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A Robust Range Spread Target Detector for Wideband Radar Using Envelope Model Prior

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***Abstract*—Wideband radar is widely used in target detection because of its high range resolution. And the scattering echo signal can be considered as a range spread target, so the traditional detectors are no longer suitable and detectors for the wideband radar need to be developed. The feature square matching detector can have better detection performance than the commonly used energy detector based on the envelope model prior of the range profile, which can alleviate the collapsing loss of the energy detector when the scattering center distribution is sparse to a certain extent. However, the detection performance may decline sharply if the prior information of the envelope model is inaccurate. To solve this problem, this paper proposes a robust range spread target detector. It uses the feature square matching detection method firstly. If the target is not detected, the energy detection method will be used in the next step. It is considered that there is no target only under the circumstances that the target is not detected by using both detection methods. The experimental results show that the proposed detector has the best performance among all detectors, regardless of whether the envelope model prior is accurate or not, which verifies the effectiveness and practicability of the detector.**

Keywords—high range resolution; range spread target; energy detector; feature square matching detector; envelope model prior

I. INTRODUCTION

With the rapid progress of microwave, computer, semiconductor and other scientific and technological fields, radar technology and its research are also developing. Among the functions of radar, target detection is one of the basic tasks. Conventional narrowband radar generally adopts wide pulses, which results in low range resolution. Generally, the scattered echo signal of the target basically occupies one range resolution unit, which is called a point target. And the overlap of these echoes of each scattering center in the time domain causes the angular flicker, resulting in the fluctuation of the radar cross section (RCS) and the deterioration of the detection performance[1].

In order to meet higher requirements of the target detection, High range resolution (HRR) radar is gradually adopted. Due to the technology of pulse compression, HRR radar transmits wideband radar signals and has much higher range resolution. In this situation, the scattering centers of the target with a complex shape usually falls within multiple range resolution units, and the echoes of the target are distributed in different radial range units, presenting the one-dimensional range profile. So it can be regarded as the sum of the vectors of electromagnetic waves reflected by multiple point targets to the radar receiver, which is called the range spread target[2]. In view of the problems of detection for the range spread target, conventional detection methods are no longer suitable. Therefore, it's necessary to study and develop the detection methods usable for the wideband radar.

At present, there are a variety of commonly used detection algorithms for the range spread targets. Research from home and abroad are based on the Gaussian noise background and gradually extended to non-Gaussian noise background with the continuous understanding of wideband radar clutter[3]. For the cases of Gaussian noise, the detector designed with the matched reception for range spread targets has the same performance as the detector for point targets. if matched emission is used at the same time, the performance of the detector will be much better[4]. X. Wen et al. studied the methods of the range spread target detection based on the normal distribution test in Gaussian noise[5]. Hughes et al. proposed a detection method for non-coherent accumulation along the range resolution units occupied by the target, and detected by accumulating all the signal energy in the range window, which had a nice performance when the scattering centers were densely distributed[6]. F. Z. Dai et al. designed the energy detector by accumulating the energy of each range unit based on the high resolution range profile (HRRP), formed by the projection of the strong scattering centers of the target in the radial direction of the radar[7].

When using wideband radar for target detection, the energy detector is more commonly used. However, this detector for the range spread targets will accumulate more noise when the distribution of the scattering centers is relatively sparse, resulting in collapsing loss[8] and its detection performance will decline sharply. Recent studies are also focusing on the effective solutions to this phenomenon. X. W. Meng et al. proposed an algorithm based on the binary accumulation, which is called the M/N detector and performs well even when the distribution of target scattering is quite sparse by adopting double threshold. It is easy for engineering implementation as well[9]. J. Guan et al. obtained the test statistics by calculating the generalized likelihood ratio (GLR). After ranking the test statistics of each distance unit, results are fused under the multiple hypothesis of effective distance units without estimating the number of distance units[10]. Z. C. Ren et al. designed an adaptive detector using the GLR with good robustness for different scattering characteristics[11]. Y. Z. Chen et al. proposed a detection method that the HRRP is arranged in descending order according to the amplitudes of the resolution units and then the top k range units will be accumulated[12].

All the algorithms mentioned above are supposed to satisfy the premise that the scattering characteristics of the target are unknown. If the prior information of the characteristics and environment can be known and used, it

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can undoubtedly improve the detection performance of the range spread targets. Y. F. Hu et al. proposed a range spread target detection method guided by HRRP prior, which uses the envelope model prior to improve the detection performance of the range spread targets[2]. However, it is difficult to obtain the accurate HRRP template of the target in the actual detection process. So we can only reconstruct the HRRP as the prior by adopting the scattering model. To solve the problem of degradation of detection performance caused by the prior error, this paper proposes a robust range spread target detector for the wideband radar using envelope model prior. By merging the detection results based on different detectors, better detection performance can be obtained.

II. DESCRIPTION OF THE RANGE SPREAD TARGET DETECTION

When a wideband radar is used for target detection, it transmits a wideband signal whose range resolution is much smaller than the size of the target. And the echoes of the target occupies multiple range units, forming a one-dimensional range profile of the target. At this time, the detection model for the range spread target is

$$\begin{aligned} &H_0 : \tilde{x}(n) = \tilde{w}(n), n = 0,1,\ldots, N-1 \\ &H_1 : \tilde{x}(n) = \tilde{s}(n) + \tilde{w}(n), n = 0,1,\ldots, N-1 \end{aligned} \tag{1}$$

Where H_0 indicates that there is no target in the detection window under this hypothesis, while H_1 means that there is one target in the detection window under this hypothesis. N is the data length, and $\tilde{x}(n)$ is the observed value of echoes in each distance unit. $\tilde{w}(n)$ is complex Gaussian white noise and $\tilde{s}(n)$ is the complex range profile of the target. If the prior information of the range spread target is unknown, the commonly used detector is the energy detector and the likelihood ratio test process can be written as the following expression

$$\Lambda(x) = \sum_{n=0}^{N-1} \tilde{x}(n)\tilde{x}^*(n) = \sum_{n=0}^{N-1} \left|\tilde{x}(n)\right|^2 \mathop{\gtrless}_{H_0}^{H_1} \gamma \tag{2}$$

The energy detector is a complex observed model and ignores the influence of phase information on the detection, only using the amplitude information of the target scattering echoes. Therefore, only the modulus of the observed data is needed in the energy detector. And the detection model can be simplified to

$$\begin{aligned} &H_0 : x(n) = \left|\tilde{w}(n)\right|, n = 0,1,\cdots, N-1 \\ &H_1 : x(n) = \left|\tilde{s}(n) + \tilde{w}(n)\right|, n = 0,1,\cdots, N-1 \end{aligned} \tag{3}$$

Where $x(n)$ is the modulus of the observed value $\tilde{x}(n)$ and

$$\begin{aligned} &\tilde{w}(n) = w_R(n) + jw_I(n) \\ &\tilde{s}(n) = s(n)\exp(j\varphi(n)) \end{aligned} \tag{4}$$

Where $w_R(n)$ and $w_I(n)$ are the real and imaginary part of the complex Gaussian white noise. $s(n)$ and $\varphi(n)$ are the envelope model and the phase of the target complex range profile. The detection process of the energy detector is shown in Fig. 1.

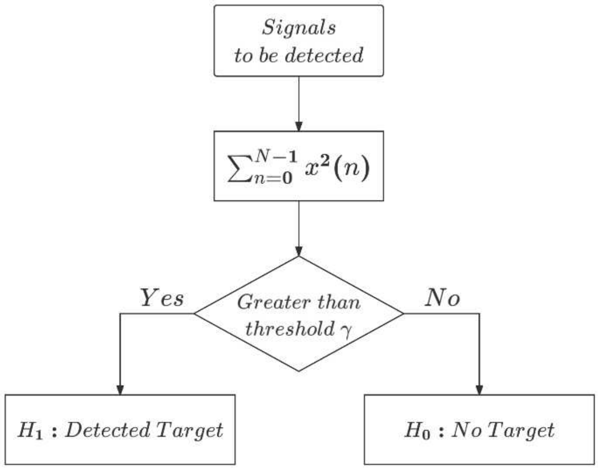

Fig. 1. The detection process of the energy detector

The energy detector is the best detector under the situation of flag signal and low signal-noise ratio. However, if the number of scattering centers of the target is less than the number of accumulated range resolution units, the accumulation of too much noise will cause the collapsing loss, resulting in the deterioration of the detection performance.

Due to this, the feature square matching detector based on the prior guidance of range profile is proposed[2], which is an effective solution to this problem and has stronger universality for different targets. Based on the detection model mentioned above, the test statistics of the feature square matching detector are

$$\Lambda(x) = \sum_{n=0}^{N-1} s^2(n)x^2(n) \mathop{\gtrless}_{H_0}^{H_1} \gamma' \tag{5}$$

The detector calculates the square of the amplitude of the envelope model of the range profile with the cross-correlation of the amplitude of the echoes. By comparing the test statistics with the threshold, the existence of the target can be determined. The detection process of the feature square matching detector is shown in Fig. 2.

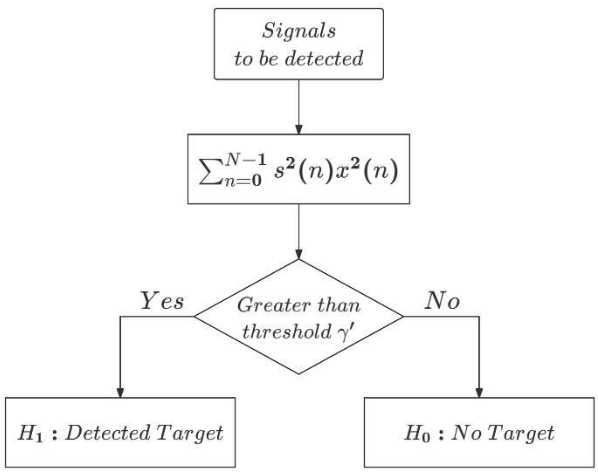

Fig. 2. The detection process of the feature square matching detector

III. Proposed Robust Range Spread Target Detector

However, even if the feature square matching detector can obtain better performance with the range profile and envelope model prior, it's difficult to obtain the accurate range profile prior template in practice, so the range profile template is often reconstructed by using the scattering center model. But under the normal circumstances, there isn't a big gap between prior range profile and the accurate one which are both normalized in the practical detection process, within a certain range of observation angle. This can be shown in Fig.3. If the observation angle gap becomes larger, the error between the accurate and reconstructed range profile will be greater which results in a decline in the detection performance of the detector.

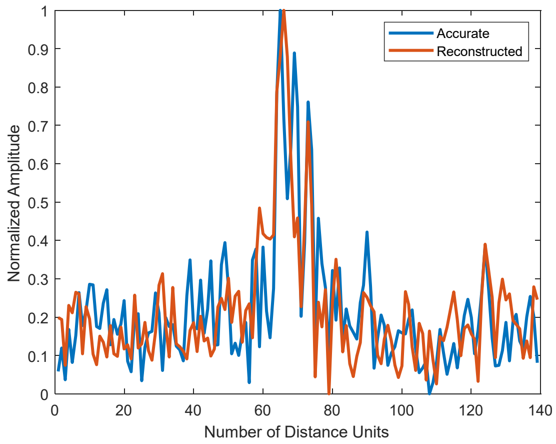

Fig. 3. Comparison between accurate and reconstructed range profile

In order to solve the problem caused by the larger error between the accurate and reconstructed range profile, which leads to the degradation of the detection performance, a robust range spread target detector based on the envelope model prior is proposed in this paper. The specific detection process of this detector is shown in Fig. 4.

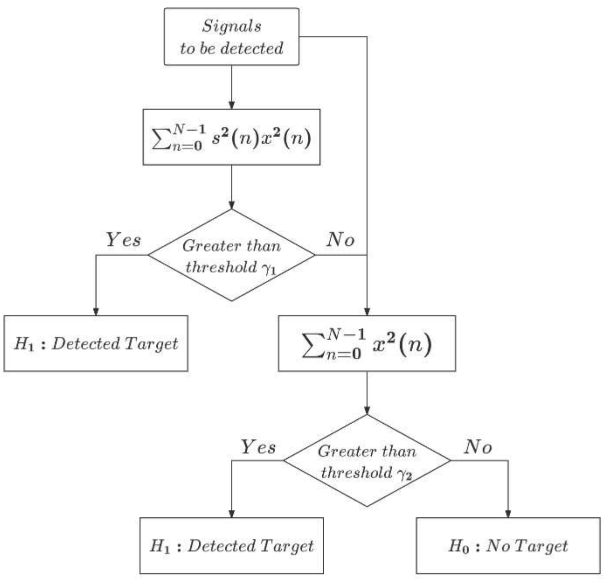

Fig. 4. The detection process of the proposed detector

The proposed detector can detect range spread targets more accurately on the basis of both energy detection and feature square matching detection methods. The detector first adopt the feature square matching detection method. If the corresponding test statistics λ_1 is greater than the threshold γ_1, it is considered that the target is detected, which means the hypothesis H_1 is accepted. Otherwise, the energy detection method will be used in the next step. If the test statistics λ_2 is still smaller than the threshold γ_2, it is considered that there is no target, which means the hypothesis H_0 is accepted. Otherwise, the hypothesis H_1 is still accepted. The following formula can express the detection process of the proposed detector.

$$\max\{\sum_{n=0}^{N-1} s^2(n)x^2(n)-\gamma_1, \sum_{n=0}^{N-1} x^2(n)-\gamma_2\} \underset{H_0}{\overset{H_1}{\gtrless}} 0 \qquad (6)$$

The meaning of each symbol in formula (6) is the same as in formula (2) and formula (5). The proposed detector effectively utilizes the advantages of the two detectors and solves the problem that the detection performance deteriorates when the prior information is not accurate.

IV. Performance Assessment by Simulation

Before using the proposed robust range spread target detector, the prior envelope model of the target needs to be obtained, which means that the one-dimensional range profile of the target is necessary.

Taking the typical scattering center model as an example, it is assumed that the wideband radar emits stepped frequency signal, which has N pulses. The signal model of the i^{th} pulse is shown in formula (7).

$$S_i(t)=\exp[j(2\pi f_i t+\theta_i)], \quad iT_r \le t \le iT_r + T_P \qquad (7)$$

Where $f_i = f_0 + i\Delta f_p$ is the frequency of the i^{th} pulse and f_0 is the carrier frequency. $\Delta f_p = 1/T_p$ and T_p, T_r are respectively the pulse width and pulse repetition interval (PRI)[13]. Consuming that the target has a number of k scattering centers, then the corresponding echo is

$$S_{ir}(t)=\sum_{j=1}^{k} A_j(f_i,t)\exp(j2\pi f_i(t-\tau_j)+\theta_i) \qquad (8)$$

Where $\tau_j = \dfrac{2R_j}{c}$ is the time delay corresponding to the j^{th} scattering center and R_j is the position of the scattering center on the radar line of sight. $A_j(f_i,t)$ is the echo amplitude of the i^{th} pulse at the j^{th} scattering center. Fourier transform can be applied to formula (8) to obtain the frequency response corresponding to the echo of the i^{th} pulse as in formula (9).

$$S_{ir}(f)=\sum_{j=1}^{k} A_j(f_i,j)\exp(-j2\pi f_i \tau_j) \qquad (9)$$

Then the coherent accumulation expression of echoes of N pulses can be obtained by the inverse Fourier transform, which is shown in formula (10).

$$S_r(t) = F^{-1}(S_r(f)) = F^{-1}(\sum_{i=1}^{N} S_{ir}(f)) \tag{10}$$

Where $F^{-1}(\cdot)$ is the inverse Fourier transform and $S_r(f)$ is the frequency response corresponding to the echoes of N pulses. Therefore, $S_r(t)$ is the complex range profile of the range spread target. When using the proposed detector, the envelope model of the one-dimensional range profile can be used to calculate the test statistics.

Measured data which is obtained by observing a real target from different angles is used to carried out the simulation. On the premise of knowing the accurate range profile of the target, the reconstructed range profile with a large error as the prior information will be set for the comparative experiment. The accurate normalized range profile of the target is shown in Fig. 5.

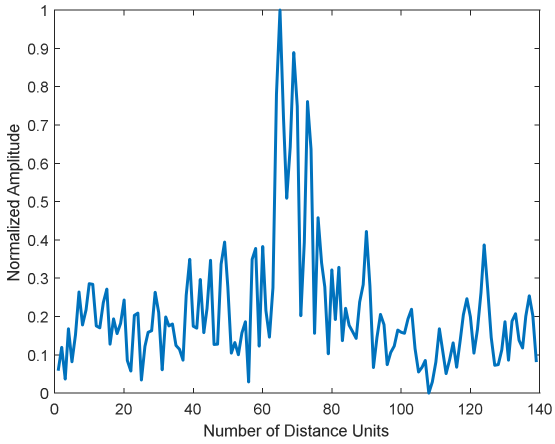

Fig. 5. The accurate one-dimensional range profile of the target

The complex Gaussian white noise with different energy-to-noise ratio is added to the one-dimensional range profile. And those three above-mentioned detector will be used to evaluate the detection performance. The expression of energy-to-noise ratio is

$$ENR = \frac{\sum_{t=1}^{N} s^2(n)}{\sigma^2} \tag{11}$$

Where $s(n)$ is the range profile of the target and N is the quantity of the distance units in $s(n)$. And σ^2 is the variance of the Gaussian white noise. Then the envelope model of the one-dimensional range profile can be used as the prior information in the detection process.

The probability density function of the test statistics are difficult to express because of its complexity, which means that it's hard to get the distribution form of it and the analytic solution of the false alarm rate and detection probability through mathematical calculation, the Monte Carlo method is adopted to obtain the detection threshold. In this simulation, the false alarm rate is set to 10^{-4} in the experiment and the threshold can be obtained by the formula (12) using Monte Carlo method.

$$\begin{aligned} P_{fa} &= \int_{\gamma}^{+\infty} p(\Lambda \mid H_0) d\Lambda \\ P_d &= \int_{\gamma}^{+\infty} p(\Lambda \mid H_1) d\Lambda \end{aligned} \tag{12}$$

Where $p(\Lambda \mid H_0)$ is the probability density function of the test statistic under the H_0 hypothesis and $p(\Lambda \mid H_1)$ is the probability density function of the test statistic under the H_1 hypothesis. γ is the detection threshold.

In the simulation, the energy-to-noise ratio is gradually increased from 6dB to 22dB and the change of the detection probability will be recorded. When the reconstructed range profile is quite accurate, as shown in Fig.3, the curves of detection probability of three detectors with energy-to-noise ratio are shown in Fig. 6.

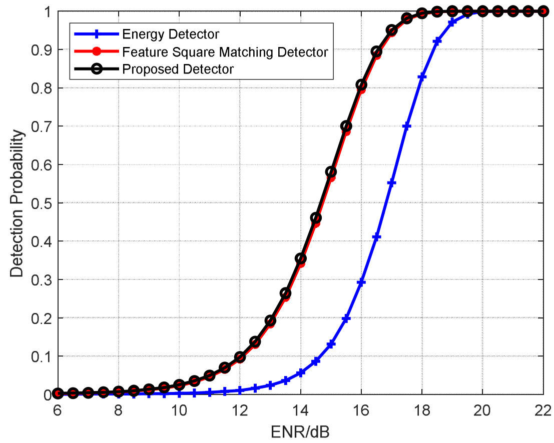

Fig. 6. Detection performance with accurate envelope model prior

Obviously, the detection performances of the feature square matching detector and our proposed detector are similar to each other, and are both much better than that of the energy detector.

If the one-dimensional range profile from another observed angle is selected as the prior information to indicate that there is a quite large error between it and the accurate one as shown in Fig.7, the curves of the detection probability of mentioned detectors will be shown in Fig. 8.

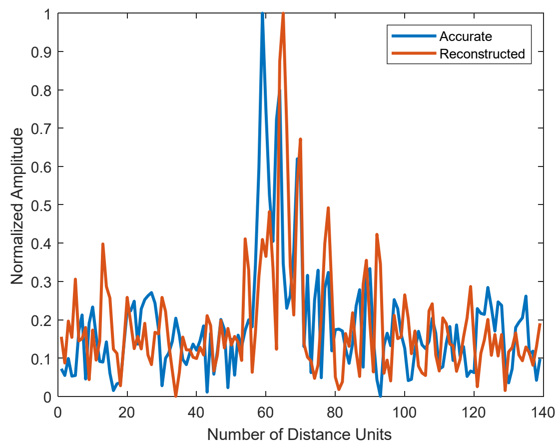

Fig. 7. Accurate and reconstructed range profile with a large error

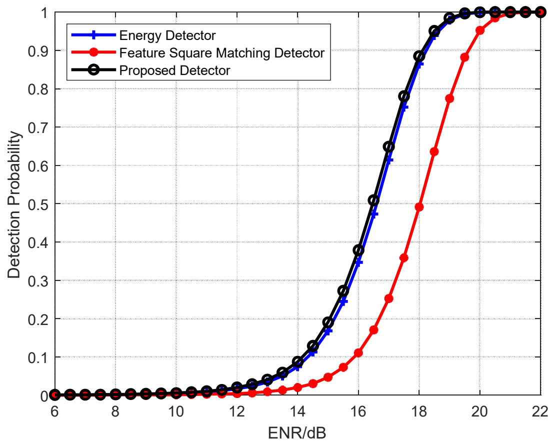

Fig. 8. Detection performance with inaccurate envelope model prior

In this case, the detection performance of the feature square matching detector shows a sharp decline and is even worse than that of energy detector. And the proposed robust range spread target detector has the best performance.

V. CONCLUSION

This paper proposed a robust range spread target detector which integrates the detection results of the energy detector and the feature square matching detector, effectively solving the problems of collapsing loss in energy detector and the degradation of detection performance in feature square matching detector due to inaccurate prior information of the envelope model. Experimental results demonstrate the feasibility and effectiveness of the proposed detector.

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