Research on the electromagnetic scattering from foam sea based on small slope approximation

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Abstract
In order to improve the research of electromagnetic scattering characteristics and mechanism of the foam in the marine environment, considering the complexity and sensitivity of the electromagnetic scattering characteristics of the sea surface, the electromagnetic scattering characteristics of the foam sea surface are studied by the improved small slope approximation (SSA) method. The double Debye dielectric constant model is adopted to calculate the dielectric constant of seawater and foam. Based on the Elfouhaily sea spectrum model, the expression of scattering coefficient of the foam sea surface under SSA is derived, and then the theoretical calculation results of the SSA method are compared with the finite-difference time-domain method and the measured values in the literature, which verifies the effectiveness of the proposed algorithm. The model of the relationship between the thickness of the foam layer and the wind speed is established, and the composite backscattering characteristics of the ocean below the wind speed of 20 m/s are simulated. It is found that as the wind speed increases, the foam layer becomes thicker and the scattering intensity increases. The foam layer will weaken the ocean specular reflection and increase the diffuse reflection, which is more obvious when viewed at grazing and large incidence angle, and when the incident angle is greater than 83 degrees, the inflexion point caused by the foam will be clearly observed in the backscattering curve. The results of this study can provide a reference for civil and military activities and optimise the detection capability in the marine environment.

1 | INTRODUCTION

The oceans account for seven-tenths of the earth’s total area and contain many extremely valuable resources, such as plants, animals, minerals and oil. However, due to the complexity of the marine environment, the lack of research on the marine environment leads to the lack of exploitation and low utilisation of marine resources. At the same time, with the development of new ocean energy, ocean exploration and target recognition, experts realise the importance of ocean research, and ocean electromagnetic scattering has become a research hotspot.

In remote sensing [1, 2], it is available to obtain much valuable information by analysing the scattering echo of the ocean, such as seawater temperature, salinity, dielectric constant, sea surface wind speed and wave height. In the electromagnetic field [3–5], a lot of information can be obtained by processing scattered echoes, which would be used for sea condition judgment, target detection and tracking, missile precision guidance and strike, providing technical support for the civilian industry and the military. However, due to the diversity and variability of the marine environment, the actual analysis and research face great difficulties: Except for waves, corrugation and breakers [6, 7], there are always white waves (ocean foam) that exist in the actual sea surface, which have a certain impact on the electromagnetic scattering characteristics of the environment, bringing greater difficulties to marine research. To this end, many scholars have carried out a lot of research.

Anguelova and Gaiser [8] did much work on the mechanical and dielectric properties of sea foam, took many parameters into consideration, which could have an influence on foam emissivity, such as foam skin depth and size parameter, and offered a conceptual understanding for the high, black-body-like emissivity of foam floating on the sea surface while the ocean foam composite scattering is rarely studied. Jiang et al. [9] incorporated the scattering and coherent interaction in the foam layer into the physical model, and mainly analysed the volume scattering effects on emissivity from the foam-covered ocean surface. However, the research focused on the range...
of 30 to 60 degrees, ignoring the influence of large angles or grazing incidence. Huang and Jin [10] found the significance of foam and whitecaps, especially for high wind speed and large observed angle, based on semi-empirical Pierson’s sea spectrum, which was obtained by ocean observation data, and did not study the impact of Elfouhaily sea spectrum. Zheng et al. [11] researched and compared six different sea spectral models, calculated the electromagnetic scattering of the sea surface based on small slope approximation (SSA), and found that it is difficult to find a specific spectral model to accurately simulate the scattering coefficient at all wind speeds or downwards, but the spectrum given by Elfouhaily and Hwang can more accurately reflect the actual wind and waves, which is essential for the accuracy of the foam layer. Dong et al. [12] analysed the microwave emissivity and scattering of foam on a seawater surface based on Monte Carlo simulations and dense-media radiative transfer theory, verified the polarisation and frequency dependencies of emissivity on microstructure properties such as foam layer thickness and the size of foam air bubbles, and also, the electromagnetic scattering characteristics of the ocean foam had not been studied in the article. Wei et al. [13] and also, the electromagnetic scattering characteristics of the ocean foam enhanced the scattering of the sea surface, and the wind speed increased and the foam layer thickened, its effect became more obvious. The research results have reference value in marine, target detection, environmental research, meteorological monitoring and other fields.

2 | SEA SPECTRUM MODEL AND CORRELATION FUNCTION

2.1 | Elfouhaily sea spectrum model

The general form of the Elfouhaily sea spectrum model [15] in polar coordinates is as follows:

\[ S(K) = S(K, \xi) = W(K) G(K, \xi) \]  

(1)

In the formula, \( K \) represents the wavenumber spectrum of ocean waves, \( \xi \) represents the angle of position, \( G(K, \xi) \) is the direction function, and \( W(K) \) is the spectrum of undirected curvature, which consists of two parts: High-frequency curvature spectrum \( B_{HF} \) and low-frequency curvature spectrum \( B_L \):

\[ W(K) = (B_L + B_{HF})/K^3 \]  

(2)

High-frequency curvature spectrum \( B_{HF} \) corresponds to gravity wave spectrum

\[ B_{HF} = \alpha_w F_w e^{c(K_m)/2c(K)} \]  

(3)

where \( c(K) \) is the phase velocity of the wave, \( K \) is the wave number, and \( K_m \) denotes the peak wave number

\[ c(K) = \sqrt{\frac{\delta}{K}(1 + K^2/K_m^2)} \]  

(4)

where \( \alpha_w \) is a function of surface friction wind speed and \( c(K) \)

\[ \alpha_w = 0.01 \begin{cases} 1 + \ln \left[ u_e/c(K_m) \right] u_e \leq c(K_m) \\ 1 + 3 \ln \left[ u_e/c(K_m) \right] u_e > c(K_m) \end{cases} \]  

(5)

\[ F_w = \exp \left[ -(1 - K/K_m)^2/4 \right] \]  

(6)

The low-frequency curvature spectrum \( B_L \) corresponds to the tension wave spectrum, and its calculation expression is as follows:

\[ B_L = \alpha_l F_l e^{c(K_l)/2c(K)} \]  

(7)

Since the power spectrum of the real sea surface is anisotropic, it is necessary to introduce the direction function \( G(K, \xi) \) to correct it

\[ G(K, \xi) = \left[ 1 + \Delta(K) \cos(2\xi) \right] /2\pi \]  

(8)

2.2 | Correlation function

The correlation function can be obtained by Fourier transform of Elfouhaily sea spectrum whose expression is

\[ C(R, \xi) = \int_0^{2\pi} \int_0^\infty W(K) \exp[jKR\cos(\xi - \varphi)] Kd\varphi dK \]  

(9)

In the formula, \( W(K) \) is the curvature spectrum and \( \xi \) denote the wind direction.

2.3 | Dielectric constant model

The dielectric constant is a very important factor that has an influence on electromagnetic scattering and varies with electromagnetic wavelength and medium composition. The
Debye model [16] is usually used to synthesise the influence of electromagnetic wave frequency \( f \), seawater temperature \( T \) and seawater salt content \( S \) on seawater dielectric constant \( \varepsilon_r \), and the model formula is
\[
\varepsilon_r = 4.9 + \frac{\varepsilon_r - 4.9}{1 + (2\pi f / \tau)^{1-a}} - j \frac{\sigma}{2\pi f \varepsilon_0} \tag{10}
\]
where
\[
\varepsilon_r(T, S) = \varepsilon_r(T, 0) \cdot a(T, S) \tag{11}
\]
\[
\tau(T, S) = \tau(T, 0) \cdot b(T, S) \tag{12}
\]
The parameters in the formula are defined in [16] and will not be repeated here. The foam is a particle of seawater wrapped in the air whose dielectric constant \( \varepsilon_f \) can be expressed in terms of the air volume fraction \( V \) and the permittivity of seawater \( \varepsilon_r \) [17]
\[
\varepsilon_f = \varepsilon_r \left[ 1 - \frac{3V(\varepsilon_r - 1)}{2\varepsilon_r + 1 + V(\varepsilon_r - 1)} \right] \tag{13}
\]

### 2.4 Modified SSA

The ocean rough surface model is shown in Figure 1.

The scattering coefficient in decibels can be expressed as [16]
\[
\sigma_{\text{total}} = 10 \cdot \log_{10}(\sigma'_{\text{mf}} + \sigma'_{\text{foam}}) \tag{14}
\]
\( \sigma_{\text{mf}} \) is the electromagnetic scattering cross-section of the ocean, and \( \sigma_{\text{foam}} \) is the electromagnetic scattering cross-section of the foam. The small slope approximation method is used to solve the problem of \( \sigma_{\text{mf}} \), whose core is to solve the scattering amplitude \( T \), the solution equation of \( T \) is as follows:
\[
T(q, k) = -\int_S e^{-i q \cdot x} \cdot \nabla P_k(x) dS \tag{15}
\]
where the points on the scattering cross-section \( S \) are marked by two-dimensional vector \( x \). \( P_k(r) \) satisfies the boundary con-
ditions and Helmholtz equation
\[
(\nabla^2 + k^2)P_k(r) = 0 \tag{16}
\]
The complete solution can be obtained from the integral equation
\[
P_k(r) = e^{ikr} - \frac{1}{4\pi} \int_S G_k(r - x) \cdot \nabla P_k(x) dS \tag{17}
\]
\( r \) is the bin vector, and Green’s function \( G_k(r - x) \) is given by the following formula:
\[
G_k(r - x) = e^{ik|\mathbf{r} - \mathbf{x}|} / |\mathbf{r} - \mathbf{x}| \tag{18}
\]
With the scattering amplitude of the ocean, \( \sigma_{\text{mf}} \) can be obtained as
\[
\sigma_{\text{mf}} = \langle T^* T \rangle / 16\pi^2 \tag{19}
\]
Combined with Equations (15) and (19)
\[
\sigma_{\text{mf}} = \frac{2}{\pi} \left( \frac{k \varepsilon_f Q_i}{Q_j} \right)^2 \cdot I(\alpha) \tag{20}
\]
where
\[
\alpha = \frac{0.08\pi}{200[\Gamma(7/4)]^2} \left( \frac{\mu^2}{\varepsilon_r} \right)^{1/2} \frac{Q_i^2}{Q_j^{3/2}} \tag{21}
\]
\( I(\alpha) \) denotes the spectral integral of roughness; \( k - q = (Q_i, Q_j), Q_i; \) and \( Q_j \) can be expressed by \( \theta_{\text{inc}}, \theta_{\text{scat}} \) and the angle \( \phi_{bi} \) between echo projection and \( x \)-axis:
\[
|Q_j| = k_0 \frac{\cos^2 \theta_{\text{inc}} + \cos^2 \theta_{\text{scat}} - 2 \cos \theta_{\text{inc}} \cos \theta_{\text{scat}} \cos \phi_{bi}}{\sqrt{\cos^2 \theta_{\text{inc}} + \cos^2 \theta_{\text{scat}}}} \tag{22}
\]
\[
Q_i = -k_0 (\sin \theta_{\text{inc}} + \sin \theta_{\text{scat}}) \tag{23}
\]
It can be seen that the scattering coefficient depends on the follows integral
\[
I(\alpha) = \int_0^{\infty} f_0(y)B(y, \alpha) dy \tag{24}
\]
In the formula, \( f_0(y) \) is the first kind of zero-order Bessel function whose expression is
\[
f_0(y) = \sum_{n=0}^{\infty} \frac{(-y^2/4)^n}{(n!)^2} \tag{25}
\]
\[
B(y, \alpha) = \exp(-\alpha y)^{1.5} \tag{26}
\]
Combined with (22), Equation (24) can be expressed as:

\[
I(\alpha) = \frac{2}{3} \alpha^{-4/3} \sum_{n=0}^{\infty} \frac{(-\alpha)^n}{(n!)^2} \left( \frac{1}{4\alpha^{4/3}} \right)^n \Gamma \left( \frac{4(n+1)}{3} \right) \tag{27}
\]

Based on the traditional SSA, the summation of the series needs to be truncated artificially, when the value of \( \alpha \) is large, and the error caused by artificial truncation can be ignored. If the value of \( \alpha \) is very small, the series convergence is slow and that will lead to the error generated by truncation beyond the engineering range, which is uncontrollable in the simulation, so it is impractical to apply Formula (27) to solve the problem. Therefore, the traditional SSA method is modified to accelerate the calculation process and reduce the error.

It is observed that for a non-negative integer \( n \), \( \Gamma(-\alpha) \) has a remainder \( -1(-1)^n/\alpha \). Using the residue theorem, the series term in \( I(\alpha) \) can be changed into

\[
\sum_{n=0}^{\infty} \frac{(-\alpha)^n}{(n!)^2} \left( \frac{1}{4\alpha^{4/3}} \right)^n \Gamma \left( \frac{4(n+1)}{3} \right) = -\frac{1}{2\pi i} \int_{C} \Gamma(\alpha) \Gamma \left( \frac{4(n+1)}{3} \right) \left( \frac{1}{4\alpha^{4/3}} \right)^n d\alpha
\]

Combined with Equations (28) and (27)

\[
I(\alpha) = -\frac{2}{\pi} \sum_{n=0}^{N} \frac{(-\alpha)^n}{(n!)^2} \cdot \Gamma \left( \frac{4(n+1)}{3} \right)^2 \sin \frac{3\pi n}{4} 2^{3n/2} \pm R_N
\]

where

\[
R_N = \alpha^{N+0.3} A(N) B(N) \tag{30}
\]

\[
A(N) = \left[ 2^{4.25+1.5(N-1/2)(N+2.5)} 0.75^{N+1} \cdot x^{0.5(N+3.5)} \right] / 3\sqrt{\pi}
\]

\[
B(N) = \int_{0}^{\infty} (1 + x^2)^{-N+3.5} \left[ (1 + \frac{1}{4\alpha^{4/3}} + x^2)^{-(N+1)/2} \exp \left[ -\alpha x (2\tan^{-1} x - \frac{4}{3}\tan^{-1} \frac{1}{1-x}) \right] \right] \frac{\cosh(\pi x \alpha)}{\cosh(4\pi x \alpha/3)} dx
\]

where \( B(N) \) decays exponentially, and with the increase of \( n \), \( B(N) \) decays faster. The accuracy and calculation speed can be guaranteed by selecting the appropriate truncation value.

In order to study the electromagnetic scattering characteristics of the sea surface foam, besides the electromagnetic scatter-

![Image](image316x257to541x336)

**FIGURE 2** Ocean foam model

From the sea surface, we need to solve the electromagnetic scattering \( \sigma_{\text{hub}} \) of the ocean foam. The bubble in the ocean can be modelled as a random distribution of irrelevant point scatterers in the depth \( d \) range:

\[
I = \int_{0}^{\infty} A_1 \sin^4 (k_0 \sin \theta) \exp(-2z/d) dz
\]

\[
= A_2 k_0^4 d^3/[1 + k_0^4 d^2 (1 + 4k_0^2 d^2)]
\]

\( k_0 = -k_0 \sin \theta, A_1 \) denote the scale factor. According to [18], we can get the functional relationship of \( \sigma_{\text{hub}} \) as follows:

\[
\sigma_{\text{hub}} = \frac{0.0019d^{5.15}k_0^{-0.6}k_0^2k_{\text{r}_d}^2}{2(1 + k_{\text{r}_d}^2k_{\text{r}_d}^2)} \left[ \frac{6 + 3(k_{\text{r}_d}^2 + k_0^2k_{\text{r}_d}^2)^2 + (k_{\text{r}_d}^2 - k_0^2)^2}{1 + (k_{\text{r}_d}^2 + k_0^2)^2} \right] \tag{34}
\]

where \( k_0 = 2\pi f_0 \) indicate the number of sound waves in the seawater without bubbles, \( f \) denotes the sound frequency, \( f_0 \) is the sound velocity in the seawater. \( k_{\text{r}_d} = -k_0 \sin \theta_{\text{inc}}, k_{\text{r}_d} = -k_0 \sin \theta_{\text{scat}} \).

The ocean foam model is shown in Figure 2, \( d \) is the thickness of foam, which is affected by the wind speed \( U \) of 10 m above sea level:

\[
d = 0.557 - 0.117U + 0.0109U^2 \quad U > 7.5 \text{ m/s}
\]

\[
= -0.19609 + 0.06503U \quad 3 \leq U \leq 7.5 \text{ m/s}
\]

\[
= 0 \quad U < 3 \text{ m/s}
\]

The variation curve of thickness with wind speed is shown in Figure 3.

When the wind speed \( U \) is less than 3 m/s, the thickness of the foam layer is zero, so we can think that there is no ocean foam at this time. When the wind speed \( U \) is greater than 3 m/s, the thickness of the foam layer becomes thicker as the wind speed increases, and the thickness of the foam layer changes more obviously with the increase of the slope of the curve.

### 2.5 Finite-difference time-domain (FDTD)

In order to provide a basis for the validity verification of the algorithm in this paper, the numerical algorithm FDTD method
is introduced according to [19]. While horizontal-horizontal (HH) polarisation mode is adopted, the expression is

\[ E_{z}^{i+1}(i, j) = C_{r}(i, j) \times E_{z}^{i}(i, j) \]

\[ + C_{\text{elb}}(i, j) \times H_{x}^{i+1/2}(i, j) - H_{x}^{i+1/2}(i - 1, j) \]

\[ + C_{\text{elc}}(i, j) \times H_{y}^{i+1/2}(i, j) - H_{y}^{i+1/2}(i, j - 1) \]

\[ H_{x}^{i+1/2}(i, j) = C_{\text{fotb}}(i, j) \times H_{x}^{i-1/2}(i, j) \]

\[ + C_{\text{locb}}(i, j) \times (E_{z}^{i}(i, j + 1) - E_{z}^{i}(i, j)) \]

\[ H_{y}^{i+1/2}(i, j) = C_{\text{fotb}}(i, j) \times H_{y}^{i-1/2}(i, j) \]

\[ + C_{\text{locb}}(i, j) \times (E_{z}^{i}(i + 1, j) - E_{z}^{i}(i, j)) \]

Parameter definitions have been described in [19] and will not be repeated here. A smoothing window function is introduced to eliminate the effect of truncation boundary, whose expression is

\[ G(x, y) = \exp \left( -\frac{(x - x_{0})^{2}(\cos \theta_{i})^{2}}{T} \right) \]

where \( \theta_{i} \) stands for the incident angle, \( \theta_{i} \) is the centre of the abscissa, and \( T \) determines the width of the window function, which is expressed as

\[ T = \frac{\rho_{m} \cos \theta_{i}}{2.6} \]

\( \rho_{m} \) is the minimum distance from the centre point of the total field boundary to the edge. While the near-field electromagnetic field equation is obtained, the far-field equation can be obtained by extrapolation. The specific process is described in [19]. Finally, the scattering coefficient is expressed as

\[ \sigma = 10 \cdot \log_{10} \left( \frac{\lim_{r \to \infty} \frac{2\pi r |E_{s}|^{2}}{|E_{i}|^{2}}}{L} \right) \]

In the formula, \( r \) is the distance from the observation point to the origin, \( E_{s}, E_{i} \) stand for the far scattering field and the incident wave electric field, respectively.

### 3 | NUMERICAL RESULTS AND DISCUSSION

#### 3.1 | Validation of the algorithm

In order to enhance the credibility of the simulation results, the effectiveness of the proposed algorithm is verified. In the verification, the backscattering coefficient of the Gaussian sea surface is calculated by the algorithm in this paper, and then the results are compared with the measured values in [20]. The results are shown in Figure 4. It is found that the calculated results of SSA agree well with the measured values, and the ocean foam mainly affects the backscattering coefficient at a low grazing angle. The incident frequency is 8.93 GHz, seawater temperature is 17.4°C, seawater salinity is 32.54‰, and the dielectric constant is (57.63, 37.73). According to [21], the Gaussian spectrum is approximately fitted to the actual sea spectrum under the wind speed of 14–16 knots (7.2–8.2 m/s).

To promote further verification and observation of the algorithm in this article, the bistatic scattering coefficients of sea surface are calculated by SSA and FDTD [22, 23] whose results are shown in Figure 5. By comparing the two curves, it is found that when using the algorithm in this paper to calculate the electromagnetic scattering of the sea surface, except for a small amount of attenuation in the mirror direction (30 degrees),
the agreement is better at most angles, which demonstrates that SSA is effective and feasible for ocean electromagnetic scattering calculation and analysis. The wind speed is 5 m/s, incident frequency is 300 MHz, seawater temperature is 20°C, 32.54‰ of seawater salinity and 30 degrees of incident angle, and the dielectric constant is (71.39, 37.51).

3.2 Electromagnetic scattering from the foam layer

In the simulation, the incident wave frequency is 10 GHz (X band) and HH polarisation is adopted. The salinity of seawater is 35‰, the temperature is 20°C and the sound velocity in seawater is 1500 m/s.

The backscatter result curves under different wind speeds at 60 degrees of incident angle are shown in Figure 6. When the wind speed above sea level is less than 3 m/s, it can be considered that no ocean foam is produced, and the two scattering results are the same. According to Formula (35), it is known that 3 m/s is the critical value of marine foam production. Therefore, when the wind speed is greater than 3 m/s, the bubble begins to appear and thickens gradually, which is positively related to the wind speed. It can be seen that the thickness of the foam layer is an important factor affecting the electromagnetic scattering characteristics of the sea foam at large incidence angle that can be used to judge the size of ocean wind speed and provide a reference for meteorological monitoring and ocean navigation.

The simulation results of the electromagnetic scattering coefficient of the foam layer, seawater layer and foam sea surface are shown in Figure 7 (wind speed 10 m/s). It can be seen that when the radar electromagnetic wave incidents at a small angle, the red and blue curves coincide, indicating that the scattering echo energy is mainly from the sea water, and the bubble scattering effect can be ignored. When the incident angle increases, the red and blue curves are separated, and the red and black curves coincide, which shows that the scattering coefficient of the sea surface foam is the same as that of the foam layer at a large incident angle, and the influence of the seawater layer can be neglected.

3.3 Electromagnetic scattering from the foam-covered sea surface

Figure 8 shows the effect of wind speed on ocean backscattering. Such a phenomenon can be seen: (1) As the electromagnetic wave incidents at a small angle, the scattering coefficient value is negatively correlated with the wind speed; (2) as the electromagnetic wave incidents at a large angle, the scattering coefficient value is positively correlated with the wind speed. The conclusion in Figure 6 explains this phenomenon well: (1) In the range of small incident angle, the influence of ocean foam on
the overall scattering is small and can be ignored. At this time, the greater the wind speed, the rougher the sea surface and the smaller the scattering coefficient; (2) at large incident angles, the influence of ocean foam is large and cannot be ignored. At this time, the greater the wind speed, the thicker the foam layer and the greater the scattering coefficient. In practice, we can use this nature of the ocean to judge and measure the wind speed and wave size in a certain sea area to guide production, rescue or military operations.

The curve of ocean backscattering coefficient versus incident angle is shown in Figure 9. It is found that the sea surface scattering coefficient increases with wind speed and the value under different observation angles is different, which is quite different. When an incident at 30 degrees occurs, the scattering intensity will even decrease as the wind speed increases, which will lead to inaccurate results. Therefore, in the actual marine environment research, the observation angle should be selected reasonably.

Observing each curve, it is found that the black curve (incidence angle 87 degrees) has a turning point at the wind speed of 3 m/s, while other curves do not have this phenomenon. After preliminary analysis, it is believed that the occurrence of the breakpoint may be related to the inherent defects of the SSA method or affected by the ocean foam layer. Therefore, in order to understand the mechanism and related factors, the scattering coefficients at grazing incidence angles of 2, 3, 4, 5 and 7 degrees were simulated, and the results are shown in Figure 10.

Observing each curve, we can see that the smaller the angle, the more obvious the turning point, and the turning point appears at the wind speed of 3 m/s. Combining Figure 3, it is obvious that 3 m/s is the critical point of foam generation. The interference of the foam layer scattering causes this phenomenon, and it also has a certain impact on the observation results. This is related to the inherent shortcomings of the SSA method. In order to effectively solve this problem, in the actual environment measurement and target detection, the observation angle should be selected reasonably. If the angle is too large or too small, the accuracy of the result will be affected.

Figure 11 shows the variation curve of the bistatic scattering coefficient under different wind speeds at 45 degrees incidence. It can be seen that each curve has a maximum value in the mirror direction, and the smaller the wind speed, the smaller the sea surface roughness and the larger the scattering coefficient. In the non-mirror direction, under the same conditions, the scattering coefficient is positively related to the wind speed, that is, the higher the wind speed, the thicker the ocean foam layer and the stronger the scattered echo energy.
4 | CONCLUSION

Based on the modified SSA, this paper improves the sea foam electromagnetic scattering model and conducts a detailed study on the sea surface foam composite electromagnetic scattering characteristics. The composite backscattering characteristics of the ocean below the wind speed of 20 m/s are simulated. It is found that as the wind speed increases, the foam layer becomes thicker and the scattering intensity increases. The foam layer will weaken the ocean specular reflection and increase the diffuse reflection, which is more obvious when viewed at grazing and large incidence angle, and as the incident angle is greater than 83 degrees, the inflexion point caused by the foam will be clearly observed in the backscattering curve. The results can be applied to the fields of fishery production, environmental measurement and target detection and have a guiding role in production and life. However, this article only conducted a modelling study for ocean foam and did not consider the impact of breaking waves or ripples. The next step is to improve the scattering model and include breaking waves and ripples into the calculation category to make the research results closer to reality.

FUNDING INFORMATION

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