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Efficient and noise-resistant parameter estimation method for maneuvering targets in stepped frequency radar

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ABSTRACT

In this paper, a novel efficient parameter estimation method is proposed for maneuvering targets based on the stepped frequency radar. Since the envelope migration can be represented by the exponential phase variance with respect to range frequency, the received echoes are first converted into the range frequency domain and modeled as cubic phase (CP) signals. Then, a new correlation transform, referred to as recursive delay correlation transform (RDCT), is defined and applied to estimate the parameters of maneuvering targets. Since RDCT is simple and only requires the fast Fourier transform (FFT) and the nonuniform FFT (NUFFT), the searching operation is unnecessary and the computational cost is significantly reduced. Compared to the other four representative methods, the proposed RDCT-based method has no error propagation and can greatly improve the anti-noise performance on the premise of retaining the computational efficiency, achieving a good balance between the computational complexity and estimation performance. Theoretical analyses of anti-noise and anti-aliasing performance, and several simulation results verify the effectiveness of the proposed parameter estimation method.

1. Introduction

With the development of modern radar technology in both military and civil fields, improving the resolution has been receiving more and more attentions. The study on forming the high-resolution signal waveforms and the corresponding signal processing methods has important significance for the high-accuracy detection, multi-targets identification and multi-targets imaging. Generally, widening the signal bandwidth and lengthening the coherent processing interval (CPI) are common approaches to achieve high-resolution range and velocity measurements. Due to the disadvantages of the high sampling rate, large data storage and high hardware cost, synthesizing a large bandwidth is preferable to directly transmitting a conventional wideband signal and has become one of the most important trends in the field of high-resolution radar system design [1]. Since stepped frequency (SF) waveforms can synthesize a very wide frequency bandwidth with narrow bandwidth transmitter and receiver, they are widely used in high-resolution radar system (such as synthetic aperture radar (SAR) imaging, inverse SAR (ISAR) imaging, etc.) [2,3].

It is well known that the "stretch" processing method [3,4] based on the inverse discrete Fourier transform (IDFT) is widely used in the SF radar. It can obtain high range resolution profiles (HRRPs) with narrow instantaneous bandwidth and low system complexity. However, the "stretch" processing method is highly sensitive to the target motion, and thus it is inappropriate for the maneuvering targets. As for the maneuvering targets with complex motion, the existence of relative motion parameters between radar and targets inevitably induces envelope migration (EM) and Doppler frequency spread (DFS) terms. These factors degrade the focusing quality of HRRPs, resulting in the resolution descending and performance deterioration for the detection and estimation. Therefore, for detecting and estimating the maneuvering targets with complex motion in the SF radar, it is quite important to precisely compensate the EM and DFS terms.

For the EM compensation, many effective methods have been presented, including envelope correlation [5,6], keystone transform [7–9], Radon transform [10] and entropy minimization algorithm [11,12], etc. The envelope correlation compensates the EM based on the estimated velocity obtained from correlation operation. Thus, it is limited to the high signal-to-noise ratio (SNR) environments. Keystone transform can compensate the EM via scaling operation without any prior kinetic information of targets and is suitable for the low SNR circumstances. However, it performs poorly in the situation of existing velocity ambiguity [9]. Although Radon transform and entropy minimization algorithm can deal with the

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velocity ambiguity, they are implemented by the searching operation, bringing heavy computational load.

For the DFS terms compensation, the straightforward way is to construct the compensation function based on the accurately estimated parameters. Generally speaking, the uniformly accelerated motion is accurate enough to describe the motion characteristics of maneuvering targets. In the SF radar, the acceleration of the target contributes to a quadratic phase term and a cubic phase term. Thus, the azimuth echoes should be modeled as the cubic phase (CP) signals. Recently, with regard to the parameter estimation of CP signals, many methods have been proposed, and they generally fall into two categories: methods based on correlation and methods without correlation. Most typical methods based on correlation include product high order ambiguity function (PHAF) [13], product high-order match phase transform (PHMT) [14], product generalized cubic phase function (PGCPF) [15], TC-dechirp Clean [16] and higher order ambiguity function-integrated cubic phase function (HAF-ICPF) [17], etc. The essence of these methods is to reduce the order of CP signals via multilinear or bilinear operators, then the estimated parameters are obtained via Fourier transform or one-dimensional search. However, they are prone to the low resolution and high SNR threshold problems. The maximum likelihood algorithm [18] and the discrete chirp Fourier transform [19] belong to the category of methods without correlation. Although these methods achieve good performance in the low SNR environments, the required multi-dimensional search consumes heavy computational burden.

Recently, in order to compensate EM and DFS terms simultaneously, several detection and estimation methods for the maneuvering targets have been proposed, such as, Radon–Fourier transform/Generalized Radon–Fourier transform (RFT/GRFT) [20,21], Radon Lv's distribution (RLVD) [22] and phase differentiation-RLVD (PD-RLVD) [23,24], etc. RFT/GRFT are typical likelihood ratio test detectors and achieve optimal estimation performance, but the ergodic search in them will inevitably introduce huge computational complexity. To reduce the computational complexity, a fast implementation based on particle swarm optimization (PSO) has been presented in [25], but it is sensitive to the set of initial parameters and may converge to the local optimal maximum, resulting in performance degradation. By calculating the LVD along the trajectory of the target, RLVD and PD-RLVD can jointly eliminate EM and DFS and coherently accumulate the energy on the two-dimensional (2D) frequency plane. LVD is free of searching and only requires the 2D Fourier transform over a scaled time-lag instantaneous autocorrelation function [26], which significantly reduces the computational complexity. However, matching the trajectory of the target requires large quantities of searching calculations, which would lead to a heavy computational burden.

Drawing lessons from the current parameter estimation methods for the maneuvering targets and considering the tradeoff between the computational complexity and the anti-noise performance, we propose a search-free and noise-resistant parameter estimation method based on a novel defined correlation transform, referred to as RDCT. In the proposed method, the received echoes are first converted into the range frequency domain to eliminate the EM and modeled as CP signals. Then, the defined RDCT is applied to directly estimate the motion parameters. The implementation of RDCT only requires FFT and NUFFT, which help avoid brute-force search, and thus the computational cost is saved. Furthermore, the analyses of cross terms, anti-noise performance and anti-aliasing performance demonstrate that the proposed method is appropriate for the situation of multiple targets with ambiguous velocities and it can acquire higher anti-noise performance compared to PHMT, HAF-ICPF and TC-dechirp Clean. Through the simulations for synthetic models, we validate the effectiveness of the proposed method.

The remainder of this paper is organized as follows. In Section 2, we establish the signal model of maneuvering targets in the SF radar. In Section 3, we introduce the principle of the proposed parameter estimation method based on the novel defined RDCT and discuss the influence of cross terms. In Section 4, we theoretically analyze the computational cost, anti-noise performance and anti-aliasing performance of the proposed method and specifically discuss the differences from the LVD-based methods. In Section 5, simulations with synthetic radar data are carried out and the conclusions are drawn in Section 6.

2. Signal model

Assume that the transmitted signal in the SF radar is

$$S_T(\tau_r, t_m) = u(\tau_r)\exp\left[j2\pi f_c(m)(\tau_r + t_m)\right] \tag{1}$$

where τ_r is the fast time (range time), $t_m = mT_r$ is the slow time (azimuth time) with T_r denoting the pulse duration time (PRT), $0 \le m \le M-1$ denoting the pulse index and M denoting the number of pulses within a CPI. $u(\tau_r)$ is the transmitted waveform. $f_c(m) = f_c + m\Delta f$ is the carrier frequency of the mth pulse where f_c is the initial carrier frequency and Δf is the frequency step size.

Suppose that there are K moving targets in the scene. For the wideband transmitted signal, the baseband received echoes can be expressed as [27,28]

$$\begin{aligned} S_B(\tau_r, t_m) = &\sum_{k=1}^{K} \sqrt{\kappa_k}\sigma_k u\left(\kappa_k\left(\tau_r - \frac{2R_k(t_m)}{c-v_k}\right)\right) \\ &\times \exp\left[-j4\pi f_c(m)\frac{R_k(t_m)}{c+v_k}\right] \\ &\times \exp\left[-j4\pi f_c(m)\frac{v_k\tau_r}{c+v_k}\right] \end{aligned} \tag{2}$$

where σ_k is the backscattering coefficient of the kth target. $\kappa_k = \frac{c-v_k}{c+v_k}$ is the scale factor of the kth target with v_k and c denoting the radial velocity of the kth target and the speed of light, respectively. $R_k(t_m)$ is the instantaneous range between radar and the kth target. The last term in (2) is the intra-pulse Doppler. Obviously, it varies with $f_c(m)$ and results in the range-Doppler coupling. To compensate this coupling term, the wideband matched filter (WFM) [27] is performed on the received echoes and the results are given by

$$\begin{aligned} S_M(\tau_r, t_m) = &\sum_{k=1}^{K} \kappa_k\sigma_k p\left(\kappa_k\left(\tau_r - \frac{2R_k(t_m)}{c-v_k}\right)\right) \\ &\times \exp\left[-j4\pi f_c(m)\frac{R_k(t_m)}{c-v_k}\right] \end{aligned} \tag{3}$$

where $p\left(\kappa_k\left(\tau_r - \frac{2R_k(t_m)}{c-v_k}\right)\right) = \int \left|u\left(\kappa_k\left(\tau_r - \frac{2R_k(t_m)}{c-v_k}\right)\right)\right|^2 d\tau_r$. Under the assumption of $|v_k|/c \ll 1$, we have $\kappa_k \approx 1$ and $c - v_k \approx c$. Thus, (3) can be further simplified as

$$S_M(\tau_r, t_m) \approx \sum_{k=1}^{K} \sigma_k p\left(\tau_r - \frac{2R_k(t_m)}{c}\right)\exp\left[-j4\pi f_c(m)\frac{R_k(t_m)}{c}\right] \tag{4}$$

Usually, the uniformly accelerated motion is accurate enough to describe the moving characteristics of the maneuvering targets. Thus, $R_k(t_m)$ can be expressed as

$$R_k(t_m) = R_{0k} + v_k t_m + \frac{1}{2}a_k t_m^2 \tag{5}$$

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