sea surfaces for different d and F are close to that of clean sea surfaces. This is because the large-scale waves serve as the main scattering elements for specular scattering in this incidence angle range, while the oil film mainly influences the small-scale wave. For an incidence angle larger than 15° , the discrepancies between clean and polluted seas increase with the incidence angle for both total scattering and specular scattering. In Fig. 4(a), the scattering coefficient slightly increases as d increases when the incidence angle is smaller than approximately 25° , but decreases when the incidence angle is larger than approximately 25° . The reason for this phenomenon is that the scattering coefficient related to specular scattering increases with oil thickness when the incidence angle is smaller than 25° as shown in Fig. 4(b). However, for the incidence angle larger than approximately 25° , the Bragg scattering becomes more pronounced and the scattering coefficient related to Bragg scattering decreases with an increase in d due to the enhanced damping effect (Fig. 1).

In Fig. 4(e)–(h), both the total scattering and specular scattering coefficients increase as wind speed increases. The backscattered power of the specular scattering originates from small facet normal to incident waves [8]. With the increase in wind speed, the slopes of the sea surface enlarged, making smaller facet normal to incidence waves. Therefore, the backscattered power from such small facets increases with wind speed. At the same time, the Bragg scattered power also increases with wind speed due to the increased spectral density of the Bragg water waves. Interestingly, in Fig. 4(e)–(l), the scattering coefficient increases as d increases, whereas it decreases as F increases. It is because the changing trend of the scattering coefficient directly relates to the damping ratio (Fig. 1). Notably, the scattering coefficient is obtained for the incidence angle of 20° , which is dominated by the specular scattering that is highly affected by sea waves for $k_w < 70$ rad/m. As mentioned earlier, when $k_w < 70$ rad/m, the value of the damping ratio increases as F increases,

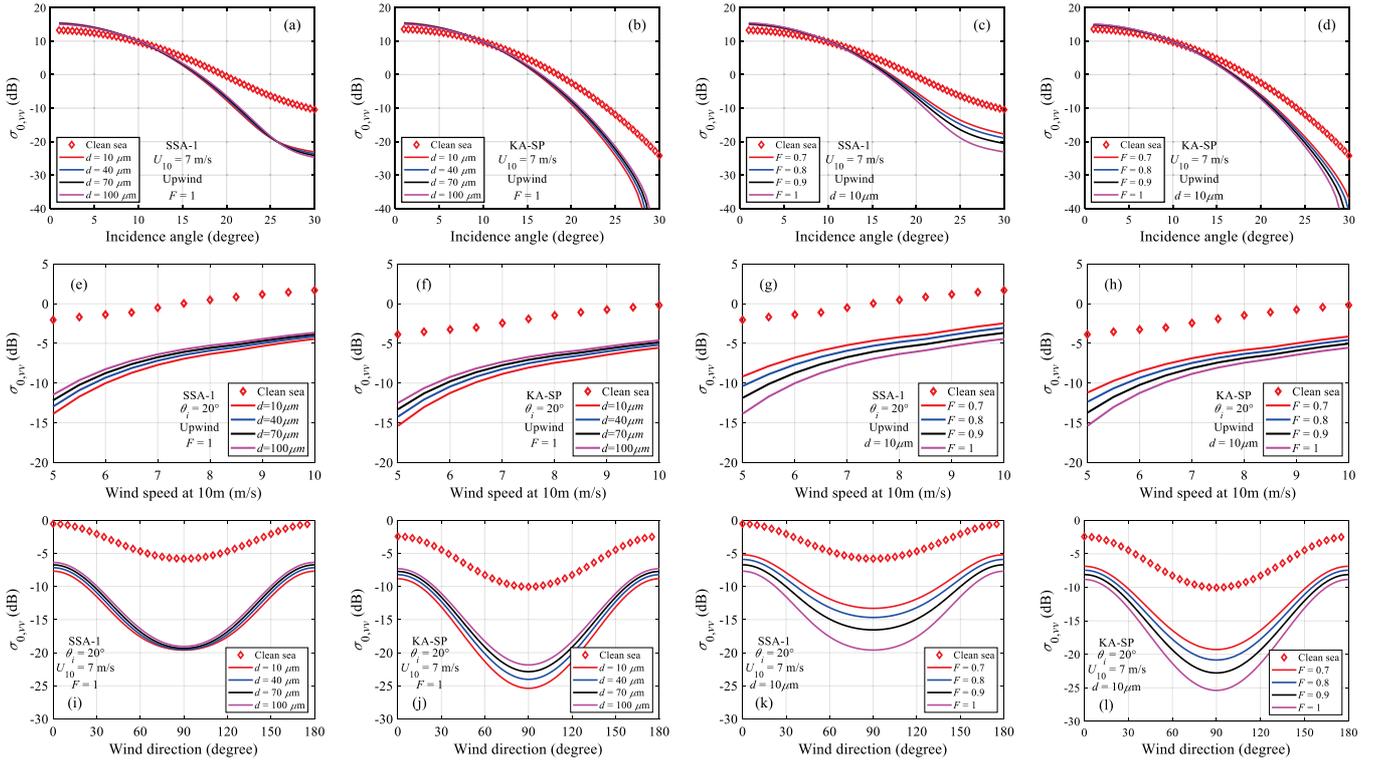


Fig. 4. Scattering coefficient of clean and polluted sea surfaces under various conditions: (a)–(d) incidence angles, (e)–(h) wind speeds, and (i)–(l) wind directions, respectively. Please note that the detailed information for the simulations has been given in the figures.

while it decreases as d increases. In addition, the scattering coefficient increases as d and F increase when the incidence angle is larger than 25° . It is because the impacts on the damping ratio by d and F are the same in the Bragg scattering dominated region (as shown in Fig. 1). Furthermore, as shown in Fig. 4(i)–(l), the discrepancy of the scattering coefficients between polluted and clean seas is more pronounced in the crosswind direction than that in the upwind direction.

In addition, the effect of oil film thickness on the scattering coefficient is not obvious. The biggest difference between the curve corresponding to 10 and 100 μm is less than 4 dB [crosswind in Fig. 4(j)], which indicates that it is difficult to probe the oil film thickness via a Ku-band microwave sensor when the incidence angle is smaller than 30° .

C. Analysis of the STR Under Various Conditions

It is known that, in the transition range of the incidence angle (for the incidence angle from about 15° to 30°), both specular scattering and Bragg scattering contribute to the scattered energy. The STR parameter is proposed in this article to directly analyze the scattering mechanism under various conditions. Fig. 5 shows the simulated STR for clean and polluted seas surface under different incidence angles, wind speeds, and wind directions. It can be observed that the STR of oil-covered sea surface increases slightly with d and F . For a fixed incidence angle, a thicker oil film or oil film with a larger fractional filling factor has larger values of STR. It is important to note that the STR of an oil-covered sea is larger than that of a clean sea. This does not mean that the scattered energy induced by specular scattering is larger than that of a clean sea. It is because the scattered energies

induced by both specular and Bragg scattering mechanisms are decreased, while the backscattered energy induced by the Bragg scattering decreases more significantly than that of the specular scattering. As shown in Fig. 5(a) and (b), for both clean and polluted sea surfaces, the values of STR decrease as the incidence angle increases, which means the proportion of the backscattered power induced by the specular scattering decreases as incidence angle increases. This phenomenon is consistent with the general conclusion that the specular scattering dominates in small incidence angles and the Bragg scattering dominates in moderate incidence angles. In Fig. 5(a), one can note that the STR of the oil-covered sea is smaller than that of the clean sea when the incidence angle is larger than approximately 27° . The reason for this phenomenon is that the backscattered power induced by specular scattering decreases rapidly as more EM waves have been scattered in the forward direction [see Fig. 4(b)].

The simulated STR of the polluted sea and clean sea for various wind speeds are shown in Fig. 5(c) and (d), and there is just a slight change in the STR in the range of 5–10 m/s wind speeds. It is because of the backscattered power induced by both the specular scattering and Bragg scattering increases with the increase in wind speeds. Fig. 5(e) and (f) shows the STR of the polluted and clean seas for various wind directions. It can be observed that the STR has larger values in the upwind and downwind directions than that in the crosswind direction, which is similar to the behavior of the scattering coefficient. It may be because the number of small facets perpendicular to the incidence wave in the upwind and downwind directions is more than that in the crosswind direction. In addition, it can be observed that d and F make significant impacts on

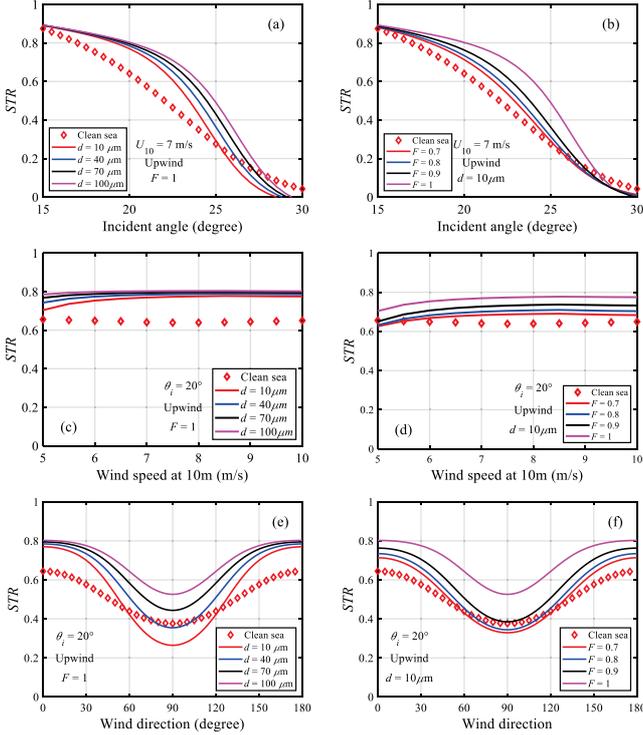


Fig. 5. STR of clean and polluted sea surfaces under various conditions: (a)–(b) incidence angles, (c)–(d) wind speeds, and (e)–(f) wind directions, respectively. Please note that the detailed information for the simulations has been given in the figures.

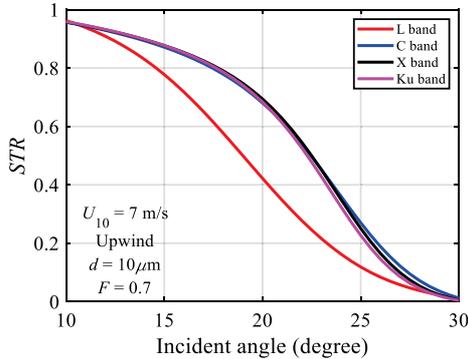


Fig. 6. STR of the polluted sea for various bands.

STR in the crosswind direction than in the upwind/downwind directions.

Apart from the Ku-band, we also carried out similar simulations for L-band (1.25 GHz), C-band (5.3 GHz), and X-band (9.65 GHz), which have been frequently applied in ocean remote sensing. Similar conclusions can be drawn from analyzing the other three bands. Fig. 6 shows the simulated STR of the polluted sea for various bands. It can be observed that the values of STR of these four bands decrease from 1 to 0 as the incidence angle increases. Interestingly, the discrepancies of STR among the C-band, X-band, and Ku-band are very small, whereas the curve corresponding to the L-band is significantly smaller than the other three bands. The sea surface roughness is relatively small for longer wavelength microwave, resulting in more microwaves scattered in the forward direction. Therefore, the specular backscattered energy accounts for a smaller proportion in the L-band.

IV. CONCLUSION

The study of microwave scattering from the sea surface is of significance to make good use of an SAR for observing oil spills on the sea surface. By comparing experimental investigations, theoretical studies can help us to have a better understanding of the scattering mechanisms. This article provides new insights into the scattering mechanisms from clean and polluted sea surfaces through numerical simulation for an incident angle smaller than 30° . The main contributions and conclusions can be summarized as follows:

- 1) The scattering coefficient in the frame of the KA-SP is derived. The results show that the difference of scattering coefficients between the KA-SP and the KA-GO cannot be neglected for incident angles larger than 15° . From a theoretical standpoint, the KA-SP is more accurate than the commonly used KA-GO, thanks for involving fewer assumptions and approximations.
- 2) As shown in Fig. 4, the impacts of oil film thickness on microwave scattering are not obvious for wind speeds between 5 and 10 m/s and incidence angles smaller than 30° . Therefore, it is difficult to probe the thickness of oil films by using a microwave sensor.
- 3) As shown in Fig. 5, for wind speeds between 5 and 10 m/s, the STR increases as the oil thickness and fractional filling factor increase, clearly indicating that the proportion of the corresponding specular backscattered power in the total backscattered power increases.
- 4) By observing Fig. 5, both for clean and polluted sea surfaces, the STR is highly dependent on the incidence angle and is not sensitive to wind speed when it is between 5 and 10 m/s. Moreover, the STR has a wind direction dependence, and the value of STR is larger in the upwind/downwind directions than that in the crosswind direction.

It should be noted that the backscattered power induced by specular scattering of the oil-covered sea surface becomes negligible when the incidence angle is larger than approximately 27° . Therefore, the conclusions (3) and (4) are only available for an incidence angle smaller than 27° . In addition, the simulated results of KA-SP are influenced by the choice of k_d (see the appendix). For instance, in Fig. 4, a larger k_d may result in a larger scattering coefficient for all conditions. However, the corresponding variation trend does not change with the value of k_d .

In this article, the EM scattering is simplified as a combination of specular scattering and Bragg scattering. In reality, the EM scattering from sea surfaces is a rather complex process that involves the breaking waves, nonlinear effects, and so on. In future works, these influence factors will be considered. A hopeful perspective pertains to designing and conducting relevant field experiments to study the scattering mechanisms, in order to confirm the conclusions drawn in this article.

APPENDIX A DERIVATION OF THE KA-SP

With the tangent plane approximation and the stationary-phase approximation, the scattering coefficient can be

expressed as [5]

$$\sigma_{0,\alpha\alpha_0}^{\text{KA-SP}} = \frac{|k_i U_{\alpha\alpha_0}|^2}{4\pi A_0} \langle |I|^2 \rangle \quad (\text{A1})$$

where α and α_0 correspond to the polarizations of scattered and incidence waves, respectively. $\alpha\alpha_0 \in \{\text{hh}, \text{hv}, \text{vh}, \text{vv}\}$, where h denotes horizontal polarization and v denotes vertical polarization; k_i is the wavenumber of incidence wave; A_0 is the illuminated area; and $U_{\alpha\alpha_0}$ is the polarization-dependent coefficient [5]. $\langle |I|^2 \rangle$ can be expressed as

$$\langle |I|^2 \rangle = \iint \langle \exp[jk_i(\hat{\mathbf{n}}_s - \hat{\mathbf{n}}_i) \cdot (\mathbf{r}' - \mathbf{r}'')] \rangle dS' dS'' \quad (\text{A2})$$

where $\hat{\mathbf{n}}_i$ is unit vector in the direction of incidence and $\hat{\mathbf{n}}_s$ is the unit vector in scattering direction. When the surface height is normally distributed, (A2) can be written as

$$\langle |I|^2 \rangle = \frac{q^2}{|q_z|^2} (2L)^2 \int_{-2L}^{2L} \int_{-2L}^{2L} \exp[jq_x u + jq_y v] \cdot \exp[-q_z^2 \delta^2 (1 - \rho)] dudv. \quad (\text{A3})$$

In (A3), $2L$ is the illuminated length, and

$$\begin{cases} q_x = k_i(\sin \theta_s \cos \varphi_s - \sin \theta_i \cos \varphi) \\ q_y = k_i(\sin \theta_s \sin \varphi_s - \sin \theta_i \sin \varphi) \\ q_z = k_i(\cos \theta_s + \cos \theta_i) \\ q^2 = q_x^2 + q_y^2 + q_z^2 \end{cases} \quad (\text{A4})$$

where θ_i is the incidence angle; θ_s is the scattering angle; φ is the angle between the radar-looking direction and the upwind direction; and φ_s is the scattering azimuth angle. δ and ρ are the rms height and the autocorrelation coefficient, respectively. The above-mentioned derivations are given in [5]. The integration in (A3) is difficult to carry out due to the oscillation of integrand. To simplify the calculation, the value is often assumed to be large enough so that the autocorrelation can be expressed as a Taylor expansion. Different from the previous method, in this article, the scattering coefficient is calculated by the following method.

By switching (A3) to polar coordinates, we can obtain

$$\begin{aligned} \langle |I|^2 \rangle &= \frac{q^2}{q_z^2} (2L)^2 \exp[-q_z^2 \delta^2] \\ &\cdot \int_0^{2\pi} \int_0^r \exp[jr(q_x \cos \varphi + q_y \sin \varphi)] \\ &\cdot \exp[q_z^2 W(\mathbf{r})] r dr d\varphi. \end{aligned} \quad (\text{A5})$$

The autocorrelation function $W(\mathbf{r})$ can be expressed in polar coordinates with the sea spectrum [36]

$$\begin{aligned} W(\mathbf{r}) &= W(r, \varphi) = W_0(r) - \cos(2\varphi)W_2(r) \\ W_0(r) &= \int_0^{k_d} S_0(k_w) J_0(k_w r) dk_w \\ W_2(r) &= \int_0^{k_d} S_0(k_w) J_2(k_w r) \Delta(k_w) dk_w \end{aligned} \quad (\text{A6})$$

where $S_0(k_w)$ denotes the omnidirectional part of sea spectrum, k_w is the wavenumber of the sea wave. k_d is set as $k_i/3$ in this article. $J_0(\cdot)$ and $J_2(\cdot)$ are the Bessel functions of the first

kind of zero and second order, respectively. Substituting the autocorrelation function into (A5), we can obtain

$$\begin{aligned} \langle |I|^2 \rangle &= \frac{q^2}{q_z^2} (2L)^2 \exp[-q_z^2 \delta^2] \cdot \int_0^{2\pi} \int_0^r \exp(q_z^2 W_0) \\ &\cdot \exp[jr q_{xy} \cos(\varphi - \chi) - q_z^2 \cos(2\varphi) W_2] r dr d\varphi \end{aligned} \quad (\text{A7})$$

where $q_{xy} = (q_x^2 + q_y^2)^{1/2}$, $\chi = \arctan((q_y)/(q_x))$. The complex exponential can be expressed as

$$\begin{aligned} \exp[jr q_{xy} \cos(\varphi - \chi)] &= \sum_{n=-\infty}^{n=\infty} j^n J_n(r q_{xy}) \exp[jn(\varphi - \chi)] \\ \exp[-q_z^2 W_2 \cos(2\varphi)] &= \sum_{m=-\infty}^{m=\infty} j^m J_m(j q_z^2 W_2) \exp[j2m\varphi]. \end{aligned} \quad (\text{A8})$$

Then, the integration for φ in (A7) can be written as [7]

$$\begin{aligned} &\int_0^{2\pi} \exp[jr q_{xy} \cos(\varphi - \chi) - q_z^2 \cos(2\varphi) W_2] d\varphi \\ &= \int_0^{2\pi} \sum_{m,n} j^{m+n} J_n(r q_{xy}) J_m(j q_z^2 W_2) \\ &\cdot \exp[j(n\varphi - n\chi + 2m\varphi)] d\varphi. \end{aligned} \quad (\text{A9})$$

With the Kronecker delta function,

$$\delta_{x,y}^K = \frac{1}{2\pi} \int_0^{2\pi} \exp[j(x-y)\Phi] d\Phi. \quad (\text{A10})$$

Equation (A9) can be written as

$$\begin{aligned} &2\pi \sum_{m,n} j^{m+n} J_n(r q_{xy}) J_m(j q_z^2 W_2) \exp[-jn\chi] \delta_{n,-2m}^K \\ &= 2\pi \sum_m j^{-m} J_{-2m}(r q_{xy}) J_m(j q_z^2 W_2) \exp[2jm\chi] \\ &= 2\pi \sum_m J_{-2m}(r q_{xy}) I_m(q_z^2 W_2) \exp[2jm\chi]. \end{aligned} \quad (\text{A11})$$

In (A11), $I(\cdot)$ is the modified Bessel function of the first kind. Substituting (A11) into (A7), we can obtain

$$\begin{aligned} \langle |I|^2 \rangle &= \frac{2\pi q^2}{q_z^2} (2L)^2 \exp[-q_z^2 \delta^2] \cdot \int_0^r \exp(q_z^2 W_0) \\ &\times \sum_m J_{-2m}(r q_{xy}) \cdot I_m(q_z^2 W_2) \exp[2jm\chi] r dr. \end{aligned} \quad (\text{A12})$$

Substituting (A12) into (A1), the scattering coefficient in backscattering configuration can be finally written as

$$\begin{aligned} \sigma_{0,\alpha\alpha_0}^{\text{KA-SP}} &= \frac{q^2 |k_i R_{\alpha\alpha_0}|^2}{q_z^2} \exp[-q_z^2 \delta^2] \cdot \int_0^r \exp(q_z^2 W_0) \\ &\cdot \sum_m J_{-2m}(r q_{xy}) I_m(q_z^2 W_2) \exp[2jm\chi] r dr \end{aligned} \quad (\text{A13})$$

where $R_{\alpha\alpha_0}$ denotes the Fresnel reflection coefficient at normal incidence. In (A13), the main contribution to the sum is given for $m = 0$. In our work, the sum is empirically calculated for $m = \pm 10$ to make it converge well.

TABLE I
VALUES OF PHYSICAL PARAMETERS OF THE OIL FILM
USED IN THIS ARTICLE

Physical parameters	Values	
Water density (ρ_w)	1023	$\text{kg}\cdot\text{m}^{-3}$
Oil density (ρ_o)	850	$\text{kg}\cdot\text{m}^{-3}$
Kinematic viscosity of water (ν_w)	0.85×10^{-6}	$\text{m}^2\cdot\text{S}^{-1}$
Kinematic viscosity of oil (ν_o)	0.09×10^{-4}	$\text{m}^2\cdot\text{S}^{-1}$
Surface tension (γ_+)	30	$\text{mN}\cdot\text{m}^{-1}$
Interfacial tension (γ_-)	20	$\text{mN}\cdot\text{m}^{-1}$
Surface elasticity (χ_+)	0	$\text{mN}\cdot\text{m}^{-1}$
Interfacial elasticity (χ_-)	25	$\text{mN}\cdot\text{m}^{-1}$
Surface viscosity (ν_{s+})	0	$\text{mN}\cdot\text{m}^{-1}$
Interfacial viscosity (ν_{s-})	0	$\text{mN}\cdot\text{m}^{-1}$

APPENDIX B
THE DAMPING MODEL

According to Jenkin's model, the damping ratio model for short-gravity and capillary waves, which relate to the thickness of oil, can be expressed as [30]

$$y(k_w) = \text{Re}(\zeta)/(2\nu) \quad (\text{B1})$$

with

$$\zeta = \left\{ 2\nu + \frac{1}{2}v_T + j\Gamma^{-1/2}[\gamma(1-\rho_+) - \gamma_-]D\sqrt{a^2 + b^2} + \frac{1}{2\nu^{1/2}j^{1/2}}\rho_+D\Gamma^{1/4}v_T + \frac{1}{2\nu^{1/2}}j^{1/2}(\rho_+D)^2\Gamma^{3/4}(R^2 - 1) \right\} / \left\{ 1 + \frac{1}{\nu^{1/2}\Gamma^{1/4}}j^{1/2}v_T + \frac{1}{\nu^{1/2}\Gamma^{1/2}}\rho_+D\Gamma^{1/4} \right\} \quad (\text{B2})$$

where

$$v_T = \frac{(\chi_+ + \chi_-)}{n} + v_{s+} + v_{s-} + 4\rho_+v_+D + \frac{v_{E+}v_{E-}D}{\rho_+v_+} \quad (\text{B3})$$

$$R = \frac{\rho_+ + \gamma_+}{\rho_+\Gamma}, \quad n = -j\sqrt{\Gamma}, \quad \Gamma = 1 + \gamma, \quad \gamma = \gamma_+ + \gamma_- \quad (\text{B4})$$

$$v_{E\pm} = \chi_{\pm}/n + v_{s\pm}, \quad j = \sqrt{-1} \quad (\text{B5})$$

$$v = k_w^{3/2}g^{-1/2}\nu_w, \quad v_+ = k_w^{3/2}g^{-1/2}\nu_o \quad (\text{B6})$$

$$D = k_w d, \quad \rho_+ = \rho_o/\rho_w \quad (\text{B7})$$

where d is the thickness of the oil film, ν_w is the kinematic viscosity of the seawater, ν_o is the kinematic viscosity of the oil film, ρ_w is the density of seawater, ρ_o is the density of the oil film. γ_+ is the surface tension, γ_- is the interfacial tension, ν_+ is the kinematic viscosity, χ_+ is the surface elasticity, χ_- is the interfacial elasticity, v_{s+} is the surface viscosity, and v_{s-} is the interfacial viscosity. The values of the physical parameters for the oil film used in numerical simulations are listed in Table I, which were derived based on experimental measurements. More information about the experimental measurements can be found in [31].

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