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Imaging and Doppler parameter estimation for maneuvering target using axis mapping based coherently integrated cubic phase function ☆

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ABSTRACT

In this paper, we propose a novel imaging and Doppler parameter estimation algorithm for ground maneuvering targets. Since the cross-track acceleration will induce the quadratic chirp rate (third-order phase) in the phase history, it may cause the maneuvering target severely smeared in the Doppler domain. To obtain a well-focused target imaging result, the quadratic chirp rate must be estimated accurately. Though cubic phase function (CPF) is efficient in estimating the parameters of a single maneuvering target, it may suffer from the identifiability problem when dealing with multiple maneuvering targets. To address these issues, an axis mapping (AM) based coherently integrated cubic phase function (CICPF) algorithm is proposed. This algorithm consists of two stages. Firstly, the linear chirp rate migration (i.e. quadratic chirp rate) of target in the time and chirp-rate domain is corrected by AM. After that, a dechirping technique is utilized to coherently integrate the auto-terms, and suppress the cross-terms and spurious peaks. Compared with several existing quadratic chirp rate estimation approaches, AM based CICPF (AMCICPF) algorithm can acquire lower signal-to-noise ratio threshold and estimate the centroid frequency, chirp rate and quadratic chirp rate of maneuvering target simultaneously. By compensating the chirp rate and quadratic chirp rate, a finely focused maneuvering target imaging can be obtained. Both simulated and real data processing results show that the AMCICPF algorithm serves as a good candidate for maneuvering target Doppler parameter estimation and imaging.

1. Introduction

Synthetic aperture radar (SAR) technology plays an important role in strategic reconnaissance and surveillance because of its advantages in all-time, all-weather and long range work [1–4]. As a combination of ground moving targets indication (GMTI) and SAR technology, SAR-GMTI can obtain stationary and moving target information, and is becoming an important application to enhance the surveillance capability of modern SAR systems [5–8]. However, range migration and Doppler frequency broadening may occur in a long-time coherent integration period due to the motion of the targets. In practice, most of the vehicles traveling on the roads or highways experience acceleration, which may induce the third-order phase term, i.e. quadratic chirp rate (QCR), in phase history [9–12]. Accordingly, this third-order term may result in unsymmetrical Doppler broadening, which makes it difficult to improve the target focusing performance during a long-time coherent integration period.

To deal with the range migration, Jao [13] has established a connection between a well-focused target and its motion parameters. By two-dimensional (2-D) parameters searching, the range walk and curvature can be well corrected. However, it suffers from huge computational cost. Perry et al. [14] has proposed a keystone transform (KT) algorithm to simultaneously compensate the linear range walks of multiple targets without a priori knowledge of their motion parameters. However, the imaging performance of this algorithm may degrade due to the range curvature and the second-order phase (chirp rate) error. In addition, it becomes invalid with the presence of the Doppler ambiguity [12]. To settle these issues, Zhou et al. [15] has subsequently presented a second-order KT (SoKT) technique for range curvature correction. After range curvature compensation by SoKT, the actual cross-track velocity can be obtained by estimating the slope ratio of echo's envelop [16]. With the estimated cross-track velocity, the range walk can be corrected even when the target exists Doppler ambiguity.

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After range migration correction, a well-focused static target imaging can be obtained by conventional range-Doppler (RD) method. However, the RD method is invalid for the moving targets since their Doppler parameters are unknown. For targets with constant velocities, many chirp rate (CR) estimation algorithms have been proposed via time–frequency analysis tools, usch as Wigner–Ville distribution (WVD) [17], Hough–WVD [18], Radon-WVD [19], Radon Ambiguity function [20], fractional Fourier transform (FrFT) [21] and coherently integrated cubic phase function (CICPF) [22]. However, a moving target with constant acceleration in one range bin is usually modeled as quadratic frequency-modulated (QFM) signal, and CR estimation algorithms may cause the integration loss in this situation [9–12]. With regard to QCR estimation, many algorithms have been proposed, and generally they can be classified as non-correlation algorithms and correlation algorithms. The maximum likelihood (ML) [23] is a typical non-correlation algorithm. Although it can get good performance at low signal to noise ratio (SNR), ML requires three-dimensional (3-D) joint maximization over the centroid frequency, CR and QCR. Moreover, ML is likely to converge to local maxima if the objective function is not convex. To avoid the exhaustive 3-D search, many correlation algorithms have been proposed, such as the phase unwrapping [24], the polynomial phase transform (PPT) [25], high-order ambiguity function (HAF) [26] and its product version (PHAF) [27]. Since highly nonlinear transformation is employed, these algorithms may work poorly at low SNR, i.e. below 0 dB. To improve the estimation accuracy under low SNR condition, cubic phase function (CPF) was proposed to estimate parameters of a mono-component QFM signal with only second-order nonlinear transformation employed [28]. Unfortunately, for multi-component QFM signals, its bilinear transformation always causes the cross-terms and spurious peaks problem which may severely impede the detection and parameter estimation. To handle this issue, HAF-integrated CPF (HAF-ICPF) [29], integrated GCPF (IGCPF) [30] and Radon-CPF [31] are proposed. These methods accumulate the energy of auto-terms along straight lines, hence they are effective to suppress the cross-terms and spurious peaks. However, the accumulation of these algorithms is noncoherent and they may not be suitable for multi-component QFM signals at low SNR.

Motivated by the previous works, a novel Doppler parameter estimation algorithm, which is based on the axis mapping (AM) and coherently integrated CPF (CICPF), is proposed to solve the identifiability problem and improve the estimation performance under low SNR scenarios. Different from the previous research in [22], which is only suitable for moving targets with constant velocities, the algorithm proposed in this paper can estimate the QCR, CR and centroid frequency parameters for maneuvering targets. According to the linear CR migration in the time-CR (T-CR) domain, the AM transform is presented to make a QFM signal distribute along straight line parallel to the time axis. Meanwhile, the QCR can be estimated according to the relationship between the QCR and axis rotation angle. After that, the energy of QFM signal is coherently integrated by the proposed CICPF algorithm. By 2-D amplitude searching in the frequency-CR (F-CR) domain, the centroid frequency and CR can be determined simultaneously. Since the accumulation is coherent and the order of nonlinear transform in the proposed algorithm is equal to or less than that in the existing approaches, AM based CICPF (AMCICPF) algorithm can effectively suppress the cross-terms and spurious peaks, and can acquire satisfactory parameter estimation performance at low SNR. Combined with the AMCICPF, a novel SAR imaging algorithm is developed, which can realize the long-time coherent integration of the maneuvering targets.

The paper is organized as follows. After the introduction, the signal model of ground maneuvering target is illustrated in Section 2. To effectively estimate the Doppler parameter, an AMCICPF algorithm is proposed in Section 3. Section 4 presents a ground maneuvering target imaging algorithm based on AMCICPF. The numerical analyses and conclusions of this paper are given in Sections 5 and 6, respectively.

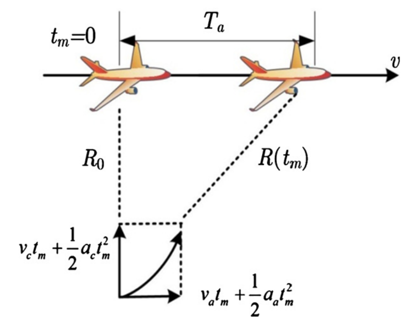

Fig. 1. Geometry of moving target.

2. Signal model

The geometry relationship between the flying platform and ground moving target for side-looking SAR is shown in Fig. 1. The platform travels with a constant velocity v and t_m is the slow time. v_a, a_a, v_c, a_c represent the along-track velocity, along-track acceleration, cross-track velocity and cross-track acceleration of a ground moving target, respectively. R_0 denotes the nearest slant range between the moving target and platform, and $R(t_m)$ denotes instantaneous slant range which can be obtained by [10]

$$R(t_m) = \sqrt{\left(vt_m - v_a t_m - \frac{1}{2}a_a t_m^2\right)^2 + \left(R_0 - v_c t_m - \frac{1}{2}a_c t_m^2\right)^2}$$
$$\approx R_0 - v_c t_m + \frac{(v-v_a)^2 - a_c R_0}{2R_0} t_m^2 - \frac{(v-v_a)a_a}{2R_0} t_m^3 \quad (1)$$

The approximation is obtained by applying the Taylor series expansion and ignoring the higher-order components.

For the side-looking SAR with zero squint angle, the received signal of the moving target after range compression can be expressed as [12]

$$s(t,t_m) = A w_a(t_m) \mathrm{sinc}\left[B_r\left(t - \frac{2R_s(t_m)}{c}\right)\right] \exp\left(-j\frac{4\pi R_s(t_m)}{\lambda}\right) \quad (2)$$

where A is the amplitude, B_r is the spectrum bandwidth of the transmitted signal, $w_a(t_m)$ is the azimuth windowing function, λ is the wavelength and c is the speed of the light, t is the fast time. Substituting (1) into (2), we can obtain

$$\begin{aligned} s(t,t_m) = A w_a(t_m) \mathrm{sinc}\Bigg\{ B_r\Bigg[t - \frac{2}{c}\Bigg(R_0 - v_c t_m \\ + \frac{(v-v_a)^2 - a_c R_0}{2R_0} t_m^2 - \frac{(v-v_a)a_a}{2R_0} t_m^3 \Bigg)\Bigg]\Bigg\} \\ \times \exp\Bigg\{ -j\frac{4\pi}{\lambda}\Bigg(R_0 - v_c t_m + \frac{(v-v_a)^2 - a_c R_0}{2R_0} t_m^2 \\ - \frac{(v-v_a)a_a}{2R_0} t_m^3 \Bigg)\Bigg\} \end{aligned} \quad (3)$$

From (3), it is noted that the range migration involves the range walk, the range curvature and the cubic range migration. It should be noted that the cubic range migration is usually ignored under the assumption of $(v - v_a)a_a \ll R_0$ [12]. Therefore, the received signal can be rewritten as