Research on Clutter Suppression for Low-altitude Slow and Small Target Detection

TONGHUI XUE, TAO SHAN and YUAN FENG

ABSTRACT

In order to solve the problem that current clutter suppression methods are not suitable for the clutter suppression in low-altitude slow and small target detection, the method of Filter DC (Direct Current) was proposed in the paper. This method can effectively suppress the clutter by forming a narrower notch filter, while protecting the low-altitude slow and small targets from being affected. In this method, the improvement in Signal-to-Clutter-Noise ratio (SCNR) in different clutter environments was simulated, which proved the superiority of the filter. In this paper, a clutter suppression method was proposed based on noise subspace for motion clutter. Compared with the feature vector method, this method has less influence on the noise of different Doppler channels, and it is more suitable for the detection of low-altitude slow and small targets. Finally, the feasibility and effectiveness of the algorithms were proved by real unmanned aerial vehicle data.

KEYWORDS
Low-altitude slow and small target, clutter suppression, Filter Direct Current, noise subspace.

INTRODUCTION

Low-altitude slow and small target refers to a target with a flying height less than 1000m, a flight speed of less than 55m/s and a radar reflection cross-sectional area (RCS) of less than 0.1m2 [1]. Because of the low velocity of small targets with low flying altitude, slow flight speed, and RCS small features, they can easily be submerged in strong ground clutter or meteorological clutter, making its detection through radar quite challenging. In the complex environment for low-altitude slow and small target detection, the clutter must be effectively suppressed, while reducing the target energy loss.

In view of the motion target detection, the clutter is generally suppressed by using the MTI (Moving-target indication) and the MTD (Moving-target detection) in the radar, such as two-pulse cancellation and FFT (Fast Fourier Transformation) or three-pulse cancellation and FFT [2]. Increase in the number of cancellation can widen the notch of the filter, thereby increasing its clutter suppression. But for clutter suppression of low-altitude slow and small targets, the filter notch formed by the two clutter suppression methods is too wide, and the velocity of the low-altitude slow and small target is relatively low, limiting its Doppler frequency and ground clutter frequency difference. Therefore, when the wide groove of the filter is adopted to suppress the clutter, it will lead to energy loss in the low-altitude slow and small target, which is not conducive to target detection.

Tonghui Xue, Tao Shan, Yuan Feng, Beijing Institute of Technology, Beijing, China
When there are motion clutters, such as cloud clutter, in the detection, the MTI method cannot effectively suppress the clutter because the center of the cloud clutter spectrum is not at zero frequency, which leads to more false alarms when detecting.

In order to improve the suppression performance of ground clutter and motion clutter, this paper designed a Filter DC filter for ground clutter and a noise subspace filter for motion clutter. The characteristics of these filters were simulated and analyzed, and the validity of the algorithm was verified using the measured data of a band of radar.

**GROUND CLUTTER SUPPRESSION**

Due to the large number of fixed buildings, trees and grasses in the application environment of radar, and the low flight height of the low-altitude slow and small targets, the clutter in the target echo signal received by radar was strong. This section used the complex environmental clutter data collected by a band of radar to analyze the ground clutter distribution characteristics. Radar PRT (Pulse Recurrent Time) is 32us, collecting 100 pulse data and the beam elevation angle is 0 degree. There is a corn field in front of radar and fixed buildings in the distance. The analysis result of the measured clutter data showed that the ground clutter was mainly concentrated near zero frequency.

The proposed Filter DC method is a new one for ground clutter suppression for low-altitude slow and small targets. The method of forming a relatively narrow and steep notch filter at zero frequency will not affect the zero frequency external signal, and can effectively inhibit the clutter and improve the detection of low-altitude slow and small targets.

![Figure 1. Amplitude response of various filters.](image)

$N$-order Filter DC clutter suppression filter specific implementation method is as follows:
a) Select a window, such as Kaiser window, with a length of $N$, $\beta=24$. Under this parameter, Kaiser window main lobe has a certain width, but the side lobe height is lower.

$$\text{window}=\text{kaiser}(N, \beta)$$  \hspace{1cm} (1)

b) The $N$-group pulse echo signal of the same distance unit is windowed, accumulated and averaged.

$$\text{sum}=\sum_{k=1}^{N} \text{window}(k)$$  \hspace{1cm} (2)

$$\bar{x} = \frac{1}{\text{sum}} \sum_{k=1}^{N} [x(k)\text{window}(k)]$$  \hspace{1cm} (3)

c) All echo signals are subtracted from the mean to obtain clutter suppression data

$$y(n) = x(n) - \bar{x}$$  \hspace{1cm} (4)

The reason for using the window to find the average way is that the filter’s passband ripple is too strong to detect the low-altitude slow and small targets without window. In different cases, different window functions can be selected which have different notch widths to suppress the passband ripple and clutter.

In this paper, the clutter suppression effect was simulated. The precondition of simulation was that the clutter power spectrum is a Gaussian spectrum. The noise type is Gaussian white noise, the variance of the clutter spectrum is 150Hz, the clutter-noise ratios are 36dB and 16dB respectively, and the accumulation pulse number is 100. The Signal-to-Clutter-Noise ratio improvement of the different clutter suppression algorithms is shown in the following figure.

![Doppler channel SCNR (dB)](image)
From the a and b of Figure 2, it can be found that, with the increase of the Doppler channel number, the improvement of the SNCR of the various clutter suppression modes is also increased, indicating that the filter formed by the filter DC mode is better than the two-pulse cancellation or the three-pulse cancellation mode about the improvement of the SNCR, both in the case where the clutter-noise ratio is high or low. In the low-frequency channel, the Filter DC clutter suppression mode is better than the two-pulse cancellation and other ways to improve 3-8dB, showing a good clutter suppression effect.

**MOTION CLUTTER SUPPRESSION**

The effect of the Filter DC clutter suppression filter mentioned in the first section is not good for the meteorological clutter with a constant velocity and a wide variation of the clutter spectrum, because the notch width of the filter cannot be adjusted according to the actual clutter spectral width [3]. In order to suppress meteorological clutter, this section proposes a noise suppression method based on noise subspace. The method can form a notch core at the center of the clutter spectrum according to the spectral center and spectral width of the meteorological clutter. The notch width equals the clutter spectrum wide filter.

The frequency characteristic of the MTI filter was determined by its weighted vector, and the weight vector based on the noise subspace was chosen to characterize the covariance matrix of the clutter. The subspace of the \( N \)-\( K \) eigenvectors corresponding to the \( N \)-\( K \) large eigenvalues in the covariance matrix of the clutter is called the clutter subspace, and the clutter is mainly concentrated in this subspace. The subspace of the eigenvector corresponding to the \( K \) small eigenvalues is called the noise subspace, and the feature vector corresponding to the \( K \) smaller eigenvalues was chosen as the filter weight coefficient. The data of the filtered clutter can be obtained by mapping the echo signal into the noise subspace.

The clutter echo has a Gaussian power spectral density, and its normalized power spectral density function is as follows [4]:

$$
\text{Normalized Power Spectral Density (PSD)} = \frac{1}{\sqrt{2\pi \sigma^2}} e^{-\frac{t^2}{2\sigma^2}}
$$
\[ S_c(f) = \frac{1}{\sqrt{2\pi\sigma_c^2}} \exp \left\{ -\frac{(f-f_c)^2}{2\sigma_c^2} \right\} \]  

(5)

where \( \sigma_c \) is the standard deviation of the clutter and \( f_c \) is the center frequency of the clutter spectrum. Since the clutter normalized power spectral density function and the clutter normalized autocorrelation function are a Fourier transform pair, the clutter normalization autocorrelation function can be obtained from the clutter power spectrum [5-6].

\[ R_c(i, j) = F^{-1}[S_c(f)] \]

\[ = \exp(-2\pi^2 \sigma_c^2 \tau^2 + 2\pi f_c \tau) \]

(6)

The repetition period was pulsed for \( T_r \) analysis, so that \( \tau = kT_r \), and there are:

\[ R_c(i, j) = \exp(-2\pi^2 \sigma^2 k^2 + i2\pi f k) \]

(7)

where \( \sigma = \sigma T_r \), which is the clutter normalized power spectrum width, and \( f = f/T_r \), which is the clutter normalization spectrum center. If an \( N \)-order filter is designed, the standard covariance matrix of the clutter is as follows:

\[ R_c = \begin{bmatrix} R_c(0,0) & R_c(0,1) & \cdots & R_c(0,N) \\ R_c(1,0) & R_c(1,1) & \cdots & R_c(1,N) \\ \vdots & \vdots & \ddots & \vdots \\ R_c(N,0) & R_c(N,1) & \cdots & R_c(N,N) \end{bmatrix} \]

(8)

The clutter power spectrum characteristic is only determined by the \( \sigma_c \) and \( f_c \), so, for the determined \( \sigma_c \) and \( f_c \), the clutter covariance matrix was uniquely determined, the eigenvectors corresponding to the smaller of the eigenvalues in the eigenvector were selected, and the weight vector of the filter was also determined.

When the order of the filter is high, the covariance matrix of the clutter is larger. Therefore, firstly, a filter needed to be designed where the notch center frequency is zero and the width equals the noise spectrum. Then, the center of the notch of the filter was moved to the center of the clutter spectrum. So, when calculating the filter weight vector, \( f_c \) was set to zero, and the sequence of the clutter normalized autocorrelation function became as follows:

\[ r(k) = \exp(-2\pi^2 \sigma^2 k^2) \]

(9)

The parameters representing the broad spectrum were recorded as \( \xi = \exp(-2\pi^2 \sigma^2) \), and the clutter covariance matrix became as follows:
The $N + 1$ eigenvalues were solved, and the smaller $K$ values were chosen to construct a linear system of equations, where $I$ is an $N + 1$ order unit matrix and $W$ is the weight coefficient of the filter.

\[
(R_c - (\lambda_1 + \lambda_2 + \cdots + \lambda_K)I/k)W = 0
\]  

(11)

The coefficient of the filter $W(\sigma_c, 0)$ can be obtained by solving the system when $f_c = 0$.

When $f_c \neq 0$, the coefficient of the filter $W(\sigma_c, f_0)$ can be solved as follows:

\[
W(\sigma_c, f_0) = U \cdot W(\sigma_c, 0) = [w_N e^{j2\pi f_0N}, \cdots, w_1 e^{j2\pi f_0}, w_0]^T
\]  

(12)

In the detection, if only the feature vector corresponding to the minimum eigenvalue is chosen as the filter weight coefficient, the small target echo will be easily suppressed as clutter, which will not be conducive to low-altitude slow and small target detection. It should choose $K$ smaller eigenvalue to constitute the noise subspace to detect targets. Generally, $K = 2$ or $K = 3$.

For example, when $N=4$, the solution of formula (13) is as follows.

\[
\begin{align*}
\lambda_1 &= 1 - \frac{\xi^9}{2} - \frac{\sqrt{5\xi^2 - 8\xi^5 - 2\xi^{10} + 4\xi^8 + \xi^{18}}}{2} - \frac{a}{2} \\
\lambda_2 &= 1 - \frac{\xi^9}{2} + \frac{\sqrt{5\xi^2 - 8\xi^5 - 2\xi^{10} + 4\xi^8 + \xi^{18}}}{2} - \frac{a}{2} \\
\lambda_3 &= 1 + \frac{\xi^9}{2} - \frac{\sqrt{5\xi^2 - 8\xi^5 - 2\xi^{10} + 4\xi^8 + \xi^{18}}}{2} + \frac{a}{2} \\
\lambda_4 &= 1 + \frac{\xi^9}{2} + \frac{\sqrt{5\xi^2 - 8\xi^5 - 2\xi^{10} + 4\xi^8 + \xi^{18}}}{2} + \frac{a}{2}
\end{align*}
\]  

(13)

where $T_c = 3.2e-5$, $\sigma_c = 150$, the corresponding clutter energy of $\lambda_1$ is only $5e-11$ of the total clutter energy, that of $\lambda_1 + \lambda_2$ is only $4e-7$ of the total clutter energy, and that of $\lambda_1 + \lambda_2 + \lambda_3$ is $0.11\%$ of the total clutter energy. Therefore, it is appropriate to choose to map the signal to the noise subspace composed of the eigenvectors of the smaller two eigenvalues, which can reduce the probability that the small target is suppressed as clutter or better suppress clutter.
As shown in Figure 3, a third-order filter is designed by using the feature vector method and the noise subspace method. The eigenvector mean of two eigenvalues was chosen as the filter weight coefficient of the noise subspace. It could be clearly found that the filter formed by the noise subspace had a narrower and steeper filter notch than that by other methods, which would be more conducive to low-altitude slow and small target detection.

**ACTUAL DATA VALIDATION**

This section used the complex environmental clutter data collected by a band of radar to analyze the improvement of signal-to-clutter-noise ratio of different clutter suppression methods. Radar PRT (Pulse Recurrent Time) is 32us, collecting 100 pulse data and the beam elevation angle is 0 degree. There is a corn field in front of radar and fixed buildings in the distance. There are unmanned aerial vehicles in the vicinity of the distance of 2.7km, and height of 100m. The UAV model is the DJI Ghost 3.
Figure 4. The SCNR improvement of various clutter suppressions in actual data.

TABLE I. COMPARISON OF DIFFERENT METHODS.

<table>
<thead>
<tr>
<th>Method</th>
<th>The amount of operation</th>
<th>The number of pulse echoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-pulse cancellation</td>
<td>N</td>
<td>N+1</td>
</tr>
<tr>
<td>Three-pulse cancellation</td>
<td>2N</td>
<td>N+2</td>
</tr>
<tr>
<td>Filter DC</td>
<td>N+2</td>
<td>N</td>
</tr>
</tbody>
</table>

This analysis used two sets of data, and one of them was UAV data in strong ground clutter environments, where the clutter-noise ratio was 36dB, and the signal-to-clutter ratio was 30dB. The other set of data is UAV data in weak clutter environments, where the clutter-to-noise ratio was 16dB, and the signal-to-clutter ratio was 6dB.

If the number of FFT points is N, different methods require different amounts of computation and different numbers of pulse echoes.

It can be found in Figure 4 that the Filter DC method with the Kaiser window has the best SNCR improvement for UAV target, which is 3 to 6 dB higher than the normal two-pulse cancellation in the low Doppler channel. It can be seen in Table I that this clutter suppression method is simple to implement and requires a small amount of computation. It is not necessary to transmit additional pulses for cancellation, saving valuable time for the radar.

When the motion clutter and ground clutter exist at the same time, due to the wide range of motion clutter spectrum, the filter DC clutter suppression method cannot accurately form a suitable filter. Therefore, considering the feasibility of the program as well as the engineering, the ground clutter was suppressed by the filter DC clutter suppression method, and the motion clutter was suppressed by the noise subspace.

The effects of various treatments on different Doppler channels were analyzed for the same distance unit as follows.
Figure 5. Effects of various clutter suppression.

It can be seen in Figure 5 that there has a ground clutter at the distance unit 1, a target at the distance unit 4, and a motion clutter at the distance unit 8. The clutter suppression mode of the feature vector method has a big influence on the noise of different channels, and that even the noise amplitude at the high frequency channel is much higher than that of the UAV target, which is likely to lead to loss of UAV targets in target agglomeration treatment. The noise subspace-based processing method can effectively avoid the influence of the filter on the noise of different channels, and improve the detection of the UAV target while suppressing the clutter. Therefore, combining the Filter DC method with the noise subspace method can effectively deal with complex clutter including ground clutter and motion clutter.

CONCLUSION

In light of the problem that the clutter interference is strong for the target detection, the current clutter suppression method is not suitable for the application, so a method to suppress the composite clutter was proposed using Filter DC and noise
subspace. In the case of ground clutter, the Filter DC method is necessary to protect the target energy and suppress the clutter, which can form a narrow and steep recess at zero frequency. This method doesn’t need transmit additional pulses for cancellation which can save valuable time for the radar. For motion clutter, the method of noise subspace can form a filter where the notch lies in the center of the clutter spectrum and its width equals the noise spectrum, which can suppress the clutter. At the same time, compared with the feature vector method, the noise subspace method has less influence on the noise of different channels, and causes less energy loss to the slow target. Compared with the existing clutter suppression method, this method has more obvious improvement which can protect the energy of the target signal while suppressing the clutter.

ACKNOWLEDGEMENTS

This research was supported in part by the National Natural Science Foundation of China under Grant Nos. 61671060, 61331021 and Beijing Natural Science Foundation under Grant No. 4172052.

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