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An Infrared DoLP Model Considering the Radiation Coupling Effect

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Abstract: The polarization degree of objects in the marine background are affected by infrared radiation from sea surface. Taking into account the radiation coupling effect (RCE), a degree of linear polarization (DoLP) model is deduced. The DoLP of painted aluminum plates at different observation angles are simulated. The simulation results show the trend of the DoLP of the object decreases first and then increases as the observation angle θ_O , with the minimum value at $\theta_O = 53^\circ$. Nevertheless, we get a monotonically increasing trend and the minimum value is at $\theta_O = 0^\circ$ without considering RCE. The experimental results accord closely with those of the simulation with RCE. This conclusion is useful for the polarization detection and identification of infrared objects in the marine background.

Keywords: infrared radiation; DoLP; pBRDF; radiation coupling effect

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1. Introduction

Compared with traditional infrared technology, polarization detection can obtain more information, such as the degree of linear polarization (DoLP) and the angle of polarization. Infrared polarization detection technology shows a promising application prospect in the field of remote sensing [1–3], and object detection and identification [4–7]. However, in the long-wave infrared (LWIR) band, the object polarization characteristics are strongly influenced by environmental factors [8,9]. When the emitted radiation is close to incident radiation, the polarization degrades and even disappears [10]. For objects in the marine background, the radiation from the sea surface and surroundings can be reflected into the detector by the object's surface, coupling with the object's radiation. Thus, the measured polarization characteristics can be remarkably changed. The radiation coupling effect (RCE) cannot be ignored for shore-based or low-altitude infrared polarization detection and identification in a marine background.

The reflection polarization characteristics of objects are usually described by the polarization bidirectional reflection distribution function model (pBRDF) [11]. In 2000, Priest and Germer [12] developed the first strictly pBRDF model based on the T-S microfacet model [13], which extended the scalar BRDF to a polarization vector model via the Mueller matrix. Hyde [14] improved the model established by Priest and Germer, and increased the geometric attenuation factor and the diffuse reflection component, which improved the simulation accuracy of the model, resulting in a relatively complete and accurate pBRDF model. Feng [15] and Liu [16] measured the pBRDF of materials such as E235B steel using a self-designed instrument. On the basis of the pBRDF model and Fresnel's reflection law, many researchers have conducted studies on object polarization characteristics. Jordan [17], Wolff [18] and Gurton [19] measured the DoLP of object with different degrees of roughness. In 2014, Yan [20] studied the long-wave infrared polarization characteristics of typical metallic objects such as aluminum and iron coated aluminum plates, focusing on the effect

of temperature on the polarization degree. In 2016, Liu [21] analyzed and discussed the influence of spatial geometric parameters such as detection distance and object shape on the object's DoLP. In 2017, based on a three-component assumption, Liu [22] established the pBRDF model of the coating, and used satellite coating samples sr107 and s781 as examples to simulate and measure the polarization characteristics. In 2020, Chen [23] analyzed polarization models and polarization properties of human bodies and transparent objects. Zhang [24] investigated the optical polarization characteristics of low-earth-orbit space targets; Su [25] and Tuo [26] studied the ship target detection method based on polarization characteristics. Zhang [27] and Wei [28] proposed a new detection method based on the infrared polarization feature of the object. The studies above present models of DoLP, taking into account various factors, such as materials, observation angle, surface roughness, temperature, and so on. The polarization characteristics of the target are directly used for detection and recognition. However, the DoLP models for the objects in strong radiation and reflection backgrounds, such as the marine background, are found lacking; and few studies have been carried out concerning the polarization characteristics of objects in these backgrounds.

In this paper, the DoLP of an object in the marine background is modelled by considering the RCE, based on the Hyde model of pBRDF. The influence of the RCE on the infrared polarization characteristics of the object is analyzed, and an LWIR polarization measurement system is built to measure the DoLP of the object at different temperatures and observation angles. The experimental results are consistent with the simulation ones.

2. Materials and Methods

For objects in the marine background, the energy entering the detector consists of three components, i.e., the path radiation (PR) between the object and the detector, the object thermal radiation (OTR), and the reflected thermal radiation (RTR) from the object surface, including reflected surroundings radiation (RSR) from the sea surface, sea-surface thermal radiation (STR), and surroundings radiation (SR) into the object, as shown in Figure 1. Because the PR has little influence on the DoLP of object [29], only two factors are considered in the DoLP modeling, that is, the OTR and the RTR.

Figure 1. The model of infrared radiation in marine background. θ_O and θ_S are the observation angle and the incidence angle, respectively; α_{O_S} is the angle between the object and the sea surface.

2.1. pBRDF Model

In this paper, a DoLP model is deduced based on the Hyde model [14], which assumes that the energy reflected by the rough surface includes specular reflection and diffuse reflection, so the pBRDF of object also includes two parts.

$$f(\theta, \theta_i, \phi_i, \theta_r, \phi_r, \lambda) = f^s + f^d = \begin{pmatrix} f_{00} & f_{01} & f_{02} & f_{03} \\ f_{10} & f_{11} & f_{12} & f_{13} \\ f_{20} & f_{21} & f_{22} & f_{23} \\ f_{30} & f_{31} & f_{32} & f_{33} \end{pmatrix} \quad (1)$$

Here, the specular reflection part f^s can be obtained by micro-faceted theory. When the microfacet element normal distribution satisfies the Gaussian distribution, its expression is

$$f^s(\theta, \theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{\exp(-\tan^2 \theta / 2\sigma^2)}{8\pi\sigma^2 \cos^4 \theta \cos \theta_i \cos \theta_r} G(\theta, \theta_i, \theta_r) M(\theta_i, \theta_r, \phi_i, \phi_r) \quad (2)$$

where $G(\theta, \theta_i, \theta_r)$ is the shadowing and masking function. $M(\theta_i, \theta_r, \phi_i, \phi_r)$ is a reflection Muller matrix of specular surface. θ_i , ϕ_i , θ_r and ϕ_r are the zenith and azimuth angle of incident light and reflected light, respectively, as shown in Figure 2. β is the angle between incident light and the normal of the micro face. σ is the slope variance of microfacet element, which is considered as surface roughness in this paper. θ is the angle between the normal of surface and the normal of the micro face. The expression of $G(\theta, \theta_i, \theta_r)$ is as follows,

$$G(\theta, \theta_i, \theta_r) = \min(1; \frac{2 \cos \theta \cos \theta_r}{\cos \beta}; \frac{2 \cos \theta \cos \theta_i}{\cos \beta})$$

From the geometric relationship, the following equation can be derived

$$\begin{cases} \cos \theta = \frac{\cos \theta_i + \cos \theta_r}{2 \cos \beta} \\ \cos 2\beta = \cos \theta_i \cos \theta_r + \sin \theta_i \sin \theta_r \cos(\phi_r - \phi_i) \end{cases} \quad (3)$$

Figure 2. Geometry relation of micro-surface model.

The specular reflection Mueller matrix $M(\theta_i, \theta_r, \phi_i, \phi_r)$ can be solved by its correspondence with the Jones matrix [30].

$$M = \begin{pmatrix} M_{00} & M_{10} & 0 & 0 \\ M_{10} & M_{00} & 0 & 0 \\ 0 & 0 & M_{22} & jM_{32} \\ 0 & 0 & -jM_{32} & M_{22} \end{pmatrix} \quad (4)$$

In which $M_{00} = \frac{R_s + R_p}{2}$, $M_{10} = \frac{R_s - R_p}{2}$, $M_{22} = \sqrt{R_s R_p}$, R_s and R_p represent reflectance of the s-polarized and p-polarized components, respectively, which can be calculated by Fresnel equations. For substances with complex refractive index $\tilde{n} = n + ik$ [31],

$$\left\{ \begin{array}{l} R_s(\beta, \tilde{n}) = \frac{(A - \cos \beta)^2 + B^2}{(A + \cos \beta)^2 + B^2} \\ R_p(\beta, \tilde{n}) = R_s \frac{(A - \sin \beta \tan \beta)^2 + B^2}{(A + \sin \beta \tan \beta)^2 + B^2} \\ A = \sqrt{\frac{4n^2k^2 + (n^2 - k^2 - \sin^2 \beta)^2 + (n^2 - k^2 - \sin^2 \beta)}{2}} \\ B = \sqrt{\frac{4n^2k^2 + (n^2 - k^2 - \sin^2 \beta)^2 - (n^2 - k^2 - \sin^2 \beta)}{2}} \end{array} \right. \quad (5)$$

Here, β is the incidence angle. The directional hemispherical reflectance (DHR) can be obtained from the pBRDF [29].

$$\rho_{DHR}^s = \int_0^{2\pi} \int_0^{\pi/2} f_{00}^s(\theta, \theta_i, \phi_i, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \quad (6)$$

Considering that the diffuse reflection component f^d is obtained after multiple reflections on the object surface and is usually non-polarized, it can be solved by the DHR and the law of energy conservation.

$$f_{00}^d(\theta_r, \phi_r) = \frac{1}{\pi} \left(1 - \int_0^{2\pi} \int_0^{\pi/2} f_{00}^s(\theta, \theta_i, \phi_i, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \right) \quad (7)$$

where $f_{00} = f_{00}^s(\theta, \theta_i, \phi_i, \theta_r, \phi_r) + f_{00}^d(\theta_r, \phi_r) M_{00}$. Therefore,

$$\begin{aligned} dS_r(\theta_r, \phi_r) &= f \cdot dS_i(\theta_i, \phi_i) \\ &= \begin{pmatrix} f_{00}^s + f_{00}^d M_{00} & f_{01}^s & f_{02}^s & f_{03}^s \\ f_{10}^s & f_{11}^s & f_{12}^s & f_{13}^s \\ f_{20}^s & f_{21}^s & f_{22}^s & f_{23}^s \\ f_{30}^s & f_{31}^s & f_{32}^s & f_{33}^s \end{pmatrix} \begin{pmatrix} S_{i,0} \\ S_{i,1} \\ S_{i,2} \\ S_{i,3} \end{pmatrix} \end{aligned} \quad (8)$$

Here, $(S_{i,0} \ S_{i,1} \ S_{i,2} \ S_{i,3})^T$ is the Stokes vector of incident light, whose common expression is $S = (S_0 \ S_1 \ S_2 \ S_3)^T$, where S_0 represents the total intensity of radiation, S_1 represents the difference between the radiation intensities in the horizontal direction and vertical direction, and S_2 and S_3 represent the modulation relationship between the amplitude and phase of horizontal light wave and vertical light wave. In polarization detection, component S_3 can usually be omitted as being small. Therefore, the DoLP can be solved according to Stokes vector.

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \quad (9)$$

2.2. DoLP Model Considering the RCE

2.2.1. Reflection DoLP Model of Rough Surface

In the marine background, the energy entering the detector mainly consists of two parts: the OTR and the RTR, as shown in Figure 1. As the RCE needs to be taken into account, the RTR includes the SR, RSR and STR. Therefore, the Stokes vector of incident light can be written as,

$$S_i = S_{SR} + S_{RSR} + S_{STR} \quad (10)$$

Because the SR is non-polarized, the Equation (10) can be written as,

$$\begin{pmatrix} S_{i,0} \\ S_{i,1} \\ S_{i,2} \\ S_{i,3} \end{pmatrix} = \begin{pmatrix} I_{SR} \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} S_{RSR,0} \\ S_{RSR,1} \\ S_{RSR,2} \\ S_{RSR,3} \end{pmatrix} + \begin{pmatrix} S_{STR,0} \\ S_{STR,1} \\ S_{STR,2} \\ S_{STR,3} \end{pmatrix} \quad (11)$$

Approximating the calm sea surface as an ideal mirror surface, the spontaneous STR and the RSR can be solved using Fresnel's law of reflection.

$$\begin{pmatrix} S_{STR,0} \\ S_{STR,1} \\ S_{STR,2} \\ S_{STR,3} \end{pmatrix} = \begin{pmatrix} \frac{1-R_{s,s}}{2} I_{STR} + \frac{1-R_{p,s}}{2} I_{STR} \\ \frac{1-R_{s,s}}{2} I_{STR} + \frac{1-R_{p,s}}{2} I_{STR} \\ 0 \\ 0 \end{pmatrix} \quad (12)$$

$$\begin{pmatrix} S_{RSR,0} \\ S_{RSR,1} \\ S_{RSR,2} \\ S_{RSR,3} \end{pmatrix} = \begin{pmatrix} \frac{R_{s,s} I_{SR}}{2} + \frac{R_{p,s} I_{SR}}{2} \\ \frac{R_{s,s} I_{SR}}{2} - \frac{R_{p,s} I_{SR}}{2} \\ 0 \\ 0 \end{pmatrix} \quad (13)$$

Here, I_{STR} and I_{SR} represent the intensity of the STR and SR, respectively. $R_{s,s}$ and $R_{p,s}$ represent reflectance of the s-polarized and p-polarized components, respectively. θ_s and $\tilde{n}_s$ are incidence angle at the sea surface and complex refractive index of sea water, respectively. Therefore, S_i can be expressed as follows,

$$\begin{pmatrix} S_{i,0} \\ S_{i,1} \\ S_{i,2} \\ S_{i,3} \end{pmatrix} = \begin{pmatrix} I_{SR} + \frac{1-R_{s,s}}{2} I_{STR} + \frac{1-R_{p,s}}{2} I_{STR} + \frac{R_{s,s} I_{SR}}{2} + \frac{R_{p,s} I_{SR}}{2} \\ \frac{1-R_{s,s}}{2} I_{STR} - \frac{1-R_{p,s}}{2} I_{STR} + \frac{R_{s,s} I_{SR}}{2} - \frac{R_{p,s} I_{SR}}{2} \\ 0 \\ 0 \end{pmatrix} \quad (14)$$

Then, according to Equation (8), the reflected Stokes vector of the object is,

$$\begin{pmatrix} S_{r,0} \\ S_{r,1} \\ S_{r,2} \\ S_{r,3} \end{pmatrix} = \begin{pmatrix} \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i) M_{00}] \cos \theta_r d\Omega_r & \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r & 0 & 0 \\ \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r & \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i) M_{00}] \cos \theta_r d\Omega_r & 0 & 0 \\ 0 & 0 & \int f_{22}^s(\theta_r, \phi_i) \cos(\theta_r) d\Omega_r & \int f_{23}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ 0 & 0 & \int f_{32}^s(\theta_r, \phi_i) \cos(\theta_r) d\Omega_r & \int f_{33}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \end{pmatrix} \begin{pmatrix} S_{i,0} \\ S_{i,1} \\ S_{i,2} \\ S_{i,3} \end{pmatrix} \quad (15)$$

$$= \begin{pmatrix} S_{i,0} * \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i) M_{00}] \cos \theta_r d\Omega_r + S_{i,1} * \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ S_{i,0} * \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r + S_{i,1} * \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i) M_{00}] \cos \theta_r d\Omega_r \\ 0 \\ 0 \end{pmatrix}$$

Finally, the reflection DoLP of the object can be solved as,

$$DoLP_r = \frac{\sqrt{(S_{r,1})^2 + (S_{r,2})^2}}{S_{r,2}} \quad (16)$$

2.2.2. Radiation DoLP Model of Rough Surface

Polarization occurs when objects with a temperature higher than 0 K emit thermal radiation. According to the law of conservation of energy and Kirchhoff's law, when the energy lost by thermal radiation penetrating the object is not considered, the directional emissivity of the object is [32]

$$\epsilon_{DE} = \epsilon_{BB} - \int f \cos \theta_i d\Omega_i \cdot \epsilon_{BB}$$

Here, $\epsilon_{BB} = [1 \ 0 \ 0 \ 0]^T$ is the blackbody emissivity matrix. The ϵ_{DE} can be solved as

$$\epsilon_{DE} = \begin{bmatrix} 1 - \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i) M_{00}] \cos \theta_r d\Omega_r \\ - \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ - \int f_{20}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ - \int f_{30}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \end{bmatrix} \quad (17)$$

Then the Stokes vector of OTR is

$$\begin{pmatrix} S_{OTR,0} \\ S_{OTR,1} \\ S_{OTR,2} \\ S_{OTR,3} \end{pmatrix} = \varepsilon_{DE} * I_{OTR} = \begin{bmatrix} I_{OTR}(1 - \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)M_{00}] \cos \theta_r d\Omega_r) \\ -I_{OTR} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ -I_{OTR} \int f_{20}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ -I_{OTR} \int f_{30}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \end{bmatrix} \quad (18)$$

Here, I_{OTR} is the intensity of the OTR. Ultimately, the object radiation polarization can be solved as,

$$DoLP_{OTR} = \frac{\sqrt{(S_{OTR,1})^2 + (S_{OTR,2})^2}}{S_{OTR,0}} \quad (19)$$

2.2.3. Infrared DoLP Model of Rough Surface

Combining Equations (15) and (18), the Stokes vector of the radiation received by the detector is

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} S_{OTR,0} \\ S_{OTR,1} \\ S_{OTR,2} \\ S_{OTR,3} \end{pmatrix} + \begin{pmatrix} S_{r,0} \\ S_{r,1} \\ S_{r,2} \\ S_{r,3} \end{pmatrix} \quad (20)$$

$$= \begin{pmatrix} I_{OTR}(1 - \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)]M_{00} \cos \theta_r d\Omega_r) + S_{i,0} \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)M_{00}] \cos \theta_r d\Omega_r + S_{i,1} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r \\ -I_{OTR} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r + S_{i,0} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r + S_{i,1} \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)M_{00}] \cos \theta_r d\Omega_r \\ 0 \\ 0 \end{pmatrix}$$

According to Equation (9), the DoLP of the object can be calculated as,

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \quad (21)$$

$$= \frac{|-I_{OTR} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r + S_{i,0} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r + S_{i,1} \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)M_{00}] \cos \theta_r d\Omega_r|}{I_{OTR}(1 - \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)]M_{00} \cos \theta_r d\Omega_r) + S_{i,0} \int [f_{00}^s(\theta_r, \phi_i) + f_{00}^d(\theta_r, \phi_i)M_{00}] \cos \theta_r d\Omega_r + S_{i,1} \int f_{10}^s(\theta_r, \phi_i) \cos \theta_r d\Omega_r}$$

It should be noted that the calculation of Equation (21) uses the observation angle θ_O and the incidence angle θ_S , which can be solved as

$$\begin{cases} \theta_S = 2\alpha_{O-S} - \alpha_D - \pi/2 \\ \theta_O = \pi/2 - \alpha_{O-S} + \alpha_D \end{cases} \quad (22)$$

Here, α_D is the included angle between the detector's axis of view and the horizontal plane, and α_{O-S} is the angle between the object and the sea surface.

3. Results

3.1. Simulation

In the simulation, the detector angle is set at $\alpha_D = 15^\circ$, and the sea water complex refractive index is set at $1.21 + 1.3i$. The roughness and complex refractive index of the object are set at $\sigma = 2.1 \mu\text{m}$ and $\tilde{n}_s = 1.5 + 1.3i$, respectively, which are the same as those of the painted aluminum plate used in the experiment. Considering the actual situation, we set the angle α_{O-S} within the range of 30° – 90° , and according to Equation (22), we can calculate the corresponding object observation angle θ_O in the range of 15° – 75° . In order to facilitate comparison with the experimental results, all simulations are conducted in this angle range.

3.1.1. Influence of RCE on the DoLP of Object

In order to study the influence of RCE on the DoLP, we calculate the R_s , R_p and DoLP of the object according to the proposed model shown in Figure 3, and the object temperature is set at 30°C in the simulation.

Figure 3. Influence of RCE on the DoLP of object: (a) Reflectance of the s-polarized and p-polarized components; (b) the DoLP of the object; and (c) the DoLP of reflection and radiation.

Figure 3a shows that $R_s > R_p$ at all observation angles, so most of the energy of the OTR is concentrated in the p-polarized direction and the Stokes component of the radiated light $S_{OTR,1}$ is less than 0. For natural light incidence, the s-polarized energy of the reflected light is greater than the p-polarized energy; accordingly, the $S_{r,1}$ component of the reflected light is greater than zero. Therefore, the DoLP of the object is related to the ratio of radiation to incident energy. The influence of RCE on the DoLP of the object is shown in Figure 3b. The DoLP of the object increases monotonically with the observation angles without considering RCE. The trend of the DoLP of the object decreases first and then increases while considering RCE, with the minimum value at $\theta_o = 53^\circ$. In order to analyze the reasons for this influence of RCE, the radiation and reflection DoLP of the object are calculated according to Equations (16) and (19), respectively, as shown in Figure 3c. It can be seen that the DoLP of reflection increases at small observation angles and decreases at larger observation angles due to the influence of RCE. The reason for this is that the RCE changes the incident light from natural light to partial polarization light, thus changing the measurement results of the object's DoLP. Therefore, RCE must be considered in the study of the polarization characteristics of objects in marine background.

3.1.2. Influence of Object Temperature on the DoLP of Object

From the above simulation analysis, it can be seen that the object's temperature changes the ratio of radiated and incident energy, thus changing the DoLP of object. The DoLP of object at different observation angles ($15\text{--}75^\circ$) for object temperatures from 30°C to 80°C were calculated, respectively, as shown in Figure 4a.

Figure 4. Influence of object temperature on the DoLP of object: (a) the DoLP of object; (b) the S_1 component of object; and (c) the S_0 component of object.

In comparison with Figure 3b, it can be seen that the trend of DoLP does not change with the object's temperature. The DoLP of the object decreases with the increase in temperature at small observation angles and increases with the growth of temperature at large observation angles. To explain this result, the S_0 , S_1 components of the Stokes vector at different temperatures are calculated as in Figure 4b,c. At small observation angles, it can be seen that as the object's temperature increases, the S_1 component remains more or less constant, while the S_0 component increases significantly. Therefore, in this case, the DoLP of the object decreases with the increase in temperature. At larger observation angles, however, the increase in the object's temperature will simultaneously increase the S_0 and S_1 components, but overall, it will cause the DoLP of the object to increase.

3.1.3. Influence of Surface Roughness on the DoLP of Object

In order to discuss the influence of surface roughness σ , the object's DoLP with different σ is calculated when the object temperature is 48°C , as shown in Figure 5. Compared with Figure 3b, it can be seen that the trend of the object's DoLP does not change with σ . The object that has an ideal mirror surface shows the maximum DoLP. With the increase in surface roughness, the DoLP of the object decreases gradually. This is because the rougher the surface is, the smaller the specular reflection component and the larger the diffuse reflection component will be. Therefore, the DoLP of the object will decrease.

Figure 5. Variation of object's DoLP with surface roughness at an object temperature of 48 °C.

3.2. Experimental Verification

3.2.1. The Experimental Setup

To validate the deduced model, an infrared DoLP measurement system is constructed within the wavelength range of 8–14 μm . The object is a painted aluminum plate with a surface roughness of 2.1 μm . The heating plate is fixed behind the object mounted on a turntable, which allows for the adjustment of the object's temperature and the included angle between the object and the horizontal plane. The turntable is placed inside a container containing sea water. The measured values of complex refractive index of the object and the sea water at the central wavelength are $1.5 + 1.3i$ and $1.21 + 1.3i$, respectively. In the experiments, an LWIR polarization system is used to acquire the object's images. The resolution of the infrared system is 640×512 pixels and the pixel size is 17 μm . Considering the actual situation, we set the angles between the object and the sea surface within the range of 30–90°, which corresponds to the object observation angles of 15–75°. Sea water temperature is set at 23.5 °C, room temperature 20 °C, relative humidity 72%, and the detector angle is set at $\alpha_D = 15^\circ$.

3.2.2. Experimental Results

In the experiment, the object is heated to the specified temperature by means of a heating plate. Rotating the polarizing plate at 0°, 45°, 90°, and 135°, the polarization intensity of the object I_{0° , I_{45° , I_{90° and I_{135° is acquired, respectively. Omitting the circular polarization component, the Stokes vector is obtained as follows,

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} (I_{0^\circ} + I_{45^\circ} + I_{90^\circ} + I_{135^\circ})/2 \\ I_{0^\circ} - I_{90^\circ} \\ I_{45^\circ} - I_{135^\circ} \\ 0 \end{pmatrix}$$

Therefore, the DoLP image can be calculated by Equation (9). In the experiment, polarization images are acquired through different observation angles θ_O at object temperatures of 40 °C, 50 °C, and 60 °C, as shown in Figure 6. It can be seen that the DoLP of the object tends to decrease first and then increase with the observation angles, and the minimum value is obtained at $\theta_O = 55^\circ$. It is basically consistent with the simulation results in Section 3.1. In addition, it can be clearly observed that the DoLP of the object does not tend to zero at small observation angles, which is rightly predicted by the simulation results of the model.

Figure 6. Experimental results: (a) The images of DoLP, S_0 , S_1 and S_2 with object temperature being 50 °C and observation angle being 45°; (b) the DoLP images of painted aluminum plate. Up to down, the object temperatures are 40 °C, 50 °C, and 60 °C; left to right, observation angles are from 15° to 75°.

The DoLP of the object is simulated and calculated with and without RCE, respectively. The comparison between the simulation and the experiment is shown in Figure 7. In Figure 7a, it can be seen that the experimental value of the object's DoLP decreases with increasing temperature for small observation angles, and increases with increasing temperature for large observation angles, which is consistent with the results of the theoretical analysis in Section 3.1.2.

Figure 7. The DoLP of the object at different temperatures: (a) comparison between simulation results and experimental results; (b) comparison results at 40 °C; (c) comparison results at 50 °C; and (d) comparison results at 60 °C.

4. Discussion

In the experiment, the minimum value of the object's DoLP is obtained at an observation angle of 55° , while the minimum value in the simulation results is at the observation angle of 53° , which is mainly caused by the insufficient accuracy of the observation angle interval in the experiment. From Figure 7b–d, it can be seen that the simulation results of the deduced model accord more closely with the experimental results compared to the results without RCE. Overall, the simulation results of the deduced model and experimental results both have the trend of first decreasing and then increasing in terms of the object's DoLP. The simulation results have smaller minimum and larger maximum values compared with the experimental results, so the simulation results have a larger amplitude than the experimental results, resulting from not taking into account detector errors in the model, such as noise. In addition, it can be found that as the temperature of the object increases, the simulation results are in better agreement with the experimental results, mainly because as the temperature increases, the radiation of the object enhances, while the noise of the detector changes little.

5. Conclusions

In this paper, a DoLP model is deduced for objects in a marine background, taking into account the RCE. The simulation results show a trend of DoLP first decreasing and then increasing, and the minimum DoLP is achieved at $\theta_O = 53^\circ$. In contrast to the results without RCE, the simulation results of the proposed model have a larger DoLP at small observation angles and a smaller DoLP at large observation angles. The DoLP of the object decreases with increasing temperature at small observation angles and increases with increasing temperature at large observation angles. The DoLP of the object decreases with the increase in roughness, regardless of observation angles.

To verify the simulation results, an LWIR polarization measurement system is constructed, and the DoLP of the object is measured at different temperatures and observation angles. The measured results are consistent with the simulation results. These conclusions are of great significance to the research of polarization detection and identification of infrared objects in the marine background.

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