

Research Article

ISAR Autofocus Imaging Algorithm for Maneuvering Targets Based on Phase Retrieval and Keystone Transform

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In the current scenario of high-range resolution radar and noncooperative target, the rotational motion parameters of the target are unknown and migration through resolution cells (MTRC) is apparent in the obtained inverse synthetic aperture radar (ISAR)images, in both slant-range and cross-range directions. In the case of the high-speed maneuvering target with a small value of rotation, the phase retrieval algorithm can be applied to compensate for the translational motion to form an autofocusing image. However, when the target has a relatively large rotation angle during the coherent integration time, phase retrieval method cannot get an acceptable image for viewing and analysis as the location of the scatterer will not be true due to the Doppler shift imposed by the target's rotational motion. In this paper, a novel ISAR imaging method for maneuvering targets based on phase retrieval and keystone transform is proposed, which can effectively solve the above problems. First, the keystone transform is used to solve the MTRC effects caused by the rotation component. Next, phase errors caused by the remaining translational motion will be removed by employing phase retrieval algorithm, allowing the scatterers are always kept in their range cells. Finally, the Doppler frequency shifts of scatterers will be time invariant in the phase of the received signal. Furthermore, this approach does not need to estimate the motion parameters of the target, which simplifies the processing steps. The simulated results demonstrate the validity of this method.

1. Introduction

Inverse synthetic aperture radar imaging is a radar technique to obtain a high-resolution image of moving targets [1–6]. In general, the target is assumed to have both translational and rotational motion, where the target's rotational motion is used to attain cross-range resolution. The conventional ISAR motion compensation algorithms [7, 8] are dedicated to the imaging of the maneuvering target with simple motion. Once the target contains complex motions such as large angle rotation, high speed, and vibration, these algorithms cannot achieve high-resolution images.

Various techniques are performed to mitigate or eliminate these unwanted motion effects in ISAR imaging [9– 11], among which some of the popular algorithms include cross-correlation method [12, 13] and minimum entropy method [14–16]. However, the computational complexity of the minimum entropy algorithm is too large, and the cross-correlation method can only measure the target's velocity within a small interval, and the accuracy of the algorithm is low. Phase retrieval is a method developed for optical imaging in recent years, and it is gradually applied in various fields [17, 18]. The principle of phase retrieval is to calculate the phase distribution of the light field by measuring the intensity distribution of the optical field. Shi et al. [19, 20] believe that the ISAR echo module of the maneuvering target is not affected by its radial motion, that is, phase retrieval can be applied to compensate for translational motion (radial velocity and radial acceleration). Furthermore, the method does not need to estimate the target motion parameters, and the autofocus images can be obtained under the condition that the rotation of the target is small for the coherent integration time of the radar. However, when the rotation angle becomes larger, phase retrieval algorithm has difficulties in eliminating the MTRC caused by the rotational motion.

Keystone transform was originally proposed in Ref. [21] for SAR imaging of moving targets, and it was called keystone remapping. To obtain high-resolution SAR images, the keystone transform is used to rescale the time axis for each frequency, and it corrects range migration in SAR images. The keystone transform has been widely used in ISAR autofocus to correct range cell migration correction (RCMC). For example, keystone transform (KT) are utilized to transform the energy of all the scatterers into one range cell [22]. Modified keystone transforms can be employed to simultaneously transform all multicomponent linear frequency modulation subechoes into multicomponent single-frequency signals [23]. Moreover, Wang and Kasilingam [24, 25] apply the first-order generalized keystone transform to remove the linear range cell migration induced by the target's uniform rotation. The effects of higher-order terms can be solved by performing secondorder or higher-order generalized keystone transforms [26, 27]. Usually, the unfavorable effect induced by the rotational motion is less severe than that induced by translational motion. In this way, keystone transform can be first applied for removing the range cell migration due to the target's rotation. However, keystone transform cannot overcome the issue of severe scatters' walk with respect to slow time imposed by translational acceleration and large translational velocity, which makes the target's resultant image defocused in range and cross-range directions. To make the Doppler frequency shifts constant among the range cells in radar signal processing, it is necessary to combine the keystone transform and phase retrieval.

Based on the above analysis, a novel ISAR imaging algorithm for maneuvering targets based on phase retrieval and keystone transform is proposed. First, keystone transform is performed to correct the MTRC due to the rotation motion. Then, we use phase retrieval to compensate for the target's translational motion component and solve the range walk effect. Finally, the returned signals from the same scatterer are always kept in the same range cell, and the time-invariant Doppler shift can be obtained.

The rest of the paper is organized as follows: maneuvering target echo signal analysis is shown in Section 2. In Section 3, we focus on the theory of keystone transform and phase retrieval. Experimental simulation analysis is presented in Section 4, and conclusions are given in Section 5.

2. Maneuvering Target Echo Signal Analysis

The space-fixed or global system (X, Y) and the body-fixed or local system (x', y'), which is rigidly fixed in the body, are the two coordinate systems commonly used to describe a maneuvering target as shown in Figure 1. To describe the rotation of the target, another reference coordinate system (x, y) is introduced, which is parallel to the global system (X, Y) with its origin at the origin of the target body-fixed system. The uniformly rotating target contains N scatterers, and the random scatterer $P(x_n, y_n)$ on the target has translational motion and rotational motion.



FIGURE 1: Geometry for a maneuvering target with respect to radar [19]. The Figure reproduced from Hongyin Shi et al. (under the Creative Commons Attribution License/public domain).

The baseband echo signal received by the radar can be expressed as

$$s_r \begin{pmatrix} \wedge \\ t \end{pmatrix} = \sum_{n=1}^N A_n p \begin{pmatrix} \wedge \\ t \end{pmatrix} \exp\left[\frac{-j4\pi f_c}{c} R_p(t_m)\right], \quad (1)$$

where $\hat{t} = t - mT_r$ is fast time; $t_m = mT_r$ is slow time, where T_r represents pulse repetition interval; A_n and $R_p(t_m)$ are the reflectivity density function from any point scatterer at P and the distance from the radar at instantaneous time t_m , respectively; $p(\cdot)$ denotes the normalized echo envelope; and f_c is the carrier frequency.

Transforming $s_r(\hat{t}, t_m)$ from fast time domain to baseband frequency domain, it can be represented to yield

$$S_r(f, t_m) = \sum_{n=1}^{N} A_n P(f) \exp\left[\frac{-j4\pi}{c} (f+f_c) R_p(t_m)\right],$$
 (2)

where, P(f) represents the Fourier transform of p(t).

The target's translational range distance, $R(t_m)$, can be modelled in terms of motion parameters:

$$R(t_m) = R_0 + v_r t_m + \frac{1}{2} a_r t_m^{2}.$$
 (3)

Here, v_r and a_r are the target's translational velocity and the acceleration, respectively. R_0 is the initial range of the target. Therefore, the distance from the scatterer *P* to the radar can be written as

$$R_p(t_m) \cong R(t_m) + x_n \cos \left[\theta(t_m) - \alpha\right] - y_n \sin \left[\theta(t_m) - \alpha\right].$$
(4)

where $\theta(t_m)$ represents the rotational angle of the target with respect to the radar line of sight axis, and $\theta(t_m) = \Omega t_m$, where Ω denotes the angular velocity of the target. Assuming that the initial angle of the target α is equal to zero and the CPI (coherent processing interval) is short, we can get

$$\cos (\Omega t_m) \cong 1 - \frac{1}{2} (\Omega t_m)^2,$$

$$\sin (\Omega t_m) \cong \Omega t_m.$$
(5)

Therefore, the backscattered signal can be rewritten as

$$\begin{split} S_r(f,t_m) &\cong \sum_{n=1}^N A_n P(f) \exp\left[\frac{-j4\pi}{c}(f+f_c)\left(R_0+v_r t_m\right.\\ &+ \frac{1}{2}a_r t_m^2+x_n-\frac{1}{2}x_n\Omega^2 t_m^2-y_n\Omega t_m\right)\right] \\ &= \sum_{n=1}^N \tilde{A_n} P(f) \exp\left[\frac{-j4\pi f}{c}(R_0+x_n)\right] \\ &\cdot \exp\left[\frac{-j4\pi f}{c}\left(v_r t_m+\frac{1}{2}a_r t_m^2\right)\right] \quad (6) \\ &\cdot \exp\left[\frac{-j4\pi f}{c}\left(-\frac{1}{2}x_n\Omega^2 t_m^2-y_n\Omega t_m\right)\right] \\ &\cdot \exp\left[\frac{-j4\pi f_c}{c}\left(v_r t_m+\frac{1}{2}a_r t_m^2+x_n\right)\right] \\ &\left. -\frac{1}{2}x_n\Omega^2 t_m^2-y_n\Omega t_m\right)\right], \end{split}$$

where, $\tilde{A}_n = A_n \exp \left[(-j4\pi f_c/c)(R_0 + x_n) \right]$, which is a constant.

The first term in the phase represents the range distribution of scatters and can be ignored for the imaging process. The second and third terms denote echo envelope shift caused by the translational motion and the rotational motion, respectively. The last term indicates the carrier phase changes caused by the Doppler effect. To have a motion-free range-Doppler image of the target, the envelope shift in the second and third terms cannot expand to more than one range resolution cell; otherwise, the range of the scatterer, P, will migrate from its original position (i.e., x_n) to a wrong position (i.e., $v_r t_m + (1/2)a_r t_m^2 + x_n - (1/2)a_r t_m^2$ $(1/2)x_n\Omega^2 t_m^2 - y_n\Omega t_m$). It is worth noting that there is a coupling between signal frequency f and slow time t_m in equation (6), which can be regarded as the MTRC effect or range drift shift. Therefore, the RCMC procedure should be applied to the second and third phase errors terms to suppress them.

According to phase retrieval theory, we know that autofocus imaging can be achieved when the raw data magnitude of the maneuvering target is approximate to the stationary one in the ISAR system [17]. Obviously, when the " $\theta(t_m)$ " is not small, this rotational motion has to be compensated for by applying an initial compensating procedure, that is, using phase retrieval alone does not eliminate the MTRC caused by the third term in equation (6). To effectively remove the rotational motion effects, we will perform the keystone transform.

3. Algorithm Theory and Application

3.1. Keystone Transform. The keystone transform was used to rescale the slow time t_m axis for each frequency [21] by

$$\tau_m = \frac{f_c + f}{f_c} t_m,\tag{7}$$

where τ_m is the rescaled slow time axis.

Then, the frequency domain signal $S_r(f, t_m)$ becomes

$$S_{r}(f,\tau_{m}) = \sum_{n=1}^{N} \tilde{A_{n}} P(f) \exp\left[\frac{-j4\pi}{c}f(R_{0}+x_{n})\right] \\ \cdot \exp\left\{\frac{-j4\pi}{c}\left[f_{c}v_{r}\tau_{m}+a_{r}\frac{f_{c}^{2}\tau_{m}^{2}}{2(f+f_{c})}\right] -f_{c}y_{n}\Omega\tau_{m}-x_{n}\Omega^{2}\frac{f_{c}^{2}\tau_{m}^{2}}{2(f+f_{c})}\right]\right\}.$$
(8)

As f_c is much larger than f, we have

$$S_{r}(f,\tau_{m}) \cong \sum_{n=1}^{N} \tilde{A_{n}} P(f) \exp\left[\frac{-j4\pi}{c}f(R_{0}+x_{n})\right]$$
$$\cdot \exp\left[\left(\frac{-j4\pi f_{c}}{c}\right)\left(v_{r}\tau_{m}+\frac{1}{2}a_{r}\tau_{m}^{2}\right) - \frac{1}{2}x_{n}\Omega^{2}\tau_{m}^{2} - y_{n}\Omega\tau_{m}\right)\right].$$
(9)

We can see that frequency f and slow time t_m have been decoupled in the second term of the phase function by applying the keystone transform, and the envelope shift position of the echo signal stays at the range x_n . In fact, the quadratic term $-(1/2)x_n\Omega^2\tau_m^2$ can certainly be neglected compared with the normal size of the range resolution cell (e.g., 1 m). For example, if $\Omega = 0.08$ rad/sec, $\tau_m = 1$ sec, and $x_n = 30$ m, the quadratic term is less than 0.1 m. The Doppler frequency shift due to carrier phase changes caused by motion can be calculated by taking the time derivative of the phase in equation (9) as

$$f_{di} = -\frac{2f_c}{c} \left(v_r + a_r \tau_m - x_n \Omega^2 \tau_m - y_n \Omega \right).$$
(10)

The Doppler frequency shift changes linearly due to the acceleration during the CPI, resulting in frequency dispersion of the echo signal and negatively affecting the range resolution. Additionally, when the target's translational velocity becomes larger, Doppler blurring occurs in the resulting ISAR image, and more importantly, the image smearing can be drastic for fast moving targets in range direction. Therefore, an algorithm needs to be applied to overcome



FIGURE 2: Block scheme of the proposed method.



FIGURE 3: (a) A hypothetical target composed of perfect point scatterers [19]. (b) The amplitude of the raw data [19]. Figures reproduced from Hongyin Shi et al. (2018) (under the Creative Commons Attribution License/public domain).

such the range walk issue and make the Doppler frequency shifts constant.

3.2. Phase Retrieval Algorithm. Phase retrieval is the process of finding the optimal solution to the phase problem of the recovered signal. Given a complex signal F(k) with the amplitude |F(k)| and phase $\varphi(k)$:

$$F(k) = |F(k)|e^{i\varphi(k)} = \int_{-\infty}^{\infty} f(x)e^{-2\pi i k \cdot x} dx,$$
 (11)

where k is an M-dimensional spatial frequency coordinate and x is an M-dimensional spatial coordinate. The principle of phase retrieval is to find a set of constrained phases that satisfy the measured amplitude, that is, the known Fourier transform information |F(k)| is applied to recover the Fourier phase information $\varphi(k)$, then the distribution function \tilde{f} is obtained by inverse Fourier transform.

However, in signal processing, the correctness of the recovery result cannot be guaranteed due to the lack of a priori information, that is, it is likely to lead to nonuniqueness of the phase retrieval result. There are two reasons for this: the first is caused by the spatial displacement, conjugate inversion, and global phase shift and the second is related to the dimension of the unknown signal. In order to eliminate the phase ambiguity and ensure the uniqueness of the recovery result when performing the phase retrieval, we use the error phase of the blurred image obtained by the traditional ISAR imaging algorithm (keystone transform) as a priori phase information. In this paper, the classic phase retrieval algorithm, namely, the oversampling smoothness (OSS) phase retrieval [19], is applied and a priori information is added to it. Besides, the support domain size of the improved OSS algorithm is set with respect to the blurred target image.

Based on the support domain constraints of the traditional hybrid input-output (HIO) algorithm [28], the OSS algorithm adds iterative steps of frequency domain filtering. To search for the phase information of the recovered signal in solution space, it iterates back and forth between the Fourier and image domains. The following steps are the process of the OSS algorithm from the *j*th to the (j + 1)th iteration at each run.

- (1) $f_j(x)$ is the input signal with the random phase. Obtain a Fourier pattern $F_j(K)$ by applying the Fourier transform
- (2) Retain the phase information of $F_j(K)$ and replace the magnitude of it with a known Fourier magnitude |Y(K)|, then a new complex—valued function $F_j'(K)$ can be formed. It should be pointed out that |Y(K)| is the magnitude of the ISAR echo signal

$$F_{j}'(K) = |Y(K)| \cdot \frac{F_{j}(K)}{|F_{j}(K)|}.$$
 (12)

- (3) Perform inverse Fourier transform to F_j'(K) and get a new image f_i'(x)
- (4) Revise f_j'(x) based on HIO equation and generate the new f_j''(x)

$$f_{j}^{\,\,\prime\prime}(x) = \begin{cases} f_{j}^{\,\,\prime}(x), & x \in \gamma \cap \left(f_{j}^{\,\,\prime}(x) \ge 0\right), \\ \\ f_{j}(x) - \beta f_{j}^{\,\,\prime}(x), & x \in \gamma \cup \left(f_{j}^{\,\,\prime}(x) < 0\right), \end{cases}$$
(13)

where γ represents a finite support and the value of the parameter β is between 0.5 and 1

(5) Calculate the image for the (j + 1)th iteration

$$f_{j+1}(x) = \begin{cases} f_j^{\prime\prime}(x), & x \in \gamma, \\ \\ \operatorname{IFT}\left[F_j^{\prime\prime}(K)W(K)\right], & x \notin \gamma, \end{cases}$$
(14)

TABLE 1: The radar parameters for SFCW (stepped frequency continuous wave) illumination.

Parameter name	Symbol	Value
The initial range of the target	R ₀	10 km
Carrier frequency	$f_{\rm c}$	3 GHz
Frequency bandwidth	В	190 MHz
Pulse repetition frequency	PRF	35 <i>KHz</i>
Number of pulses	$N_{\rm pulse}$	128
Number of bursts	$M_{ m burst}$	256

TABLE 2: The motion parameters of the maneuvering target in different experiments.

Symbol	Parameter value
P1	$v_r = 3 \text{ m/s}, a_r = 0 \text{ m/s}^2, \Omega = 0.1 \text{ rad/s}$
P2	$v_r = 3$ m/s, $a_r = 0$ m/s ² , $\Omega = 0.14$ rad/s
Р3	$v_r = 13$ m/s, $a_r = 0$ m/s ² , $\Omega = 0.1$ rad/s
P4	$v_r = 3$ m/s, $a_r = 0.5$ m/s ² , $\Omega = 0.1$ rad/s
P5	$v_r = 25$ m/s, $a_r = 2$ m/s ² , $\Omega = 0.07$ rad/s
Р6	$v_r = 25 \text{ m/s}, a_r = 2 \text{ m/s}^2, \Omega = 0.13 \text{ rad/s}$

where $F_{j}^{\prime\prime}(K)$ is the Fourier transform of $f_{j}^{\prime\prime}(x)$ and W(K) is a normalized Gaussian function in the Fourier domain. It is defined as

$$W(K) = \exp\left[-\frac{1}{2}\left(K/\partial\right)^2\right].$$
 (15)

The smoothing filter W(K) is only applied to the density outside the support domain. By changing parameter ∂ , the width of the Gaussian filter can be adjusted to overcome the issue of high-frequency information outside the support, while the density inside the support domain is not disturbed.

By applying OSS phase retrieval algorithm, the maneuvering target's module in (9) becomes

$$\begin{aligned} |S_r(f,\tau_m)| &= \left| \sum_{n=1}^N \tilde{A_n} P(f) \exp\left[\frac{-j4\pi f}{c} (R_0 + x_n)\right] \right| \\ &\cdot \left| \sum_{n=1}^N \exp\left[\frac{-j4\pi f_c}{c} \left(v_r \tau_m + \frac{1}{2}a_r \tau_m^2 - y_n \Omega \tau_m\right)\right] \right| \\ &= \left| \sum_{n=1}^N \tilde{A_n} P(f) \exp\left[\frac{-j4\pi f}{c} (R_0 + x_n)\right] \right| \\ &\cdot \exp\left[\frac{-j4\pi f_c}{c} (-y_n \Omega \tau_m)\right] \right|. \end{aligned}$$
(16)



FIGURE 4: Imaging results with the target's motion parameters P1. (a) RD algorithm. (b) Keystone transform. (c) The proposed method.



FIGURE 5: Imaging results with the target's motion parameters P2. (a) RD algorithm. (b) Keystone transform. (c) The proposed method.



FIGURE 6: Imaging results with the target's motion parameters P3. (a) RD algorithm. (b) Keystone transform. (c) The proposed method.

From (16), ISAR echo module is not affected by the target's translational velocity and the acceleration with respect to the rescaled slow time τ_m . As an autofocus processing procedure, OSS phase retrieval effectively removes the effects of Doppler blurring and range walk. Specifically, the first term in the absolute value can be ignored for the imaging process as mentioned in Section 2. Noting that the Doppler frequency shift is equal to $f_{di}' = (2f_c/c) \cdot y_n \Omega$, which is constant between the scatterers. Therefore, the module in (16) is approximate to the ideal module of the target autofocus imaging, so the RCMC procedure has been performed by OSS phase retrieval. In other words, phase retrieval performs a fine phase compensation, and the target's resultant image will be completely focused in range and cross-range directions.

The overall flow diagram of the proposed method is shown in Figure 2.

4. Simulation Analysis

To verify the feasibility of this method, we conduct several experiments. A finite number of perfect point scatterers are



FIGURE 7: Imaging results with the target's motion parameters P4. (a) RD algorithm. (b) Keystone transform. (c) The proposed method.



FIGURE 8: Profile comparison of the scattering point marked by the red circle in Figure 4. (a) Comparison in range. (b) Comparison in azimuth.

assumed to be located as shown in Figure 3(a), and the module of the raw data is plotted in Figure 3(b). Table 1 shows the radar parameters that are used in the simulation.

4.1. Target Imaging Results with Different Translational Motion Parameters. To obtain a more intuitive view, the different parameters from each experiment are listed in Table 2.

When the angular velocity of the target is large, Figure 4(a) shows the ISAR image with applying the RD algorithm, where the blur occurs due to the range cell migration caused by the rotational motion. As can be seen from Figure 4(b), because of the small translational velocity of the target, keystone transform can correct the MTRC caused by rotation and translation and obtain a focused ISAR image. Keeping the translation parameters unchanged and increasing the rotation velocity, then the resultant rotation motion-compensated ISAR image after applying keystone transform are still relatively focused in Figure 5(b), which proves that keystone transform can perform the RCMC procedure in this case. When the radial velocity becomes larger, by utilizing keystone transform, the ISAR image is still smearing in Figure 6(b), which is induced by larger carrier phase changes with respect to Figure 4(b) imposed by the Doppler effect. In addition, due to the existence of radial acceleration, Figure 7(b) shows the keystone transform cannot handle the difficulties of the nonlinear Doppler shift. The proposed method can effectively eliminate carrier phase errors caused by the target translational motion while compensating for the rotational motion to obtain a highresolution image.

In Figure 8, the range and azimuth profiles of the scattering point on the aircraft head marked by the red circle related to Figures 4(a), 4(b), and 4(c) are plotted, which intuitively demonstrates profile comparison of the target imaging through RD, keystone transform, and the proposed method. Due to the target's translational motion and rotational motion, the peak sidelobe ratio produced by RD algorithm is the largest, indicating that the point scatterer has the most serious range and azimuth defocusing. Obviously, the



FIGURE 9: Imaging results with the target's motion parameters P5. (a) RD algorithm. (b) Minimum entropy method. (c) OSS phase retrieval algorithm. (d) The proposed method.

profiles with respect to keystone transform show the range broadening are alleviated, which indicates that keystone transform removes the envelope shift related to fast time in equation (6) under the condition of small velocity. As can be clearly seen from the figures, the proposed method has the minimum peak sidelobe ratio and therefore possesses good focusing performance in the process of reconstructing images.

4.2. Target Imaging Results with Different Rotational Motion Parameters. Figures 9(a) and 9(b) show RD algorithm produces degradations such as blurring and smearing. In the case of high speed and small rotation angle, the scatters' range walk caused by the target's rotation motion does not exceed a range cell. Therefore, as shown in Figures 9(b) and 9(c), high-quality images can be obtained by using both the minimum entropy method and the OSS phase retrieval algorithm. However, by comparing the two resultant motioncompensated ISAR images, the one with applying the OSS phase retrieval algorithm is more focused. When the rotation velocity is much larger, the minimum entropy method has difficulty in eliminating the MTRC caused by the rotation motion. Figure 10(b) clearly demonstrates the rotational motion-based defocusing is noted in the ISAR image. In this case, the application of phase retrieval alone does not remove the echo envelope shift induced by the rotational component in equation (6), so some scattering points of the target in Figure 10(c) are missing. In Figure 10(d), the resultant motion-free ISAR image is well focused, which confirms that the proposed method can perform autofocus imaging of the maneuvering target with high-speed and large angle.

Figures 11(a) and 11(b) show profile comparison of the scatterer point on the airplane head marked by the red circle in Figures 10(a), 10(b), and 10(d). Seen from the peak side-lobe ratio of the two figures above, the imaging result of the minimum entropy method clearly demonstrates the broadening of the range direction and azimuth direction, which can also indicate the poor performance of the minimum entropy method under the condition of the high-speed maneuvering target with large angle. Compared with the RD algorithm and the minimum entropy method, the proposed method has a smaller peak sidelobe ratio, that is, it obtains a more focused image in both directions.

5. Conclusions

In this paper, we introduce a new method for maneuvering target ISAR imaging based on phase retrieval and keystone transform. By applying the keystone transform, the range cell migration caused by the target's rotation motion can be corrected to obtain an initial phase compensation. Furthermore, phase retrieval is dedicated to performing the remaining translational motion compensation with respect to slow time, so that the time-invariant Doppler shifts can be obtained. Finally, the method can obtain resultant motion-free ISAR image after completely removing the phase error of the received signal, which clearly demonstrates that the unwanted effects due to the target's motion are eliminated.



FIGURE 10: Imaging results with the target's motion parameters P6. (a) RD algorithm. (b) Minimum entropy method. (c) OSS phase retrieval algorithm. (d) The proposed method.



FIGURE 11: Profile comparison of the scattering point marked by the red circle in Figure 10. (a) Comparison in range. (b) Comparison in azimuth.

In the experimental simulation, we compare the imaging results of the keystone transform, phase retrieval, and minimum entropy method with the imaging results of the proposed method. In the case of the high-speed maneuvering target with a large value of rotation, the former three traditional methods cannot successfully eliminate the motion effects. Consequently, the motion-compensated ISAR image is obtained while the effect of motion in the scattered field can be mitigated by applying the proposed method, wherein the target's scattering centers are very well displayed with good resolution. In summary, the results of this study provide a new way of thinking for ISAR imaging problem of the maneuvering target with complex motion. At the same time, it should be pointed out that the approach has a high accuracy, and it does not need to estimate the motion parameters of the target.

Data Availability

No data were used to support this study.

Disclosure

The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

All the authors made significant contributions to this work. Hongyin Shi proposed the novel ISAR imaging method. Ting Yang performed the experiments and wrote the paper. Yue Liu performed part of the experiments. Jingjing Si revised the manuscript.

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