Abstract: During the detection and tracking of high-speed moving target by radar, the coherent accumulation and the energy accumulation of target echo signal are poor. In order to solve this problem, this study discusses speed estimation based on the Hough transform, across distance of radar echo signal and pre-tracking detection method based on dynamic programming. The authors propose an energy accumulation method of target echo based on speed estimation. Using this method, speed estimation accuracy reaches 98.87%, signal-to-noise ratio increases by 10 dB and the goal amplitude is 4.81 times more than the original amplitude. Simulation results show that this method can improve the energy accumulation effectiveness and improve detection and tracking ability of high-speed moving target by radar.

1 Introduction

During high-speed moving target detection by radar, radar signal echo exists distance migration in a coherent processing period and has a low signal-to-noise ratio (SNR), the traditional detection is hard to find target. In order to track and detect high-speed targets, we must adopt a method to detect this kind of target [1].

In this paper, we propose a new method to detect and track high-speed moving target based on velocity estimation. This method used speed estimation to realise range walk correction and coherent accumulation of target echo signal. Then dynamic programming method is used to accumulate the energy of the target echo signal to realise the target detection and tracking based on velocity estimation value [2, 3].

Section 2 analyses the basic principle and realisation method of the Hough transform [4] and introduces the method of velocity estimation. Secondly, the echo signal model of high-speed target is established and analysed the reason of range migration and compensation. Then the implementation process of echo coherent accumulation based on velocity estimation is introduced. Again, a pre-detection tracking method based on dynamic programming is proposed and introduced in detail. Lastly, clarifies the framework of the overall implementation of the high speed and weak target detection method based on velocity estimation. Section 3 carries out the experimental verification and analysis of this method and finally summarises the full text.

2 Overall frame

This method is mainly realised by two aspects. One is the high-speed moving target speed estimation and radar echo coherent accumulation based on the Hough transform. The second is the pre-detection tracking of weak target using dynamic programming based on the speed. This method is based on the speed estimation, the method of non-coherent accumulation after the initial coherent accumulation of the echo energy of the weak target, to achieve the purpose of target detection and trajectory backtracking, and then to achieve high-speed moving target tracking detection. The specific implementation process is shown in Fig. 1. K represents the number of maximum storage of echo data and k represents the value of the current frame.

Fig. 1 shows the implementation flowchart of the target speed estimation and radar echo signal coherent accumulation using Hough transform. The implementation process is this.

i. i Fast time unit pulse compression, radar target echo compression to a point.

ii. ii The Hough transform is performed on the compressed echo signal to obtain the speed estimation value of the target at this moment.

iii. iii Target echo span calibration using target speed estimation.

iv. iv Perform fast Fourier transform (FFT) of slow time unit on echo signals to achieve coherent accumulation of echo signals.

v. v Store the processed echo data and mark the location of the echo data.

vi. vi Take the data observation value of the first frame as the energy accumulation value of the first frame, and use the target speed estimation value and the coherently accumulated echo data to determine the associated region of the previous frame under the state.

vii. vii Using the current frame state, according to the determined size of the associated area, energy accumulation is performed under this frame and the position corresponding to the maximum energy accumulation in the associated area is recorded.

viii. viii The target judgement compares the accumulated energy with the detection threshold. If the accumulated energy
 exceeds the detection threshold, the target is judged and the track traceback is performed. The calculation ends; otherwise, the current frame is compared with the maximum frame number, and the current frame is greater than the maximum. In the frame, the calculation is completed and the next accumulation period is entered. Otherwise, the detection is continued from (vi) to (viii).

In the process of co-accumulation of target speed estimation and radar echo signals, the accuracy of velocity estimation determines the effect of distance walk correction and coherent accumulation, and at the same time determines whether the associated region in dynamic programming is accurate or not. Therefore, speed estimation by using the Hough transform is the key to implementing this method.

3 Basic principle of this method

3.1 High-speed moving target speed estimation based on Hough transform

This section uses the Hough transform to estimate the straight line’s parameters and the straight line is formed by the echo signal across the distance unit. Through calculate the number of distance gates and the time of coherent processing period, we can get the radial speed between the target and the radar. The target's speed estimate includes the following steps:

i. Acquire an echo signal in a reference processing period and perform pulse compression on the echo signal;
ii. Given a high false alarm probability, using the detection threshold under the high false alarm probability, low-noise suppression processing is performed on the pulse compression signal;
iii. Perform Hough transform on the echo signal after low-noise suppression processing, find the peak point of the Hough transform result, and use the peak point to calculate the parameter of the echo signal after noise suppression across the range unit;
iv. Using radar system parameters, calculate the radial velocity between the radar and the high-speed moving target.

The formula is as follows:

\[
R = \text{Num} \times \Delta R
\]

\[
T_{\text{int}} = \text{prt} \times N_t
\]

\[
V_e = R/T_{\text{int}}
\]

(1)

where ‘Num’ is the number of units across the distance, \( \Delta R \) is the width of the distance unit, \( \text{prt} \) is the pulse repetition period, \( N_t \) is the number of pulses of a reference processing period, and \( V_e \) is the estimated speed.

As can be seen from the above equation, when calculating the number of distance units, there is a quantisation error, which results in a difficult-to-correct error between the theoretical and actual values of the speed estimation.

3.2 Cross-range unit correction and coherent accumulation of echo signal

3.2.1 Reason of radar echo signal across distance unit: Let radar transmits signal as coherent chirp pulse train. Pulse signal is \( T_p \), frequency modulation slope is \( k \), carrier frequency is \( f_c \) and pulse repetition period is \( T \), its form is this

\[
p(t) = \text{rect}(\frac{t}{T}) \exp\left(j2\pi k t^2\right)
\]

(2)

Let \( t = t' + tm \), \( t' \) is the fast time, \( tm = mT \) is slow time. Suppose the initial distance between the target and the radar is \( R_0 \), radial velocity is \( V_r \), radial velocity between target and radar is constant and \( |V_r| < c \). Then the target echo of the \( m \) pulse can be written as

\[
s(t', t_m) = p(t - \frac{2R(t_m)}{c}) \exp\left(-j\frac{4\pi}{c}R(t_m)\right)
\]

(3)

where \( c \) is speed of light, \( \lambda \) is wavelength, \( R(t_m) = R_0 - V_t t_m \). The Fourier transform of (3) is \( P(f) \). Using the property of Fourier transform, \( s(t', t_m) \) can be converted to frequency domain as

\[
s(f, t_m) = P(f) \exp\left(-j\frac{4\pi}{c}fR(t_m)\right) \exp\left(-j\frac{4\pi}{c}fV_t t_m\right)
\]

\[
\exp\left(-j\frac{4\pi}{c}fR_{\text{int}}\right) \exp\left(-j\frac{4\pi}{c}fV_t t_m\right)
\]

(4)

In the above equation, the first exponential term is the position of the target 0 moment, the second index term is the distance walk caused by the radial velocity of the target and the third exponent term is a constant. The fourth exponential term is the Doppler effect caused by the radial velocity of the target. In order to eliminate the range walk, the following equation can be used to eliminate the cross-range unit walk:

\[
S'(f, t_m) = S(f, t_m) \exp\left(-j\frac{4\pi}{c}fV_t t_m\right) = P(f) ABC
\]

(5)

where \( V_c \) is assumed as the estimated speed, \( A \) is the position of target 0, \( B \) is the constant and \( C \) is the Doppler effect caused by the radial velocity of the target. From (5), we know that the original echo signal is compensated in fast time and frequency domain. The correction of different echo span distance unit can be realised.

3.2.2 Cross-distance unit correction and coherent accumulation: It can be seen from (5) that the radial speed between target and radar needs to be used in the cross-range unit correction. In the actual working process of radar, the radial velocity is difficult to be obtained. So in this part, the radial velocity estimated by the Hough transform is used to realise the cross-range unit correction of the target echo signal, and the echo signal after the cross-range unit correction is filtered by Doppler filter. The realisation of coherent accumulation of echo energy in a coherent processing period is shown by the chart in Fig. 2.

Fig. 2 shows the flowchart of the algorithm. Firstly, the original echo data is converted to fast time frequency domain after fast time dimension FFT transform for pulse compression and cross-distance cell compensation. Then, IFFT is done along the fast-time dimension to convert the data to the fast–slow time domain. Finally, by performing FFT along the slow time dimension, the Doppler filtering between the slow time pulses is completed, and the coherent accumulation of echo data is realised.

3.3 Principle and implementation of track-before-detect based on dynamic programming

Assume that range Doppler data is composed of \( N_x \times N_y \) number of resolution units, \( x \) represents the direction of distance and \( y \) represents the direction of Doppler (velocity). \( N_t \) represents the...
number of distance units, and $N_0$ represents the number of Doppler units. The location of each resolution unit represents a possible distance and velocity of the target. Regarding this method, the radial uniform motion of the target is assumed [5, 6].

Due to the regularity of the target motion, the state in the current frame can be determined by the motion characteristics of the target to determine the state-related area of the previous frame. The position of the target in the current frame is $s(n)$, and the position of the $X$-axis and the direction of the $Y$-axis is $(r_x(n), r_y(n))$. The velocities of the $X$-axis and the $Y$-axis are $v_x$ and $0$, respectively. After a scanning period $T$, the correlation region $P_s(n)$ of this state in the previous frame is

$$P_s(n) = s(n-1)\{r_x(n-1), r_y(n-1)\}$$

When the target speed is determined, the positional relationship between the current frame and the previous frame is determined by the following equation:

$$r_x(n-1) = r_x(n) + v_xT$$

$$r_y(n-1) = r_y(n)$$

The position of the distance unit varies with the estimated speed, and the position of the Doppler unit remains the same. When the correlation area is determined, the energy value of each state in the current frame is added to the maximum value of the energy accumulation in the corresponding associated area, and the maximum energy accumulation of each state is obtained

$$f_s(n) = \max_{s(n-1) \in P_s(n)} \{J_d(s(n), u_d(s(n))) + f_y.s.(s(n-1))\}. \quad n = 2, 3, \ldots, N$$

In the equation, $f_d(s(n))$ represents the maximum energy accumulation from the initial state $s(1)$ to the state $s(n)$, $J_d(s(n), u_d(s(n)))$ represents the energy value of state $s(n)$. $P_s(n)$ is the associated area of state $s(n)$ in the previous frame. $u_d(s(n))$ indicates the state corresponding to the maximum energy accumulation in the associated area. $N$ is the number of frame processed. The decision of each frame state $s(n)$ is recorded by the following equation:

$$\eta_s(n) = \arg \max_{s(n-1) \in P_s(n)} f_y.s.(s(n-1))$$

In the equation, $\eta_d(s(n))$ is used to record the decision of state $s(n)$ in the associated area.

With the constant arrival of the observed data, according to the type accumulates energy without intervals. When all the observation data are processed, the following equation is the baseline of target judgment. If the energy accumulation value is greater than the detection threshold, the target is detected and a trajectory is given

$$s(N|N) = \{s(N) : f_s(N) > V_T\}$$

$V_T$ is the detection threshold, $s(N|N)$ is the state in which the energy accumulation in the last frame exceeds the detection threshold, which means the estimated value of the $N$-moment state obtained by using the $1$-$N$ moment data. Trace back according to the following equation:

$$s(n|n) = \eta_s(n+1)(s(n+1), n = N - 1, N - 2, \ldots, 1)$$

The estimated target track is

$$s(N|N) = \{s(1)|1), s(2)|2), \ldots, s(N|N)\}$$

Based on speed estimation, this method uses target estimation velocity as a prior knowledge of the current moment to determine the current location of the target at the last moment of the associated region; thus reducing the range of the correlation region. It is beneficial to the effective accumulation of target echo signal when the computation is reduced and the efficiency is improved.

4 Simulation analysis

4.1 Simulation parameters

Table 1 points out the parameters related to this simulation. The transmitted pulse is a linear frequency modulation pulse signal. This parameter is only used in the simulation condition and does not aim at a certain type of radar.

4.2 Simulation results and analysis

4.2.1 Simulation analysis of speed estimation accuracy of Hough transform: Using the simulation parameters in Table 1, set the SNR of the initial echo signal to be $-20$ to $-11$ dB for a total of 10 points, the radial velocity of the radar and the target to be $16,000$ m/s, and the estimated theoretical value is $16,406$ m/s. The actual values and estimated theoretical values are shown in Table 2.

From the simulation results shown in Table 2, when the SNR of the initial echo signal is $-20$ dB, the target trajectory has lower SNR, and it is difficult for the Hough transform to extract the true trajectory of the target, and the speed estimation value and the actual speed error are larger. When the initial echo signal SNR is $-18$ dB, the speed estimation error is reduced, but it is still difficult to meet the application requirements. When the initial echo signal SNR is increased to $-17$ dB, the speed estimation error is further reduced and the relative error is only 1.13%. The radial speed between the radar and the target can be estimated basically. When the SNR is further increased, the parameter of the straight line will not be changed during the Hough transform parameter estimation. In the case of a certain linear parameter, the distance and time across the distance unit are constant, so the range of estimated speed change is small and even the estimated speed remains unchanged. Therefore, under the condition that the parameters of the straight line have been estimated, further improving the signal-to-noise ratio will not change the estimation accuracy of the speed.

To further analyse the robustness of this method, according to the simulation parameters of Table 1, different radial velocities are

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**Table 1** Simulation parameters

| Parameter name       | Value  |
|----------------------|--------|
| carrier frequency    | 1.5 GHz|
| pulse repetition frequency | 1 kHz |
| pulse width          | 0.2 μs |
| pulse accumulating number | 64    |
| LFM bandwidth        | 2 MHz  |
| antenna scanning period | 1 s    |
| target echo SNR      | -10 dB |
| target initial distance | 120 km |

**Table 2** Speed estimation simulation results

| SNR, dB | Estimated value, m/s | Actual value, m/s | Estimated theoretical value, m/s | Relative error, % |
|---------|----------------------|-------------------|-------------------------------|------------------|
| -20     | 213,925              | 16,000            | 16,406                        | 1237.03          |
| -19     | 213,984              | 16,000            | 16,406                        | 1237.4           |
| -18     | 122,168              | 16,000            | 16,406                        | 663.55           |
| -17     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -16     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -15     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -14     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -13     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -12     | 15,820               | 16,000            | 16,406                        | 1.13             |
| -11     | 15,820               | 16,000            | 16,406                        | 1.13             |
value fluctuates around the theoretical value, but the general trend pulse accumulation is 64. If the target does not move across the velocity values are independent on each other, and the velocity simulations to calculate the deviation between the radial velocity different conditions, indicating the coherent effect of this method.

This method estimated theoretical values and theoretical values. This method under different theoretical values under the same conditions, and Table 1 shows the magnitude of the relative errors under different theoretical values.

The estimated speed value of different simulations under the same conditions is given in Fig. 3. The results show that the velocity values are independent on each other, and the velocity value fluctuates around the theoretical value, but the general trend remains the same. Table 3 gives the estimated value of velocity under different theoretical values under the same conditions, and gives the absolute value of the error relative to the true value. The maximum absolute value of the error under this simulation condition is 6.21%. The minimum is 0.45% and the estimation accuracy of radar is different with different velocity of the target. In this experiment, all of speed estimate values are between

4.2.2 Simulation analysis of coherent accumulation effect: During the simulation process of coherent accumulation effect, the basic simulation parameter is taken as Table 1. The input SNR is −10 dB. The time wide band product is 400. The theoretical value of SNR after pulse compression is 16.02 dB. The number of pulse accumulation is 64. If the target does not move across the distance unit, the SNR of coherent accumulation is 34.08 dB. The radial velocity set between target and radar is 10,000 m/s, and 100 times simulation is carried out. Calculate the echo SNR under different conditions, indicating the coherent effect of this method.

4.2.3 Simulation and analysis of the effect of tracking energy accumulation before detection: Table 1 is the basic simulation parameter. The antenna scan period is 1 s, the number of scanned frames is five frames and the detection threshold is 2000 mV. The energy accumulation value of each frame and the previous frame is 7000 m/s.

According to Fig. 5 and Table 4, it can be seen that when there is no cross-range element phenomenon in target echo, the SNR after coherent accumulation is the closest to the theoretical value, with an average deviation of 2.8 dB. When the target has cross distance unit, the result of coherent accumulation of target echoes after the correction of distance unit is 4.24 dB. When the effect of coherent accumulation is better it means that the speed estimation precision can basically meet the actual use demand under this condition. When the target echo does not have the range correction, target echo coherent integration is conducted directly. In this case, the accumulation value and the actual value deviation is 14.13 dB. The energy of the signal is weak, not conducive to the detection of the actual target.

4.2.3 Simulation and analysis of the effect of tracking energy accumulation before detection: Table 1 is the basic simulation parameter. The antenna scan period is 1 s, the number of scanned frames is five frames and the detection threshold is 2000 mV. The energy accumulation value of each frame and the previous frame is 7000 m/s.

From Table 5, it can be seen that first, when the speed estimation error is small, the amplitude of the initial accumulation frame is larger. Second, because of the smaller error between the estimated velocity and the actual velocity, the error in the target amplitude accumulation is smaller.

When the theoretical speed of the target is 7000 m/s and the target exceeds the detection threshold after the fifth frame accumulation, the target estimation trajectory is backtracked, see Fig. 4.
According to the simulation results of Fig. 4, when the target exceeds the detection threshold, tracking and detection of the moving state of the target are achieved by tracing the track back.

5 Conclusions

In this paper, we focus on the effective energy accumulation of high-speed moving target echo signal, and propose a high-speed moving target detection method based on speed estimation. This method uses coherent integration and non-coherent integration to improve the target echo SNR. This method has the following advantages.

i. The speed estimation method of high-speed moving target based on the Hough transform can be used to estimate the speed of the target in a coherent processing period.

ii. Using the estimation of radial speed to realise the range migration correction of echo signal, the coherent accumulation of echo signal after correction can be carried out directly, and the energy accumulation efficiency of echo signal is effective.

iii. By using dynamic programming method, the energy accumulation value can be further improved, and the detection probability can be further increased without changing the detection threshold.

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7 References

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