A FBLP Based Method for Suppressing Sea Clutter in HFSWR

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Abstract- **This paper presents a novel method for suppressing sea clutter in the high frequency surface wave radar (HFSWR). The proposed algorithm is based on the combination of the linear prediction technique and the multidimensional feature of the sea clutter. In order to ensure the accurate suppression of the first order sea clutter, the feature detection matrix (FDM) has been defined and constructed. Eventually, the performance of the derived algorithm is testified by the experimental data.**

I. INTRODUCTION

High frequency surface wave radar, which is based on the surface wave diffraction, provides a unique capacity to detect the target far beyond the conventional microwave radar coverage. Therefore, it has been widely used in remote surveillance [1]. However, the sea clutter, constituting the major target detection background, has deteriorated the target detection performance significantly, since the amplitude of the first order sea clutter (Bragg Peak), which constructs the dominate component of the sea clutter, often masks the target. Besides, the Doppler frequency of the Bragg peak is similar with the targets with low velocity such as vessels [2]. Thus, how to suppress the strong sea clutter appears to be a fairly critical issue in order to enhance the capacity of HFSWR.

Recently, some methods have been put forward to address this problem. Specifically, after studying the time varying behavior of the two dominant narrowband frequency components in sea clutter echo, which corresponds to the Bragg peak Doppler frequency, Khan proposed a Hankel rank reduction method based on SVD to suppress the first order clutter [3-5]. However, the selection of the rank lacks in theoretical support and the computational complexity deteriorates as the rank increases, which limits the real time processing efficiency of the radar system. In [6-7], Root solved this problem through clutter cancellation, which is similar with the CLEAN algorithm, while the performance depends on the estimation accuracy of the sinusoid parameters. Inspired by the inverse synthetic aperture radar imaging technique, an idea combining the adaptive chirplet transform with one-class SVM has been developed to separate the target and the first order sea clutter because of the difference in the chirp rate [8-10]. While this algorithm fails as a matter of fact that the target could not be modeled as a chirp signal and the difference existed in the chirp rate appears too tinny to be identified. Besides other interference could also express the feature of a chirp signal; therefore making this method invalid in the real system.

Different from the present methods, the one described in this paper takes fully account of the multidimensional feature of sea clutter expressing in range and Doppler frequency, so as to maintain an accurate detection performance. Specifically, the signal model has been studied firstly. Afterwards, the sea clutter echo signal is decomposed into many sinusoidal signals by means of the forward backward linear prediction (FBLP) algorithm. Then, with the help of feature detection matrix, we could identify the signal parameters corresponding to the Bragg peaks, eventually we could make the corresponding sea clutter amplitude into zero in the temporal domain, realizing the purpose of suppressing the sea clutter.

II. THE PARAMETER ESTIMATION OF THE SEA CLUTTER SIGNAL

A. Sea Clutter Signal Model

In [12], it is argued that the dominant first order sea clutter exhibits a time varying characteristic which can be modeled with two narrowband signals, interpreted as two independent angular modulated components. And it could be demonstrated that the spectrum of such an angular modulated signal corresponds with that of the experimental sea clutter echo signal perfectly.

The time varying model could be expressed as the signals, composed of M superimposed complex sinusoids.

$$y(n) = \sum_{i=1}^{M} a_i e^{j(2\pi f_i n + \varphi_i)} \qquad (1)$$

Where a_i, f_i and φ_i are the corresponding signal parameters indicating amplitude, frequency, and phase respectively.

B. Forward and Backward Linear Prediction Method

The linear prediction based method could be used to estimate the parameters of sinusoidal signals, when the signal to noise is high enough, the parameters of which can be predicted as the weighted sum of L previous values.

$$y(n) = -\sum_{i=1}^{L} y(n-i) \cdot \alpha_i \qquad (2)$$

Where α_i stands for the weight coefficients.

Besides, so as to track the time varying behavior of the sea clutter, the coefficients of the prediction error filter must be estimated over short data segments so that the filter coefficients could be updated adaptively. And the prediction equation matrix, which is defined in [15], could be expressed as follows:

$$\begin{bmatrix} y(L) & y(L-1) & \cdots & y(1) \\ y(L+1) & y(L) & \cdots & y(2) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-1) & y(N-2) & \cdots & y(N-L) \\ y^*(2) & y^*(3) & \cdots & y^*(L+1) \\ y^*(3) & y^*(4) & \cdots & y^*(L+2) \\ \vdots & \vdots & \ddots & \vdots \\ y^*(N-L) & y^*(N-L+1) & \cdots & y^*(L) \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_L \end{bmatrix} = - \begin{bmatrix} y(L+1) \\ y(L+2) \\ \vdots \\ y(N) \\ y^*(1) \\ y^*(2) \\ \vdots \\ y^*(N-L) \end{bmatrix} \quad (3)$$

Simply, we denote as:

$$A \cdot \alpha = -y \quad (4)$$

And the weight coefficient matrix α could be estimated by the following equation:

$$\alpha = -A^{-1}y \quad (5)$$

As the linear equations above are over-determined, the total least square method is used to solve this problem [13], namely:

$$\alpha = -A^{-1}y = -(A^H A)^{-1}A^H y \quad (6)$$

Where H indicates the conjugate transpose. Simultaneously, the order of prediction error filter polynomial L could be determined by [14], which satisfies the inequality as follows:

$$M \le L \le (N - M/2)$$

That is to say, the order of prediction error filter should exceed the estimated signal number. Afterwards, we define frequency estimation matrix as:

$$f = [f_1, f_2, \cdots, f_M] \quad (7)$$

Where

$$f_k = (1, e^{-s_k}, e^{-2s_k}, \cdots, e^{-Ls_k}) \quad k = 1, 2, \cdots, M$$

It is easy to observe that each row in A is a linear combination of L linearly independent vectors in f_k. That is to say, the rank of A is M as long as A has at least M rows. Thus, the dimension of null space in A is $L+1-M$ dimension. In addition, as α_k lies in the null space of A, we have:

$$\alpha_0 + \alpha_1 e^{-s_k} + \alpha_2 e^{-2s_k} + \cdots + \alpha_L e^{-Ls_k} = 0 \quad (8)$$

The signal frequency could be estimated from the roots of (8). Besides, in order to obtain the amplitude and initial phase of each signal, we define the following matrix equation as:

$$\begin{bmatrix} \beta_1^0 & \beta_2^0 & \cdots & \beta_M^0 \\ \beta_1^1 & \beta_2^1 & \cdots & \beta_M^1 \\ \vdots & \vdots & \ddots & \vdots \\ \beta_1^{N-1} & \beta_2^{N-1} & \cdots & \beta_M^{N-1} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_M \end{bmatrix} = \begin{bmatrix} y(1) \\ y(2) \\ \vdots \\ y(N) \end{bmatrix} \quad (9)$$

Simply, we denote as:

$$R \cdot h = Y \quad (10)$$

Where $\beta_i^k = e^{j2\pi f_i k/f_s}$, $h = (R^H R)^{-1}R^H Y$, f_s represents the sampling frequency and N is the sampling number. In addition, the amplitude and initial phase could be obtained after taking the manipulation of the absolute and angular value of h respectively.

$$a_k = |h_k| \quad k = 1, \cdots, M \quad (11)$$

$$\varphi_k = acrtan(Im(h_k)/Re(h_k)) \quad k = 1, \cdots, M \quad (12)$$

Where $Im(\cdot)$ and $Re(\cdot)$ represents taking the image and real part of the signal respectively.

C. The Multidimensional Feature of the First Order Sea Clutter

The detection and extraction of the first order sea clutter appears a much tougher problem especially in the background with the ocean current, the ionosphere interference and atmosphere noise, resulting in the Doppler shift and split to the Bragg peak. Therefore, it is hardly to approach a desiring clutter suppressing performance without taking the characteristics of sea clutter into consideration.

Actually, according to Fig. 1, it is straightforward to observe that the first order of sea clutter expresses a multi-dimension feature, not only in the range bins but also in the Doppler bins, which could be used to provide more effective and accurate identification of Bragg peak and therefore make it possible to suppress the sea clutter without canceling the target by mistake.

After studying many batches of experimental data, we could conclude the spectral multi-dimensional feature of the Bragg peak as follows:

1) Given a single range bin, the Doppler frequency of the sea clutter is nearly symmetry about the zero frequency. And the ocean current would give rise to the Doppler shift to the first order sea clutter, while the offset towards the positive and negative Bragg peaks is consistent.

2) Given the continuous range bins, the position of the Bragg peaks maintain fairly good continuity along the continuous range bins which could be evidently observed in Fig.1.

3) As for the spectral magnitude, the first order sea clutter exhibits a local maximum feature, which makes it possible to estimate the clutter parameter exactly.

4) In some range bin, sea clutter may appear to be dominant in either the positive or the negative Doppler frequency. That is to say, the sea clutter is asymmetric in some range bin.
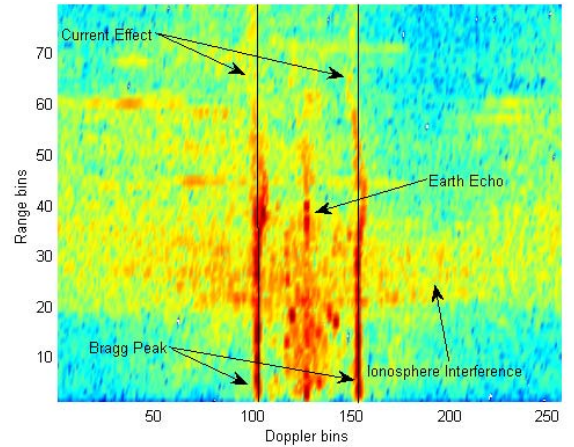

Figure 1. The range and Doppler map of the sea clutter in HF surface wave radar including different kinds of clutter and interference.

III. SUPPRESSION OF THE FIRST ORDER SEA CLUTTER

A. The Derivation of the Algorithm

The complexity of first order sea clutter distribution prompts us to take the multi-dimension feature into account to ensure a robust identification performance. Based on which, we would like to obtain each signal domain parameters so that we could

suppress the sea clutter according to the feature expressed in Fig.1.

However, in order to use the FBLP method, the number of interested signals should be determined firstly. Instead of conventional signal number estimation method [11], we put forward a SNR criterion to limit the number of estimated signals in a simple way. Specially, we suppose S as the number of signals, and the total power of sea clutter echo could be obtained by

$$P = \sum_{n=1}^{N} |y_n|^2 \tag{13}$$

Where N is the length of signal sampling points. Then the power of each signal and noise is:

$$P_k = \sum_{n=1}^{N} |a_k \beta_k^{n-1}|^2 = |a_k|^2 \frac{1 - |\beta_k|^{2N}}{1 - |\beta_k|^2} \quad (k=1,2,\cdots,S) \tag{14}$$

$$P_{nosie} = \sum_{n=1}^{N} \left| y_n - \sum_{k=1}^{S} a_k \beta_k^{n-1} \right|^2 \tag{15}$$

The SNR of each signal is given by

$$SNR_k = P_k / P_{noise} \quad (k=1,2,\cdots,S) \tag{16}$$

The number of signal M could be determined by letting the SNR_k exceed a fixed threshold, thus reducing the number of the estimated signals to a large extent.

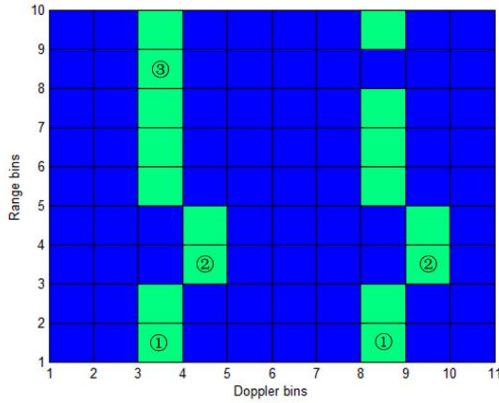Figure 2.The schematic illustration of sea clutter spatial distribution

As a matter of fact, the feature of sea clutter expressed in Fig.1 could be simplified as Fig.2. In order to detect the location of the first order sea clutter distributed as in Fig. 2, a clever way is proposed to get around this based on the derivation of Feature Detection Matrix (FDM).

In terms of the sea clutter signal model defined in (1), the frequency corresponding to each signal could be estimated from the roots of polynomial. Now that the position of the Bragg peak exhibits a symmetric feature, even when the influence of ocean current exits; Therefore, the detection of the Bragg peak could be summarized as the maximum symmetry identification.

So as to construct the FDM, we calculate the relative offset towards the theoretical Bragg frequency f_{MB} by manipulating as follows:

$$f_i' = \begin{cases} f_i + f_{MB} & f_i < 0 \\ f_i - f_{MB} & f_i > 0 \end{cases} \tag{17}$$

Where $f_{MB} = \sqrt{g\pi / \lambda}$, λ indicates the wave length , g is the acceleration of gravity. Afterwards, we define the Feature Detection Matrix as:

$$F = \begin{bmatrix} f(1,2) & f(1,3) & f(1,4) & \cdots & f(1,M) \\ 0 & f(2,3) & f(2,4) & \cdots & f(2,M) \\ 0 & 0 & f(3,4) & \cdots & f(3,M) \\ 0 & 0 & 0 & \cdots & f(M-1,M) \end{bmatrix} \tag{18}$$

Where $f(i,j) = |f_i' - f_j'|$ $(i = 1,\cdots,M-1; j = i+1,\cdots,M)$

For the upper triangular matrix F , we search for the minimum value, the coordinates of which correspond with the Doppler frequency in (7) satisfying the best symmetry. We denotes the coordinates as (m,n) .Based on the feature proposed previously, we suppose that the Doppler frequency detected is in conformity with that of the first order sea clutter. Afterwards, we let the amplitude of a_m and a_n zero, which correspond to the detected Doppler frequency f_m and f_n . Then the residual $M-2$ signals would be used to reconstruct the time series data with the help of (7), (11) and (12). The new time series data are the one with the clutter signal suppressed.

Additionally, given the third condition illustrated in Fig.2, the method derived would be revised by taking the adjacent range bin as a reference now that the sea clutter maintains continuous along the range dimension.

B. The Procedure of the Algorithm

Based on the analysis mentioned before, the procedures of the algorithm could be interpreted as follows:

1) Construct the prediction equation matrix in (3) based on the sea clutter echo from each range bin and estimate the sinusoidal parameters including the amplitude, frequency and initial phase under the assumption of the signal model in (1).

2) According to the SNR criterion, we determine the number of the interest signals according to the SNR threshold.

3) Construct the feature detection matrix F in (18) based on the frequency estimation matrix in (7) and we search F for the values below a symmetric threshold. Then we choose the coordinates of the minimum value as the index of the first order sea clutter.

4) If there is not a value satisfying the symmetric threshold, we would compare it with the reference range bin to cancel the sea clutter failing to be dominant both in the negative and positive Doppler bins (the third condition in Fig.2).

5) We make the amplitude of the signals corresponding to the index obtained in procedure 3) and 4) to be zero and then reconstruct the signals after suppression with the residual parameters.

IV. EXPERIMENT AND RESULT ANALYSIS

The performance of the algorithm could be testified with the experimental data in the HFSWR. Fig.3 illustrates the contrast result before and after suppression.

It is obvious to observe that the Bragg peak is fairly evident in the range and Doppler map of the experimental sea clutter echo data. While the dominant first order sea clutter is nearly canceled by virtue of the algorithm derived, which can be

easily observed in Fig.4. It is noticeable to spot that the suppressed signal still maintains the characteristics of other clutter and interference so as to ensure the validity of other clutter and interference algorithms. Besides, as the method is mainly based on the symmetry detection, the signal of the target would be reserved, even when the Doppler frequency of target and the first order sea clutter is closed in the Doppler.
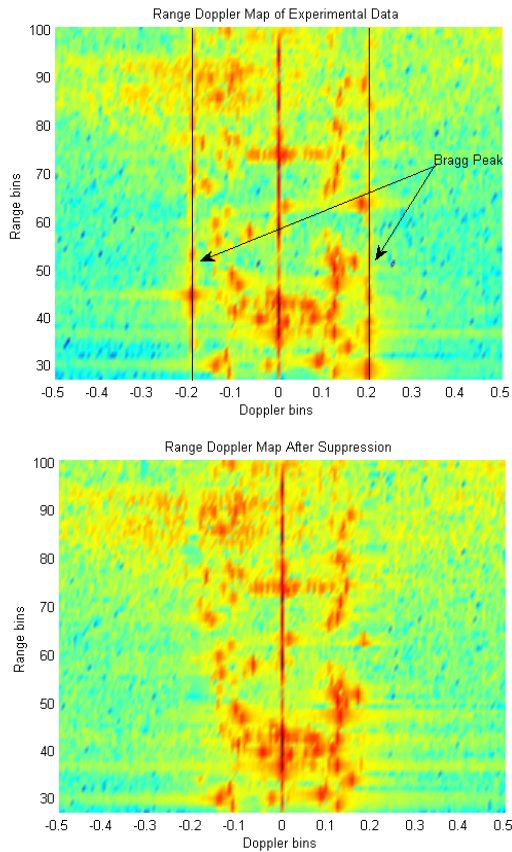

Figure 3. The contrast result before and after the first order sea clutter suppression based on the experimental data.
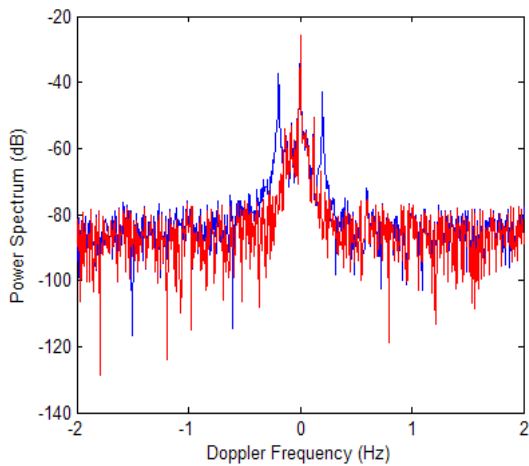

Figure 4. The suppression of the first order sea clutter in a certain range bin.

V. CONCLUSIONS

It has been demonstrated that the method, based on the combination of forward and backward linear prediction and the multidimensional feature of sea clutter, can identify the first order sea clutter accurately even in the complicated detection background.

While the feature of sea clutter depends on the sea state and the ocean current field significantly, the method present would work only when the sea clutter is in conformity with the feature proposed. And the algorithm also exits some limitations especially when the peak of the first order sea clutter is splitting, which should be improved in the later work.

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