Research Article

Rotation Estimation for Wide-Angle Inverse Synthetic Aperture Radar Imaging

Wei Zhou,¹ Chun-mao Yeh,² Rui-jin Jin,¹ Jian Yang,¹ and Jian-she Song³

¹Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

²Beijing Institute of Radio Measurement, Beijing 100854, China

³Xi'an Research Institute of Hi-Technology, Xi'an 710025, China

Correspondence should be addressed to Wei Zhou; zhouw06@mails.thu.edu.cn

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To present focused ISAR imaging results in the homogenous range and cross-range domain, an integrated scheme is proposed to estimate both the targets equivalent rotational velocity (RV) and rotational center (RC). The RV estimation is improved by radial projection combined with keystone processing, and then the RC is estimated through image entropy minimization. Finally, delicate imaging results may be obtained for wide-angle scenarios. Experiment results are provided to demonstrate the effectiveness of the proposed method.

1. Introduction

Inverse synthetic aperture radar (ISAR) may provide high-resolution images for noncooperative moving targets [1], and it has been widely used for both military and civilian purposes [2, 3]. ISAR gets high range resolution by transmitting and processing waveform with large bandwidth and gets high cross-range resolution by coherently processing echoes from different aspect angles. Generally speaking, with careful imaging interval selection [4, 5], the target's movement is usually considered as planar rotation relative to the radar after effective translational motion compensation (TMC).

When the integrated aspect angle interval is small, ISAR images may be formed using the efficient range-Doppler (RD) algorithm. For better image understanding and target feature extraction, it is more preferable to rescale the RD image into the homogeneous range-cross-range domain. However, the cross-range scaling factor (SF) is related to the rotational velocity (RV) of the target, which is usually unknown, and it should be estimated for a noncooperative moving target. Furthermore, when echoes are collected from a relatively large aspect angle interval, more sophisticated imaging algorithms such as convolution back projection

(CBP) algorithm or the polar format algorithm (PFA) should be used to compensate the scattering centers' migration through resolution cells (MTRC). In these cases, both the RV and the equivalent rotational center (RC) should be known, which are necessary for high-resolution ISAR image forming and understanding.

In recent years, a number of methods have been proposed for the RV estimation from collected wideband echoes. These data-driven methods may be roughly categorized into three classes. The first is to search the RV which provides the best image focusing quality using the PFA [6], CBP [7], or a frame processing [8] structure. These methods are limited by the computation burden, and their effectiveness may be undermined by the unknown RC. The second is to get the RV by exploiting the high-order phase coefficients [9–15] of prominent scattering centers. This kind of methods may be limited by the scattering centers' MTRC as well as the computational burden. The third is to search the RV by exploiting the target's pose difference on RD image series [16–18]. However, the extraction and association of scattering centers between neighboring images may be difficult to implement due to the aspect angle change. In order to avoid the extraction and association of scattering centers, a method based on image

rotation correlation was proposed in [17], but the accuracy may also be undermined by the unknown RC. Later, an equivalent algorithm using two-dimensional (2D) Fourier transform (FT) and polar mapping was proposed in [18] to eliminate the impact of the target's unknown RC. However, the computation is still not so efficient for the 2D interpolation in each iteration.

In this paper, a method combining the 2D FT with radial projection is proposed to estimate the RV. The radial projection is used to convert the 2D maximum correlation into a one-dimensional (1D) polar curve matching problem. Then, a representation of the polar curves using the cosine series is introduced to avoid the interpolation operation. With an easy initialization, the 1D maximization problem can be solved in a few iterations more efficiently.

There have been few reports about the estimation of the target's RC in open literatures. Here, on the basis of effective RV estimation, the RC may be found with the minimum entropy criterion. With all the rotational parameters, the delicate CBP imaging algorithm is then used to generate size-scaled ISAR images with high resolution.

The paper is organized as follows. The existing RV estimation methods are introduced in Section 2 based on image correlation and polar mapping. Then, the improved RV estimation method is proposed in Section 3 based on radial projection. With the known RV, the equivalent RC of ISAR targets is determined by a minimum entropy criterion. Finally, experimental results with both simulated and collected wideband echoes are provided to demonstrate the effectiveness of the proposed parameter estimation scheme.

2. RV Estimation Based on Image Correlation

After careful imaging interval selection and effective TMC, an ISAR target may be considered as a uniformly planar rotating object as shown in Figure 1. (r_o, θ_o) is the polar coordinates for an arbitrary scattering center $P(x_o, y_o)$, r_a is the distance from the radar to the RC, and the far-field condition is satisfied when $r_a \gg r_o$. For a RD image formed around t_m , the scatter center is mapped on the discrete image domain as [17]

$$\begin{aligned} X(t_m) &= \frac{[r_c + x_o \cos(\omega_o t_m) - y_o \sin(\omega_o t_m)]}{\eta_r}, \\ Y(t_m) &= \frac{[x_o \sin(\omega_o t_m) + y_o \cos(\omega_o t_m)]}{\eta_a}, \end{aligned} \quad (1)$$

where ω_o is the unknown RV, r_c is the range bias of RC and is supposed to be a constant after TMC, $\eta_r = c/(2f_s)$ is the range SF, $\eta_a = \lambda f_r / (2M\omega_o)$ is cross-range SF, f_s is the sampling frequency, c is the velocity of light, λ is the wavelength, f_r is the pulse repetition frequency, and M is the number of accumulated pulses for this RD image.

FIGURE 1: Rotating target imaging geometry.

Suppose that two RD images are formed at t_{m1} and t_{m2} by equally dividing all received echoes in the coherent processing interval (CPI). Then, the scatters' coordinates on two RD images are related as follows:

$$\begin{bmatrix} X(t_{m2}) \\ Y(t_{m2}) \end{bmatrix} = H(\theta_d) \begin{bmatrix} X(t_{m1}) \\ Y(t_{m1}) \end{bmatrix} + \begin{bmatrix} X_c \\ Y_c \end{bmatrix}. \quad (2)$$

There is a displacement term $[X_c, Y_c]^T$ in (2) caused by the range bias of RC, $\theta_d = \omega_o(t_{m2} - t_{m1})$ is the aspect angle difference between the neighboring RD images, and $H(\theta_d)$ is a generalized rotational matrix, given by

$$\begin{aligned} H(\theta_d) &= \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \\ &= \begin{bmatrix} \cos(\theta_d) & -\left(\frac{\eta_a}{\eta_r}\right) \sin(\theta_d) \\ \left(\frac{\eta_r}{\eta_a}\right) \sin(\theta_d) & \cos(\theta_d) \end{bmatrix}. \end{aligned} \quad (3)$$

Equation (2) shows that there is a translation and a generalized rotation between two adjacent RD images. With this linear mapping relationship, a method based on the concept of rotation correlation was proposed to obtain the RV in [17]. However, the accuracy of RV estimation may be affected by the unknown RC. Later, the authors in [18] proposed to use two-dimensional (2D) Fourier transform (FT) and polar mapping to eliminate the impact of the target's unknown RC. The 2D FT is defined by

$$F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y) e^{-j2\pi ux} e^{-j2\pi vy} dx dy, \quad (4)$$

where $F(u, v)$ is the 2D FT of the image $I(x, y)$.

Let $I_k(x, y)$ be the RD image formed around t_{mk} , $k = 1, 2$, and $F_k(u, v)$ is the relative 2D spectrum. Then, based on the linearity of FT, we will get

$$F_2(u, v) = F_1((u, v) H(\theta_d)) \cdot \exp(-j2\pi(u, v) H(\theta_d) (X'_o, Y'_o)^T). \quad (5)$$

By taking amplitudes of the spectrum on two sides, the influence of unknown RC is eliminated; that is,

$$|F_2(u, v)| = |F_1((u, v) H(\theta_d))|. \quad (6)$$

The normalized power spectrum is defined as follows:

$$\varepsilon_k(u, v) = \frac{|F_k(u, v)|^2}{|F_k(0, 0)|^2}, \quad k = 1, 2. \quad (7)$$

Then, in the polar coordinate system, $\rho = \sqrt{u^2 + v^2}$, $\theta = \arctan(v/u)$, the normalized energies become

$$\bar{\varepsilon}_2(\rho, \theta) = \bar{\varepsilon}_1(\lambda(\theta; H) \rho, \varphi(\theta; H)), \quad (8)$$

where

$$\begin{aligned} \bar{\varepsilon}_k(\rho, \theta) &= \varepsilon_k(\rho \sin \theta, \rho \cos \theta), \quad k = 1, 2, \\ \lambda(\theta; H) &= ((h_{11} \cos \theta + h_{21} \sin \theta)^2 \\ &\quad + (h_{12} \cos \theta + h_{22} \sin \theta)^2)^{1/2}, \\ \varphi(\theta; H) &= \arctan \left(\frac{h_{12} \cos \theta + h_{22} \sin \theta}{h_{11} \cos \theta + h_{21} \sin \theta} \right). \end{aligned} \quad (9)$$

Here, $\lambda(\theta; H)$ may be treated as a SF in the radial direction and $\varphi(\theta; H)$ represents the relative angular displacement. If $H(\theta_d)$ is a standard rotation matrix, which means $\eta_r/\eta_a = 1$, it is easy to show that $\lambda(\theta; H) = 1$, for all θ , and $\varphi(\theta; H) = \theta + \theta_d$ is a simple translation. Therefore, the target's rotation in image domain was converted to only translation on the polar spectrum images. The same idea was used in [18] for the estimation of RV, although the relationship between two polar images is not given directly like (8). However, the computation is still not so efficient for the 2D interpolation which is required in each iteration. Further, when the aspect angle is relatively large, the two subaperture images may be defocused and the performance of the RV estimation may be decreased. Still, no information about the RC is given by these two methods, and thus this may hamper focused image forming with large aspect angle. Based on this, three main improvements are proposed in this paper:

- (1) The keystone transform is introduced in the preprocessing step to get better focused subaperture images.
- (2) The radial projection is introduced for the estimation of RV, and the time cost 2D image interpolation and correlation operations are avoided.
- (3) With the estimated RV, a method is proposed to search the RC based on minimum entropy criterion, and both the RV and RC may be provided for focused image forming with large aspect angle.

FIGURE 2: Proposed method for rotation estimation.

A block diagram of the whole procedure for rotation estimation is illustrated in Figure 2, and the main differences compared with [17, 18] are shown with another color.

3. The Improved Rotation Parameters Estimation Method

3.1. RV Estimation Based on Radial Projection. Before the RD image formation of two subapertures, the keystone processing [19] is used to compensate the linear range migration through resolution cells, in order to get more focused subimages. Then, the two neighboring subimages are Fourier transformed, normalized, and polar mapped according to (4), (7), and (8).

To make the computation more efficient, we introduce the radial projection for the estimation of RV. Radial projection is proved to be an efficient and robust algorithm for the estimation of 2D affine transformations in frequency domain [20]. Here, the $H(\theta_d)$ can be treated as the affine transformation matrix between two neighboring RD images, and it is even more simple compared with the case of [20], because it is

determined by only one variable, while the transformation matrix in [20] has four degrees of freedom:

$$\begin{aligned}
 P\{Q_{dn} \leq T_d\} &= P\{\Lambda_{01} \leq T_d, \Lambda_{02} \leq T_d\} \\
 &= (P\{\Lambda \leq T_d\})^2 = (P_{fa,1})^2, \\
 P\{Q_d \leq T_d\} &= 1 - P\{Q_d \geq T_d\} \\
 &= 1 - (P\{Q_{dn} \geq T_d\})^N \\
 &= 1 - \left[1 - (P_{fa,1})^2\right]^N = P_{fa,d}.
 \end{aligned} \tag{10}$$

The radial projection is defined as

$$P_k(\theta) = \int_0^\infty \rho \bar{\epsilon}_k(\rho, \theta) d\rho, \quad k = 1, 2 \tag{11}$$

and the relationship between two projections is determined by

$$P_2(\theta) = \frac{1}{\lambda^2(\theta; H)} P_1(\varphi(\theta; H)). \tag{12}$$

According to (12), the RV can be estimated by solving a maximum correlation problem; that is,

$$\begin{aligned}
 \hat{\omega}_o = \arg \max_{\omega_o} C \left(P_2(\theta), \frac{1}{\lambda^2(\theta; H(\theta_d))} \right. \\
 \left. \cdot P_1(\varphi(\theta; H(\theta_d))) \right),
 \end{aligned} \tag{13}$$

where $C(\cdot)$ means the function of correlation coefficient, and we will replace it with $f(\omega_o)$ in the following sections for convenience.

In (13), $P_1(\varphi(\theta; H(\theta_d)))$ may be calculated numerically using interpolation method. Here, we propose to approximate $P_1(\theta)$ using cosine series to make the computation more efficient without loss of accuracy. $P_1(\theta)$ is a periodic function with period, so it can be approximated as

$$P_1(\theta) \approx \tilde{P}_1(\theta) = \gamma_0 + \sum_{m=1}^{M_0} \gamma_m \cos(2m\theta - \phi_m), \tag{14}$$

where

$$\begin{aligned}
 \alpha_m &= \frac{2}{\pi} \int_0^\pi P_1(\theta) \cos(2m\theta) d\theta, \quad m = 0, 1, \dots, M_0, \\
 \beta_m &= \frac{2}{\pi} \int_0^\pi P_1(\theta) \sin(2m\theta) d\theta, \quad m = 1, 2, \dots, M_0, \\
 \phi_m &= \arctan \frac{\beta_m}{\alpha_m}, \\
 \gamma_m &= \frac{\alpha_m}{\cos(\phi_m)}, \\
 \gamma_0 &= \frac{\alpha_m}{2}.
 \end{aligned} \tag{15}$$

M_0 is the number of terms used in the cosine series. Usually, 30–40 cosine series could have been used without any loss of accuracy. Here, we set $M_0 = 40$.

By combining (13) and (14), it is possible to solve the gradient of $f(\omega_o)$, but the optimization method based on gradient is not recommended. Here, the Nelder-Mead approach [21] is used to solve the optimization of (13), for it is a very effective line search method. Although an arbitrary initialization may be enough for the Nelder-Mead approach, a better start point can greatly reduce the number of iterations. Assuming the $H(\theta_d)$ to be a standard rotational matrix, there will be a simple translation between $P_1(\theta)$ and $P_2(\theta)$. If the radial projections in (11) are computed at increments $\Delta\theta = \pi/N_0$ (in our experiments, $N_0 = 360$) over $[0, \pi)$, then, ω_o can be initialized using

$$\begin{aligned}
 k &= \arg \max_k \left[\text{IFT}_\theta \left((\text{FT}_\theta(P_1))^* \text{FT}_\theta(P_2) \right) (k) \right], \\
 \omega_{o,\text{Init}} &= \frac{k\Delta\theta}{(t_{m2} - t_{m1})},
 \end{aligned} \tag{16}$$

where $\text{FT}_\theta(\cdot)$ and $\text{IFT}_\theta(\cdot)$ are the 1D FT and inverse FT in the θ -direction.

In the total procedure for the estimation of RV, the 2D interpolation is done only once in the polar coordinate system, and the 2D maximum correlation problem is converted to a 1D polar curve matching problem according to (13), which can be solved in a few numbers of iterations efficiently, so the computation burden is greatly reduced here.

3.2. RC Estimation Based on Entropy Minimization. When echoes are collected from a relatively large aspect angle interval in wideband radar imaging system, the target's MTRC cannot be ignored. In order to apply the delicate imaging algorithm like CBP for high-resolution imaging, not only the RV but also the RC should be known. The commonly used autofocus methods are not able to locate the target's equivalent RC in the RD images. Generally speaking, the range bias of RC is caused by the range alignment and the unknown reference point. It is usually difficult to estimate the RC directly. However, on the basis of effective RV estimation, the range bias of RC may be obtained by 1D searching directly.

After range compression and TMC, the radar echoes related to a single scatter $P(x_o, y_o)$ take the following form:

$$\begin{aligned}
 s(r_n, t_m) &= A_o \text{sinc} \left(\frac{2B}{c} (r_n - r_o(t_m)) \right) \\
 &\quad \cdot \exp \left(-j \frac{4\pi f_c}{c} r_o(t_m) \right),
 \end{aligned} \tag{17}$$

where A_o is the scattering coefficient, B is the bandwidth of the transmitted pulse, f_c is the carrier frequency, r_n is the sampling position in range direction, and $r_o(t_m)$ is the relative distance between the radar and the scattering point; that is,

$$r_o(t_m) = r_c - x_o \cos(\omega_o t_m) + y_o \sin(\omega_o t_m), \tag{18}$$

where r_c is the residual range bias of RC after TMC.

Taking the second-order approximation of (18) and substituting it into (17),

$$s(r_n, t_m) = A_o \operatorname{sinc}\left(\frac{2B}{c}(r_n - r_c + x_o - r'_o(t_m))\right) \cdot \exp(j\varphi_o) \exp\left(-j\frac{4\pi f_c}{c}r'_o(t_m)\right), \quad (19)$$

where $r'_o(t_m) = y_o\omega_o t_m + (1/2)x_o\omega_o^2 t_m^2$ is the scatter's migration during CPI and φ_o is a constant phase. The second-order phase component of (19) will cause a Doppler modulation and resulting blurring in cross-range direction. To compensate this rotating phase, the received echoes in (19) are shifted in range direction by τ and multiplied with the corresponding secondary phase compensation factor; that is,

$$s_\tau(r_n, t_m) = s(r_n + \tau, t_m) \exp\left(j\frac{4\pi f_c}{c}\frac{1}{2}r_n\omega_o^2 t_m^2\right). \quad (20)$$

The range position of RC is then estimated by the following:

$$\hat{r}_c = \min_{\tau} \operatorname{IE} \left\{ \left| \operatorname{FT}_{t_m}(s_\tau(r_n, t_m)) \right| \right\}, \quad (21)$$

where $\operatorname{FT}_{t_m}(\cdot)$ means FT in the cross-range direction to form the RD image, $\operatorname{IE}(\cdot)$ represents the 2D entropy function of the radar image [22], and the minimization of (21) can be solved by a simple line search in range direction.

With all the rotation parameters known, the CBP algorithm is then used to generate a high-resolution and rescaled image. The traditional CBP can be accelerated using GPU parallelization [23].

4. Simulations and Analysis

This section demonstrates the effectiveness and robustness of the proposed algorithm using both simulated and some collected ISAR data, and the algorithm proposed by [18] is taken for comparison during the RV estimation.

4.1. Simulation Results Using Point Scattering Model

4.1.1. RV and RC Estimation Results. In the numerical simulation, a 3D target which contains 330 isolated scattering points is used. The 3D model of the target and its three projected views are shown in Figure 3. The target is located 10 km away from the origin on the y -axis and moves along a straight line with speeds $V_x = 151.03$ m/s, $V_y = 87.20$ m/s, and $V_z = 0$ m/s. The simulated ISAR system transmits 400 chirp signals with 800-MHz bandwidth per second. The carrier frequency is 9.15 GHz, and the echoes are coherently demodulated and inphase/quadrature phase channel- (I/Q-) sampled with a rate of 1 GHz for pulse compression. The data collection time is 10.24 s, and during this time interval, the rotated angle is 8.8° , and the resulting RV is 0.015 rad/s. The simulated raw data is shown in Figure 4(a), the TMC is taken by minimum entropy methods [22], and the range compressed data after TMC is shown in Figure 4(b).

By dividing the received data equally into two parts and taking the keystone transform, the RD images are formed as in Figures 5(a) and 5(b). The corresponding squared FT magnitudes are shown in Figures 5(c) and 5(d). There is a clear rotation among the two radial projections (Figure 5(e)). $P_1(\theta)$ is approximated using 40 terms of cosine series (Figure 5(f)).

The RV is initialized to be 0.0124 rad/s using (16), and it takes 11 iterations to reach the maximum point (Figure 6(a)), respectively; the RV is estimated to be 0.0149 rad/s, which is very close to the theoretical value. Before estimating the RC, the image center of gravity is first moved to the zero point in RD domain to reduce the searching area; then, the range position of RC is searched by entropy minimization from $-15\eta_r$ to $15\eta_r$ with a step of η_r . Finally, the RC is estimated to be $\hat{r}_c = 3.15$ m (Figure 6(b)). With all the rotational parameters, the CBP algorithm is taken and the result is shown in Figure 6(d). Compared with the RD imaging result in Figure 6(c), the energy of scattering point in Figure 6(d) is well focused, and the size of the target is properly rescaled.

4.1.2. Performance Analysis. Since the estimation of RC is directly related to the result of RV estimation, this section only illustrates the effectiveness of the proposed RV estimation. The root mean square error (RMSE) of the proposed RV estimation method against the signal-to-noise ratio (SNR) is presented in Figure 7, and the RMSE curve of the proposed method in [18] is presented for comparison. It is shown that the proposed method outperforms the method in [18] for low SNR scenarios when radial projection is introduced for RV estimation, partially because the radial projection may be viewed as a feature extraction process with a weighting operator and thus may suppress the impact of the noise. What is more, the performance of RV estimation gets better when keystone processing is included in the rotation estimation scheme, as in Figure 7, because keystone processing compensates for the range migration of scattering centers in each RD image. Thus, an integrated RV estimation scheme in the proposed method includes both the keystone processing and radial projection.

Then, the performance of proposed RV estimation method is compared with the method in [18] when the image forming plane is not so stationary, which may occur for wide-angle ISAR imaging applications. In the first case, the target is rotating with a constant acceleration, where the central RV is set to be 0.015 rad/s. The RMSE of the RV estimation against different rotational acceleration, which varies from 10^{-5} rad/s² to 10^{-4} rad/s², is shown in Figure 8(a). It can be seen from Figure 8(a) that the RV estimation gets worse for both methods when the rotational acceleration gets larger because the focusing quality of each RD image degrades. However, the proposed method still outperforms the method in [18]. In the above analysis, the imaging plane is considered to be planar. In the second case, the imaging plane is disturbed with a periodic error. The period of the disturbance is set to be 2 s, while the amplitude of the disturbance varies from 0.2 deg. to 2 deg. The RMSE of the RV estimation

FIGURE 3: Three-dimensional model of the target, consisting of 330 points. (a) The three-dimensional distribution of the scattering points. (b) Front view. (c) Side view. (d) Top view.

FIGURE 4: The simulated raw data and the TMC results. (a) The simulated raw data with line motion. (b) The received data after motion compensation.

FIGURE 5: Experiments with simulated data (I). (a) RD image of 1–2048 echoes (dB). (b) RD image of 2049–4096 echoes (dB). (c) Squared FT magnitude relative to (a) (dB). (d) Squared FT magnitude relative to (b) (dB). (e) Radial projections. (f) $P_1(\theta)$ and its approximation with 40 terms of cosine series.

FIGURE 6: Experiments with simulated data (II). (a) The iteration steps of Nelder-Mead algorithm. (b) The entropy of RD images when searching for RC. (c) RD image of total 4096 echoes (dB). (d) CBP imaging result (dB).

is presented in Figure 8(b), and the performance degrades when the disturbance gets serious. Still, the proposed RV estimation method is more robust.

4.2. Simulation Results Using Collected Data. Experiments with some real data of a Yak-42 airplane (see Figure 9) recorded by a C-band (5.52 GHz) ISAR system [17, 22] are also used to demonstrate the effectiveness of the proposed method. This system transmits 400 MHz chirp signals with $25.6 \mu\text{s}$ pulse width, and the target's echoes are dechirped and I/Q-sampled with a frequency of 10 MHz. The pulse repetition frequency is 400 Hz, and a total of 4096 pulses are collected. These echoes are also equally divided to form two

RD images, as in Figures 10(a) and 10(b). The squared FT magnitudes are shown in Figures 10(c) and 10(d), and the corresponding radial projections are shown in Figure 11(a). $P_1(\theta)$ is approximated using 40 terms of cosine series (Figure 11(b)). The RV is initialized as 0.0043 rad/s and is finally estimated to be 0.0096 rad/s in 12 iterations (Figure 11(c)), corresponding to an aspect angle interval of 5.87 deg. The RC is estimated to be 3.373 m using the minimum entropy criterion, and the entropy curve is shown in Figure 11(d). The CBP image of Yak-42 (Figure 11(f)) is rescaled and more focused compared with the RD imaging result (Figure 11(e)), the length of line AB is 36.094 m, and CD is 34.325 m; both are very close to the real target contour.

FIGURE 7: The RMSE of RV estimation versus SNR.

FIGURE 8: Robustness analysis in presence of nonuniform rotating. (a) The RMSE of RV estimation with different rotational acceleration. (b) The RMSE of RV estimation in presence of 3D rotation.

5. Conclusion

An improved method for estimating the target rotation parameters has been proposed in this paper. For the RV estimation, the keystone transform was used to compensate the linear range migration through resolution cells in subaperture. Then, the two adjacent RD images were processed by 2D

FT to eliminate the influence of unknown RC, and the radial projection was applied to avoid the time-consuming process of 2D interpolation and image correlation. In addition, the RV was found by solving a 1D polar curve matching problem in a few iterations efficiently. Then, the influence of unknown RC on wideband ISAR imaging was studied in this paper. Based on the RV estimation, the target's RC was estimated

FIGURE 9: Graph of Yak-42.

FIGURE 10: Experiments with real ISAR data (I). (a) RD image of 1–2048 echoes (dB). (b) RD image of 2049–4096 echoes (dB). (c) Squared FT magnitude relative to (a) (dB). (d) Squared FT magnitude relative to (b) (dB).

FIGURE 11: Experiments with real ISAR data (II). (a) Radial projections. (b) $P_1(\theta)$ and its approximation with 40 terms of cosine series. (c) The iteration steps of Nelder-Mead algorithm. (d) The entropy of RD images when searching for range bias of RC. (e) RD image of total 4096 echoes (dB). (f) CBP imaging of Yak-42 (dB).

by a line search using minimum entropy criterion. With all the rotation parameters, the parallelized CBP algorithm was used to obtain the high-resolution and rescaled image.

In a simulation performed with known RV using 3D point scattering model, the target was properly rescaled and the scatters' MTRC were compensated very well. And the robustness of the proposed method has been validated with numerous experiments in presence of noise or nonuniform rotation. Furthermore, experiments with some collected data also demonstrated the effectiveness of the proposed algorithm, the CBP image of Yak-42 was well focused, and the contour of the target on image was very close to the real aircraft.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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