Doppler Centroid Estimation for Ocean Surface Current Retrieval from Sentinel-1 SAR Data

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Abstract — Synthetic aperture radar (SAR) is the most efficient tool to provide high-resolution data for Earth Observation (EO). Doppler centroid (DC) estimation is indispensable for high precision SAR data analysis such as extracting the ocean surface current, which is important for scientific pursuits. Correlation doppler estimation (CDE), and energy balancing (EB) based DC methods are implemented in this paper. A 2-D sliding window is deployed to estimate DC on small blocks of data while covering the whole scene so that all parts of the scene are potentially represented. We analyzed Sentinel-1 single look complex (SLC) data from the coastline of a non-homogeneous scene. The CDE method utilizes the azimuth shift in the time domain which is associated with the DC, and this $f_{Dc}$ history is used to extract ocean surface current. We find the results of DC estimates are confined to primitive baseband ($±PRF/2$). Moreover, the corresponding retrieved ocean surface current component is reasonable, particularly values vary within the limit of error bounds. Finally, the parameters of ocean surface current are compared with ocean wave models reported in the literature. Efficacy and simulation of implemented methods are good fit for Sentinel-1 SAR data.

Keywords — SAR, Doppler Centroid, Ocean Surface Velocity, SNR

I. INTRODUCTION

For more than three decades, synthetic aperture radars (SARs) have been used in a variety of EO applications, including the generation of digital elevation models, the detection of changes in the terrestrial surface, and the monitoring of displacements, including landslides, and infrastructures [1].

The frequency shift in radar back scattered signals is a significant way to acquire information about surface features through appropriate signal processing, including mapping and monitoring of ocean surface currents. Doppler centroids (DC) can be estimated by an azimuth shift in the time domain, whereas surface currents are associated with this DC history [2, 3].

An essential part of SAR processing is the accurate estimation of the DC of the received data. Poor estimates add noise and ambiguity levels in the processed image, sometimes seriously affecting image clarity. The precise DC estimate is difficult because measurements are made solely through geometry, and the received data contains local anomalies that hamper the estimation process. An improper DC could cause SNR loss, a rise in azimuth ambiguity, and loss of a certain set of information (surface current and wind speed) [4, 5].

The DC can be estimated by analyzing the characteristics of the received data. There have been many approaches taken for DC estimation, as evidenced by the references cited [6-8]. The conventional algorithms perform poorly, as inaccurate $f_{Dc}$ causes ambiguous images and degrades resolution due to slow processing. As SNR reduces, the instability of peak power may result in the loss of the target scene’s profile.

In literature the DC estimation algorithms are available, including energy balance, correlation Doppler estimator, and maximum-likelihood estimation. A DC estimate based on energy balancing implemented to avoid the influence of a single frequency. The EB method is based on the assumption that the spectrum distribution is symmetrical [8]. This assumption therefore only applies to a uniform scene or a point target, and when this method applies to a non-homogeneous scene, it causes an intense loss of information, and leads to erroneous information. Typically, to obtain the estimation of the DC, Madsen proposed methods both in the spatial and spectral domains [9].

In the traditional method, geophysical interpretation of $f_{Dc}$ can be calculated from satellite orbit parameters [3].

\[
\begin{align*}
f_{Dc} &= \frac{2V}{\lambda} \sin(\theta) \\
\end{align*}
\]

whereas $\lambda$ is the wavelength of transmitted signal, however, the orbit parameters velocity $V$, and incident angle $\theta$ in practical are usually not accurate enough to get $f_{Dc}$ which fulfills the need of SAR imaging. Therefore, we can estimate the DC from echo data.

The main contribution in this paper is the use of a 2-D sliding window and convolution filter for the estimation of DC based the prevailing algorithms of CDE and EB. Simulations are much more efficient and faster in classical method as compared to the traditional method discussed in the literature. In section-II, we implement two classical methods for DC estimation. Section-III discusses fine parameter estimation including SNR and surface current, whereas results are disclosed in Section-IV, and made comparison with traditional method, while conclusions are stated in Section-V.

II. THE METHODS FOR ESTIMATING DOPPLER CENTROID

The Doppler centroid $f_{Dc}$ can be estimated from the SAR processed data. If the area under observation is stationary, the anormal Doppler shift will be zero. The prevailing algorithms...
to estimate $f_{Dc}$ either by finding the centroid of power spectrum of signal in the azimuth direction i.e., EB [8]; or through the phase of auto correlation function i.e., CDE [9].

A. Doppler Centroid Estimation in Spatial Domain

In this section we implement the algorithm known as correlation Doppler estimator (CDE). DC estimates are estimated over the entire scene with small blocks of data via sliding window. This window moves over the data as a 2-D filter and returns the computed DC information to represent the imagery of the whole scene. The following technique correlates the signals $S(\tau_a, \tau_r)$ with a delayed mean kernel $K_d$ of $[0; 1]$ in azimuth direction:

$$C(\tau_a, \tau_r) = \sum_{\tau_a} S(\tau_a, \tau_r) \times \text{conv}(K_d)$$  \hspace{1cm} (2)

Here $S(\tau_a, \tau_r)$ is the time domain SAR signal, $C$ denotes the correlation calculation of adjacent echo pulses, $\tau_a$ is the azimuth time, and $\tau_r$ corresponds to the range time. The result in (2) is using 2-D convolution filter. The PRF obtained from metadata to extract DC information so that the physical model can be easily fitted. The estimated doppler centroid $f_{Dc}$ based on PRF and cross correlation function is given as:

$$f_{Dc}(\tau_a, \tau_r) = \frac{-PRF}{2\pi} \phi_{acc}(\tau_a, \tau_r)$$  \hspace{1cm} (3)

The phase of cross correlation $\phi_{acc}$ estimated by the mean value of the correlation coefficient in the range direction with a sum mean kernel:

$$\phi_{acc}(\tau_a, \tau_r) = \frac{1}{N} \sum_{k=1}^{N} C(\tau_a, \tau_r_k)$$  \hspace{1cm} (4)

Where $N$ is the average number of cross correlation coefficients.

B. Doppler Centroid Estimation in Spectral Domain

DC is estimated with short sliding windows in azimuth direction and for each range data over the entire scene.

**Step-1** To estimate the $f_{Dc}$ by using energy balancing method, at first, we need to calculate average power spectrum in the azimuth direction:

$$S(n) = \text{mean}([FFT\{S_a\}]^2)$$  \hspace{1cm} (5)

$S_a$ represents the echo data in azimuth direction, and mean is performed in azimuth direction.

**Step-2** To achieve the reference function $R(f)$ and ensure EB is attained, the circular cumulative summation is applied, so that the energy of spectrum equals on both sides:

$$R(f) = \begin{cases} -1, & \text{for } 0 < f < \frac{PRF}{2} \\ +1, & \text{for } \frac{PRF}{2} < f < 0 \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (6)

**Step-3** As $R(f)$ is in the continuous form, circular correlation can be determined as follows:

$$C(n) = \text{IFFT}(FFT(S(n)) \times \text{conj}(R(n)))$$  \hspace{1cm} (7)

**Step-4** Finally, through the circular correlation information, $f_{Dc}$ would be estimated as:

$$f_{Dc} = \frac{N_{DC}}{N} \times \text{PRF}$$  \hspace{1cm} (8)

In above equation $N_{DC}$ is zero crossing point of circular correlation, while $N$ belongs to length of azimuth data.

III. FINE PARAMETERS ESTIMATION AND SURFACE CURRENT RETRIEVAL

To make the algorithm efficient, we deploy short sliding window while moving over the whole scene, so that the full scene is potentially represented. Otherwise, the Doppler spectrum may become blurred, compromising the estimator’s accuracy. Since SAR signals have periodicity, then signal to noise ratio can be calculated from “Harmonic ratio”. By examining SNR, we can ensure estimation accuracy and it can be estimated from the input data:

$$\text{SNR} = 10 \log_{10} \left( \frac{S_1}{S_0} \right)$$  \hspace{1cm} (9)

$S_1$ and $S_0$ are the main-peak and the side-lobe of the data respectively in the azimuth direction. The SNR plays significant role to determine the performance and accuracy of the parameters of interest. When a scene depicted over an ocean, the Doppler frequency becomes a mean quantity. Although it is complex problem to extract the ocean surface current from SAR data, we can measure it by using the line-of-sight component [10-12] and $f_{Dc}$ as given below:

$$V_D = -\frac{\pi}{k_r} \frac{f_{Dc}}{\sin \theta}$$  \hspace{1cm} (10)

Since $\theta$ is incident angle, while wave number $K_r$ can be calculated from the radar frequency as follows:

$$K_r = \frac{2\pi \lambda}{c}$$  \hspace{1cm} (11)

Whereas $\lambda$, and $f_{rad}$ denote the wavelength of the sensor and the radar frequency respectively, $c$ is speed of light, while calculated value of $K_r$ is 113.28 m$^{-1}$ for Sentinel-1.

IV. RESULTS

We use Sentinel-1 SAR data with VH-polarization of Strip-map mode from a coastline. We test data with CDE and give a comparison with EB technique, then retrieve the ocean surface currents based on measured DC history. The deployed scene is from a non-homogeneous location with dynamic ocean waves striking the coastline and moving objects in the ocean water. The fundamental parameters are given in Table-1 and the intensity image of SAR data is shown in Fig.1.

A 2-D sliding window of 64*64 pixels is used to estimate DC with the help of 2-D convolution filter. The estimated DC signatures based on the CDE method shown in Fig.2. The results are confined to the primitive baseband range ($\pm PRF/2$). We can clearly see the land-water border, river water falling into the ocean, a water golf course can be viewed clearly and ocean water is in a dynamic state. The positive values indicate that for the surface is moving toward the satellite.
Table 1. Essential parameters of SAR data.

| Parameters               | Values                                      |
|--------------------------|---------------------------------------------|
| Acquisition date         | April 14, 2021                              |
| PRF                      | 1663.4783 Hz                                |
| Azimuth length           | 6000 pixels                                 |
| Range length             | 6000 pixels                                 |
| Radar frequency \((f_{rad})\) | 5.405 GHz                                  |
| Data type                | Single look complex (SLC)                   |
| Wavelength \((\lambda)\) | 5.55 cm                                     |
| Product type             | Sentinel-1 SM                               |
| Resolution               | 1.7x4.3m to 3.6x4.9 m                      |
| Latitude                 | -23.925 to -24.205 [deg] N-S               |
| Longitude                | -46.128 to -46.331 [deg] E-W               |

DC over homogeneous scene varies with a smaller amount of standard deviation. As compared to EB method CDE provides more accurate DC and less ambiguous imagery as a result. DC signature from EB method is in a good agreement, however, DC values get dominated due to the point targets.

Surface currents are retrieved from DC history, and the range of incident angles. We find the current fluctuates up to 3 m/sec depending on the nature of location. However, (+ and -) signs depend on the DC information. Dynamics of surface current based on the CDE method are shown in Fig.3., and the estimated current is zero for land. These properties from the solution of the EB method are the same but with a regular wavy surface and a number of breaking zones. The implemented CDE approach comprehends the properties of ocean currents and also takes into account information from ocean wave models [10-12].

The SNR biases the Doppler to achieve the centroid. As shown in Fig. 4, the error in DC decreases gradually, and the Doppler shifts towards the center as SNR increases. The mean Doppler deviation from the centroid is less likely the same for CDE and EB with difference of 5Hz, while the traditional method exhibits error to achieve the centroid.

Fig.5. represents the numerical merit comparison of DC for the given two methods. The quantitative comparison of DC derived from CDE against EB methods. The good spatial correlation (of 0.9741) illustrates that both methods observe the same DC. However, for distributed and non-homogeneous scenes, CDE performs very well, and the EB method performs nicely for homogeneous scenes.

Computation of the retrieved surface current based on the DC of CDE and EB is given in Fig.6. When compared to ocean wave models proposed in the literature, the ocean surface current retrieved from DC of the CDE approach is an excellent fit with reasonable RMSE (of 0.0882). Despite the difference of implementation in spectral and spatial domain, both methods observe similar patterns.

V. CONCLUSIONS

We implement two classical techniques to estimate DC and then extract surface current, comparing their performance numerically. The CDE method achieves stable DC within the primitive baseband range \((\pm PRF/2)\). The difference between both methods is dramatic for a reason, the EB method dominates DC due to the presence of point targets in the scene. The versatility of DC to retrieve surface currents has been shown, which is a reasonable component and comprehends
the information from ocean wave models, particularly values that vary within the limit of error bounds. In-situ data for ocean currents is limited and much sparse. However, SAR offers high resolution for mapping this. We conclude that, for distributed and non-homogeneous SAR scenes, CDE performs very well, and the EB method performs nicely either for point targets or homogeneous scenes. Its estimation decreases when homogeneity is destroyed in a scene with prominent point targets. Future work focuses on making these estimators optimum enough in such a case to achieve CRLB [13].

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