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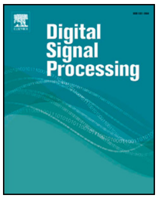

Radar high speed small target detection based on keystone transform and linear canonical transform

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ABSTRACT

High speed small target detection is a challenging problem for ground-based radar due to its maneuverability and low radar cross section (RCS). The range migration (RM) and Doppler frequency migration (DFM) will occur during the coherent integration period, which makes it difficult to improve the coherent integration ability and radar detection performance. In this study, a novel algorithm based on Keystone transform (KT) and linear canonical transform (LCT) for high speed small target detection with narrowband radar is proposed. Firstly, it employs KT to eliminate RM. Thereafter, the LCT is applied to compensate DFM and realize coherent integration for the target in the LCT domain. Two typical forms of LCT are given for easy realization and good detection performance. Finally, the constant false alarm ratio (CFAR) detector is performed to confirm a target and motion parameters are then estimated. Moreover, in order to realize fast compensation for velocity ambiguity effect, an improved method is proposed based on coarse and fine search. Compared with the generalized Radon Fourier transform (GRFT), the proposed method can acquire a close detection performance but with relatively low computational cost. Simulation results are provided to demonstrate the validity of proposed method.

1. Introduction

High speed small target detection has attracted a lot of attention for modern radar because of its importance for target tracking, imaging and the exploration of space resources [1–5]. In general, a small target has strong maneuverability and low radar cross section (RCS), which makes it more challenging for radar target detection [6,7]. It is well-known that the ultimate target detection performance can be improved by increasing the observation time. Unfortunately, the long coherent integration for high speed small target could generate range migration (RM) and Doppler frequency migration (DFM) effects, which lead to severe performance loss for the traditional moving target detection (MTD) algorithm [8,9].

In the past decades, several long-time integration detection algorithms have been presented to detect the moving target. These detection algorithms could be divided into three kinds: incoherent integration detection [10–16], coherent integration detection [17–29], and hybrid coherent–incoherent integration detection [30,31]. As for the incoherent integration detection, Radon transform [13,14], Hough transform [10–12], and track-before-detection technique [15,16] are the typical algorithms, which are simple in realization because of no dependency upon the strict coherence of the radar system. However, incoherent integration detection methods have a low integration gain without utilizing the echo phase information. In addition, these methods heavily rely on the input signal-to-noise ratio (SNR), and would suffer from a large integration performance loss when in low SNR condition. The coherent integration detection algorithms make the best of the echo's magnitude and phase information. Thus, they have the greatest integration gain and the largest computation cost among these three sorts of detection methods. The hybrid coherent–incoherent integration detection algorithms divide the integration time into several segments, which can accomplish coherent integration during the segments and incoherent integration among the segments. Recently, Xu et al. [30] propose a hybrid integration method named MTD and generalized Radon transform (MTD-GRT) to detect highly maneuvering target. Although the hybrid integration can be realized in a lower computation than the coherent integration, its integration performance is worse.

To detect high speed small target, the coherent integration is required due to its extremely low RCS. With respect to the coherent integration detection, Keystone transform (KT) [17,18] and Radon Fourier transform (RFT) [4,19,20] are the classic methods. The KT can compensate the linear RM effectively via rescaling the slow time variable, and make the target's energy accumulated in the fast time-Doppler frequency domain via fast Fourier transform

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(FFT). The RFT is proposed to decouple the echo between the RM and phase modulations by searching range and velocity parameters, which can realize coherent integration for the high speed target and improve the radar coverage significantly. Recently, some efficient coherent integration methods based on KT are developed in [41,42]. However, the above methods cannot compensate DFM induced by radial acceleration, and could result in integration performance loss [32]. Considering the compensation of DFM, coherent detection algorithms based on motion parameter estimation are proposed. These algorithms take advantage of specific signal processing methods, such as two-dimensional median filtering [5], the minimum criterion [6], Radon transform [6,24] and fractional Fourier transform (FRFT) [23], to estimate motion parameters, and then construct compensation function to remove RM and DFM. Although they can be realized in relatively low computational cost and achieve good detection performance in high SNR condition, they will suffer from great performance loss or even fail under the low SNR circumstance, which limits their applications to the high speed small target detection. In order to further improve the detection performance, several popular methods based on motion parameter search are proposed, such as generalized Radon–Fourier transform (GRFT) [21], Radon–Fractional Fourier transform (RFRFT) [22], and Radon–Lv's distribution (RLVD) [9]. These methods can remove RM and DFM simultaneously via the combined search of motion parameters, and achieve optimal energy accumulation when the searching motion parameters are matched with the actual ones. Nevertheless, they are computationally prohibitive because of three-dimension searching of range, velocity, and acceleration, which may limit their practical applications. In [25], a new method based on KT and Lv's distribution (KT-LVD) is proposed. It can achieve good detection performance for maneuvering target in the low SNR environment. However, the LVD depends on the radar signal redundant information, and has its estimated range of the frequency and chirp rate, which may not suitable for the case of high speed small target when the estimated motion parameters are out of the range [33,39]. In order to reduce the computational load, Pang et al. propose a high-speed target detection algorithm based on frequency compensation [43]. However, this algorithm leads to performance loss and inaccurate parameter estimation because of its rough searching step and no compensation for DFM.

In this paper, a novel high speed small target detection algorithm based on KT and linear canonical transform (LCT) is proposed. The KT is firstly applied to correct RM, and then LCT is performed to compensate DFM induced by acceleration and realizes the coherent integration for high speed small target detection. In order to realize fast compensation for velocity ambiguity effect, an improved method is proposed based on coarse and fine search. Thereafter, the likelihood ratio test (LRT) detector of the proposed algorithm is derived, which indicates the proposed algorithm is an optimal detector. The effectiveness of the proposed algorithm is demonstrated by numerical experiments. Compared with MTD-GRT and the methods in [23] and [24], the proposed method can realize coherent integration detection for high speed small target in very low SNR condition. In comparison with GRFT, the proposed method can achieve a close detection performance with relatively low computational cost.

The rest of the paper is organized as follows. The target signal model is established and the problems faced is analyzed in Section 2. In Section 3 the novel detection method based on KT and LCT is provided. The analysis of the provided algorithm and some remarks are given in Section 4. Then, some numerical experiments are provided in Section 5. Finally the conclusion is presented in Section 6.

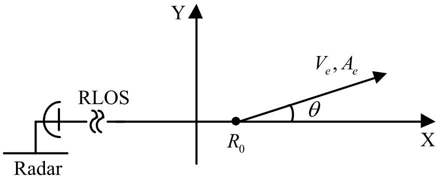

Fig. 1. The high speed small target model.

2. Signal model and problem analysis

The high speed small target can be regarded as a point-scattering model [6], which is shown in Fig. 1. The X coordinate denotes the radar line of sight (RLOS). R_0, V_e, and A_c are the initial range, velocity, and acceleration, respectively. The angle between target detection and RLOS is θ, which is assumed to be a constant during the observation time. Therefore, the target radial range $R(t_m)$ with respect to slow time t_m can be expressed as

$$R(t_m) = R_0 + V_e\cos(\theta)t_m + \frac{1}{2}A_c\cos(\theta)t_m^2 \tag{1}$$

where $t_m = mT_r$ is the slow time, $m = 1, 2, \ldots, M$, M is the number of radar pulses, and T_r is the pulse repetition interval.

Define $v = V_e\cos(\theta)$ and $a_s = A_c\cos(\theta)$, (1) can be rewritten as

$$R(t_m) = R_0 + vt_m + \frac{1}{2}a_s t_m^2 \tag{2}$$

where v and a_s are respectively the target radial velocity and acceleration.

Suppose the narrowband radar transmits the linear frequency modulation (LFM) signal, which is stated as follows

$$s(\hat{t}, t_m) = \mathrm{rect}\left(\frac{\hat{t}}{T_p}\right)\exp\left(j\pi\gamma\hat{t}^2\right)\exp\left[j2\pi f_c(\hat{t} + t_m)\right] \tag{3}$$

where $\mathrm{rect}(u) = \begin{cases} 1, |u| \le \frac{1}{2} \\ 0, |u| > \frac{1}{2} \end{cases}$, T_p is the pulse width, f_c denotes the carrier frequency, γ denotes the chirp rate of LFM signal, $\hat{t}$ is the fast time.

After down conversion and pulse compression, the received signal can be expressed as [5,24]

$$\begin{aligned} s_{PC}(f, t_m) = {} & A_1 \mathrm{rect}\left(\frac{f}{B}\right)\exp\left(-j\frac{2\pi f_d f}{\gamma}\right) \\ & \times \exp\left[-j\frac{4\pi}{\lambda}\frac{f + f_c}{f_c}R(t_m)\right] \end{aligned} \tag{4}$$

where A_1 is the target reflectivity, B denotes the bandwidth, $f_d = 2v/\lambda$ denotes the Doppler frequency, $\lambda = c/f_c$ denotes the wavelength, and c is the speed of light.

Performing MTD on (4), we obtain

$$\begin{aligned} & s_{MTD}(\hat{t}, f) \\ & \approx A_2 \left| \sum_{m=0}^{M-1} \mathrm{sinc}\left[B\left(\hat{t} - \frac{2R_0}{c} - \frac{2v}{c}mT_r - \frac{f_d}{\gamma}\right)\right] \right. \\ & \qquad \left. \times \exp\left[-j2\pi(f_d + f)mT_r\right]\exp\left[-j\frac{2\pi a_s (mT_r)^2}{\lambda}\right] \right| \end{aligned} \tag{5}$$

where $\mathrm{sinc}(a) = \sin(\pi a)/(\pi a)$.

The envelope shift caused by the high speed target's acceleration is ignored here [5,6]. It is noted from (5) that the target envelope is shifted from its initial position and changes with the observation time. The RM will occur when the change exceeds the