Doppler Algorithm for Modeling Sea Surface Current from RADARSAT-1 SAR Images

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Summary

This work introduces a new approach for modeling sea surface current from microwave satellite RADARSAT-1 SAR images. The Doppler shift frequency model was modified by using robust model. The modified Doppler shift frequency model was experienced on the RADARSAT-1 SAR data of two different modes (Wide-3 and Standard 2). The results of the study were validated using real time ocean current measurements by using AWAC equipment. It is interesting to find that the Doppler shift frequency affected the pattern of current variations in the SAR images. The statically analysis showed that there was a high correlation between real ocean current measurements and ones was simulated from SAR images.

Keywords:

SAR, Doppler shift frequency model, Robust model, Surface current.

1.Introduction

Synthetic aperture radar (SAR) has unique capability of imaging sea surface under all weather and lighting conditions. Nevertheless, it is barley to estimate the surface current velocity in the SAR image due to the impact of the Doppler frequency shift along track direction. This major problem requires modulation procedures which can be estimated only under certain circumstances. Three modulation mechanisms are involved with SAR data analysis to estimate sea surface current from SAR image. These are tilt, hydrodynamic and velocity. In spite of sensing of ocean current by SAR is barley, the current variations are imaged through energy transfer toward the waves.

Inglanda and Garello [5] stated that the energy transfer between the current gradients and the waves is described by the action balance equation (ABE) which gives the nonlinear relationship between the surface current and the perturbation of the wave spectrum from its equilibrium. Further, several studies have been conducted to solve the action balance equation by numerical methods to compute the normalized radar cross section (NRCS) of sea surface roughness, then utilizing modulation model to retrieve surface current. The linearization of ABE, however, produces a weak linear hydrodynamic modulation which is involved the problem of the relaxation rate or wave growth. In this context, Ingland and Garello [4] have used Volterra series expansion to explicit the non-linear relationship between the surface current and the SAR image pixel intensity. With Volterra model they can compute the energy contained in the different orders (linear, quadratic and higher) and by using inverse of Volterra model, the sea surface current can be estimated. In this paper we address the question of the impact of tidal force in inducing ocean current movement. According to Wrytki [10], Maged [6], Maged and Mazlan [7], the South China Sea is characterized by peak tidal currents commonly in excess o 1.6 m/s [6, 7]. This can indicate that ABE model can not be used to extract sea surface current movement in the South China Sea. The main question that we address in this paper is how the robust model can be used to improve the model of Doppler frequency shift for estimating sea surface current from different RADARSAT-1 SAR modes i.e., Wide-3 and Standard-2 modes. Three hypothesis examined are: (i) Doppler spectra model can be used to estimate sea surface current variation using C_{HH} band of RADARSAT-1 SAR, (ii) sea surface current can be estimated from different RADARSAT-1 SAR modes; (iii) the robust model is providing accurate estimation of sea surface current from RADARSAT-1 SAR data.

2. Data Set

RADARSAT-1 SAR imaging modes include Standard, Fine, Wide, Extended, and ScanSAR modes. In Standard

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Manuscript received May 5, 2008
Manuscript revised May 20, 2008

mode, seven beam configurations are possible with at least a 10% overlap between adjacent swaths. Wide mode is supported by wider antenna beam widths at large incident angles which results in reduced resolution. The Extended modes are obtained with small incident angles in the near range and large incident angles in the far range. Both Wide and Extended modes are designed with 3% swath overlap. Further, SAR data acquired in this study were derived from the RADARSAT-1 images that involve Wide beam mode (W3) and Standard beam mode (S2) images, respectively. Both images are C-band and have a lower signal-to noise ratio due to their HH polarization with a wavelength of 5.6 cm and a frequency of 5.3 GHz. In situ measurements are collected during RADARSAT-1 SAR passed over the study area. Acoustic Wave and Current (AWAC) equipment used to collect real time sea surface current speed and direction. Further details on suing AWAC for wave and current measurements can be found in AWAC [2].

3. Robust Model

3.1 Doppler Spectra Model

According Hassel man [4] SAR utilizes the Doppler shift of the complex received field to locate scatterers in the flight direction. This complex field and its associated residual Doppler shift can be used to infer the velocity of these scatterers as advected by ocean currents. The analysis method to extract ocean currents by using the Doppler spectral shift is given in details. The analysis method is useful in inferring ocean currents from the RADARSAT-1 SAR Wide-3 and Standard-2 modes. The spectral density is a response from infinitesimal point scatterers. A closed form solution can be given for the Doppler spectral density as the following expression [3]:

$$G(x_0,\omega)=H(\omega)e^{i\omega x_0/V}\int_{-\infty}^{\infty}\exp\left[-\frac{2}{T_s^2}\left(1+\left(\frac{T_s}{T}\right)^2-\frac{ibT_s^2}{4}\right)\tau^2 - \frac{4}{T_s}\left(\frac{x_0}{VT_s}+i\frac{\omega' T_s}{4}\right)\tau-\frac{2x_0{}^2}{V^2T_s{}^2}\right]d\tau \qquad (1)$$

where x_0 is the location of a point target in the SAR image. T_s is the Gaussian function with width, V is the satellite velocity = 6212m/s, τ is the delay time = $t - x_0/V$ and $x_0 = vt$, and b is the chirp rate $= 2kv^2/R$. Equation (1) has been solved to determine the spectral magnitude. Image intensity related to spectral magnitude to find out the radial current velocity. Equation (1) equivalents to the following equation

$$G(x_0,\omega)=H(\omega)\exp\left[\frac{i\omega x_0}{V}-\frac{2x_0{}^2}{V^2T_s^2}\right]\cdot\int_{-\infty}^{\infty}\left[-\frac{2}{T_s^2}\left(1+\left(\frac{T_s}{T}\right)^2-\frac{ibT_s^2}{4}\right)\tau^2 - \frac{4}{T_s}\left(\frac{x_0}{VT_s}+i\frac{\omega' T_s}{4}\right)\tau\right]d\tau \qquad (2)$$

Following Gonzalez *et al.*, [3], the Doppler spectral density which is

$$|G(x_0,\omega)|^2 \cong \frac{4\pi^2}{b^2}\exp\left[-\left(\frac{2}{bT_h}\right)^2\omega^2\right] \exp\left[-\left(\frac{2}{bT}\right)^2(\omega-\omega_d)^2\right] \exp\left[-\left(\frac{2}{bT}\right)^2\left(\omega-\omega_d-\frac{bx_0}{V}\right)^2\right] \qquad (3)$$

where the approximation $(bT^2/4)$, $(bT_h{}^2/4)$, and $(bT_s{}^2/4)$ > 1 have been assumed to simplify this expression. This assumption, large time-bandwidth products, is reasonable for most radar and processor characteristics.

According to Hasselmann [4], the position of the Doppler spectral density peak, $\omega_{\max}$ can be described as

$$\omega_{\max} = \frac{\omega_d\left(1+(T_s/T)^2\right)+b(x_0/V)}{1+(T_s/T)^2+(T_s/T_h)^2} \qquad (4)$$

Or in the terms of system bandwidths

$$\omega_{\max} = \frac{\omega_d\left(1+(\Delta\omega_s/\Delta\omega_a)^2\right)+b(x_0/V)}{1+(\Delta\omega_s/\Delta\omega_a)^2+(\Delta\omega_s/\Delta\omega_h)^2} \qquad (5)$$

where the $\Delta\omega_a$ is the received signal azimuthally bandwidth $= bT$, $\Delta\omega_h$ is the processor bandwidth $= bT_h$, and $\Delta\omega_s$ is the laser weighting bandwidth [9].

The RADARSAT-1 SAR ocean current values have been converted to the horizontal ocean current V_c on the ocean surface. The radial component of ocean current deduced from RADARSAT-1 SAR images is given in terms of the Doppler peak frequency shift, $f_{\max}$ therefore the horizontal ocean current is

$$V_c = \frac{2}{N}\left[\frac{\lambda V\left(1+\Delta f_a/\Delta f_h\right)^2}{2\rho_a \sin\theta \sin\Phi}\right]\left(\Delta f_a\right)^{-1} \tag{6}$$

$\Delta f_a = \left(\Delta\omega_a/2\pi\right)$ and $\Delta f_h = \left(\Delta\omega_h/2\pi\right)$ have been used to compute the frequency. The received signal bandwidth of RADARSAT-1 C-band for the Standard 2 has been used in to retrieve sea surface current.

3.2 Robust Doppler Model for Current Speed and Direction Estimation

Following Rufench et al. [9] the RADARSAT-1 SAR ocean current values must be converted from radial component U_r to the horizontal ocean component U_c by a given equation:

$$U_c = \frac{c * 0.5\lambda f_D}{\sin\theta \sin\varphi} \tag{7}$$

where θ is the incidence angle of RADARSAT-1 SAR different modes, φ the azimuth angle, *C* is constant value which was determined by using least square method between Real Ocean current and the Doppler Centroid f_D which is function of surface current velocity. The crucial issue can be raised due to the performing of least square method is a lack of robustness. The least squares error function to be minimized is as follows

$$e^2(U_c) = d^{-1}\sum_i w^{-1}(U_i - U_c(f_{DC_i}))^2 \tag{8}$$

where U_i is real measured of surface current by using AWAC equipment, *i* is number of observation, w is a weight that is assigned to each respective observation, *d* are the number of degrees of freedom and U_c is the surface current which is function of Doppler Centroid (f_{DC}). The robust standard deviation $\hat{\sigma}$ is estimated by combination of least median of squares (LMedS) method with weighted least squares procedure can be expressed as

$$\hat{\sigma} = 1.5\{1+5/n-p\}med\sqrt{r_i^{\,2}} \tag{9}$$

where r_i is the residual value, med is median absolute deviation of residual value and the factor 1.4826 is for consistent estimation in the presence of Gaussian noise, and the term 5/(n-p) is recommended as a finite sample correction. Then, the parameters can be estimated by solving the weighted least squares problem,

$$\min\sum_i w(r_i)r_i^{\,2} \tag{10}$$

Following Maged and Mazlan [7] the quasi-linear transform of tidal current (*V*) can be given as

$$V = h\{U_c;\min\sum_i w(r_i)r_i^{\,2};W\} \tag{11}$$

where *h* represents the linear operator, which is the tidal current-RADARSAT-1 SAR transform. *W* represents parameters of the tidal current-RADARSAT-1 SAR map, which readily based on the physical conditions of current pattern movements (i.e. velocities and direction) and RADARSAT-1 SAR properties such as Doppler frequency shift.

The main problem in simulating current direction is SAR imaged current in range direction. The simulation of ocean current direction was adopted from the study of Martin [8]. According to Maged and Mazlan [7], the tidal current has two components which are in azimuth and range directions. In this study the edge of frontal zone area is chosen and then divided to sequences kernel windows with frame size of *n x n*. In fact, the frontal zone pixels in SAR data consists of several adjoining pixels which have highest signal amplitude than the surrounding pixels. Then, the Doppler spectrum of range compressed RADARSAT-1 SAR data was estimated by performing a Fast Fourier transform (FFT) in the azimuth direction. Further details of this approach are in Maged and Mazlan [7]. The current speed direction Θ can be given by

$$\Theta = \tan^{-1}\left[\frac{(\lambda f_D)(2\sin\theta)^{-1}}{v_s(1-(1-2\Delta x\partial x v_s)^{-0.5}(\Delta f_D R\lambda)^{-1}}\right] \tag{12}$$

where v_s is satellite velocity, R is slant range, Δx is the displacement vector and ∂x is the pixel spacing in the azimuth direction.

4. Results and Discussion

Fig. 1 shows the simulated sea surface current from RADARSAT-1 SAR W3 and S2 mode data. It notices that the current arrows coincided with the grey level variation in both modes. Fig.1b shows that the arrows disappeared totally in dark patch areas due to the absent of backscatter. This attributed to signal backscatter away from RADARSAT-1 SAR sensor. These results aggress with Alpers [1]. According to Maged and Mazlan [7], the dark patch areas in SAR data could be due to the present of oil spill, look-alike and wind low zone. The pattern of dark patch in Fig.1b might be corresponded to the existence of low wind zone [1 &7]. Further, it is obvious that the vertical area of stripping noise has affected the estimation of sea surface current from W3 beam mode data. This stripping appears as most brightness area in W3 mode data. This result confirms the study of Martin [8]. Both mode shows the northerly current pattern moved parallel to coastline with maximum current velocity values of 0.2 ms^{-1} and 0.6 ms^{-1} which were occurred in W3 and S2 mode data, respectively. This study confirms the result of Maged [6] and Wrytki [11].

Fig.2 shows the spectra of Doppler frequency shift was used to simulate the sea surface current from both mode data. Both modes show that the spectra peak of Doppler was more shifted towards the azimuth direction due to the effect of the nonlinearity between SAR pulse and sea surface current movements. This confirms studies of [3&7&9]. The maximum spectra peak of 0.04 occurs in S2 mode data. This spectrum shows strong shift towards the azimuth direction whereas the spectra peak of Doppler frequency shifted towards the range direction in W3 mode data. This is attributed to the strong current occurrence during S2 overpass which leads to strong nonlinearity as compared to W3 mode data. According to Hassel man et al., [4] the maximum shift along azimuth direction is due to strong nonlinearity occurred between radar signal and surface orbital velocity which can be called as velocity bunching effect. These concepts aggress with studies of [5&6&7].

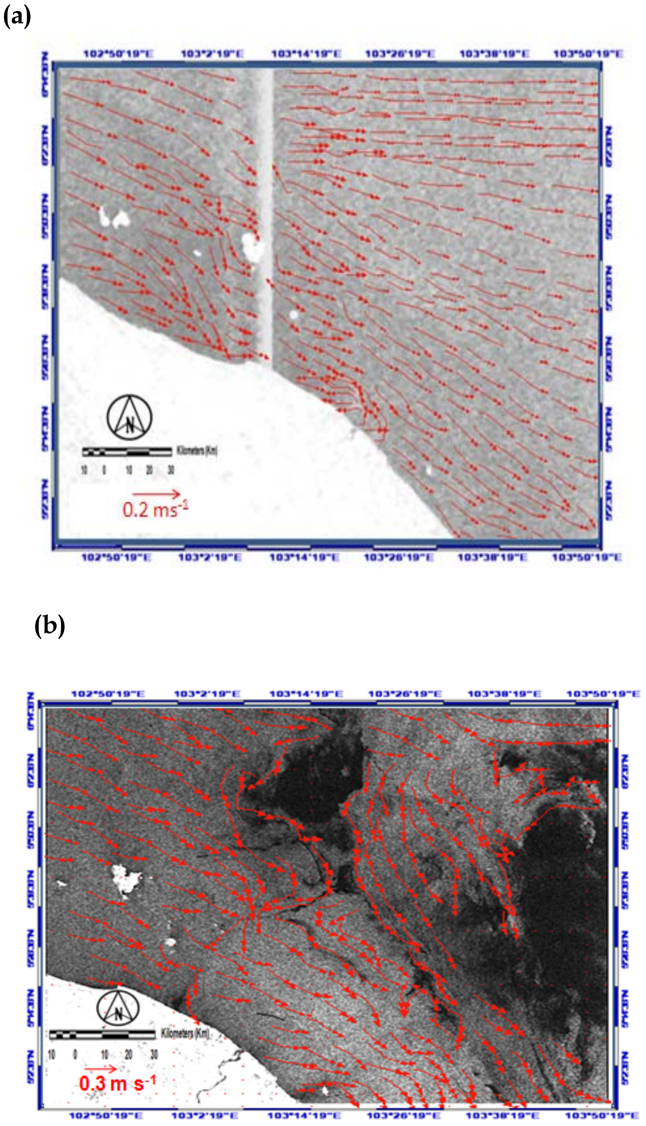

Fig.1. Sea Surface Current Direction Extracted from RADARSAT-1 SAR (a) Wide-3 and (b) Standard-2 mode data.

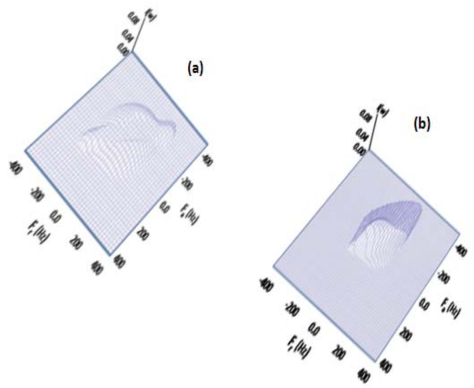

Fig.2. Doppler Spectra Extracted from RADARSAT-1 SAR (a) Wide-3 and (b) Standard-2 mode data.

Figure 3 shows the regression analysis was used to establish the coefficient of determination between the velocities extracted from RADARSAT-1 SAR data and the AWAC in situ measurements. In Standard 2 beam data, a fairly high correlation of r² of 0.63 with the highest velocity of 0.75 ms^{-1} and lowest standard error of 0.11 ms^{-1} as compared to Wide 3 beam data. This could be attributed to impact of physical sea surface roughness on backscatter pattern variations in SAR images which allows the standard 2 beam data to detect the sea surface current features. This confirms the studies of Alpers et al. [1], Hasselmann et al. [4] and Maged and Mazlan [8].

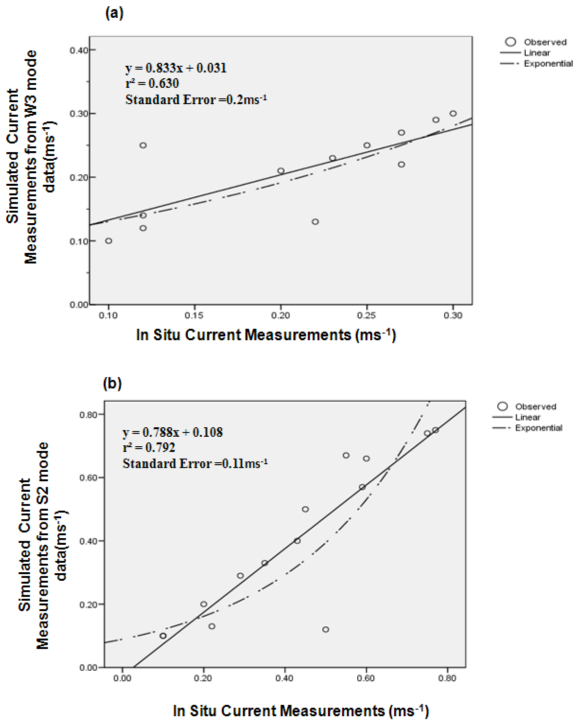

Fig.3. Results of Robust Model for Current Simulation from (a) W3 mode data and (b) S2 mode data

5. Conclusion

This paper has been shown the application of robust model to estimate sea surface current from different RADARSAT-1 SAR different modes. It can be said that the different RADARSAT-1 SAR modes of W3 and S2 are able to detect surface ocean current movement. In conclusion, involving the robust model in sea surface current estimation based on the Doppler Centroid is improving the accuracy modeling of ocean current from RADARSAT-1 SAR data.

5. Acknowledgement

This work is supported by E-science program of Malaysian Ministry of Science (MOSTI) and the assistance of research management center of Universiti Teknologi Malaysia.

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