A Novel Spread Clutter Suppression Algorithm based on Multiple-Dimension Matched Field Processing Technique

Kun Lu and Xingzhao Liu

Department of Electronic Engineering, Shanghai JiaoTong University, Shanghai, 200030,China
Email: mimimomo@sjtu.edu.cn, Xzhliu@sjtu.edu.cn

ABSTRACT

High-frequency skywave over-the-horizon radar (OTHR) can provide a wide coverage over the horizon by means of the refraction within the ionosphere. However due to the complex propagation conditions of electromagnetic wave in HF band, many disadvantageous effects, such as phase path contamination and multimode propagation, will cause the target submerged by the neighboring spread clutter. In this paper, the spread effect of identical clutter backscattered from the adjacent dwell illumination region (DIR) has been discussed. On the basis of the existing matched field processing (MFP) method developed for this problem, the multiple-dimension cross-relation method using the multiple channel signals has been proposed and used to the temporal data directly. Experimental simulations are given to demonstrate that the improved method is effective to suppress the spread clutter.

1. INTRODUCTION

Doppler processing is a key step of High-frequency skywave over-the-horizon radar target detection. However, due to the unavoidable multipath effect in skywave propagation mode, radar echoes backscattered by land or sea arrive at the received array from different rays and cause the multipath clutter. Usually the energy of target echoes is much smaller than those of land or sea clutter. Therefore when the Doppler frequency of targets is adjacent to those of land or sea clutter, the peaks corresponding to targets maybe smear by dominated clutter in Doppler spectrum. It is known as clutter masking effect (CME).

When several propagated paths existed and they are with close Doppler frequencies, there is a 'clutter strip' with wide bandwidth in Doppler spectrum. It looks as a spread single signal spectrum and unacceptable for target detection. Especially for aircraft target detection whose coherent integration time (CIT) is short, it is sensitive for clutter energy. This kind of spread 'clutter strip' can submerge easily weak target spectral peaks.

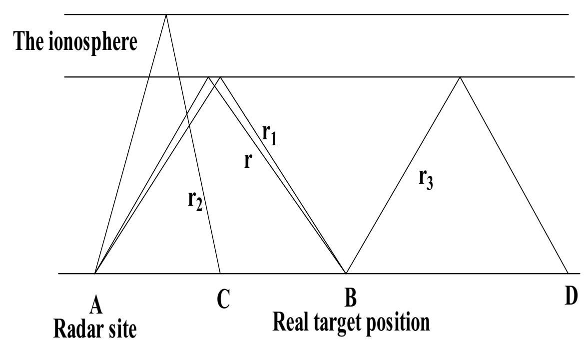

Fig.1. Three kinds of spread clutter

For different spread clutter mechanism, several clutter suppression algorithms have been proposed [1]. As shown in Fig.1, the first kind of spread clutter is 'separated clutter' (Ray r_3 in Fig.1). It has the same slant range as the normal target echo (Ray r in Fig.1) but derives from the range ambiguity. So it is also known as the range-folded clutter. The separated clutter approaches the received array by multiple-hop propagated mode and can be eliminated by using nonrecurrent signal transmitting waveform [2]. In this algorithm, transmitting waveform in different dwell time has a different quadratic phase term. And after traditional range-Doppler transform, the clutter propagated in multiple-hop mode has a frequency shift related to those propagated in single-hop mode. The size of frequency shift is determined by the coefficient of quadratic phase term and the number of hop. Thus by the frequency shift the multiple-hop clutter can be resolved with the single-hop clutter.

The second kind of clutter is known as 'proximate clutter' (Ray r_2 in Fig.1). It also has the same slant range (i.e. time delay) as the normal target echo but has different received elevation since they refract by different ionospheric layer. Selecting the operation frequency, which is only suitable for certain single propagation mode in real time by frequency management system (FMS), we can suppress this kind of clutter [3]. Another method to eliminate this kind of clutter is applying an array scanning in elevation dimension. By zeroing the elevation angle of 'proximate clutter' in elevation array pattern, adaptive clutter cancellation can also be realized.

The last kind of clutter is 'coincident clutter' (Ray r_1 in Fig.1), which will be discussed at length in this paper. It has similar slant range and elevation angle of arrival as the target echo. Since the propagation media is highly correlated in time and space, some algorithms based on time, space or joint space-time processing techniques have been proposed [4][5][6].

In this paper, on the basis of the reference [4] we improve the matched field processing technique. By using multiple input signals, the cross-relation (CR) blind identification algorithm is extended to multiple dimensions. Better estimation performance can be obtained by this improvement. Some simulation results and analysis are also given to demonstrate the proposed method.

2. MULTIPLE-DIMENSION MATCHED FIELD PROCESSING TECHNIQUE

In the nonstationary ionospheric propagation condition, the received clutter signal is modulated by a time-varying Doppler spread sequence $a(n)$. It can be expressed as

$$\boldsymbol{x}_i(\boldsymbol{n}) = \boldsymbol{a}(\boldsymbol{n}) \cdot \boldsymbol{c}_i(\boldsymbol{n}) + \boldsymbol{w}_i(\boldsymbol{n}), \qquad n = 0,1,\ldots, N-1 \tag{1}$$

where $\boldsymbol{x}_i(\boldsymbol{n})$ is the received signal in i-th processing bin, $1 \le \boldsymbol{i} \le \boldsymbol{M}$, $\boldsymbol{M}$ is the maximum available processing bin number, $\boldsymbol{c}_i(\boldsymbol{n})$ is the clutter echo sequence without spread in i-th processing bin, $\boldsymbol{w}_i(\boldsymbol{n})$ is noise sequence and $\boldsymbol{N}$ is the snapshot number in a dwell time. Since the ionospheric variation has highly correlation in time and space, we suppose the data in adjacent processing bin are modulated by the same ionospheric spread sequence, where the processing bin can apply the adjacent range bin or azimuth bin. For simplicity and without loss of generality, in this paper data from adjacent range bins are used. Simultaneously the target echo is also modulated by the same sequence and spread. The spread clutter and target smear across in Doppler spectrum, detection is difficult to accomplish.

If the spread sequence is considered as impulse response of a wireless multipath channel, the cross-relation (CR) algorithm applied in blind identification can be introduced to estimate the sequence [4]. When the noise is ignored, we have

$$\boldsymbol{c}_i(\boldsymbol{n}) \cdot \boldsymbol{x}_j(\boldsymbol{n}) = \boldsymbol{c}_j(\boldsymbol{n}) \cdot \boldsymbol{x}_i(\boldsymbol{n}), \quad 1 \le \boldsymbol{i} \ne \boldsymbol{j} \le \boldsymbol{M} \tag{2}$$

And multiplying the both sides of the above expression with the same term,

$$\begin{aligned} &\boldsymbol{c}_i(\boldsymbol{n}) \cdot \boldsymbol{x}_1(\boldsymbol{n}) \cdots \boldsymbol{x}_{i-1}(\boldsymbol{n}) \cdot \boldsymbol{x}_{i+1}(\boldsymbol{n}) \cdots \boldsymbol{x}_M(\boldsymbol{n}) \\ &\quad = \boldsymbol{c}_j(\boldsymbol{n}) \cdot \boldsymbol{x}_1(\boldsymbol{n}) \cdots \boldsymbol{x}_{j-1}(\boldsymbol{n}) \cdot \boldsymbol{x}_{j+1}(\boldsymbol{n}) \cdots \boldsymbol{x}_M(\boldsymbol{n}) \end{aligned} \tag{3}$$

Now we define

$$\boldsymbol{P}_i(\boldsymbol{n}) = \boldsymbol{x}_1(\boldsymbol{n}) \cdot \boldsymbol{x}_2(\boldsymbol{n}) \cdots \boldsymbol{x}_{i-1}(\boldsymbol{n}) \cdot \boldsymbol{x}_{i+1}(\boldsymbol{n}) \cdots \boldsymbol{x}_M(\boldsymbol{n}) \tag{4}$$

then

$$\boldsymbol{c}_i(\boldsymbol{n}) \cdot \boldsymbol{P}_i(\boldsymbol{n}) = \boldsymbol{c}_j(\boldsymbol{n}) \cdot \boldsymbol{P}_j(\boldsymbol{n}), \quad 1 \le \boldsymbol{i} \ne \boldsymbol{j} \le \boldsymbol{M} \tag{5}$$

Transform the formula (5) to the frequency domain, we get

$$\boldsymbol{c}_i(\boldsymbol{u}) \otimes \boldsymbol{P}_i(\boldsymbol{u}) - \boldsymbol{c}_j(\boldsymbol{u}) \otimes \boldsymbol{P}_j(\boldsymbol{u}) = 0, \quad 1 \le \boldsymbol{i} \ne \boldsymbol{j} \le \boldsymbol{M} \tag{6}$$

where $\otimes$ denotes circular convolution, $\boldsymbol{P}_i(\boldsymbol{u})$ and $\boldsymbol{c}_i(\boldsymbol{u})$ are the Fourier transform of $\boldsymbol{P}_i(\boldsymbol{n})$ and $\boldsymbol{c}_i(\boldsymbol{n})$ respectively. Rewriting (6) with the vector expression, we have

$$\boldsymbol{U} \cdot \boldsymbol{c} = 0 \tag{7}$$

where

$$\boldsymbol{U} = \begin{bmatrix} \boldsymbol{G}_1 \\ \boldsymbol{G}_2 \\ \vdots \\ \boldsymbol{G}_{M-1} \end{bmatrix} \text{ and } \boldsymbol{c} = \begin{bmatrix} \boldsymbol{c}_1 \\ \boldsymbol{c}_2 \\ \vdots \\ \boldsymbol{c}_M \end{bmatrix} \tag{8}$$

thereinto

$$\boldsymbol{G}_i = \begin{bmatrix} 0 & \cdots & \boldsymbol{P}_{i+1} & -\boldsymbol{P}_i & 0 & \cdots & 0 \\ 0 & \cdots & \boldsymbol{P}_{i+2} & 0 & -\boldsymbol{P}_i & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \underbrace{0 \quad \cdots}_{i} & & \underbrace{\boldsymbol{P}_M \quad 0 \quad 0 \quad \cdots \quad -\boldsymbol{P}_i}_{M-i} \end{bmatrix}, \quad 1 \le \boldsymbol{i} \le \boldsymbol{M} \tag{9}$$

and

$$\boldsymbol{P}_i = \begin{bmatrix} \boldsymbol{P}_i(0) & \boldsymbol{P}_i(\boldsymbol{N}-1) & \boldsymbol{P}_i(\boldsymbol{N}-2) & \cdots & \boldsymbol{P}_i(1) \\ \boldsymbol{P}_i(1) & \boldsymbol{P}_i(0) & \boldsymbol{P}_i(\boldsymbol{N}-1) & \cdots & \boldsymbol{P}_i(2) \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \boldsymbol{P}_i(\boldsymbol{N}-1) & \boldsymbol{P}_i(\boldsymbol{N}-2) & \boldsymbol{P}_i(\boldsymbol{N}-3) & \cdots & \boldsymbol{P}_i(0) \end{bmatrix} \tag{10}$$

$$\boldsymbol{c}_i = \left(\boldsymbol{c}_i(0) \;\; \boldsymbol{c}_i(1) \cdots \cdots \boldsymbol{c}_i(\boldsymbol{N}-1)\right)^{\boldsymbol{T}}, \quad 1 \le \boldsymbol{i} \le \boldsymbol{M} \tag{11}$$

When the noise exists, the formula (3) does not hold. But the estimation of clutter sequence without spread can be realized by the following expression

$$\hat{\boldsymbol{c}} = \arg\max_{\boldsymbol{c}} \boldsymbol{c}^{\boldsymbol{T}} \cdot \left(\boldsymbol{U}^{\boldsymbol{T}} \boldsymbol{U}\right) \cdot \boldsymbol{c} \tag{12}$$

Obviously, the above formula needs to solve a multiple dimension maximum problem and causes heavy computing load. It is not feasible to practical application.

To simplify the computation, some prior knowledges about the unspread clutter are used to model the clutter spectrum. Here a low rank expression of sea clutter model is applied

$$\boldsymbol{c}_i(\boldsymbol{n}) = \sum_{\boldsymbol{l}=1}^{\boldsymbol{L}} \boldsymbol{k}_{\boldsymbol{l},i} \psi_{\boldsymbol{l}}(\boldsymbol{n}) \tag{13}$$

where $\psi_i(\boldsymbol{n})$ are determined by dominated eigenvectors in correlation matrix of the unspread clutter, $\boldsymbol{L}$ is the rank of the unspread clutter model, and $\boldsymbol{k}_{\boldsymbol{l},\boldsymbol{i}}$ are corresponding model coefficients of each order. The Fourier transform of both sides of (13) can be expressed as

$$\boldsymbol{c}_i(\boldsymbol{u}) = \sum_{\boldsymbol{l}=1}^{\boldsymbol{L}} \boldsymbol{k}_{\boldsymbol{l},i} \psi_{\boldsymbol{l}}(\boldsymbol{u}) \tag{14}$$

Thus

$$\boldsymbol{c} = \Psi \cdot \boldsymbol{K} \tag{15}$$

where

$$\Psi = \underbrace{\begin{bmatrix} \tilde{\psi} & 0 & \cdots & 0 \\ 0 & \tilde{\psi} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \tilde{\psi} \end{bmatrix}}_{M}, \text{ and } K = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_M \end{bmatrix} \tag{16}$$

$$k_i = \left(k_{i,1} \ k_{i,2} \cdots \cdots k_{i,L}\right)^T \qquad 1 \le i \le M \tag{17}$$

$$\tilde{\psi} = \begin{bmatrix} \psi_1(0) & \psi_1(1) & \cdots & \psi_1(N-1) \\ \psi_2(0) & \psi_2(1) & \cdots & \psi_2(N-1) \\ \cdots & \cdots & \cdots & \cdots \\ \psi_L(0) & \psi_L(1) & \cdots & \psi_L(N-1) \end{bmatrix}_{L\times N} \tag{18}$$

where $\psi_l(u)$ is the Fourier transform of $\psi_l(n)$, $1 \le l \le L$.

Therefore by introducing the clutter model, the multiple-variables maximum problems is transformed to a one-variable maximum problem,

$$\hat{K} = \arg\max_{K} K^T \Psi^T U^T U \Psi K. \tag{19}$$

This problem can be solved by calculating the minimum eigenvector of matrix $\Psi^T U^T U \Psi$.

After obtaining the estimate of K, the unspread clutter sequence $c_i(u)$ can be calculated in theorem by (15). However, this result contains only information of clutter since it derived from the prior clutter model. Target echo and noise are suppressed in the same time. To restore the original target echo and clutter, matched field processing is used to compensate the Doppler spread modulation using the estimate of Doppler spread sequence.

First, we get the estimate of unspread clutter sequence $\hat{c}_i(u)$ from (15), and then construct a circular convolution matrix $\hat{C}$ with the similar method as (9) and (10). Thus the Doppler spread sequence $\hat{a}$ can be estimated by the least squares method

$$\hat{a} = \left(\hat{C}^T \hat{C}\right)^{-1} \hat{C}^T x \tag{20}$$

where $\hat{a}$ is the estimate of discrete Fourier transform of Doppler spread sequence $a(n)$. And x is given as

$$x = \begin{bmatrix} x_1 & x_2 & \cdots & x_M \end{bmatrix}^T \tag{21}$$

where x_i is the Fourier transform of sequence $x_i(n)$.

In matched field processing to suppress the sidelobe of spread target echo spectrum, a Chebyshev windowing function is designed. The resultant Doppler spectrum is expressed as

$$S_i(\omega) = \left| \sum_{n=1}^{N} \hat{\omega}_i(n) \cdot x_i(n) \cdot \ell^{j\omega n} \right|^2, \qquad 1 \le i \le M \tag{22}$$

where $x_i(n)$ is the temporal data in the i-th range bin, $\hat{\omega}_i(n)$ is the Chebyshev windowing coefficient of the i-th range bin which satisfies

$$\Gamma(0) = 1, \qquad \frac{d\Gamma}{d\omega}(0) = 0 \tag{23}$$

where

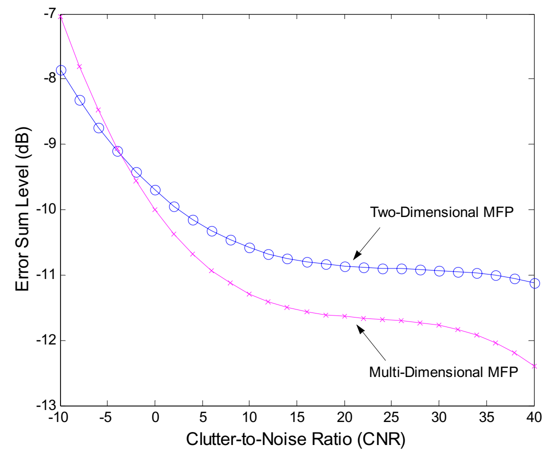

Fig.2 Performance comparison between two-dimension and multiple-dimension matched field processing technique

$$\Gamma(\omega) = \sum_{n=0}^{N-1} \hat{\omega}_i^*(n) \cdot \hat{a}(n) \ell^{j\omega n} \tag{24}$$

Since the echoes in M adjacent range bin are supposed to be modulated by the same Doppler spread sequence, therefore for the range bins in slant range it can be considered as a sliding window with length M.

3. CLUTTER SUPPRESSION ALGORITHM

On the basis of the above section, the detailed clutter suppression algorithm can be described as following:

1. Determining the maximum available processing bin M according to ionospheric time and spatial correlation.
2. Determining the proper rank L of sea clutter model.
3. Constructing $P_i(n)$ from (4) and transform it to frequency domain $P_i(u)$
4. Constructing matrix Ψ from (16) and (18) with clutter model.
5. Getting matrix U from $P_i(u)$ according to (8) and (9).
6. Decomposing matrix $\Psi^T U^T U \Psi$ and let $\hat{K}$ be the eigenvector corresponding to the minimum eigenvalue.
7. Getting $\hat{c}_i(u)$ and $\hat{C}$ with the estimated $\hat{K}$.
8. Getting the estimate of the Doppler spread sequence $\hat{a}(u)$ from (20).
9. Transforming $\hat{a}(u)$ to the temporal domain by inverse FFT and getting $\hat{a}(n)$.
10. Getting the processing result after spread clutter suppression from formula (22) to (24).

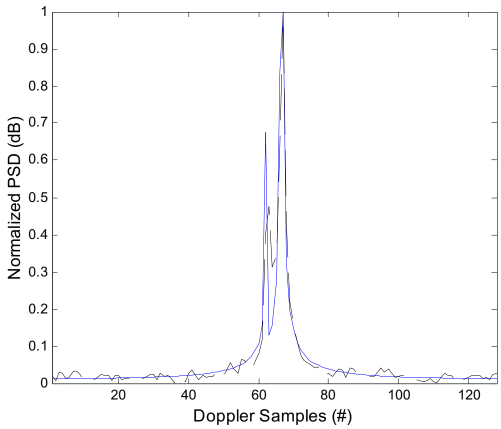

Fig. 3 The estimate of Doppler spread sequence (M=3) with real over-the-horizon radar data.

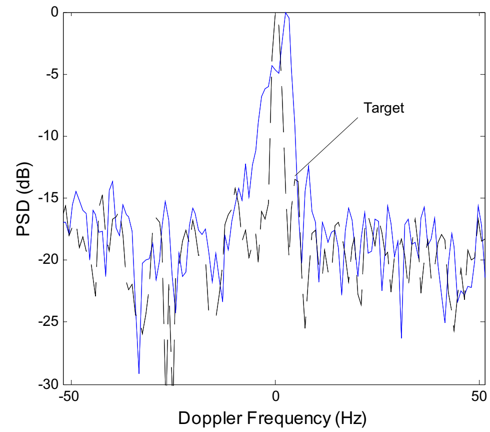

Fig.4 The Doppler spectrum before and after spread clutter suppression with MFP(M=3).

4. EXPERIMENTAL SIMULATIONS AND ANALYSIS

In this test, we let $\boldsymbol{M} = 3$ and the rank of clutter model $\boldsymbol{L} = 3$. In the sea clutter model, two components are symmetrical about zero in Doppler spectrum and the third one is located at zero. The ionospheric spread model is given as follows:

$$a(n) = \exp\left(j2\pi\left(f_1 n T_{sw} + \beta_1 \sin\left(2\pi\alpha_1 n T_{sw}\right)\right)\right) + \exp\left(j2\pi\left(f_2 n T_{sw} + \beta_2 \cos\left(2\pi\alpha_2 n T_{sw}\right)\right)\right) \quad (25)$$

The statistical performance analysis is given in Fig.2. The result of multiple-dimension matched field processing technique is compared with that of two-dimension. Here we execute Monte-carlo simulation of 200 times and the normalized error sum is used as the performance criteria. The 'o'-marked line is the performance curve of two dimension processing while the 'x'-marked line is the performance curve of multiple-dimension ($\boldsymbol{M} = 3$). When the CNR is high, the multiple-dimension processing is much better.

The estimate of Doppler spread sequence is shown in Fig.3. In our test, the real skywave Doppler spread sequence is not available. So we add artificial Doppler spread sequence to the real unspread echo data. The Doppler spread sequence is given as (25). Here the phase variation is neglected, that is $\beta_1 = \beta_2 = 0$, $\boldsymbol{f}_1 = 0.012$ and $\boldsymbol{f}_2 = -0.022$.

It is clear that there exists two propagated path in Fig.4. The dashed line is the estimate of Doppler spread sequence in frequency domain with multiple-dimension MFP method.

In Fig.5, the Doppler spectrum before spread clutter suppression is represented by the solid line while the dashed one is the spectrum after clutter suppression. Obviously after the clutter suppression the spectral peaks sharpen and the target adjacent to the 'clutter strip' is visualized.

5. CONCLUSIONS

The simulation results demonstrate that the multiple-dimension MFP method has better estimation performance than conventional two-dimension MFP method. When the used processing bin increases, the performance will be improved further but cause to heavy computational burden. An accurate clutter model is also help to achieve better estimation accuracy.

6. REFERENCES

[1] S. J. Anderson, F. J. Mei, and P. N. Jiao, "Enhanced OTHR ship detection via dual frequency operation," *Proc. 2001 CIE International Conf. on radar,* Beijing, China, Oct, 2001, pp. 85-89.

[2] M. P. Hartnett, J. Clancy, and R. J. Denton, Jr., "Utilization of a nonrecurrent waveform to mitigate range-folded spread Doppler clutter," *Radio Sci*., vol.33, pp. 1125-1133, July-Aug, 1998.

[3] R.I. Barnes, "Automated propagation advice for OTHR ship detection," *IEE Proceedings - Radar, Sonar and Navigation,* vol. 143, no. 1, 1996, pp. 53-63.

[4] K. Harmanci and J.Krolik, "Matched window processing for mitigating over-the-horizon radar spread Doppler clutter," *Proc. ICASSP '99,* Phoenix, AZ, USA, Mar 1999, pp. 2789-2792.

[5] K. Harmanci and J.Krolik, "Adaptive temporal processing for equatorial spread Doppler clutter suppression," *Proc. ICASSP '00,* Istanbul, Turkey, July 2000, pp. 3041-3044.

[6] S. Kraut, K. Harmanci, and J.Krolik, "Space-time adaptive processing for over-the-horizon spread-Doppler clutter mitigation," *Proc. IEEE Sensor Array and Multichannel Signal Processing Workshop 2000*, Cambridge, MA , USA, Mar 2000, pp. 245 –249.