Multi-clutter Adaptive Suppression of Ball-borne Radar

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Abstract. Compared with conventional radar, the ball-borne radar faces a special clutter environment. Because the irregular moving ground clutter of the platform is no longer fixed but has unknown spectral characteristics as the cloud rain clutter, it faces multiple unknown mixed clutter. It is not possible to filter ground clutter and then suppress motion clutter like a conventional radar. In this paper, the eigenvector method that can suppress multiple clutter at the same time is used to construct the filter, and the correlation function method is used to estimate the spectral characteristics of the clutter to achieve adaptive clutter suppression. Firstly, the calculation method of filter weight vector is discussed theoretically. Aimed at the problem that the performance of the method is deteriorating when suppressing multiple clutter with different spectral characteristics, the method is improved and its performance superiority is analyzed. The theory of multi-clutter estimation is deduced. For the problem of large spectral width deviation, the bandwidth coverage method is proposed to reduce the influence of error.

1. Introduction

In recent years, ball-borne radars have become more and more popular among military forces all over the world because of their strong early warning capability, strong survivability, long blanking time and high cost-effectiveness [1,2]. In the face of the threat of low-altitude and ultra-low-altitude penetration, ball-borne radar is one of the effective means of resistance. There are two main difficulties in the detection of these targets by the ball-borne radar: First, the clutter environment is different from the conventional radar [3], the beam topology causes the clutter strength to be large, and the movement of the radar platform causes the fixed ground clutter spectrum to occur. Moving and broadening, it is difficult to know exactly the spectral characteristics of clutter [4]. Second, the low-altitude low-speed target is interfered by strong ground clutter [5]. Due to its slow speed, its characteristics are very close to the clutter in the Doppler domain, which makes the traditional frequency domain filtering method difficult to handle.

In view of the above problems, this paper uses the eigenvector method to design the filter to match the clutter spectrum features, and uses the correlation function method to estimate the spectral features. The cover method is used to eliminate the influence of errors as much as possible for the problem of excessive estimation error. The effectiveness of the method was verified by computer simulation.

2. Clutter model

The echo signals received by the ball-borne radar may contain various clutter such as ground, waves, and clouds and rain. The clutter faced by the ball-borne radar can generally be represented by a Gaussian model [6]. For multiple clutter, the normalized form is.

\[ S(f) = \sum_{k=1}^{n} \frac{1}{\sqrt{2\pi\sigma_{ck}^2}} \exp\left(-\frac{(f - f_{ck})^2}{2\sigma_{ck}^2}\right) \] (1)
In the formula: \( f_{dk} \) is the center frequency of the k-th clutter, \( \sigma_{dk} \) is the standard deviation of the k-th clutter, which represents the degree of broadening of the spectrum.

\[
f_{dk} = \frac{2 \nu_k}{\lambda} \cos \psi
\]  (2)

In the formula: \( \nu_k \) is the relative horizontal velocity of k-th clutter, \( \psi \) is the top view angle, and \( \lambda \) is the radar wavelength.

\[
\sigma_{ck}^2 = \sigma_{\text{ak}}^2 + \sigma_{\text{bk}}^2 + \sigma_{\text{ck}}^2
\]  (3)

The broadening of the clutter consists of three parts, \( \sigma_{\text{ak}} \) is the 3dB azimuth beamwidth of the antenna, \( T_{\text{scan}} \) is the antenna scanning time; \( \sigma_{\text{bk}} = 2 \sigma_{ck} / \lambda \) -- the broadening caused by the internal motion of the clutter, \( \sigma_{\text{ck}} \) is the clutter power Spectral standard deviation; \( \sigma_{\text{ck}} = (2 \nu_k / \lambda) \sin \psi \) -- broadening caused by platform motion [7].

For example, when the wavelength is 0.3m, the repetition frequency is 300Hz, and the antenna rotation speed is 6r/min, \( \theta_l = 2 \), Table 1 gives the typical spectral width of several kinds of clutter spectrum under normal conditions.

| Clutter type   | \( \sigma_c \) (Hz) | \( \sigma_f \) (Hz) | \( \sigma_w \) (Hz) | \( \sigma_{\text{ck}} \) (Hz) |
|---------------|---------------------|---------------------|---------------------|---------------------|
| Ground clutter| 7.9                 | 2.1                 | 6.0                 | 10.1                |
| Cloud clutter | 7.9                 | 26.7                | 6.0                 | 28.1                |

According to Wiener filtering theory, the autocorrelation function of the clutter and the power spectral density are each a Fourier transform, so the autocorrelation function of the clutter can be expressed as

\[
R_{c}(i, j) = F^{-1} [S(f)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(f) \exp(j2\pi f (t_i - t_j)) df
\]  (4)

Set \( \tau_{ij} = t_i - t_j \) be the relevant time, bring the formula (1) into the formula (4) and get the following result

\[
R_{c}(i, j) = \sum_{k=1}^{n} \exp \left( \frac{f_{dk}^2 + j2\pi \sigma_{ck}^2 \tau_{ij}}{2\sigma_{ck}^2} - f_{dk}^2 \right)
\]  (5)

It can be seen from formula (5) that the mixed clutter of multiple Gaussian spectra has an autocorrelation function composed of the sum of corresponding multi-clutter components. It can be known from the theory of random process that the autocorrelation function of the stationary stochastic process is its covariance matrix. Therefore, the multi-clutter covariance matrix composed of \( R_{c}(i, j) \) is

\[
R_{c} = \begin{bmatrix}
R_c(0,0) & R_c(0,1) & \cdots & R_c(0,N-1) \\
R_c(1,0) & R_c(1,1) & \cdots & R_c(1,N-1) \\
\vdots & \vdots & \ddots & \vdots \\
R_c(N-1,0) & R_c(N-1,1) & \cdots & R_c(N-1,N-1)
\end{bmatrix}
\]  (6)

3. Real-time processing technology based on eigenvector method

The design goal of the filter is to design a suitable set of filter coefficients to effectively suppress clutter and ensure that the target signal can pass without loss. The output of the filter [8] is

\[
y(t) = w^T x(t) = w(i) x(t - iT_r)
\]  (7)

In the formula: \( w = (w_0, w_1, \cdots, w_N)^T \) is the weight vector, \( x(t) \) is the signal vector, and \( T_r \) is the pulse repetition period of the ball-borne radar.
In engineering, the improvement factor is often used to measure the performance of the weight coefficient. The improvement factor is defined as 

\[ \frac{I_o}{I_o} \cdot \frac{S_i}{S_o} = I_{SC} \]

Obviously, the larger the improvement factor, the better the suppression effect on the clutter.

The filter designed by the characteristic method has a good filtering effect on the mixed clutter composed of multiple clutter [9]. The eigenvector method is a clutter suppression method based on the maximum improvement factor. It has been proved\[^{10,11}\] that to maximize the improvement factor, the optimal weight vector of the filter should be the eigenvector corresponding to the minimum eigenvalue \( \lambda_{\text{min}} \) of the covariance matrix \( R_c \) of the input clutter.

\[ R_{w_{opt}} = \lambda_{\text{min}} w_{opt} \tag{8} \]

At this point, the average improvement factor is maximized.

\[ I_{max} = \frac{1}{\lambda_{\text{min}}} \tag{9} \]

It can be known from equation (8) that the filter coefficient \( w \) calculated by the eigenvector method depends on the clutter covariance matrix \( R_c \), which is determined by equations (5) and (6), and \( R \) is determined by \( f_{ck} \) and \( \sigma_{ck} \), so the optimal weight coefficient \( w \) is the binary multidimensional complex function vector of \( f_{ck} \) and \( \sigma_{ck} \) which is denoted as \( w(f_{ck}, \sigma_{ck}) \).

In order to facilitate the explanation, without loss of generality, this paper uses two clutters (ground clutter and cloud rain clutter) as an example to illustrate multi-clutter adaptive suppression.

Figure 1 simulation conditions: \( f_{d1} = 20Hz, f_{d2} = 130Hz, \sigma_{c1} = 2Hz, \sigma_{c2} = 20Hz \)

Figure 2 simulation conditions: \( f_{d1} = 20Hz, f_{d2} = 125Hz, f_{d3} = 130Hz, \sigma_{c1} = \sigma_{c2} = \sigma_{c3} = 2Hz \)

![Figure 1. Multi-notch frequency response (when the spectral width is different)](image1)

![Figure 2. improves the filter response](image2)
set), and their spectral widths are all 2 Hz, so the virtual setting of the clutter \((f_d = 125\text{Hz}, \sigma = 2\text{Hz})\) will play a role in widening the cloud rain clutter spectrum. The effect is shown in figure 2, and the virtual clutter settings are shown in figure 3. Note that the order of the filter should be greater than the total number of clutter (true clutter plus virtual set clutter).

\[
\begin{align*}
(f_{d1}, \sigma_{c1}) & \quad \rightarrow \quad W \rightarrow \quad (f_{d1}, \sigma_{c2}) \\
(f_{d2}, \sigma_{c2}) & \quad \rightarrow \quad W \rightarrow \quad (f_{d1}, \sigma_{c3}), (f_{d2}, \sigma_{c4}) \ldots
\end{align*}
\]

Virtual clutter

Figure 3. Schematic diagram of virtual clutter setting

It can be clearly seen from figure 4 that the feature vector method deals with the deterioration of performance when the two spectral features are different, and the greater the difference, the more serious the performance deterioration. It can be seen from figure 5 that the improvement of the feature vector method obviously improves the improvement factor, and the improvement of performance is related to the position of the set clutter, but the improvement effect does not exceed the feature vector method to deal with the clutter with the same spectral width.

4. Clutter feature extraction

To achieve adaptive clutter suppression, we need to extract the clutter spectrum features (clutter center frequency and clutter spectrum width) to calculate the filter coefficients. In the first section of this paper, it is mentioned that the ground clutter of the ball-borne radar is not fixed. As the movement of the platform will exhibit the characteristics of similar motion clutter, for the spherical radar clutter, it is necessary to simultaneously extract the spectral features of multiple clutter including ground clutter. It can be seen from formula (5) that the spectral characteristics of the clutter are determined by the spectral width \(\sigma\) and the power spectrum center \(f_d\). The filter weight vector based on the eigenvector method for the determined \(\sigma\) and \(f_d\) is also determined. For the low-altitude low-speed target detected by the ball-borne radar, the accuracy of the clutter feature estimation determines the performance of the detection because the target and the clutter spectrum are similar. Therefore, it is necessary to take a method to estimate the spectral characteristics of multiple clutter at the same time, and take measures to minimize the estimation error as much as possible. The correlation function method \([11, 12]\) can be used to estimate the characteristics of multiple clutter. Note that when multi-clutter features are simultaneously estimated, it is necessary to satisfy multiple clutter at different distances, that is, the clutter does not coincide at the distance.

Multi-clutter can be expressed as follows:
\[ u(t) = \sum_{k=0}^{n} \text{rect}(\frac{t}{T_k}) A(t) \exp(j2\pi f_{dk} t + \varphi_0) + n(t) \]  

(10)

In the formula: \( A(t) \) is the complex envelope, \( T_k \) is the time width corresponding to the existence range of the \( k \)-th clutter, \( f_{dk} \) is the Doppler frequency of the \( k \)-th clutter, \( \varphi_0 \) is the initial phase, and \( n(t) \) is the additive white noise. A delay of one cycle can be written as:

\[ u(t-T_r) = \sum_{k=1}^{n} \text{rect}(\frac{t-T_T}{T_k}) A(t-T_T) \exp(j2\pi f_{dk} (t-T_T) + \varphi_0) + n(t-T_T) \]  

(11)

In general, the noise is not related to the clutter. It is noted that the clutters are not related to each other due to time differences, so their correlation functions are:

\[ R(T_r) = E[u(t)u^*(t-T_r)] = \begin{cases} 
B(T_r) \exp(j2\pi f_{d1} T_r), & t \in T_1 \\
B(T_r) \exp(j2\pi f_{d2} T_r), & t \in T_2 \\
\vdots \\
B(T_r) \exp(j2\pi f_{dk} T_r), & t \in T_k 
\end{cases} \]  

(12)

\( B(T_r) = E[A(t)A(t-T_r)] \). \( A(t) \) is a narrowband signal, in the same time \( A(t) = A(t-T_r) \), then \( B(T_r) = E[A(t)A^*(t)] \) is a real number. Available from formula (12)

\[ f_{dk} = \frac{1}{2\pi T_r} \arctan \frac{\Im[R(T_r)]}{\Re[R(T_r)]} \]  

(13)

For the general traversal, the stationary stochastic process can be replaced by the time average instead of the statistical average, and the estimated expression is obtained.

\[ \hat{R}(T_r) = \frac{1}{N} \sum_{i=1}^{N} [u_i(t)u^*_{i}(t-T_r)] \]  

(14)

In the formula: \( i \) represents the independent sample sequence number of the clutter on different pulses. Combining formula (13) (14) to obtain the Doppler frequency estimate of the clutter

\[ \hat{f}_{dk} = \frac{1}{2\pi T_r} \arctan \frac{\Im[\hat{R}(T_r)]}{\Re[\hat{R}(T_r)]} \]  

(15)

Assume that the ground clutter is located at 5~15km, the spectral center is 65Hz, the spectral width is 11Hz, the cloud rain clutter is located at 25~80km, the spectral center is 130Hz, and the spectral width is 26Hz. The correlation function method is used to estimate. The result is shown in figure 6.

Figure 6. correlation function method estimation results

It can be seen from figure 6 that the clutter is estimated by the correlation function method. The frequency estimation has a certain gap in the adjacent units, but both fluctuate above and below the preset value, that is, there is a certain spectral width. The frequency values of adjacent units are averaged as the spectral center estimate, and the standard deviation is used as the spectrum width.
estimate. Table 2 gives the simulation results of the correlation function method for estimating the broad spectrum center of multi-hybrid spectrum.

**Table 2. Correlation function method spectrum estimation results**

| Spectrum center | Spectral width | Spectrum estimation result | Spectral width |
|-----------------|----------------|----------------------------|---------------|
| Ground clutter  | 65             | 65.9                       | 12.1          |
|                 | 10             | 65.3                       | 11.6          |
|                 |                | 64.6                       | 8.4           |
| Cloud clutter   | 130            | 130.2                      | 31.2          |
|                 | 26             | 131.4                      | 20.7          |
|                 |                | 129.0                      | 20.9          |

It can be seen from the results of Table 2 that the spectral center estimation effect of the adjacent function method is ideal, but the spectral width estimation has a large error. The default value of the clutter spectrum width is 10 Hz, the estimated value is 8.4~12.1 Hz, and the error is -1.6~2.1Hz. The default value of cloud rain clutter width is 26Hz, the estimated value is 20.7~31.2Hz, the error is -5.3~5.2Hz, the relative error is large and may be too large or too small, which is the commonality of most spectrum estimation methods.

5. Multi-clutter adaptive suppression of ball-borne radar

5.1 Bandwidth coverage method:

Considering that the estimation error of the spectral width $\sigma_c$ is too large, the detection of low-speed small targets is intolerable. Therefore, it is necessary to reduce the impact of errors as much as possible. The ball-borne radar over land mainly faces the interference of ground clutter and cloud rain clutter. From the previous analysis, it can be known that the comprehensive spectral width of the ground clutter is generally about 10 Hz, the estimated error is about ±2 Hz, and the spectral width of the cloud rain clutter is generally about 26 Hz, and the estimated error is around ±5 Hz. It can be seen that the larger the spectral width, the larger the error.

Set relative error

$$\delta \sigma_c = \left| \sigma_c - \sigma_c^\wedge \right| / \sigma_c$$  \hspace{1cm} (16)

The relative error of ground clutter is $\delta \sigma_c = 0.19$, and the relative error of cloud rain clutter is $\delta \sigma_c = 0.25$. Therefore, based on the estimation of the spectral width, the value of the spectral width can be quantized and expanded to form multiple sets of filters for simultaneous filtering. The quantization extension of the spectral width is matched with the improvement of the eigenvector method in the second section, which is realized by setting the form of virtual clutter. The spectral width of each clutter is very different. In theory, the spectral width of the ground clutter is the smallest, and the spectral width of the cloud rain clutter is generally 1~3 times that of the ground clutter. Other clutter such as chaff is generally ground 1~2 times of clutter. Therefore, the spectral characteristic value of the ground clutter is selected as a reference value. The steps of the bandwidth coverage method:

1) Selecting the minimum value from the estimated spectral width value which is the spectral width value of the ground clutter $\sigma_c = \min \sigma_c^\wedge$, and then replacing the value of the other clutter with it, set $\sigma_c = \sigma_c$.
2) Set the virtual zero to broaden the spectral width of other clutter, set the stepping frequency $\Delta f = \sigma_c / 4$, take the cloud rain clutter $f_c$ as an example. Considering the calculation amount, set a virtual clutter around $f_c$, and set three sets of $f_c \pm 2\Delta f$, $f_c \pm 3\Delta f$, and $f_c \pm 4\Delta f$. The setting of the three sets of virtual clutter corresponds to the formation of three sets of filters with different
spectral widths, which covers the clutter spectrum width and is likely to include the true value of the spectral width. The number of virtual clutter and the number of groups covered by the bandwidth can be flexibly set, and the number of groups set in consideration of the calculation amount is small here. According to the foregoing, these three groups can find three filter coefficients. For example, the frequency response of the filter in a certain case is shown in Fig. 7.

Figure 7. multiple sets of filter frequency response

5.2 System composition
Aiming at the simultaneous suppression problem of multi-clutter, the eigenvector method is used to solve the weight coefficient. The adaptive clutter suppression needs to estimate the spectral characteristics of multiple clutter. Due to the large error of the estimated spectral width, the system uses the bandwidth covering method to reduce as much as possible. Estimate the impact of the error. The system composition is shown in figure 8.

The system consists of clutter storage unit, clutter feature estimation, weight coefficient solution and extended weight coefficient, multiple sets of filters and a comparator. The specific steps are as follows:
(1) In this system, first, N pulses are sampled on the clutter to obtain \( u_i(t) \), \( i = 1, 2, \ldots, N \) and stored.
(2) From equation (14), the time average of N pulses is used to obtain $\hat{R}(T_k)$, and the calculated value $f_{\delta_k}$ of each distance unit is obtained by equation (15), and the calculated value of the neighboring unit is averaged as the estimated value $f_{\delta_k}$, and the standard deviation is used as the estimated value of $\sigma_{\delta_k}$.

(3) Considering that the estimation deviation of the spectral width is too large, multiple sets of filters are formed by the bandwidth covering method, and then the clutter data is input into the filter in parallel, and compared output result of each filter, then select the output of filter whose clutter remaining is minimum, as the best output.

6. Conclusion

The particularity of the ball-borne radar clutter environment leads to the incompatibility of the traditional adaptive clutter suppression method. This paper analyzes the clutter characteristics of the ball-borne radar, and uses the eigenvector method based on the maximum average improvement factor for the simultaneous suppression of multiple clutter to calculate the filter coefficients. The eigenvector method can degrade the performance when dealing with multiple spectral characteristics. It is proposed to improve the performance by setting the virtual clutter, and the performance is improved. Based on the correlation function method, the related theory of multi-clutter spectrum estimation is derived. For the problem of large estimation error, combined with the improved eigenvector method, the characteristics of the virtual clutter can be freely set to extend the spectrum width, and a variety of spectral width covers are formed nearby. Compared with the traditional clutter suppression, the system can process multiple unknown clutter at the same time, and has the advantage of reducing the error. The method has clear meaning, uncomplicated calculation, strong operability, and strong use value for ball-borne radar.

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