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A fast ground moving target focusing method based on first-order discrete polynomial-phase transform

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ABSTRACT

A new ground moving target focusing method for airborne synthetic aperture radar (SAR) is introduced in this paper. Firstly, first-order discrete polynomial-phase transform (DPT) is used to reduce the target phase order. Secondly, Keystone transform (KT) is applied to correct the residual range walk, and then the target second-order motion parameter can be estimated after performing the azimuth fast Fourier transform (FFT). Finally, the target first-order motion parameter can be estimated after the Doppler frequency migration (DFM) compensation and a well-focused result of a moving target can be obtained. Compared with the conventional SAR imaging methods, the proposed method can eliminate the effects of Doppler ambiguity and azimuth spectrum split. In addition, the proposed method is computationally efficient since the target motion parameter searching procedure is avoided, which can satisfy the target real-time imaging requirements. Real data processing results are provided to validate the effectiveness of the proposed algorithm.

1. Introduction

Synthetic aperture radar (SAR) is widely used in many civil and military areas, working under all-time and all-weather conditions [1–5]. It is well known that SAR is capable of obtaining a good imaging quality of stationary ground scene. Nevertheless, the moving targets may make its SAR image smeared and position shifted due to the unknown motion parameters. Therefore, in order to finely focus the moving targets, the defocusing effects caused by target's motions should be well compensated [6–8].

The across-track velocity of a ground moving target may cause the range walk, which makes the target's energy distribute in multiple range gates. Keystone transform (KT) [9] can be applied to correct the range walks of multiple targets without knowing target kinetic information. However, KT suffers from the Doppler ambiguity problem. To deal with this issue, the Radon-FFT (RFT) method is proposed [10,11]. RFT searches the target linear motion trajectory in the range-time and azimuth-time domain, and thus can be free of the effect of the Doppler ambiguity. In addition, an axis-rotation method which is similar to the principle of RFT is proposed to correct the target linear walk via axis-rotation operation [12]. However, for a moving target with an along-track velocity, these types of methods cannot effectively deal with the range curvature and DFM, resulting in a severe integration loss.

The second-order KT (SOKT) is presented in [13], which compensates the range curvature via a time scaling transform. Then the residual range walk and the DFM are compensated by adopting the Hough transform (HT) [14] and time–frequency analysis methods [15,16]. However, when the target azimuth spectrum occupies two PRF bands, the target motion trajectory may be split into two parts after the SOKT [17,18]. In [19], the 2-D matched filtering method is proposed to eliminate the coupling effects between the range and azimuth. This method can effectively avoid the target spectrum split via Doppler center shifting procedure. However, when the target Doppler bandwidth is larger than half of pulse repetition frequency (PRF), the target Doppler spectrum may still span over two PRF bands [20]. The same problem also exists in [21]. In [20], the deramp–keystone processing (DKP) method constructs an azimuth deramp function to compensate the defocusing effects derived from the range curvature and DFM, and it can effectively deal with the spectrum splitting issue. However, this method may smear the moving target, since the target along-track velocity is not effectively compensated.

In [8], Huang et al. proposed a second-order WVD (SoWVD) method to image a ground moving target. In this method, the range curvature is compensated by constructing a matched filter-

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ing function related to the platform velocity, which can effectively avoid the issue of target spectrum split. Besides, this procedure is computationally efficient since the interpolation operation is avoided [8]. Then the DFM is compensated by adopting the SoWVD transform. However, for a high-resolution SAR system, the range curvature compensation error caused by target along-track velocity cannot be ignored, so this method may lead to the integration loss.

The methods of Radon-fractional Fourier transform (RFRFT) [22], Radon-Lv's distribution (RLVD) [23], and RSoWVD [24] are subsequently proposed to focus a moving target via the 2-D grid searching along the target curved motion trajectory. These methods can not only eliminate the range migration (RM) and DFM effects, but also avoid the Doppler ambiguity and spectrum split influences. However, this kind of searching methods is burdened with a large computational complexity, especially in condition of a long synthetic aperture time. So they may not be applicable to the target real-time imaging.

In this paper, the range-compressed signal is first depicted in the range-frequency and azimuth-time domain. Then the first-order DPT [25] is carried out to transform the second-order phase into first-order phase, so a single-frequency signal whose Doppler center is related to the second-order motion parameter is acquired. Though the range curvature is entirely compensated, the linear range walk still exists and the slope of linear range trajectory is related to the second-order motion parameter. Considering that the value of second-order motion parameter is usually far smaller than that of the first-order motion parameter in a SAR system, thus the Doppler ambiguity caused by the second-order motion parameter does not occur. Therefore, the residual range walk is effectively compensated after the KT. Then a well-focused peak is obtained after the azimuth FFT, and thus the second-order motion parameter can be estimated according to the peak position in the range-time and azimuth-Doppler domain. Finally, the second-order motion parameter is used to compensate the second-order phase, and then a well-focused image and the first-order motion parameter of a moving target can be obtained after KT. Compared with the conventional SAR moving target imaging algorithms [3,6–8,13,24], the proposed method has the following advantages: 1) the proposed method can avoid the Doppler ambiguity and Doppler splitting problems; 2) the proposed method can accurately compensate the range curvature without the residual range curvature errors; and 3) the proposed method is computationally efficient since the motion parameter searching procedure is avoided. The real data is utilized to validate the effectiveness of the proposed SAR imaging algorithm.

This paper is organized as follows. Section 2 establishes the signal model of an airborne SAR system. Section 3 introduces the proposed ground moving target imaging algorithm based on the first-order DPT and presents the multiple targets focusing performance. Section 4 verifies the practicality of the proposed method by using the real SAR data. Finally, conclusions are drawn in Section 5.

2. Signal model

Similar to the signal model described in [8,19,20], Fig. 1 shows the geometry configuration between a SAR platform under the side-looking mode and a ground moving target, which is defined in a 2-D slant plane. During the synthetic aperture time T_a, the moving target moves from a to b.

According to geometry configuration shown in Fig. 1, the instantaneous range $R_s(t_m)$ is given as [8,19,20]

$$R_s(t_m) = \sqrt{(vt_m - v_a t_m)^2 + (R_0 - v_c t_m)^2} \tag{1}$$

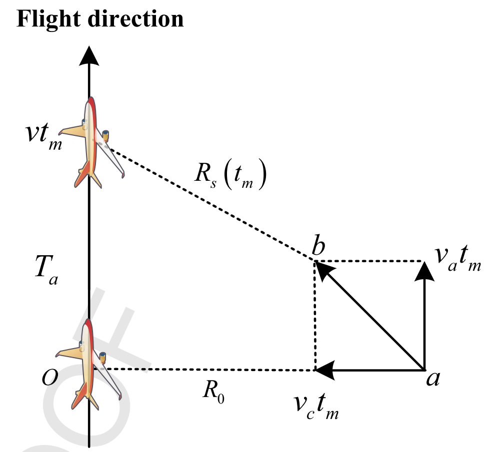

Fig. 1. Geometry relationship between a SAR platform and a ground moving target.

where t_m denotes the slow time variable, which represents the relative motion between the moving target and the radar. v_a and v_c denote, respectively, the along- and across-track velocity of a ground moving target. R_0 denotes the nearest slant range. According to the Taylor series expansion, $R_s(t_m)$ can be expanded into the second-order term as follows

$$R_s(t_m) \approx R_0 - v_c t_m + \frac{(v - v_a)^2}{2R_0} t_m^2 \tag{2}$$

After range compression, the received signal of a moving target in the range-frequency and azimuth-time can be given as [8,20]

$$\begin{aligned} S_1(f, t_m) &= \sigma \cdot rect\left[\frac{f}{\mu T_p}\right] w_a(t_m) \\ &\quad \times \exp\left[-j\frac{4\pi}{c}(f + f_c)\left(R_0 - v_c t_m + \frac{(v - v_a)^2}{2R_0} t_m^2\right)\right] \end{aligned} \tag{3}$$

where σ is the signal amplitude of a moving target in the range-frequency and azimuth-time domain, μ denotes the chirp rate, T_p denotes the pulse duration, f denotes the range-frequency variable, f_c denotes the carrier frequency, $w_a(t_m)$ denotes the azimuth slow-time window, and c denotes the speed of light. After performing the range IFFT, then the transformed signal, denoted by $s_1(t, t_m)$, is given as

$$\begin{aligned} s_1(t, t_m) &= A \cdot \text{sinc}\left[B\left(t - \frac{2}{c}\left(R_0 - v_c t_m + \frac{(v - v_a)^2}{2R_0} t_m^2\right)\right)\right] \cdot w_a(t_m) \\ &\quad \cdot \exp\left[-\frac{j4\pi}{\lambda}\left(R_0 - v_c t_m + \frac{(v - v_a)^2}{2R_0} t_m^2\right)\right] \end{aligned} \tag{4}$$

where A is the complex reflectivity after pulse compression, $B = \mu T_p$ is the bandwidth of transmitted signal, t is the fast-time variable, and $\lambda = c/f_c$ denotes the wavelength of the transmitted signal. From (4), one can see that the target across-track velocity v_c will induce the linear range walk and the additional Doppler center shift. The target along-track velocity v_a will cause the range curvature and the DFM. In the following, in order to focus a ground moving target, the range walk, range curvature, and DFM are required to be accurately compensated.