Sādhanā (2020) 45:179
https://doi.org/10.1007/s12046-020-01376-4

Target detection method in short coherent integration time for sky wave over-the-horizon radar

HUAN LUO

Air Force 95519 Army, People's Liberation Army of China, Zunyi 563000, China
e-mail: luohuan5566@sina.com

MS received 30 May 2019; revised 14 December 2019; accepted 3 April 2020

Abstract. In order to reduce the Doppler spread effect caused by ionospheric disturbance, sky wave over-the-horizon radar often detects ships in a short coherent integration time (CIT). In short CIT, an effective means to detect ships is clutter suppression. Through the analysis of the real data, it is found that the sea clutter has a strong correlation when the sea state is relatively stable, whether in long CIT or short CIT. To avoid estimating clutter subspace dimension and clutter cancellation times of the available methods, an adaptive clutter suppression method based on sea clutter correlation is proposed. This method does not need to estimate the parameters of the clutter, even when the Doppler frequency of the ship target is close to the sea clutter, the target can be detected. Theoretical analysis and real data processing indicate that the proposed method can detect ship target effectively.

Keywords. Over-the-horizon radar (OTHR); clutter suppression; correlation of sea clutter; ship target detection.

1. Introduction

Sky wave over-the-horizon radar (OTHR) operating in the high frequency band (3–30 MHz) can provide over-the-horizon detection of targets on large surveillance areas [1, 2]. Because the ship speed is slow, in order to detect the ship target from the sea clutter background, it need to use a longer coherent integration time (CIT) than the detection of the aircraft target to improve the Doppler resolution of the radar system. Normally, when OTHR is working with sea detection mode, the required CIT is a few dozen seconds or even a few minutes. However, there are two problems in choosing long CIT for sea surface detection. The first problem of prolonging CIT is that it will reduce the OTHR revisit times in surveillance area, and reduces the ability of OTHR to detect multiple targets simultaneously. The second problem with extending CIT is that it increases the probability of sea clutter Doppler spectrum broadening, when CIT is long, the ionosphere is no longer stable, the random and time-varying nature of the ionosphere will cause the sea clutter to be extended in the Doppler domain thereby smearing the presence of the ship target [3, 4]. Therefore, it is very important to study a useful method to suppress the sea clutter so that the ship detection mission can be executed with short CIT.

There are two ways to solve the problem of target being covered by clutter: one is clutter suppression method, which can suppress clutter as much as possible without losing the energy of the ship; the other is to improve the resolution of Doppler spectrum, which mainly uses high resolution spectral estimation method to distinguish the ship from clutter [5]. There are three kinds of clutter suppression methods: the first is sea clutter cancellation method, including Root method [6, 7] and APES cancellation method [8]; the second is eigenvalue decomposition (EVD) method [9, 10]; the third is singular value decomposition (SVD) method [11–13]. In this paper, the problems of three sea clutter suppression methods in practical application are analyzed. Based on the strong correlation of sea clutter, an adaptive sea clutter suppression method in frequency domain is proposed, and the detection performance of the proposed method is studied with real data.

2. Problems of existing sea clutter suppression methods

In the ocean echo of OTHR, the two Bragg peaks can be represented by sinusoidal signals [14, 15], and the high-order sea clutter can also be approximated by a set of sinusoidal signals [16]. Therefore, a sinusoidal model can be used to describe the suppression process of sea clutter. Suppose the number of echo pulses is N, at moment t, $\mathbf{x} = [\,x(t-(N-1)\Delta_t) \quad \cdots \quad x(t-\Delta_t) \quad x(t)\,]^{\mathrm{T}}$ is the sampling data of the range cell under test in a short CIT, where Δ_t is sampling interval, 'T' is transposition operation. In general,

Published online: 15 July 2020

$\mathbf{x}$ contains sea clutter, potential targets and noise. The sea clutter of different orders are described by r sinusoidal signals with frequency of $f_1, f_2, \ldots, f_r$. Assuming the Doppler frequency of the target is f_T, the sea surface echo of OTHR can be expressed as a matrix

$$\mathbf{x} = \begin{bmatrix} 1 & \cdots & 1 & 1 \\ e^{j\Delta_t 2\pi f_1} & \cdots & e^{j\Delta_t 2\pi f_r} & e^{j\Delta_t 2\pi f_T} \\ \vdots & \ddots & \vdots & \vdots \\ e^{j(N-1)\Delta_t 2\pi f_1} & \cdots & e^{j(N-1)\Delta_t 2\pi f_r} & e^{j(N-1)\Delta_t 2\pi f_T} \end{bmatrix} \begin{bmatrix} c_1 \\ \vdots \\ c_r \\ s_T \end{bmatrix} + \mathbf{n} \tag{1}$$

where $c_1, \cdots, c_r$and s_T are the amplitude of the sea clutter and the target respectively, and $\mathbf{n}$ is the Gaussian white noise.

High-resolution spectrum estimation methods can solve the problem of low Doppler resolution in short CIT, but these methods are generally affected by the selected order and the estimated covariance matrix. How to avoid false peaks and reduce the computational complexity need to be solved. In addition, the physical interpretation of high-resolution spectrum is still unsatisfactory, which means that there may be information distortion. Different from the high-resolution spectrum estimation method, the sea clutter suppression method solves the problem of low Doppler resolution by suppressing the clutter components, in this way, the signal-to-noise ratio is also improved. Therefore, sea clutter suppression method has become an effective means to detect ship target in short CIT, and has been widely used, but there are still many problems.

2.1 *Root method*

Root method reconstructs the positive and negative sea clutter components in time domain and subtracts the estimated components from the echo to achieve clutter suppression. The core of the algorithm is to accurately estimate the amplitude, frequency and initial phase of the two first-order sea clutter components. The amplitude a and frequency f of the clutter component are estimated directly according to the peak value of the clutter in the Doppler spectrum obtained by fast Fourier transform (FFT). The initial phase ϕ of the clutter is estimated by minimizing the following formula

$$\varepsilon(\phi) = \sum_{n=0}^{N-1} \left| \mathbf{x}(n\Delta_t) - ae^{j\phi}e^{j2\pi fn\Delta_t} \right|^2 \tag{2}$$

Due to the low frequency resolution in short time and the large spacing between spectral lines, the frequency of the first-order Bragg peak is usually not at the discrete frequency point, which will decrease the estimation accuracy of frequency and amplitude, thus the initial phase cannot be accurately estimated. With the increase of the cancellation times, the residual clutter will spread in the Doppler domain, and the cancellation times and cancellation regions are difficult to determine, so it is easy to cause the target to be suppressed incorrectly. APES cancellation method uses spectrum analysis technique to estimate clutter amplitude, frequency and initial phase at the same time, so as to improve the accuracy of parameter estimation, but the cancellation times and cancellation regions are still difficult to establish.

2.2 *EVD method*

Assuming that $\mathbf{x}_i$ is the echo data of the ith range cell in N pulse periods, $i = 1, \ldots, M$, $M$is the number of reference range cells, the covariance matrix is

$$\mathbf{R} = \frac{1}{M}\sum_{i=1}^{M} \mathbf{x}_i \mathbf{x}_i^{\mathrm{H}} \tag{3}$$

where "H" denotes conjugate transpose. The eigenvalue decomposition is applied on $\mathbf{R}$, the eigenvectors $\mathbf{u}_1, \mathbf{u}_2, \ldots, \mathbf{u}_r$ corresponding to r large eigenvalues are expanded to clutter subspace. The cell under test ($\mathbf{x}_t$) is projected to clutter subspace and filtering the projection component, the data vector $\mathbf{y}$ containing only the target and noise can be obtained

$$\mathbf{y} = \mathbf{x}_t - \sum_{i=1}^{r} \mathbf{u}_i^{\mathrm{H}} \mathbf{x}_t \mathbf{u}_i \tag{4}$$

The problem of EVD method is how to divide the subspace [17]. In theory, we can use the information theory criterion [18, 19] to judge the dividing point between large eigenvalues and small eigenvalues. However, the practical effect of this method is not ideal and misjudgement often occurs. In addition, the inflection point of eigenvalues variation can be used as the boundary point between the clutter subspace and the target/noise subspace. However, when sea clutter is not stationary, the clutter eigenvalues can easily diffuse into the target eigenvalue, and the eigenvector corresponding to the target can easily be classified into the clutter subspace. As a result, the target will be weakened or even suppressed.

2.3 *SVD method*

The process of SVD method is: (1) a Hankel matrix $\mathbf{H}$ is constructed from the original time series data, the singular values of $\mathbf{H}$ can be obtained via singular value decomposition. (2) The first r large singular values represent most energy of the clutter, and the rest singular values represent target and noise. To cancel the clutter, the singular values corresponding to the clutter are first zeroed, and a reduced rank Hankel matrix $\mathbf{H}'$ can be constructed by the Hankel rank reduction method [12], then a new series data with clutter components removed is constructed from $\mathbf{H}'$. In this way, only the target and noise are contained in the echo, and the clutter is suppressed. If the target is mistakenly suppressed as clutter, the output signal-to-clutter-plus-noise ratio (SCNR) will be reduced. Similar to the EVD method, SVD method also regards the inflection point of the singular values as the boundary point between clutter and target/noise. In the real data, the singular vectors of clutter often diffuse into the target singular vectors, which results in the clutter cannot be completely suppressed or the target is weakened.

From the above analysis, all the aforementioned methods need to estimate the parameters of clutter, and the performance of these methods will be greatly decreased once the parameters of the clutter are inaccurate. To avoid the error caused by inaccurate parameters, a new method of clutter cancellation based on adaptive filter is proposed in this paper.

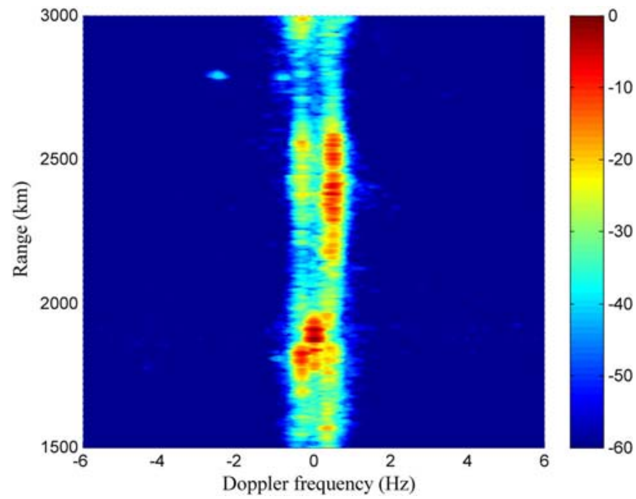

Figure 2. Range-Doppler image of real data with CIT = 5.568*s*.

3. Correlation of sea clutter in real data

This section mainly analyses the correlation of clutter in real data, this data comes from the sky wave over-the-horizon radar of China. Figures 1 and 2 are range-Doppler images of the same batch of real data under different CIT conditions. The parameters of the real data are: the operating frequency of OTHR is 14.6 MHz, the bandwidth is 60 kHz, the pulse interval is 58 ms, the transmitted power is 420 kW and the sensitivity of the receiver is $-70\sim-90$ dBm. The CIT of figures 1 and 2 are 44.544 s and 5.568 s, respectively. It can be seen that the two range-Doppler maps contain a large number of sea clutters and ground clutters, and there are also ship and aircraft targets in a few range cells. The aircraft is a small aircraft, with a speed of about 60 m/s; the ship is a large freighter, with a length of about 160 m and a speed of about 15 m/s.

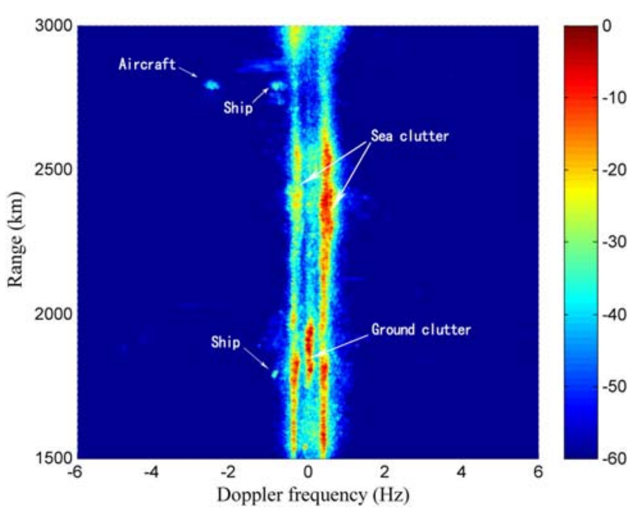

Figure 1. Range-Doppler image of real data with CIT = 44.544*s*.

The two images have different CIT, so their Doppler spectral resolution is also different. Compared with figure 2, the aircraft and ship targets in figure 1 are easier to distinguish from clutter. The main reason is that long CIT can get more echo pulses, the more pulses, the higher Doppler resolution. However, long CIT means that the surveillance area of radar becomes smaller. In order to improve the multi-area surveillance ability of radar, the target resolution ability in short CIT should be improved.

For this real data, we use the following formula to calculate the correlation coefficients of clutter between the range cell under test and the ith neighbouring range cell [9]

$$\eta_i = \frac{\mathbf{x}_t^{\mathrm{H}}\mathbf{x}_i}{||\mathbf{x}_t||\,||\mathbf{x}_i||} \tag{5}$$

where $\mathbf{x}_t$ is the range cell under test, $\mathbf{x}_i$ is the ith range cell adjacent to $\mathbf{x}_t$, we call it reference cell, η_i is the correlation coefficient between the cell to be tested and the reference cell. Figure 3a is the correlation coefficient between the 400th range cell and reference cells. Figure 3b is the correlation coefficient between the 750th range cell and reference cells. The CIT of the solid line and the dashed line are 44.544 s and 5.568 s, respectively, and the number of reference cells is 80. From figure 3, it can be seen that the range correlation coefficient of sea clutter has a fluctuation approximate to "periodicity", and the average correlation coefficient is about 0.7. Because the motion state of ocean wave is relatively stable in a certain CIT, the variation of range correlation coefficient in different CIT is very small and can be neglected. Therefore, sea clutter can be regarded as a range-dimensional stationary clutter because of its strong correlation in the range domain.

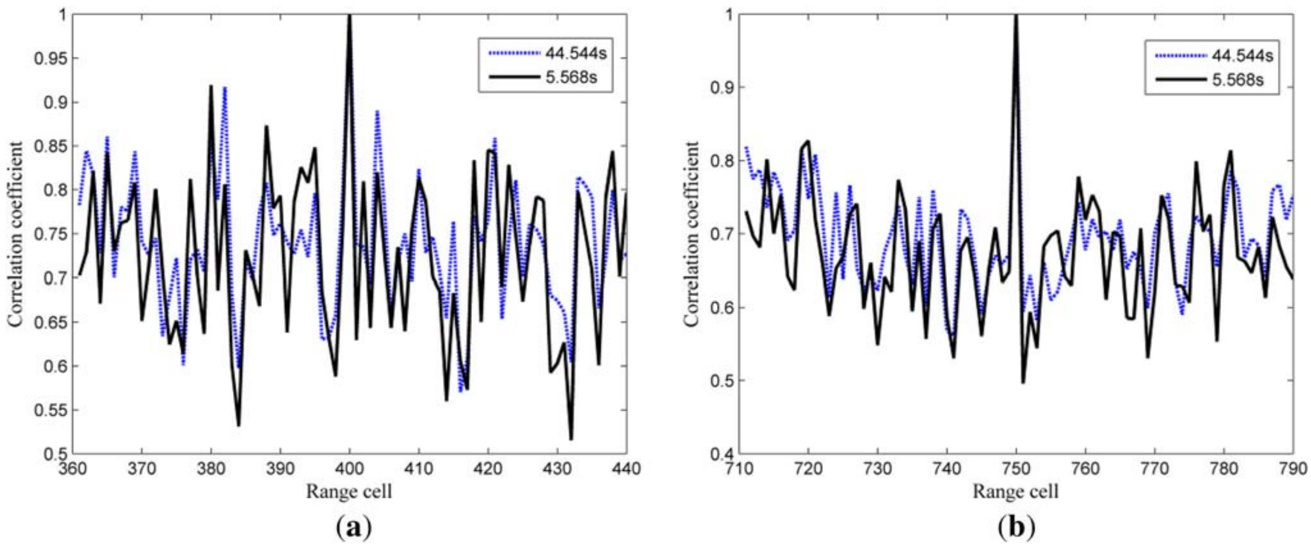

Figure 3. Correlation coefficient between the detected range cell and reference cells: (**a**) The 400th range cell, (**b**) The 750th range cell.

4. Adaptive clutter suppression method

The analysis of the real data in section 3 shows the variation of OTHR Doppler spectrum in neighbouring range cells are slow, and the sea clutter has high correlation to its neighbouring range cells, the correlation coefficient could be as high as 0.8–0.9 [9]. Based on this conclusion, a frequency domain adaptive clutter suppression (FACS) method is proposed in this section.

For the received echoes in (1), matched filtering and range compressing are implemented in the range domain, then we do FFT on the data in slow time domain so as to obtain Doppler cells. Through the above operations, range-Doppler data $\mathbf{X}$ can be obtained. In matrix $\mathbf{X}$, in addition to strong sea clutter and noise, there may be some targets. The lth range cell ($\mathbf{X}(l,:)$) in $\mathbf{X}$ is to be detected, the matrix $\mathbf{X}_R$ is constructed by several range cells adjacent to $\mathbf{X}(l,:)$

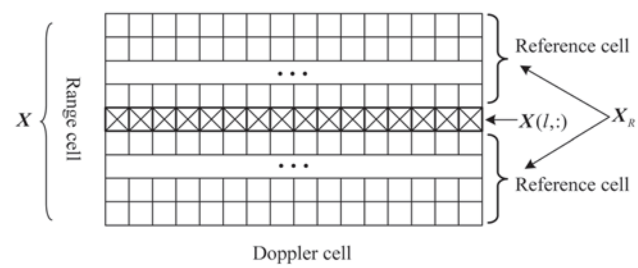

Figure 4. Data matrix after FFT.

$$\mathbf{X}_R = \left[\mathbf{X}\left(l - {}^{I}\!/_{2} + 1,:\right)| \quad \cdots \quad \mathbf{X}(l-1,:)| \quad \mathbf{X}(l+1,:)| \quad \cdots \quad \mathbf{X}\left(l + {}^{I}\!/_{2} + 1,:\right)\right] \tag{6}$$

where $\mathbf{X}(i,:)$ represents the ith row in matrix $\mathbf{X}$, it is the slow time data after FFT of the ith range cell, the size of matrix $\mathbf{X}_R$ is $I \times N$. The range-Doppler data $\mathbf{X}$ is shown in figure 4.

Because the clutter has good correlation in the range direction, the clutter components of the range cell to be detected can be estimated by weighting the data of the reference cells. Assuming that the weight vector is $\mathbf{W}$, where $\mathbf{W} = [w_1, \ldots, w_I]^{\mathrm{T}}$, the output ($\mathbf{e}$) of the detected range cell $\mathbf{X}(l,:)$ is given by

$$\mathbf{e} = \mathbf{X}(l,:) - \mathbf{W}^{\mathrm{H}}\mathbf{X}_R \tag{7}$$

where $\mathbf{W}^{\mathrm{H}}\mathbf{X}_R$ is the estimation of the clutter components of the detected range cell. By subtracting $\mathbf{W}^{\mathrm{H}}\mathbf{X}_R$ from $\mathbf{X}(l,:)$, the clutter can be rejected. It can be seen that $\mathbf{W}$ is equivalent to an adaptive clutter filter, the key of the method is how to estimate the vector $\mathbf{W}$ accurately. The power of $\mathbf{e}$ in (7) is $p = E\left[|\mathbf{e}|^2\right]$, when p reaches the minimum, the corresponding weight vector $\mathbf{W}_{opt}$ is the accurate estimation of **W**. By the derivation of the equation (7), the solution of **W**can be obtained

$$\mathbf{W}_{opt} = \mathbf{R}_l^{-1}\mathbf{r}_l \tag{8}$$

where $\mathbf{r}_l = E\left[\mathbf{X}_R\mathbf{X}^{\mathrm{H}}(l,:)\right]$ is the cross-correlation vector between the current detected range cell and neighbouring range cells, $\mathbf{R}_l$ is the clutter covariance matrix, which is estimated by multiple reference cells, $\mathbf{R}_l$ is estimated by

$$\mathbf{R}_l = E\left[\mathbf{X}_R\mathbf{X}_R^{\mathrm{H}}\right] \tag{9}$$

Constructing a weight vector $\mathbf{w}_l$ of $(I+1)\times 1$ dimension

$$\mathbf{w}_l = \begin{bmatrix} 1 \\ -\mathbf{W}_{opt} \end{bmatrix} \tag{10}$$

and $\mathbf{w}_l$ is normalized as $\mathbf{w}_{Nl} = \mathbf{w}_l \Big/ \sqrt{\mathbf{w}_l^{\mathrm{H}}\mathbf{w}_l}$.

The weight vector $\mathbf{w}_{Nl}$ is multiplied with the echo, and then the clutter of the lth range cell can be suppressed

$$\mathbf{X}^{'}(l,:) = \mathbf{w}_{Nl}^{\mathrm{H}}[\mathbf{X}(l,:)| \quad \mathbf{X}_R] \tag{11}$$

where $\mathbf{X}^{'}$ is the range-Doppler data matrix after clutter suppression.

Figure 5 is a schematic diagram of FACS method. From figure 5, it can be seen that this method uses the correlation of the adjacent range cells to eliminate the sea clutter components of the detected range cell, and the effectiveness of FACS is related to two factors: one is the correlation of sea clutter in adjacent range cells, the other is the accuracy of estimated weight $\mathbf{w}_{Nl}$ which can be calculated by minimizing the power of **e** in (7).

5. Experimental results

5.1 *Doppler spectrum of real data after adding ship target*

In this section, SVD method, EVD method, Root method and FACS method are used to process OTHR sea clutter data, and their clutter suppression ability in short CIT is discussed and analyzed. The CIT of real data is 5.568s and the number of reference range cells is 45. In order to verify whether the ship target appears or not after sea clutter suppression by different methods, a ship target with signal-to-clutter ratio (SCR) of − 20 dB is added to the short CIT data, its Doppler frequency is 0.72 Hz. In the experiment, the short data is expanded to 512 points by filling zero, and then the Doppler spectrum is obtained through FFT. Figure 6a shows the Doppler spectrum before clutter suppression. It can be seen that the ship target with Doppler frequency of 0.72 Hz is covered by sea clutter and cannot be identified.

The parameters of the above four methods are chosen as follows: in SVD method, the column number of Hankel matrix is set to 15, and the 5 largest singular values are set to zero; in EVD method, the rank of clutter subspace is set to 10; in Root method, the clutter cancellation times is 7. The proposed FACS method does not need to set parameters. The processing results of four methods are shown in

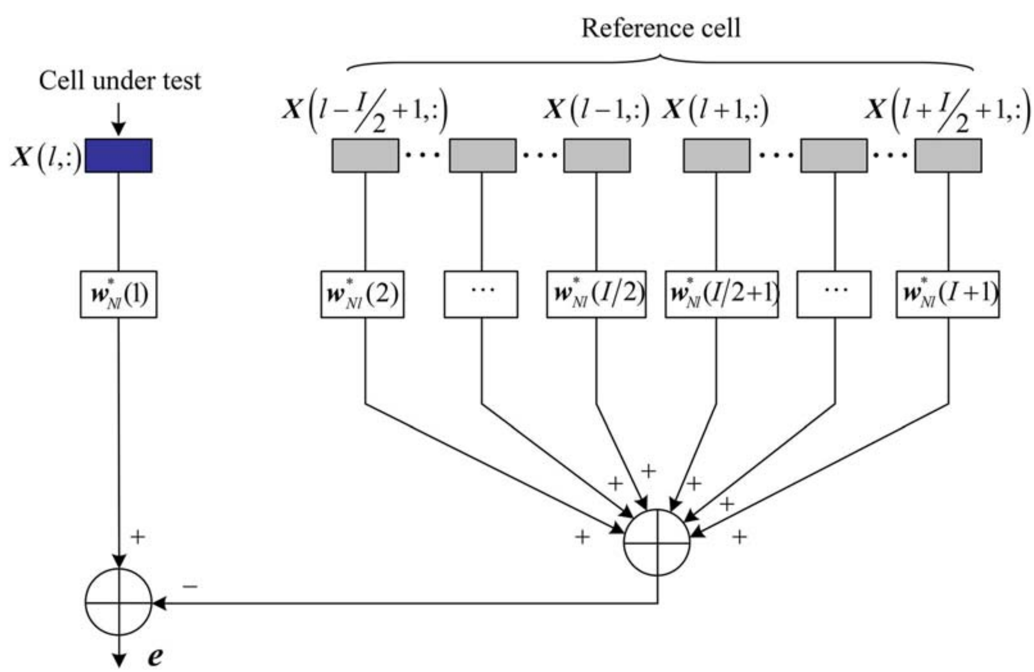

Figure 5. Schematic diagram of FACS method.

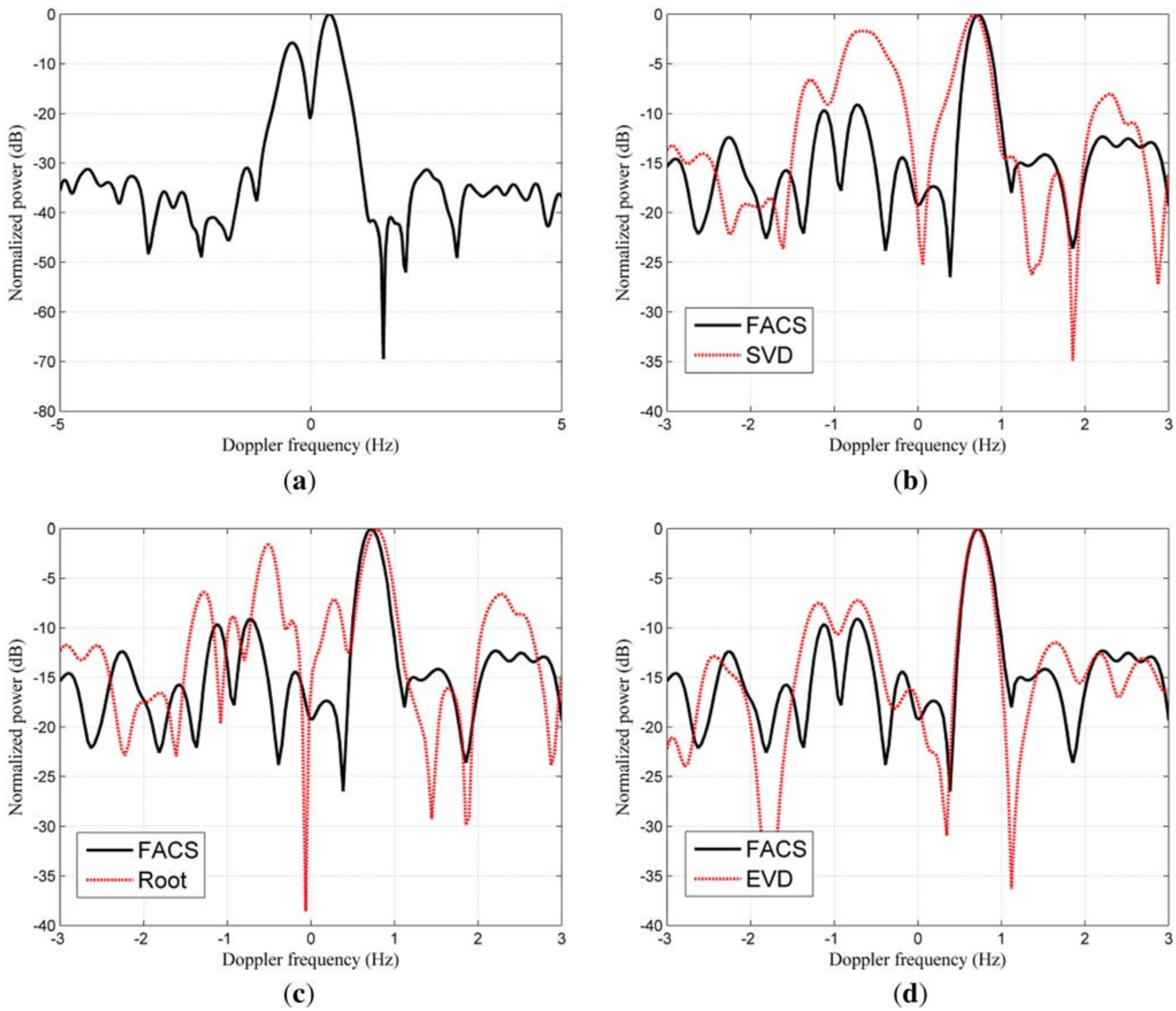

Figure 6. Spectrum before and after clutter suppression: (**a**) Before clutter suppression, (**b**) Clutter suppressed by SVD and FACS, (**c**) Clutter suppressed by Root and FACS, (**d**) Clutter suppressed by EVD and FACS.

figure 6b, c and d. It can be seen that: after using SVD method, although ship target is exposed, there is too much residual sea clutter. It is found in the experiment that if the 6 largest singular values are zeroed, although the remaining sea clutter is less, the ship is also suppressed. When the data is processed by Root method, there are still obvious residual clutter, and if more cancellation is carried out, the ship is also eliminated. EVD method can suppress clutter completely, target appears at 0.71 Hz, but this method has two application limits: the first limitation is the clutter subspace dimension is not easy to establish, inaccurate dimension will seriously weaken the effect of algorithm, the second problem is that eigenvalue decomposition computation of the high-dimensional covariance matrix is relatively large, which will reduce the efficiency of EVD algorithm. FACS method has the same clutter suppression effect as EVD method, but FACS does not need to determine the clutter parameters manually, and the performance of FACS is very stable when sea clutter correlation coefficient is greater than 0.6.

5.2 *Range-Doppler image of real data after clutter suppression*

In the short CIT, the original range-Doppler image of the real data is shown in figure 2. It can be seen that: in addition to strong sea clutter and ground clutter, there are also ship and aircraft targets in some range cells, especially around 1750 km there is a ship target close to the sea clutter, the Doppler frequency is about − 0.8 Hz. Because CIT is only 5.568s and the number of accumulated pulses is

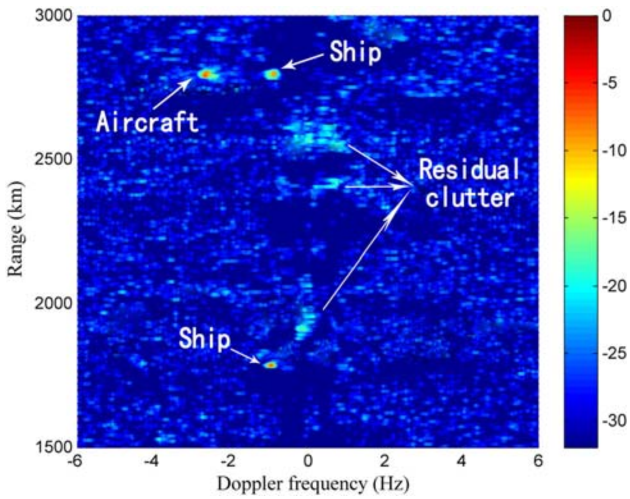

Figure 7. Range-Doppler image after clutter suppression by FACS method with CIT = 5.568*s*.

not enough, the resolution of range-Doppler image is low, so it is difficult to separate ship target from sea clutter in 1750 km. Figure 7 is the result of clutter suppression using the FACS method. The number of reference cells is 40. It can be seen that sea clutter and ground clutter have been completely suppressed. Aircraft target in 2780 km and ship target in 1750 km are clearly visible. Especially for the ship target in 1750 km, although its Doppler frequency is very close to sea clutter, the energy of the target is not be weakened when removing clutter. In figure 7, there are still a few residual clutter, which mainly concentrate in the clutter area and does not affect the detection of targets. From figure 7, we can see the power of target is about 20 dB higher than that of the residual clutter.

5.3 *Output SCNR comparison under stationary sea clutter condition*

In order to compare the performance of various sea clutter suppression methods under stationary sea clutter condition, the output SCNR of different methods is given with different target velocities. Define the output SCNR as $SCNR = 10\log\left(E_{S'}/\left(E_{C'+W'}\right)\right)$, where $E_{S'}$ is the target energy after sea clutter suppression, $E_{C'+W'}$ is the energy of residual clutter and noise in the sea clutter region after clutter suppression. The Doppler frequency of the target varies from − 1.5 Hz to 1.5 Hz with the step size of 0.0375 Hz. Other simulation parameters are: OTHR transmission frequency is 18 MHz, it means Doppler frequencies of the positive and negative Bragg peaks are 0.43 Hz and − 0.43 Hz, and their signal-to-noise ratio is 45 dB and 35 dB, respectively. The noise is white Gauss noise with mean value is 0 and variance is 1, for Gaussian white noise, power and variance are equal, according to the sensitivity of real radar receiver, it is reasonable to set the noise energy as 1 μW, that is, the unit is μW. The data length is 64, and the number of reference cells is 40. In the EVD method, the noise covariance matrix is replaced by the unit matrix, the clutter covariance matrix is estimated by the reference cells, and the rank of the clutter subspace is chosen as 2; in the SVD method, the first two large singular values are zeroed; and the cancellation times of Root method is 2. The results came from 100 Monte Carlo experiments, the SCNR of the data processed by various sea clutter suppression methods is shown in figure 8.

Figure 8 shows that under the condition of stationary sea clutter, EVD and FACS method have the same performance because of the strong correlation of sea clutter in adjacent range cells. They are superior to SVD method and Root method. The four methods have power attenuation effect on target in − 0.5 ∼ − 0.35 Hz and 0.35 ∼ 0.5 Hz, while in the other frequency regions, hardly weaken the target. In the non-clutter region, the attenuation of target power by FACS method is slightly larger than that by EVD method, but smaller than that by Root and SVD method. SVD method removes target in − 0.6 ∼ − 0.15 Hz and 0.23 ∼ 0.6 Hz, especially, when the Doppler frequency of ship target is in − 0.52 ∼ − 0.32 Hz, the target energy eliminated by SVD method is the largest of the four methods. Root method cancels the target in − 0.56 ∼ − 0.3 Hz and 0.3 ∼ 0.6 Hz, and in other Doppler frequency regions, the suppressing effect on target is the most serious of the four methods. Figure 8 illustrates that the FACS and EVD methods are more effective than the SVD and Root method when the sea state is stable, especially when the ship Doppler frequency is close to the sea clutter, the clutter can be suppressed without damaging the energy of the target.

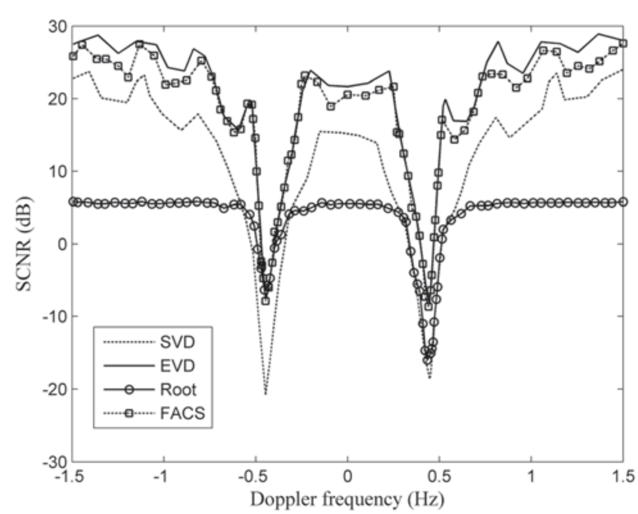

Figure 8. Output SCNR after clutter suppression by four method (sea state is stationary).

5.4 *Output SCNR comparison under non-stationary sea clutter condition*

Generally, OTHR echo is easily polluted by ionosphere disturbance [20], and sea clutter tends to be unstable. Next, the SCNR after clutter suppression is analyzed under the condition of non-stationary sea clutter. The simulation parameters are consistent with section 5.3. In order to simulate non-stationary sea clutter, the sea clutter of each range cell is processed as follows: adding $-5\sim5$ dB random disturbance on the amplitude, adding $-0.1\sim0.1$ Hz random disturbance on the frequency and adding $-\pi\sim\pi$ random disturbance on the phase, so that the correlation of sea clutter of adjacent range cells will be reduced. The result is shown in figure 9, it shows that the performance of FACS method and EVD method is almost the same. When sea clutter is non-stationary, the correlation of adjacent range cells becomes weaker, the performance of both EVD and FACS decrease. Root method and SVD method do not utilize the correlation of sea clutter, nor do they need reference cells, so the power attenuation of target in non-clutter area is less than the previous two methods. However, SVD method weakens the target most severely in the Doppler region of $-0.52\sim-0.3$ Hz and $0.35\sim0.52$ Hz. Root method suppresses the target more severely in the Doppler region of $0.33\sim0.6$ Hz than EVD and FACS method.

Under the condition of non-stationary sea clutter, the simulation results show that SVD method is better than FACS method, because the clutter dimension of SVD is set artificially by the accurate parameters of the simulation clutter, but it is difficult to estimate the clutter dimension accurately when processing real data, so the effect of SVD method in engineering application is relatively poor. FACS method does not need to set parameters artificially, so its performance in simulation experiment is consistent with that in practical application. In a word, when the sea clutter is non-stationary, more effective clutter suppression methods need to be studied.

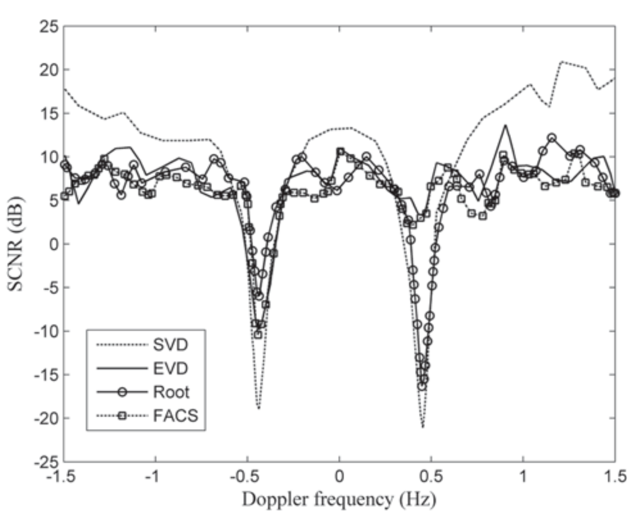

Figure 9. Output SCNR after clutter suppression by four method (sea state is non-stationary).

6. Conclusions

In this paper, the correlation of sea clutter in different CIT is analyzed. The analysis of the real data shows that even the CIT is short, the clutter in the adjacent range cells still have a strong correlation. The problems of SVD method, EVD method and Root method are analyzed, in order to avoid the clutter parameter estimation error of the three methods, based on the strong correlation of sea clutter, FACS method is proposed. FACS method does not need to estimate the clutter parameters and the clutter cancellation times, has almost the same clutter cancellation performance as the EVD method, and can detect the ship target whose Doppler frequency is close to the sea clutter. It should be pointed out that if the sea state is bad, the correlation of sea clutter will be reduced, the performance of FACS method and EVD method will be degraded, SVD method and Root method also cannot effectively suppress sea clutter in real data. In this case, a combination of multiple methods may be used to eliminate the clutter of a single range cell.

Acknowledgements

The funding was provided by National Natural Science Foundation of China (Grant No. 51309232).

References

[1] Frazer G J 2017 Experimental results for MIMO methods applied in over-the-horizon radar. *IEEE Aerosp. Electron. Syst. Mag.* 32(12): 52–69
[2] Luo H and Xiao H 2018 Establishment of ionospheric model containing sporadic E and its applications in target height measurement. *Acta Phys. Sin.* 67(7): 079401
[3] Hu J F, Ai H, Xue C P, He X, Li W, Li H, Xia W and Xie J 2016 Ionospheric decontamination based on sparse reconstruction for skywave radar. *EURASIP J. Adv. Sig. Process* 2016: 1–10
[4] Zhu Y P, Wei Y S and Yu L 2017 Ionospheric decontamination for HF hybrid sky-surface wave radar on a shipborne platform. *IEEE Geosci. Remote Sens. Lett.* 14(11): 2162–2166
[5] Barnum J 1986 Ship detection with high-resolution HF skywave radar. *IEEE J. Ocean. Eng.* OE-11(2): 196–209
[6] Root B T 1998 HF-over-the-horizon radar ship detection with short dwells using clutter cancelation. *Radio Sci.* 33(4): 1095–1111
[7] Root B T 1998 HF radar ship detection through clutter cancellation. In: *Proceedings of the IEEE Radar Conference*, pp. 281–286
[8] Raout J, Santori A and Moreau E 2010 Space-time clutter rejection and target passive detection using the APES method. *IET Signal Process.* 4(3): 298–304

[9] Wang G, Xia X G, Root B T, Root V C, Zhang Y and Amin M 2003 Manoeuvring target detection in over-the-horizon radar using adaptive clutter rejection and adaptive chirplet transform. *IEE Proc.-Radar Sonar Navig.* 150(4): 292–298

[10] Zhao Z G, Chen J W and Bao Z 2012 Modified adaptive ocean clutter suppression approach in OTHR. *Chin. J. Syst. Eng. Electron.* 34(5): 909–914

[11] Lu K, Liu X Z and Liu Y T 2005 Ionospheric decontamination and sea clutter suppression for HF skywave radars. *IEEE J. Ocean. Eng.* 30(2): 455–462

[12] Khan R H and Le-Ngoc S 1993 A singular value decomposition (SVD) based method for suppressing ocean clutter in high frequency radar. *IEEE Trans. Signal Process.* 41(3): 1421–1425

[13] Chen Z, He C, Zhao C and Xie F 2017 Using SVD-frft filtering to suppress first-order sea clutter in HFSWR. *IEEE Geosci. Remote Sens. Lett.* 14(7): 1076–1080

[14] Walsh J, Huang W and Gill E 2010 The first-order high frequency radar ocean surface cross section for an antenna on a floating platform. *IEEE Trans. Antennas Propag.* 58(9): 2994–3003

[15] Ma Y, Gill E W and Huang W 2016 First-order bistatic high-frequency radar ocean surface cross-section for an antenna on a floating platform. *IET Radar Sonar Navig.* 10(6): 1136–1144

[16] Walsh J, Huang W and Gill E 2012 The second-order high frequency radar ocean surface cross section for an antenna on a floating platform. *IEEE Trans. Antennas Propag.* 60(10): 4804–4813

[17] Wang W and Wyatt L R 2011 Radio frequency interference cancellation for sea-state remote sensing by high-frequency radar. *IET Radar Sonar Navig.* 5(4): 405–415

[18] Wax M and Kailath T 1985 Detection of signals by information theoretic criteria. *IEEE Trans. Acoust., Speech Signal Process.* 33(2): 387–392

[19] Fishler E, Grosmann M and Messer H 2002 Detection of Signals by Information Theoretic Criteria: General Asymptotic Performance Analysis. *IEEE Trans. Signal Process.* 50(5): 1027–1036

[20] Luo H 2019 Ionospheric decontamination method based on optimization criteria in over-the-horizon radar. *J. Commun. Technol. Electron.* 64(11): 1283–1287