A Novel Algorithm for Doppler Frequency Rate Estimation of Spaceborne Synthetic Aperture Radar

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Abstract. Synthetic Aperture Radar (SAR) can obtain high-resolution radar images under all weather, day and night and long distance conditions, and has been applied widely in military and civil fields. Range-Doppler (RD) algorithm is a simple and typical imaging algorithm. The key of it is Doppler parameters estimations, including Doppler centroid frequency and Doppler frequency rate. Doppler frequency rate is variational with range. If the estimation of it is inaccurate, it will bring severe defocusing effect and blurring in azimuth direction. The previous estimations of Doppler frequency rate usually use image field instead of data field, the calculated amount is very large and the imaging speed is slow. In order to improve them, this paper proposes a novel Doppler frequency rate estimation algorithm for spaceborne SAR imaging. The raw data of ERS are used to test effectiveness and feasibility of this method.

1 Introduction

Radar imaging remote sensing has become a main technique for Earth observation system. Spaceborne SAR imaging system adopts side-look imaging in general and RD algorithm is usually used by this imaging mode. The key technique of RD algorithm is Doppler parameter estimation. The accuracy of Doppler parameter estimation directly impacts on SAR image quality. In order to get high precise Doppler parameter value and avoid using ephemeris data and attitude data to estimate Doppler parameters that bring many errors, some people have obtained quite accurate Doppler parameter estimation values from echo data itself. These methods of Doppler parameter estimation are called "automatic estimation approach"[1]. The purpose is to abstract phase errors that impact SAR image quality from radar echo data and to eliminate them, getting high-resolution images. The errors of Doppler frequency rate estimation will make images defocus and blur, and it will still impact range migration correction.

There are some familiar Doppler frequency rate estimation methods for spaceborne SAR, including subaperture correlation method (map drift algorithm)[2][3], time-frequency analysis method [4], image contrast method [5] and minimum entropy method [6], etc. The common shortcomings of these algorithms are

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calculation complex, calculated amount great and unusable to real-time imaging. Then others present some algorithms to estimate Doppler frequency rate from raw data, such as reflectivity displacement method [7] and Shift-and-Correlation (SAC) method [8]. However, the two methods are only fit for airborne SAR Doppler frequency rate estimation and can't be used on spaceborne SAR.

In real-time imaging, it demands that the algorithm can satisfy some accuracy requirement and less calculated amount. So a novel Doppler frequency rate estimation algorithm, Mean Frequency Shift Correlation (MFSC) method, is presented in this paper. MFSC algorithm directly estimates Doppler frequency rate from echo data and does not image. Therefore, the computational efficiency of it improves, and it is fit for real-time processing. Obviously is it better than traditional MD algorithm. So it has some theory and practical value for studying spaceborne SAR imaging. The algorithm is validated to be feasibility and validity with ERS-2 raw data of ESA.

2 Doppler Frequency Rate

The key technique of azimuth compression or azimuth focus is Doppler parameter estimation, namely, Doppler centroid frequency and Doppler frequency rate estimations. The equation of Doppler frequency rate is given by [9]

$$f_{DR} = -2V^2 / \lambda R_0 \ . \tag{1}$$

Where V is the ground track velocity, λ is wavelength, R_0 is range from target to spacecraft track. And the R_0 is given by

$$R_0 = \sqrt{H^2 + R_g^2} = R_{near} + n \times (c / F_s) \ . \tag{2}$$

Where H is spacecraft height, R_g is ground range, R_{near} is the distance to the first range bin, c is velocity of light, F_s is the sampling frequency of range direction, n is sampling point number, namely, the number of range gate. The changes of f_{DR} are shown in Fig.1.

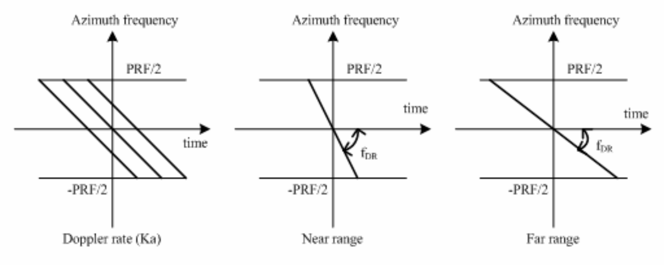


Fig. 1. The changes of Doppler frequency rate with range

3 Mean Frequency Shift Correlation Algorithm

Jorgen presented Shift and Correlation algorithm in 1991[8]. He uses the correlation characteristics of Doppler signal to estimates Doppler frequency rate f_{DR}, obtaining very much high efficiency. An echo of a point target is

$$s(t) = \exp[i\pi f_{DR}(t-t_0)^2]\,;\ t_0 - T/2 \le t \le t_0 + T/2\,. \tag{3}$$

Signal s(t) is divided into two parts which are SL(f) and SU(f) in frequency field and they are the lower half and the upper half of Doppler spectrum, respectively. SAC algorithm refers to relative frequency shift of SL and SU, and then makes correlation. The sketch diagram of principle of SAC algorithm is shown in Fig.2.

s(t) has the characteristic of wide-time-bandwidth accumulation, and the corresponding time field signal of SL(f) and SU(f) is sl(t) and su(t), respectively.

$$\begin{cases} sl(t) = \exp[i\pi f_{DR}(t-t_0)^2] & t_0 - T/2 \le t \le t \\ su(t) = \exp[i\pi f_{DR}(t-t_0)^2] & t_0 \le t \le t_0 + T/2 \end{cases}; \ . \tag{4}$$

Then, sl(t) and su(t) make frequency shift processing, SL(f) shifts FRF/4 to upper half of spectrum and SU(f) shifts PRF/4 to lower half of spectrum. The results are

$$\begin{cases} SL^{+}(f) = SL(f + PRF/4) \\ SU^{+}(f) = SU(f - PRF/4) \end{cases}. \tag{5}$$

The corresponding time field signal is $sl^{+}(t)$ and $su^{+}(t)$.

$$\begin{aligned} sl^{+}(t) &= sl(t)\exp(i2\pi \cdot PRF/4 \cdot t) \\ &= \exp[-i\pi f_{DR}(\delta/2)^2 + i\pi f_{DR} t_0 \delta]\exp[i\pi f_{DR}(t - t_0 + \delta/2)^2] \end{aligned};\ t_0 - T/2 \le t \le t_0. \tag{6}$$

$$\begin{aligned} su^{+}(t) &= su(t)\exp(-i2\pi \cdot PRF/4 \cdot t) \\ &= \exp[-i\pi f_{DR}(\delta/2)^2 - i\pi f_{DR} t_0 \delta]\exp[i\pi f_{DR}(t - t_0 - \delta/2)^2] \end{aligned};\ t_0 \le t \le t_0 + T/2. \tag{7}$$

Where $\delta = PRF/2 \cdot f_{DR}$. If $sl^{+}(t)$ and $su^{+}(t)$ correlate each other, the correlation peak will appear in position δ, which Fig. 2(e) shows. Assume the position δ of correlation peak and pulse repeat frequency PRF is given, f_{DR} may be gained, as is called shift and correlation method. It is a pity that SAC method is only adapt to airborne SAR and the high contrast grade terrain. If we directly utilize it to image for spaceborne SAR, the result is that none can be obtained, which is shows in Fig.4(a). This article proposes using the geometry of spaceborne SAR, which are V, λ and R_0, to estimate Doppler frequency rate of every range gate cursorily, then compute is estimated with SAC acts as adjustable value of Doppler frequency rate estimation.

The basic value plus adjustable value may gain accurate Doppler frequency rate. As is the Mean Frequency Shift Correlation algorithm. The flow chat is displayed in detail in Fig.3.

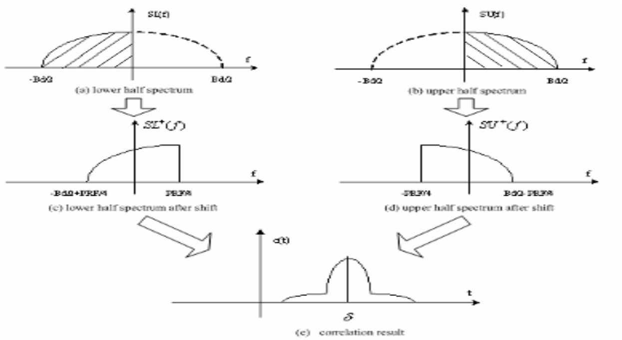


Fig. 2. Sketch diagrams of Shift and Correlation

MFSC method is an autofocus algorithm that has high computed efficiency and has some similar sections as MD algorithm. In order to obtain Doppler frequency rate errors, MD algorithm makes azimuth correlation with the corresponding images of lower half and upper half of azimuth spectrum. It is autofocus algorithm with image field. Its operation quantity is quite large and needs reiterative operation to form an image. Therefore, it is not fit for real-time imaging processing. However, MFSC doesn't need reiterative operation, which may reduce operation quantity greatly. And it may reach good accuracy for Doppler frequency rate estimation and not only be fit for real-time imaging processing but also agrees with all kinds of terrain.

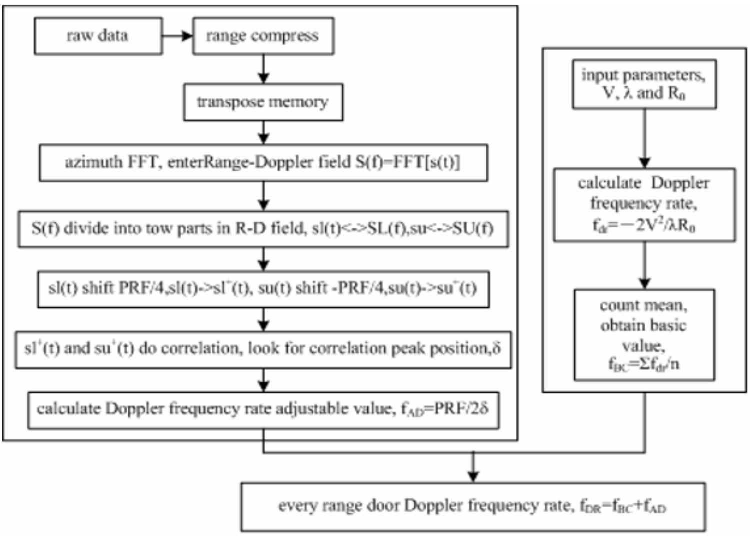


Fig. 3. Flow chart for MFSC algorithm

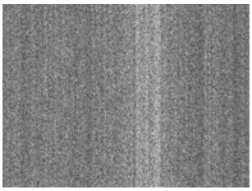
4 Experimental Results and Performance Comparisons

In order to prove efficiency and correctness of MFSC algorithm, we utilize real measured data to image with MFSC algorithm. The experimental results are shown in Fig.4(c)-4(f), note that these images are cut out. These data comes from ERS-2, and some parameters as follows: V is 7040 m/s, λ is 5.7cm, n is from 0 to 5615, c is 3E8m/s, Fs is 18.96MHz, and R_{near} is 838000m.

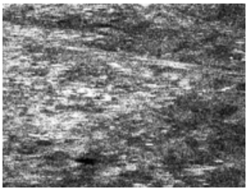
The Fig.4 (a) explains that SAC algorithm can't image for spaceborne SAR. No focus processing also can't obtain legible image that is shown in Fig.4 (b), in other words, the Doppler frequency rate is estimated with

$$f_{DR} = -\frac{2V^2}{\lambda}\frac{1}{R_{near} + n \times (c / Fs)} \quad . \tag{8}$$

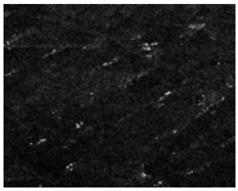
Whereas, MFSC algorithm can image to all kinds of terrains for spaceborne SAR, which are shown in Fig.4(c)-(f). Table.1 is the performance compare of several algorithms including MFSC algorithm, MD algorithm, time-frequency analysis algorithm and image contrast algorithm.



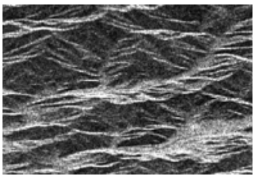
(a) SAC algorithm image



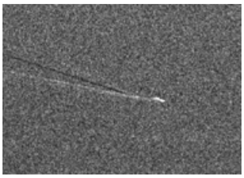
(b) No focus image



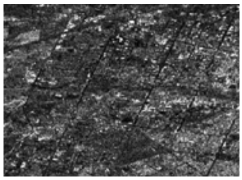
(c) Countryside image



(d) Mountain image



(e) Ocean image



(f) Urban image

Fig. 4. Experiment results of real test data. (a) directly using SAC algorithm for spaceborne SAR imaging, (b) no focus, (c)-(f) the image of countryside area, mountain area, ocean area and urban area with MFSC algorithm, respectively.

We may know from it that MD algorithm, time-frequency algorithm and image contrast are all work in image field, so their real-time feature is bad and their account scalar is large. The terrain adaptability of MD algorithm and image contrast is bad and they demand strong contrast terrain. MFSC algorithm and rime-frequency algorithm have good terrain adaptability, but the work filed of MFSC algorithm is data filed, so it has good real-time feature and less account scalar.

Table 1. Performance compare of several algorithms

	Image or data field	Account scalar	Real-time feature	Terrain adaptability
MD	image field	large	bad	strong contrast
MFSC	data field	little	good	good
Time frequency analysis	image field	large	bad	good
Image contrast	image field	large	bad	strong contrast

5 Conclusions

The processed object of Doppler frequency rate estimation method was images instead of data ago. In general, they need repeating replace operation, so their account scalar is large, account course is complex and real-time is very bad. MFSC algorithm directly estimates Doppler frequency rate with echo data, without repeating replace operation, which reduces a lot of account scalar and imaging time, and its adaptability for terrain is wide. Experiment proves that it is right and effective. This has some theory and practice reference value for next studying the imaging and application of spaceborne SAR.

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