Uniform Scattering Power for Monitoring the Spilled Oil on the Sea

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Yang Zhou

Principle diagram of light paths

Experimental samples

Using MATLAB program to calculate the right angle bistatic matrix.

Using Fowad equations to verify the scientific nature of our model.

Measured effect diagram

Our model can be used to obtain the spilled oil on the sea.

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Uniform Scattering Power for Monitoring the Spilled Oil on the Sea

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Abstract: The physical model of polarized light scattered from oil film had been analyzed, which helped us to derive the Mueller matrix of uniform scattering. The parameter, uniform scattering power (USP), has been proposed to analyze the scattering intensity of regular, smooth, and raised surfaces in the observation direction. USP could overcome the influence of angles in oil spill detection and provide us with better monitoring signals. The actual spilled oil had been measured by this model, and the oil film could been accurately identified at various angles.

Index Terms: Oceanic scattering, optical vector-matrix systems, scattering

1. Introduction

Holographic Marine oil spill accident could produce different damages on seawater [1], [2]. The pollution of oil is very serious to the marine environment and marine biological resources. The oil spill on the sea will greatly reduce the exchange rate of oxygen between the seawater and atmosphere to destroy the ecological balance of the oceans [3], [4].

Therefore, how to detect the oil spill on sea quickly and take corresponding measures is always the research focus of marine environment ecological security [5]–[8]. At present, the oil spill detection methods are mainly of visible light, synthetic aperture radar, high spectrum, laser radar and so on [9]–[12]. These methods are based on the information of scattering intensity from the material surface to identify the different kinds of objects in the measurement area. The distribution of scattered light intensity also represents the photon radiation of various spatial angles from the rough surface [13]–[16]. The signal intensity received at different observation angles are discrepant, and the measured value may exceed the threshold range of detectors. Therefore, the accuracy of traditional measurement techniques are affected by the observation angles.

For that reason, this paper has used the relationship between multiple scattering and polarization degree to derive the physical model of polarization scattering, and the USP has been extracted...
IEEE Photonics Journal USP for Monitoring the Spilled Oil on the Sea

Fig. 1. Principle diagram of light paths.

as the basis for detection of spilled oil on the sea. USP can be used to analyze the polarization scattering intensity of regular, smooth and raised surfaces in the observation direction. The theory compensates for the shortcomings of traditional measurement techniques which rely on the scattering intensity distribution characteristics of the medium surface. And it has been proved in the multi angle measurements of spilled oil on the sea.

2. Uniformly Scattered Power and Its Calculating Model
2.1 The Propagation Paths of Polarized Light

When electromagnetic wave enters the medium, it will produce scattering effect on the surface. The distribution of scattered signals is related to the irregularities of material surface. Therefore, the total intensity \( I_0 \) of scattered light can be divided into two parts. One is the scattering intensity \( I_{oA} \) from the regular, smooth and raised surfaces, the other \( I_{oB} \) is from the irregular, rough and no convex surfaces. The expression formula can be written as:

\[
I_0 = I_{oA} + I_{oB}.
\]

Seawater and crude oil belong to the mixed medium, both \( I_{oA} \) and \( I_{oB} \) must be considered in the analysis of backscatter. In the unit area, the impurities in crude oil are relatively dense. The surface layer of oil film is prone to single scattering, while the secondary layer is prone to multiple scattering. The principle of light paths is shown in Fig. 1.

In the total scattering energy, there are many uncertainties (such as direction, absorption, etc.) in \( I_{oB} \), it is complicated and not conducive to our study. Therefore, we mainly focused on the research of \( I_{oA} \), and used it as the basis for detecting spilled oil on the sea.

It is assumed that the energy of incident light is constant. As shown in Fig. 1, when the incident angle (the angle between the direction of the incident light and the normal direction) is small, the light will enter into the deeper layer of the oil film, and a large amount of energy is absorbed by the oil film [17], the detection signal is mainly based on the single scattering of the surface, so the \( I_{oA} \) of the oil film must be larger than that of seawater. When the incident angle is large, the vertical path of the incident light wave is shorter, the multiple scattering will occur in the measurement region, and the detection signal is mainly based on the multiple scattering of the surface, so \( I_{oA} \) of the oil film must be less than that of seawater. The size of the angle is determined by the Brewster angle. And the conclusion had been verified by the following experimental results.

The ratio values \( R_1 = I_{oA}/I_0 \), \( R_2 = I_{oB}/I_0 \) can be used to distinguish the different kinds of media with different surface structures. However, the scattering property also has its detection dead zone. Such as, in the direction of main reflection angle, the reflected light will produce a large flare, which is beyond the detection threshold of detectors.

Therefore, in the process of signal acquisition and data processing, it is necessary to enlarge the dimension of signal and find more physical optical differences between the target and the background. Through a long period of study, we have found that there is a functional relationship
between the scattering characteristics and the polarization optical characteristics of the medium [17], [18].

### 2.2 Multiple Scattering and Polarization

With multiple scattering, the randomness of the interactions tends to be averaged out by the large number of scattering events, so the final result appears to be a deterministic distribution. Hence, multiple scattering can be modeled multiple random paths, and each random path has an equivalent Jones matrix [18]. The Mueller-Jones matrix contains a lot of polarized information, which could help us study the multiple scattering characteristics of medium better [19], [20].

When modeling surface reflection, Jones matrix can be modeled as

\[
J = \begin{bmatrix}
A_{//} & 0 \\
0 & A_\perp e^{i\delta}
\end{bmatrix}.
\]  

(2)

Where \(A_{//}\) is the vector component of the incident field parallel to the incident plane, \(A_\perp\) is the vector component of the incident field perpendicular to the incident plane, and \(\delta\) is the phase retardation angle which describing phase difference between horizontal and vertical caused by reflection. Here \(A_{//}, A_\perp\) and \(\delta\) are real numbers. Then

\[
J \otimes J^* = \begin{bmatrix}
A_{//}^2 & 0 & 0 & 0 \\
0 & A_{//} A_\perp e^{i\delta} & 0 & 0 \\
0 & 0 & A_{//} A_\perp e^{-i\delta} & 0 \\
0 & 0 & 0 & A_{\perp}^2
\end{bmatrix}.
\]

(3)

And the Mueller matrix can be converted into

\[
M = \begin{bmatrix}
A_{//}^2 + A_\perp^2 & A_{//}^2 - A_\perp^2 & 0 & 0 \\
A_{//}^2 - A_\perp^2 & A_{//}^2 + A_\perp^2 & 0 & 0 \\
0 & 0 & 2A_{//} A_\perp \cos \delta & 2A_{//} A_\perp \sin \delta \\
0 & 0 & -2A_{//} A_\perp \sin \delta & 2A_{//} A_\perp \cos \delta
\end{bmatrix} + dM_\phi.
\]

(4)

Where, \(d\) is the coefficient of depolarization, and is closely related to multiple scattering. And

\[
M_\phi = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}.
\]

(5)

Hence, the single scattering Mueller matrix can be expressed as

\[
M_s = \omega \begin{bmatrix}
A_{//}^2 + A_\perp^2 & A_{//}^2 - A_\perp^2 & 0 & 0 \\
A_{//}^2 - A_\perp^2 & A_{//}^2 + A_\perp^2 & 0 & 0 \\
0 & 0 & 2A_{//} A_\perp \cos \theta & 2A_{//} A_\perp \sin \theta \\
0 & 0 & -2A_{//} A_\perp \sin \theta & 2A_{//} A_\perp \cos \theta
\end{bmatrix}.
\]

(6)

Where \(\omega\) represent the weight coefficient.

### 2.3 Uniformly Scattered Power

The USP (\(\tau\)) of the scattering intensity \(I_{0\lambda}\) from regular, smooth and raised surfaces has been derived from the Mueller matrix, which could describe the scattering intensity distribution of uniform
surface in the observation direction. And the expression is

$$\tau = \frac{\alpha + \beta}{2}. \quad (7)$$

And

$$\alpha = \frac{1}{S_{i3}} \left\{ S_{o3} - C S_{i1} - G S_{i2} - E S_{i4} \right\}$$
$$\beta = \frac{1}{S_{i4}} \left\{ S_{o4} - H S_{i1} - D S_{i2} - E S_{i3} \right\}. \quad (8)$$

Where, $S_{i1}, S_{i2}, S_{i3}$ and $S_{i4}$ are the four elements of the Stokes vector of incident polarized light, which can be measured by photometer. $S_{o3}$ and $S_{o4}$ are the third and fourth elements of the Stokes vector of scattering polarized light, which can be calculated by Stokes vector of incident polarized light and (17). $C$ is the shape factor of the target (the greater the value is, the closer it is to the line object); $D$ is the measure of local curvature difference (curvature); $E$ is the surface torsion of the target (distortion); $G$ represents the coupling between symmetric and non-symmetric parts of target; $H$ represents the degree of overlap between the global symmetry and asymmetry of target. These values can be obtained by the Mueller matrix. In order to make the parameters of polarized light signal more precise, this experiment had collected 36 groups of measurement data at each measurement point.

Model experiments were carried out in a dark room. The light's wavelength was 632.8 nm, and the incident and emergent angles were $40^\circ, 45^\circ, 50^\circ, 55^\circ, 60^\circ, 65^\circ$ and $70^\circ$. The detector was a photometer (THORLABS-PM100D) which was used to measure the light intensity value of scattering polarized light.

As shown in Fig. 2, the experiment device was composed of light source, optical lens, diaphragm, deviation device, polarizer, quarter-wave plate and photometer. The laser light was focused to the parallel beam by lens, and through a diaphragm with 1.88 mm circular aperture to be the controllable linear polarized light. Then the polarizer and quarter-wave plate were controlled to simulate different polarized lights with the unique polarization states. According to the scattering principle, the signal of scattering light could be acquired by photometer which was through the quarter-wave plate and polarizer of receiving terminal. Finally, the Matlab software had been used to analyze the measurement data, the polarization parameters and Mueller matrixes of the samples. And the USP had been calculated accurately.

In this study, six kinds of oil film and seawater had been measured at seven incident angles. The values of USP were shown in Table 1, and the variation trends are shown in Fig. 3.

As shown in Fig. 3, the changing trends of USP are concave shape, and their minimum values are all near their Brewster angles. In the measurement of seven angles, the values of the oil film samples are very close, which are different from that of seawater. The intersection point exists between the
TABLE 1
The USP at Different Angles

<table>
<thead>
<tr>
<th>Incident Angle / °</th>
<th>Yiyang Oil (Thick Oil Film)</th>
<th>Yiyang Oil (Thin Oil Film)</th>
<th>G2 Oil (Thick Oil Film)</th>
<th>G2 Oil (Thin Oil Film)</th>
<th>Ningxi Oil (Thick Oil Film)</th>
<th>Ningxi Oil (Thin Oil Film)</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.6420</td>
<td>0.7100</td>
<td>0.6400</td>
<td>0.6207</td>
<td>0.5597</td>
<td>0.6236</td>
<td>0.5267</td>
</tr>
<tr>
<td>45</td>
<td>0.4984</td>
<td>0.4612</td>
<td>0.4780</td>
<td>0.4492</td>
<td>0.4458</td>
<td>0.3514</td>
<td>0.3353</td>
</tr>
<tr>
<td>50</td>
<td>0.2572</td>
<td>0.2694</td>
<td>0.2681</td>
<td>0.2498</td>
<td>0.2248</td>
<td>0.2069</td>
<td>0.0887</td>
</tr>
<tr>
<td>55</td>
<td>0.0154</td>
<td>0.0212</td>
<td>0.0213</td>
<td>0.0204</td>
<td>0.0100</td>
<td>0.0034</td>
<td>0.1662</td>
</tr>
<tr>
<td>60</td>
<td>0.2334</td>
<td>0.2165</td>
<td>0.2399</td>
<td>0.2392</td>
<td>0.1264</td>
<td>0.2953</td>
<td>0.3956</td>
</tr>
<tr>
<td>65</td>
<td>0.4806</td>
<td>0.4523</td>
<td>0.4880</td>
<td>0.4602</td>
<td>0.4902</td>
<td>0.4509</td>
<td>0.5919</td>
</tr>
<tr>
<td>70</td>
<td>0.7002</td>
<td>0.6253</td>
<td>0.6757</td>
<td>0.6538</td>
<td>0.6177</td>
<td>0.6505</td>
<td>0.7512</td>
</tr>
</tbody>
</table>

Fig. 3. The changing trends of USP at different measurement angles.

Brewster angles of the two kinds of substances. Therefore, the monitoring of oil spills on sea should be carried out outside the range of Brewster angle to avoid the experimental misjudgment. When light is incident at the Brewster angle, complete polarized light will be produced in the reflecting direction, and the polarization degree of the uniformly scattered light tends to one. In other words, the light in the reflected direction has no depolarization phenomenon. According to the theory of Paths-Correlation matrix, the scattered power should be close to zero at this time. This feature shows that the model of USP is reliable and accurate.

3. Verification of the Model

3.1 Verification Theory

As shown in Fig. 1, we resolve each vector into components parallel (denoted by subscript //) and perpendicular (subscript ⊥) to the plane of incidence. The perpendicular components must be visualized at right angles to the plane of the figure.

The components of the electric vector of the incident field then are

\[
\begin{align*}
E_x^{(i)} &= -A_{//} \cos \theta_i e^{-i\delta_i} \\
E_y^{(i)} &= A_{\perp} e^{-i\delta_i} \\
E_z^{(i)} &= A_{//} \sin \theta_i e^{-i\delta_i} 
\end{align*}
\]

(9)
Where, $\theta_i$ is the incident angle, and $\delta_i$ is the phase delay of the incident field vector.

The components of the magnetic vector are

$$
\begin{align*}
H_x^{(i)} &= -A_\perp \cos \theta_i \sqrt{\varepsilon_1} e^{-i\delta_i} \\
H_y^{(i)} &= -A_\parallel \sqrt{\varepsilon_1} e^{-i\delta_i} \\
H_z^{(i)} &= A_\perp \sin \theta_i \sqrt{\varepsilon_1} e^{-i\delta_i},
\end{align*}
$$

(10)

Where, $\varepsilon$ is magnetic permeability.

Similarly if and are the complex amplitudes of the transmitted and reflected waves, the corresponding components of the electric and magnetic vectors are:

**Transmission field**

$$
\begin{align*}
E_x^{(t)} &= -T_\parallel \cos \theta_i e^{-i\delta_t} \\
E_y^{(t)} &= T_\perp e^{-i\delta_t} \\
E_z^{(t)} &= T_\parallel \sin \theta_i e^{-i\delta_t} \\
H_x^{(t)} &= -T_\perp \cos \theta_i \sqrt{\varepsilon_2} e^{-i\delta_t} \\
H_y^{(t)} &= -T_\parallel \sqrt{\varepsilon_2} e^{-i\delta_t} \\
H_z^{(t)} &= T_\perp \sin \theta_i \sqrt{\varepsilon_2} e^{-i\delta_t},
\end{align*}
$$

(11)

And $\theta_t$ is the refraction angle, $T_\parallel$ is the vector component of the transmission field parallel to the incident plane, $T_\perp$ is the vector component of the transmission field perpendicular to the incident plane, $\delta_t$ is the phase delay of the transmission field vector.

**Reflection field**

$$
\begin{align*}
E_x^{(r)} &= -R_\parallel \cos \theta_i e^{-i\delta_r} \\
E_y^{(r)} &= R_\perp e^{-i\delta_r} \\
E_z^{(r)} &= R_\parallel \sin \theta_i e^{-i\delta_r} \\
H_x^{(r)} &= -R_\perp \cos \theta_i \sqrt{\varepsilon_1} e^{-i\delta_r} \\
H_y^{(r)} &= -R_\parallel \sqrt{\varepsilon_1} e^{-i\delta_r} \\
H_z^{(r)} &= R_\perp \sin \theta_i \sqrt{\varepsilon_1} e^{-i\delta_r},
\end{align*}
$$

(12)

And $\theta_r$ is the reflection angle, $R_\parallel$ is the vector component of the reflection field parallel to the incident plane, $R_\perp$ is the vector component of the reflection field perpendicular to the incident plane, $\delta_r$ is the phase delay of the reflection field vector.

The tangent component of $E$ and $H$ should be continuous, hence we must have.

$$
\begin{align*}
E_x^{(i)} + E_x^{(t)} &= E_x^{(r)} \\
E_y^{(i)} + E_y^{(t)} &= E_y^{(r)} \\
H_x^{(i)} + H_x^{(t)} &= H_x^{(r)} \\
H_y^{(i)} + H_y^{(t)} &= H_y^{(r)}.
\end{align*}
$$

(13)

On substituting into (13) for all the components, and using the fact that $\cos \theta_r = \cos (\pi - \theta_i) = -\cos \theta_i$, we obtain the four relations

$$
\begin{align*}
\cos \theta_i (A_\parallel - R_\parallel) &= \cos \theta_i T_\parallel \\
A_\perp + R_\perp &= T_\perp \\
\sqrt{\varepsilon_1} \cos \theta_i (A_\perp - R_\perp) &= \sqrt{\varepsilon_2} \cos \theta_i T_\perp \\
\sqrt{\varepsilon_1} (A_\parallel + R_\parallel) &= \sqrt{\varepsilon_2} T_\parallel.
\end{align*}
$$

(14)
We note that the (14) fall into two groups, one of which contains only the components parallel to the plane of incidence, whilst the other contains only those which are perpendicular to the plane of incidence. These two kinds of waves are, therefore, independent of one another.

We can solve (14) for the components of the reflected and transmitted waves in terms of those of the incident wave, giving (using again the Maxwell relation $n = \sqrt{\varepsilon}$)

\[
T_{\parallel} = \frac{2n_1 \cos \theta_i}{n_2 \cos \theta_i + n_1 \cos \theta_i} A_{\parallel}
\]

\[
T_{\perp} = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_i} A_{\perp}
\]

\[
R_{\parallel} = \frac{n_2 \cos \theta_i - n_1 \cos \theta_i}{n_2 \cos \theta_i + n_1 \cos \theta_i} A_{\parallel}
\]

\[
R_{\perp} = \frac{n_1 \cos \theta_i - n_2 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_i} A_{\perp}
\]

(15)

They are usually written in the following alternative form, which may be obtained from (15) and (16) by using the law of refraction:

\[
T_{\parallel} = \frac{2 \sin \theta_i \cos \theta_i}{\sin (\theta_i + \theta_i) \cos (\theta_i - \theta_i)} A_{\parallel}
\]

\[
T_{\perp} = \frac{2 \sin \theta_i \cos \theta_i}{\sin (\theta_i + \theta_i)} A_{\perp}
\]

\[
R_{\parallel} = \frac{\tan (\theta_i - \theta_i)}{\tan (\theta_i + \theta_i)} A_{\parallel}
\]

\[
R_{\perp} = -\frac{\sin (\theta_i - \theta_i)}{\sin (\theta_i + \theta_i)} A_{\perp}
\]

(16)

\[
(17)
\]

\[
(18)
\]

Since $\theta_i$ and $\theta_t$ are real (regardless of the Brewster angle), the trigonometrically factors on the right-hand sides of (17) and (18) will also be real. Consequently the phase of each component of the reflected or transmitted wave is either equal to the phase of the corresponding component of the incident wave or differs from it by $\pi$. Since $T_{\parallel}$ and $T_{\perp}$ have the same signs as $R_{\parallel}$ and $R_{\perp}$, the phase of the transmitted wave is actually equal to the phase of the incident wave, and we do not need to do too much research. In the case of the reflected wave, the phase will, however, depend on the relative magnitudes of $\theta_i$ and $\theta_t$, and this research point requires further analysis.

3.2 Model Information Analysis

According to the (17) and (18), we can get

\[
1 - P e^{-i\Delta} = \frac{-\sqrt{n^2 - \sin^2 \theta_i}}{\sin \theta_i \tan \theta_i}
\]

(19)

Where $n$ is the complex refractive index, and we have calculated the amplitude ratios $P$ and phase retardations $\Delta$ of multi-angle-reflection vector of seven medium, and the results are shown in the Fig. 4.

As shown in Fig. 4, the green triangles are the measured polarization parameters of seawater, and the others are the measured values of six kinds of oil film (three of them are thin oil film, and the others are thick oil film; thin oil film represents an oil film that can be transparent, and thick oil film represents an oil film that has a strong absorption capacity to the incident light). At the small measured angles, the amplitude ratios and phase retardations of seven medium are similar. The amplitude ratios of uniformly scattered polarized light of the seawater and oil film are close to zero, and the phase retardations are differ $\pi$. But the two polarized parameters have a sudden change at Brewster angles ($\theta_{B - \text{seawater}} = 53.06^\circ$, $\theta_{B - \text{oil}} = 56.83^\circ$), the amplitude ratios are reaching
Fig. 4. The amplitude ratios and phase retardations of multi-angle-reflection vector of seven medium. (a) Amplitude Ratio, (b) Phase Retardation.

the maximum, and the phase retardations are dropping to zero. And these phenomena show that our measured values are in good agreement with the Fresnel equation. In the process of changes, the values of amplitude ratios of the seven medium have the obvious difference. The maximum amplitude ratio of seawater is at 50°, and the bottom of the value is 25. The maximum values of oil film are at 55°, and the average value is higher than 75. There is also the difference in phase retardations. The decrease in phase retardation of seawater is earlier than that of oil film in the range from 50° to 60°. The results showed that the parameters of incident polarized light had been changed by the samples, which could be the basis to identify the different objects. And we had found a reasonable way to discuss the polarization characteristics of measured targets [17]. In the process of measurement, the measured values were in good agreement with the values of Fresnel equation. The conclusion could prove the scientific and reliable of our theoretical model.

4. Experimental Results

In order to measure the real reliable experimental results and prove the validity of this model, we had measured the oil film on the sea by the model in a natural light. 35 gram of sodium chloride had been dissolved in one liter of water, and got the 35 percent salinity of seawater. Then 200 uL Yiyang oil was dropped on the surface of seawater by pipette. The experimental samples could be observed in Fig. 5.

In the process of measurement, the air temperature was 30°, and the incident angle of sunlight was 45.38°. Because of the hot weather, the diffusivity of oil film was better. In the measurement area, most of the area was oil film, and only a small part of the area was seawater. The angles of data acquisition were 45° and 65°, which were located on both sides of the Brewster angle respectively. The aim was to make the measured values adequately reflect the scatter polarization optical properties of the samples. According to the model formula, the Mueller matrixes and USP of measurement samples are as follows:

\[ M_{45_{\text{oil}}} = 1.0 e^{-3} \begin{bmatrix} 0.2478 & -0.1799 & 0.0081 & -0.0232 \\ -0.1927 & 0.2112 & 0.0007 & 0.0264 \\ -0.0191 & 0.0147 & -0.1225 & 0.0024 \\ 0.0056 & 0.0027 & 0.0020 & -0.1165 \end{bmatrix} \]  \hspace{1cm} \text{(20)}

\[ M_{45_{\text{seawater}}} = 1.0 e^{-3} \begin{bmatrix} 0.1712 & -0.1250 & -0.0026 & -0.0138 \\ -0.1390 & 0.1382 & 0.0076 & 0.0156 \\ -0.0107 & 0.0089 & -0.0580 & 0.0004 \\ 0.0025 & 0.0026 & 0.0015 & -0.0568 \end{bmatrix} \]  \hspace{1cm} \text{(21)}
IEEE Photonics Journal

USP for Monitoring the Spilled Oil on the Sea

Fig. 5. The contrast chart of experiment effect [(a) is the oil spill image at the measured angle of 45°; (b) is the scatter polarization effect diagram of (a) by this model; (c) is the oil spill image at the measured angle of 65°; (d) is the scatter polarization effect diagram of (c)].

\[
M_{65\text{Oil}} = 1.0 e^{-3 \cdot \begin{bmatrix}
0.2882 & -0.2002 & -0.0023 & -0.0227 \\
-0.2270 & 0.2254 & -0.0128 & 0.0077 \\
-0.0160 & 0.0195 & 0.1391 & -0.0022 \\
-0.0026 & -0.0113 & -0.0044 & 0.1315
\end{bmatrix}}.
\]

\[
M_{65\text{Seawater}} = 1.0 e^{-3 \cdot \begin{bmatrix}
0.1997 & -0.1196 & -0.0019 & -0.0180 \\
-0.1362 & 0.1669 & -0.0050 & 0.0045 \\
-0.0099 & 0.0149 & 0.1191 & -0.0011 \\
-0.0034 & -0.0112 & -0.0023 & 0.1173
\end{bmatrix}}.
\]

\[
\begin{align*}
\tau_{45\text{Oil}} &= 0.4788 \\
\tau_{45\text{Seawater}} &= 0.3353 \\
\tau_{65\text{Oil}} &= 0.4665 \\
\tau_{65\text{Seawater}} &= 0.5919
\end{align*}
\]

As shown in Fig. 5, the measurement results of spilled oil on sea are related to the observation angles. In the direction of the main reflection angle (5(a)), we could blur out the seawater and the oil film faintly. But in the direction of large scattering angle (5(c)), the intensity information reflected by the oil film was very close to that of the seawater. However, the model of USP can make up for this defect. In Fig. 5(b) and (d), we can identify the area of the spilled oil accurately in the two directions, and we also could clearly observe the accumulation area of the spilled oil bubbles on the sea. Therefore, this detection technique has good practicability in the monitoring of spilled oil on the sea.

5. Conclusion

Starting from the physical structure of medium, the polarization characteristics of scattered light had been analyzed, and the concept of USP had been proposed and applied to the detection of spilled
oil on the sea. First, the scattering intensity signal had been divided into uniform scattering part and inhomogeneous scattering part by utilizing the scattering polarization characteristic of material surface, and the physical model of USP had been established. Secondly, seven substances were used to verify the correctness and scientific nature of the model, the data from several angles had been analyzed, and the results were in good agreement with the theoretical model. Finally, the practicability of this technique had been proved by measuring the actual spilled oil on the sea. The results show that the USP could be used as a basis of the detection of spilled oil on the sea, and is scientific and effective. The USP of the seawater and six kinds of crude oil were obviously different during the whole measurement. Our approach can compensate for the shortcomings of existing methods, and the area of the spilled oil can be identified accurately. All of these verify that the model will be an efficient way to realize the monitoring of spilled oil on the sea.

References