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Two-dimensional Length Extraction of Ballistic Target from ISAR Images Using a New Scaling Method by Affine Registration

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ABSTRACT

The length of ballistic target is one of the most important features for target recognition. It can be extracted from ISAR Images. Unlike from the optical image, the length extraction from ISAR image has two difficulties. The first one is that it is hard to get the actual position of scattering centres by the traditional target extraction method. The second one is that the ISAR image's cross scale is not known because of the target's complex rotation. Here we propose two methods to solve these problems. Firstly, we use clustering method to get scattering centers. Secondly we propose to get cross scale of the ISAR images by affine registration. Experiments verified that our approach is realisable and has good performance.

Keywords: ISAR image, affine registration, cross scaling, scattering center, clustering

1. INTRODUCTION

In ballistic missile defence system, wideband radars are widely used to get the ISAR images by range compression and azimuth compression[1]. As we know, images are hard to be used for automatic target recognition directly. Extracted features such as target's length, shape are more likely used[2]. This paper focuses on the two-dimensional length extraction of ballistic target from ISAR images. Which can help to differentiate targets such as seeking warheads from decoys.

Commonly, the length extraction from optical images is not very difficult. But for ISAR images obtained by microwave sensors, the extraction has difficulties. The first one is scattering centres extraction because of the ISAR image's specialty. A lot of research is done for target extraction from SAR image[3-4]. These use the edge information to get target. But for ISAR images of ballistic targets, these methods are not quite effective. The second one is the ISAR image's cross scale is not known because of the target's complex rotation. At present, cross scale algorithms are mainly used for the uniform rotating targets. Nagesha[5] presents a scaling method based on trajectory fitting. Xi[6] presents a method based on chirp rate estimation where the imaging angle is estimated according to the cross chirp rate. Yong[7] proposes a method to estimate the cross scale by the third order phase estimation. However, for ballistic targets, the posture changing is highly non-uniform. The ISAR image is gotten by range-instantaneous-Doppler (RID) imaging algorithm[8-10]. The cross scale is decided by the instant rotation speed. It can not be estimated by rotation angle or trajectory fitting. The algorithms[5-7] above can not be used for non-uniform rotating targets. These are not applicable for ballistic targets.

Here we have proposed two methods to solve these problems. Firstly, we use clustering method to get scattering centres. This method is suitable for ballistic target extraction from an ISAR image. Secondly we propose to get cross scale of the ISAR images by affine registration. This method needs two ISAR sub-aperture images. Because the relative positions of scattering centres in ISAR images are fixed[11], it can be verified that the ISAR images can be registered only when the cross scales are correct. Based on this conclusion, the paper proposes a new scaling method by affine transform. The merit is that it can be used for non-uniform rotation targets. At last, the length is extracted based on the results above. Experiment results have shown good performance.

2. ISAR IMAGE OF BALLISTIC TARGET

2.1 Specialty of Ballistic Target ISAR Image

Compared with the space shuttles, space stations or man-made satellites, the ballistic targets are often rotation-symmetric. Rotation around the axis does not change the shape. Therefore, the scattering field does not change either. According to the geometry optics (GO) computing theory, the scattering field is only affected by the area round the diffraction. Theory computation and measured data verified this conclusion[11]. So, the total scattering field can be seen as the composition of diffraction of some local parts. These local parts are called scattering centres. In geometry, these are some discontinuous locations on the target surface. For ballistic target, these scattering centres are some fixed locations in the section through the axis. The typical target shape and scattering centre model is shown in Fig. 1.

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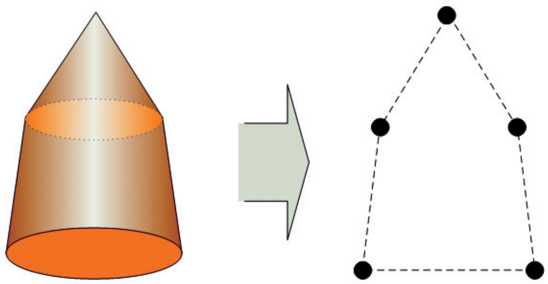

Figure 1. Typical ballistic target and its scattering centre composition.

Because the target is rotation-symmetric, the rotation around its axis does not change the scattering centre model. Based on the ISAR imaging theory, the ISAR image reflects the distribution of scattering centres. Because the scattering centres are in accordance with the fixed positions on the target, the relative positions will not change in different ISAR images. This conclusion will be a support for our algorithm for the cross scaling.

2.2 Cross Scale of ISAR Image

Suppose the radar transmits linear frequency-model (LFM) signal. The typical imaging geometry is shown in Fig. 2 where *u*, *v* are radar coordinates and *x*, *y* are target coordinates.

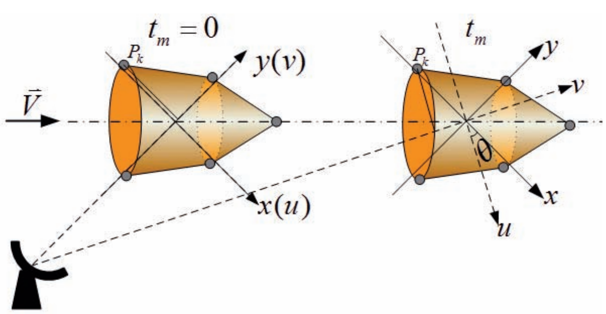

Figure 2. Geometry of radar on target for ISAR imaging.

According to Guangyue and Zheng[9], the target under microwave light can be regarded as the combination of several scattering centres. Denoting K as the total number of scattering centres, A_k as the scattering amplitude, and R_k as the distance between the scattering centres of target and radar, the radar echo after stretch processing is

$$S_i(\hat{t})=\sum_{k=1}^{K} A_k \,\mathrm{rect}\left(\frac{\hat{t}-2R_k/C}{T_p}\right)\exp\left\{-j\frac{4\pi}{C}f_c\left(R_k-R_{ref}\right)\right\}$$
$$\exp\left\{-j\frac{4\pi}{C}\gamma\left(\hat{t}-\frac{2R_k}{C}\right)\left(R_k-R_{ref}\right)\right\}\exp\left\{j\frac{4\pi\gamma}{C^2}\left(R_k-R_{ref}\right)^2\right\} \quad (1)$$

where γ is the chirp rate of LFM signal, C is the velocity of the light, T_p is the pulse width, f_c is the central frequency, and $\hat{t}$ is the sampling time. Range compression can be realised by Fourier Transform (FT). Define $\Delta R_k = R_k - R_{ref}$, the high resolution range profile (HRRP) is

$$S_r(f_i)=\sum_{k=1}^{K} A_k T_p \,\mathrm{sinc}\left[T_p\left(f_i+\frac{2\gamma\Delta R_k}{C}\right)\right]\cdot\exp\left\{-j4\pi\left(\frac{f_c\Delta R_k}{C}+\frac{\gamma\Delta R_k^{\,2}}{C^2}+\frac{f_r\Delta R_k}{C}\right)\right\} \quad (2)$$

Equation (2) shows that a pulse appears at the position where $f_i=-2\frac{\gamma}{c}\Delta R_k$. If the sampling frequency is f_s, the total sample points number is $N=T_p f_s$. Define B as the radar bandwidth which is equal to γT_p. If we do range compressing by N'-points FFT, the distance between two neighbored sample points is:

$$\sigma_r=\frac{fs}{N'}\frac{c}{2\gamma}=\frac{N}{N'}\frac{C}{2B} \quad (3)$$

Equation (3) shows that the range scale is determined by the bandwidth. It can be calculated precisely.

Aperture synthesising is executed after range compression. The aperture synthesising time is $\left[-T_m/2, T_m/2\right]$. Considering the posture changing separately, the target motion can be regarded as rotating around the reference centre. Under the far-field condition, the rotation can be regarded as uniform rotation. Define ω as rotation speed, the projection distance on the radar line-of-sight (LOS) between the scattering centre k and the reference centre can be expressed in one order approximation which is

$$\Delta R_k(t_m)=x_k\omega t_m + y_k \quad (4)$$

Equation (4) to Eqn. (2), omitting the $x_k\omega t_m$ impact on the profile, compensate the RVP phase (the second and the third phase item in Eqn. (2)), and do Fourier transform for t_m to compress in cross range. The ISAR image can be expressed as

$$s_{if}(f_i,f_m)=\sum_{k=1}^{K}\left\{AT_p e^{-j\frac{4\pi f_c y_k}{c}}\cdot\mathrm{sinc}\left[T_p\left(f_i+\frac{2\gamma y_k}{c}\right)\right]\cdot\mathrm{sinc}\left[MT_{prf}\left(f_m+\frac{2f_c\omega x_k}{c}\right)\right]\right\} \quad (5)$$

Supposing the number of pulses for aperture synthesis is M. The cross scale between two points after do M' FT points is

$$\sigma_c=\frac{\lambda}{2M'\omega\cdot PRT} \quad (6)$$

Equation (6) shows that the cross scale is decided by rotation speed. If the rotation speed is not constant, the image will be ambiguous. A common choice is substituting FFT with time frequency transform such as short time Fourier transform (STFT) which is called RID algorithm. Therefore, the cross scale is determined by the instant rotation speed.

2.3 Precession of the Ballistic Target and Effects on the ISAR Imaging

The ballistic target is a kind of target with some special motion characteristics. For effective ground attack, warheads are usually designed to spin around their axis to ensuring that it has a almost fixed direction when interfered by other forces. In practice, some extra forces are inevitable. The targets will precess around an axis called precess axis. The geometry is shown in Fig. 3.

Except for the rotation around itself which does not change the scattering field, the posture changing relative to radar can

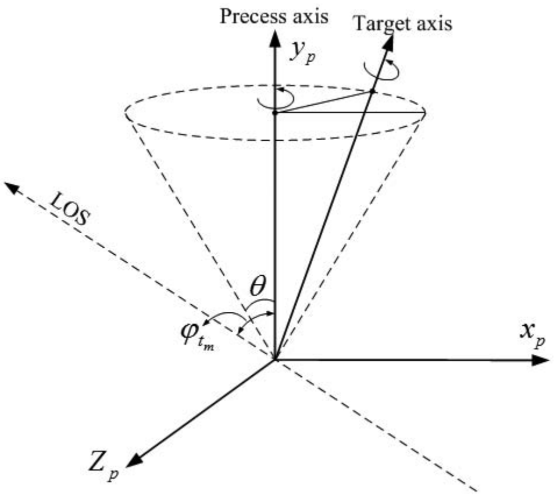

Figure 3. The rotation of ballistic target.

be divided into two processes. The first one is that the target sways in the plain formed by precess axis and the LOS. The second one is that the target rotates around the LOS. Because the target is rotation-symmetric, the second process does not change the scattering field. Such a complex rotation can be equivalent to a one-dimensional swaying in the plain formed by the precess axis and the LOS[12-13]. Under this equivalent, the sway angle changing will be highly non-uniform. To get clear ISAR image, the RID ISAR imaging algorithm is often applied. The ISAR images's cross scale is determined by the instant rotation speed, therefore, alogrithms[5-7] are not applicable.

3. TWO-DIMENSIONAL LENGTH EXTRACTION FROM ISAR IMAGES

3.1 Target Extraction with Clustering from ISAR Images

For ballistic target's ISAR images gotten at microwave band, these are composed of a few distributed scattering centres. Target extracting is to extract the scattering centres. For ballistic target ISAR image, which is composed of some distinct scattering centres, clustering technique was choosen to get the target. For ISAR images with overlapping and elongated clusters, one can use image segmentation method to extract the target.

Define *f(x, y)* as the original ISAR image of the target where $z_1 < f(x,y) < z_2$. Firstly, one needs to set a threshold z to screen the background.

$$\begin{cases} a(x,y) = f(x,y), & if \;\; f(x,y) \geq z \\ a(x,y) = 0, & if \;\; f(x,y) < z \end{cases} \tag{7}$$

Commonly, the threshold can be gotten by statistics of the image. After the filtering above, one gets a rather clean image *a(x, y)*. Then we should set the minimum scattering centre distance. Every single point whose intensity is not zero is defined as one scattering centre. If the distance between two centres is shorter than the minimum scattering centre distance, these two centres are clustered into one new scattering centre, till all the distances between two scattering centres are longer than the minimum scattering centre distance. The clustering process is over.

3.2 Registration of Ballistic Target ISAR Images

From Section 2, it is known that the scattering centres have fixed relative positions. So, two ISAR images can be registered. In the following text, it will be proved that two images can be registered only when the cross scale is right.

Define *f*(*x*,*y*) as the original ISAR image of target under real scale, image *A* and image *B* are two ISAR images under some postures. Compared with the original image *f*(*x*,*y*), images *A* and *B* have a certain rotation with angle θ_1, θ_2. Image *A* and *B* are

$$\begin{cases} g(x,y) = f\left(x\cos\theta_1 - y\sin\theta_1, y\cos\theta_1 + x\sin\theta_1\right) \\ h(x,y) = f\left(x\cos\theta_2 - y\sin\theta_2, y\cos\theta_2 + x\sin\theta_2\right) \end{cases} \tag{8}$$

In practical situations, the cross scales have mistakes. The wrong-scaled images A' and B' with flex coefficients a_1 and a_2 are

$$\begin{cases} g(x,y) = f\left(a_1\left(x\cos\theta_1 - y\sin\theta_1\right), y\cos\theta_1 + x\sin\theta_1\right) \\ h(x,y) = f\left(a_2\left(x\cos\theta_2 - y\sin\theta_2\right), y\cos\theta_2 + x\sin\theta_2\right) \end{cases} \tag{9}$$

The registration includes cross flex and rotation of the image. Supposing the flex parameters of images A' and B' is b_1 and b_2 ($b_1 > 0$, $b_2 > 0$), and the rotation angles are γ_1 and γ_2, images A'' and B'' after flex and rotation are

$$\begin{cases} p(x,y) = f\left(a_1 b_1\left(x\cos\gamma_1 - y\sin\gamma_1\right)\cos\theta_1 - \left(y\cos\gamma_1 + x\sin\gamma_1\right)\sin\theta_1,\right. \\ \qquad\qquad \left.\left(y\cos\gamma_1 + x\sin\gamma_1\right)\cos\theta_1 + a_1 b_1(x\cos\gamma_1 - y\sin\gamma_1)\sin\theta_1\right) \\ q(x,y) = f\left(a_2 b_2\left(x\cos\gamma_2 - y\sin\gamma_2\right)\cos\theta_2 - \left(y\cos\gamma_2 + x\sin\gamma_2\right)\sin\theta_2,\right. \\ \qquad\qquad \left.\left(y\cos\gamma_2 + x\sin\gamma_2\right)\cos\theta_2 + a_2 b_2\left(x\cos\gamma_2 - y\sin\gamma_2\right)\sin\theta_2\right) \end{cases} \tag{10}$$

If the image is registered, the scattering centres should have the same positions. So the equations below should be satisfied.

$$\begin{cases} a_1 b_1 \cos\gamma_1 \cos\theta_1 - \sin\gamma_1 \sin\theta_1 = a_2 b_2 \cos\gamma_2 \cos\theta_2 - \sin\gamma_2 \sin\theta_2 \\ \cos\gamma_1 \sin\theta_1 + a_1 b_1 \sin\gamma_1 \cos\theta_1 = \cos\gamma_2 \sin\theta_2 + a_2 b_2 \sin\gamma_2 \cos\theta_2 \\ \sin\gamma_1 \cos\theta_1 + a_1 b_1 \cos\gamma_1 \sin\theta_1 = \sin\gamma_2 \cos\theta_2 + a_2 b_2 \cos\gamma_2 \sin\theta_2 \\ \cos\gamma_1 \cos\theta_1 - a_1 b_1 \sin\gamma_1 \sin\theta_1 = \cos\gamma_2 \cos\theta_2 - a_2 b_2 \sin\gamma_2 \sin\theta_2 \end{cases} \tag{11}$$

It is easy to verify that the only answer of the equations above is

$$\begin{cases} b_1 = 1/a_1 \\ b_2 = 1/a_2 \end{cases} \tag{12}$$

Substituting Eqn. (12) to Eqn. (10), after doing flexing with images A' and B', the images after flex are

$$\begin{cases} g'(x,y) = f\left(x\cos\theta_1 - y\sin\theta_1, y\cos\theta_1 + x\sin\theta_1\right) \\ h'(x,y) = f\left(x\cos\theta_2 - y\sin\theta_2, y\cos\theta_2 + x\sin\theta_2\right) \end{cases} \tag{13}$$

Comparing Eqn. (13) with Eqn. (8), it shows that the images are restored with right scale. Therefore it is realisable to scale the ISAR image if the flex coefficients b_1 and b_2 are obtained.

3.3 ISAR Image Cross Scaling based on Affine Transform

Image register can be accomplished by many techniques. Here, with the position of the scattering centres obtained above by clustering, the affine transform was choosen to register the images.

The above section verified that the two images will be restored with correct scales after the registration. To scale the ISAR image, the key is to get the flex coefficients b_1 and b_2. Analysing the process above, it is easy to find that the image A' can be transformed to image B' with three steps. The first step is cross flex. The cross flex parameter is α_1 which is equivalent to b_1. The second step is rotation. The rotation angle is θ, which is equivalent to $\theta_2-\theta_1$. The last step is cross flex again. The flex parameter is α_2, which is equivalent to $1/b_1$. So the three steps can be described as three transform matrices.

$$M_1=\begin{bmatrix}\alpha_1 & 0\\ 0 & 1\end{bmatrix} \tag{14}$$

$$M_2=\begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix} \tag{15}$$

$$M_3=\begin{bmatrix}\alpha_2 & 0\\ 0 & 1\end{bmatrix} \tag{16}$$

After registration, the scattering centre (x, y) in image A' is projected to (x', y') in image B'. The transform is expressed as

$$\begin{pmatrix}x'\\ y'\end{pmatrix}=M_3M_2M_1\begin{pmatrix}x\\ y\end{pmatrix}=\begin{bmatrix}\alpha_1\alpha_2\cos\theta & -\alpha_2\sin\theta\\ \alpha_1\sin\theta & \cos\theta\end{bmatrix}\begin{pmatrix}x\\ y\end{pmatrix} \tag{17}$$

The equation above is a typical affine transform. The key of the transform is to get the matrices $M_3M_2M_1$. This research has been done by many researchers[14]. The affine transform based on controlled points is applied here. Define M as the registration matrix which has four elements.

$$M=\begin{bmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{bmatrix} \tag{18}$$

This matrix should be equal to the matrices $M_3M_2M_1$. Therefore, the equations below should be satisfied.

$$\begin{cases}\alpha_1\alpha_2\cos\theta-m_{11}=0\\ \alpha_2\sin\theta+m_{12}=0\\ \alpha_1\sin\theta-m_{21}=0\\ \cos\theta-m_{22}=0\end{cases} \tag{19}$$

From the formula above, one can get:

$$\begin{cases}\alpha_1=-\dfrac{m_{21}}{m_{12}}\sqrt{-\dfrac{m_{11}m_{12}}{m_{21}m_{22}}}\\ \alpha_2=\sqrt{-\dfrac{m_{11}m_{12}}{m_{21}m_{22}}}\\ \theta=\operatorname{atan}\left(-\dfrac{m_{12}}{m_{11}}\right)\end{cases} \tag{20}$$

In practice, mistakes will be induced inevitably. The Eqn. (19) (three unknown parameters with four equations) can not be fully satisfied. The optimised solution can be obtained through optimisation method based on the least square error criterion. Define the criterion function:

$$f=\left\|\alpha_1\alpha_2\cos\theta-m_{11}\right\|^2+\left\|\alpha_2\sin\theta+m_{12}\right\|^2+\left\|\alpha_1\sin\theta-m_{21}\right\|^2+\left\|\cos\theta-m_{22}\right\|^2 \tag{21}$$

The optimisation procedure is searching the parameters to let $f\to\min$. Many algorithms such as the Newton-Poisson algorithm[15] can be employed. The procedure needs a start point. It can be gotten by solving Eqn. (20). When the optimised solution for Eqn. (21) is obtained, the ISAR image can be scaled by Eqn. (10).

3.4 Two-dimension Length Extraction for Ballistic Target

Define the centres of certain scattering centres gotten by clustering

$$\begin{cases}\bar{x}_k=\sum_{i=1}^{N_k}x_i\\ \bar{y}_k=\sum_{i=1}^{N_k}y_i\end{cases} \tag{22}$$

Because we have gotten the range and cross range scale σ_r and σ_c. So the distances at range direction and cross direction are

$$\begin{cases}dx_{jk}=\left\|\bar{x}_j-\bar{x}_k\right\|\cdot\sigma_c\\ dy_{jk}=\left\|\bar{y}_j-\bar{y}_k\right\|\cdot\sigma_r\end{cases} \tag{23}$$

The distance between two scattering centres is

$$d_{jk}=\sqrt{\left(\bar{x}_j-\bar{x}_k\right)^2\cdot\sigma_c^{\,2}+\left(\bar{y}_k-\bar{y}_k\right)^2\cdot\sigma_r^{\,2}} \tag{24}$$

4. EXPERIMENTS AND RESULTS

Experiments were executed to verify the proposed algorithm. The ballistic missile flies without forces from the point (-50, 000 m; 6,360,000 m; 19,000 m) at earth-fixed coordinates with initial velocities (2000 m/s, 2000 m/s, 0 m/s). The wideband radar has 1 GHz bandwidth. The central frequency is 10 GHz. Pulse width is 60 µs. The target precession period is 5 s. The precession angle is 10°. Figure 4 (a) describes the ballistic target motion scenery. Figure 4(b) pictures the target shape. Figure 4(c) shows the target dimensions.

The pulse repeat frequency (PRF) is 300 Hz. The radar observation starts at 200 s after the beginning of fly without

(a) (b) (c)

Figure 4. The target motion scene and target shape: (a) The scenery (b) target shape, and (c) target dimensions.

driving forces. The data is gotten by interpolation from the all posture scattering database calculated by electromagnetism software. 24,000 pulses were sampled in total. Eight times interpolation was adopted when executing range compression. The HRRP series and rotation speed is shown as Fig. 5(a) and Fig. 5(b).

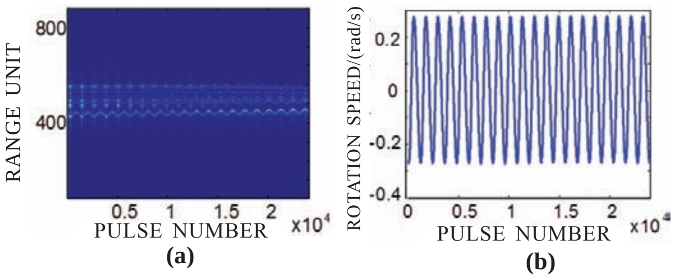

Figure 5. The HRRP series and rotation speed curve: (a) The HRRP series of target, and (b) the rotation speed curve.

The rotation speed curve shows that the rotation is highly non-uniform. It is hard to get clear ISAR image by RD algorithm. Here, RID algorithm was adopted with STFT. The imaging results based on 1-80 pulses and 10001-10080 pulses are shown in Fig. 6(a) and 6(b). The cross scale was also interpolated with 8 times. So the ISAR image size is 800 p × 640 p. Because the rotation speed was not known in advance, the cross range can not be scaled. Here, it was scaled equally with the range scale temporarily. According to the scattering centres distribution, control points were extracted by clustering. The control points 1-5 used for registration are shown in Fig. 6(a) and 6(b) with black dots. Comparing with Fig. 4(b), one can see that the target shape has changed because of the scaling error. The length between point 3 and point 5 in

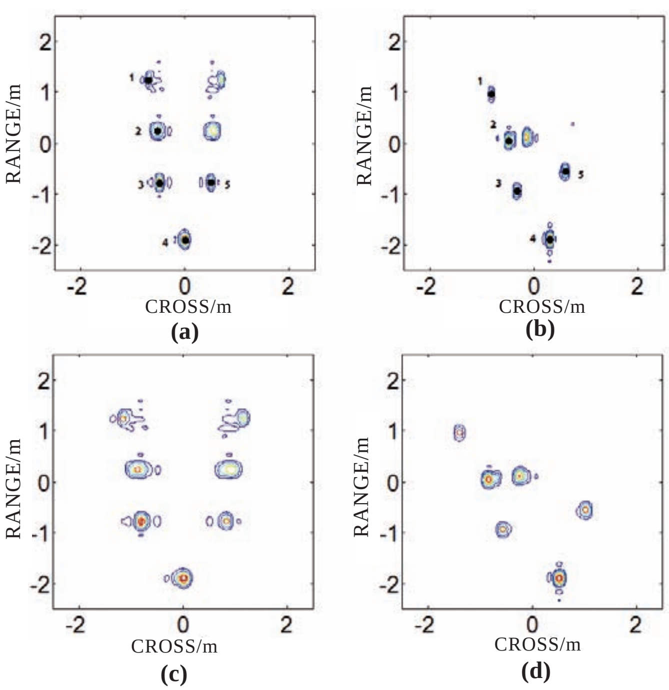

Figure 6. The scaled ISAR images under the algorithm: (a) original ISAR image A, (b) original ISAR image B, (c) ISAR image A after scaling, and (d) ISAR image B after scaling.

Fig. 6(a) is about 1 m. It is much shorter than the real value, 1.5 m. Images distort severely in cross range. Based on the new estimated scale, the updated scaled images are shown as Fig. 6(c) and 6(d).

Through affine transform of the extracted centres and parameter optimization, the estimated parameter is:

$$\begin{cases} \alpha_1 = 1.6340 \\ \alpha_2 = 0.5917 \end{cases} \tag{25}$$

So the estimated cross scale is

$$\begin{cases} \sigma_1 = 0.15/8 \times 1.6340 = 0.0306 \\ \sigma_2 = 0.15/8/0.5917 = 0.0317 \end{cases} \tag{26}$$

Substituting the rotation speed $\omega = 0.261 rad/s$ at pulse 41 and $\omega = 0.241 rad/s$ at pulse 10041 to Eqn. (6), it can be obtained that the correct cross scale is $\sigma_1 = 0.0269$, $\sigma_2 = 0.0291$. So, the error is 13.9 per cent and 8.9 per cent. So one can get that the distance in range is 3.156 m. The distance in cross range is 2.276 m. The error is 0.006 m and 0.276 m.

Because errors exist in the scattering centres extraction and affine registration, the result will have some errors inevitably. Of course, may be some other clustering and registration techniques can be used in our algorithms to reduce the errors. We do not intent to try every means here.

5. CONCLUSIONS

For ballistic target length extraction from ISAR images, two important tasks should be done. One is the scattering enters extraction. Another is the cross scaling. Here, we have proposed to get scattering centres by clustering and get cross scale by affine registration. Theoretical analysis and experiments prove its feasibility and correctness of the algorithm. Here, the author would like to figure out that this algorithm can be used only for rotation-symmetric targets. For other targets, because of the three-dimensional rotation, these algorithm is not suitable.

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