A Clutter Samples Increase Jamming Method to Airborne STAP

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Abstract. Proposed a clutter samples increase non-homogeneous jamming method to airborne space-time adaptive processing. The method uses digital radio frequency storage as a realization method. First, the number of interference samples is obtained by estimating the radar range resolution and the target radar interference distance, and then modulate jamming information with non-homogeneous clutter background environment parameters on the radar clutter echo, include signal amplitude, interference phase and Doppler frequency. Lastly, with the Clutter echo in protected areas for the pollution of the co-variance matrix by STAP, the method can reduce the STAP processing target detection ability. The validity is verified by the simulated processing results of a real airborne radar data.

Keywords: Non-homogeneous clutter · Space-time adaptive processing · Digital radio frequency memory · Airborne radar

1 Introduction

Airborne early warning radars widely use space-time adaptive processing (STAP) to locate accurate target information in a complex clutter background [1]. The technology not only eliminates clutter and interference, but also improves the ability of early warning radar to detect targets in complex backgrounds through adaptive filtering in the space and time domain. Since the 1990s, one began to propose a series of STAP algorithms for dimensionality reduction [2–4]. However, the algorithms are all in the case of sub-optimal adaptive performance, reducing the amount of calculation and sample requirements by reducing the

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degree of adaptive freedom, so as to solve the real-time work problem of STAP in engineering.

One of the core contents of STAP is how to achieve the problem of quasi-optimal interference filtering in a non-uniform environment. Non-uniform environments include non-uniform power, interference targets, and isolated interference. The clutter samples of different distance gates have different statistical characteristics. If the range gate samples do not contain part or all of the clutter information in the sample to be detected, adaptive processing will not be able to effectively suppress the clutter in the sample to be detected, resulting in an increase in the false alarm rate and a decrease in detection performance. In order to obtain independent and identically distributed (IID) samples, SATP usually screens the collected samples through a non-homogeneous detector (NHD), and detects and eliminates the samples in the training samples that do not meet the clutter distribution conditions of the samples to be filtered.

For the SATP of non-uniform detection to obtain sufficient IID samples, a STAP method to enhance the non-uniform characteristics of echo samples is proposed. Firstly, the method estimates the radar range resolution and interference distance data to obtain the number of interference samples through digital radio frequency storage [5,6], and then obtains the interference density of complex background clutter through the number of interference samples to achieve accurate generation of complex background template interference. After that, The interference signal is calculated, which is based on the target scattering modulation matrix and the radar range resolution, and forwards it to the interference radar. Finally, the preset non-uniform clutter environmental parameters are superimposed on the early warning radar echo, Comprehensive interference modulation is performed on the amplitude, phase and Doppler frequency of the signal re-transmitted to realize the pollution of the STAP processing covariance matrix by the interference echo in the protection area, thereby reducing the STAP target detection capability. Based on the actual processing results of an early warning radar data, the effectiveness of the method in this paper is verified [7].

2 The Principles of Space-Time Adaptive Processing

Due to the movement characteristics of airborne radar, its Doppler frequency of ground clutter varies from different directions. The radar will seriously broaden the Doppler frequency of the moving target according to the Doppler frequency of the ground clutter received by its antenna pattern. From the perspective of the Doppler domain, the moving target and the clutter are aliased together, and the traditional one-dimensional time-domain Doppler filter processing method of separating the moving target and the stationary ground clutter will no longer be effective. The space-time coupling characteristic that the Doppler spectrum of the clutter will change with the spatial direction of the scattered clutter is a basic characteristic of the moving platform radar. According to the Doppler (time domain) and the direction of arrival (space domain), the method to distinguish moving targets and stationary ground clutter is space-time signal processing. In addition to the uncertainties of the environment and the system, adaptive space-time adaptive processing (STAP) is usually used in practice.

The airborne radar causes the space and time domain of the echo signal to be coupled due to the movement of the platform. Assuming that the radar antenna has a uniform linear array structure (it can also be an equivalent linear array structure of a surface array synthesized by microwaves), the number of array elements is N, for the lth range gate, the number of pulses in a coherent processing interval (CPI) is K, the received space-time data X is a matrix of $N \times K$, the echo of the nth element under the kth pulse is represented by $x_{n,k}$ in the matrix, and the matrix can be expressed as follows.

$$\mathbf{X} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,K} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N,1} & x_{N,2} & \cdots & x_{N,K} \end{bmatrix} \tag{1}$$

According to the same matrix structure, the target signal S can also be expressed as a one-dimensional matrix of $N \times K$, which is composed of a spatial steering vector and a time-domain steering vector. The two vectors are as follows:

$$\mathbf{S}_S(\psi_{S0}) = [1, \exp(j\phi_S(\psi_{S0})), \cdots, \exp(j(N-1)\phi_S(\psi_{S0}))]^{\mathrm{T}} \tag{2}$$

$$\mathbf{S}_T(f_{d0}) = [1, \exp(j\phi_T(f_{d0})), \cdots, \exp(j(K-1)\phi_T(f_{d0}))]^{\mathrm{T}} \tag{3}$$

Here, $\varphi_S(\psi_{S0}) = \frac{2\pi d}{\lambda}\cos\theta_0\cos\varphi_0$ represents spatial steering vector, where d is the element spacing, λ and θ_0 is the wavelength and the azimuth angle of the target respectively. Similarly, $\varphi_T(f_{d0}) = \frac{2\pi f_{d0}}{f_r}$ is the time-domain steering vector, where f_{d0} and f_r is the Doppler frequency of the target and the pulse repetition frequency. Here are examples of the front view array, the target signal S is expressed as follows.

$$\mathbf{S} = \mathbf{S}_S(\psi_{S0}) \otimes \mathbf{S}_T^{\mathrm{T}}(f_{d0}) \tag{4}$$

Space-time processing is the weighted summation of the $N \times K$dimensional matrix X, and the detection output of the target direction and Doppler. The process can be illustrated in Fig. 1.

The premise of dimensionality reduction STAP is that the degree of freedom of clutter should be less than NK, which provides a theoretical basis for dimensionality reduction processing. The dimensionality reduction STAP technology is divided into two types: adaptive dimensionality reduction structure and fixed dimensionality reduction structure. The processing structure of the former is variable, while the latter is fixed. Either fixed dimensionality reduction or adaptive dimensionality reduction can be considered to obtain an N-dimensional dimensionality reduction matrix, where N and K are the dimensions of the space-time signal before and after the dimensionality reduction, respectively. Of course,

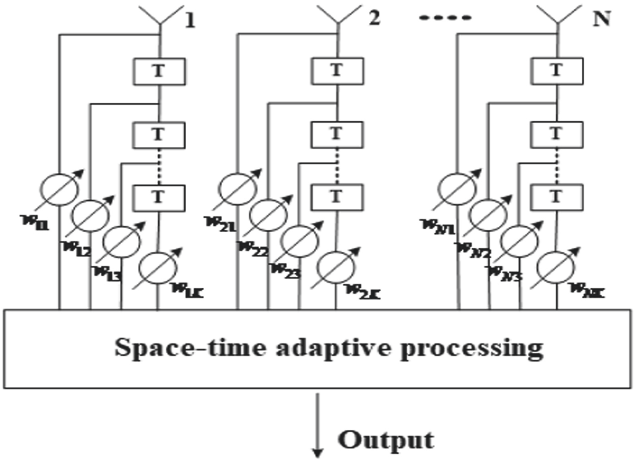

Fig. 1. Block diagram of space-time adaptive processing principle.

this is a dimensionality reduction only when the situation of $Q < NK$ is true.The difference is that the acquisition of the former has nothing to do with the data than the latter. The following relationship exists between the data vector before and after the dimensionality reduction and the signal steering vector.

$$\begin{cases} \mathbf{x}_r = T^H \mathbf{x} \\ \mathbf{s}_r = T^H \mathbf{s} \end{cases} \tag{5}$$

The clutter co-variance matrix after dimensionality reduction is as follows:

$$\mathbf{R}_{\mathbf{X}_r} = E\left[\mathbf{x}_r \mathbf{x}_r^H\right] = T^H \mathbf{R}_{\mathbf{X}} T \tag{6}$$

STAP for dimensionality reduction is equivalent to solving the following optimization problem:

$$\begin{cases} \min\limits_{\mathbf{W}_r} \mathbf{W}_r^H \mathbf{R}_{\mathbf{X}_r} \mathbf{W}_r \\ s.t.\mathbf{W}_r^H \mathbf{s}_r = 1 \end{cases} \tag{7}$$

The optimal weight vector is obtained as follows:

$$\mathbf{W}_r = \mu_r \mathbf{R}_{\mathbf{X}_r}^{-1} \mathbf{s}_r \tag{8}$$

Where $\mathbf{R}_X = E[xx^{\mathrm{H}}]$ is the co-variance matrix of space-time sampled data, which is obtained by estimation. Therefore, the clutter co-variance matrix of STAP can be obtained through distance sample statistics. The prerequisite for the optimal performance of STAP is that there are sufficient clutter samples that meet the independent and identical distribution condition, so that the clutter co-variance matrix can be estimated according to $\hat{\mathbf{R}}_x = \frac{1}{L} \sum\limits_{l=1}^{L} \mathbf{x}_l \mathbf{x}_l^H$. Literature

[8] discussed the convergence characteristics of statistical STAP in the Gaussian independent identically distributed sample environment, and pointed out that when the number of independent identically distributed training samples is more than twice the dimension of the processor, it can ensure that the output signal-to-noise ratio loss does not exceed 3 dB compared with ideal optimal processing.

It is well known that the basic problem of setting one is to correctly estimate the true unknown interference co-variance matrix and to calculate an excellent adaptive weight vector when designing the STAP system. In a non-uniform environment, choosing appropriate training samples is an important way to correctly estimate the interference co-variance matrix. The STAP including sample rejection is as follows: select A training samples along the distance dimension, process these training samples with an NHD (Non-Homomorphic Detector), and pick out B uniform training samples (i.e. does not include interfering targets) to estimate the co-variance matrix according to the NHD processing results. The basis for this is that NHD is a statistic that can reflect changes in the statistical characteristics of the sample. According to whether there are interfering samples, the different output results of NHD are used to achieve the effect of eliminating samples containing interfering targets. Training the STAP processor with the remaining samples will not cause performance loss due to interference with the target.

The generalized inner product is defined as following:

$$\eta(\mathbf{X}_l, \hat{\mathbf{R}}_{L+O}) = \mathbf{X}_l^H \hat{\mathbf{R}}_{L+O}^{-1} \mathbf{X}_l \tag{9}$$

Where $\hat{\mathbf{R}}_{L+O}$ is the co-variance matrix estimated with $L + O$ candidate reference samples. The generalized inner product is a typical non-uniform detector, which represents the remaining energy after whitening and suppressing the clutter in the vector $\mathbf{X}_l$. Generally, if the structure of the co-variance matrix of $\mathbf{X}_l$ is the same or similar to that of $\hat{\mathbf{R}}_{L+O}$, it is uniform and should be retained; otherwise, it should be eliminated. The expected value of the GIP test statistic under a uniform sample is expressed as follows:

$$E[\eta(\mathbf{X}_\mathbf{l}, \hat{\mathbf{R}}_{L+O})] \approx trace(\hat{\mathbf{R}}_{L+O}^{-1} \hat{\mathbf{R}}_{L+O}) = M \tag{10}$$

Let M denote the dimension of the processor and *trace* represents the trace calculation of the matrix. In the case of non-uniform samples, there are the following equations.

$$E[\eta(\mathbf{X}_\mathbf{l}, \hat{\mathbf{R}}_{L+O})] = trace(\hat{\mathbf{R}}_{L+O}^{-1} \varDelta \hat{\mathbf{R}}) + M \tag{11}$$

It can be seen that the GIP test statistics under non-uniform samples will deviate from the output under uniform samples. Therefore, the non-uniformity can be detected based on the degree of deviation of the GIP test statistic from the expected value, that is, the non-uniformity can be detected based on the degree of deviation of $\eta(\mathbf{X}_\mathbf{l}, \hat{\mathbf{R}}_{L+O})$ from M.

$$\eta(\mathbf{X}_l, \hat{\mathbf{R}}_{L+O}) = \mathbf{X}_l^H \hat{\mathbf{R}}_{L+O}^{-1} \mathbf{X}_l \tag{12}$$

3 Implementation of Non-uniform STAP Radar Interference

For generalized inner product sample extraction, if the conventional isolated strong interference method is used, the statistical characteristics of the range gate echo where the jammer is located will be different from the samples within other distances around it. The GIP test statistic under non-uniform samples will deviate from the output under uniform samples, and thus will be eliminated and cannot achieve effective interference.

The jammer uses a higher power method to interfere, and the corresponding STAP samples will be eliminated. Therefore, the interference signal power needs to be equivalent to the actual background echo. According to the characteristics of actual radar processing, an interference modulation parameter library with a complex city as the background is constructed. The specific interference realization process is as follows:

(1) According to the echo parameters received by the jammer, estimate the distance range that needs to be interfered and calculate the required distance towing delay.

$$\tau = \frac{R_{\max} - R_{\min}}{\mathrm{c}} \tag{13}$$

Where c is the speed of light, $R_{\max}$ and $R_{\min}$ represent the longest and shortest jamming range respectively.

(2) Then refer to the reconnaissance receiver to obtain the radar signal parameters to estimate the radar range resolution $\rho = \frac{c}{2B}$,where B is the bandwidth of the radar signal. And calculate the number of samples that need interference as follows:

$$N = \mathrm{int}\left(\frac{R_{\max} - R_{\min}}{\rho}\right) \tag{14}$$

(3) Take complex background templates to extract radar echo parameters such as urban areas, and generate interference scene modulation parameters to construct target scattering modulation matrix S_J according to the number of range gates.

$$S_{J(K\times N)} = \left\{\begin{matrix} A_1 e^{j\phi_1} e^{jf_1}, A_2 e^{j\phi_2} e^{jf_1}, ..., A_{N-1} e^{j\phi_{N-1}} e^{jf_1} & A_N e^{j\phi_N} e^{jf_1} \\ A_1 e^{j\phi_1} e^{jf_2}, A_2 e^{j\phi_2} e^{jf_2}, ..., A_{N-1} e^{j\phi_{N-1}} e^{jf_2} & A_N e^{j\phi_N} e^{jf_2} \\ ... & ... \\ A_1 e^{j\phi_1} e^{jf_{K-1}}, A_2 e^{j\phi_2} e^{jf_{K-1}}, ..., A_{N-1} e^{j\phi_{N-1}} e^{jf_{K-1}} & A_N e^{j\phi_N} e^{jf_{K-1}} \\ A_1 e^{j\phi_1} e^{jf_K}, A_2 e^{j\phi_2} e^{jf_K}, ..., A_{N-1} e^{j\phi_{N-1}} e^{jf_K} & A_N e^{j\phi_N} e^{jf_K} \end{matrix}\right\} \tag{15}$$

(4) The constant K can be set with reference to the number of radar pulses acquired by the electronic reconnaissance aircraft. Among them, A_N is the amplitude corresponding to the Nth distance unit, $e^{j\phi_N}$ is the phase, and e^{jf_K} is the Doppler modulation amount.

(5) Two-dimensional modulation of the amplitude and frequency of the echo received by the jammer to produce an interference signal based on a complex background is as follows.The entire interference process is shown in Fig. 2.

$$S_{\mathrm{J}}(n,t)=\sum_{n=1}^{N}\sum_{k=1}^{\mathrm{K}}S_{J(n,\mathrm{k})}S_{t}(n,t-\frac{n\rho}{c}) \tag{16}$$

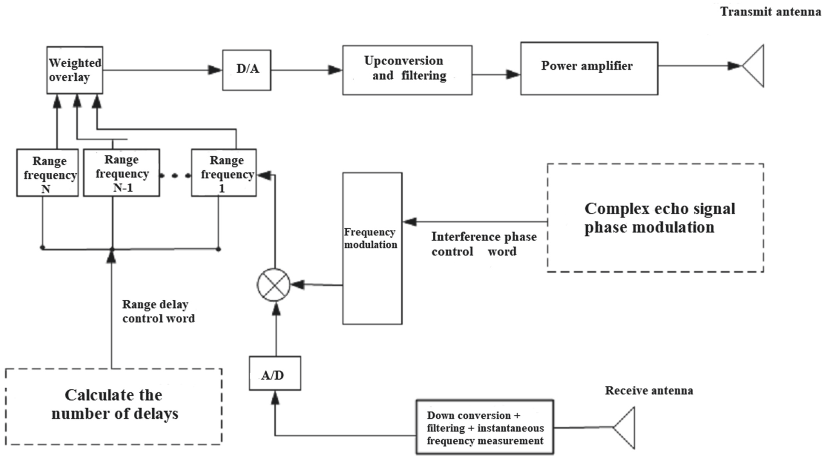

Fig. 2. Block diagram of space-time processing interference.

4 Simulation Results

Take the airborne early warning MCARM radar measured data (without considering the distance ambiguity) to verify the performance of the jamming method in this paper. The height of the early warning carrier is 3073 m, the speed of the carrier is 100 m/s, the operating frequency is about 1.2 GHz, the distance gate is 630, and the number of antennas is 11. Intercept the data from 200 to 630 range gates. Figure 3 shows the echo power brightness map of the fifth spatial channel after MTD processing.

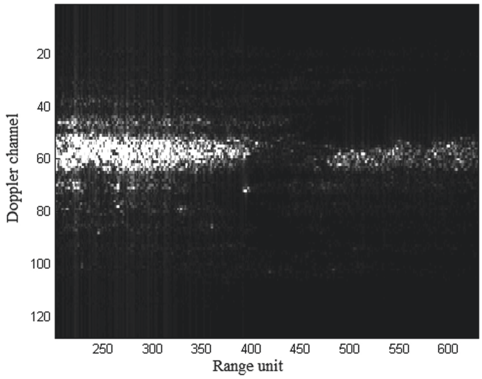

Fig. 3. Single-channel MTD processed image.

Take the interference 150 to 300 range gate as the complex interference background, because this piece of data belongs to the urban background, it can be seen that the main clutter area occupies nearly 20 Doppler channels and the echo is strong. The 450–600 range gate is used as the processing target to verify the interference effect of this method, and 3DT-STAP is used for clutter suppression.

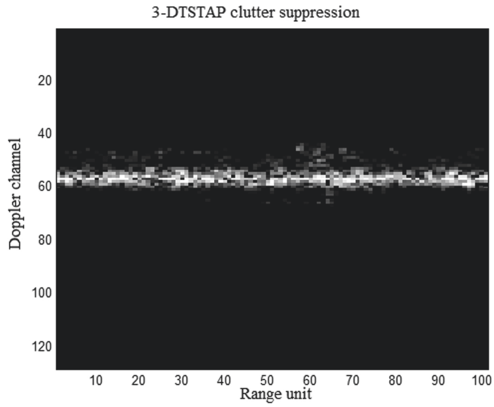

Fig. 4. 3DT-STAP space-time adaptive processing results.

It can be seen from Fig. 4 that after 3DT-STAP space-time adaptive processing, the ground clutter can be significantly suppressed, while the Doppler channel of the main clutter is significantly narrowed. This verifies the effectiveness of space-time adaptive processing. The method in this paper modulates the urban clutter with complex background to the relatively uniform range gate echo, which produces interference effects on the original IID samples, thereby reducing the clutter suppression and moving target detection capabilities of STAP.

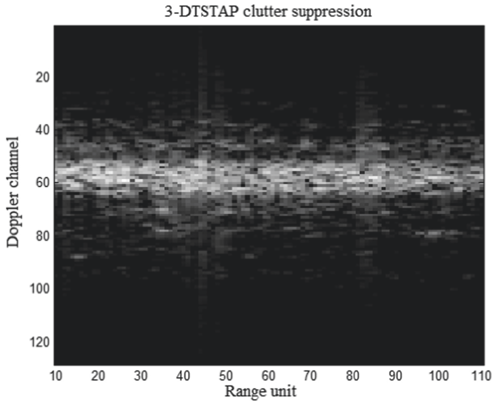

Fig. 5. Channel MTD image with increased interference.

Figure 5 is a single-channel range Doppler image after adding non-uniform echoes. It is obvious that the modulated clutter still has certain distribution characteristics. 3DT-STAP can no longer achieve better clutter suppression, especially after the contamination of non-uniform samples Compared with the processing result without sample contamination, the main clutter area is obviously widened.

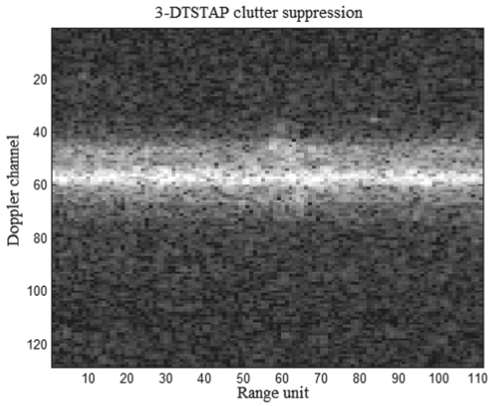

Fig. 6. 3DT-STAP with increased interference.

It is obvious from Fig. 6 that the use of complex echoes to forward interference samples destroys the independent and identical distribution characteristics of the original better sample distribution, resulting in a significant decrease in clutter suppression. At the same time, the target detection ability of the Doppler channel outside the main clutter is also reduced, which effectively suppresses the clutter suppression ability of STAP.

5 Conclusion

Aiming at the typical processing process of STAP's non-uniform sample detection to obtain sufficient IID samples, this paper proposes a STAP interference method that enhances the non-uniform characteristics of echo samples. This method obtains the number of interference samples by estimating the radar range resolution and target radar interference distance. Then the interference density of the complex background clutter can be effectively obtained through the number of interference samples, and the accurate generation of the interference of the complex background template can be realized. By superimposing the preset non-uniform clutter environmental parameters on the early warning radar echo, comprehensive interference modulation is performed on the amplitude, phase and Doppler frequency of the forwarded signal to achieve the pollution of the STAP co-variance matrix. Enhance the non-uniformity of the echo, thereby reducing the ability of STAP to process target detection. The processing results based on the actual data of a certain early warning radar verify that improving the non-uniformity of the echo can reduce the target detection performance of SATP.

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