Research on attitude insensitive feature extraction algorithm of airborne pulsed laser radar target at low SNR

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Abstract: Aiming at airborne multi-pulse laser radar target echo waveform irradiated by the nanosecond pulse width laser, the geometric section ratio feature is proposed, which is insensitive to target attitude and can be used for target detection and tracking combined with target motion state information. And then, the feature extraction algorithm is given. Firstly, by analyzing the relationship between target waveform and target features based on the laser target waveform model, it is pointed out that geometric section ratio of laser target is an attitude insensitive feature. Next, for the separation of target waveform from noises without distortion, the improved Donoho threshold de-noising algorithm is given in wavelet domain using discrete wavelet transform, the target waveform sequence length is obtained with wavelet reconstruction signal, the peaks of target waveform are detected through first order and second order difference equations, and then laser target scattering center and geometric section ratio can be extracted. Finally, the performance of the proposed algorithm is verified through simulation experiment. In the test with airborne multi-pulse laser target simulator, the laser target multi-frame matching detection experiment is developed, using the features which are extracted by the algorithms proposed in this paper and combining with the target motion state information .The multi-pulsed laser target detection become more reliable.

Key words: pulsed laser radar target echo waveform; attitude insensitivity; wavelet transform; feature extraction

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低信噪比下机载多脉冲激光雷达姿态不敏感性特征提取研究

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摘 要: 针对纳秒量级脉宽机载多脉冲激光照射目标的回波波形, 提出几何分割比这一目标姿态不敏

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感特征,给出了特征提取算法,可用于与激光目标运动状态结合开展目标检测与跟踪。首先,基于激光目标波形数学模型分析目标波形与目标特征的关系，指出激光目标的几何分割比特征具备姿态不敏感特性。接着,结合目标特征提取对目标波形和噪声不失真分离的要求,提出在小波域利用对称小波基进行改进 Donoho 阈值降噪处理,在时域利用小波重构信号阈值获取目标波形序列,再由一阶二阶差分计算检测目标波形峰值点,进而提取激光目标散射中心及几何分割比等特征。最后,通过仿真实验验证算法在低信噪比下提取激光目标特征信息的有效性。在与机载多脉冲激光目标模拟器联试实验中,利用文中算法提取激光目标特征结合目标的运动状态信息,开展多帧相关匹配检测,多脉冲激光目标检测的可靠性明显提高。

关键词: 脉冲激光雷达目标回波波形； 姿态不敏感； 小波变换； 特征提取

0 Introduction

The airborne multi-pulse laser radar achieves remote ranging by emitting single pulse or pulse string at hundreds interval of 1-10 Hz repetition frequency[1-2]. During the single irradiation, the potential target chain is established through multi-pulse laser echo signal accumulation, filtering and threshold processing, the false targets are removed from the chain by multi-frame relevant matching with target position and velocity state information, then the laser target detection and tracking can be achieved [3]. As the emission frequency of airborne multi pulse laser ranging radar is very low, the target position, velocity and attitude states vary greatly in multi-frame echo. As the target distance gets farther, the laser optical axis is hard to aim at target steadily, the echo SNR changes dynamically, even sometimes the target is lost [4]. For the non-stationary characteristics of laser target detection, it is difficult to detect and track only based on the target motion state information.

At present, airborne multi-pulse laser target detection is developed in the direction of more narrow laser pulse-width (nearly 1 ns, corresponding to the range resolution is 0.75 m), greater peak power and much more multi-pulses. While nanosecond laser pulse irradiating aircraft and ships which have tens of meters radial size, the laser echo waveform reflects the laser target cross section (LCS), which contains distance, size, strong scattering center features of laser target[5]. In the field of high resolution microwave radar, research on feature extraction of one dimension range profile in time domain and frequency domain is already presented [6]. However, unlike the microwave radar range image, the pulse laser radar signal is a non-coherent signal, and the waveform feature extraction is usually performed in time domain[7-8]. The time domain laser echo waveform changes dynamically with the target attitude. It is significant to extract the attitude insensitive characteristic information of laser target for detection and tracking. In this paper, a continuous convolution model of the pulse laser target echo waveform is given, and the discretization of the model based on transmission pulse distance resolution unit is made, then target echo waveform sequence can be calculated by using linear convolution of finite sequences. Then, the intrinsic relations between the laser target waveform and the basic features are analyzed, and the characteristics of the geometric section ratio of the laser target with attitude insensitivity are proposed. Later, combined with laser echo signal de-noising, it is pointed out that there are some distortion problems in the target waveform extracted from the echo signal in the low SNR, such as the loss of detail, position deviation of peak point of strong scattering center and so on. Furthermore, the noise reduction process based on the improved Donoho threshold is given in the wavelet domain, and the algorithm of extracting the target waveform and the target feature from the reconstructed echo signal is presented in the time domain. Finally, simulation and experiment are brought together to verify performance of the pulse laser target feature extraction algorithm.

1 Analys is of the characteristic of laser target attitude without sensitivity

1.1 Laser target waveform model

Pulse laser target echo signal is obtained by working in a linear mode of APD photodetector to receive and convert the target reflected pulse laser power. The received light power P_R of the pulse laser radar can be regarded as the system response of the transmitting laser pulse excitation input atmospheric propagation and through the target reflection. P_R can be obtained by convolution calculation of transmitted signal, atmospheric channel pulse response and the response of target reflection:

$$P_R(R)=C_A P_0 \tau_H(R) * h_c(R) * h_t(R)=$$
$$\left[\left(\beta\frac{D^2}{\pi R^4\theta_t^2}\eta_{\text{atm}}^2 P_0\right)\times\frac{c\tau_H}{2}\right] * A_c(R)=$$
$$K\cdot\tau_H(R) * A_c(R) \quad (1)$$

From Formula (1), it can be seen that the laser echo waveform is determined by laser beam width τ_H along the direction of incidence and the function $A_c(R)$ of laser target reflection area with distance changing when the system and environment parameters K is relatively stable. The discrete sequence of the laser target waveform can be obtained by the linear convolution of finite length sequence $\tau(n)$ and $A_c(n)$:

$$S(n)=\tau(n)*A_c(n)=\sum_{k=0}^{\infty}\tau(k)*A_c(n)(n-k) \quad (2)$$

Assuming that the laser pulse width is 10 ns, the corresponding range resolution unit dR can be calculated to be 1.5 m with the light speed. The radial length of the emission pulse beam is 3 m. According to dR, the $\tau(n)=\{1,1\}$ can be obtained with 2 points. The discrete sequence of the laser target cross section (LCS) along the radial length can also be obtained by dR. The length of 15 meters of target can be discretized into 10 points sequence of $A_c(n)$. When the pulse width is changed to 5 ns, the range resolution unit becomes 0.75 m. At this point, $\tau(n)$ is still a two point sequence, but the $A_c(n)$ will be of 20 points. Obviously, the narrower pulse width τ_H, the more clear resolution of the target characteristics of the echo waveform.

1.2 Basic features of pulsed laser target

The basic features of the waveform of pulse laser target echo include the target waveform sequence length, strong scattering center and so on.

1.2.1 Target waveform sequence length

The size of laser target can be characterized by the total length of the waveform sequence at the target location. The echo waveform is a sequence of the target attitude fluctuation, but the overall trend is discussed, and feature of target size is obviously different from that of the noise and other targets. The length of target waveform sequence is related to the radial dimension of the target, the attitude of the target (or laser incident angle), and the width of the laser pulse. The length of target waveform varies with laser incident angles, and the length of the sequence is the longest at 0°. The narrower the transmitting pulse is, the higher the range resolution, the longer the target waveform sequence, and clearer target features are observed.

1.2.2 Target strong scattering center

Scatter center of the target area corresponds to the larger reflection laser target area, the number of scattering centers, peak position and amplitude in the radial dimension of the variations reflect the overall structure of the target. The scattering center is the wave crest of the target echo wave, and its quantity does not change as the changing of the target attitude. The scattering center can be determined by the peak value of the waveform. The position of the peak point of the strongest scattering center can be used to calculate the target distance. The moving state of the airborne pulse laser target, including the position, velocity and acceleration of the target, can be derived from the target distance. The fluctuation of the scattering center waveform reflects the shape characteristic of the target, and the waveform amplitude is related to the laser reflection area of target at a certain laser incident angle.

1.3 Laser target geometric section ratio feature

The basic features of the laser target described in the previous section, the number of scattering center belongs to attitude insensitive features, target waveform sequence length and the fluctuation of the scattering center have a certain sensitivity to target attitude also. In target detection and recognition, the features with rotation invariant characteristics of the target attitude are required.

As shown in Figure 1, the airborne laser radar is located at O point, airplane target is expressed by AB, where $BT=l_1$, $AT=l_2$. The maximum reflection area on the target is located at T point (such as a certain position of airplane wing). The laser beam divergence angle is Ψ, OT is the target distance R, the angle between AB and OT is α, CD is the laser spot diameter D.

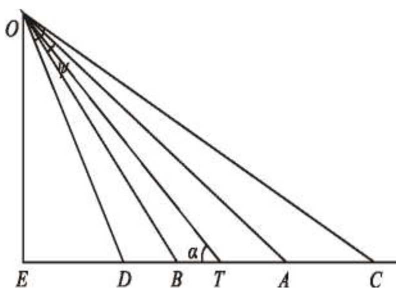

Fig.1 Schematic diagram of target attitude

The size of target is set to L, the beam divergence angle is 1 mrad, then the spot diameter $D=R/1\,000$ according with $D=2R\tan(\Psi/2)$. When the distance R from the machine greater than 20 km, spot diameter D is larger than the target size, the target $L=l_1+l_2$, which belongs to the remote point target. As can be seen from Figure 1, for point target, when the laser incident angle changes or the target rotates, the relative attitude of the target and pulse laser radar will change. In the laser echo signal, the length of the target waveform sequence corresponding to the length of the target along the direction of incidence, which is the projection of AB to the incident direction, so $OT=BT\cdot\cos\alpha+TA\cdot\cos\alpha$. Peak point position of the strongest scattering centers in the laser target waveform is at T. Target geometric section ratio of target waveform sequence is defined as:

$$G=\frac{BT\cdot\cos\alpha}{BT\cdot\cos\alpha+TA\cdot\cos\alpha}\frac{BT}{AB} \tag{3}$$

By the Formula (3), it can be seen that $BT\cdot\cos\alpha$ is not affected with the target attitude α. Set the length of target waveform sequence $S(N)$ is N, whose starting point is $S(\kappa_0)$, and the peak point of the strongest scattering center is located in $S(\kappa_T)$ in the whole echo sequence, so that:

$$G=\frac{\kappa_T-\kappa_0}{N} \tag{4}$$

Geometric section ratio can be obtained by the combination of the peak position and target size, which removes the attitude sensitivity and reflects the position of the strongest reflection area of the target. It can be seen that the geometric section ratio G gives the "body scale" feature of target. Some geometry of geometric section ratio parameters of typical aircraft target in China and abroad are shown at Tab. 1.

Tab.1 Geometric section ratio of typical aircraft

Airplane	F-16	J-10	Su-30	Rafale
G	10/15	13/16	16/22	12/15

2 Extraction algorithm of laser target echo attitude insensitive feature

2.1 Laser echo signal de-noising

The features of laser target exist in the time domain waveform of the echo signal. The key to extract the target features from echo signal under low signal to noise ratio is to separate the target waveform and the noises, that is, to remove the signal noise and retain the characteristics of the target waveform without distortion. The waveform distortion implies that the noise reduction processing algorithm need keep strict linear phase frequency characteristics.

Laser target echo belongs to the pulse signal, usually takes the differential and window smoothing algorithm to implement filtering in time domain. The time domain smoothing filter is simple and has good real-time performance, but it does not possess the linear phase shift. In the low SNR, the algorithm is greatly affected by the noises, which causes the laser target waveform distortion. Wavelet analysis has a very good detection performance for noisy signal with lower signal to noise ratio[9]. Mallat algorithm have implemented the discrete sequence wavelet decom-position and reconstruction for signals with quadrature mirror filter banks. Wavelet decomposition coefficients correspond to the low frequency profile and high frequency details of signal. Laser target echo waveform is mainly concentrated in the low frequency range, after the wavelet decomposition, a part of the coefficients can be removed as noises, and then the waveform after de-noising can be reconstructed with the residual wavelet coefficients. How to remove the coefficients appropriately is the crux of the matter. Combined with the different assessment methods, soft threshold, hard threshold and other different processing algorithms were given[10]. In low SNR, the wavelet de-noising algorithms must have the characteristics of linear phase-frequency[11-12]. Therefore, it is necessary to select the symmetric wavelet basis functions to implement wavelet decomposition. The common wavelet functions including d*bN*, Sym*N*, Coif*N* and so on can be used to implement the discrete wavelet decomposition, where N is the order of the wavelet. The bigger the order N, the better the signal waveform smoothness is, the stronger the frequency domain localization ability is, while the computational cost increases, and the real-time performance becomes worse. The db*N* (N>1) wavelet basis function is not symmetry, in the analysis and reconstruction of the signal it will produce a certain phase distortion. The Sym*N* and Coif*N* wavelet basis functions are symmetry.

2.2 Laser target feature extraction algorithm

$$\text{Set } f(k)=s(k)+n(k),\ f(k)=1-N \tag{5}$$

In the formula, $f(k)$ is a noisy laser echo signal, $s(k)$ is a sequence of N points obtained from the target waveform sequence of length L, $L<N$ by zero-padding, and $n(k)$ is a random Gauss white noise.

Step 1 Using discrete wavelet decomposition of given signal $f(k)$, the high frequency part of the wavelet coefficients is obtained as $d_{j,k}$ and low frequency part is $c_{j,k}$, the scale $j=0-J$, the length of the sequence $k=0-N$.

Step 2 Using discrete wavelet reconstructing, the time domain target echo waveform $f(k)$ is obtained after improved Donoho threshold processing with the wavelet coefficients.

For the high frequency coefficient part $d_{j,k}$, by setting an appropriate threshold, it is considered that the wavelet coefficients smaller than the threshold are generated by noise and will be removed, such wavelet coefficients greater than the threshold value are generated by the target which will be retained or contracted, so as to realize the separation of signal and noises. Donoho proposed wavelet threshold de-noising method based on the wavelet transform, and proved that the method can achieve the best estimation in the minimum variance sense. Therefore, wavelet de-noising based on Donoho threshold processing can better retain the original signal waveform. The fixed threshold value given by Donoho is:

$$\lambda=\sigma\sqrt{2\ln N} \tag{6}$$

Among them, σ is the noise intensity, and N is the length of the signal. Taking into account that the wavelet transform coefficient modulus changes with the scale j, the threshold value can be improved as:

$$\lambda=\frac{\gamma\sigma\sqrt{2\ln N}}{\ln(j+1)} \tag{7}$$

Among them, γ is the noise adjustment factor, which can be adjusted according to the type of noise. When noises belong to Gauss distribution, γ can be set as 1, and will be set less than 1 while the non-Gauss impulse noises occur. The j is wavelet scale, and N_j is the length of signal decomposed in j layer. When j increases, the wavelet coefficient values of noises decrease, the threshold is also reduced, so that the threshold can be adjusted according to different scales.

$$d_{j,k}=T_h(d_{j,k},\lambda)=\begin{cases}0, & |d_{j,k}|<\lambda \\ d_{j,k}, & |d_{j,k}|\geqslant\lambda\end{cases} \tag{8}$$

The improved wavelet domain Donoho threshold processing is used to remove the noises and preserve the details of the waveform.

Step 3 For the reconstructed signal, the target waveform sequence $s'(k-i)$ can be obtained with time-domain threshold changing with actual noise RMS value, in which $i=N_0\sim N_0+L'$. The sample $s'(k-N_0)$ is the starting point of the target waveform sequence, the target length are L' points.

Noise can be estimated by selecting a certain number of points of the noise data samples to evaluate the root mean square value of RMS.

$$RMS=\sqrt{\frac{1}{N}\sum_{k=1}^{N}(n(k)-\bar{n})^2} \tag{9}$$

Threshold is usually set to $\alpha\cdot RMS$. Target waveform sequence is composed with the sample points which are larger than the threshold value, and its length can be used to characterize the size of the target. It can be observed that the better the effect of the echo signal noise reduction, the more accurate the target size estimation.

Step 4 According to the maximum value point searching, the scattering center peak point $s'(k-N_0-K_n)$ can be obtained in $s'(k-i)$

The position searching of waveform peak employs a time domain detection function with difference equations. The definition of discrete sequence first order forward difference equation is:

$$\Delta f(n)\triangleq f(n+1)-f(n) \tag{10}$$

First order backward difference is:

$$\nabla f(n)\triangleq f(n)-f(n-1) \tag{11}$$

Second order forward difference is:

$$\Delta^2 f(n)\triangleq\Delta[\Delta f(n)]=f(n+2)-2f(n+1)+f(n) \tag{12}$$

Second order backward difference is:

$$\nabla^2 f(n)\triangleq\nabla[\nabla f(n)]=f(n)-2f(n-1)+f(n-2) \tag{13}$$

If $n=k\in N,\varepsilon>0$ in epsilon neighborhood of k, k is the local maxima, we have the following relationship established

$$\begin{cases}\Delta f(k)<0\\ \Delta f(k)>0\\ \nabla^2 f(k)<0\\ \nabla^2 f(k)>0\end{cases} \tag{14}$$

Further, the formula 16 can be changed to:

$$\begin{cases}\Delta f(k)\nabla f(k)>0\\ \Delta^2 f(k)\nabla^2 f(k)<0\end{cases} \tag{15}$$

Then, when $n=k$, the corresponding $f(k)$ is a peak point of waveform sequence $f(n)$. Taking into account the noises, set peak detection threshold δ_r, only to detect the peak point above the threshold, so the final target waveform peak detection function is:

$$\begin{cases}f(k)\geqslant\delta_r\\ \Delta f(k)\nabla f(k)<0\\ \Delta^2 f(k)\nabla^2 f(k)<0\end{cases} \tag{16}$$

Step 5 Calculating the geometric section ratio with peak point position of the strongest scattering center and the length of the target sequence L'. And the number of scattering centers can be obtained by the number of peak points obtained in step4.

3 Simulation experiment of laser target feature extraction

3.1 Laser echo signal de-noising and target waveform extraction

According to the Formula (2), the discrete finite length linear convolution algorithm is presented to simulate the laser target waveform sequence. When the laser incident angle is 0°, the target waveform sequence length is 18 points, the first scattering center is located at 995 point with amplitude of 5, and the second scattering center is located at 1 004 point with amplitude of 2.

For laser echo signal SNR=1.5, using improved Donoho threshold de-noising (IDTD), low frequency wavelet coefficient reconstruction de-noising (LFRD), digital smooth filtering(SF) to reduce the noises in the signal, and then obtain the target waveform sequence.

Figure 2 shows de-noising performance of the SF algorithm in time domain, LFRD algorithm and IDTD algorithm in wavelet domain. The original target waveform (horizontal axis for distance, vertical axis for signal strength) is mixed with Gauss noises. It can be seen that the output echo waveform of IDTD is most close to the original target waveform, the scattering center details of the target waveform are preserved.

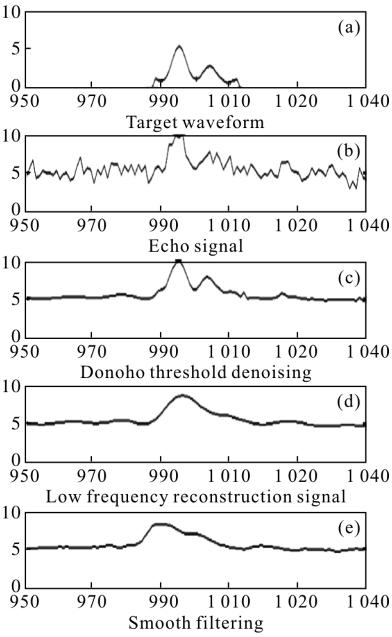

Fig.2 Target waveform of different noise reduction algorithms

In LFRD, as the high frequency coefficients of wavelet decomposition are all deleted, the reconstruction signal is only come from the low frequency coefficients. Although the noises can be reduced effectively, the feature of the scattering center is lost.

In SF, the noise is reduced after smoothing, but the position of the scattering center is shifted, the waveform is distorted.

Figure 3 shows that the mean value of target waveform sequence length extracted by the three algorithms which are carried out 20 simulation experiments in different SNR. It can be observed that the target waveform sequence length will be short when SNR is low. In IDTD, the estimated value and the true value can be consistent when the SNR increases to 2. In SF and LFRD, the length of the target waveform both have deviation, the error of LFRD is the maximum.

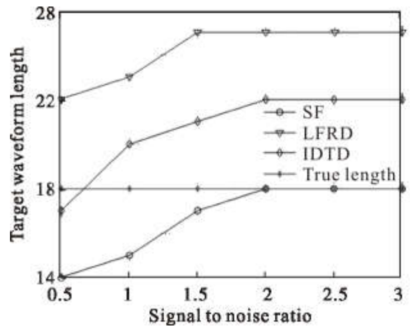

Fig.3 Target sequence length extraction in different SNR

3.2 Peak position detection of scattering centers

Table 2 shows the mean and maximum deviation of the peak point position of the two scattering centers based on the differential peak point detection function at different SNR(20 simulation experiments).

Tab.2 Peak position extraction of scattering centers

SNR	0.5		1.0		1.5	
LFRD	998±1	None	998	None	998	None
IDTD	995±1	1 004±2	995	1 004±1	995	1 004±1
SF(M=6)	991±2	None	991±1	None	991±1	None
SF(M=3)	993±1	1001±2	993±1	1 001±1	993±1	1 001±1

It can be seen that the IDTD algorithm based on Coif4 wavelet transform can be utilized to extract the peak position of the two scattering centers, but there is a fluctuation in low signal noise ratio. In LFRD, only one peak position can be detected, but there still have 3 points offset. In SF, when smooth window width M=6, it can only extract one peak position, offset by 4 points, and in the low SNR, the data have larger errors. When $M=3$, SF algorithm can detect two peak positions. Therefore, SF algorithm does not possess self adaptability which the IDTD algorithm does have.

3.3 Target Geometric section ratio feature extraction

When the *SNR* is 1.5, the different target attitudes at different incident angle from 0° to 75°, the peak position of the strongest scattering center and the length of the waveform sequence are extracted, and the geometric section ratio of the laser target is calculated. The mean value of the 20 extraction experiments with different attitudes are shown in Tab. 3.

Tab.3 Section ratio of laser target at different incident angles when *SNR*=1.5

α	0	15	30	45	60	75
G	6/18	6/17	5/15	4/13	4/9	2/5

It can be seen that the geometric section ratio changes from 0.3 to 0.45, which basically remains stable. In general, the smaller radial direction of incident angle deviating from the target is, the longer the target waveform sequence is, the smaller the error of geometric section ratio is.

Experiment 1: Dynamic target detection comparison at low SNR

The target detection experiment is completed with an airborne multi-pulse laser radar dynamic target signal simulator of Luoyang Institute of Electro-optic Equipment, setting test parameters as:

(1) False alarm rate: 1×10^{-3};

(2) Laser pulse string repetition frequency: 1–5 Hz;

(3) Multi pulses number: 100;

(4) Multi pulses emission frequency: 1 kHz;

(5) Target disappearance probability: 1‰;

(6) SNR range: 0.5–3 dB;

(7) SNR dynamic variation: SNR±50%.

Table 4 shows the SNR gain of different de-noising signal processing algorithms. Firstly, multi-pulse echoes summation by 100 laser pulses can achieve $\sqrt{100}$ SNR gain. The LFRD algorithm can get max SNR gain of 4. The SNR gain of IDTD algorithm is more smaller than that of LFRD, it is because that IDTD keeps some high frequency coefficients for feature extraction.

Tab.4 SNR gain of different signal processing algorithms

Algorithm	Sum(100)	SF(M=3)	SF(M=6)	LFRD	IDTD
SNR gain	10	1.5	2	4	3.5

The target detection and tracking are carried out by using the traditional target detection algorithm only based on moving target state information (I), and the target detection algorithm based on target feature information and motion state fusion (II). The target detection probability of the two methods are compared with continuous 2 000 frame echo signal, as shown in Fig. 4.

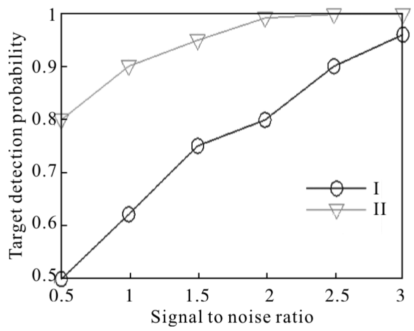

Fig.4 Comparison of target detection probability of two methods

It can be seen that the probability of target detection is improved effectively by using the algorithm of fusion detection of target feature and motion state information in low SNR. From the process of target detection using traditional algorithm, as the target waveform amplitude fluctuation is large in multi frame echoes, when multi-frame target matching could not detect the target in low SNR, the target will be considered as "lost" mostly. And then the recapture process would require another multi-frame matching process, which is one of the main reasons that leads to the low detection probability with traditional algorithm only based on moving state information. By using the feature information extracted with the algorithm proposed in this paper and the moving state information both, target detection decision can be made more quickly and reliably.

4 Conclusion

In this paper, the intrinsic relationship between the target waveform and the basic features of the target is simulated and analyzed based on the pulse laser target waveform convolution model, the target geometric section ratio is proposed which is a kind of attitude insensitive feature, can be used for fusion with motion information and carry out the target detection and tracking. For laser echo signal de-noising, improved Donoho threshold wavelet de-noising algorithm using the symmetric wavelet basis is proposed, which can separate the target waveform from the noise with few distortion. For the laser target feature, the extraction of target waveform sequence from the time domain reconstruction echo signal is proposed, which uses first order and second order difference calculation to build the peak point detection function and extract scattering center peak point, then the basic features of the pulsed laser target and the geometric section ratio are obtained. In airborne multi pulse laser target detection, using target′s geometric section ratio feature which is extracted with the algorithm proposed in this paper with target moving state information, developing data fusion in multi frame correlation detection, the probability of remote target detection in low SNR can be improved effectively. In the laser target tracking process, this algorithm can quickly detect the target again when the target is lost and then enter the field of view. So the performance of target recapture can be improved. Also, the laser target geometric section ratio feature proposed in this paper, which is insensitive to target attitudes, can be used as a basis for the next step to develop laser target classification and recognition.

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