Sea clutter suppression based on sea spikes identification and matrix completion

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Abstract. The increase of small targets on the sea surface poses a great threat to public security. Sea surface has extremely complex scattering characteristics and sea clutter is mixed with radar target echoes, which seriously affects the detection performance of radar for small targets on the sea surface. Therefore, a method based on sea spikes identification and matrix completion is proposed in this paper. By analyzing the characteristics of sea spikes, the sea spikes in radar echoes are distinguished and eliminated from the original signals. Then, the unqualified data are filled up by matrix completion method, which effectively improves the signal-to-noise ratio of target signals. Finally, the validity of the method is verified by using measured data and simulation data.

1. Introduction

Small targets detection on the sea surface plays a very important role in the field of sea surface rescue and other fields. Sea surface is a constantly changing surface, which has extremely complex scattering characteristics. Sea clutter has become one of the main constraints affecting radar detection performance. How to effectively overcome the interference of sea clutter has been recognized as a difficult point in the field of radar technology.

The rough sea surface is mainly composed of wind wave, gravity wave and capillary wave [1]. When observing the rough sea surface with low grazing angle, the radar echo of sea clutter shows a sea spike, which is not continuous in time and uneven in space, and its probability density function (PDF) curve shows a long tail phenomenon. Because of its short occurrence time, sea clutter changes from steady state to unsteady state and from non-time-varying to time-varying. The Doppler spectrum of sea clutter broadens and deviates from 0 frequency to cover up the weak target echoes, and the radar may distinguish the sea spike as a moving target, resulting in the increase of false alarm probability.

At present, there is no strict physical explanation for the generation of sea spikes. Posner points out that the sea spikes are mainly affected by wind direction, radar view angle and polarization mode [2]. Statistical characteristics of sea spikes are analyzed in [3]. It is considered that amplitude threshold, minimum interval and minimum spike width are three important parameters in describing sea spikes.

With the popularity of compressed sensing theory, matrix completion has attracted more and more attention. The second-order sparsity of matrix is used to restore the target matrix by sampling some elements. It is mainly used in image restoration, network traffic monitoring, and seismic data reconstruction [4].
In this paper, a sea clutter suppression method based on sea spikes identification and matrix completion is proposed to improve the signal-to-clutter ratio (SNR) and enhance the detection performance for weak targets.

2. Sea spikes identification

Accurate identification of sea spikes is an important part of this method. As mentioned in [3], radar echo from the same range-gate can be distinguished as sea spikes only if the three conditions are satisfied: (1) The amplitude of the sampling points must exceed a specified threshold; (2) The duration of sampling points exceeding the threshold should not be less than the specified minimum spikes width; (3) The time interval between the sampling points exceeding the threshold should not exceed the specified minimum spikes interval.

\[
\begin{align*}
|x_i| & \geq T \\
W & \geq W_{\text{min}} \\
I & \geq I_{\text{min}}
\end{align*}
\]

where \(x_i\) is the \(i\)th sampling point, and \(W\) and \(I\) represent the width and interval of the sea spikes, respectively. The threshold of sea spikes amplitude is usually \(L\) times the average power of sea clutter, that is

\[
T = \sqrt{\frac{1}{N} \sum_{i=1}^{N} |x(i)|^2}
\]

where \(N\) is the sequence length.

In this paper, the same parameters as [3] and [5] are used. The minimum spike width is set to 0.1s, the minimum spike interval is set to 0.5s, and the spike amplitude threshold is set to 5 times the average power of sea clutter. The sea clutter data collected by X-band IPIX radar [7] from McMaster University in Canada are analyzed. The main parameters are shown in Table 1.

| Radar parameters          | Parameter values |
|---------------------------|------------------|
| Radar frequency           | 9.4 GHz          |
| Intermediate frequency    | 150 MHz          |
| pulse width               | 20-5000 ns       |
| Transmitting signal wavelength | 3 cm        |
| Pulse repetition rate (PRF) | 0-2000 Hz     |
| Range resolution          | 30 m             |
| Ground angle              | <1°              |
| Sampling distance         | 15 m             |

In this paper, the data #19931118_162658_stareC0000 is selected for analysis. Figure 1 gives the identification results of sea spikes under HH polarization and VV polarization. The red region in the figure represents the sea spikes. It can be seen that under HH polarization, the sea spikes has shorter duration and higher amplitude than VV polarization.

Figure 1. Results of sea spikes identification.
3. Matrix completion

3.1. Algorithm principle

Matrix completion method restores data by using the low rank property of the matrix. At the same time, the method can suppress interference and noise. Suppose that the element \( M_{ij} \in \Omega \) in the given set \( \{(i,j):1 \leq i \leq m, 1 \leq j \leq n\} \), \( \Omega \) is the set of \( p \) known elements in \( X \). Than low rank matrix completion can be expressed as a minimizing matrix rank. Its definition is as follows:

\[
\min_{X \in \text{rank}\in \Omega} \text{rank}(X) \text{ s.t. } X_{ij} = M_{ij}, \forall (i,j) \in \Omega
\]  

(3)

The radar echo of a range-azimuth unit can be expressed as

\[
\mathbf{r}(m) = \mathbf{s}(m) + \mathbf{i}(m), m = 1, 2, \ldots, M
\]  

(4)

where \( m \) represents the pulse sequence, \( \mathbf{s}(m) = \mathbf{t}(m) + \mathbf{c}(m) \) represents the target signal and residual clutter, and \( \mathbf{i}(m) \) is the sea spike. Than we construct the \( P \times L \) dimensional Hankel matrix by using radar echo sequence \( \mathbf{r}(m), m = 1, 2, \ldots, M \), where \( M = P + L - 1 \). The rank of Hankel matrix is approximately 3 when the target has low maneuverability [6]. Set \( R = H(r), \ S = H(s), \ I = H(i) \), the Hankel matrix of the echo signal can be expressed

\[
H = \mathbf{R} + \mathbf{S} + \mathbf{I} + \mathbf{N}
\]  

(5)

Hankel matrix \( S \) can be expressed as \( S = \sum_{m=1}^{M} \alpha_m \mathbf{B}_m \) equivalently, where \( \mathbf{B}_m \) is the base matrix and \( \alpha_m \) is the weighted value. According to the theory of matrix completion, the data can be recovered by following optimization problems after the sea spikes are identified and eliminated.

\[
\min_{S \in \rho \times \omega} \|S\|_n, \text{s.t.}, P_{\omega}(R) = P_{\omega}(S + N), S = \sum_{m=1}^{M} \alpha_m \mathbf{B}_m
\]  

(6)

where \( \|\cdot\|_n \) represents the nuclear norm.

3.2. Optimization of cost function

In this section, we use the generalized Lagrange multiplier method to solve the optimization problem. Document [6] extends the classical matrix completion algorithm to the complex domain, and effectively utilizes the phase information. Therefore, we use this method to solve the proposed optimization problem. The Lagrange function in the complex field can be expressed as

\[
L(S,Z,\alpha) = \|S\|_n + \Re \langle Y_1, R - S - Z \rangle + \frac{\mu}{2} \|R - S - Z\|_F^2 + \Re \langle Y_2, S - \sum_{m=1}^{M} \alpha_m \mathbf{B}_m \rangle + \frac{\mu}{2} \|S - \sum_{m=1}^{M} \alpha_m \mathbf{B}_m\|_F^2
\]  

(7)

where \( \Re \langle \cdot \rangle \) denotes the real part of the signal, \( \alpha = [\alpha_1, \alpha_2, \cdots, \alpha_M]^T \) denotes the complex weighted vector, and \( \langle A, B \rangle = \text{tr}(A^H B) \) is the inner product of the matrix. \( Y_1 \) and \( Y_2 \) are Lagrange multiplier matrices, and \( \mu > 0 \) is the penalty factor. The steps to solve the problem are as follows.

a) Parameter initialization. \( \mathbf{Z} = 0, \ Y_{1,0} = Y_{2,0} = 0, \ k = 0, \ \rho = 1.3, \ P = 40, \ \eta = 10^{-3}, \ \mu_0 = 10^{-5}. \)

b) Updating matrix \( S \).

\[
S = U T_{1/(2\mu_k)} (\Sigma) V^H
\]  

(8)
where $E_k = U \sum V^H$ represents the singular value decomposition of the matrix $E_k$.

c) Updating matrix $Z$ and vector $\alpha$.

$$Z = P_{\Omega} \left( R - S_{k+1} + \mu^{-1} Y_{1,k} \right),$$

$$\alpha_{m,k} = \|B_m\|^{-1} \text{tr}\left( (S_{k+1} - \mu^{-1} Y_{1,k})^T B_m \right)$$

where $\Omega = E - \Omega$, $E$ is a matrix whose elements are all 1, and $\alpha_{m,k}$ represents the $k$th update of the $m$th element of vector $\alpha$.

e) Updating $Y_1$, $Y_2$ and $\mu$.

$$Y_{1,k+1} = Y_{1,k} + \mu_k \left( R - S_{k+1} - Z_{k+1} \right)$$

$$Y_{2,k+1} = Y_{2,k} + \mu_k \left( S_{k+1} - \sum_{m=1}^{M} \alpha_m B_m \right)$$

$$\mu_{k+1} = \rho \mu_k$$

f) Iteration and outputting results.

Turn to the second step until $\|S_k - S_{k-1}\|_F / \|S_k\|_F \leq \eta$. Then, the recovery data is given by

$$\hat{r} = [\alpha_{1,k}, \alpha_{2,k}, \cdots, \alpha_{M,k}]^T$$

4. Performance of the proposed method

The IPIX data #19931118_162658_stareC0000 was used for validation of the proposed method. Figure 2(a) is the time-frequency plot of the original signal. It can be seen from the figure that there are many sea spikes, and it is very easy to cause false alarm for radar detection. Figure 2 (b) is a time-frequency plot with the spikes data set at 0. Although the number of spikes decreases, a large number of gate lobes appear in the spectrum, which will also cause false alarms to a certain degree. Figure 2 (c) is the result of data recovery by compressed sensing after eliminating sea spikes. As we can see from the figure, the sea spikes are recovered due to the sparsity of clutter, and the amplitude is even higher than the original signal. Figure 2 (d) is the result of the proposed method. Compared with figure 2 (b) and figure 2 (c), it can be found that most of the sea spikes have been eliminated, which can greatly improve the detection performance for weak targets in sea clutter.
Figure 2. The STFT of the sea clutter. (a) Sea clutter before processing. (b) The unqualified data are filled up 0. (c) The unqualified data are filled up by compressed sensing method. (d) The unqualified data are filled up by matrix completion method.

Besides, we add the simulated moving target into the measured sea clutter data to verify the proposed method. The target parameters are as follows: the radar pulse repetition frequency is 1000 Hz, the velocity is about 0.2 m/s. The frequency spectrum and time-frequency plot of the target range-gate are shown in figure 3(a) and (c), respectively. Figure 3(b) and (d) show the frequency spectrum and time-frequency plots of the data after processing by the sea spikes identification and matrix completion algorithm. It can be seen that the sea clutter is obviously weakened and the SNR is increased by about 7.4 dB. Thus, the proposed algorithm can effectively suppress the sea clutter in radar target and improve the SNR.

Figure 3. (a) Time-frequency plot of sea clutter data with simulated targets. (b) Time-frequency plot of the data after the proposed method. (c) Frequency spectrum plot of sea clutter data with simulated targets. (d) Frequency spectrum plot of the data after the proposed method.
5. Conclusion
In this paper, a method of sea clutter suppression based on the combination of spikes identification and matrix completion is proposed. Firstly, three important parameters are used to identify and eliminate sea spikes. Then, we construct the Hankel matrix after sea spikes removal, and the unqualified data are filled up by matrix completion method. The Lagrange multiplier method is used to solve the optimization problem. The simulation data and the measured data show that the method can effectively suppress the sea spikes and improve the SNR of weak targets on the sea surface.

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