Ocean Surface Current Retrieval Using Doppler Centroid of ERS-1 Raw SAR Data

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Abstract : Extraction of ocean surface current velocity offers important physical oceanographic parameters especially on understanding ocean environment. Although Remote Sensing techniques were highly developed, the investigation of ocean surface current using Synthetic Aperture Radar (SAR) is not an easy task. This paper presents the results of ocean surface current observation using Doppler Centroid of ERS-1 SAR data obtained off the coast of Korea peninsula. We employed the concept, in which Doppler frequency shift and the ocean surface current are closely related, to evaluate ocean surface current. Moving targets cause Doppler frequency shift of the backscattered radar waves of SAR, thus the line-of-sight velocity component of the scatters can be evaluated. The Doppler frequency shift can be measured by estimating the difference between Doppler Centroid of raw SAR data and reference Doppler Centroid. Theoretically, the Doppler Centroid is zero; however, squinted antenna which is affected by several physical factors causes Doppler Centroid to be nonzero. The reference Doppler Centroid can be obtained from measurements of sensor trajectory, attitude and Earth model. The estimated Doppler Centroid was compensated by considering the accurate attitude estimation of ERS-1 SAR. We could verify the correspondence between the estimated ocean surface current and observed in-situ data in the error bound.

Keywords : Doppler Centroid, Raw SAR Data, Ocean Surface Current

I. Introduction

A Synthetic Aperture Radar (SAR) system is an active microwave sensor that used the Doppler shift of the radar echo to synthesize a much longer aperture increasing the spatial resolution attainable in the along-track direction [1]. The range resolution is acquired through accurate time-delay measurements using either extremely short pulses or time-dispersed phase-coded pulses. Space-borne and airborne remote sensing techniques have been developed as the most effective research tools these days for rapidly advancing ocean observation. SAR techniques have been of great interest because of the all weather imaging capability without sunlight and the high spatial resolution of large ocean areas. Along-track SAR interferometry has developed for high resolution current velocity measurements. ATI SAR uses the phase difference between the two antenna phase centers, so it is appropriate for airborne SAR system. For a space-borne SAR system, the Doppler phase shift is adapted to estimate the ocean surface current.

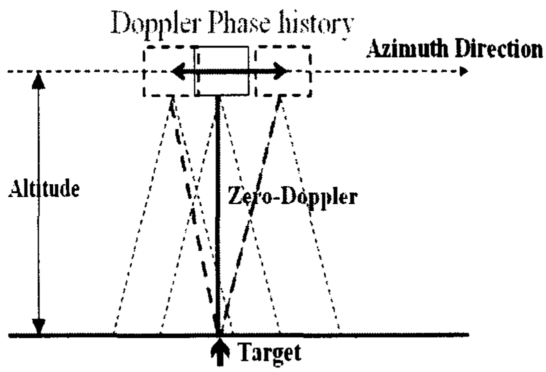
In SAR system, the concept of Doppler Centroid is required to improve the azimuth resolution by recording the Doppler history of the backscattered signals of the individual target as the target traverses the antenna beam [2], [3]. The Doppler frequency rate is deranged by the along-track moving targets mainly, and the cross-track moving targets cause the Doppler Centroid shift, [4].

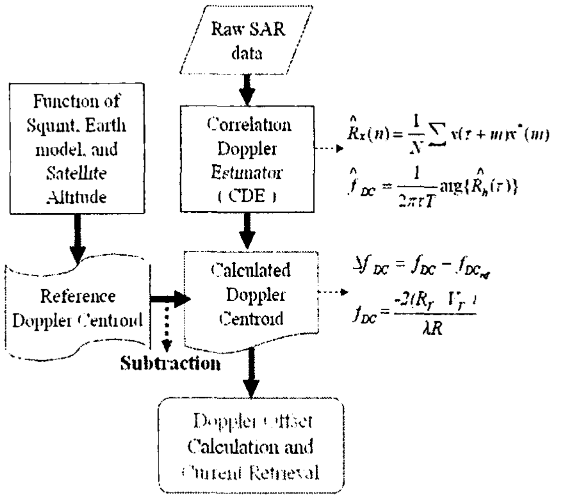
Squinted antenna which is affected by several physical factors makes Doppler Centroid to be nonzero differently from the ideal Doppler Centroid. Theoretically, Doppler Centroid which has nonzero value can be calculated by measuring the sensor trajectory, attitude and earth rotating model. Moving targets cause the extra Doppler frequency shift of the backscattered signals. The Doppler frequency shift can be measured by estimating the difference of Doppler Centroid obtained and reference Doppler Centroid.

Doppler Centroid of raw SAR data was estimated using the Correlation Doppler Estimator (CDE) algorithm, which is well represented in [8]. CDE algorithm extracts Doppler Centroid of raw SAR data in time domain. Time domain estimation of Doppler Centroid is executed by using the relation between a signal power spectrum and correlation function. The reference Doppler Centroid is obtained by using trajectory parameters in terms of satellite orbit, [1]. We estimate the Ocean surface Current in the direction of line-of-sight by obtaining the difference of Doppler Centroid from raw SAR data and reference Doppler Centroid calculated. With an identical conception, ocean surface current can be evaluated by estimating Doppler frequency shift of raw SAR data.

II. Methodology

In SAR system, the significant image is obtained by using the forward motion of the radar. SAR system offers





the improved azimuth resolution by recording and combining the individual reflected signals. The echo signals changes as the sensor is getting closer to the target and passes it away. This change of the reflected signals, the phase history, is explained by Doppler frequency. The temporal rate of change of phase is equivalent to Doppler frequency shift that is caused by relative motion of the platform and the scatter. Mean Doppler Frequency, the Doppler Centroid, is the fundamental operation in RADAR data processing. In Synthetic Aperture Radar system, the Doppler Centroid is used to focus the azimuth direction data processing, [5]. Fig.1. indicates the schematic process of the ocean current retrieval in this study.

1) Estimation of Doppler Centroid from Raw SAR Data

We focused on estimating Doppler Centroid from SAR raw data to evaluate ocean surface current vector. The phase history, $\phi(t)$, of the target can be written as follows

$$\phi(t) = 4\pi \frac{\left|\overline{R_T}(t) - \overline{R_S}(t)\right|}{\lambda} \quad (1)$$

where λ is the wavelength of the radar. $\overline{R_T}$ and $\overline{R_S}$ denote the position vectors of a surface target and of the sensor respectively. The Doppler phase history changes as the sensor moves relative to the target on the surface. The instantaneous Doppler frequency is given by Eq. (2) with two terms, Doppler Centroid, f_{DC} and Doppler frequency rate f_R, Eq. (3).

$$f(t) = -\frac{2}{\lambda}\frac{d}{dt}\left|\overline{R_T}(t) - \overline{R_S}(t)\right| \approx f_{DC} + f_R \quad (2)$$

where

$$f_{DC} = \frac{-2(R_r \cdot V_r)}{\lambda R} \quad \text{and} \quad f_R = \frac{-2(R_r \cdot A - V_r \cdot V_r)}{\lambda R} \quad (3)$$

R_r, V_r and A are the relative position, velocity, and acceleration vectors between the satellite and a surface target.

The relation of the correlation function and power spectrum provides an essential basis for the estimation of Doppler Centroid from raw SAR data. The correlation function and correlation coefficient in the stochastic process are represented as Eq. (4) and (5)

$$R_x(n) = e^{j2\pi\tau f_{DC}} R_0(\tau) \quad (4)$$

$$\hat{R}_x(n) = \frac{1}{N}\sum x(\tau+m)x^*(m) \quad (5)$$

With this concept, the estimator for the Doppler Centroid is represented as Eq. (6)

$$\hat{f}_{DC} = \frac{1}{2\pi\tau T}\arg\{\hat{R}_h(\tau)\} \quad (6)$$

The Doppler Centroid was computed for each pixel and then averaged into significant patch sizes.

2) Estimation of Reference Doppler Centroid

Squinted antenna of the sensor makes Doppler Centroid to be nonzero. Doppler Centroid can be estimated from measurements of sensor altitude, attitude and the earth rotating model. To estimate reference Doppler Centroid more precisely, we exploited the accurate physical model that connects the satellite trajectory, attitude and the earth model to the Doppler Centroid correctly. By compensating ERS-1 attitude and altitude errors, we could obtain reference Doppler Centroid that induced more accurate Doppler shift offset. Attitude accuracy of air-borne SAR can be affected adversely by a squinted angle. The dominant reason of attitude error is that the sensor may yaw, pitch and roll. Squint angle is defined as the beam pointing angle from the zero Doppler direction. Squint angle can be expressed with the pitch and yaw angle of the spacecraft, Eq. (7).

$$f_{DC_{attitude}} = -2 \cdot \frac{V_s}{\lambda}[\sin(\tan^{-1}(\cos\theta_0 \tan\alpha_p - \sin\theta_0 \tan\alpha_y))] \quad (7)$$

Attitude errors due to the squinted beam pointing angle can be partially reduced in ERS-1 system through the yaw steering law. Although the squint error was compensated by yaw steering law of ERS-1 so that ERS-1 has little attitude error comparing to another satellite SAR sensors, Doppler offset cannot be perfectly neglected because of the orbit perturbations. Table.1.which we tested for this study shows that the variation of Doppler offset is extremely sensitive to the yaw error change.

Table. 1. The variation of Doppler offset depending on the yaw and pitch error ranging. Yaw error ranges over 0.0 to 10 degree and pitch error over 0.0 to 0.5 degrees.

Yaw error (degree)	0.0	0.1	0.2	0.3	0.4	0.5
Doppler offset (Hz)	0.0	137.93556	275.87180	413.80954	551.74957	689.69238
YAW error (degree)	1	2	3	4	5	10
Doppler offset (Hz)	1379.4761	2759.6816	4141.3486	5525.2104	6912.0059	13916.313
Pitch error (degree)	0.0	0.1	0.2	0.3	0.4	0.5
Doppler offset (Hz)	0.0	-444.1305	-888.2598	-1332.388	-1776.512	-2220.633

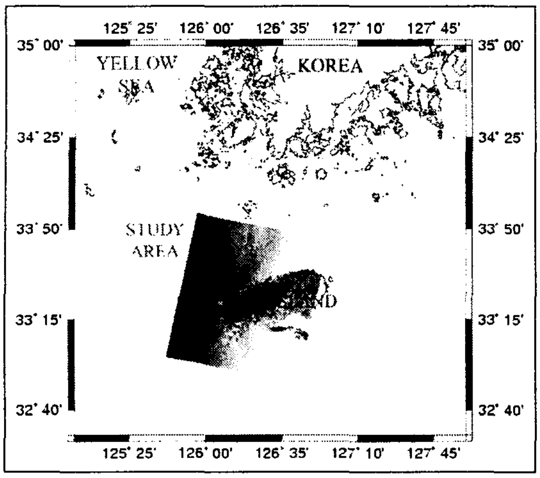


Fig. 3. Study Area. The area around Jeju Island, off the south coast of Korea peninsula, was selected for this

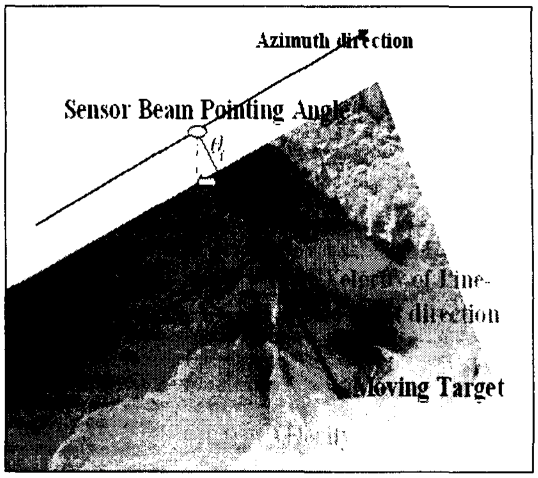


Fig. 4. The Schematic Geometry of the line-of-sight component and the horizontal ocean surface current component

III. Measurements of Sea Surface Currents

1) Test Site and Study Area

Fig.3 depicts the study area, Jeju Island, which was selected for this research. Jeju Island is located off the south coast of Korea peninsula. European Space Agency (ESA) launched ERS-1 C-band SAR in 1991 for Earth Observation. ERS-1 SAR data used for this study was collected on January 01, 1996.

2) Ocean Surface Current Retrieval

The Doppler frequency shift was estimated by eliminating the Doppler Centroid of non-moving targets from Doppler Centroid of raw SAR data. The velocity component of a moving target can be estimated in the direction of line-of-sight component of the cross-track. Ocean surface current velocity was evaluated from the direction of line-of-sight component. Fig.4. indicates the schematic geometry of the line-of-sight component and the horizontal ocean surface current component. The mathematical formula for this geometry can be represented as

$$\Delta f_{DC} = f_{DC} - f_{DC_{ref}} = 2 \cdot \frac{V_{line-of-sight} \sin\theta_i}{\lambda} \tag{10}$$

where Δf_{DC} is Doppler offset which reference Doppler Centroid is subtracted from Doppler Centroid of raw SAR data. θ_i , λ denote target pointing angle and the wavelength of the sensor respectively. Theoretically, on the assumption that the incidence angle is around 23°, the 1m/s ocean current velocity causes about 13.79Hz Doppler frequency shift for ERS-1. Table. 2. manifests variation of the Doppler Centroid according to target velocity in the given radar pointing angles.

Table. 2. Variation of the Doppler Centroid according to target velocity in a given radar pointing angle. Doppler offset is sensitive to the moving target velocity.

$\lvert v \rvert$ *Target velocity (m/s)*	θ_i *Radar pointing angle (deg)*	Δf_{DC} *Doppler Centroid (Hz) caused by a moving target*
0.0	17	0.0
0.5	19	18.6639
1.0	21	37.8052
10.0	23	383.422

IV. Results

Ocean surface current retrieval was performed by using Doppler Centroid of ERS-1 raw SAR data near Jeju Island off Korea peninsula. One can estimate the Doppler frequency shift for the moving target by removing the non-moving target component in SAR image.

To estimate azimuth Doppler spectrum, Correlate Doppler Estimate (CDE) algorithm was executed in time domain. We estimated Doppler Centroid of raw SAR data over each pixel of data covering a whole scene to attain precise accuracy at first, and then averaged each value into 2km by 2km patch sizes. Fig. 5. depicts the primitive Doppler Centroid and fitted Doppler Centroid which were extracted from raw SAR data.

Reference Doppler Centroid should be estimated and fitted to the Doppler Centroid of raw SAR data precisely to estimate the Doppler offset accurately. We used compensated ERS-1 satellite position and velocity vectors within the accuracy that the latitude and longitude coordinates are in 0.1 micro-degree order. Fig. 6. indicates the Doppler offset of Doppler Centroid from SAR raw data and reference Doppler Centroid at a fixed line of the scene. The red line shows the reference Doppler Centroid of the ocean area.

A large of ocean surface current velocity vectors were estimated, which were associated with each location. Doppler frequency offset due to a moving target leads directly to the velocity component of the target. The ocean surface current velocity retrieved through this process varies from 0.001 m/sec up to around 1.6 m/sec depends on the direction and the location.

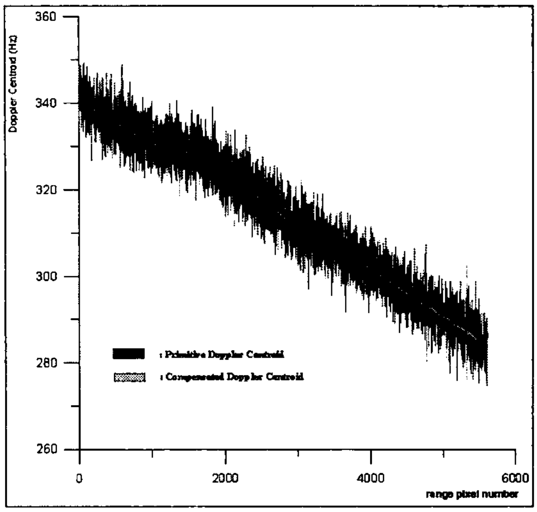


Fig. 5. Primitive Doppler frequency and Doppler Centroid from raw SAR data using CDE(time domain estimation) algorithm. The Doppler Centroid was computed for each pixel and averaged into significant patch size.

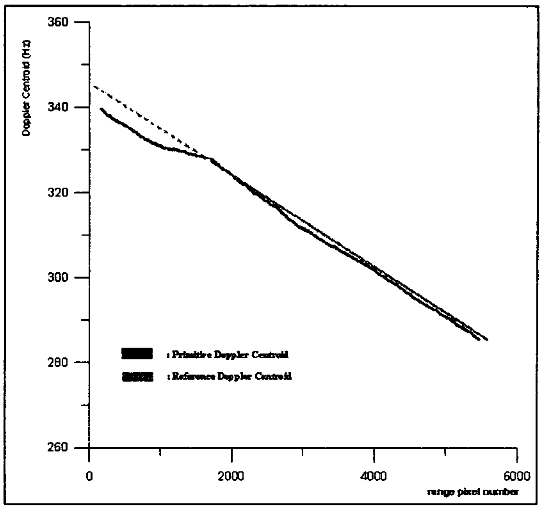


Fig. 6. Doppler offset between Doppler Centroid of raw SAR data and the estimated reference Doppler Centroid at a fixed line of the Image. The red line shows the reference Doppler Centroid over the ocean area.

Doppler analysis will provide less ambiguous and extensive information about ocean surface current features over large area through the improved research. Although it is intricate to extract ocean surface current from raw SAR data, the ocean surface current which was retrieved over large area offers precious information.

In future research, improved approach will be performed to set up reference Doppler Centroid befitting to remove the non-moving terrain from raw SAR.

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