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Retrieval of ocean surface wind stress and drag coefficient from spaceborne SAR*

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Abstract A model for retrieval of wind stress and drag coefficient on the sea surface with the data measured by spaceborne synthetic aperture radar (SAR) has been developed based on the SAR imaging mechanisms of ocean surface capillary waves and short gravity waves. This model consists of radiometric calibration, wind speed retrieval and wind stress and drag coefficient calculation. A Radarsat SAR image has been used to calculate wind stress and drag coefficient. Good results have been achieved.

Keywords: **SAR, wind stress, drag coefficient.**

The wind stress and drag coefficient on the sea surface are very important parameters in the studies of ocean and atmospheric dynamics, and air-sea interaction. The capability of the traditional methods to measure the wind stress and the drag coefficient are limited by covered area. Therefore the measurements of these parameters by airborne or spaceborne sensors have attracted more and more attention[1]. Spaceborne SAR is capable of observing ocean surface continuously and repeatedly with high spatial resolution (from several meters to tens of meters) in all weather conditions day and night. The SAR measurements of the properties of marine atmospheric boundary layer can complement the data of both traditional *in situ* measurements and other remotely sensed measurements.

1 Mechanism

Spaceborne SAR is an active microwave imaging sensor. Its beam has a wavelength (λ_0) of several centimeters to tens of centimeters with an incidence angle (θ) between 20° ~ 70°. Its backscattered microwave is primarily the Bragg scattering of capillary waves and short gravity waves which are called Bragg waves having a wavelength of $\lambda = \lambda_0/2\sin\theta$[2]. The intensity or gray scale (I) of SAR images changes with the variations of backscattered radar cross-section caused by Bragg scattering[2, 3].

In the Bragg scattering, the normalized radar cross section σ_0 is proportional to the sum of the spectral energy density of Bragg waves with wave vector of $\pm 2\boldsymbol{k}_0$[2],

$$\sigma^0 = M \cdot (E(+2\boldsymbol{k}_0) + E(-2\boldsymbol{k}_0)), \tag{1}$$

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where $\boldsymbol{k}_0$ is the projection of radar wave vector (in the look direction of radar) on the horizontal plane; M is a scattering coefficient dependent on the radar incidence angle, radar wavelength, polarization and complex dielectric constant of sea water, which can be calculated using Bragg scattering theory.

Wind is the origin of Bragg waves and changes the spectral energy density of these waves. These changes can be observed from the variations of gray scale in SAR images. Therefore wind speed (U_{10}, the subscript denotes 10 m above the sea surface), wind stress (τ) and drag coefficient (C_D) can be derived from SAR image.

2 Model

A reversing model for wind stress and drag coefficient retrieval with the data measured by spaceborne SAR is developed based on SAR imaging mechanism of ocean surface capillary waves and short gravity waves. The model consists of I-σ^0 equation, σ^0-U_{10} equation, and U_{10}-τ, C_D equation.

The procedure to calculate σ^0 from I is called radiometric calibration. A large number of experiments and theoretical research show that the relationship between σ^0 and I for Radarsat SAR image is as follows[1)]:

$$\sigma_j^0 = 10\lg[(I_j^2 + A_{0j})/A_{Gj}] + 10\lg[\sin\theta_j], \tag{2}$$

where subscript j represents each pixel in an SAR image, A_G and A_0 are the scaling gain and offset respectively; their values can be found in the header files of SAR data. The incidence angle θ is calculated with

$$\theta_j = \cos^{-1}\left[\frac{h^2 - R_j^2 + 2rh}{2R_jr}\right], \tag{3}$$

where r is the radius of the earth, h the height of satellite platform, and R the slant range.

There are many formulations for calculating U_{10} from σ^0. In this paper, we use CMOD-IFR2 model, which is originally developed for reversing wind speed retrieval from C band VV polarization scatterometer. Using this formulation and Kirchhoff polarization correction, U_{10} can be calculated from radiometrically calibrated C band HH polarization SAR image.

The CMOD-IFR2 model is formulated as follows[4]:

$$\sigma^0 = 10\lg\{10^{a+b\sqrt{U_{10}}}[1 + b_1\cos(\phi - \psi) + b_2\cos2(\phi - \psi)]\}, \tag{4}$$

where a and b are polynomials of θ; b_1 and b_2 the polynomials of U_{10} and θ; ψ is the azimuth angle of radar antenna, and ϕ the wind direction which can be obtained from two-dimensional low wave number spectrum of wind streaks in SAR image[2)].

1) Shepherd, N. Extraction of beta naught and sigma naught from Radarsat CDPF products. Report No. AS97-5001, ALTRIX Systems, 22 May, 1998.

2) Yang, J. S. et al. Coastal ocean surface wind retrieval from SAR imagery. Journal of Remote Sensing (in Chinese), accepted.

Kirchhoff polarization correction is done according to[5]:

$$\sigma^0 = \sigma^0_H + 10\lg\left[\frac{(1 + tg^2\theta)^2}{(1 + 2tg^2\theta)^2}\right], \tag{5}$$

where σ^0_H is the normalized radar cross section of the HH polarized SAR image.

When the temperature difference between the air and the sea is small, the atmosphere is in a neutral stratified or nearly neutral stratified condition. In this case, C_D is related to U_{10} according to the theory of marine atmospheric boundary layer and can be expressed as an empirical formula[6]:

$$C_D = 4.4 \times 10^{-4} U_{10}^{0.55}. \tag{6}$$

The wind stress on the sea surface is given by[6]

$$\tau = \rho u_*^2 = \rho C_D U_{10}^2, \tag{7}$$

where $\rho = 1.225$ kg/m^3 is the air density and u_* the friction velocity.

3 Data

The image used in this study (Fig. 1) is from Radarsat SAR. It was acquired at 6:33 on Feb. 16, 1997. The image covers the south coastal area of Hainan Province with its center at 18.27°N, 109.91°E. The covered area of the image is about 100 km × 100 km, and one pixel corresponds to 12.5 m × 12.5 m.

4 Result and discussion

We choose 10 points (shown as a ~ j in Fig. 1) for calculation. The horizontal and vertical distances between two points are about 20 km. The calculated values of U_{10}, C_D and τ from the SAR image using the model given in this paper are listed in Table 1. The wind speed on the sea surface (U_{10}^*) reported by Hangzhou Meteorological Office, and the correspondingly calculated drag coefficient (C_D^*) and wind stress (τ^*) of these positions are also listed in Table 1. The root-mean-square errors of U_{10}, C_D and τ with respect to U_{10}^*, C_D^* and τ^* are 0.94 m/s, 0.08×10^{-3} and 0.05 N/m^2 respectively, which show that the calculated U_{10}, C_D and τ from the SAR image using our model are in good agreement with the traditional measurements.

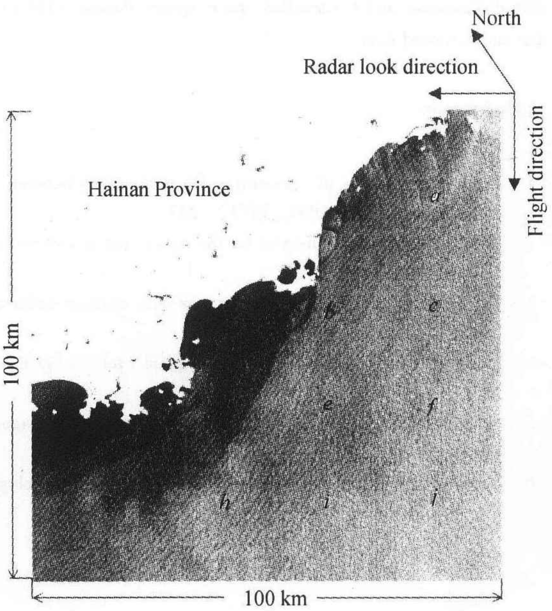

Fig. 1 Radarsat SAR image of the area on the south of Hainan Province.

Table 1 Values of U_{10}^*, U_{10}, C_D^*, C_D, τ^* and τ at different positions

Position	U_{10}^*/ms^{-1}	U_{10}/ms^{-1}	$C_D^*/\times 10^{-3}$	$C_D/\times 10^{-3}$	τ^*/Nm^{-2}	τ/Nm^{-2}
a	8.53	8.11	1.43	1.39	0.13	0.11
b	8.01	7.91	1.38	1.37	0.11	0.11
c	10.06	11.08	1.57	1.65	0.19	0.25
d	7.60	7.58	1.34	1.34	0.10	0.09
e	12.00	12.58	1.72	1.77	0.30	0.34
f	13.21	12.80	1.82	1.78	0.39	0.36
g	8.97	7.47	1.47	1.33	0.15	0.09
h	10.05	11.65	1.57	1.70	0.19	0.28
i	13.03	11.77	1.81	1.71	0.38	0.29
j	11.88	12.75	1.72	1.78	0.30	0.36

In the numerical simulation of ocean and atmospheric dynamics, it is usually assumed that C_D is constant (for example, $C_D = 1.5 \times 10^{-3}$) due to the lack of measurements[6]. This situation can be changed by utilizing SAR remote sensing. Parameter τ is one of the driving forces of ocean currents, whose calculated accuracy is very important for the study of ocean and atmospheric dynamics. The wind speed on the sea surface, the drag coefficient and the wind stress retrieved from SAR imagery can have a spatial resolution of 100 m × 100 m although a 20 km × 20 km grid has been chosen in this study. These parameters retrieved with different spatial resolution can be used in all the realms of ocean and atmospheric dynamics on different scales.

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