A High Resolution ISAR Imaging Method for Wideband Radar

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***Abstract*—Wideband radar can get high range resolution. In order to obtain high azimuth resolution, a large rotation angle of moving targets relative to the radar line of sight is required. As the migration of scatterers in different range resolution cells is different, range alignment cannot compensate it completely. When the rotation angle of the moving target is large, the migration through resolution cell (MTRC) will occur obviously, which results in great image resolution degradation. A new ISAR imaging algorithm is proposed in this paper to solve the problem. In the proposed algorithm, the process of large-angle high-resolution imaging is divided into several small-angle low-resolution imaging processes. Then after image scaling, image rotation, image translation, inverse process of ISAR imaging, data splicing and re-ISAR imaging, high resolution image will be produced. Theoretical analysis and simulations show that the proposed algorithm can compensate the MTRC of scatterers and obtain high-resolution images.**

***Index Terms*—ISAR, migration through resolution cell, high resolution imaging, image registration**

I. Introduction

INVERSE Synthetic Aperture Radar (ISAR) can obtain two-dimensional images (the images of range and azimuth directions) of moving targets. Usually the range-Doppler (RD) algorithm is used for ISAR imaging[1]. To get high azimuth resolution images, it needs a large angle of the rotating target relative to the radar line of sight during the coherent accumulation time. However, too large rotational motion will cause the migration through resolution cell (MTRC) of part of scatterers, and the imaging quality based on the traditional RD algorithm will decline.

Currently, a number of papers have proposed methods to compensate the MTRC of scatterers. In [2], the traditional RD algorithm, the polar formatting algorithm (PFA) and the keystone algorithm are analyzed. PFA can compensate the MTRC of scatterers, while the range and cross range interpolation operation is required, which will affect the imaging precision and the computational efficiency. The Keystone algorithm[3] and the MTRC compensation algorithm (MTRCCA)[4] can both compensate the MTRC. Unfortunately, these methods are not applicable to the large rotational motion. In [5] the sub-image fusion algorithm (SIF) is proposed. The algorithm can compensate the large rotational motion in high-resolution ISAR imaging and reduce the image blurring. However, it is limited to the situation with equal range resolution and azimuth resolution.

Considering the above problems, we propose a new high resolution ISAR imaging algorithm. Echo segmenting is performed first, and low-resolution images (sub-image) can be obtained from the segments. Then after image scaling, image registration including image rotation and translation, inverse process of ISAR imaging, data splicing and re-ISAR imaging, the synthetic high resolution image can be obtained finally. The proposed method just needs to estimate the angles between one of the sub-images and the others, which can greatly reduce the computation. Besides, it is suitable for any resolution imaging due to the new process of scaling and registration. The simulation results show that the proposed algorithm avoids the MTRC in the situation of large rotational motion, and the azimuth resolution is significantly improved.

II. Algorithm Description

The proposed algorithm has two main steps: echo segment imaging and high-resolution imaging. The segment imaging will be performed first to obtain sub-images. And then the high-resolution imaging will be performed which includes scaling, image rotation, image translation, inverse process of ISAR imaging, data splicing and ISAR imaging. The high resolution image can be obtained at last. The equivalent rotation angle is large in the proposed algorithm, and the MTRC does not exist.

A. Echo Segment Imaging

The relative motion between the radar and the target can be decomposed into translational motion and rotational motion. The translational motion should be accurately compensated in ISAR imaging, which is called motion compensation. The compensated signals can be treated as the echoes of a rotating scatterer with respect to the reference center as shown in Fig.1.

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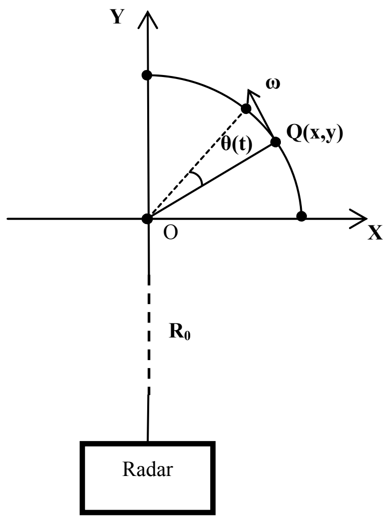

Fig.1 ISAR imaging geometry

Firstly, the echoes should be segmented to several equal parts. In order to obtain clear sub-images, the migration of the scatterers in each echo segment should not be through resolution cell. After segmenting, the rotation angle and the walking distance of the scatterers in each segment are small. In that condition, the traditional imaging methods can be used. The total number of the echoes is assumed to be *N*. The echoes are segmented to *k* parts. Then the number of echoes in each part is *n,* which can be written as

$$\mathrm{n}=\frac{N}{k} \tag{1}$$

In Fig. 1, point *O* is the reference point, and the scatterer *Q*(*x, y*) rotates about *O*. During the coherent processing, the rotation angle of *Q*(*x, y*) is defined as θ, and the angular velocity is represented by ω. T_a is the observing duration. R_0 is the range from the radar to the reference center. Suppose that the radar transmits a linear frequency modulated (LFM) signal, which can be written as

$$s(t)=rect(\frac{t}{T_p})\exp\left[j2\pi(f_c t+\frac{\mathrm{u}}{2}t^2)\right] \tag{2}$$

f_c is the carrier frequency, *u* is the chirp rate, T_p denotes time width of the chirp pulse, the signal bandwidth is *B*, and *rect*(·) is the unit rectangular function. *B* can be written as

$$B=T_p\cdot u \tag{3}$$

After range compression, phase compensation and Keystone transformation, the echo segment data is transformed from time domain to range domain by applying the Fourier Transformation in the azimuth direction, which can be written as

$$s(t,f_d)=A\cdot\sin c\left[B\left(t-y\right)\right]\cdot \sin c\left[T_a\left(f_d-\frac{2\omega x}{\lambda}\right)\right]\exp\left(-j4\pi\frac{y}{\lambda}\right) \tag{4}$$

where A is the backward scattering amplitude (A can be viewed stationary during the coherent processing), and λ is the wavelength[5]. From the above, the sub-images are produced.

B. High Resolution Imaging

We have got sub-images after echo segment imaging. Because of the different original time of the sub-images, the coordinates of the scatterers are different. The sub-images should be rotated and aligned to make the coordinates of the scatterers same which is called image registration. However, rotating directly with different range resolution and azimuth resolution will cause the image distortion. So scaling should be done before image rotating. After image registration, the inverse process of ISAR imaging should be performed. Then by splicing the entire segment data and re-ISAR, the high resolution image is obtained.

Assume that the actual distance denoted by the sampling unit in the range direction is δ_y, and f_s is the sampling frequency. We know that

$$\frac{1}{f_s}=\frac{2\delta_y}{\mathrm{c}} \tag{5}$$

So,

$$\delta_y=\frac{\mathrm{c}}{2f_s} \tag{6}$$

Assume that the size of azimuth resolution cell is δ_x which can be written as

$$\delta_x=\frac{PRF}{n}\cdot\frac{\lambda}{2\omega} \tag{7}$$

Where *n* is the number of echoes in each segment, and *PRF* is the pulse repetition frequency.

When δ_x doesn't equal δ_y, image scaling must be performed before image rotating which means adjusting the range resolution and the azimuth resolution to be the same by stretching the range image. All the sub-images can be rotated to the same coordinate after scaling. The angles between the first sub-image and the others should be estimated before rotating. Currently, some approaches[6][7] have been introduced to estimate the rotational angular velocity. In this paper, we will not describe it in detail.

Suppose that the coordinate of a scatterer in the first sub-image is (x_0,y_0) and the coordinate in another sub-image is (u_0,v_0).When the rotation angle between them is β, the coordinate transformation relationship is

$$\begin{cases} x=ucos\left(\beta\right)-vsin(\beta) \\ y=vcos\left(\beta\right)+usin(\beta) \end{cases} \tag{8}$$

The matrix size will change while rotating, so it is necessary to do the image translation and then cut the sub-images to the same size. The image translation is composited by rough translation and accuracy translation. The image moves integral sampling units in rough translation. Then fractional delay algorithm[8] is used for accuracy translation. The sub-images are cut to the same size after translation.

As all the echo segments contain the same motion information after processing, the data can be spliced to produce a high resolution image. The segment data in the azimuth direction should be transformed from range domain to time domain by IFFT (Inverse Fast Fourier Transform). After splicing all the segments data and transforming the spliced data by FFT in the azimuth direction, we can get high resolution ISAR image.

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The algorithm flow chart is shown as Fig.2.

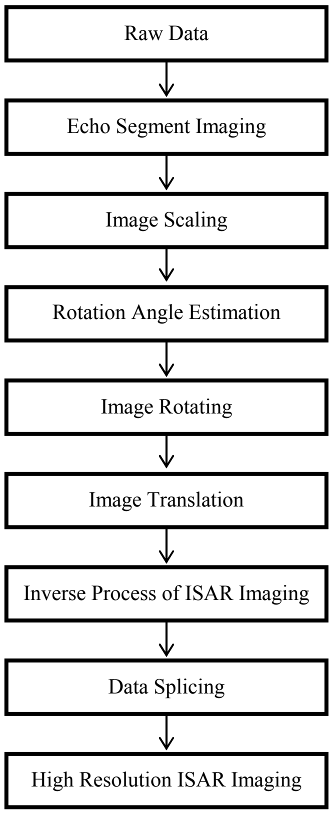

Fig. 2 the flow chart of the proposed algorithm

III. SIMULATION AND ANALYSIS

The proposed algorithm divides the large rotation angle into several small ones. The length of the data after splicing increases to N ($N=n\times k$). The actual distance represented by the azimuth resolution cell of the proposed algorithm is $\delta_x^{'}$, which can be written as

$$\delta_x^{'} = PRF \cdot \frac{\lambda}{2N\omega} \tag{9}$$

According to (9), the actual distance represented by the azimuth resolution cell can be reduced to 1/k. The azimuth resolution is improved significantly. As the process involved in the interpolation, the resolution will be reduced to a certain extent, and actually it is difficult to achieve the theoretical resolution.

Assume that a moving target is composed with four points (A, B, C and D), with coordinates being A (-2m, 0), B (-2m, 0m), C (2m, 0), D (1.84m, 0) respectively, shown as Fig. 3.

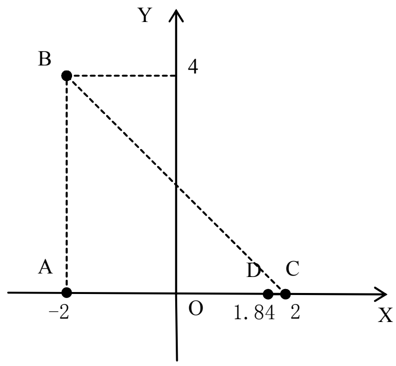

Fig. 3 coordinates of the target

The angular velocity of the target is ω, and ω=0.15rad/s. The distance between the radar and the target is R_0=4000m. Radar parameters are set as follows: the pulse repetition frequency is 400Hz, the bandwidth is 2GHz, the center frequency is 10GHz, the sampling frequency is 2GHz. and the range resolution is 3/40m. To avoid sub-image degradation caused by the rotational motion, the number of the echoes should be limited. Suppose that D_r and D_a are the maximum in range and azimuth directions of the target respectively. The following equations should be satisfied in RD algorithm.

$$\begin{cases} D_r < \dfrac{4{\rho_x}^2}{\lambda} \\ D_a < \dfrac{4\rho_x\rho_y}{\lambda} \end{cases} \tag{10}$$

As D_a is supposed to be 4, the number of echoes is limited to 100 according to equations (7) and (10). We take 500 echoes for ISAR imaging and divide the echoes to five equal parts. 100 echoes are used for producing one sub-image and the migration of the scatterers in each sub-image is not through resolution cell. According to (8), the azimuth resolution is 0.08m. The distance between C and D is 0.16m. So C and D can be separated theoretically. The imaging results of the traditional RD algorithm and the proposed algorithm are shown in Fig. 4 and Fig. 5.

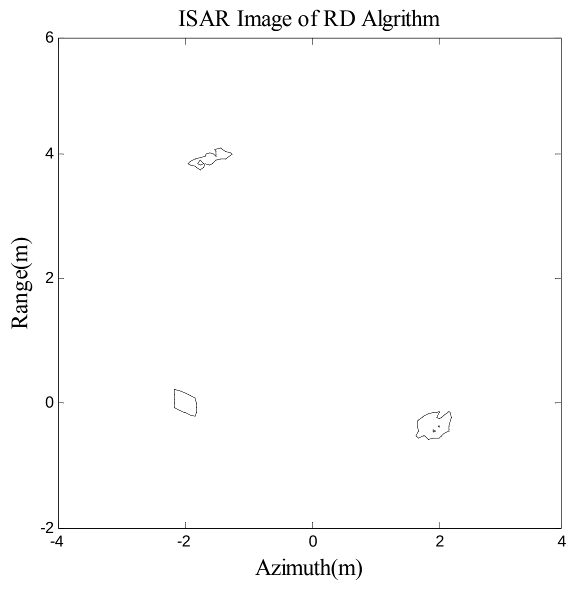

Fig. 4 ISAR image of RD algorithm

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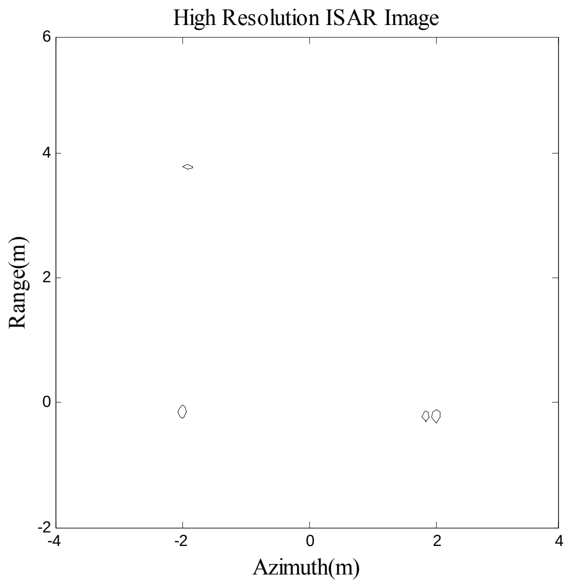

Fig.5 ISAR image of the proposed algorithm

It can be seen from the simulations that the points C and D are mixed in the image generated by the RD algorithm. However, they can be separated by the proposed algorithm in this paper.

IV. Conclusion

To compensate the MTRC in the situation of large rotation angle, a new algorithm is proposed in this paper. The algorithm is utilized by dividing the large-angle high-resolution imaging process into multiple small-angle low-resolution images. Firstly, we should divided the echoes into several parts and do echo segment imaging. Then after image scaling, image rotation, image translation, inverse process of ISAR imaging, data splicing and re-ISAR imaging, high resolution image will be produced. It is verified by simulation results.

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