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An approach for refocusing of ground fast-moving target and high-order motion parameter estimation using Radon-high-order time-chirp rate transform

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A B S T R A C T

Long synthetic aperture time can improve the imaging quality of a ground moving target, whereas a moving target may be severely smeared in the cross-range image due to the range migration and the Doppler frequency migration. In this paper, the effects of the third-order Doppler broadening and Doppler ambiguity of a fast-moving target are considered. To address these issues, a novel motion parameter estimation method named high-order time-chirp rate transform (HTRT) is proposed, and then a new synthetic aperture radar (SAR) imaging method based on Radon-HTRT (RHTRT) for a ground moving target is developed. The major contributions are as follows: 1) The proposed SAR imaging method can eliminate the Doppler ambiguity effect. 2) The proposed method can realize longer time coherent integration than Radon–Fourier transform (RFT) and Radon–fractional Fourier transform (RFRFT) methods. 3) The proposed method is computationally efficient since HTRT can obtain the motion parameters of a moving target via performing the 2-dimensional (2-D) fast Fourier transform (FFT). Both the simulated and real data processing results show that the proposed method can finely image a ground moving target in a high signal-to-clutter and noise ratio (SCNR) environment.

1. Introduction

In recent years, synthetic aperture radar (SAR) plays an important role in many civilian and military applications with the increasing demands, such as ground moving target identification, motion parameter estimation, positioning, etc., days and nights and in all-weather environment, which has drawn much attention of many researchers all over the world [1–7]. In a modern SAR system, in order to obtain a high azimuth resolution SAR image and improve the motion parameter estimation accuracy, the synthetic aperture time may usually be of seconds long [8]. However, defocusing may occur in a long aperture time due to the range migration and Doppler frequency migration caused by the target's motion. Furthermore, the high-order term (e.g., third-order term) of a ground moving target may also bring about the severe integration loss during a long coherent integration time. Therefore, the effective compensations of range migration and high-order Doppler frequency migration become a key factor to obtain a well-focused image of a ground moving target [9].

To deal with the range migration in a low signal-to-clutter and noise ratio (SCNR) environment, Keystone transform (KT) provides a good performance in range walk compensation, which can simultaneously correct the range walks of multiple moving targets in one processing step without the target kinetic knowledge [10]. However, a moving target may be defocused in the SAR image since the range curvature and the Doppler frequency migration may not be well compensated. In addition, as for a fast-moving target, the imaging quality may further degrade due to the Doppler ambiguity effect.

To address above issues, the second-order Keystone transform (SoKT) is subsequently proposed by Zhou et al. [11]. In this method, the range curvature is compensated by SoKT. Then the slope of target trajectory with respect to the target cross-track velocity is obtained according to the peak position in the Hough transform domain [12]. Finally, the azimuth compression is achieved by the Wigner–Ville distribution (WVD) method [13–15]. This method may suffer from a heavy computation due to the exhaustive search for the Doppler chirp rate and the slope of range walk trajectory. To decrease the computational complexity, a SAR ground moving target imaging method named Deramp–Keystone processing (DKP) is proposed by Sun et al. [16], which can image a moving target without the search procedure of target's mo-

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tion parameters. However, it may suffer from the focusing quality degradation because the along-track velocity of a ground moving target is neglected. In [17], the fractional Fourier transform (FrFT) [18,19] combined with the along-track interferometry (ATI) [20,21] is proposed to estimate the target's motion parameters. In this method, the target's energy can be well accumulated in the fractional Fourier domain via searching the optimum fractional angle, and thus greatly increases the signal-to-clutter ratio (SCR), resulting in a significant improvement of the subsequent interferometric phase estimation accuracy. Compared with the matched-filter (MF) approach, this method requires only matching the target's Doppler rate, and thus it is more straight-forward and robust.

Based on the principle of the stationary phase (PSP) method [22,23], a type of 2-D matched filtering methods is developed. Zhu et al. [24] propose a 2-D matched filtering method to focus a ground moving target in the 2-D frequency domain based on the constructed function with respect to the platform velocity, which may cause an azimuth defocusing since the along-track velocity of a moving target is ignored. To deal with this issue, a modified 2-D matched filter method is proposed in [25] to detect and image a high-speed maneuvering weak target, which eliminates the Doppler broadening effect by performing the 1-D search of the quadratic phase. The major drawback of these methods is that they are not suitable for the case of small time-bandwidth product (TBP) when the range-compressed signal is mapped into the 2-D frequency domain. In addition, if the Doppler ambiguity number is not well estimated, the focusing performance of these methods may further deteriorate.

To overcome the Doppler ambiguity effect caused by a fast-moving target, the Radon-based methods are proposed in recent years [26–30]. Xu et al. [26,27] propose the Radon–Fourier transform (RFT) to realize the coherent integration of a fast-moving target via jointly searching along the range and velocity directions, whereas it may suffer from the integration loss in the case of range curvature and Doppler frequency migration. To alleviate the integration loss, Chen et al. [29] propose Radon–fractional Fourier transform (RFRFT) to achieve the long-time coherent integration by jointly compensating the range migration and the Doppler frequency migration. The drawback of this method is that it requires too much calculation time in the 3-D search procedure of target's motion parameters, which may limit its practical application.

The above-mentioned methods only consider the second-order Doppler frequency migration without taking the third-order Doppler frequency migration into account. In practical application, the third-order phase may cause an azimuth defocusing in the synthetic aperture time of seconds long. Therefore, it is necessary for us to accurately compensate the third-order phase to fully focus a ground fast-moving target.

As for the third-order Doppler frequency migration, Sharma et al. [31] propose the pseudo-Wigner–Ville distribution (PWVD) to improve the target focusing quality and to detect the presence of target acceleration. In this method, a significant loss in peak power caused by the accelerating targets can be effectively avoided via performing the PWVD and the polynomial fitting. In [9], Yang et al. propose the polynomial Fourier transform (PFT) to deal with the third-order phase of a fast-moving target in a single-antenna SAR system. In this method, range walk is corrected by the Hough transform after range curvature compensation by the matched function corresponding to the platform velocity, which can effectively eliminate the Doppler ambiguity effect. After range migration compensation based on the above two steps, the signal is modeled as a quadratic frequency-modulated (QFM) signal (also known as the cubic phase signal), and then the motion parameters are estimated by the PFT method. This method has a heavy computational complexity because of the Hough transform and the time-consuming 2-D maximizations of PFT. In order to decrease the computational complexity, a fast non-searching parameter estimation method based on adjacent cross-correlation function (ACCF) is proposed by Li et al. [32]. This method eliminates the range migration and the Doppler frequency migration via the iterative adjacent cross-correlation operations. Then the high-order motion parameters of a fast-moving target can be obtained via Fourier transform (FT). Therefore, this method is computationally efficient since the parameter search procedure is avoided. However, this method is only suitable for the high signal-to-noise ratio (SNR) condition since the multiple iterative operations enhance the noise energy significantly.

Motivated by the previous works, we propose a novel QFM signal parameter estimation method named high-order time-chirp rate transform (HTRT), which can directly estimate the high-order motion parameter in the 2-D frequency domain with respect to the time and the delay-time variables according to the peak position, and thus it is computationally efficient since the search procedure of high-order motion parameter is eliminated. Combined with the Radon transform, a new SAR imaging method is developed based on the Radon-HTRT (RHTRT), which can realize the long-time coherent integration of a moving target without the restriction of the Doppler ambiguity effect. Compared with the conventional imaging methods using the second-order phase model, the proposed method is more suitable for the strong target imaging in a high resolution SAR system since the effects of the third-order phase can be effectively eliminated. Thus, the imaging resolution of a moving target is improved after the third-order phase compensation. Both the simulated and the real data are utilized to validate the effectiveness of the proposed RHTRT method.

The remainder of this paper is organized as follows. Section 2 establishes the mathematical model of the received signal in a SAR system. Section 3 introduces the principle of the HTRT and the corresponding SAR ground moving target imaging algorithm based on RHTRT. Section 4 presents some simulated and real data processing results and gives discussions to validate the proposed SAR imaging method. Finally, conclusions are drawn in Section 5.

2. Mathematical model of received signal

The geometry relationship between a SAR platform with the velocity v and a ground moving target is shown in Fig. 1, which is defined in a 2-D plane with a side-looking working mode. v_a, a_a, v_c, and a_c denote the along-track velocity, along-track acceleration, cross-track velocity, and cross-track acceleration of a ground moving target, respectively. R_0 and $R_s(t_m)$ denote the nearest range and the instantaneous range between the flying platform and a ground moving target, respectively. t_m is the slow time variable. During the synthetic aperture time T_a, the moving target moves from point a to b.

According to geometry relationship shown in Fig. 1, the instantaneous range $R_s(t_m)$ can be expanded into the third-order term based on the Taylor series expansion, i.e.,

$$\begin{aligned} R_s(t_m) &= \sqrt{\left(vt_m - v_at_m - \frac{1}{2}a_at_m^2\right)^2 + \left(R_0 - v_ct_m - \frac{1}{2}a_ct_m^2\right)^2} \\ &\approx R_0 - v_ct_m + \left[\frac{(v-v_a)^2}{2R_0} - \frac{a_c}{2}\right]t_m^2 \\ &\quad + \left[\frac{v_c(v-v_a)^2}{2R_0^2} + \frac{a_a(v_a-v)}{2R_0}\right]t_m^3 \end{aligned} \tag{1}$$

The above approximation holds under the assumption of $(v - v_a)T_a \ll R_0$. In order to write conveniently, $R_s(t_m)$ can be simplified as