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Phase Function of Seawater Polluted by Oil Emulsion

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Abstract. Oil droplets suspended in the seawater will seriously affect the transmission characteristics of electromagnetic wave from ultraviolet and visible light to infrared. The scattering phase function can show the laser transmission characteristics in seawater polluted by oil. Water with oil emulsion has a phase function significantly different from that of natural ocean water. The accurate calculation of phase function can lay the foundation for laser propagation in the oil spill seawater, and is of great significance for protection of marine environment. This paper presents the modeling of phase function of seawater polluted by dispersed oil based on Mie scattering theory. Numerical calculation of scattering phase function of dispersed oil droplets in various times and at different wavelengths is conducted, and the numerical results of Henyey-Greenstein phase function and the modified Henyey-Greenstein phase function is given. The results show that the shapes of Mie scattering phase function of water with oil emulsion depend on wavelength and the oil emulsion ageing. The forward scattering attenuates with the time of oil emulsion ageing and the increase of incident wavelength, and the scattering gradually becomes homogeneously. Compared with Henyey-Greenstein the modified Henyey-Greenstein phase function can describe the scattering property of oil emulsion in the seawater better. But the fitting effects of both Henyey-Greenstein phase function and the modified Henyey-Greenstein phase function are undesirable for long time oil droplets, long wavelength and strong absorption ultraviolet light.

Keywords: Oil spill, Mie scattering, phase function.

1. Introduction

In recent years, frequent offshore oil spill accidents have polluted water bodies and seriously damaged the Marine surrounding environment and Marine ecological balance. Crude oil or refined oil is released at sea, the oil film interacts with seawater and others to form emulsion suspended in a large amount of seawater [1,2]. Preliminary studies show that the salinity, temperature, illumination, and various organisms of sea water will affect the oil emulsification process, and its shape, size, structure, concentration and distribution will change slowly [3]. The emulsified oil droplets become light absorbers and scatterers[4], which will seriously affect the electromagnetic wave transmission characteristics of ultraviolet, visible and infrared laser. Therefore, it is of great significance to study the light scattering characteristics of oil-spilled seawater for ocean laser remote sensing.

The scattering phase function is a parameter expressing the spatial distribution characteristics of scattered light intensity [5], and is one of the important parameters for studying the light scattering characteristics of oil-spilled seawater. Accurate calculation of the phase function can lay a foundation for the study of light transmission characteristics in seawater. The Mie scattering phase function, HG phase function and HG* phase function are commonly used. HG phase function has the advantages of simple expression and convenient numerical calculation, but this method has some limitations in describing backscattering characteristics. Cornette and Shanks propose the improved HG phase function, namely the HG * phase function [6-8].These two methods are currently widely used in numerical calculations of optical transport. However, whether it is suitable for simulating the light scattering characteristics of oil-spilled seawater needs further verification. Based on the Mie scattering theory, the Mie phase scattering functions of suspended oil droplets in seawater at different time periods and in different bands of laser incident are numerically calculated, and the results are compared with those of HG and HG* phase functions. The accurate calculation

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of the phase function of oil droplets in seawater can lay a theoretical foundation for the study of laser transmission characteristics in oil-spilled seawater.

2. The scattering phase function

The scattering phase function is one of the parameters used to study the inherent optical properties of seawater, characterizing the relationship between scattering and direction. The volume scattering function (VSF)β can describe the phase function and the scattering coefficient, which is defined as follows

$$\beta(\theta)=\frac{dI(\theta)}{EdV}[m^{-1}sr^{-1}] \tag{1}$$

Where dI(θ) is the radiation intensity of volume dV in the direction of scattering angle θ, and E is the incident irradiance. The scattering coefficient b is obtained by integrating the full solid angle of β. The scattering phase function (PF) can be obtained by normalizing the volume scattering function with scattering coefficient, which denotes the ratio of scattered light energy in unit solid angle to the average scattered light energy in unit solid angle in all directions.

$$P(\theta)=\beta(\theta)/b \tag{2}$$

According to Mie scattering theory, the phase function is [9]

$$P_{Mie}(\theta)=\frac{|S_1(\theta)|^2+|S_2(\theta)|^2}{2\pi\alpha^2 Q_{sca}} \tag{3}$$

Where α=2πr/λ is the size parameter of oil droplets, S1 (θ) and S2 (θ) are scattering complex amplitude functions, Qsca is scattering efficiency factor, and their expressions are [10]

$$Q_{sca}(\alpha,m)=\frac{2}{\alpha^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2+|b_n|^2) \tag{4}$$

$$S_1(\theta)=\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}[a_n\pi_n(\theta)+b_n\tau_n(\theta)] \tag{5}$$

$$S_2(\theta)=\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}[a_n\tau_n(\theta)+b_n\pi_n(\theta)] \tag{6}$$

$\pi_n=P_n^1 cos(\theta)/sin(\theta)$, $\tau_n=dP_n^1 cos(\theta)/d\theta$ is the angle dependent function, which can be solved by Legendre recursive relations. an and bn are expansion coefficients, and its expression is

$$a_n=\frac{\psi_n(\alpha)\psi'_n(m\alpha)-m\psi'_n(\alpha)\psi_n(m\alpha)}{\zeta_n(\alpha)\psi'_n(m\alpha)-m\zeta'_n(\alpha)\psi_n(m\alpha)} \tag{7}$$

$$b_n=\frac{m\psi_n(\alpha)\psi'_n(m\alpha)-\psi'_n(\alpha)\psi_n(m\alpha)}{m\zeta_n(\alpha)\psi'_n(m\alpha)-m\zeta'_n(\alpha)\psi_n(m\alpha)} \tag{8}$$

Where m is the complex refractive index of the particle, $\psi_n(\alpha)=\alpha j_n(\alpha)$ .The Mie phase scattering function PMie can be calculated numerically according to the Bessel function recursive formula.

For convenience, an empirical formula proposed by Henyey and Greenstein, the HG phase function, is expressed as [11]

$$P_{HG}(\theta,g)=\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}} \tag{9}$$

Formula: g is an asymmetric factor, and its expression is

$$g=\langle\cos(\theta)\rangle=\frac{\int p(\theta)\cos(\theta)d\theta}{\int p(\theta)d\theta} \tag{10}$$

According to the Mie theory, the expression of g can be calculated by the following equation

$$g=\frac{4}{\alpha^2 Q_{sca}}\sum_{n=1}^{\infty}[\frac{n(n+2)}{n+1}\mathrm{Re}(a_n a_{n+1}^*+b_n b_{n+1}^*)+\frac{2n+1}{n(n+1)}\mathrm{Re}(a_n b_n^*)] \tag{11}$$

HG phase function has the advantages of simple expression, saving calculation time, and can be easily applied to Monte Carlo method on scattering direction sampling. Although it can characterize the forward scattering, it is not very accurate for backscattering, so it has certain limitations. Therefore, Cornette and Shanks proposed an improved HG phase function, namely, HG* phase function, whose expression is

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$$P_{HG^*}(\theta,g)=\frac{3}{2}\frac{1-g^2}{2+g^2}\frac{1-\cos^2\theta}{(1+g^2-2g\cos\theta)^{3/2}} \tag{12}$$

Compared with the HG phase function, the HG* phase function can better characterize both the forward scattering and the backward scattering of Mie scattering. The expression is more complex, but it can better fit the scattering characteristics of the particles and has good applications.

3. Size distribution of suspended oil droplets in seawater

For suspended oil droplets in seawater, the size distribution is polydisperse. According to Mie scattering theory, the scattering phase function PMie is

$$P_{Mie}(\theta)=\frac{\int_{r_{\min}}^{r_{\max}}[|S_1(\theta)|^2+|S_2(\theta)|^2]f(r)dr}{2k^2\int_{r_{\min}}^{r_{\max}}Q_{sca}(\alpha,m)\pi r^2 f(r)dr} \tag{13}$$

Where $k=2\pi/\lambda$, $f(r)$ is the size distribution function of the oil droplet particle. In addition to the time-varying size distribution of oil in seawater, oil droplets may be adsorbed or even biodegraded by other suspended substances, which may affect their size distribution. Regardless of the influence of sea surface fluctuation on the particle size distribution of oil droplets, the commonly used function $f(r)$ to describe the particle size distribution of oil droplets is the lognormal distribution as follows [12]

$$f(r)=A\exp[-\frac{\ln^2(r/r_0)}{2\sigma^2}] \tag{14}$$

Where A is the parameter related to oil concentration, r0 is the mean radius, and σ is the standard deviation. Otremba et al. measured the relationship of size distribution parameters of crude oil with time by microscopy [13], as shown in Figure 1. The curve reflects the change of size distribution parameters R0 and σ with time. When the average diameter of suspended oil droplets in sea water is less than 0.125 m, the oil droplet particle diameter is in a relatively stable state. The particle size of oil droplets changed slowly with time after 1 week of formation, and changed little after 1 month. In this paper, the scale range of the oil droplet size is 0.01-10 m.

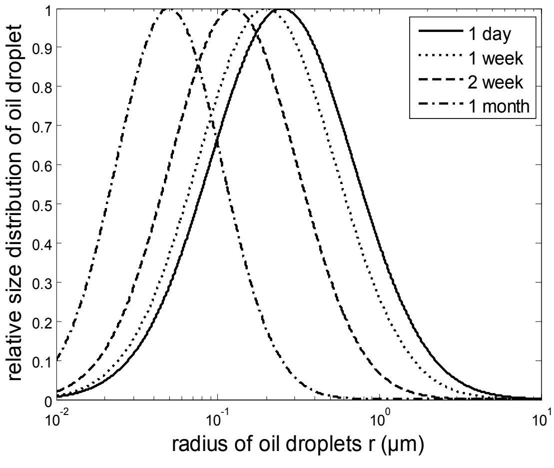

Figure 1. Normalized size distribution function of oil drop size in seawater

4. Numerical results

The laser transmission in oil-spilled seawater is scattered and absorbed by oil droplets and seawater. The scattering phase function of oil droplets depends on the type of oil, the wavelength of incident laser, and the time of oil droplets suspended in the sea water. The type of oil determines the

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complex refractive index of suspended particles, the wavelength of incident laser determines the size parameters of oil droplets, and the time of oil droplets suspended in sea water determines the size distribution of oil droplets. In order to study the transmission characteristics of laser in oil-spilled seawater, the Mie scattering phase functions of spherical oil droplets suspended in seawater for different time and different incident laser wavelengths were numerically calculated. Figure 2 shows the phase scattering function of spherical suspended oil droplets at the incidence of 532nm laser for 1 day, 1 week, 2 weeks and 1 month. The compound refractive index m does not change with the time of the suspension droplets in sea water is 1.488, the imaginary part is 0.004 [14]; the sea water refractive index is 1. 34 and the imaginary part is 0. 001 [15].As the time of the oil droplet suspended in the sea water increases, the particle size r0 and the standard deviation are gradually smaller. The Mie scattering phase function shows that the forward and backward scattering decreases and the other direction scattering increases. Figure 3 (a)-(d) shows the comparison of Mie scattering phase function with HG phase function and HG* phase function with oil drops in Marine water for 1 day, 1 week, 2 weeks and 1 month respectively. The asymmetry factors were ga=0.9527, gb=0.9371, gc=0.8948, and gd=0.7367. As can be seen from Figure 3, the HG * phase function fits the polydisperse system Mie phase function of suspended oil droplets in seawater at different periods better than the HG phase function, especially in the forward of small and large scattering angles. With the increase of oil droplet suspension time in seawater, the fitting effect of HG phase function and HG* phase function on Mie scattering phase function becomes worse. Therefore, the simulation of laser transmission characteristics in oil-spilled seawater by HG and HG* phase function of oil droplets suspended in sea water for a long time has a large error.

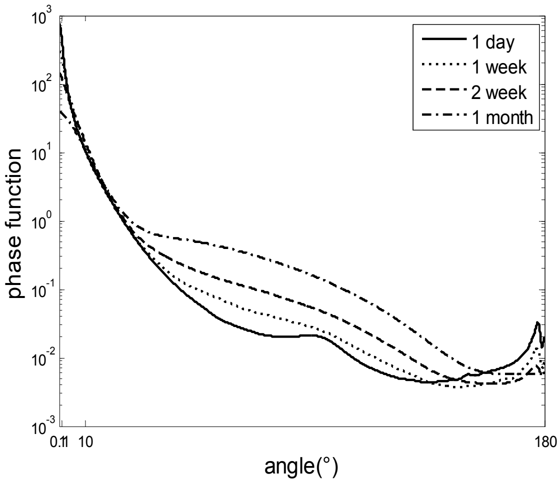
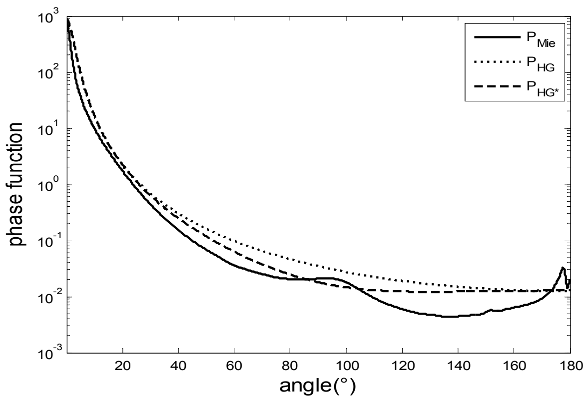


Figure 2. Mie scattering phase functions of oil droplets in seawater at different time periods



a) phase function with oil drops in Marine water for 1 day

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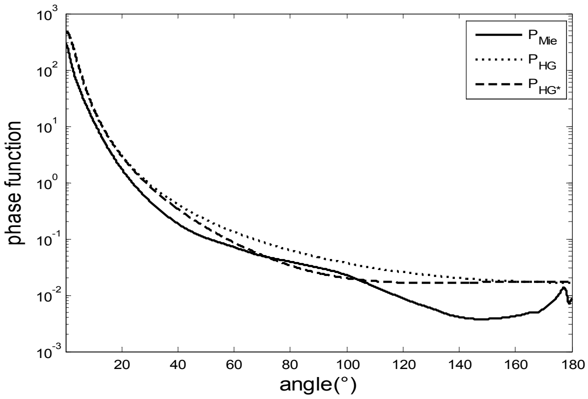
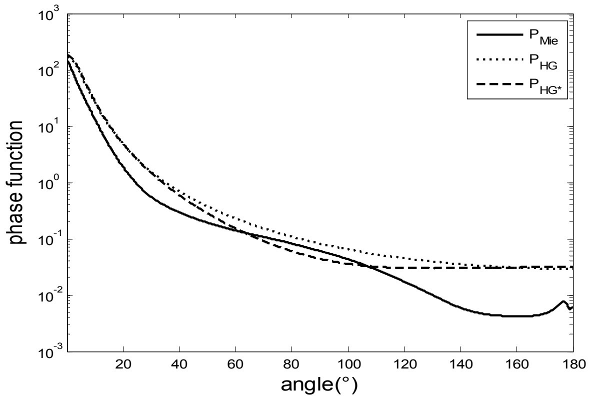
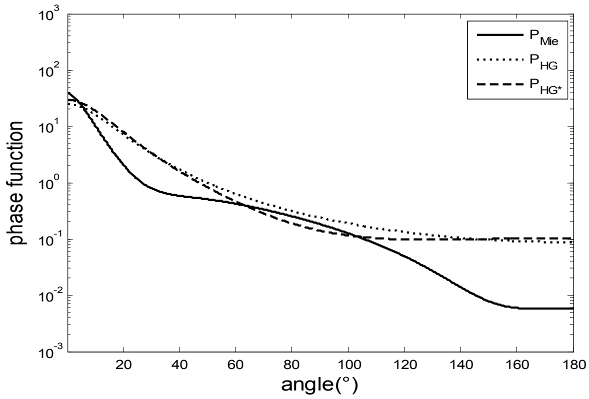


b) phase function with oil drops in Marine water for 1 week



c) phase function with oil drops in Marine water for 2 weeks



d) phase function with oil drops in Marine water for 1 month

Figure 3. Comparison of Mie scattering phase function, HG phase function and HG* phase function of oil droplets in seawater at different time periods

As the wavelength of the incident laser increases, the complex refractive index of the oil species and the size parameters of the oil droplet all change. FIG. 4 shows the phase scattering function of the spherical suspended oil droplet at 355nm, 532nm, 632nm, and 1064nm laser incidence. As shown in Figure 4, the Mie scattering phase function shows that the forward scattering decreases and the scattering homogenizes gradually with the increase of incident laser wavelength. FIG. 5 (a) - (d) shows the angular distribution of the Mie scattering phase function at 355nm, 532nm, 632nm, and 1064nm oil droplets suspended in sea water, respectively. The asymmetry factors were ga=0.9576, gb= 0.9527, gc= 0.9447, and gd=0.9226. As can be seen from Figure 4, the HG* phase function fits better to the polydisperse system in suspended oil droplets at different incident laser wavelengths than the HG phase function. As the laser wavelength increases, the HG phase function and the Mie scattering phase function fit worse. For the strongly absorbed UV band, the imaginary

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refractive index is larger than that of the other band laser, resulting in poor HG phase function and HG* phase function fitting the Mie scattering phase function.

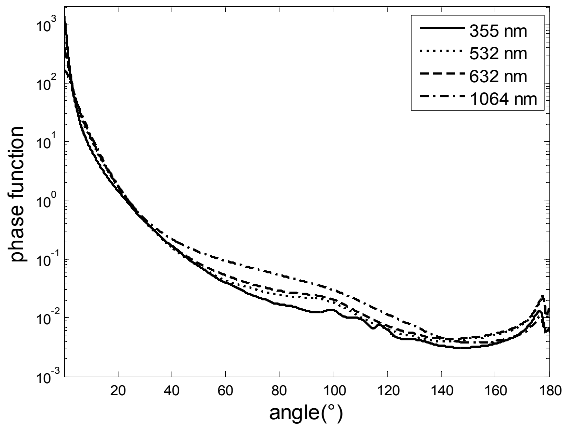
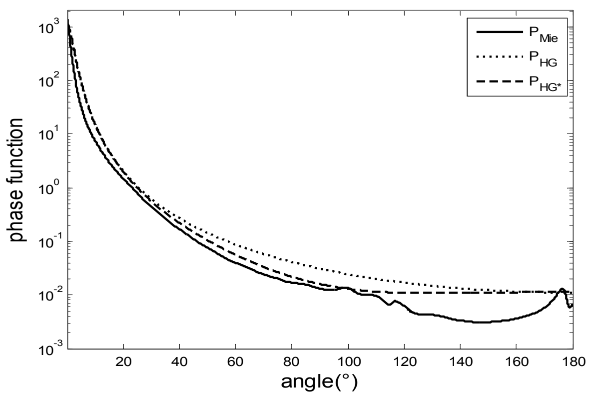
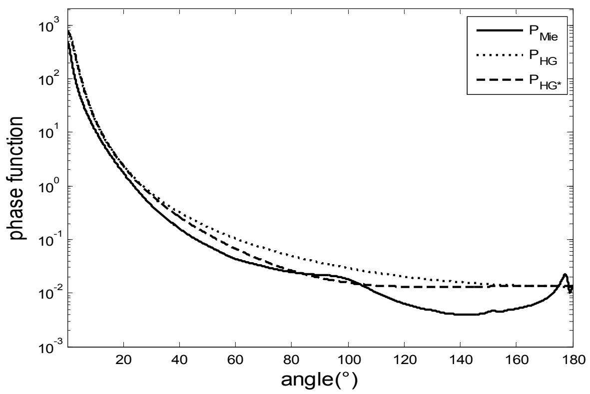


Figure 4. Mie scattering phase functions of oil droplets in seawater at different incident wavelength



a) The scattering phase function of 355nm



b) The scattering phase function of 532nm

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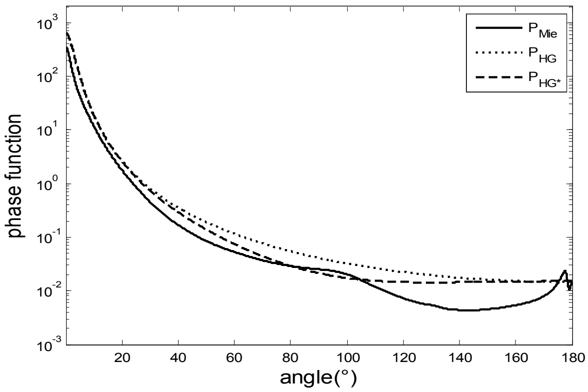
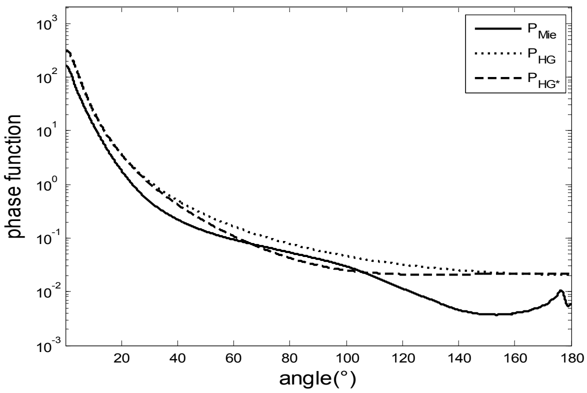


c)The scattering phase function of 632nm



d) The scattering phase function of 1064nm

Figure 5. Comparison of Mie scattering phase function, HG phase function and HG* phase function of oil droplets in seawater of different bands

5. Conclusion

The accurate calculation of the scattering phase function can lay a theoretical foundation for the study of laser transmission characteristics in oil-spilled seawater, which has very important significance. In this paper, based on Mie scattering theory, the phase scattering functions of spherical suspended oil droplets in sea water for 1 day, 1 week, 2 weeks and 1 month and incident wavelength 355nm, 532nmm, 632nmm and 1064nm are numerically calculated. The numerical results of HG and HG* phase functions of suspended oil droplets in seawater are given and compared with the Mie scattering phase functions. The results show that the fitting effect of HG* phase function is better than HG phase function for spherical suspended oil droplets in seawater, which is more suitable for studying laser transmission characteristics in oil-spilled seawater. However, the fitting effect of HG* phase function and HG phase function becomes worse with the increase of the time of oil droplet suspension in sea water and the increase of incident laser wavelength. The fitting effect of HG* phase function and HG phase function is also poor for the short-wave ultraviolet laser with strong absorption of oil droplets. Therefore, it is limited to use HG and HG* phase function to study the transmission characteristics of ultraviolet, visible and infrared laser in oil-spilled seawater, while Mie scattering phase function is more widely applicable.

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