Real-time Infrared Characterization Simulation and Research of Wind-roughened Sea Surface

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Abstract. The sea surface is an important background of sea surface targets and its infrared radiation characterization is the basis of infrared detection and recognition of sea surface targets. The model of linear wave theory and JONSWAP spectrum was used to achieve shape and display of ocean wave. Real-time infrared characterization simulation model was established for the sea surface, considering the solar radiance, the sky background radiance and the effects of atmospheric transmission. The sea surface was divided into many wavelet facets and the radiance of every facet was calculated on the basis of infrared simulation model. Three typical time, 9:00, 12:00, 15:00 in one day were selected and the radiance of every facet about 3~5μm and 8~12μm waveband was respectively calculated. Real-time infrared simulation images of sea surface were generated by converting wavelet facets radiance value to image gray value. The results show that the sea surface infrared images of 3~5μm waveband display the bright spots of reflected solar irradiance, and the spots appear the same direction with the solar azimuth while the impact of solar irradiance in 8~12μm waveband isn’t usually required, and the method can effectively simulate the sea surface infrared characterization and provide the basis for infrared detection and recognition of sea surface targets.

Keywords: Infrared characterization; JONSWAP spectrum; Sea surface simulation; Radiance

1. Introduction
With the development of infrared track and guidance technology, different kinds of infrared precision-guided weapons are increasingly serious threats against sea surface military targets. The sea surface is a decisive background of sea targets, and its infrared radiation characterization is the basis of infrared detection and recognition of sea targets, which can directly influence the results of detection. Meanwhile, due to the impacts of sea surface waves and sea clutter effects existence, there is a certain roughness of the sea itself and inconsistent reflection of radiation on the surrounding environment. The detection of comparatively weak radiant objects in the thermal band becomes much more difficult. Therefore, analysis and simulating sea surface infrared characterization are significant for studying missile tracking guidance, feature recognition and infrared stealth technology of ship.

A widely previous work has been done about the infrared characterization of the sea. In 1954, C. Cox and W. Munk established the classic Cox-Munk model\cite{1}. Based on this model, other scholars established the calculation model of sea surface emissivity and reflectivity\cite{2}\cite{3}, which had a wide range of application in infrared remote sensing and simulation fields\cite{4}. In the construction of the ocean wave, using the wave spectrum analysis method, currently used mainly focus on Bretschneider spectrum, PM spectrum, Phillips spectrum, JONSWAP spectrum, Wallops spectrum, etc.. Each model
has its scope of application and can be selected according to actual needs. In 1968-1969, scientists from NATO countries built the first international spectrum, called JONSWAP[5] spectrum, which is widely used by many researchers over the world as a useful tool for analyzing the optical, infrared, and other spectrum characteristics of the sea for its authority and practicality. In terms of infrared imaging simulation, I. Wilf and Y. Manor[6], F. Schwenger and E. Repasi[7] did the effective work of excellence. In this paper, we focus on the real-time infrared characterization of the sea surface. The ocean waves are simulated with JONSWAP spectrum model. Then the radiance of sea surface is calculated, considering the solar radiance, sky background radiance, atmospheric path transmission and surface structure of the wavelet facets’ impacts on emission and reflection of the sea. In the end, infrared radiation characterization of the sea of different times in one day under the 3~5µm and 8~12µm waveband is simulated.

2. Modelling the sea surface pattern
Linear wave theory[8] indicates that the ocean waves can be superimposed by different periods and different random initial phases of irregular cosine waves. We use the method based on wave spectrum to achieve the wave simulation and display. The international general duty JONSWAP spectrum is used, which can be expressed as:

\[ S(\omega, \mu) = S(\omega)G(\omega, \mu) \]

\[ S(\omega) = \frac{\alpha g^2}{\omega^4} \exp \left[- \frac{5}{4} \left( \frac{\omega_m}{\omega} \right)^4 \right] \exp \left[-\frac{(\omega-\omega_m)^2}{2\sigma^2}\right] \]

\[ L = \frac{Lg}{v^2} \]

\[ \alpha = 0.076L^{-0.22} \]

\[ \omega_m = 2\pi \times 3.5 \frac{g}{v} L^{-0.33} \]

\[ G(\omega, \mu) = \begin{cases} \frac{2}{\pi} \cos^2(\mu - \psi) & -\pi/2 + \psi \leq \mu \leq \pi/2 + \psi \\ 0 & \text{others} \end{cases} \] 

(1)

Where, \( \omega \) is the spatial angular frequency; \( \theta \) is the wave vector direction; \( g \) is the acceleration of gravity; \( \omega_m \) is the spectrum peak frequency; \( v \) is the wind velocity; \( L \) is the wind fetch; \( G(\omega, \mu) \) is directional distribution function; \( \psi \) is the angel of wind direction and X-axis.

The 3D grids image of ocean wave is presented according to the linear wave theory and JONSWAP spectrum model (Figure 1).
3. Modelling the infrared radiation of sea surface

Generally, the sea surface can be approximated as a surface of a non-black body. When the sea surface is watched by a camera, then the radiance reaching the detector from an element of the sea can be divided into three parts (Figure 2): (1) sea itself infrared radiance; (2) sky background radiance, solar irradiance and reflection radiance; (3) atmospheric path radiance. In addition, atmospheric absorption and scattering effect should be considered in the calculation of radiance.

Therefore, the total radiance $L_{\text{sea}}^\lambda$ of one waveband at the detector from the sea surface in the direction of $(\theta_e, \varphi_e)$ can be approximated as:

$$L_{\text{sea}}^\lambda = (1 - \tau_{\text{air}}^\lambda) \cdot L_{\text{air}}^\lambda + s_e \cdot \tau_{\text{air}}^\lambda \cdot (\varepsilon_{\text{sea}}^\lambda(\theta_e, \varphi_e) \cdot L_{\text{bb}}^\lambda(T_{\text{sea}}) + \rho_{\text{sea}}^\lambda(\theta_e, \varphi_e) \cdot (L_{\text{sky}}^\lambda + L_{\text{sun,s}}^\lambda))$$

$$+ \rho_{\text{sea}}^\lambda(\theta_e, \varphi_e, \theta_{\text{sun}}, \varphi_{\text{sun}}) L_{\text{sun,d}}^\lambda$$

(2)

Where, $\tau_{\text{air}}^\lambda$ is radiant transmittance of the path between a point on the sea and the sensor; $s_e$ is the slope-shadowing factor; $\varepsilon_{\text{sea}}^\lambda(\theta_e, \varphi_e)$, $\rho_{\text{sea}}^\lambda(\theta_e, \varphi_e)$, $\rho_{\text{sea}}^\lambda(\theta_e, \varphi_e, \theta_{\text{sun}}, \varphi_{\text{sun}})$ are respectively sea surface emissivity, hemisphere reflectivity and bidirectional reflectivity in the direction of $(\theta_e, \varphi_e)$; $\theta_{\text{sun}}, \varphi_{\text{sun}}$ are respectively the zenith angle and azimuth angle of the sun; $L_{\text{air}}^\lambda$ is the radiance of the atmospheric path; $L_{\text{bb}}^\lambda(T_{\text{sea}})$ is the radiance of a black body of $T_{\text{sea}}$; $L_{\text{sky}}^\lambda$ is the radiance of the sky measured at sea level; $L_{\text{sun,s}}^\lambda$, $L_{\text{sun,d}}^\lambda$ are respectively the radiance of the scattered and direct sun energy.

Because of the influence of wind-roughened waves, sea surface itself is rough. In the calculation of infrared radiation, we can not simply take it as a flat surface. However, it can be seen as a combination of different slopes of wavelet facets. Reflection schematic diagram wavelet facet is shown in Figure 3.
The bidirectional reflectivity of a wavelet facet can be expressed as:

$$\rho_{\text{sea}}^{\lambda} = \rho(n, \chi) \cdot (\pi \sigma^2)^{-1} \exp(-\frac{s_i^2 + s_e^2}{\sigma^2}) \cdot \frac{1 + \cos \theta_i \cos \theta_e + \sin \theta_i \sin \theta_e \cos(\phi_i - \phi_e)}{(\cos \theta_i + \cos \theta_e)^2}$$  \hspace{1cm} (3)

Where, $\rho(n, \chi)$ is the reflectivity of calm sea, which can be calculated from the Fresnel formula\(^9\); $\chi$ is the incidence angle, $n$ is complex refractive index of seawater; $\theta_i, \phi_i, \theta_e, \phi_e$ are respectively zenith angle and azimuth angle in the direction of incidence and reflection; $\sigma$ is the mean-square slope.

$$\sigma^2 = 0.003 + 0.00512 \nu \pm 0.004$$ \hspace{1cm} (4)

Where, $\nu$ is the wind velocity above the sea.

Therefore, $\rho_{\text{sea}}^{\lambda} (\theta_e, \phi_e), \mathcal{E}_{\text{sea}}^{\lambda} (\theta_e, \phi_e)$ can be approximated as:

$$\rho_{\text{sea}}^{\lambda} = \int_0^{\pi/2} \int_0^{\pi/2} \rho_{\text{sea}}^{\lambda} (\theta, \phi, \theta_e, \phi_e) \sin \theta_i \sin \phi_i \sin \theta_e \sin \phi_e \, d\theta \, d\phi_i$$ \hspace{1cm} (5)

$$\mathcal{E}_{\text{sea}}^{\lambda} = 1 - \rho_{\text{sea}}^{\lambda} (\theta_e, \phi_e)$$ \hspace{1cm} (6)

Sky background radiance is diffused reflection, and it can be acquired without considering the issue of location of radiation sources. But the reflection of solar direct irradiance is concerned with the surface roughness. For the incident direct radiance of sun, the surface only to meet the specific conditions of the wavelet facets can reflect to the detector. Suppose incident direction of the sun $i$, wavelet facet normal to $n$, the direction of detector $e$. If the surface solar radiation can be reflected by the wavelet facet into the detector, then the sun, the detector and wavelet facet must satisfy:

$$\{ n \cdot i = n \cdot e$$

$$e = 2n(n \cdot i) - i$$ \hspace{1cm} (7)

In the calculation of the sea infrared radiance, firstly, it need to generate the surface shape of sea surface to calculate the wavelet facets slope distribution of all area; secondly, according to the slope size of each wavelet facet to judge whether the sensor can receive the reflection of solar irradiance from the surface; finally, on the combination of sea itself and its surrounding radiance, and considering the impact of atmospheric transmission, acquire the value of the infrared radiance of the entire surface. After calculation of radiance of facets, we also have to know how many facets correspond to a pix of the sensor. The number of wavelet facets in the perpendicular and parallel direction $N_H, N_V$ can be approximated as\(^6\):

$$N_H = R \Delta \theta / \Delta y$$

$$N_V = R \Delta \theta / (\Delta x \sin \phi)$$ \hspace{1cm} (8)

Where, $R$ is the path length between the sensor and the facet; $\Delta \theta$ is the instantaneous field of view; $\Delta x, \Delta y$ are the horizontal and vertical size of a facet; $\phi$ is the viewing angle. Therefore, a pix of the sensor can be the average of $N_H \times N_V$ facets’ radiance.

4. Infrared characterization simulation of sea surface

After infrared radiance value of each wavelet facet based on sea surface infrared radiance model, convert wavelet facets radiance value to image gray value according to some algorithm, then the infrared radiation imaging will be generated. The algorithm can be expressed as:

$$G_{mi} = \frac{L_{mi} - L_{\text{min}}}{L_{\text{max}} - L_{\text{min}}} \cdot 255$$ \hspace{1cm} (9)
Where, $G_{mi}$ is the grey value of $mi$ wavelet facet; $L_{\text{max}}, L_{\text{min}}$ are respectively the maximum value and minimum value of radiance of entire surface.

Three typical time, 9:00, 12:00, 15:00 in one day are selected and the radiance of every facet about 3~5µm and 8~12µm waveband is respectively calculated on the basis of infrared simulation model. The following parameters are used. The direction of detector is north, detecting elevation angle is 40˚, and the height is 5 km. The wind velocity is 6 m/s and wind fetch is 100 km. The seawater temperature is 20°. The highest temperature of local atmosphere is 25°, and the lowest is 18°. The field of the sensor is $1.8^\circ \times 3.5^\circ$.

![Infrared image of sea surface (3~5µm)](image)

**Fig.4.** Infrared image of sea surface (3~5µm)

In figure 4, for the 3~5µm waveband, we can find that, as the sun changes position, the sea surface infrared image shows difference corresponding to the changes. At 9:00 in the morning, when the sun’s in the eastern direction, then only the specific wavelet facets of eastern direction can reflect the incident radiation of direct sunlight, so that part of the eastern wavelet facets appear bright spots for the whole surface of the sea. At 12:00 in the daytime, the sun direction points to south, and this time the incident direction of the sun is almost perpendicular to the sea. There are less wavelet facets directly reflecting sunlight to the sensor and less difference in the overall brightness of the sea surface. At 15:00 in the afternoon, the sun’s direction is western. Sea surface infrared image is the corresponding features with 9:00 pm. Part of the western wavelet facets appear bright spots. Comparison of three images of figure 4, it is found that at 9:00 and 15:00, the sun's elevation angle is small, so that more solar irradiiance can be reflected and bright spots appeared more.
In Figure 5, for the 8–12 µm waveband, it can be seen, with the changes of sun orientation in the day, the sea surface infrared characterization change little. Compared with 3–5 µm waveband, the solar irradiance is very low, and it also indicates that solar irradiance in 8–12 µm waveband is usually negligible.

To further discuss the impacts of solar irradiance in the 3–5 µm and 8–12 µm two wavebands on sea surface infrared images, the results of considering and not considering the solar irradiance in both wavebands are compared, then the difference and derivation of two results in each waveband are calculated, setting sun elevation angle 14°, the viewer elevation angle changing from 0° to 40°.
From Figure 6 and Figure 7, it can be found that, in the 3~5µm waveband, solar irradiance is very apparent. The reflection intensity is largest when the elevation angle of both sun and sensor is approximated, and the deviation percentage of solar irradiance is even approaching to 200%. In the 8~12µm waveband, solar irradiance has little effect, usually negligible, which is consistent with well-known results.

5. Conclusions
In this paper, the model of linear wave theory and JONSWAP spectrum is used and the sea surface is simulated. The sea surface infrared radiation model is established, considering the radiance of sea surface itself, surrounding environment and effects of atmospheric transmission path. Infrared radiation images of 3~5µm and 8~12µm waveband of different day times are generated. The results are consistent with the actual situation and the difference of whether or not considering solar irradiation is compared. The conclusions are as follows:

(1) Infrared characterization of sea surface in 3~5µm waveband changes over time, and bright spots of the sea and the sun appear bearing the same orientation, while infrared characterization change little over time in 8~12µm waveband;
(2) When the elevation angle of detector and sun is similar, the wavelet facets can reflect more solar irradiance to the sensor;
(3) In 8~12µm waveband, solar irradiance has little impact on the sea surface infrared characterization, often negligible.

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