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A Coherent Accumulation Detection Method Based on SA-DPT for Highly Maneuvering Target

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ABSTRACT The emergence of highly maneuverable weak targets has led to a serious degradation or even failure of traditional radar detection. In this paper, a coherent accumulation algorithm based on combination of scaling algorithm (SA) and discrete polynomial-phase Transform (DPT) is proposed in terms of the calculation burden and detection performance, which can, firstly, perform fewer times of speed parameter compensation based on SA for the transmitted signal, and selects the effective delay range of the target signal; secondly, for the extracted echo signal, the DPT algorithm is used to estimate the target speed and acceleration. The proposed algorithm analyzes the influence of time delay range, compensation speed and delay unit on the detection performance, and gives the improvement degree of output SNR and the amount of complex multiplication. Finally, the experimental data verify the effectiveness of the proposed algorithm in accumulation gain and parameter estimation. This method is for sub-optimal estimation, requiring much less computation than joint search methods, but performs better than cross-correlation methods.

Keywords highly maneuvering target, weak signal detection, scaling algorithm (SA), discrete polynomial phase Transform (DPT)

1. Introduction

With the development of aircraft technology, more and more aircraft have the characteristics of high speed, high maneuverability and stealth, which brings great challenges to conventional radar detection. With the same observation time, the echo accumulation energy of a highly maneuverable weak target is lower than that of conventional target.

To improve the detection probability of targets, the common method is long time accumulation, which includes coherent accumulation and noncoherent accumulation. Among them, the accumulation gain of noncoherent accumulation method is low, this paper mainly studies the coherent accumulation method. At present, there are mainly two kinds of methods for long time coherent accumulation [1-6], one is joint search methods based on parameter, which first estimates the range of target speed, acceleration and other parameters, and then detects the target signal through two-dimensional or multi-dimensional parameter search. For example, [7] studied the parameter compensation methods for speed and acceleration based on SA, improving the probability of target detection. [8] studied the parameter estimation methods for distance, speed, and acceleration based on Maximum likelihood estimator (MLE), and analyzed the parameter errors using

the Cramer-Rao Lower Bound (CRLB). [9]-[12] studied the compensation method for range migration (RM) based on the keystone (KT) method, but there were speed ambiguity numbers for the target with higher speed. [13]-[16] studied a highly maneuvering target detection methods based on Radon Fourier transform (RFT), which used Radon transform and FT to complete RM compensation and Doppler frequency migration compensation, respectively. [17] studied the detection method for highly maneuvering targets based on Three-dimensional scaled transform (TDST), whose output signal-to-noise ratio (SNR) had improved by more than 10 dB compared with that of the MTD method. [18] studied the RM compensation based on Radon transform and Doppler frequency migration compensation based on Lv's distribution (LVD), in which the detection performance is close to RFT. [19]-[22] studied the coherent accumulation method for high speed target based on FRFT. [23]-[24] studied the sparse Fourier transform (SFT) method to accelerate the speed compensation and spectrum computation of high speed targets.

Among the above methods, they have high accumulation gain and good detection performance for low SNR signals, but have large calculation burden and poor

real-time performance. In order to reduce the amount of computation, the other is cross-correlation parameter estimation methods based on order reduction processing. This kind of method first performs cross-correlation processing on the target echo signal to realize the decoupling operation between speed and accumulation time, as well as dimension reduction processing. On this basis, it uses two-dimensional FFT to detect the target. For example, [25]-[28] studied the highly maneuvering target detection methods based on the Discrete polynomial-phase Transform (DPT). [29]-[33] studied the highly maneuvering target detection methods based on the thoughts of adjacent cross correlation function (ACCF). The second kind of method has the advantage of lower computational complexity than that of the first kind of method, but requires a higher input SNR than that of the first kind of method and is not suitable for detecting weak target signals.

Considering both the improvement of the detection performance and the reduction of calculation burden, this paper focuses on analyzing the reasons why the DPT method reduces the detection ability of weak target signals. In order to further improve the detection performance of the DPT method, a coherent accumulation detection method based on combination of SA-DPT for highly maneuvering targets has been proposed in this paper, with its structure arranged as follows: The first part that overviews the long time coherent accumulation method commonly used for weak signal detection, and analyzes its detection performance and calculation burden; In the second part that gives out the maneuvering target echo model based on the LFM radar; In the third part, a long time coherent accumulation method based on the combination of SA and DPT is proposed; In the fourth part, the implementation process of the proposed method is given, and the effects of signal processing range, speed compensation factor and delay unit on the detection performance are analyzed, and the complex multiplication operation of different methods are compared and analyzed; In the fifth part, the experimental data are used to verify the effectiveness of the proposed method. The sixth part summarizes and discusses the full text.

2. High maneuvering target echo model

Assuming that the detection system is an LFM pulse radar, the frequency spectrum of the transmitted and received signal after down-conversion can then be expressed as^[19]:

$$R(f, n) = \frac{1}{\sqrt{\mu}} \text{rect}\left(\frac{f}{\mu T_0}\right) \exp\left(-j\pi \frac{f^2}{\mu}\right) \quad (1)$$

$$\begin{aligned} S(f, n) = & \frac{A_0}{\sqrt{\mu}} \text{rect}\left(\frac{f-f_d}{\mu T_0}\right) \exp\left[-j\pi \frac{(f-f_d)^2}{\mu}\right] \\ & \times \exp(j2\pi f_d nT) \exp\left(-j\frac{4\pi R_0}{\lambda}\right) \\ & \times \exp[j\pi \alpha_d (nT)^2] \exp[-j2\pi (f-f_d)(\tau_0 - \beta_0 nT)] \end{aligned} \quad (2)$$

where, A_0 is the amplitude of the signal, μ is frequency modulation rate, T_0 is pulse width, R_0 is the initial range of the target distance from radar, $\tau_0 = 2R_0/c$ is the initial time delay of the target, $b_0 = 2v_0/c$ is the time delay change rate of the target, $f_d = 2v_0/l$ is the Doppler frequency of the target, $a_d = 2a/l$ is the first-order term of the Doppler frequency change, v_0 is the target radial speed, a is the target radial acceleration, T is pulse repetition period, c is velocity of light, f_c is signal carrier, $\lambda = c/f_c$ is the transmitted signal wavelength.

Multiplying Equation(1) by (2) to arrive at the frequency domain and time domain signals after pulse compression of the echo signal as:

$$X(f, n) \approx \frac{A_0}{\sqrt{\mu}} \text{rect}\left(\frac{f}{B}\right) \exp[-j2\pi f(\tau_0 - \beta_0 nT)] \exp(-j\frac{4\pi R_0}{\lambda}) \quad (3)$$

$$\begin{aligned} & \cdot \exp[j2\pi f_d(nT + \tau_0 - \beta_0 nT)] \exp[j\pi \alpha_d (nT)^2] \\ x(t, n) \approx & A_0 \sqrt{D} \text{sinc}\left[\pi B\left(t - \tau_0 + \beta_0 nT + \frac{f_d}{\mu}\right)\right] \exp\left(-j\pi \frac{f_d^2}{\mu}\right) \\ & \cdot \exp\left(j\pi f_d\left(t + \tau_0 - \beta_0 nT + \frac{f_d}{\mu}\right)\right) \exp(j2\pi f_d nT) \exp(j\pi \alpha_d (nT)^2) \end{aligned} \quad (4)$$

where, $D = BT_0$ is the product of the time width and the bandwidth, B is the bandwidth of input signals.

It can be seen from Equation(3) and (4) that the exponential functions that cause the target envelope to produce time delay migration and Doppler frequency migration are:

$$R(f, v) = \exp[-j2\pi f(t_0 - Dt)] \quad (5)$$

$$F(f_d, a) = \exp[j2\pi f_d(1 + Df)] \quad (6)$$

where,

$$\Delta\tau \approx \beta_0 nT \quad (7)$$

$$\Delta f \approx \alpha_d (nT) \quad (8)$$

Equation (7) to (8) show that in the same accumulation time, the greater the target speed and acceleration, the more serious the target energy diffusion, and therefore the detection probability will fall significantly. The time delay migration caused by speed and the Doppler frequency migration caused by acceleration have been mainly considered in this paper.

3. COHERENT ACCUMULATION METHOD BASED ON SA-DPT

In order to overcome the energy expansion caused by speed and acceleration, a coherent accumulation method based on SA-DPT is proposed in this paper. The SA method can store the speed compensation factor and complete the speed compensation processing of the transmitted signal in advance, but the compensation processing mentioned in [2,5-8] can complete the speed compensation after

receiving the echo signal. Therefore, the SA method can improve the operation efficiency.

In addition, the delay range of the target after SA compensation is extracted, on this basis, the speed and acceleration information of the target can be obtained by using DPT. Compared with DPT processing in [27-29], the proposed method improves the detection probability of weak signal. At the same time, the operation of the proposed method is mainly one-dimensional parameter search and two-dimensional FFT processing, and its amount of operation is much less than that in [5-8]. The proposed method achieves a compromise in computational complexity, detection performance, and parameter estimation accuracy.

3.1 Speed compensation method based on SA

(1) Speed compensation of transmitted signal

In order to correct the echo envelope range migration (RM) caused by $\sin c\left[\pi B\left(t - \tau_0 + \beta_0 nT + \frac{f_d}{\mu}\right)\right]$ in Equation (4) and improve the efficiency of the method, the SA method is used to compensate the speed of the transmitted signal.

Equation (1)~(7) suggest that the factor that causes the target echo envelope to migration is the exponential function term $\exp(-j2pf_d T)$. Therefore, after speed compensation on Equation (1), its expression can be written as:

$$R'(f, n) = R(f, n) * \omega(f, n) \quad (9)$$

where,

$$\begin{aligned} \omega(f, n) &= \exp(j2\pi f \Delta \tau) \\ &= \exp(-j2\pi f \beta_0 nT) \end{aligned} \quad (10)$$

In (10), $\beta_0 = \frac{2v_0}{c}$, v_0 is the speed compensation value.

Substituting (10) for (1), Equation (4) can be rewritten as:

$$\begin{aligned} x(t, n) &\approx A_0 \sqrt{D} \sin c\left[\pi B\left(t - \tau_0 + \Delta \beta nT + \frac{f_d}{\mu}\right)\right] \exp\left(-j\pi \frac{f_d^2}{\mu}\right) \\ &\cdot \exp\left(j\pi f_d \left(t + \tau_0 - \Delta \beta nT + \frac{f_d}{\mu}\right)\right) \exp(j2\pi f_d nT) \exp(j\pi \alpha_d (nT)^2) \end{aligned} \quad (11)$$

where, $\Delta \beta = b_0 - b'_0$.

After MTD for equation (11), it can be approximately expressed as:

$$\begin{aligned} z(t, f) &\approx A_0 \sqrt{D} \sum_{n=0}^{N-1} \sin c\left[\pi B\left(t - \tau_0 + \Delta \beta nT + \frac{f_d}{\mu}\right)\right] \exp\left(-j\pi \frac{f_d^2}{\mu}\right) \\ &\cdot \exp\left(j\pi f_d \left(t + \tau_0 - \Delta \beta nT + \frac{f_d}{\mu}\right)\right) \exp(j2\pi f_d nT) \exp(j\pi \alpha_d (nT)^2) \end{aligned} \quad (12)$$

In (12), the closer when b_0 is approaching to b'_0 , the smaller the RM of the echo envelope is, which is more conducive to the detection of the target. Next, the selection

method of speed parameters v_0 in equation (12) is given.

(2) Selection of $\tilde{v}$

If the envelope migration is less than a distance unit, the relationship among the speed compensation factor and the target speed and accumulation time NT in (12) can be expressed as follows:

$$\frac{\Delta v}{2} NT \leq \frac{c}{2f_s}, \Delta v = v - v_0 \quad (13)$$

It can obtain from (13)

$$\Delta v \leq \frac{c}{NTf_s} \quad (14)$$

Let the target maximum speed is $n_{\max}$. The range of $\tilde{v}$ is then:

$$\tilde{v} \in [0, \pm \Delta v, \pm Q \Delta v], Q = \left\lfloor \frac{v_{\max}}{\Delta v} \right\rfloor \quad (15)$$

Equation (15) gives out the compensation speed range and step interval. For the sake of fast acquiring the compensation range of the speed, the speed is searched using the binary search technique; then the Q in (15) can be rewritten as:

$$Q = \left\lfloor \frac{n_{\max}}{c} \frac{1}{Dn} \frac{2^z}{\mu} Dn, z = 1, 2, 3, L, L \right\rfloor \quad (16)$$

3.2 The target detection and parameter estimation based on DPT

In (12), only speed compensation processing can be completed, but when the target acceleration becomes larger, the accumulated energy of echo signal in (12) diffuses seriously. When the first kind of method in the introduction is used for processing, the amount of calculation is large and the real time performance is poor. Therefore, considering the advantages of the first kind method and the second kind method, this paper proposes to use (12) to first obtain the time delay estimation range of the target, and then carry out DPT to the signal within this range to complete the target detection, and then obtain the information such as speed and acceleration.

3.2.1 Estimation of delay range

After finding the maximum value in (12), the target delay position can be estimated from the peak corresponding to the parameter. This process can be expressed as:

$$\Delta t = \arg \max_t [z(t, f_i)] \quad (17)$$

where, Δt is the time delay estimation of the initial position of the target, the corresponding range is:

$$\Delta \tau' \in [\Delta t - b, \Delta t + b] \quad (18)$$

where, b can be set according to Equation (7).

After selecting the target signal in (11) using the Equation (18), the Equation (11) can be modified as:

$$x(t', n) \gg A_0 \sqrt{D} \text{sinc}\left(\frac{f_d}{B}\right) \exp\left[-j2pf_d(t_0 - DbnT) + \frac{f_d}{m} \exp(j2pf_d nT) \exp(jpa_d(nT)^2)\right] \exp\left[j2pf_d(t_0 - b_0 nT) + \frac{f_d}{m} \exp(j2pf_d nT) \exp(jpa_d(nT)^2)\right] \quad (19)$$

3.2.2 The target detection based on DPT

(1) Speed and acceleration estimation based on DPT

If the IFFT transformation is performed on (19), the frequency domain expression of the signal can be obtained as:

$$X(f', n) \gg \frac{A_0}{\sqrt{m}} \text{rect}\left(\frac{f'}{B}\right) \exp\left[-j2pf_d(t_0 - DbnT)\right] \exp\left(-j\frac{4pR_0}{l}\right) \exp\left[j2pf_d(nT + t_0 - DbnT)\right] \exp\left[jpa_d(nT)^2\right] \quad (20)$$

Considering the influence of noise, after cross-correlation processing of (20) by column, it can be obtained:

$$C(f', n, t_N) = X(f', n) * X(f', n - t_N) \\ = A_1 \text{rect}\left(\frac{f'}{B}\right) \exp\left[j2pf_d(DbnT - 2t_0)\right] \exp\left[j2pa_d t_N T(nT)\right] \\ L + w(f', n), n \in [1, N - t_N] \quad (21)$$

where, $A_1 = \frac{A_0^2}{\mu} \exp(-j\frac{8\pi R_0}{\lambda}) \exp(j4\pi f_d \tau_0) \exp[-j\pi \alpha_d (\tau_N T)^2]$, w is Gaussian noise with 0 mean and variance σ^2 , τ_N is the delay unit relative to N .

When performing IFFT and FFT processing on f', n in (21) respectively, it can obtain:

$$z'(t', f_a, t_N) = \text{FFT}_n [\text{IFFT}_f, C(f', n, t_N)] \\ = A_1 (N - t_N) \text{sinc}\left(\frac{f_a}{B} (t' - DbnT)\right) \exp\left[j2pf_d(t' - a_d t_N T)\right] + w(t', n') \quad (22)$$

where, $T_{t_N} = (N - t_N)T$.

According to the results of (10) and (22), the values of the target velocity and acceleration can be approximately expressed respectively as:^[28]

$$b' = \frac{c}{2\tau_N T} \frac{1}{f_s} \Delta m + \phi \quad (23)$$

$$d' = \frac{\lambda}{2T^2} \frac{1}{(N - \tau_N)\tau_N} \Delta n \quad (24)$$

where, Δm , Δn respectively represent the time delay position and Doppler frequency position in (22), and ϕ is the compensation value of the speed in (10).

According to b' and d' , the compensation function

$\exp(-j2pf_d \frac{2b'}{c} nT) \exp[-jp \frac{2d'}{c} (nT)^2]$ is constructed, and is substituted into the Equation (3), the parameters such as the distance and speed of the target can be obtained by using the MTD method.

The implementation process of the above method is shown in Figure 1.

FIGURE 1. Flow chart of the proposed method

(2) Analysis on output SNR

In (22), the echo output power $P_{out|signal}$ and noise power $P_{out|noise}$ can be expressed as^[26]:

$$P_{out|signal} = (N - \tau_N)^2 A_0^4 \quad (25)$$

$$P_{out|noise} = \sum_{n=1}^{N-\tau_N} |A_0^2 \delta^2 + \delta^2 + \delta^4| = (N - \tau_N)(2A_0^2 \delta^2 + \delta^4) \quad (26)$$

Comprehensive equations (25) and (26), the output SNR can be obtained:

$$SNR_{out} = \frac{P_{out|signal}}{P_{out|noise}} \\ = \frac{N \Delta \tau'}{2} \frac{SNR_{in}^2}{1 + 2SNR_{in}} \Big|_{\tau_N = \frac{1}{2}}, SNR_{in} = A_0^2 / \delta^2 \quad (27)$$

Comparing the output SNR in (27) with the output SNR of DPT in [26,28], it can be obtained:

$$\Delta SNR = \frac{\Delta \tau' SNR_{in}^2 \Big|_{\tau_N = \frac{1}{2}}}{MSNR_{in}^2 \Big|_{\tau_N = \frac{1}{2}}} \quad (28)$$

where, $SNR' = A_0^2 / \delta_0^2$, δ_0^2 is the noise variance of DPT in [26], and the relationship with δ^2 in this paper is:

$$\delta^2 = \frac{\Delta\tau'}{M} \delta_0^2 \quad (29)$$

Substituting (29) into (28), it can be obtained:

$$\begin{aligned} \Delta SNR &= \frac{\Delta\tau}{M} \left(\frac{\delta_0^2}{\delta^2} \right)^2 \\ &= \frac{M}{\Delta\tau'} \end{aligned} \quad (30)$$

According to the equation (30), the smaller $\Delta\tau'$, the more obvious the improvement of output SNR, which is more conducive to the detection of weak signals.

4. Performance analysis of the proposed method

4.1 Implementation process of the proposed method

In order to clearly understand the execution process of the proposed method, the relevant processing results are given in Figure 2. Suppose that the carrier frequency of the radar is 3GHz, the pulse repetition period is 3ms, the number of accumulated pulses is 128, the signal bandwidth is 5MHz, the baseband sampling rate is 10MHz, the target is a point target, the maximum radial speed is 1000m / s, the maximum radial acceleration is 10m /s², and the SNR is -30dB, $\Delta\tau'=10$, $\tau_N=0.5$. Figure 2 (a) shows the MTD results, and Figure 2 (b) shows the direct DPT results in [26], from which it can be seen that the target signal is difficult to be found. Figure 2 (c) shows the MTD results based on SA, from which it can be seen that the SNR of echo signal is higher than that of Figure 2 (a), but the energy diffusion is still serious, and it is difficult to accurately judge the target. Figure 2 (d) is the target signal extracted by the proposed method, in which the delay range is the area between the two red lines in Figure 2 (c). Figure 2 (e) shows the DPT result of the signal in Figure 2 (d), and its output SNR is greatly improved compared with Figure 2 (b), from which the target can be clearly found.

FIGURE 2. The execution process of the proposed method. (a)MTD, (b) the direct DPT,(c)MTD after SA, (d) Extract the target signal after SA, (e) DPT of extracted signal.

4.2 Influence of $\Delta\tau'$ on detection performance

In order to analyze the influence of $\Delta\tau'$ on detection performance, the simulation parameters are set as in 4.1. Figure 3 shows the comparison of detection performance under different $\Delta\tau'$, from which it can be seen that the smaller $\Delta\tau'$ is, the better the detection performance. When the detection probability is 80%, the requirement for the input SNR when $\Delta\tau'$ is 20 is about 5dB lower than that when $\Delta\tau'$ is 100, which is basically consistent with the theoretical value of the Equation (30), which is more conducive to the detection of weak signals.

FIGURE 3. Comparison of detection performance under different $\Delta\tau'$

4.3 The influence of t_N on detection performance

Let the simulation parameters be the same as in 4.1, $\Delta\tau'=20$. Figure 4 shows the detection performance analysis of the proposed method with different t_N , from which it can be seen that the larger t_N is, the greater the required input SNR with the same detection probability, but the smaller the relative estimation error of speed and acceleration is. On the contrary, the smaller t_N is, the smaller the required input SNR is with the same detection probability, but the larger the relative estimation error of speed and acceleration is. In order to facilitate the detection of weak signals, t_N can be set as 0.3~0.5.

(a)

(b)

(c)

FIGURE 4. With different t_N , the detection performance and parameter estimation of the proposed method. (a) Detection performance with different t_N , (b) Error of speed estimation, (c) Error of acceleration estimation.

4.4 The influence of $\hat{v}$ on detection performance

Let the simulation parameters be the same as in 4.1, $\Delta\tau'=20$. Figure 5 shows a comparative analysis on the detection performance of the proposed method with different $\hat{v}$. In addition, it can be seen from Figure 5 (a) that there is little difference in detection performance when the speed compensation value is 500m/s and 1000m/s, which shows that the proposed method has great adaptability to the speed compensation value, which can improve the execution efficiency of the method. Under the same conditions, the speed search times of the proposed method are about 30% less than that of MLE. Figure 5 (b) shows that when the detection probability is 80%, with the proposed method the input SNR is about 10dB higher than with the MLE and about 5dB lower than with the DPT, indicating that the detection performance of the proposed algorithm is between the two.

FIGURE 5. Comparative analysis on the detection performance of the proposed method. (a) The detection performance of the proposed method with different v , (b) Comparison of detection performance of different methods.

4.5 Computation load

In what follows, the computational complexities of MLE, KT, the direct DPT, and the proposed method are analyzed. Assume that M and N denote the number of range cells and the number of pulses, k represents the number of speed compensation in MLE, KT, and k' represents the number of speed compensation in the proposed method, where $k' \ll k$. With the proposed method, the phase compensation of the transmitted signal is before the pulse pressure, and therefore its calculated value can be stored in the register beforehand. The pulse pressure processing after one speed compensation requires $O(MN \log_2 M)$ complex multiplication operation, and one cross-correlation operation involves $O(MN \log_2 MN)$ complex multiplication operation, so the amount of complex multiplication required for k' times of speed compensation is approximately $O(k'NM \log_2 MN)$. The detailed computational costs of the above mentioned methods are shown in Table 1 and Figure 6. Table 1 shows

that, in addition to the direct DPT, the proposed method has obvious advantages over other methods in terms of complex multiplication burden. As can be seen from Figure 6, as the speed increases, the computational advantage of the proposed method becomes more obvious. Therefore, combined with the results in Table 1, Figure 6 and Figure 5 (b), it can be seen that the proposed method has a good balance in detection performance and real-time performance, thus conducive to the detection of weak target signals and the real-time realization at the same time.

Table 1 Complex multiplication amount of different methods

Methods	Computational complexity
MLE	$O(kNM^2 \log_2 N)$
KT	$O(NM^2) + O(k^2NM \log_2 M)$
the direct DPT	$O(NM \log_2 MN)$
Proposed method	$O(k'NM \log_2 MN)$

FIGURE 6. Comparison of calculation complexity

5. Experimental results and discussion

In order to further verify the performance of the method, simulation and measured data are analyzed.

5.1 Simulation experiment

(1) Single target detection performance

Suppose the radar system parameters be the same as 4.1, the target speed is 1000m/s, the acceleration is 15m/s^2 , its distance from the radar is 100 km, the SNR of the input signal is -25 dB, the speed compensation value is 500m/s, and $\Delta\tau = 20$. Figure 7(a) gives the MTD processing result of the echo signal, Figure 7(b) gives the processing result by the direct DPT, and Figure 7(c) shows the processing result by the proposed method. Compared with the results in Figure 7, the MTD method still has obvious energy diffusion after speed compensation. The direct DPT method and the proposed method can achieve target detection, but the output SNR of the proposed method is larger, which is more conducive to improving the target detection probability and parameter estimation accuracy.

FIGURE 7. Single target detection performance by different algorithms.

(a) MTD , (b) the direct DPT,(c) the proposed method.

(2) Multi-target detection performance

Two targets are assumed, with a speed of 1000m/s, 1050m/s, an acceleration of 5m/s^2 , 10m/s^2 respectively. The SNR of the input signals is -25 dB, and the speed compensation value is 500m/s, $\Delta\tau'=100$, and other parameters are the same as 4.1. Figure 8 shows that MTD has caused serious energy diffusion. The direct DPT

method can detect two targets, but it suffers from Doppler spectrum spread. In contrast, the proposed method is capable of satisfactory detection of two targets and the target resolution is the highest among the several methods.

(d)

(e)

(f)

FIGURE 8. Dual target detection performance by different methods. (a) MTD, (b) Range-Doppler dimension in Figure (a), (c) the direct DPT, (d) Range-Doppler dimension in Figure (c), (e) the proposed method, (f) Range-Doppler dimension in Figure (e).

The above experiments show that the proposed method can effectively detect weak signals without accurate speed compensation, and has a good compromise between detection performance and target resolution.

5.2 Verification of measured data

5.2.1 S-band radar data

In order to further verify the effectiveness of the method, the following measured data from aircraft were

used for analysis, and the White Gaussian Noise that was added was -25 dB. The radar operated at the S band, the carrier frequency is 3GHz, the signal bandwidth is 2 MHz, the pulse repetition time is 600 μ s, the pulse duration is 60 μ s, the integration pulse number is 2048, and the sampling frequency is 4 MHz, the maximum speed of the target is 600m/s, and the acceleration is 0.1m/s². Figure 9 shows the processing results of different methods, among which Figure 9(a) is the results of MTD, from which it can be seen that the accumulated energy of the target signal is smaller and the phenomenon of diffusion occurs; Figure 9(b) is the result of the direct DPT, from which the target can be observed, but the probability of false alarm is relatively high. Figure 9(c) indicate the processing results of the proposed method, with the speed compensation value to be 300m/s. Comparing the results of Figure 9, it can be concluded that the proposed method can detect weak target signals, which verifies the effectiveness of the proposed method.

(a)

(b)

(c)

FIGURE 9. Results of different algorithms for S-band radar data. (a) MTD , (b) the direct DPT,(c) the proposed method.

5.2.2 X-band radar data

The radar operates in the X-band, the transmission waveform is LFM signal, the pulse repetition frequency is 10kHz, the bandwidth is 2GHz, and the accumulation time is 100ms. Figure 10 (a) shows the MTD results, Figure 10 (b) shows the Time-Doppler results of MTD, Figure 11 (a) shows the results of the proposed method with a compensation speed of 150m / s, and Figure 11 (b) shows the Time-Doppler results of the proposed method. Comparing Figure 10 and Figure 11, it can be seen that after the processing of the proposed method, the time-delay migration of the target is corrected, which is conducive to subsequent target detection and imaging processing.

(b)

FIGURE 10. Results of MTD for X-band radar data. (a) MTD ,(b) Range-Doppler .

(a)

(a)

(b)

FIGURE 11. Results of the proposed method for X-band radar data. (a) the proposed method,(b) Range-Doppler.

6 . CONCLUSION

Aiming at the problem of large amount of computation in high maneuvering target detection method, a hybrid coherent accumulation algorithm is proposed in this paper. This method combines the respective advantages of parameter compensation method and cross-correlation processing method. The specific performance is as follows: 1) The proposed method only needs to compensate the target speed for a few times, and then the DPT method can be used to obtain the target speed and acceleration information. 2) The proposed algorithm uses SA to obtain the time delay estimation range of the target, which can improve the output SNR of DPT, which is not only conducive to improving the accuracy of parameter estimation, but also conducive to reducing the amount of operation. 3) The proposed method is suitable for coherent accumulation detection of long time weak signals. when the accumulation time further increases, the target may appear cross beam. The authors will consider integrating TBD method for research in the future in [34,35].

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Abbreviations

SA:Scaling algorithm;MLE:Maximum likelihood Estimator;RM:Range migration;KT: keystone;RFT:Radon fourier ;TDST:Three-dimensional scaled transform ;LVD:Lv's distribution SFT:sparse Fourier transform; DPT:Discrete polynomial-phase Transform ACCF:Adjacent cross correlation functio;SNR: Signal-to-noise ratio.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed to the conception and design of the experiments and the interpretation of simulation results.

PCS wrote the software, performed the experiments and data analysis, and wrote the first draft of the manuscript.

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