# Ship Motion Parameters Estimation and Refocusing Method with Geosynchronous Synthetic Aperture Radar Image Sequences

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**Keywords:** Geosynchronous synthetic aperture radar (GEOSAR), ship detection, image sequences, constant false alarm rate (CFAR), amplitude weighting.

**Abstract:** Geosynchronous synthetic aperture radar (GEOSAR) is a powerful and wide-covered remote sensing system. The main characteristic of GEOSAR is the long synthetic aperture time and the wide-covered scene, which is suitable for ship detection and tracking. In this paper, the ship detection with constant false alarm rate (CFAR) is executed by using GEOSAR image sequences of sub-apertures based on the statistical characteristics of sub-aperture sea clutter, then the ship centroid estimation method of each image sequence is proposed by the ship amplitude weighting of the detection results, i.e., the coordinates of detected ship locations. Amplitude weighting reduces the fluctuations of the ship centroid, which is useful for ship motion parameters estimation and refocusing. Finally, the ship motion parameters are iteratively estimated by the detection results between the all of adjacent sub-aperture SAR image sequences. The simulated results validate the effectiveness of the proposed procedure.

## 1. Introduction

The scattering powers of ship and sea clutter are quite different in the SAR images. Generally, the targets like ships show stronger power than the sea clutter, therefore, the ships are shown as “bright” targets [1]. However, because of the long integration time of geosynchronous synthetic aperture radar (GEOSAR) system, the moving ships will be defocused seriously if the full aperture echoes are used. Therefore, it is difficult for the ship targets parameter estimation and ship targets image refocusing. The typical ship detection method includes the ship wake detection [2], polarimetric features detection method [3], multi-layer resolution detection method [4], and contrast algorithm [5]. Among those methods, the statistical-model based constant false alarm rate (CFAR) methods, such as [6-7], is widely used in ship detection of SAR images. The K-distribution ship detection method in local window is proposed in [8], Novak proposed the double-parameter CFAR method for ship detection [9]. The performance of these methods is validated by the low-orbit SAR satellite systems.

Though the CFAR method is investigated thoroughly, the refocusing method of ship targets should be further researched after the detection procedure, which is useful for ship size estimation and recognition. Before ship target refocused, the motion parameters should be estimated. Several methods are given based on the low-orbit satellite system and/or the airborne SAR systems with short integration time. These methods are based on the approximation that the ship scattering signal in the same range cell is linear frequency modulation (LFM). And then the signal components of LFM are analyzed based on the “Clean” method, such as the adaptive chirp let decomposition [10], fractional Fourier transform [11], Radon-Wigner transformation [12], and smoothing Pseudo-Wigner-Ville distribution [13]. As is mentioned above, these methods are suitable for the short time observation of

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the SAR systems. Therefore, for the long synthetic aperture time of GEOSAR, new methods should be developed for ship targets refocusing.

In the paper, we propose a ship motion parameter estimation method combining with ship targets refocusing of GEOSAR based on sub-aperture image sequences. Firstly, the sub-aperture images are obtained and primary focused by dividing the whole GEOSAR echoes into several fragments. Secondly, the conventional CFAR method is used to detect the ship targets in every sub-aperture images. Thirdly, the ship centroid estimation method is proposed with amplitude-weighting. Fourthly, ship track can be obtained by the ship centroid fitting, and then the velocity in range and azimuth direction can be obtained simultaneously, so does the moving direction. Finally, the ship targets can be refocused iteratively with the estimated motion parameters.

The paper is arranged as follows: Section 2 gives the proposed processing scheme in detail. The processing results with simulated data are used to validate the effectiveness of the proposed method in section 3. Section 4 summarizes the whole paper.

## 2. Ship motion parameter estimation and refocusing with GEOSAR image sequences

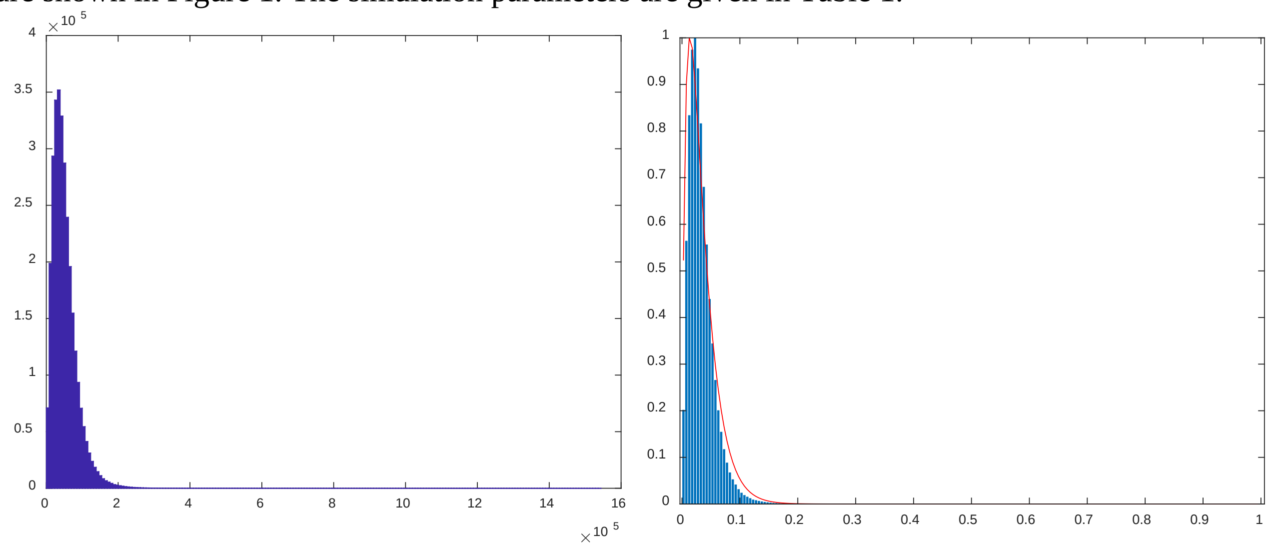
In this section, we will give the detailed processing chain the proposed method for ship motion parameter estimation and ship targets refocusing.

### 2.1 GEOSAR sub-aperture image sequences focusing

The full aperture radar echoes are divided into sub-apertures firstly. Generally, the coherent time of sea clutter are less than 2 seconds, and the ship posture variation can be ignored, which is helpful for target focusing. Therefore, in order to obtain the primary sub-aperture focused SAR images with moderate signal to noise ratio (SNR), the sub-aperture time is determined as 2 seconds.

### 2.2 CFAR ship detection with GEOSAR sub-aperture image sequences

Generally, the sea clutter with short integration time is modeled as K-distribution. However, for the GEOSAR system with long synthetic aperture time, the sea clutter cannot be focused well. Furthermore, with sub-aperture SAR imaging processing, the azimuth resolution will be sharply decreased. Therefore, the statistical characteristics should be investigated with the GEOSAR sub-aperture images. The histogram of the simulated sea clutter and the K-distribution fitting curve are shown in Figure 1. The simulation parameters are given in Table 1.




(a) Histogram of Sub-aperture Sea clutter (b) K-distribution fitting of sub-aperture sea clutter

Figure 1. GEOSAR sub-aperture images' statistical characteristics of sea clutter.

We can see that the sea clutter of sub-aperture is well fitted by the K-distribution. Therefore, we can first detect the ships with CFAR method. Generally, the detection model is formulated as:

$$H_0\text{:}\quad x > T \quad \text{Ship target} \tag{1}$$

$$H_1\text{:}\quad x < T \quad \text{Sea clutter} \tag{2}$$

Where $T$ is the CFAR detection threshold, and it can be determined by the dichotomy? However, it should be noted that $T$ should be adaptively determined for different sub-aperture radar images. If $T$ is constant for all the sub-aperture images, the false alarms and missing alarms will be increased because the K-distribution parameters of GEOSAR sub-aperture images are different. Therefore, the estimation accuracy of ship velocity will be deteriorated.

### 2.3 Ship centroid estimation with amplitude weighting

Because the ship images are defocused, the ship centroid cannot be accurately estimated. Therefore, the amplitude-weighting method for ship centroid estimation is proposed in this paper. If the ship scattering power is uniformly distributed, the ship centroid is located at the geometric centroid of the detection results. However, the scattering power of the ship is different because of the ship geometry and ship attitudes. Therefore, the amplitude-weighting method is proposed to estimate the centroid with the CFAR ship detection results (i.e., the corresponding pixels) as follows:

$$Y_0 = \sum_{i=1}^{N} y_i \bullet \rho_i \Big/ \sum_{i=1}^{N} \rho_i \tag{3}$$

$$X_0 = \sum_{i=1}^{N} x_i \bullet \rho_i \Big/ \sum_{i=1}^{N} \rho_i \tag{4}$$

Where $x_i$ and $y_i$ are the coordinates of the detected results, $\rho_i$ is the corresponding scattering power of the CFAR detected pixels.

### 2.4 Ship track formation and motion parameter estimation

For every sub-aperture SAR image with short integration time, the CFAR detected result can be obtained like the low-orbit satellite system. After the short time SAR image detection, we can link all the centroid of the detected results for the long synthetic aperture time. Even though the azimuth displacement will be occurred because of the range velocity, the linked results represent the moving direction and moving distance on the SAR images.

### 2.5 Ship target refocusing with motion parameters compensation

By using the fitting track of the detected results, the moving velocity of the ships can be estimated in both range and azimuth direction. Because of the ship motion, the relative positions of ship target and radar platform are changed with time, and then the instantaneous slant range can be expressed as:

$$R_{(t_a)} \approx R_0 + \frac{YV_y}{R_0} t_a + \frac{\left(V_a - V_x\right)^2}{2R_0} t_a^2 \tag{5}$$

Where $R_0$ is the reference slant range, $V_y$ is the range velocity, $V_x$ is the azimuth velocity, and $t_a$ is the azimuth time. Through the fitted trajectory curve, the range and azimuth velocity can be simultaneously estimated, then the Doppler chirp rate can be modified and the matched filter is formulated as below:

$$H_{RWM} = \exp\left(-j\frac{4\pi\left(f_c + f_r\right)}{c} V_r t_a\right) \tag{6}$$

By using the phase compensation, the ship targets can be refocused.

It should be noted that all the above steps can be executed iteratively for better focusing results.

## 3. Simulation results investigation and discussion

In this section, we use the simulated GEOSAR data and ship targets to investigate the performance of the proposed method. The used parameters are listed in Table 1.

Table 1. Parameters for GEOSAR simulation

| | | | |
|---|---|---|---|
| Radar frequency | 5.4GHz | Pulse repeated frequency | 100Hz |
| Bandwidth | 120MHz | Full synthetic aperture time | 30s |
| Pulse duration time | 10 $\mu s$ | Radar look angle | $35^{\circ}$ |
| Platform height | 36000km | Sub-aperture synthetic time | 2s |
| Platform velocity | 2480m/s | | |

The full aperture synthetic aperture GEOSAR image and ship target are shown in Figure 2.

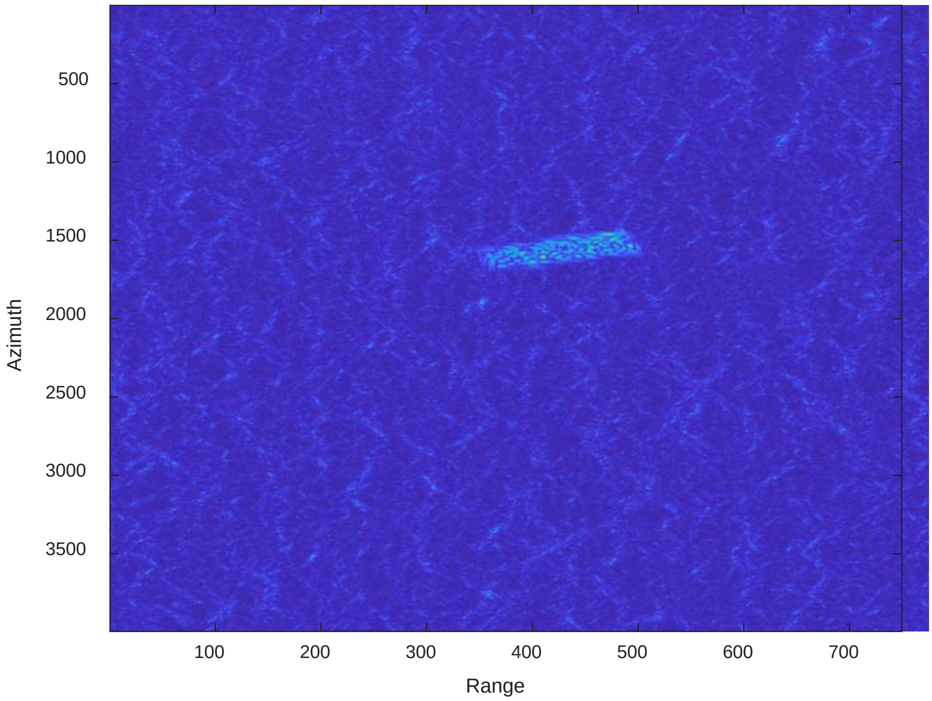
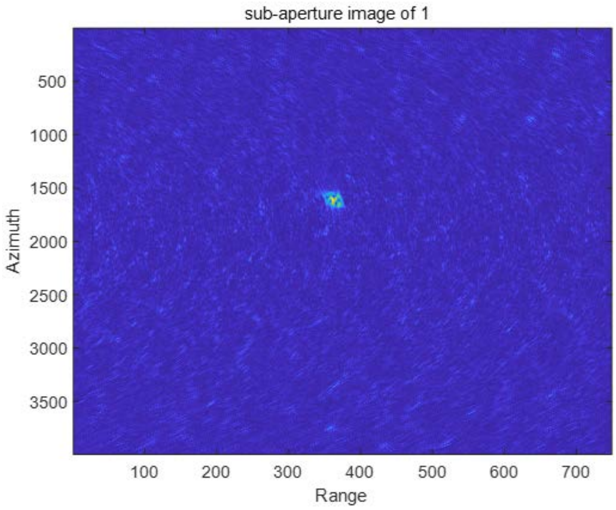
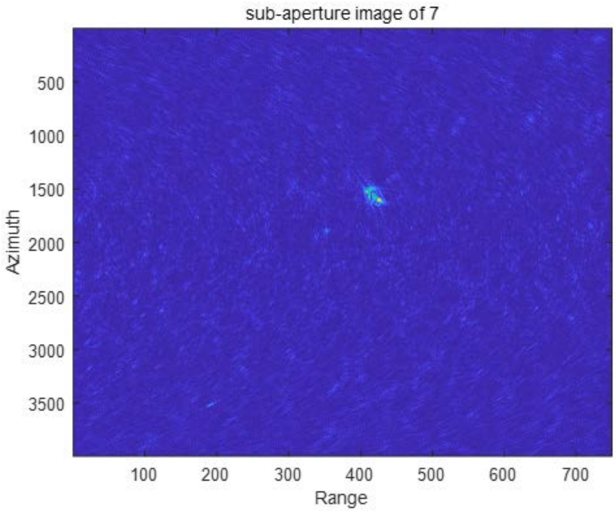



Figure 2. GEOSAR image of sea clutter and ship target

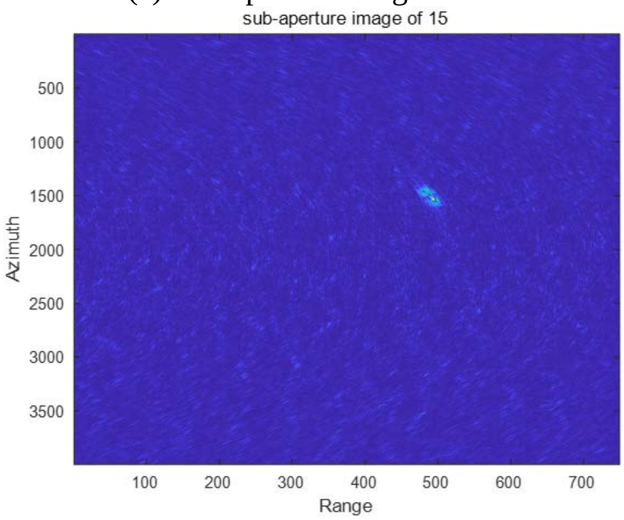
From Figure 2, we can see that the ship target is defocused seriously, and it is difficult for us to estimate the motion parameters from the single image. Therefore, we use the sub-aperture radar sequences to estimate the motion parameters. From Table 1, we know that the GEOSAR echoes can be divided into 15 sub-aperture SAR images. With CFAR detection, we can obtain the ship locations (i.e., pixel coordinates) in every sub-aperture GEOSAR image. Herein, we give the #1, #7, #15 sub-aperture images and the detection results in Figure 3.



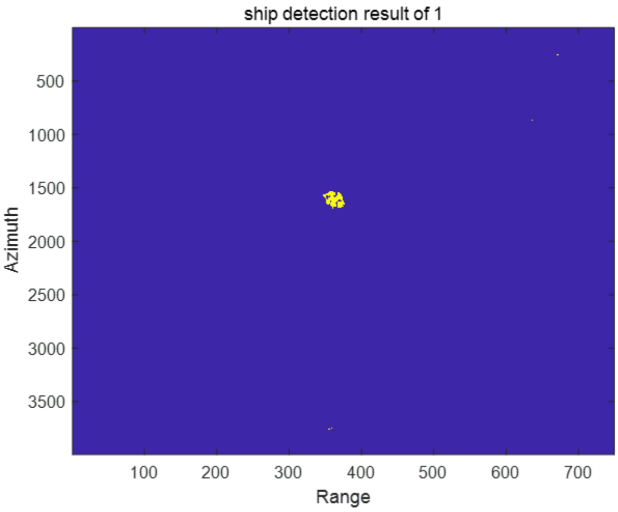
(a) Sub-aperture image of #1



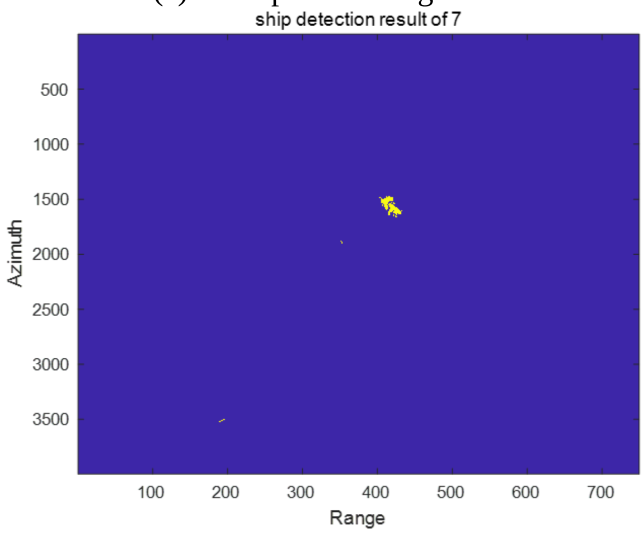
(b) sub-aperture image of #7



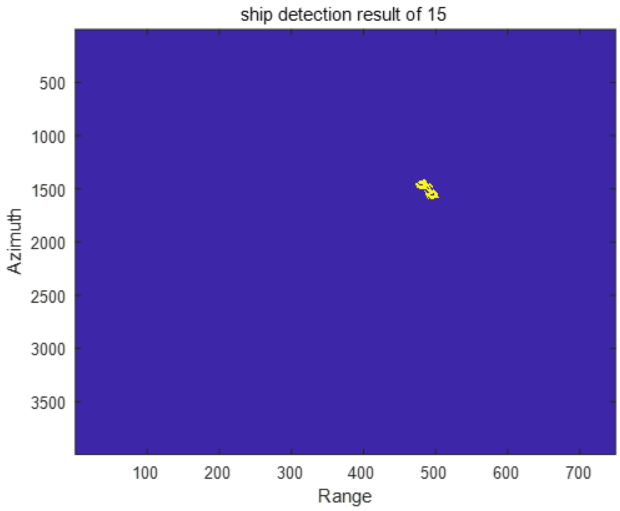
(c) Sub-aperture image of #15



(d) Ship detection result of #7



(e) Ship detection result of #7

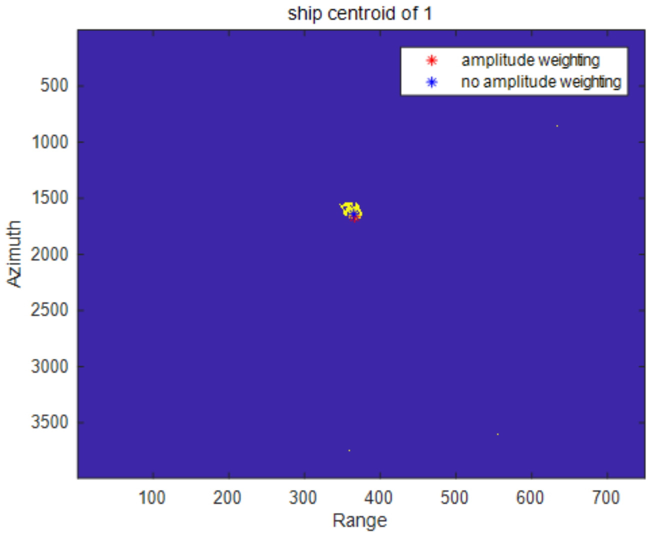


(f) ship detection result of #15

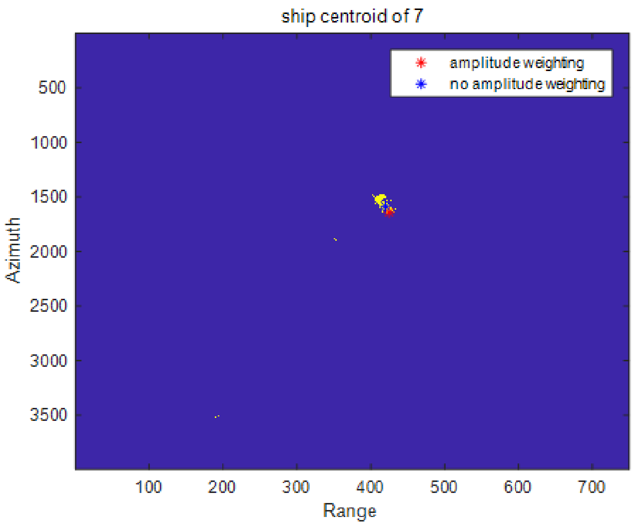
Figure 3. (a) (b) (c) (d) (e) (f) Sub-aperture GEOSAR images and ship detection results

From Figure 3, we can see that the ship targets in sub-aperture images are still defocused. And the detection results are distributed in several neighboring pixels, which is not convenient for ship motion parameters estimation. Therefore, we use the ship centroid for parameter estimation. In the previous section, we point out that the amplitude-weighting method can be considered for the non-uniform scattering power distribution. Figure 4 shows us the centroid location with/without amplitude-weighting of #1, #7 and #15 sub-aperture GEOSAR images. We can see that the centroid location with amplitude-weighting is closer to the geometric center than that without amplitude-weighting, which is facilitated for motion parameters estimation.

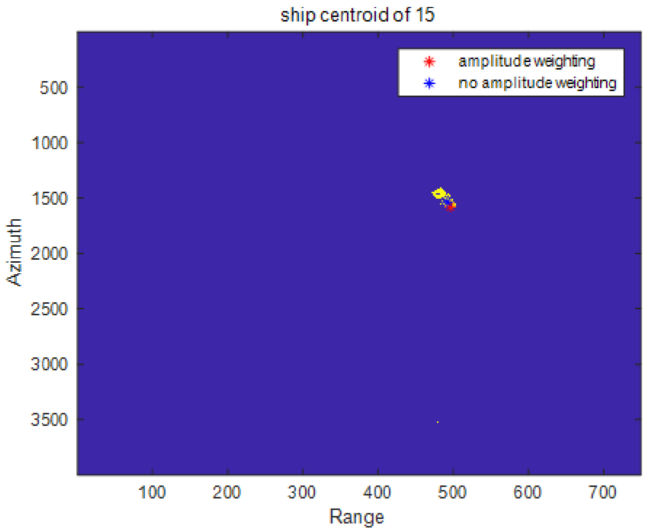
The centroids of all sub-aperture images with/without amplitude weighting are shown in Figure 5. Based on the centroid locations, the detected results can be linked together, and then the moving direction can be obtained from the fitted trajectory.




(a) Ship centroid of #1




(b) Ship centroid of #7




(c) ship centroid of #15

Figure 4. (a) (b) (c) Sub-aperture ship centroid estimation with/without amplitude weighting

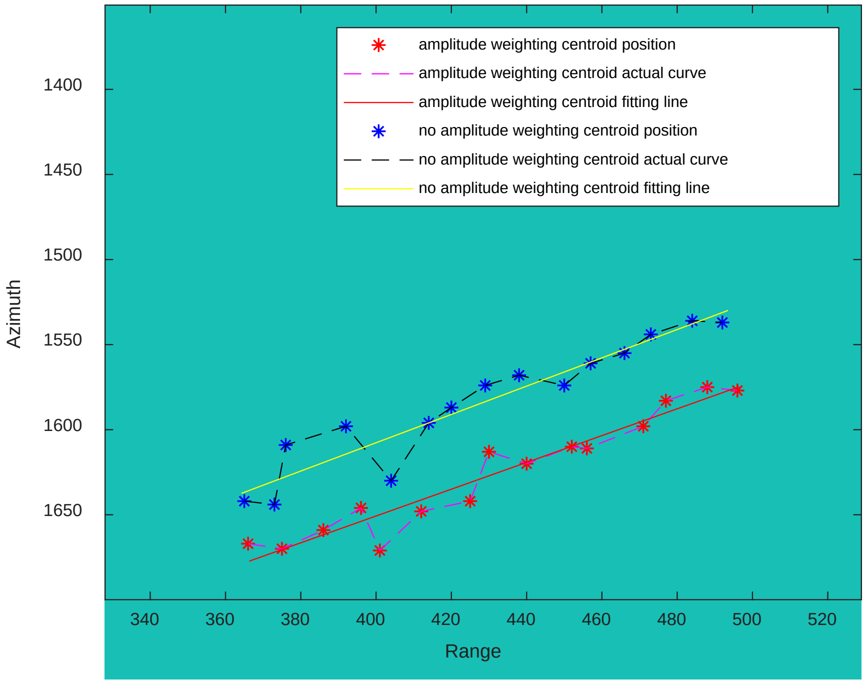


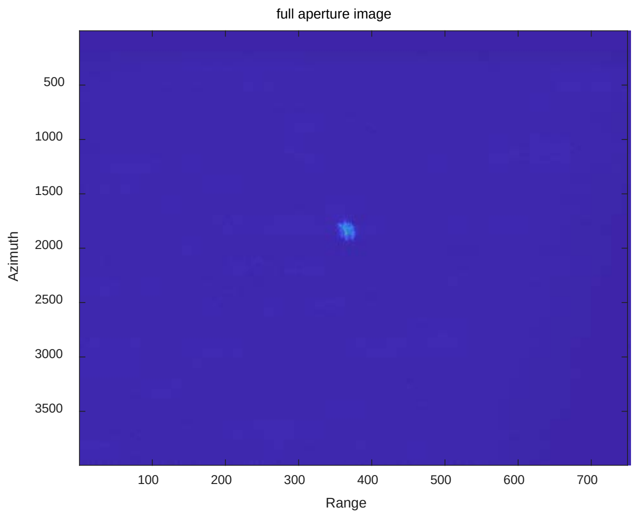

Figure 5. Sub-aperture centroid fitting results

From Figure 5, the variance of centroid with amplitude-weighting is smaller than that without amplitude-weighting, which means that the moving direction is more accurately fitted. From the fitting curve and the parameters in Table 1, the ship velocity can be obtained as Table 2 shows us.

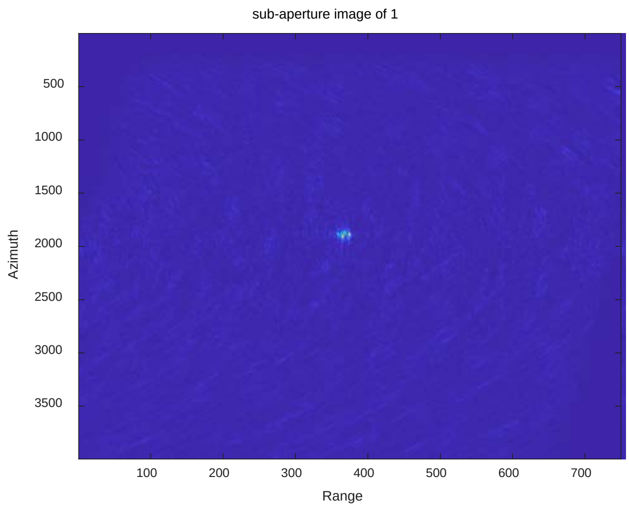
Table 2. Velocity estimation with/without amplitude weighting

| | Range velocity | Azimuth velocity | Estimated ship velocity | Actual ship velocity | Estimation error |
|---|---|---|---|---|---|
| amplitude weighting | 4.3333m/s | 3.4333m/s | 5.5286m/s | 5.1444m/s | 7.468% |
| no amplitude weighting | 4.4000m/s | 3.8000m/s | 5.8138m/s | 5.1444m/s | 11.514% |

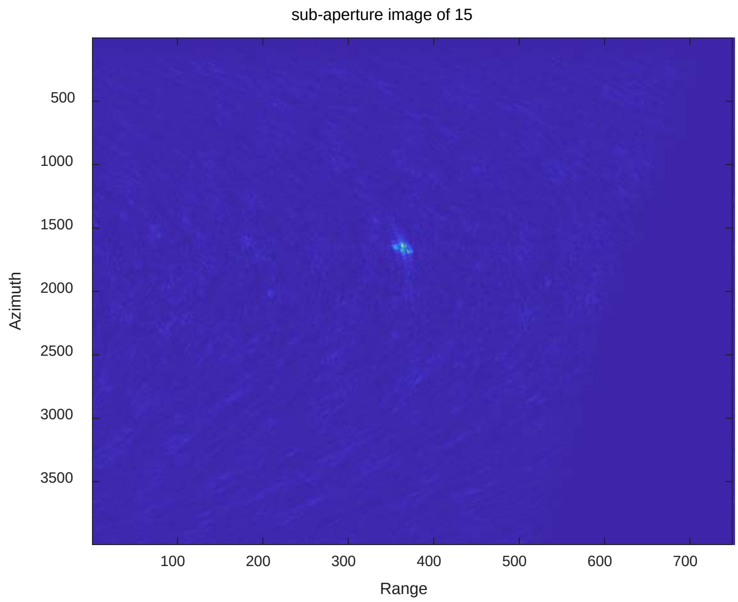
Table 2 shows us that we can obtain more accurate velocity estimation results with amplitude-weighting. With the estimated velocity, we can refocus the ship images, including full-aperture and sub-aperture SAR images which are shown in Figure 6 iteratively.




(a) Full aperture image




(b) sub aperture image of #1




(c) sub aperture image of #15

Figure 6. (a) (b) (c) Full aperture and sub-aperture radar images with two iterations

Comparing Figure 6, Figures 2 and 3, we can see that ship images in both full aperture image and sub-aperture image are focused well. The focused results validate that the motion parameters estimation method and phase compensation method are effective with GEOSAR image sequences.

## 4. Conclusion

Unlike the low-orbit satellite system, GEOSAR system has much longer synthetic aperture time. Therefore, the ship detection method is quite different from the low-orbit satellite system. In this paper, an amplitude weighting method for ship centroid and motion parameters estimation with GEOSAR image sequences is proposed, followed by the phase compensation method for ship target refocusing. The simulated results validate the effectiveness of the proposed processing flowchart.

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## References

[1] Quanhua Zhao, Xiao Wang, Yu Li, Guanghui Wang, Ship detection optimization method in SAR imagery base on multi-feature weighting[J]. Journal on Communications, 2020, 41(3): 91-101.

[2] Guozheng Yang, Jing Yu, Chuangbo Xiao, etc. Ship wake detection in SAR images with complex background using morphological dictionary learning [J]. Acta Automatica Sinica. 2017, 43(10): 1713-1725.

[3] Jujie Wei, Pingxiang Wang, Jie Yang, etc. Removing the effects of azimuth ambiguities on ships detection based on polarimetric SAR data [J]. Acta Geodaetica ET Cartographica Sinica, 2013, 42(4): 530-539.

[4] Deyuan Chen, Guofang Tu, A new algorithm of ship targets detection in SAR images using wavelet transform [J]. Journal of Electronics and Information Technology. 2007, 29(4): 855-858.

[5] Biao Hou, X Z. Chen, L. C. Jiao. Multilayer CFAR detection of ship targets in very high-resolution SAR images [J]. IEEE Geoscience and Remote Sensing Letters, 2015, 12(4): 811-815.

[6] Yinghua Wang, Hongwei Liu. A hierarchical ship detection scheme for high-resolution SAR images [J]. IEEE Trans. On GRS. 2012, 50(10):4173-4184.

[7] Mingbo Zhao, Jun He, Qiang Fu, Survey on fast CFAR detection algorithms for SAR image targets [J]. Acta Automatica Sinica, 2012, 38(12): 1885-1895.

[8] Jinsong Zhong, Minhui Zhu, K-distribution target detection in local window of SAR image [J]. Journal of Electronics and Information Technology, 2003(9): 1276-1280.

[9] Novak, L M, Halveren S D, Owirka G. etc. Effects of polarization and resolution on SAR ATR [J]. IEEE Tran. On Aerospace and Electronic Systems, 1997, 33(1): 102-116.

[10] Yong Wang, Yicheng Jiang, The ISAR imaging of ship based on adaptive chirplet decomposition [J]. Journal of Electronics and Information Technology, 2006, 28(6): 982-984.

[11] Ran Tao, Yunsong Zhou, A novel method for the direction of arrival estimation of wideband linear frequency modulated sources based on fractional fourier transformation. Transactions of Beijing Institute of Technology [J], 2005, 25(10): 895-899.

[12] Xin Ran, Shiwei Ma, Jialin Cao, Analysis of multi-component LFM signal based on Radon Wigner Transformation [J]. Journal of Shanghai University. 2001, 7(2): 119-122.

[13] Chuanan Yang, Xiangyang Qi, Ning Li, A method for moving ship SAR imaging based on parameter estimation [J]. Foreign Electronic Measurement Technology, 2017, 36(5): 29-36.