Research on employment of adaptive beamformer based on weight iterative algorithm in suppressing radio frequency interferences

JP1.13

Ren-Zhou Gui
Dept. of electronic information
Wuhan University
Wuhan, China
rzgui@126.com

Zi-Jie Yang
Dept. of electronic information
Wuhan University
Wuhan, China
ZJY43117@126.com

Abstract—By comparing the disadvantages and advantages of conventional algorithms of adaptive beamformer, we put forward an adaptive beamformer based on weight iterative algorithm for suppressing radio frequency interference (RFI), according to the distributing properties of RFI in different range cell. We get the initial weight vector of the adaptive beamformer by utilizing the algorithm of minimum variance distortionless response (MVDR). The other weight vectors are computed by the algorithm of linearly constrained minimum variance (LCMV) based on the last time weight vector. The covariance matrix of the two algorithms, i.e. MVDV and LCMV, are constructed with the array snapshots in the far range cells which have not useful radar echo. Thus the free degree of antenna array is increased. The feasibility of the adaptive beamformer is proved by utilizing it to process the actual radar data.

Keywords—**LCMV, MVDR, RFI, adaptive beamformer**

I. INTRODUCTION

High frequency ground wave radar works usually within the frequency range of 3~30MHz in which there are serious RFI. How to suppress the RFI efficiently and improve the detective ability of high frequency ground wave radar is an important problem [1].

At present, we can suppress RFI in the three fields, i.e. time field, frequency field and space field. The paper discusses the problem of suppressing RFI in space field. As for an antenna array, all kinds of disturbances such as intended disturbance, the disturbance of adjacent devices and clutter disturbance can enter from the mainlobe of antenna array, at the same time, they can come in from the sidelobes of antenna array. The first thing which we should consider is to minimize the influences of disturbances which come in from sidelobes. In the frequency range in which high frequency ground wave radar works, there exist many RFIs, which are particularly serious at night. The power of RFI is 70~80dB greater than that of useful radar echo. It is difficult to design the antenna, whose sidelobe is lower than -30dB~-40dB, according to the contemporary technology. Even if useful signal comes in from mainlobe and RFI enters from sidelobe, the power of RFI is 30~50dB or more greater than the power of useful signal [2]. That makes it difficult to detect useful radar signal correctly. If the direction of RFI is stable, we can design a corresponding pattern of antenna array so that the great null of pattern can appear in the direction of RFI. However, the direction of RFI is different from time to time. So we hope the null of pattern can change according to the direction of RFI automatically. So we propose a special method of adaptive beamformer for suppressing RFI. The adaptive beamformer can be constructed with antenna array having the ability of signal processing, which can provide more free degree to designer. The adaptive beamformer can allocate the high gain to the desired direction and adjust low null to the direction of RFI for the purpose of suppressing or reducing RFI. So the detective ability of radar system can be enhanced.

II. THE SELECTING SUITABLE ALGORITHM OF ADAPTIVE BEAMFORMER

The conventional algorithms of adaptive beamformer are listed as follows, multiple sidelobe canceller (MSC), use of reference signal, maximization of signal to noise ratio (MSNR), linearly constrained minimum variance beamforming (LCMV), minimum variance distortionless response (MVDR). Different algorithms have different properties.

1.1 MSC beamformer

MSC is the earliest algorithm of beamformer. A MSC beamformer includes a main antenna with high gain and one or a few auxiliary antennas. Its function is to cancel the part of disturbance in the main antenna by adjusting the weights of auxiliary antennas. The desired signal, which occupies part of the output power, can be weakened along with the minimization of the whole power by selecting suitable weights of auxiliary antennas. When the SNR is high, the useful signal is weakened seriously since it occupies greater part of the whole power. So MSC is a useful method when SNR is low, because the optimization of weights has little influence on useful signal.

1.2 Beamformer of using reference signal

If the reference signal is known, the weights of beamformer, which are determined by the autocorrelation matrix of input signal and the crosscorrelation matrix between the input signal and reference signal, can be computed by minimizing the difference between the output of linear combination and the reference signal. But it is difficult to select reference signal.

1.3 MSNR beamformer

The weight of beamformer based on MSNR algorithm is selected by ensuring the biggest SNR. We should know the autocorrelation matrixes of noise and signal before using the MSNR algorithm.

1.4 LCMV beamformer

The algorithms which is concerned with above are not suitable for many applications. The useful signal can be weakened in the MSC algorithm, because its power can not be known in advance. The lack of knowledge about reference signal limits the utilization of beamformer of using reference signal. It is difficult to estimate the autocorrelation matrixes of noise and signal in the application of MSNR beamformer. All the limits can be overcome by using LCMV algorithm. We allow the useful signal go through with a certain phase and gain, while preventing the disturbances whose directions are different from that of useful signal from coming in. By doing that and also by minimizing the output power of the beamformer, we can acquire the weights of LCMV beamformer. So using LCMV beamformer has the advantage of suppressing the disturbances coming from the other directions while preserving the useful signal.

1.5 MVDR beamformer

When beamformer has consistent response in the direction of useful signal, LCMV algorithm becomes MVDR algorithm. The details of MVDR algorithm can be described as follows. Using MVDR algorithm to suppress disturbances as greatly as possible, we do not have to know the direction of disturbance or powers of useful signal and white noise, we need only the direction of useful signal. The limit of MVDR algorithm can be expressed by the formulas

$$\min P(W) = \min(W^H R_{xx} W) \qquad \text{（1）}$$

$$W^H a(\theta_0) = 1 \qquad \text{（2）}$$

That is to say, we minimize the output power of MVDR beamforemer, while ensuring that the gain of the useful signal equals one in the direction of useful signal. The limit of formulas 1 and 2 can ensure the useful signal goes through without any loss, so the output power of beamformer is the same as the power of useful signal. The output of maximum SNR can be realized by minimizing the power of output noise while ensuring that the power of useful signal is constant. The optimization weight vectors can be acquired by the formula 3 according to the limited formulas 1 and 2.

$$W_{MVDR} = \frac{R_{xx}^{-1} a(\theta_0)}{a^H(\theta_0) R_{xx}^{-1} a(\theta_0)} \qquad \text{（3）}$$

The method requires that the number of disturbances is smaller than M-2 (M is the number of element in antenna array), because antenna array with M elements possesses M-1 free degree and one free degree is used as the limit of useful signal direction [3,4].

There are two problems which need considering in the actual application. First problem is how to construct the covariance matrix of the algorithms in adaptive beamformer. Second problem is how to ensure the consistent and continuous ocean echo during the coherent integration time despite the changing weights. The two problems are discussed in the following two sections.

III. THE CONSTRUCT COVARIANCE MATRIX

The covariance matrix in formula 3 is constructed conventionally with unlimited snapshots. But it is estimated by using limited snapshots $X(t_i)$ in actual application. It can be expressed with

$$\overset{\Lambda}{R} = \frac{1}{K} \sum_{i=1}^{K} X(t_i) X^H(t_i) \quad (4)$$

,where K is the number of snapshots. We consider that the disturbance has the property of time-varying. While we are estimating the covariance matrix, the number of snapshots can not be so big as to exceed the correlative time of disturbance. Otherwise the detective ability of radar would be reduced. However, if the number of snapshots is too small, the times of changing weights will become too great. It is difficult to process rapidly because of the increase of computation. Considering the two factors, i.e. the properties of RFI and computing capacity of algorithm, we divide the coherent integration time into n sections. Each section which lasts 3s has q scanning periods.

It is obvious that the majority of signals which the radar receives are echoes of ocean waves which are continuous in wide angle range. That is to say, the echoes of ocean waves in a test range cell have many directions [5]. So, the echoes of ocean waves whose direction are different from the desired direction of adaptive beamformer are also suppressed. The problem can be overcome by using the special covariance matrix estimation, which is according to the properties of RFI such as great power, a certain direction and wide existing range [6]. RFI exists all range cells, but the useful signal of ocean wave occupies a small part of range cells. To solve the problem mentioned above, we can utilize the snapshots of far range cells which have not useful signal of ocean wave to estimate covariance matrix. The processing details are described as follows. Supposedly, the number of far distance cells which have not useful echo signal is N_{ref} and there are p times of scanning data before a certain point of time in the far distance cell. We can construct the vector $X_{j,k} = \left[x_j(k-p+1), \cdots, x_j(k)\right]^T$, T expresses transpose, j is the number of far distance cells, $j = 1,2,\cdots,N_{ref}$, k is the current time. So, at the current time k, the covariance matrix of estimation the RFI is expressed by the formula

$$R_x = \left(1 \big/ N_{ref} \right) \sum_{j=1}^{N_{ref}} X_{j,k} X_{j,k}^H \qquad \text{（3）}.$$

Here H is the transpose of complex conjugate.

IV. THE SOLVING THE PROBLEM OF CONSISTENT DETECTION CAUSED BY ANTENNA PATTERN CHANGE

The purposes of utilizing adaptive beamformer are to suppress RFIs which have different directions from that of desired signal and to avoid influencing the correct detection of useful echo signal. That is to say, the consistent detection of ocean echo should be preserved in the process of weight change. $W_1, W_2, \cdots, W_n$ are the weight vectors which correspond to M time parts mentioned above and $R_1, R_2, \cdots, R_n$ are the covariance matrix correspondingly. Formula 3 can be conventionally solved by utilizing the sample matrix inversion (SMI) algorithm [7]. W_i is acquired by using R_i according to MVDR criterion. Then the *i*th output of adaptive beamformer can be expressed by using the weight vector W_i and the input signal of antenna array during the *i*th time-span. It can be described by

$$y(t)=W_i^H X(t)\text{, where } t=q(i-1),\cdots,qi-1 \quad (6).$$

There exists a problem to be discussed in the next section. W_1 is acquired by using covariance matrix R_1 according to MVDR criterion. The output of beamformer can be expressed by $y(t)=W_1^H X(t)$, where $t=0,1,\cdots,q-1$. It is obvious that the consistent detection can be preserved during the first time-span, because the weight vector W_1 is unchanged during the first time-span. If the second weight vector W_2 of beamformer can be computed by the same method, we can ensure the consistent detection during the second time-span for the same reason that the weight vector W_2 is unchanged during the second time-span. The adaptive beamformer during the 2q scannings consists of the two beamformers whose weight vector are W_1 and W_2 respectively. If weight vector W_2 is computed separately and without any relation with W_1, the consistent detection can not be preserved where the last part of the first time-span meets the initial part of the second time-span, because the pattern of antenna array changes instantaneously with the variety of weight vector.

How to preserve the consistent detection is the crux of the matter. We can make the pattern of antenna array more stable by using loaded SMI (LSMI) algorithm whose sample can be expressed by $R_m+\alpha I$, where α must be selected properly. The weight vector based on LSMI algorithm can be computed by the formula

$$W_m=\left[V^H(\theta)\{R_m+\alpha I\}^{-1}V(\theta)\right]^{-1}\{R_m+\alpha I\}^{-1}V(\theta) \quad (7)$$

The pattern becomes more stable as α increases, but its ability of suppressing RFI is weakened. The value of α is great enough to change the adaptive beamformer into conventional digital beamforming. So in the selection of α 's value we should consider the balance between the stability of pattern and the ability of suppressing RFI [8].

The paper proposes the weight iterative algorithm to ensure consistent detection. The initial weight vector is acquired by using the conventional MVDR criterion, but the other weight vectors is derived from the late weight vector by using the conventional LCMV criterion. The change of antenna pattern is orthogonal to the echo subspace of the late time-span. So the purposes of suppressing RFI and overcoming the discontinuity caused by instantaneous change of antenna pattern can be achieved at same time.

The following illustrates how to construct the signal subspace. The ocean echo signal which the radar receives can be expressed with the formula

$$r_i(t)=A_i e^{j\{2\pi(f_s+f_b)t+\phi_i(t)\}}+\tilde{A_i}\, e^{j\{2\pi(f_s-f_b)t+\phi_i(t)\}}+e_i(t) \quad (8)$$

A_i 、 $\tilde{A_i}$ express the amplitudes of the negative and positive first-order spectral peaks of ocean echo respectively. f_b is Bragg frequency. $\phi_i(t)$ expresses the influence caused by ocean current. $e_i(t)$ expresses the influence caused by the second-order scatter. The echo signals of *i* ocean current directions can be expressed with

$$c(t)=c_g+c_a(t)e^{j2\pi(f_s+f_b)t}+c_r(t)e^{j2\pi(f_s-f_b)t} \quad (9)$$

Here c_g expresses the section of zero Hertz Doppler frequency. The influences of advance Bragg wave components can be described with

$$c_a(t)=\sum_{i=1}^{I}\left(A_i e^{j2\pi\phi_i(t)}+\beta_{a,i}(t)\right)V(\theta_i) \quad (10)$$

, where $A_i e^{j2\pi\phi_i(t)}$ 、 $\beta_{a,i}(t)$ express the influences of the first-order and second-order scatter of the *i*th ocean wave respectively. The influences of recede Bragg wave components can be described with

$$c_r(t)=\sum_{i=1}^{I}\left(\tilde{A_i}\, e^{j2\pi\phi_i(t)}+\beta_{r,i}(t)\right)V(\theta_i) \quad (11)$$

, where $\tilde{A_i}\, e^{j2\pi\phi_i(t)}$ 、 $\beta_{r,i}(t)$ express the influences of the first-order and second-order scatter of the *i*th ocean wave respectively. We believe that the Doppler shift caused by ocean current is not changed during the small time-span. Assuming that the Doppler shift caused by ocean currents at the new time-span is δf_m, we can express the ocean echo with the formula

$$c(t)=A_m p(t), \qquad t=Q(M-l),\cdots,QM-1 \quad (12)$$

Here $A_m=\left\lfloor c_g, c_a(\tau_m), c_r(\tau_m)\right\rfloor$ (13),

$$p(t)=\left[1, e^{j2\pi(f_m+f_b)t}, e^{j2\pi(f_m-f_b)t}\right]^T \quad (14)$$

$f_m=f_s+\delta f_m$, $\tau_m=Q(M-1)$. So we can express the signal subspace of the *m*th time-span as A_m. That is to say, the signal subspace during the coherent integration time is in constant change. How to realize the adaptive beamformer based on the weight iterative algorithm is described in the following section.

The first weight vector W_1 is computed by using the covariance matrix R_1 according to MVDR criterion. The second weight vector W_2 is formed by limiting the change of corresponding antenna pattern to preserve orthogonal to the signal subspace of the second time-span. What is discussed can be expressed with the formula

$$(W_2-W_1)^H A_2=0 \quad (15)$$

That makes the weight vector W_2 change from the weight vector W_1, and the difference $\Delta W_{1,2}=W_2-W_1$ has no influence on the ocean echo data of the second time-span $c(t)=A_2 p(t)$. In other words, the results of processing the second time-span ocean echo with the output of beamformer whose weight is W_2 are the same as the results of processing the second time-span with the output of beamformer whose weight is W_1. So the consistent detection of the two time-spans can be preserved with the above method.

When the second-order scatter is considered in the treatment, we utilize W_1 to operate in initial 7 pluses in the second time-span to make the computation simple. We define the formula

$$W_2^H X(t) = W_1^H X(t) \text{ for } t = q,\cdots,q+6 \quad (16)$$

to make the second filter satisfy the constraints of 7 linear equations. Because of limits of the 7 equations, the change of antenna pattern caused by $W_1 \neq W_2$ is orthogonal to the signal subspace. The discontinuity can be overcome during the two time-spans. In a word, the second beamformer based on weight W_2 can suppress the nonstationary RFIs and preserve consistent detection. The process can be expressed with the following formulas. We get the first weight W_1 from formulas17 and 18 directly based on MVDR algorithm.

$$\min_{W_1} W_1^H R_1 W_1 \quad (17)$$

$$W_1^H V(\theta) = 1 \quad (18)$$

The second weight W_2 can be acquired by the formula 19 based on LCMV algorithm.

$$\min_{W_2} W_2^H R_2 W_2 \quad \text{subject to } C_2 W_2 = f_2 \quad (19)$$

Here

$$C_2 = [V(\theta), X(Q), \cdots, X(Q+6)]^H \qquad ,$$

$$f_2 = [1, X^H(Q)W_1, \cdots, X^H(Q+6)W_1]^T .$$

So, the weight W_2 can be computed with the formula

$$W_2 = R_2^{-1} C_2 \left[C_2^H R_2^{-1} C_2\right]^{-1} f_2 \quad (20)$$

The other ocean echo data in the surplus time-spans can be treated with the same method. The *i*th weight vector can be computed with

$$W_i = R_i^{-1} C_i \left[C_i^H R_i^{-1} C_i\right]^{-1} f_i \quad (21).$$

Here

$$C_i = [V(\theta), X(q(i-1)), \cdots, X(q(i-1)+6)]^H$$

$$f_i = [1, X^H(q(i-1))W_{i-1}, \cdots, X^H(q(i-1)+6)W_{i-1}]^T .$$

The iterative processing is not over until the date of whole coherent integration time is used.

V. APPLICATION

At first, we select the actual data from the Radio Propagation Lab in Wuhan University to extract ocean dynamic parameters on the Zhujiajian Island of Zhejiang province in China at 23:45 on Apr. 17 2004. The radar parameters are set as follows. Carrying frequency is 7.973MHz and range resolution is 2.5km. Sweep period is 0.653s and coherent integration time is about 13 minutes. The number of range cell is 23. The number of elements in antenna array arranged in one line is 8 and the distance between two neighboring elements is d. Each time-span is 3s. The 8 channels are calibrated in the phase and amplitude. The direction which right faces the antenna array is 0 degree. The desired direction is 20 degree. The antenna pattern of conventional beamformer is shown in Fig.1. The corresponding Doppler spectrum in the range cell is shown in Fig.2.

The antenna pattern of conventional beamformer is fixed and its null is stationary during the coherent integration time. It can not suppress time-varying RFI effectively. The negative first-order peak can not be seen because of the existence of time-varying RFI. The weight vector in the adaptive beamformer changes automatically once every 3S during the whole coherent integration time according to time-varying RFI. The nulls of antenna pattern are adjusted to trace the RFI variety. There are two antenna patterns which correspond to two weight vectors among all the weight vectors in Fig.3 and Fig.4.

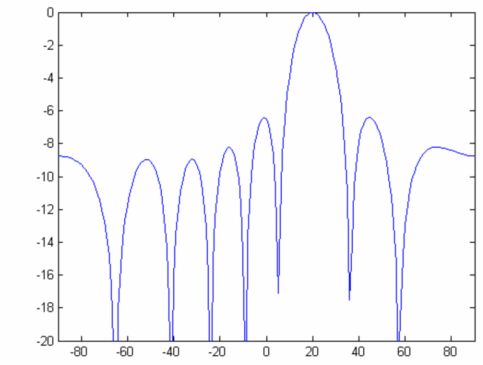

Fig.1 antenna pattern of conventional beamformer

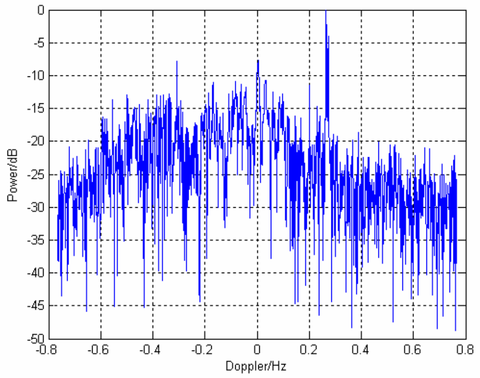

Fig.2 Doppler spectrum which corresponds to conventional beamformer

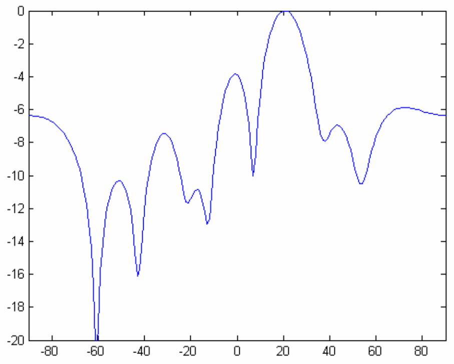

Fig.3 an antenna pattern of adaptive beamformer

The deepest null in Fig.1 is at –62 degree, but the deepest null in Fig.2 is at –37degree. That is to say, when the direction of strongest RFI is time-varying, the adaptive beamformer can adjust the position of the deepest pattern null to suppress it. The Doppler spectrum in the same range cell which corresponds to adaptive beamformer is shown in Fig.5. The negative first-order peak can be seen clearly.

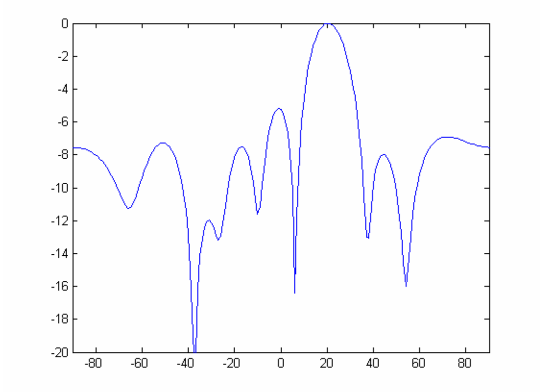

Fig.4 another antenna pattern of adaptive beamformer

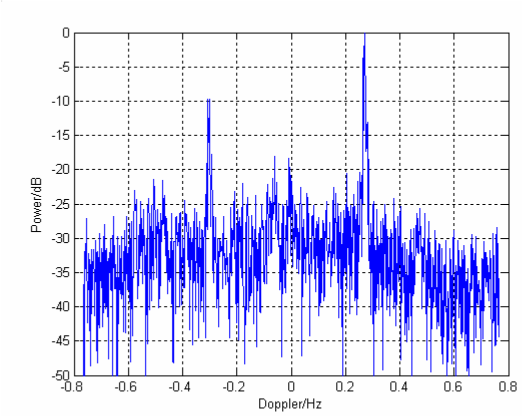

Fig.5 Doppler spectrum corresponding with adaptive beamformer

VI. CONCLUSION

The paper proposed the method of special adaptive beamformer for suppressing RFI in the space field. The method can improve the detective ability of high frequency ground wave radar. The first weight vector is acquired by using MVDR algorithm. The other weight vectors are computed by using LCMV. The change of weight vector which depends on the late weight vector is realized by iterative method. So the previous weight vector can influence latter weight vector. It can ensure the consistent detection while suppressing RFI. The method can be utilized in the other phase-controlled array radars. Because the number of elements in our antenna array is 8, the maximum number of RFIs which can be effectively suppressed is 6. That is to say, the number of elements in antenna array limits the ability of suppressing RFI in the way mentioned in this paper. When the number of RFIs exceeds the degree of freedom in antenna array, using the method in this paper to suppress RFI can not achieve perfect effect [9].

REFERENCES

[1] Madden, J.M., The adaptive suppression of interference in HF ground wave radar[J], IEE Int. Conf. Radar 87, London, UK, pp. 98-102

[2] L C Codara. Application of Antenna Array to Mobile Communication, Part II: Beamforming and Direction of Arrival consideration[J]. Proceedings of the IEEE, 1997, 85(8): 1195-1245.

[3] Van Veen, B.D., Buckley, K.M., Beamforming: a versatile approach to spatial filtering[J], ASSP Magazine, IEEE, Volume: 5, Issue: 2, April 1988, Pages: 4-24.

[4] Thomas Dean Moore, B.S.E.E., M.S.E.E., Analytic study of space-time and space-frequency adaptive processing for radio frequency interference suppression[D]., thesis of degree doctor in the Ohio State University, 2002.

[5] YANG Shao-lin, KE Heng-yu, WU Shi-cai, et al. Signal Preprocessing for Bearing Determination of Ocean Surface Radial Current Mapping Based on MUSIC[J], Modern Radar, 2001, 23(4): 49-54.

[6] Madden, J.M., The adaptive suppression of interference in HF ground wave radar[J], IEE Int. Conf. Radar 87, London, UK, pp. 98-102

[7] Gershman, A.B., Nichel, U., Bohme, J.F., Adaptive beamforming algorithms with robustness against jammer motion[J], Signal Processing, IEEE Transactions on, Volume: 45, Issue: 7, July 1997 Pages: 1878-1885.

[8] B. B. Carlson, Covariance matrix estimation errors and diagonal loading in adaptive arrays[J], IEEE Trans. Aerosp. Electron. Syst., Vol.24, pp. 397-401, July 1988.

[9] SHEN Fu-ming, adaptive signal processing(M), XIAN University Press, March, 2003.