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Full Length Research Paper

Developing robust model for retrieving sea surface current from RADARSAT-1 SAR satellite data

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This paper introduces a new approach for retrieving sea surface current from RADARSAT-1 SAR standard beam mode (S2) data. In doing so, the robust algorithm that involves the wavelength diversity ambiguity resolving (WDAR) and multi look beat frequency (MLBF) algorithms was used to remove Doppler Centroid ambiguity. The result shows that the proposed robust algorithm can acquire accurate Doppler Centroid and fine spatial sea surface current variations in RADARSAT-1 SAR standard beam mode (S2) data. The current velocities ranged between 0.18 and 0.78 m/s. In conclusion, RADARSAT-1 SAR S2 mode data can be used to retrieve sea surface current with root mean square error (RMSE) of ± 0.11 m/s. Both WDAR and MLBF algorithms can provide accurate information on Doppler Centroid which can acquire accurately sea surface current pattern in RADARRSAT-1 SAR image.

Key words: RADARSAT-1 SAR, robust model, sea surface current, wavelength diversity ambiguity resolving (WDAR) algorithm, multi look beat frequency (MLBF) algorithm.

INTRODUCTION

Mathematical model plays tremendous role for understanding a complicated phenomenon. Indeed, several studies have implemented mathematical algorithms to solve nonlinearity of complex system (Zaki, 2007; Messaoudi et al., 2007; Stephen, 2009; Adeyemo and Fred, 2009; Mehmet, 2009; Ugwu, 2009; Akintorinwa and Adesoji, 2009; Boumaza et al., 2009; Khadijeh et al., 2011; Guillermo et al., 2011). This study attempts to solve the nonlinearity of radar signal and ocean surface current, because of Doppler impact (Inglada and Garello, 2000). This work addresses the question of Doppler Centroid (f_{DC}) ambiguity impact on accurate retrieving of sea surface current in synthetic aperture radar (SAR). Two hypotheses that were evaluated are: (i) accurate Doppler Centroid can be modeled using both wavelength diversity ambiguity resolving (WDAR) and multi look beat frequency (MLBF) algorithms; and (ii) accurately sea surface current speed can be retrieved in SAR satellite data using robust algorithm. Indeed, synthetic aperture radar (SAR) has been recognized as a powerful tool for environmental dynamic studies. Ocean surface current is considered as a major element in marine environment. In fact, the climate change, marine pollution and coastal hazardous are basically controlled by intensity of ocean current (Alpers et al., 1981). The main concept to model sea surface current from SAR images is based on Doppler shift (Chapron et al., 2005). In this context, Doppler shift of the radar signal backscattered from the sea surface occurred by orbital motions of ocean wave and surface currents (Hasselman, 1980). In fact, the surface velocity relative to the SAR, or equivalently the Doppler shift, relies on the antenna view angle relative to the trajectory (Shemer et al., 1993). Therefore, the Doppler shift can be used to determine the line-of-sight velocity of the scatterers and thus, the surface currents (Alpers et al., 1981). Furthermore, the distribution of the line-of-sight velocity of the scatterers is associated with the Doppler spectrum within the radar resolution cell (Romeiser et al., 2003). A wide range of mathematically and physically based models, however, have been developed to convert a surface Doppler velocity to be of geophysical origin. Although, various analytical models have been developed which describe overall effects of sea surface roughness on the Doppler signal mechanisms, such approaches are limited in the complexity of the sea surface current estimation that can be used. In azimuth direction, the resolution of the sea surface doppler velocity is typically coarser as compared to the normalized radar cross section image (Chapron et al., 2005). In fact Doppler frequency Centroid must be estimated from Doppler spectrum (Shemer et al., 1993). The general geophysical interpretation of surface Doppler velocity is however imperfectly established. For instance, Shemer et al. (1993) reported that the surface drift current is significantly different from the surface Doppler velocity. In contrast, Romeiser et al. (2003) stated that a surface Doppler velocity is well correlated with surface currents with strong geostrophic or tidal currents, because the imaging mechanism of ocean surface current gradients by SAR is complicated due to its nonlinearity. This makes it a difficult task to retrieve sea surface current information using a surface Doppler velocity (Chapron et al., 2005). According to Inglanda and Garello (1999), the wave-current interaction and velocity bunching effects are the main sources of nonlinearity in the imaging mechanism of ocean surface current by SAR. This impact is known as the tilt bias. Romeiser and Thompson (2000), however, have implemented theoretical linear modulation transfer function to express 'a' to solve the problem of tilt bias in order to estimate sea surface Doppler velocity. In this context, Chapron et al. (2005) have commanded that the exact shape of the high-frequency spectrum and poor knowledge of linear modulation transfer function are perhaps the main sources in uncertainty for this model. Moreover, they used quantitative forward model which is based on a practical two-scale decomposition of the surface geometry and kinematics where the wind impacts through the wave spectrum is considered. The authors have expressed this contribution as an amplified stokes drift with a gain factor controlled by relative modulation of radar cross section with incident angles. Furthermore, Chapron et al. (2005) have acquired a surface Doppler velocity by using an average over the random wave phases. In this context, the Doppler Centroid frequency was anomaly divided by the electromagnetic wave number assuming that Doppler Centroid frequency anomaly is a simple geometrical mean weighted by normalized radar section of each element. Romiser and Thompson (2000), nevertheless stated that when Doppler Centroid estimators are applied to SAR data, biased estimates are often obtained, because of anomalies in the received data. Typical anomalies include areas of low signal-to noise ratio (SNR), strong discrete targets and radiometric discontinuities. Incidentally, this study extends the pervious theory of Doppler Centroid (f_{DC}) (Gonzalez et al., 1981; Romiser and Thompson 2000; Chapron et al., 2005) by implementing robust formula (Marghany and Mazlan, 2009). In the previous study of Marghany and Mazlan (2009), the robust algorithm provided R^2 of 0.79 between *in situ* measurements and sea surface current that were retrieved by robust algorithm. The contribution of this work is to implement both WDAR and MLBF algorithms to acquire accurate sea surface current pattern from RADARSAT-1 SAR beam mode data that is the standard beam mode (S2).

METHODOLOGY

Study area

The study area is situated in the South China sea between 5°21' N to 5°25' N, East coast of Peninsular Malaysia (Figure 1). Consistent with Marghany et al. (2009), there are four seasons: the two Monsoons and the two transitional Inter-Monsoon periods. The Monsoon winds and tidal effects (Marghany et al., 2010) affect the seas around Malaysia. The winds during the Northeast Monsoon are normally stronger than the Southwest Monsoon (Wrytki, 1961; Zelina et al., 2000). The accompanying waves are with a height that exceeds 3 m (Marghany, 1994). The bathymetry near the area has gentle slopes with 40 m water depth (Figure 1). A clear feature of this area is the primary hydrologic communications between the estuary and the South China sea. As stated by Marghany et al. (2010), this estuary is the largest estuary along the Terengganu coastline.

Data set

The SAR data acquired in this study are derived from RADARSAT-1 satellite that involve standard beam mode (S2) image (Figure 2). RADARSAT-1 SAR data are C-band and have a lower signal-to-noise due to their HH-polarization with a wavelength of 6.6 cm and frequency of 5.3 GHz. RADARSAT-1 SAR S2 mode data have 3.1 looks and cover an incidence angle of 23.7° and 31.0° (RADARSAT, 2010; Marghany and Mazlan, 2011). Furthermore, S2 mode data covers a swath width of 100 km and ground range resolution of 25 × 28 m (Table 1).

In situ measurements

Field measurements are performed between 1.00 am to 17.00 pm local time at coastal water of Kuala Terengganu and were carried out in March 29 till March 30, 2005. Vertical current measurements are obtained from acoustic wave and current (AWAC) equipment (Figure 1). The deployment location is at 5°31'16"N and 103°08'40"E in the East coast of Malaysia (Figure 1) where the location is an artificial reef. The deployment water depth was 18.5 m. Two navigation buoys are used as guidance points to ensure the safety of AWAC equipment. The procedures used to calibrate the AWAC involved: a set-up of one burst every half hour that is measured by AWAC, current velocity and direction are measured in bursts of 1024 samples at sampling rate of 1 Hz which are made while the instrument is out of the water (Figure 3). Information retrieved from AWAC is stored as American Standard Code for Information Interchange (ASCII) format that involved current velocity and direction data through the water column of 18.5 m (Marghany and Mazlan, 2010). These data are used to validate the results of the sea surface current patterns which are extracted from RADARSAT-1 SAR data.

Robust model

The term robust estimation means estimation techniques which are robust with respect to the presence of gross errors in the data. In this context, gross errors are defined as observations which do not fit to the stochastic model of parameter estimation (Messaoudi et al., 2007). In this context, uncertainties in the estimation of Doppler

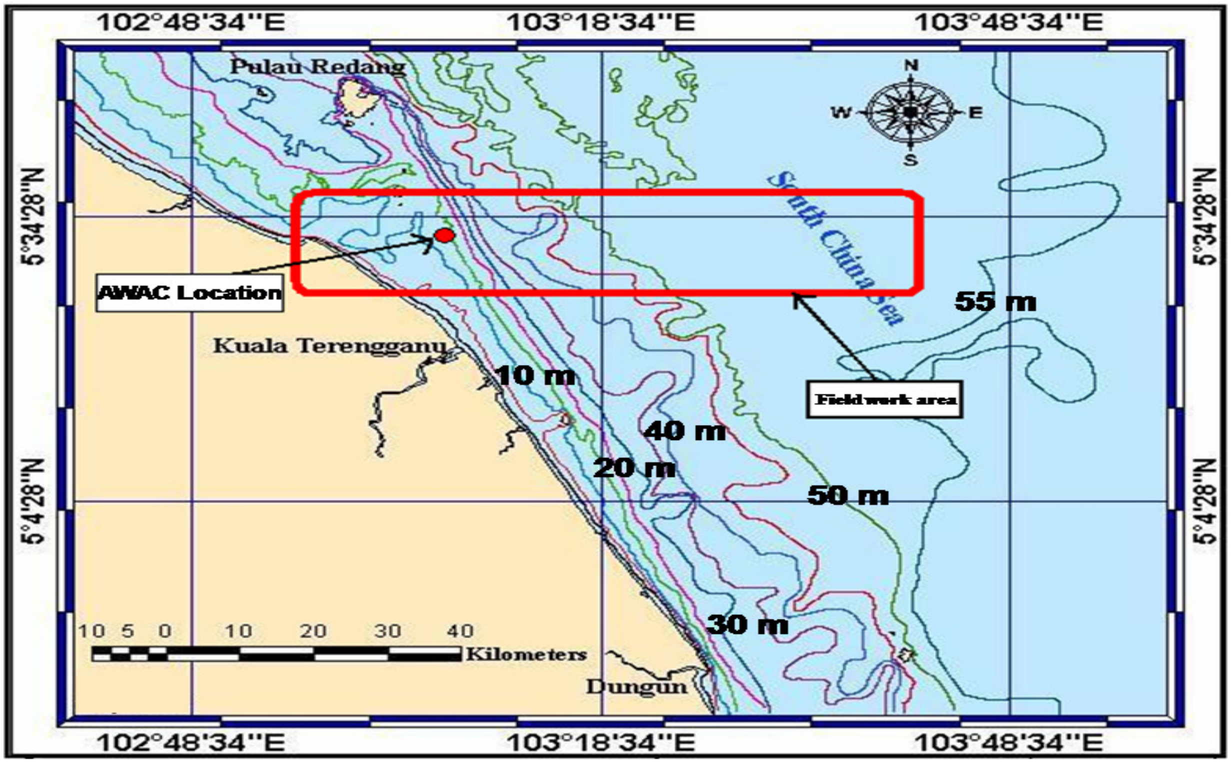

Figure 1. Location of study area and *in situ* measurements by AWAC.

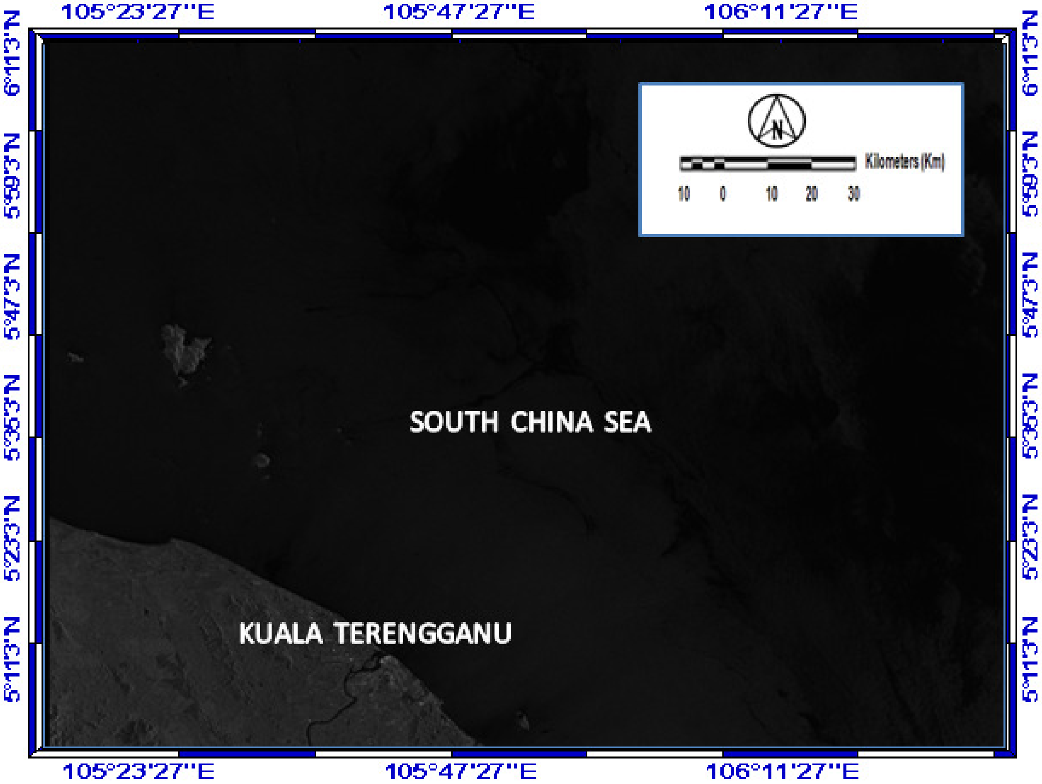

Figure 2. RADARSAT-1 SAR standard beam mode (S2) image.

Table 1. RADARSAT-1 SAR image description.

Start time	Orbit	Beam	Swath area (km)	Incidence angle (°)	Width (km)	Resolution (Range × Azimuth) (m)
03/30/2005 6:57:16 AM	293D	Standard-2 (Descending)	100	23.7-31	100	25 × 28

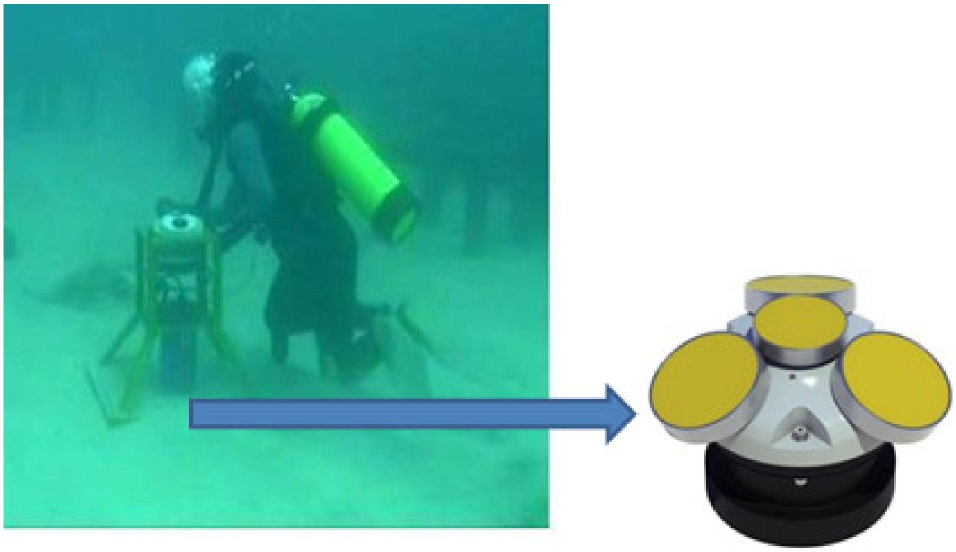

Figure 3. AWAC instrument for current measurement.

centroid frequency can lead to completely false results of sea surface current and might even prevent convergence of adjustment. Robust estimators are estimators which are relatively insensitive to limited variations in the frequency distribution function of the Doppler Centroid frequency f_{DC} . Chapron et al. (2005), however, did not take into account the problems of estimating the Doppler Centroid which might begin from a range-compressed dataset acquired by conventional single pulse repetition frequency (PFR). Stefano and Guarnieri (2003) stated that for efficiency, the constraint of operating on range-compressed data is required. Following Stefano and Guarnieri (2003), the ambiguous estimation and wavelength diversity ambiguity resolving algorithm (WDAR) and multi look beat frequency (MLBF) are implemented to correct f_{DC} ambiguity and to fit a fine polynomial estimate in SAR images. First, the RADARSAT-1 SAR image is divided in several blocks. In each block, both a second order statistic estimator (WDAR) and a higher order technique (MLBF) have been exploited to resolve coarse unambiguous Doppler Centroid. These techniques have been chosen due to the large variation of f_{DC} with range as can be noticed clearly in RADARSAT-1 SAR data. Stefano and Guarnieri (2003) gave polynomial inversion model is as:

$$f_{DC}(a,r) = Xr^2 + Yr + Za + h \qquad (1)$$

where *a* and *r* are range and azimuth indexes of the samples at the center of each block and *X*,*Y*,*Z*, and *h* are the polynomial coefficients to be estimated. Two steps have been required to achieve the polynomial inversion technique: (i) wrapped plane is regressed and (ii) the model then inverted on the residuals (*res*). The selection between both steps is mainly done by means of a threshold on the contrast parameter which is based on the pixel intensity of each block. For instance, unambiguous f_{DC} is computed with WDAR in low contrast blocks as compared to MLBF. Taking into account the value of the ambiguity (*p*) and the polynomial parameters (*X*,*Y*,*Z*,*h*), the unambiguous f_{DC} polynomial can be given by this formula:

$$\hat{f}_{DC}(a,r) = X_{res}r^2 + (Y_p + Y_{res})r + (Z_p + Z_{res})a + (h_p + h_{res}) \qquad (2)$$

Finally, offset frequency is implemented by subtraction of MLBF estimate from WDAR. This is done with an assumption of the ambiguity estimate based on the MLBF technique is correct. Following Rufench et al. (1983), the RADARSAT-1 SAR ocean current values must be converted from radial component V_r to the horizontal ocean component V_c by a given equation:

$$V_c = \frac{c * 0.5\lambda \hat{f}_{DC}(a,r)}{\sin\theta \sin\varphi} \qquad (3)$$

where θ is the incidence angle of RADARSAT-1 SAR different modes, φ the azimuth angle, *c* is the constant value which is determined by using least square method between *in situ* measured ocean current and the Doppler Centroid $\hat{f}_{DC}(a,r)$ which is a function of surface current velocity. The crucial issue that 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 (Gonzalez et al., 1981):

$$e^2(V_c) = d^{-1}\sum_i w^{-1}[V_i - V_c(\hat{f}_{DC_i}(a,r)]^2 \quad (4)$$

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

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

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:

$$\min \sum_i w(r_i)r_i^{\,2} \quad (6)$$

Following Marghany and Mazlan (2005), the quasi-linear transform of tidal current (*V*) can be given as:

$$V = H\{V_c; \min\sum_i w(r_i)r_i^{\,2}; W\} \quad (7)$$

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 is readily based on the physical conditions of current pattern movements (that is, velocities and direction) and RADARSAT-1 SAR properties, such as Doppler frequency shift.

Tidal current direction estimation

The main problem in simulating current direction is SAR imaged current in range direction. According to Marghany and Mazlan (2009), 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 × n.* Due to the fact that the frontal zone consists of several adjoining pixels which must have highest signal amplitude than the surrounding pixels. Then, the Doppler spectrum of range compressed RADARSAT-1 SAR data is estimated by performing a fast Fourier transform (FFT) in the azimuth direction. Marghany and Mazlan (2009) work have further details of this approach. The current speed direction Θ can be given by:

$$\Theta = \tan^{-1}\left[\frac{(\lambda\hat{f}_{DC}(a,r))(2\sin\theta)^{-1}}{v_s(1-(1-2\Delta x\partial x v_s)^{-0.5}(\Delta\hat{f}_{DC}(a,r)R\lambda)^{-1}}\right] \quad (8)$$

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. The robust model is examined with RADARSAT-1 SAR standard-2 mode image which was the acquired area on March 30, 2005.

RESULTS AND DISCUSSION

Figure 4 shows the Doppler velocity retrieved using estimator (WDAR) and a higher order technique (MLBF). The Doppler velocity is ranged between 0 to 0.3 m/s. Obviously, land and low wind zone have zero Doppler rate. It is interesting to find out that the rate of Doppler spatial variation has a positive value among onshore and offshore. Indeed, WDAR and MLBF techniques were exploited to resolve the coarse unambiguity of Doppler centroid. This result confirms the study of Stefano and Guarnieri (2003).

The Doppler spectra ambiguity is as shown in Figure 5a. It can be noticed that the spectra intensity peaks are repeated along azimuth and range directions. Figure 5b, nevertheless, presents neither the Doppler spectra frequency which was clearly positioned along the range direction nor the azimuth direction. The Doppler spectra are characterized by spectra intensity of 0.025 and band width of 50 Hz. In fact the robust estimators, WDAR and MLBF are estimators which are relatively insensitive to limited variations in the frequency distribution function of the Doppler Centroid frequency f_{DC}. Furthermore, both algorithms are capable of retrieving the correct Doppler Centroid ambiguity and to fit a fine polynomial estimate both on uniform and contrasted scenes (Stefano and Guarnieri, 2003). Clearly, the sharp Doppler spectra peak has existed by using WDAR and MLBF algorithms as compared to the one estimated directly by using conventional algorithm. These results confirm the spatial variation of Doppler speed which is illustrated in Figure 4. Figure 6 shows the sea surface current pattern which is retrieved using robust technique. It is obvious that the current pattern movements are shown clearly. The current velocity exceeds from offshore towards onshore within 0.78 m/s. The northeast current flow is a dominated feature along the coastal water of Kuala Terengganu, Malaysia (Figure 6). Figure 7 shows *in situ* current speed and direction that were acquired by AWAC equipment during S2 mode overpass. The current flows from northeast direction with maximum speed of 0.68 m/s. This mainly confirms the result in Figure 6. Both *in situ* measurement and retrieved current pattern confirm these studies (Wrytki, 1961; Zelina et al., 2000; Marghany, 2009; Marghany and Mazlan, 2011).

It was also noticed that the current deviated from range direction. This confirms the study of Marghany and Mazlan (2006). Figure 8 represents the robust statistical analysis where the R^2 is 0.92 with RMSE of ± 0.11 m/s. This confirms that the robust model of WDAR and MLBF

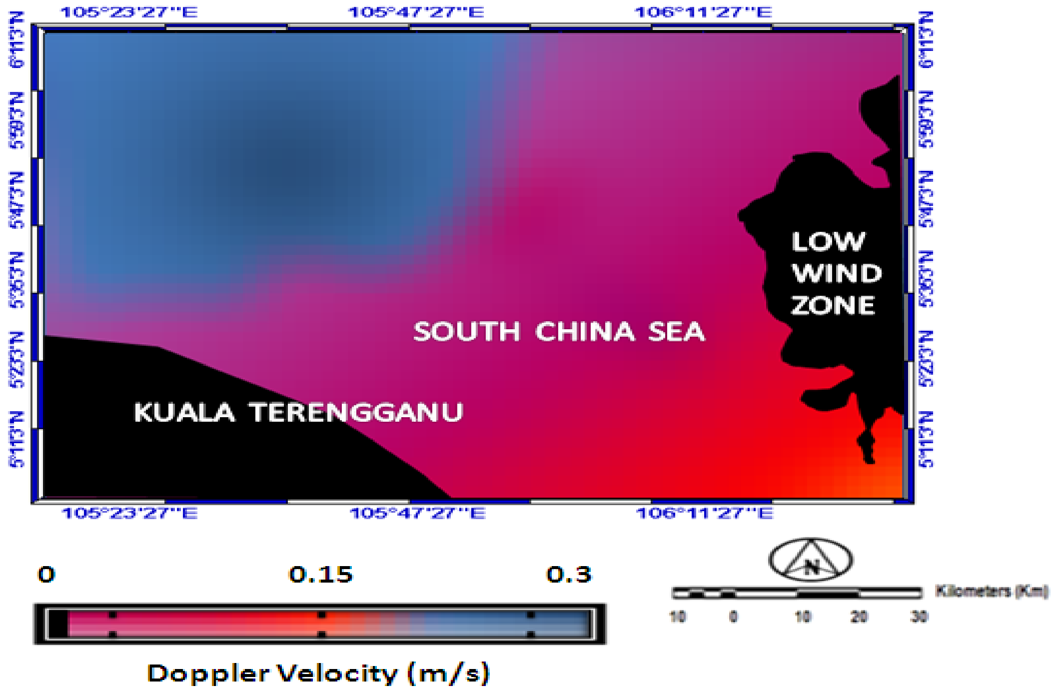

Figure 4. Doppler velocity retrieved using WDAR and MLBF techniques.

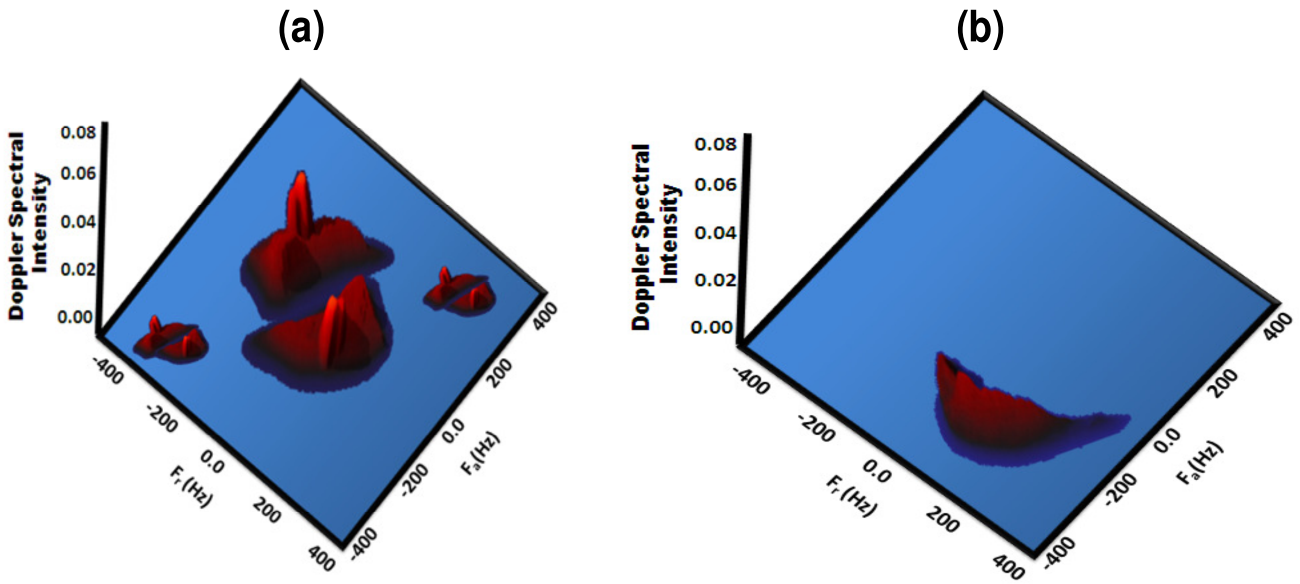

Figure 5. Doppler spectra intensity (a) conventional algorithm and (b) robust estimator WDAR and MLBF.

techniques produce accurate pattern of sea surface current from RADARSAT-1 SAR S2 mode data.

The computational efficiency of sea surface current from S2 mode data, therefore, is improved and fit for real-time processing. In general, SAR ocean current modeling based on Doppler Centroid analyses, through future research perhaps can provide more accurate and less ambiguity of sea surface current flows in SAR data. This confirms the result of these studies (Marghany, 1994; Marghany and Mazlan, 2009, 2010). In addition, the ambiguous estimate techniques are based on power spectrum estimation. Thus, the ambiguous estimator is the autocorrelation that includes the estimated phase of the first sample of the azimuth autocorrelation. Indeed,

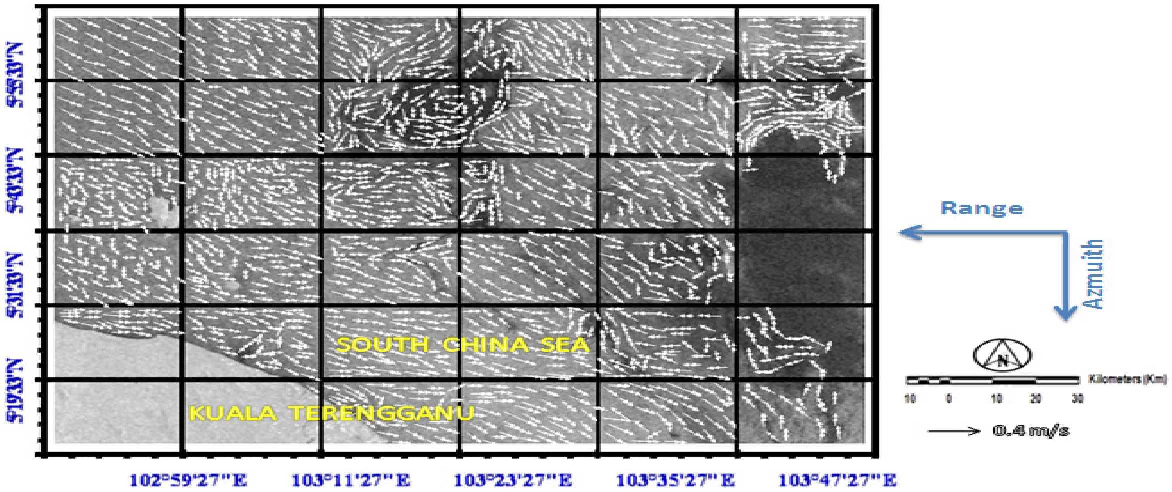

Figure 6. Sea surface current simulated by using robust estimators for Doppler Centroid.

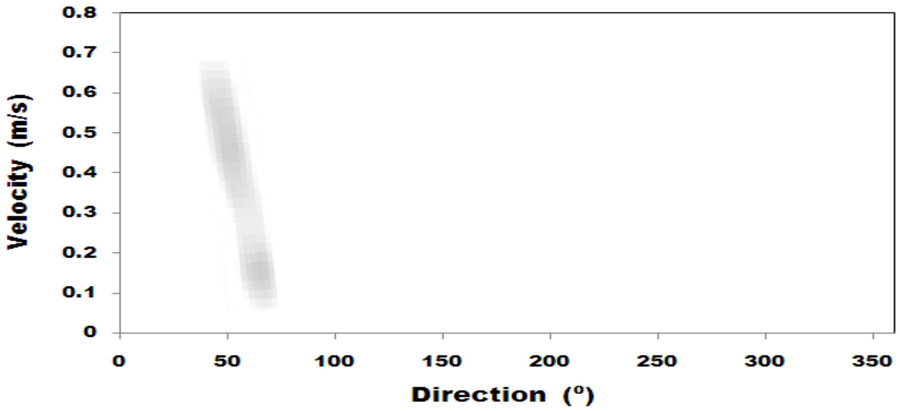

Figure 7. *In situ* current direction and speed.

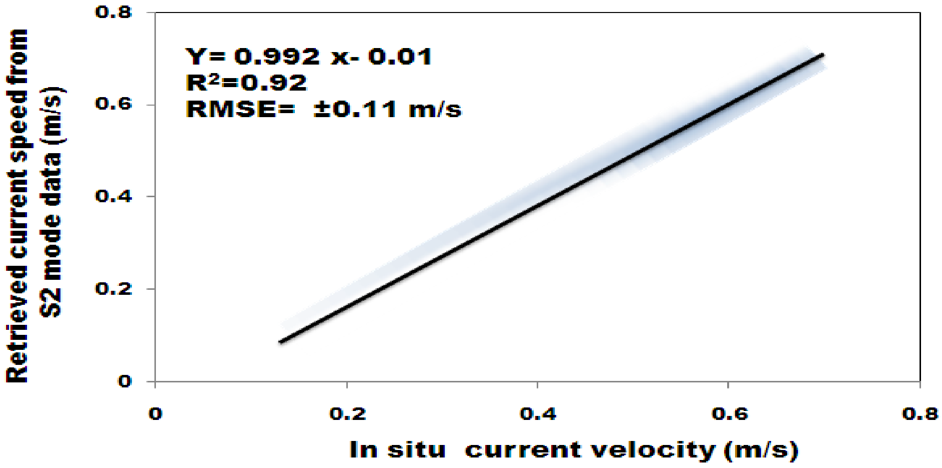

Figure 8. Regression model of surface current estimated from in situ measurements by AWAC and robust model.

this estimator is implemented with an offset frequency.

In general, the robust algorithm can retrieve the exact Doppler centroid uncertainty using polynomial estimator. In each block, consequently, a coarse unambiguous estimator is provided by utilizing both a second order statistic estimator (WDAR) and a higher order technique (MLBF). Weighted average of block measures provides accurate confidence of the robust estimator. This helps to estimate and calibrate the offset frequency constant. Incidentally, WDAR is less sensitive to the offset frequency than MLBF. This confirms the previous work of Stefano and Guarnieri (2003).

Conclusions

This paper has demonstrated a new approach to retrieve the sea surface current from RADARSAT-1 SAR mode data of standard-2 (S2) mode. In doing so, the wavelength diversity ambiguity resolving (WDAR) and multi look beat frequency (MLBF) algorithms were used to correct the Doppler Centroid ambiguity. The study shows the robust algorithm retrieved accurate sea surface current pattern which ranged between 0.18 and 0.78 m/s. The *in situ* measurement agreed with retrieving sea surface current using robust algorithm with R^2 of 0.92 and RMSE of ± 0.11 ms^{-1}. It can be concluded that the robust model examined with RADARSAT-1SAR standard mode 2 has provided an excellent improvement for extracting ocean surface current from RADARSAT-1 SAR data. The future work will aim to improve the accuracy of modeling surface current in SAR data by applying an appropriate algorithm and using random variation of spatial AWAC measurements.

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