A hypersonic target coherent integration detection algorithm based on Doppler feedback

LI Lin1,* , WANG Guohong1, SUN Dianxing2, and ZHANG Xiangyu1

1. Institute of Information Fusion, Naval Aviation University, Yantai 264001, China; 2. College of Electronic Science, National University of Defense Technology, Changsha 410073, China

Abstract: The traversal search of multi-dimensional parameter during the process of hypersonic target echo signal coherent integration, leads to the problem of large amounts of calculation and poor real-time performance. In view of these problems, a modified polynomial Radon-polynomial Fourier transform (MPRPFT) hypersonic target coherent integration detection algorithm based on Doppler feedback is proposed in this paper. Firstly, the Doppler estimation value of the target is obtained by using the target point information obtained by subsequent non-coherent integration detection. Then, the feedback adjustment of the coherent integration process is performed by using the acquired target Doppler estimation value. Finally, the coherent integration is completed after adjusting the search interval of compensation. The simulation results show that the algorithm can effectively reduce the computational complexity and improve the real-time performance on the basis of the effective coherent integration of hypersonic target echo signals.

Keywords: hypersonic target, coherent integration, non-coherent integration, Doppler estimation, feedback adjustment.

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1. Introduction

In recent years, with the continuous development of hypersonic vehicle technology and the successive tests of high-speed and high-maneuverability aircraft such as X-51A and CM-401, the hypersonic vehicle, with its high-speed, high-maneuverability and low radar cross-section (RCS) characteristics, has brought severe challenges to the traditional radar detection and tracking system [1 – 3]. Faced with the real threat of hypersonic vehicles, how to achieve effective detection and tracking of hypersonic targets has become a key issue to be solved, and it is also the focus and difficulty of the current research [4,5].

Unlike traditional conventional aircraft, first of all, hypersonic targets with its high-speed characteristic can span multiple radar detection units instantaneously, resulting in the phenomenon of range gate stride, which makes difficulties in coherent integration of echo signals. Secondly, the high maneuverability of hypersonic targets makes the Doppler frequency, Doppler change rate and Doppler second-order change rate of the target much more severe than that of the conventional target, resulting in the distribution of target echoes in multiple Doppler units and Doppler extension phenomenon, which limits the integration time and increases the difficulty of coherent integration. In addition, the low RCS characteristic of hypersonic targets reduces the signal-to-noise ratio (SNR) of echo signals and further increases the difficulty of coherent integration [6 – 8].

For the problem of range gate stride compensation, the typical methods at present are Keystone transform [9 – 11] and Radon-Fourier transform [12 – 14], etc. However, the above methods are only applicable to uniform moving targets. When considering non-uniform moving targets, the effects of acceleration and higher-order motion items need to be considered. When considering the acceleration of the target, it is necessary to compensate for the non-linear range gate stride and Doppler expansion problems. At present, the main methods include second-order Keystone transform [15], Keystone-Lv’s distribution [16], second-order Keystone-Radon Fourier transform [17], Radon-fractional Fourier transform [18], etc. However, the above algorithms are only applicable to uniformly accelerated moving targets. For high-order moving targets such as hypersonic vehicles, there are also some related researches at present. A generalized Radon-Fourier transform (GRFT) method was proposed in [19]. The algorithm is extended on the basis of the Radon-Fourier transform method. By multi-dimensional search compensation of the target parameters, the range gate stride and Doppler expansion problem can be corrected simultaneously. In [20], a
polynomial Radon-polynomial Fourier transform (PRPFT) method was proposed, and the polynomial was used to model the target non-linear range stride and Doppler expansion. Then polynomial Radon transform (PRT) is used to solve the non-linear range gate stride problem, and polynomial Fourier transform (PFT) is used to solve the Doppler spread problem. Two transforms are combined to achieve the coherent integration of the target.

However, through analysis, it can be found that both the GRFT method and the PRPFT method require multi-dimensional parameter search in the parameter space, and the computational complexity of the algorithm is very high. Especially when the SNR of target echoes is low, with the increase of the coherent integration pulses number, the calculation amount of the algorithm increases sharply, which makes the algorithm’s real-time performance poor. Therefore, the fast implementation of the hypersonic target coherent integration algorithm is a problem that needs to be solved urgently.

Aiming at the above problems, a modified PRPFT (MPRPFT) hypersonic target coherent integration detection algorithm based on Doppler feedback is proposed in this paper. After coherent integration, the Doppler estimation value of the target is obtained by using the target point information obtained by the non-coherent integration part. Then the feedback adjustment of the coherent integration process is performed by using the acquired target Doppler estimation value. Finally, adjust the search interval of compensation and complete the rapid and effective integration of the target echo signal.

The following content of the article is arranged as follows. Section 2 introduces the target model used in this paper. Section 3 describes the principle and the specific implementation steps of the algorithm. Section 4 analyzes the performance of the algorithm based on the simulation results. Finally, Section 5 draws the conclusion of this paper.

2. Hypersonic target model

2.1 Target signal model

For pulse Doppler radar, taking the linear frequency modulation (LFM) signal as an example, the single radar pulse signal is modeled as follows:

\[ s(t) = u(t) \cdot e^{j2\pi f_0 t} = \text{rect} \left( \frac{t}{T} \right) \cdot e^{j2\pi (f_0 t + \frac{1}{2} Kt^2)} \]  \hspace{1cm} (1)

where \( u(t) \) denotes the signal complex envelope, \( t \) denotes the fast time, \( T \) denotes the signal width, \( f_0 \) denotes the carrier frequency, \( K = B/T \) denotes the frequency modulation slope, and \( B \) denotes the signal bandwidth.

After down-conversion and the carrier frequency being removed, the baseband echo signal is obtained as follows:

\[ s_r(t, \tau) = A_r \text{rect} \left( \frac{t - t_r}{T} \right) \cdot e^{-j2\pi f_0 t_r + j\pi K(t - t_r)^2} + N(t, \tau) \]  \hspace{1cm} (2)

\[ e^{j\pi K(t - \frac{2R(t)}{c})^2} + N(t, \tau) \]  \hspace{1cm} (3)

where \( \lambda \) denotes the wavelength, \( c \) denotes the speed of light, \( A_r \) denotes the complex envelope of echo signals, \( t_r = 2R(t)/c, \) \( R(t) \) denotes the radial distance between the target and the radar, \( \tau \) denotes the slow time, and \( N(t, \tau) \) denotes the additive complex Gaussian white noise.

After matched filtering, the echo signal after pulse compression is obtained as follows:

\[ s_c(t, \tau) = A_s \text{sinc} \left[ B \left( t - \frac{2R(t)}{c} \right) \right] \cdot e^{-j4\pi f_0 \frac{R(t)}{c}} + N_c(t, \tau). \]  \hspace{1cm} (3)

2.2 Target motion model

For hypersonic targets, considering the computational complexity, we believe that the third-order polynomial signal model can better reflect the target motion characteristics and perform the subsequent target integration detection. Therefore, the target radial motion function \( R(\tau) \) is modeled as follows:

\[ R(\tau) = R_0 + v_T \tau + a_T \tau^2 + \dot{a}_T \tau^3 \]  \hspace{1cm} (4)

where \( R_0 \) denotes the initial radial distance between the target and the radar, \( v_T \) denotes the target radial velocity, \( a_T \) denotes the target radial acceleration, and \( \dot{a}_T \) denotes the target second-order radial acceleration.

For the target measurement traces obtained after non-coherent integration detection, the target radial distance measured by radar is defined as

\[ R_k = R(\tau) + dr \]  \hspace{1cm} (5)

where \( dr \sim N(0, \sigma_r^2) \), and \( \sigma_r \) denotes the radar range measurement error.

For the \( N \)-frame measurement data obtained after non-coherent integration detection, the set of the target measurement data can be expressed as

\[ z_k = \{ [R_k, \theta_k, \varphi_k, \gamma_k]^T | k = 1, 2, \ldots, N \} \]  \hspace{1cm} (6)

where \( z_k \) denotes the \( k \)-frame measurement data of the target, \( R_k, \theta_k, \varphi_k \) and \( \gamma_k \) respectively denote the radial distance information, azimuth information, pitch angle information, and echo energy information of this frame target measurement data.
3. Algorithm principle

The traversal search of multi-dimensional parameters during the processing of hypersonic target echo signal coherent integration, leads to the problem of large amounts of calculation and poor real-time performance. In view of these problems, an MPRPFT hypersonic target coherent integration detection algorithm based on Doppler feedback is proposed in this paper. Firstly, the coherent integration is used to improve the SNR of the target echo signal, and the information is provided for the subsequent non-coherent integration. Then, the Doppler estimation value of the target is obtained by using the target point information obtained by subsequent non-coherent integration based on the radial distance-time plane Hough transform track-before-detect (RHTT-TBD) algorithm [21]. The feedback adjustment of the coherent integration process is performed by using the acquired target Doppler estimation value, which effectively reduces the search compensation interval and realizes the fast implementation of the coherent integration algorithm. The overall flow of the algorithm is shown in Fig. 1.

3.1 Coherent integration processing of multidimensional search compensation

It can be seen from the hypersonic target signal model that when the target performs high-order motion, it is necessary to compensate the non-linear distance walking and non-linear Doppler expansion simultaneously to achieve effective coherent integration of the target echo signal. Accordingly to [20], since the hypersonic target moves along the polynomial curve in the distance, it can be extended on the basis of the Radon-Fourier transform method. The PRT is used to integrate along the polynomial trajectory. The expression of PFT can be expressed as follows:

\[ G_{\text{PRT}}(r, a_k) = \int s(\tau, r + f(\tau))d\tau \]  

where \( f(\tau) = a_1\tau + a_2\tau^2 + \cdots + a_k\tau^k \) is a \( k \)-order polynomial of \( \tau \), if the parameter \( (r, a_1, a_2, \ldots, a_k) \) matches the target motion equation \( R(\tau) \) along the direction of target motion, the signal energy will gather on PRT.

For the non-linear Doppler expansion problem caused by the high-order phase term of the target, it can be seen from (3) that the phase of the target echo signal is a high-order polynomial after pulse compression. Therefore, the PFT can be used to integrate the polynomial phase signal. The expression of PFT can be expressed as

\[ G_{\text{PFT}}(\omega, b_k) = \int s(\tau, \omega \cdot z(\tau))e^{(-j\hat{b}_1\tau - j\hat{b}_2\tau^2 - \cdots - j\hat{b}_k\tau^k)}d\tau \]  

where \( z(\tau) = \exp\left(\sum_{n=1}^{k} b_n\tau^n\right) \), and when parameter \( b_n = \hat{b}_n( n = 1, 2, \ldots, k) \), the signal energy will gather on PFT.

Therefore, for the \( k \)-order polynomial function \( r_s(\tau) = r_0 + \dot{r}\tau + \ddot{r}\tau^2 + \cdots + r(k)\tau^k \) corresponding to the two-dimensional complex signal \( S_m(\tau, r_s) \) defined in the \( (\tau, r) \) plane, the corresponding PRPFT can be defined as

\[ G_{\text{PRPFT}}(r, a_k) = \int S_m(\tau, r_0 + f_s(\tau))e^{(-j\alpha_1\tau - j\alpha_2\tau^2 - \cdots - j\alpha_k\tau^k)}d\tau \]  

where \( f_s(\tau) = \sum_{l=1}^{k} r(l)\tau^l = \dot{r}\tau + \ddot{r}\tau^2 + \cdots + r(k)\tau^k \), \( \alpha_i = (-4\pi f_{0i}^{(i)})/c, i = 1, 2, \ldots, k \).

Specific to the target motion function in this paper, according to (4) and (9), \( \dot{v} = v_T, \dot{r} = a_T, r^{(3)} = \ddot{a}_T \), at this time, (9) can be expressed as

\[ G_{\text{PRPFT}}(r, a_k) = \int S_m(\tau, R(\tau))e^{(-j\alpha_1\tau - j\alpha_2\tau^2 - j\alpha_k\tau^k)}d\tau. \]  

After range gate stride and Doppler expansion compensation, the echo energy of the hypersonic target can be integrated effectively in parameter space, and the subsequent non-coherent integration processing can be carried out.

3.2 Doppler estimation value acquisition and feedback adjustment

After non-coherent integration and threshold detection of the target echo signal, multi-frame target tracking measurements including radial distance and time sequence information of the target can be obtained. According to the
obtained multi-frame target trace information, the Doppler estimation value of the target can be extracted, and the feedback adjustment of the coherent integration process can be performed by using the acquired target Doppler estimation value. After that, the search interval of compensation can be adjusted and realized the rapid and effective integration of the target echo signal.

3.2.1 Acquisition of the Doppler estimation value

Assume that the $N$-frame target point measurement obtained after non-coherent integration is

$$z_i = [R_i, \theta_i, \varphi_i, \gamma_i, t_i]^T, \; i = 1, 2, \ldots, N$$ (11)

where $z_i$ denotes the target $i$-frame measurement information, $R_i$, $\theta_i$, $\varphi_i$ and $\gamma_i$ respectively denote the radial distance information, azimuth information, pitch angle information, and echo energy information of this frame target measurement, $t_i$ denotes the timing information of this frame measurement, $t_i = (i - 1)T_s + t_1$, and $T_s$ denotes the radar scanning period.

Define the target motion equation:

$$R = r_0 + v_T t + a_1 t^2 + a_2 t^3 + \cdots + a_{k-1} t^k$$ (12)

where $R$ denotes the radial distance between the radar and the target, $r_0$ denotes the initial radial distance, $v_T$ denotes the target radial velocity, and $a_k$ denotes the $k$-order radial acceleration of the target.

According to the obtained $N$-frame measurement data, a set of equations can be obtained:

$$\begin{cases} R_1 = r_0 + v_T t_1 + a_1 t_1^2 + a_2 t_1^3 + \cdots + a_{k-1} t_1^k \\ R_2 = r_0 + v_T t_2 + a_1 t_2^2 + a_2 t_2^3 + \cdots + a_{k-1} t_2^k \\ \vdots \\ R_N = r_0 + v_T t_N + a_1 t_N^2 + a_2 t_N^3 + \cdots + a_{k-1} t_N^k \end{cases}$$ (13)

Then the sum of squared deviations between $N$-frame measurements and target motion curves is

$$R^2 = \sum_{i=1}^{N} [R_i - (r_0 + v_T t_i + a_1 t_i^2 + a_2 t_i^3 + \cdots + a_{k-1} t_i^k)]^2$$.

(14)

In order to obtain the qualified Doppler fitting value, the partial derivative of $t_i$ on the right side of (14) can be ob-
Simplify the Vandermonde matrix represented by (17):

\[
\begin{bmatrix}
1 & t_1 & t_1^2 & \cdots & t_1^{k-1} \\
1 & t_2 & t_2^2 & \cdots & t_2^{k-1} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & t_N & t_N^2 & \cdots & t_N^{k-1}
\end{bmatrix}
\begin{bmatrix}
r_0 \\
v_T \\
a_1 \\
\vdots \\
a_{k-1}
\end{bmatrix}
= \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_N
\end{bmatrix}.
\]  
(18)

The above equations can be expressed as

\[
\begin{align*}
TT \ast A &= R \\
A &= [r_0, v_T, a_1, \ldots, a_{k-1}]^T \\
R &= [R_1, R_2, \ldots, R_N]^T \\
TT &= \begin{bmatrix}
1 & t_1 & t_1^2 & \cdots & t_1^{k-1} \\
1 & t_2 & t_2^2 & \cdots & t_2^{k-1} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & t_N & t_N^2 & \cdots & t_N^{k-1}
\end{bmatrix}
\end{align*}
\]  
(19)

According to the target motion model of (4), the hypersonic target coefficient matrix is \( A = [r_0, v_T, a_1, \ldots, a_{k-1}]^T \). Therefore, the matrices \( TT \) and \( R \) can be obtained according to the target \( N \)-frame measurements, thereby obtaining the coefficient matrix \( A \), and realizing the fitting of the target motion equation and the extraction of Doppler information.

### 3.2.2 Feedback adjustment processing

Through the analysis of the coherent integration algorithm principle for hypersonic targets, it can be seen that in order to compensate the range gate stride and Doppler extension of the target echo signal, the algorithm needs multidimensional search in velocity dimension, acceleration dimension and second-order acceleration dimension. If \( N_r, N_v, N_a \) and \( N_\sigma \) respectively denote the target range unit number, the target speed step search number, the target acceleration step search number, and the target second-order acceleration step search number, and \( M \) is the number of integration pulse, then the amount of calculation caused by parameter searches is

\[
O = N_rN_vN_aN_\sigma(0.5M(\log_2 M)I_m + M(\log_2 M)I_a)
\]  
(20)

where \( I_m \) denotes the amount of computation brought about by a single complex multiplication, and \( I_a \) denotes the amount of computation brought about by a single complex addition.

For hypersonic targets, due to its high velocity and high maneuverability, the target’s velocity variation range is extremely large and can span dozens of Mach intervals. It can be seen from the analysis of (20), as the target velocity search is the first layer search of multi-dimensional search compensation, the number of search step numbers will directly affect the calculation amount and the real-time detection of the algorithm. At this time, if the entire range of the target’s velocity change is taken as the search interval, the calculation amount of the algorithm will undoubtedly be large, and as the number of integration pulses increases, the calculation amount of the algorithm will increase sharply, which greatly affects the real-time performance of the target detection.

At this time, if an estimated value of the target velocity and the corresponding error interval can be determined, the search interval can be significantly narrowed, which will greatly reduce the amount of computation caused by large-scale search. Therefore, the algorithm uses the target point information obtained by the non-coherent integration part, extracts the estimated value of the target Doppler information, and performs feedback adjustment on the coherent integration to complete the effective and fast integration of the target echo signal.

Ideally, Doppler information of the target can be extracted accurately according to matrices \( TT \) and \( R \), but measurement errors will inevitably be introduced in the process of radar detection, which makes the obtained radial distance deviate from the true value. According to Section 2.2, \( \Delta_r = R_i + dr, \sigma_r \) denotes the radial range measurement error, and \( dr \sim N(0, \sigma_r^2) \). At this time, the coefficient matrix obtained is the estimated value of the target Doppler information, which is denoted as

\[
\tilde{A} = [\tilde{r}_0, \tilde{v}_T, \tilde{a}_T, \tilde{a}_r]^T.
\]  
(21)

It should be noted that the estimated radial velocity of the target obtained at this time is the initial radial velocity before feedback adjustment, not the target radial velocity estimate required for velocity compensation. Then the target radial velocity estimate for the coherent integration compensation is

\[
\tilde{v}_T = \tilde{v}_T + 2\tilde{a}_TNT_s + 3\tilde{a}_r(NT_s)^2.
\]  
(22)

Considering the influence of measurement errors, the estimated value of the acquired target Doppler information will be concentrated within a certain range centered on the real parameter:

\[
|\tilde{v}_T - v_T| \leq \Delta_{v_T}
\]  
(23)

where \( \Delta_{v_T} \) denotes the estimation error of the target radial velocity estimation. Then the search interval of target radial velocity after feedback adjustment is as follows:

\[
\tilde{v}_T - \Delta_{v_T} \leq v_T \leq \tilde{v}_T + \Delta_{v_T}
\]  
(24)
where $\Delta v_T = 3\sigma_{v_T}$, then the allowable error $\sigma_{v_T}$ is defined as

$$\sigma_{v_T} = \frac{2\sigma_r}{\kappa NT_s}$$

(25)

where $\sigma_r$ denotes the radar range measurement error, $N$ denotes the feedback adjustment frame number, $\kappa$ denotes the weight coefficient of $N$, and $T_s$ denotes the radar scanning period.

As for the problem of target point accuracy obtained by non-coherent integration, the analysis of (23) and (24) shows that the main factor affecting the accuracy of the target point is the radar range measurement error $\sigma_r$, and according to [22], the main factor affecting $\sigma_r$ is SNR. The range measurement error caused by SNR fluctuation is

$$\sigma_r = \frac{\zeta \sqrt{2(\text{SNR})m}}{2}$$

(26)

where $\zeta$ denotes the pulse width after pulse compression, $S/N$ denotes the average SNR after integration, and $m$ denotes the number of pulses.

At the same time, after non-coherent integration of $N$ frames, the average SNR is $\sqrt{N}$ times higher than that of coherent integration, so it can be seen that non-coherent integration can effectively improve the range measurement accuracy, thus ensuring the accuracy of the target points.

For the purpose of this paper, the range of hypersonic target acceleration and second-order acceleration terms is limited, and the search interval for search compensation is relatively small compared with the target velocity search interval, which has little influence on the calculation of the algorithm. Therefore, in the case that the radar range measurement error is relatively large, feedback adjustment can be performed only on the target velocity search interval, to achieve effective and fast integration of the target signal.

### 3.3 Algorithm implementation

Because the proposed algorithm in this paper needs the $N$-frame non-coherent integrated measurement data as the data base, the PRPFT algorithm is still used to process the first $N$-frame coherent integrated radar echo signal. After the first $N$-frame non-coherent integrated measurement data are obtained, the MPRPFT algorithm proposed in this paper is used for subsequent processing to realize the effective and fast integration of the target echo signal.

The proposed MPRPFT algorithm in this paper mainly includes the following steps:

**Step 1** Mix the frequency of the received target echo signal, and the burst signal $S_i(t)$ $(i = 0, 1, \ldots, M - 1)$ with sinc envelope is obtained after pulse compression with the matched filter.

**Step 2** Determine the radial velocity search interval, radial acceleration search interval, second-order radial acceleration search interval and their corresponding search spacing according to the relevant parameters of the radar and the target.

**Step 3** Use the PRPFT method to process the acquired signals with multi-dimensional searching compensation coherent integration.

**Step 4** Use the results of coherent integration processing. The target echo signal is subjected to non-coherent accumulation based on the RTHT-TBD algorithm, and the $N$-frame target measurement information including the radial range and time sequence of the target is obtained.

**Step 5** According to the obtained $N$-frame target measurement information, the fitting of the target motion equation and the extraction of Doppler information are realized.

**Step 6** The compensation search interval for feedback adjustment is determined based on the estimated value of target Doppler information $\hat{\alpha}$ and the allowable error corresponding to the estimated value.

**Step 7** Use the search interval obtained by feedback adjustment and repeat Step 3. The effective and fast integration of the hypersonic target echo signal is realized.

### 4. Simulation and analysis

Assuming that radar transmits an LFM signal, then the simulation parameters of radar is shown in Table 1.

| Simulation parameter  | Value |
|----------------------|-------|
| Signal pulse width/μs | $T_P = 500$ |
| Bandwidth/MHz         | $B = 0.5$ |
| Radar carrier frequency/GHz | $f_0 = 1$ |
| Sampling frequency/MHz | $f_s = 1$ |
| Pulse repetition frequency/Hz | $f_{PRF} = 500$ |
| Radar range measurement error/m | $\sigma_r = 200$ |
| Radar scanning period/s | $T_s = 2$ |

Assume that the target is flying at a hypersonic speed, the simulation parameters of the target is shown in Table 2.

| Simulation parameter                  | Value          |
|---------------------------------------|----------------|
| Initial radial range between the target and the radar/km | $R_0 = 200$ |
| Initial radial velocity/(m/s)         | $v_T = 3400$ |
| Initial radial acceleration/(m/s²)     | $a^T = 30$    |
| Initial second-order radial acceleration/(m/s³) | $\dot{a}_T = 10$ |
| Maximum radial velocity/(m/s)         | $v_{T_{\text{max}}} = 6800$ |
| Maximum radial acceleration/(m/s²)     | $a_{T_{\text{max}}} = 200$ |
| Maximum second-order radial acceleration/(m/s³) | $\dot{a}_{T_{\text{max}}} = 200$ |

The number of target measurement frames used for feedback regulation is $N$, $\kappa = 0.4$, and the number of pulse integration is $M$. The SNR is the pre-pulse compression parameter and the noise is additive complex Gaussian white noise.
noise. The simulation is completed in Intel Core i7-6700, 3.4 GHz, 8 GB RAM and MATLAB R2014a environment.

4.1 Validation of the algorithm

In order to verify the effectiveness of the proposed MPRPFT algorithm, for the above parameters, the coherent integration of the target echo signal is performed under the condition of feedback adjustment target measurement frame number $N = 4$, pulse integration number $M = 64$, and input SNR $D_{SNR} = -25$ dB.

Firstly, the target Doppler information obtained by non-coherent integration is used to extract the target Doppler information, and then the estimated value of target radial velocity $\tilde{v}_T = 3.712 \times 10^3$ m/s and its estimation error $\Delta v_T = 375$ m/s are obtained. Further, the search interval of the target radial velocity after feedback adjustment is $[3337, 4087]$ m/s. Next, the feedback adjustment interval is used to search and compensate the target echo signal, and the integration result is shown in Fig. 2.

![Fig. 2 Integrated results of the algorithm in this paper](image)

Fig. 2 Integrated results of the algorithm in this paper

It can be seen from the integrated results in Fig. 2 that the MPRPFT algorithm can achieve effective compensation integration for hypersonic targets under low SNR conditions, and the running time of the algorithm is 28.8 s, while the running time of the PRPFT algorithm proposed in [20] is 365.3 s under the same conditions. It can be seen that the processing time of the algorithm is significantly shortened, and the calculation amount is effectively reduced, which proves the effectiveness of the proposed MPRPFT algorithm.

4.2 Simulation verification under different SNR conditions

In order to analyze the performance of the algorithm in this paper, the following simulation analysis is carried out by changing the input SNR. When other conditions remain unchanged, set false alarm probability $P_{fa} = 10^{-6}$, feedback adjusting target measurement frame number $N = 4$, pulse accumulation number $M = 64$. After 400 Monte-Carlo simulation experiments, the change of target detection probability and running time between the proposed MPRPFT algorithm and the PRPFT algorithm under different SNR conditions is obtained, as shown in Fig. 3 and Fig. 4.

![Fig. 3 Diagram of target detection probability with the change of SNR](image)

Fig. 3 Diagram of target detection probability with the change of SNR

Fig. 3 shows the change of the target detection probability of the two algorithms under different SNR conditions. By analyzing the detecting probability curve in the figure, it can be seen that the performance of the MPRPFT algorithm is comparable to that of the PRPFT algorithm in terms of detection probability, and the superiority performance of the PRPFT algorithm in hypersonic target detection has been verified in [20]. From Fig. 4, we can see the variation of algorithm running time under different SNR conditions. By analyzing the trend of the algorithm curves, we can see that the change of SNR has little effect on
the calculation of the algorithm. And by comparing the curves of the two algorithms, it can be seen that the running time of the MPRPFT algorithm is significantly shorter than that of the PRPFT algorithm. Under the above simulation conditions, the efficiency of the proposed algorithm is improved by about 13 times.

![Graph](image)

**Fig. 4** Variation of algorithm running time with different SNRs

By analyzing the performance of the algorithm under different SNR conditions, it can be seen that the proposed MPRPFT algorithm can effectively detect hypersonic targets under low SNR conditions, significantly reducing the calculation amount and improving the computational efficiency.

### 4.3 Simulation experiments under different pulse integration numbers

In order to further analyze the performance of the algorithm in this paper, under other conditions unchanged, simulation analysis is carried out under different pulse integration numbers. Set false alarm probability $P_{fa} = 10^{-6}$, $D_{SNR} = -25$ dB, feedback adjusting target measurement frame number $N = 4$. After 400 Monte-Carlo simulation experiments, the changes of target detection probability, integration peak and running time under different pulse integration numbers are obtained, as shown in Table 3.

| Pulse integration number | Performance index 1 | Performance index 2 | Performance index 3 |
|-------------------------|---------------------|---------------------|---------------------|
|                         | Detection probability | Integration peak | Running time/s      |
| 128                     | 1.00                 | 171.64              | 179.88              |
| 64                      | 1.00                 | 89.44               | 28.86               |
| 32                      | 0.80                 | 44.06               | 10.10               |
| 16                      | 0.14                 | 22.93               | 2.92                |

The analysis of the integrated results in Table 3 shows that as the pulse integration number increases, the detection probability and integration peak of the algorithm increase accordingly. It can be concluded that with the increase of the pulse integration number, the target echo integration performance of the algorithm improves gradually. At the same time, it can be seen from the change of the running time of the algorithm that with the increase of the pulse integration number, the calculation amount of the algorithm increases synchronously and the computational time becomes longer. Therefore, in practical applications, the integration performance and the calculation amount could be comprehensively considered according to the demand, and select the appropriate pulse integration number for coherent integration. Under the simulation conditions of this paper, it is more appropriate to select the pulse integration number $M = 64$ for integration.

In order to further analyze the computational complexity of the MPRPFT algorithm in this paper and the PRPFT algorithm under different pulse integration numbers, Monte-Carlo simulation experiments are carried out according to the above conditions, and the comparison results of the two algorithms are shown in Table 4.

| Calculation amount | Pulse integration number |
|--------------------|--------------------------|
| Running time of MPRPFT algorithm/s | 179.88 | 28.86 | 10.10 | 2.92 |
| Running time of PRPFT algorithm/s    | 2 891.14 | 365.29 | 117.56 | 21.57 |
| Efficiency improvement index $n$    | 16.07 | 12.66 | 11.64 | 7.39 |

Define the efficiency improvement index $n$:

$$n = \frac{\text{Running time of PRPFT algorithm}}{\text{Running time of MPRPFT algorithm}}$$

From Table 4, we can see the changes of the running time between the MPRPFT algorithm and the PRPFT algorithm under different pulse integration numbers. According to the obtained efficiency improvement index $n$, the computational efficiency of the MPRPFT algorithm is obviously improved compared with the PRPFT algorithm. And with the increase of the pulse integration number, the computational efficiency and calculation amount improvement of the MPRPFT algorithm has an upward trend compared with the PRPFT algorithm.

### 4.4 Simulation verification under different feedback adjustment frame numbers

In order to further analyze the performance of the proposed MPRPFT algorithm, under other conditions unchanged, simulation analysis is carried out for different feedback adjustment frame numbers. Set false alarm probability $P_{fa} = 10^{-6}$, $D_{SNR} = -25$ dB, pulse integration number $M = 64$. After 400 Monte-Carlo simulation experiments, the changes of target detection probability, running time and allowable error under different feedback adjustment frame numbers are obtained, as shown in Table 5.
According to the analysis of the integrated results in Table 5, with the increase of the feedback adjustment frame number, the running time of the algorithm decreases gradually on the premise of effective target detection, that is, the calculation amount of the algorithm is continuously reduced and the algorithm efficiency is gradually improved. This is mainly because as the feedback adjustment frame number increases, the fitting effect of the algorithm to the target trajectory is constantly improved, and the allowable error of the estimated radial velocity of the target is gradually reduced, which makes the feedback-adjusted searching interval of the radial velocity tightened and the searching range reduced.

Through the analysis of the algorithm performance under different feedback adjustment frame numbers, it can be seen that with the development of the detection process and the increase of the feedback adjustment frame number, the proposed MPRPFT algorithm can further reduce the calculation amount and improve the real-time performance of the detection.

5. Conclusions

The coherent integration problem of hypersonic target echo signal is studied in this paper. During the processing of hypersonic target coherent integration, in order to solve the problem of large amounts of calculation and poor real-time performance caused by the traversal search of multi-dimensional parameters, an MPRPFT hypersonic target coherent integration detection algorithm based on Doppler feedback is proposed. The simulation results show that the algorithm can effectively reduce the calculation amount and improve the real-time performance of the algorithm based on the effective coherent integration detection of hypersonic target echo signals.

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Biographies

LI Lin was born in 1991. He received his B.S. degree in 2014 and M.S. degree in 2016 from Naval Aeronautical and Astronautical University. Now he is a Ph.D. candidate in Naval Aviation University. His research interests are radar target detection and information fusion.
E-mail: fengzhite@126.com

WANG Guohong was born in 1963. He received his M.S. degree from Xidian University in 1991 and Ph.D. degree from Beihang University in 2002. Now he is a professor and doctor advisor in Naval Aviation University. His research interests are anti-jamming of radar network, radar target detection and tracking, and information fusion.
E-mail: wangguohong@vip.sina.com

SUN Dianxing was born in 1983. He received his M.S. degree in 2009 and Ph.D. degree in 2015 from Naval Aeronautical and Astronautical University. Now he is a post-doctoral researcher in National University of Defense Technology. His research interests are anti-jamming of radar network and information fusion.
E-mail: sdxdd.hi@163.com

ZHANG Xiangyu was born in 1986. He received his M.S. degree in 2011 and Ph.D. degree in 2015 from Naval Aeronautical and Astronautical University. Now he is a lecturer in Naval Aviation University. His research interests are radar target tracking and information fusion.
E-mail: zxy627289467@sina.com