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Electromagnetic Scattering from Rough Sea Surface with PM Spectrum Covered by an Organic Film *

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The rough sea surface covered by an organic film will cause attenuation of capillarity waves, which implies that the organic films play an important role in rough sea surface processes. We focus on a one-dimensional (1D) rough sea surface with the Pierson–Moskowitz (PM) spectrum distributed to the homogeneous insoluble organic slicks. First, the impact of the organic film on the PM surface spectrum is presented, as well as that of the correlation length, the rms height and slope of the rough sea surface. The damping effect of the organic film changes the physical parameters of the rough sea surface. For example, the organic film will reduce the rms height and slopee of the rough sea surface, which results in the attenuation of the high-frequency components of the PM spectrum leading to modification of the surface PM spectrum. Then, the influence of the organic film on the electromagnetic (EM) scattering coefficients from PM rough sea surface covered by the organic film is investigated and discussed in detail, compared with the clean PM rough sea surface through the method of moments.

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In recent years, with the rapid development of oil exploration, volumes of oil-polluted water and organic mixtures from offshore oil rigs, drilling platforms and oil tankers are often drained into the ocean, which causes serious ocean pollution. It is important for us to discover ocean pollution such as this in time by radar surveillance before the pollution spreads. Consequently, it is particularly important to study the effects of organic films (e.g. oil film) on the electromagnetic (EM) scattering from the ocean surface. This subject actually refers to the study of EM scattering from layered rough sea surfaces, which has attracted much interest in recent years because of its extensive applications in a number of important research areas[1−3] such as optics for coated surfaces, buried interfaces detection, radar surveillance and imaging. Many researchers have investigated EM scattering from multilayered rough surfaces.[4−6] In Ref. [7] the small perturbation method (SPM) is employed to compute the scattering coefficient from a three-dimensional layered dielectric structure with slightly rough interfaces. The extended boundary condition method (EBCM) and truncated singular value decomposition is applied to analyze the EM scattering from multilayered rough surfaces in Ref. [8]. In addition, some other methods[9−12] such as the finite-difference time-domain (FDTD), the forward backward method with spectral acceleration algorithm (FBM/SAA), the geometric optics approximation (GOA) and the KA have been used to compute the EM scattering from multilayered rough surfaces.

This study is mainly devoted to a detailed analysis of the EM scattering from rough sea surface with the Pierson–Moskowitz (PM) spectrum covered by an organic film. More precisely, it focuses on the rough sea surface distributed homogeneous insoluble organic slicks. We will investigate the impacts of the organic film on the PM spectrum, the correlation length, rms height, as well as the rms slopee. Then, with the knowledge of the relative permittivities[13,14] of the sea water and organic film, the EM scattering coefficients of the rough sea surface covered by an organic film are compared to those of the clean sea surface.

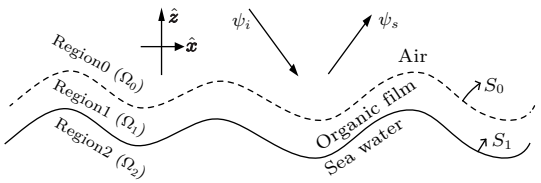


Fig. 1. Geometry for 1D rough sea surface covered by an organic film.

The geometry for one-dimensional (1D) rough sea surface covered by an organic film is shown in Fig. 1. Assume that the rough sea surface is invariant along the $\hat{\boldsymbol{y}}$ direction and the incident wave locates in the $(\hat{\boldsymbol{x}}, \hat{\boldsymbol{z}})$ plane. Consider an incident wave ψ_i impinging upon this layered model ($z = f_0(x)$ and $z = f_1(x)$), ψ_s is the scattered field in region 0 (Ω_0) which denotes the free space with the relative dielectric constant ε_0. Regions 1 and 2, with the relative dielectric constants ε_1 and ε_2, mean the organic film and sea water, respectively. S_0 in the figure defined by the surface equation $z = f_0(x)$ denotes the profile of the organic film and S_1 defined by $z = f_1(x)$ denotes the sea surface profile.

We simulate the profile of the clean rough sea surface with the PM spectrum $W(K)$ [15] via

$$W(K) = \begin{cases} \frac{\alpha}{4|K|^3} \exp\left(-\frac{\beta g^2}{K^2 U_{19.5}^4}\right), & K \geq 0, \\ 0, & K < 0, \end{cases} \quad (1)$$

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where $U_{19.5}$ is the windspeed at a height of 19.5 m and K denotes the surface spatial wavenumber. Other constants are $\alpha = 8.10 \times 10^{-3}$, $\beta = 0.74$ and $g = 9.8\,\mathrm{m/s^2}$. The challenge here is how to simulate the profile of the rough sea surface covered by the natural sea slicks composed of organic material which is usually present as monomolecular films. When the concentration of organic material attains some values (e.g. $1\,\mathrm{mg/m^2}$),[16] the monomolecular film becomes relatively incompressible and the sea surface can no longer be considered to be "free". The film begins appreciably to modify physical processes at the air/sea interface from low film tension of 1–2 $\mathrm{mN/m^2}$.[16] One of the most obvious and sensible effects induced by organic film is the attenuation of capillary waves.

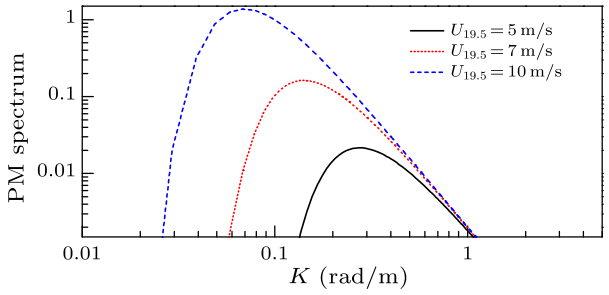


Fig. 2. PM spectrum with different windspeeds.

It is well known that the capillary waves correspond to the high frequencies of the PM spectrum $W(K)$. The modified PM spectrum W' for the rough sea surface covered by the organic film is related to $W(K)$ by

$$W'(K, \xi_0, \omega_D) = W(K)/[y_s(f_\Lambda, \xi_0, \omega_D)], \quad (2)$$

where $y_s(f_\Lambda, \xi_0, \omega_D)$ is the attenuation ratio.[16] Here the organic film is considered as an insoluble organic material and $y_s(f_\Lambda, \xi_0, \omega_D)$ can be written for this case as

$$y_s(f_\Lambda, \xi_0, \omega_D) = \frac{1 + 2\tau + 2\tau^2 - X + Y(X + \tau)}{1 + 2\tau + 2\tau^2 - 2X + 2X^2}, \quad (3)$$

with

$$\tau = \left(\frac{\omega_D}{2\omega}\right)^{\frac{1}{2}}, \quad X = \frac{\xi_0 K^2}{\rho(2\upsilon\omega^3)^{0.5}}, \quad Y = \frac{\xi_0 K}{4\rho\upsilon\omega}, \quad (4)$$

where ρ is the sea water density, υ is the kinematic viscosity, ξ_0 denotes the elasticity modulus and ω_D is a characteristic pulsation which depends on the structural relaxation between intermolecular forces for the insoluble films,

$$f_\Lambda = \frac{\omega}{2\pi} = \frac{(\varsigma K^3/\rho + gK)^{1/2}}{2\pi}, \quad (5)$$

is the dispersion law with ς being the surface tension and f_Λ the spatial frequency. Thus, the damping ratio y_s depends on ξ_0, ω_D and f_Λ (or K). In general, when the sea surface is only partially covered by the organic film, a fractional filling factor C could be introduced and y_s in Eq. (2) should be substituted by $y_s' = (1 - C + C/y_s)^{-1}$. This study concentrates on a fully covered sea, i.e., $C = 1$ and $y_s' = y_s$.

Figure 2 represents the change of the PM spectrum with the windspeeds. It is readily found that the high frequencies have partial loss with the increase of the windspeed. In Fig. 3, the modified PM spectrum $W'$for the contaminated sea surface (sea surface covered by the organic film) is plotted in comparison to the PM spectrum for different windspeeds (Fig. 3(a) for $U_{19.5} = 5\,\mathrm{m/s}$ and Fig. 3(b) for $U_{19.5} = 10\,\mathrm{m/s}$). The parameters of the organic film are $[\xi_0 = 0.009\,\mathrm{N/m}, \omega_D = 6\,\mathrm{rad/s}]$ and $[\xi_0 = 0.025\,\mathrm{N/m}, \omega_D = 11\,\mathrm{rad/s}]$, respectively. As is expected, it can be observed that the high frequencies of the modified PM spectrum trend obviously to weaken for $U_{19.5} = 5\,\mathrm{m/s}$ (shown as in Fig. 3(a)). This implies that the organic film strongly restrains the capillary waves for $U_{19.5} = 5\,\mathrm{m/s}$, which just corresponds to the high frequencies. Furthermore, the attenuation of the high frequencies is more evident for $[\xi_0 = 0.025\,\mathrm{N/m}, \omega_D = 11\,\mathrm{rad/s}]$ than for $[\xi_0 = 0.009\,\mathrm{N/m}, \omega_D = 6\,\mathrm{rad/s}]$. It is worth noting that the difference between the modified PM spectrum and the PM spectrum is very slight for $U_{19.5} = 10\,\mathrm{m/s}$, as shown in Fig. 3(b). The reason is that the PM spectrum has a lower frequency for $U_{19.5} = 10\,\mathrm{m/s}$ than for $U_{19.5} = 5\,\mathrm{m/s}$ (as shown in Fig. 2) and the modification of the spectrum mainly lies in high frequencies, so the curves of the modified PM spectrum almost coincide with those of the original PM spectrum.

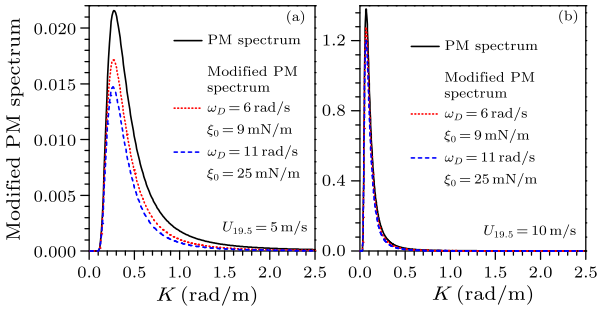


Fig. 3. PM and modified PM spectra versus the surface spatial wavenumber K for different windspeeds.

Note that for 1D rough surface, the self-correlation function $G(R)$ can be written as

$$G(R) = \int_{-\infty}^{\infty} W(K) \exp(iKR) dK, \quad (6)$$

where R is the distance between two arbitrary points on the rough surface. Then, the correlation coefficient $\rho(R)$ is defined as

$$\rho(R) = \frac{G(R)}{\delta^2} = \frac{\int_{-\infty}^{\infty} W(K) \exp(iKR) dK}{\delta^2}, \quad (7)$$

where δ is the rms height and it reads

$$\delta^2 = G(0) = \int_{-\infty}^{\infty} W(K) dK = 2\int_{0}^{\infty} W(K) dK. \quad (8)$$

Substituting $W(K)$ and $W'(K,\xi_0,\omega_D)$ into Eq. (7), we can obtain the correlation coefficients for the PM spectrum and the modified PM spectrum, respectively. The correlation coefficient for the modified PM spectrum is shown in Fig. 4, compared with the PM spectrum.

The rms slope can be expressed as

$$\sigma_s = \left(\int_0^\infty K^2 W(k) dK \right)^{1/2}. \tag{9}$$

For simplicity, the correlation length l is often counted as R when $\rho(R) = 1/e$. From Fig. 4, it can be found that the correlation length l of the clean sea surface is smaller than that of the contaminated sea surface. We attribute this behavior to the fact that the capillarity waves, which have a great influence on the correlation length, are dampened by the organic film.

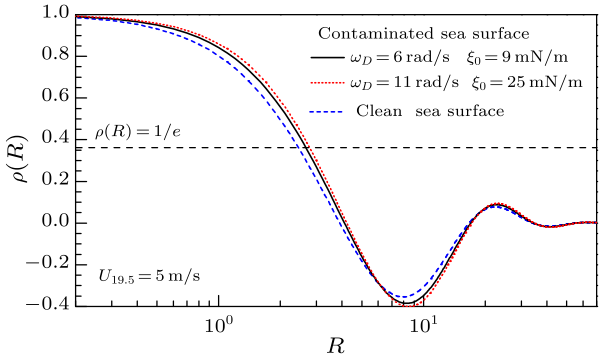


Fig. 4. Correlation coefficient for clean sea surface and contaminated sea surface.

Figures 5 and 6 illustrate the rms height and rms slope of the clean sea surface compared to those of the contaminated sea surface versus the windspeeds. It can be observed that the surface height and the slope are dampened by the organic film for the contaminated sea surface with two different types of the organic film parameters: (1) $\xi_0 = 0.009\,\mathrm{N/m}$, $\omega_D = 6\,\mathrm{rad/s}$, (2) $\xi_0 = 0.025\,\mathrm{N/m}$, $\omega_D = 11\,\mathrm{rad/s}$. This still results from the attenuation of the capillarity wave.

The rough sea surfaces $S_{0,1}$ in Fig. 1 can easily be generated by a spectral method. For the scattering computation, surface realizations are needed at a set of N points with spacing Δx over a length of $L = N\Delta x$. Realizations with the desired properties can be generated at points $x_n = n\Delta x$ $(n = 1, \cdots, N)$ using

$$f(x_n) = \frac{1}{L} \sum_{j=-N/2}^{N/2-1} F(K_j) \exp(jK_j x_n), \tag{10}$$

where for $j \geq 0$,

$$F(K_j) = \sqrt{2\pi L W(K_j)} \times \begin{cases} \frac{1}{\sqrt{2}}[N(0,1) + iN(0,1)], & j \neq 0, \frac{N}{2}, \\ N(0,1), & j = 0, \frac{N}{2}, \end{cases} \tag{11}$$

and for $j < 0$, $F(K_j) = F(K_{-j})^*$, with $K_j = 2\pi j/L$ and each time $N(0,1)$ appears, which indicates an independent sample taken from a zero mean, unit variance Gaussian distribution. Equation (10) is computed with a fast Fourier transform. $W(K_j)$ is the surface spectrum function and $f(x_n)$ is the rough sea surface height function.

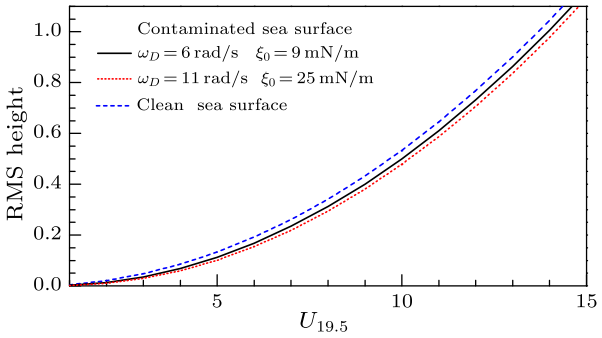


Fig. 5. Root-mean-squared height of clean and contaminated sea surface versus windspeeds.

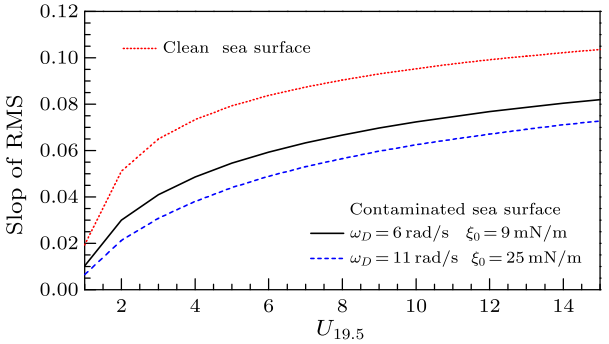


Fig. 6. Root-mean-squared slope of clean and contaminated sea surface versus the windspeed.

An example of rough sea surface realization with different sea surface spectra is shown in Fig. 7. It is obvious that the sea surface heights $f(x)$ with the modified PM spectrum are smaller than that with the PM spectrum resulting from the attenuation of the capillarity wave. Moreover, this effect on the surface height is more prominent for $\xi_0 = 0.025\,\mathrm{N/m}$, $\omega_D = 11\,\mathrm{rad/s}$ than that for $\xi_0 = 0.009\,\mathrm{N/m}$, $\omega_D = 6\,\mathrm{rad/s}$, as observed in the changes of the rms height and slope shown in Figs. 5 and 6.

To determinate the impact of the sea surface spectrum on the EM scattering from contaminated rough sea surface, Fig. 8 give us the bistatic scattering coefficients of a contaminated sea with the PM spectrum and the modified PM spectrum for different polarizations based on MOM.[17–19] The frequency $f = 3\,\mathrm{GHz}$, the incident angle $\theta_i = 0^\circ$ and the wind speed $U_{19.5} = 5\,\mathrm{m/s}$. At this frequency, the relative permittivity[13,14] of the insoluble organic film is $\varepsilon_{\mathrm{organic}} = (2.25, 0.01)$ and that of the sea water is $\varepsilon_{\mathrm{sea}} = (70.4, 40.6)$. The mean thickness of the organic film is 0.01 m. The short-dashed lines in these two figures represent the bistatic scattering coefficients of

the contaminated sea with the PM spectrum, and the solid lines (fine and heavy lines) indicate the modified PM spectrum with two sets of parameters, i.e. $\xi_0 = 0.009\,\mathrm{N/m}$, $\omega_D = 6\,\mathrm{rad/s}$ and $\xi_0 = 0.025\,\mathrm{N/m}$, $\omega_D = 11\,\mathrm{rad/s}$.

It can be seen that the differences of the EM scattering coefficients based on PM spectrum and modified PM spectrum are very obvious. From the figures, we can see that the scattering energy mainly distributea around the special direction and decreases more rapidly away from the special direction for the modified PM spectrum than that for the PM spectrum, which is due to the fact that the rough sea surface with the modified PM spectrum has a lower rms slope, as just observed in Fig. 6. Moreover, the phenomenon is more evident for $\xi_0 = 0.025\,\mathrm{N/m}$, $\omega_D = 11\,\mathrm{rad/s}$ than that for $\xi_0 = 0.009\,\mathrm{N/m}$, $\omega_D = 6\,\mathrm{rad/s}$.

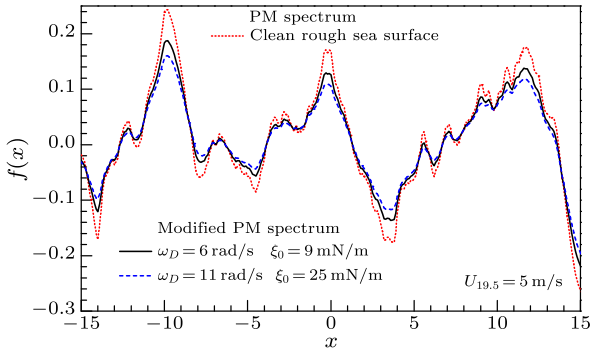


Fig. 7. Sea surface realization with the PM spectrum and the modified PM spectrum.

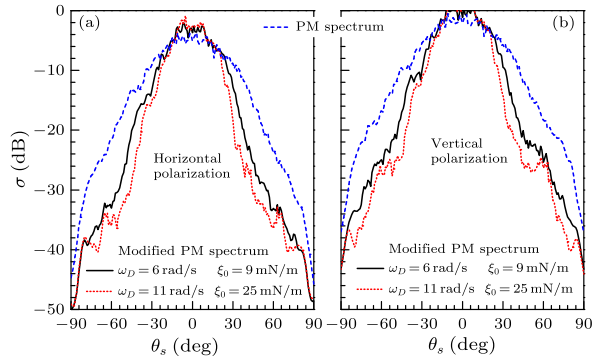


Fig. 8. The comparison of the scattering coefficients of a contaminated sea with different spectra.

Figure 9 gives us the bistatic scattering coefficients of the contaminated rough sea surface compared with those of a clean rough sea surface and an organic film for different polarizations. Here the parameters of the organic film are $\xi_0 = 0.009\,\mathrm{N/m}$, $\omega_D = 6\,\mathrm{rad/s}$. The other parameters are the same as those given in Fig. 8. It is found that the scattering coefficients of the sea surface plotted in solid lines are higher than those of the organic film plotted in dotted lines for all the scattering angles. This is mainly because the relative permittivity of the sea water $\varepsilon_{\mathrm{sea}}$ is larger than that of the organic film $\varepsilon_{\mathrm{organic}}$. The differences of the scattering coefficient between the contaminated sea surface plotted in short-dashed lines and clean rough sea surface is very clear, which may be attributed to the differences in their own surface spectra mentioned above.

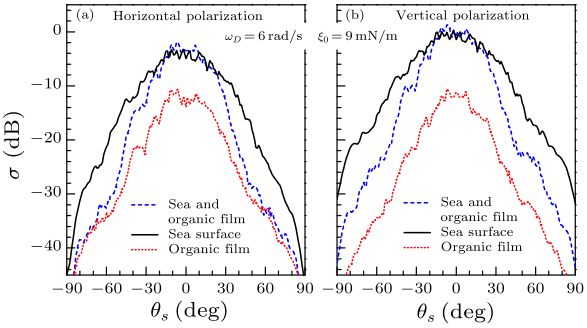


Fig. 9. Comparison of the scattering coefficients of sea surface, organic film and contaminated sea surface.

In summary, we have studied the influence of an organic film on the EM scattering coefficients from 1D rough sea surface with the PM spectrum covered by the organic film. The influence results from the fact that the organic film can modify the physics of the rough sea surface, causing the attenuation of the capillarity waves. Compared the scattering coefficients of the contaminated rough sea surface with those of the clean rough sea surface, it is conceivable that the organic film can clearly influence remotely-sensed microwave imagery.

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