Simulation Study on SAR Signatures of ocean thermal fronts

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ABSTRACT: Thermal fronts are common ocean phenomena with obvious characteristics of strong temperature gradient. The strong gradient causes the change of the air-sea temperature differences at both sides of the front, leading to the local circulation and wind field change in the thermal front regions. Based on the thermal unstable stratification, friction velocity model is established, according to which the influence of air-sea temperature differences on friction velocity is analyzed. Friction velocity is also selected to be the intermediate variable to simulate the backscattering coefficient in the front regions, using the classical Bragg backscattering model and E_H ocean wave spectrum, and the influences of wave band, polarizations and background wind speed on NRCS in the front regions are discussed. Simulation results indicate that VV polarization, higher frequency and strong wind are most favorable to ocean front detection. The simulation of NRCS in the front regions helps to observe and understand the ocean fronts on SAR images and lays the theoretic foundation for ocean front detection by active radar.

1. INTRODUCTION
Ocean fronts are important ocean regions, where ocean properties(such as temperature, salinity and flow field) often change abruptly and thus cause the sea surface roughness change. The normalized radar backscattering cross section(NRCS) \( \sigma^0 \) is the quantification of sea surface roughness, so it has its own feature in the ocean fronts. Three main physical mechanisms that can explain the change of NRCS of ocean fronts are as follows.(1)Hydrodynamic wave-current interaction modulates the wave spectrum.(2)Air-sea temperature differences at both sides of ocean fronts determine the atmospheric stratification which influence the wind field and the wind wave spectrum.(3)Convergent currents on the surface dampens short waves. For thermal fronts, the strong temperature gravity is the most obvious feature, so researches on NRCS of ocean thermal fronts are mainly based on the second mechanism.

Retrieving ocean thermal fronts from Sea Surface Temperature(SST) measurements from infrared radiometer is the foundation of most front detection methods. But it is well known that infrared remote sensing is limited by weather conditions, especially the cloudy and rainy days. Synthetic Aperture Radar(SAR) can be used independently of night-time or weather conditions and is sensitive to the change of sea surface roughness in ocean front regions with high resolution. In studies by CHEN Biao et al, SAR images are used to detect the ocean fronts related to upwelling existing in the coastal areas of Fujian and Zhejiang. The above method is based on the SAR image brightness, where image processing methods such as edge detection are adopted. However, \( \sigma^0 \),an important physical quantity in active remote sensing, is not used directly.

In this paper, considering the atmosphere instability, we established the relationship between the air-sea temperature difference and the friction velocity in thermal front regions. Based on E_H wave spectrum and Bragg backscattering model, we simulated the \( \sigma^0 \) of ocean thermal fronts and analyzed
the influence of wavelength, polarization mode and background wind speed on it. These provide theoretical reference for ocean front detection using active radar.

2. SIMULATION MODEL

2.1 friction velocity model

Based on the similarity theory of Monin-Obukhov, the wind profile considering the atmosphere instability varies logarithmically with height \[2\]:

\[ u_z = \frac{u_f}{\kappa} (\ln \frac{z}{z_0} - \Phi) \]  

where \( u_z \) is the mean wind speed at height \( z \), here \( z_0 = 10 \) m; \( u_f \) is the friction velocity; \( \kappa \) is Karman constant; \( z_0 \) is the roughness length and \( \Phi \) is a stability function \[3\]:

\[
\Phi = \begin{cases} 
2\ln\left(\frac{1+a}{2}\right) + \ln\left(\frac{1+a^2}{2}\right) - 2\tan^{-1}a + \frac{\pi}{2}, & z/L < 0 \text{ unstable} \\
-5z/L, & z/L \geq 0 \text{ stable}
\end{cases}
\]  

(2)

where \( a = (1 - 16z/L)^{1/4} \), \( L \) is Obrov length which describes the atmospheric stability of the boundary layer and \( z/L \) depends on Richard index \( R_i \),

\[ z/L = \kappa C_f C_D^{-3/2} R_i (\Delta T) \]  

(3)

where \( C_f \approx 1.0 \times 10^{-3}, C_D \approx 1.25 \times 10^{-3}, R_i = 3.55 \Delta T / u_{10}^2 \) \[3\], \( \Delta T = T_a - T_u \), \( T_a \) and \( T_u \) are air temperature and SST.

For neutral stratifications (\( \Phi = 0 \)), the equivalent neutral wind becomes:

\[ u_{en} = \frac{u_f}{\kappa} \ln \frac{z}{z_0} \]  

(4)

Using (1) and (4), the equivalent neutral wind can be written as:

\[ u_{en} = u_z + \frac{u_f}{\kappa} \Phi \]  

(5)

The relationship between air-sea temperature difference and the friction velocity are as shown in Figure 1 (\( u_{en} = 10m/s \)). Figure 1 shows that \( U_f \) under unstable condition is much larger than that of stable condition, the main reason of which is that vertical convection is enhanced, generating local circulation, changing the stratification function and increasing the friction velocity when the atmospheric stratifications is unstable.
2.2 Rough sea surface backscattering model

According to the scattering theory of electromagnetic wave, the NRCS generated by Bragg resonance scattering under the first-order approximation condition can be expressed as:

$$
\sigma_{pp}^{\phi}(\theta) = 16\pi k^2 \cos^4 \theta |g_{pp}|^2 S(k_B, \varphi_B)
$$

(6)

where $k$ is the radar wave number, $k = 2\pi / \lambda$; $k_B$ is the wave number of sea surface gravity capillary waves when the resonance condition was satisfied, $k_B = 2k_\varphi \sin \theta_i$; $\theta_i$ is the incident angle; $\phi_B$ is the azimuth of radar beam (the angle between the projection of the radar beam at the sea surface and the wind direction). $g_{pp}$ is a weighting factor related to polarization state, $pp \in \{HH, VV\}$:

$$
g_{pp} = \begin{cases} 
\frac{\varepsilon_r - 1}{[\cos \theta_i + \varepsilon_r - \sin^2 \theta_i]^2} & \text{HH-pol} \\
\frac{(\varepsilon_r - 1)[(\varepsilon_r (1 + \tan^2 \theta_i) - \tan^2 \theta_i]}{[\varepsilon_r \cos \theta_i + \varepsilon_r - \sin^2 \theta_i]^2} & \text{VV-pol}
\end{cases}
$$

(7)

where $\varepsilon_r$ is the relative dielectric constant which can be calculated according to the Debye equation.

To calculate the wave number spectrum $S(k_B, \varphi_B)$ in (6), we used E-spectrum (infra gravity wave) and H-spectrum (capillary gravity wave, short gravity wave). This directional spectrum is

$$
S(k, \Phi)_{E,H} = f(k, \Phi) \begin{cases} 
M_E(k) & k < k_{lc} \\
M_H(k) & k_{lc} \leq k < k_{hc} \\
M_H(k) & k \geq k_{hc}
\end{cases}
$$

(8)

where $f(k, \Phi) = \frac{1}{2\pi} [1 + \Delta_k \cos(2\varphi)]$ is the directional distribution function.

For the C, X, and Ku bands commonly used in ocean remote sensing, its wave number $k_B > k_{hc}$. So the following is adopted:

$$
M_H(k) = \frac{A(k)}{k^4} \left( \frac{u_f}{c} \right)^{a(k)}
$$

(9)

where $A(k)$ and $a(k)$ are empirical expression.

In (9), the $u_f$ is introduced into the backscattering model. Hence we combined the friction velocity
model and backscattering model to simulate $\sigma^0$ of ocean thermal fronts.

2.3 Ocean thermal fronts set up
To study the effect of band, polarization, and background wind speed on $\sigma^0$ of ocean thermal fronts, $\sigma^0$ under different conditions are simulated. The radar parameters and wind field are set as table 1.

| Radar parameters | Wave band | Polarization | Incident angle | Radar viewing angle |
|------------------|-----------|--------------|----------------|--------------------|
|                  | C (5GHz)  | HH, VV       | 45°            | 0°                 |
|                  | X (10GHz) |              |                |                    |
|                  | Ku (15GHz)|              |                |                    |

| Wind field       | Background wind speed | Wind direction |
|------------------|-----------------------|----------------|
|                  | 5, 7, 10 m/s          | 45°            |

The one-dimensional temperature field of thermal fronts can be simplified as

$$T_w(x) = \begin{cases} T_1 & x < x_1 \\ \frac{T_1 + T_2}{2} + (T_2 - T_1) \tanh\left(\frac{x}{100} - 35\right) / d & x_1 \leq x < x_2 \\ T_2 & x \geq x_2 \end{cases}$$

where $d = 50$ is a dimensionless parameter of front width; the total length of thermal fronts is set to 7000m, $x_1 = 1000$, $x_2 = 6000$, the total length of area existing temperature gravity is 5000m; $T_1 = 20^\circ C$, $T_2 = 25^\circ C$, $T_a = 20^\circ C$. The temperature, air-sea temperature differences and temperature gravity of thermal fronts are shown in figure 2.

![Figure 2. Simulation of the temperature field of thermal fronts. (a) The temperature and air-sea temperature differences of thermal fronts. (b) The temperature gravity.](image)

3. RESULTS
The simulation results of $\sigma^0$ in thermal front regions under different conditions are shown in figure 3 and figure 4.
Figure 3. Comparison of $\sigma^0$ under different condition of wave band (C, X, Ku) in thermal front regions. (a) VV and (b) HH polarizations. Background wind speed is 10 m/s.

Figure 4. Comparison of $\sigma^0$ under different condition of background wind speed (5, 7, 10) in thermal front regions. (a) VV and (b) HH polarizations. Radar frequency is 5 GHz (C band).

Figure 3 shows that $\sigma^0$ in thermal front regions increases as the $T_\Delta$ increases. But Figure 1 demonstrates that in the case of $T_\Delta < 0$, the frictional wind speed increases slowly as the increases, as a result of which the $\sigma^0$ increases slowly and the increase is small correspondingly. With different polarization, $\sigma^0$ and its variation in thermal front regions both increase with the increase of frequency. Besides, when the frequency increases from the C band to the X band, the increase of $\sigma^0$ and $|\Delta \sigma^0|$ are relatively large, while they increase little or remain unchanged when the frequency increases from the X band to the Ku band despite the same frequency variation. Comparing (a) and (b), it can be seen that, under the same conditions, $\sigma^0$ of the VV polarization is much larger than that of the HH polarization, and $|\Delta \sigma^0|$ is basically the same. In summary, for ocean thermal front detection, high frequency and VV polarization should be used to obtain strong echo signals and large echo signal differences between two sides of the front area.

Figure 4 shows that with the same band and polarization, wind speed does not affect the positive relationship between $\sigma^0$ and $|T\Delta|$. However, the wind speed affects the value of $|\Delta \sigma^0|$ and $|\Delta T\Delta|$, and the echo signal differences between two sides of the front area get larger when the wind speed become...
higher.

4. CONCLUSION

The results of this study suggest that when the atmosphere of the front area is unstable, $\sigma^0$ will increase slowly with $\Delta T$ decreasing. According to the simulation result, the thermal front should appear as bright zone on SAR images, providing theoretical basis for active thermal fronts remote sensing. Vertical polarization, large frequency and strong wind speed are suitable condition for active radar remote sensing for ocean thermal front detection, where the echo signal $\sigma^0$ is quite large.

In this paper, only Bragg waves are considered in the backscattering model. To obtain $\sigma^0$ of ocean thermal fronts that is closer to the real situation, it is also necessary to superimpose the mean square slope caused by the large-scale wave tilt to achieve a more accurate simulation of $\sigma^0$ in thermal front regions.

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