Computationally efficient coherent detection and parameter estimation algorithm for maneuvering target

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ABSTRACT

In this paper, a computationally efficient coherent detection and parameter estimation algorithm via symmetric autocorrelation function (SAF) and scaled Fourier transform (i.e., SAF-SFT) is proposed, involving range cell migration (RCM) and Doppler spread (DS) within the coherent integration (CI) time. In particular, the first SAF and SFT operations are applied to achieve the range and velocity estimations after the generalized keystone transform. With the estimations, the remaining RCM induced by target's velocity could be removed and the target signal could be extracted along the range cell. Then the second SAF and SFT operations are performed on the extracted signal, where the target energy could be coherent integrated and the acceleration estimation can be obtained. Cross term of SAF-SFT is also analyzed and its characteristic indicates the applicability in the scenario of multi-targets. Detailed comparisons of SAF-SFT with several typical algorithms with respect to computational cost, detection probability and parameter estimation ability show that the SAF-SFT could strike a balance between computational cost and detection probability as well as the estimation performance. Simulation results and real test experiment are given to verify the SAF-SFT based approach.

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1. Introduction

Effective detection and parameter estimation of maneuvering targets is a challenging problem in the field of radar [1–4]. With the help of long-time coherent integration (CI) technique, the radar detection and estimation performance of maneuvering targets can be significantly improved. Nevertheless, the high speed and acceleration motion of maneuvering target will bring about range cell migration (RCM) and Doppler spread (DS) effects within the CI time [4–7]. Then the integration gain and target detection ability of traditional coherent integration method will be reduced sharply [8–14].

As to the RCM correction, some popular methods have been introduced, such as sequence reversing transform (SRT) [15,16], keystone transform (KT) [17–20], axis rotation moving target detection (AR-MTD) [21], Radon-Fourier transform (RFT) [22], adjacent cross correlation function (ACCF) [23,24], scaled inverse fourier transform (SIFT) [25], and frequency-domain deramp-keystone transform (FDDKT) [26]. For example, SRT could remove the RCM via the correlation operation between the received signal and its reversed conjugate signal. KT is able to correct the RCM via rescaling in the time-frequency domain. AR-MTD and RFT could eliminate the RCM with the two-dimensional searching process. ACCF can remove the RCM with the help of adjacent cross correlation operation. Nevertheless, the ACCF-based algorithm needs a high signal-to-noise ratio (SNR) input and will suffer detection performance loss when the SNR of target's echo reduced. SRT requires a strictly demand on the time symmetry property, which limits its application in the radar field. Moreover, KT, AR-MTD, RFT, SIFT and FDDKT could not remove the DS effect induced by target's acceleration.

In order to deal with the DS effect, some popular methods, such as Lv's distribution (LVD) [27,28], fractional Fourier transform (FRFT) [29] and polynomial Fourier transform (PFT) based methods [30], are introduced to eliminate the DS and obtain the focused result of target energy. Compared with the PFT and FRFT, LVD can obtain better integration performance and detection ability of weak target's signal in the centroid frequency chirp rate (CFCR) domain. Unfortunately, these three algorithms can only eliminate the DS effect and can not deal with the RCM effect. For the high speed target with acceleration motion, the RCM and DS effects will occur simultaneously and then the methods mentioned above would become invalid.

In this regard, Xing et al. combined the KT and minimum entropy (i.e., KTME) to remove the RCM and DS effects [31]. Unfortunately, this method needs high SNR input due to the minimum-entropy based operation. In [32], Tian et al. introduced a CI approach combing generalized keystone transform and RFT (GKT-

RFT). Nevertheless, the RCM correction performance of this algorithm may be affected by the previous DS compensation process. Thus, in [33] and [34], the Radon-Lv's distribution (RLVD) and Radon-fractional Fourier transform (RFRFT) are respectively presented, which can simultaneously remove the RCM and DS effects. However, the multi-dimension searching process of RLVD [33] and RFRFT [34] make them are of huge computational burden. To reduce the computational cost, Sun. et al. introduced an approach based on KT and matched filter process (i.e., KTMFP) for maneuvering target detection [35]. Unfortunately, the computational burden of KTMFP is still huge.

In this paper, a computationally-efficient radar maneuvering target detection and motion parameter estimation algorithm is proposed based on the symmetric autocorrelation function (SAF) and scaled Fourier transform (SFT), i.e., SAF-SFT. This algorithm is coherent and could totally eliminate the RCM and DS without the parameter-searching process. The computational complexity, detection ability, and estimation performance are analyzed and compared with several typical algorithms, which leads us to conclude that the proposed SAF-SFT algorithm could strike a balance among the computational burden, detection probability and motion parameter estimation ability. Moreover, the cross term characteristic of SAF-SFT under multi-target scene is also analyzed and shows the applicability of the proposed algorithm in the scenario of multiple targets. Finally, experiments with the real measured radar data are conducted to verify the proposed algorithm.

The paper is organized as follows. Signal model is given in Section 2. The SAF-SFT based algorithm is described in Section 3. The cross terms analysis is placed in Section 4. Computational cost analysis is provided in Section 5. Simulation examples and real data processing are given in Section 6 followed by conclusions.

2. Signal model

Assume that the radar transmits the linear-frequency modulated signal [10,13,21,34], i.e.,

$$s_{trans}(\hat{t}) = \text{rect}\left(\frac{\hat{t}}{T_p}\right) \exp\left(j\pi \mu \hat{t}^2\right) \exp(j2\pi f_c \hat{t}), \tag{1}$$

where

$$\text{rect}(x) = \begin{cases} 1, & |x| \leq \frac{1}{2} \\ 0, & |x| > \frac{1}{2} \end{cases}$$

μ, T_p, $\hat{t}$ and f_c denote the frequency modulated rate, pulse duration, fast time and carrier frequency, respectively.

Without loss of generality, the signal model of the ith ($i = 1, 2, \cdots, K$) target is established for simplicity, where the instantaneous slant range $R_i(t_m)$ of the ith target satisfies [34]

$$R_i(t_m) = R_{0i} + v_i t_m + a_i t_m^2, \tag{2}$$

where $t_m = mT$ ($m = 0, \cdots, N$) is the slow time, N and T are respectively the pulse number and pulse repetition time. a_i, v_i and R_{0i} are ith target's radial acceleration, velocity and initial slant range, respectively.

The received signal of the ith target after pulse compression (PC) could be formulated as [34]

$$s(\hat{t}, t_m) = A_{1i}\text{sinc}\left[B\left(\hat{t} - \frac{2(R_{0i} + v_i t_m + a_i t_m^2)}{c}\right)\right] \\ \times \exp\left(-j4\pi \frac{R_{0i} + v_i t_m + a_i t_m^2}{\lambda}\right), \tag{3}$$

where λ represents the wavelength, i.e.,

$$\lambda = c/f_c, \tag{4}$$

c, B and A_{1i} are respectively the speed of light, bandwidth and amplitude after PC.

Because of target's high speed and radar's low pulse repetition frequency (PRF), Doppler ambiguity would occur. As a result, the target's velocity could be expressed as

$$v_i = F_i v_a + v_{0i}, \tag{5}$$

where v_a represents the blind velocity, i.e.,

$$v_a = \lambda f_p/2, \tag{6}$$

v_{0i} is defined as the unambiguous velocity and it satisfies $v_0 \in \left[-\frac{\lambda f_p}{4}, \frac{\lambda f_p}{4}\right]$, F_i denotes the fold factor (also called as ambiguous number) of the ith target, f_p is the PRF.

Instituting (5) into (3) and considering that $2\pi f_p F_i t_m$ is an integral multiple of 2π, we have

$$s(\hat{t}, t_m) = A_{1i}\text{sinc}\left[B\left(\hat{t} - \frac{2(R_{0i} + v_i t_m + a_i t_m^2)}{c}\right)\right] \\ \times \exp\left(-j4\pi \frac{R_{0i} + v_{0i}t_m + a_i t_m^2}{\lambda}\right). \tag{7}$$

Perform the Fourier transform (FT) on (7) along the fast time axis, we have

$$S(f_r, t_m) = A_{2i}\text{rect}\left(\frac{f_r}{B}\right) \exp\left(-j4\pi f_r \frac{F_i v_a t_m}{c}\right) \\ \times \exp\left[-j4\pi (f_c + f_r)\frac{(R_{0i} + v_{0i}t_m + a_i t_m^2)}{c}\right], \tag{8}$$

where A_{2i} denotes the signal's amplitude after FT, i.e.,

$$A_{2i} = A_{1i}/B. \tag{9}$$

Eq. (8) shows that target's acceleration and velocity are all coupled with f_r, which will result in DS and RCM effect within the CI time.

3. Coherent integration and parameter estimation

3.1. Range and velocity estimation

First of all, the generalized keystone transform (GKT) is used to correct the RCM caused by target's acceleration, which performs scaling as follows:

$$t_m = [f_c/(f_r + f_c)]^{1/2}u_m. \tag{10}$$

Apply the GKT on (8) yields

$$S(f_r, u_m) = A_{2i}\text{rect}\left(\frac{f_r}{B}\right) \exp\left[-j4\pi (f_c + f_r)\frac{R_{0i}}{c}\right] \\ \times \exp\left[-j4\pi f_r \frac{F_i v_a u_m}{c}\left(\frac{f_c}{f_c + f_r}\right)^{1/2}\right] \\ \times \exp\left[-j4\pi \left(1 + \frac{f_r}{f_c}\right)^{1/2} f_c \frac{v_{0i} u_m}{c}\right] \\ \times \exp\left(-j4\pi \frac{a_i u_m^2}{\lambda}\right). \tag{11}$$

Take the first-order Taylor series expansion on $f_r[f_c/(f_c + f_r)]^{1/2}$ and $(1 + f_r/f_c)^{1/2}$, we have

$$f_r[f_c/(f_c + f_r)]^{1/2} \approx f_r, \tag{12}$$

$$(1 + f_r/f_c)^{1/2} \approx 1 + f_r/(2f_c). \tag{13}$$