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The post-Doppler adaptive processing method based on the spatial domain reconstruction

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ABSTRACT

Space-time adaptive processing (STAP) has a huge computational complexity and a large training samples requirement, which limit its practical applications. The traditional post-Doppler adaptive processing methods such as factored approach (FA) and extended factored approach (EFA) can significantly reduce the computational complexity and the training sample requirement in adaptive processing, and maintain nearly the same performance as the optimal STAP. However, because training samples are restricted in real-world environments, their performances can be considerably degraded in the large-scale antenna array. To solve this problem, the post-Doppler adaptive processing method based on the spatial domain reconstruction is proposed. In this method, the spatial clutter data after Doppler filtering is reconstructed as a matrix that has close columns and rows. The spatial weights vector in FA or EFA is also re-expressed as the product of two shorter weight vectors. Then the cyclic minimizer is applied to find the desired solution. Experimental results show that the proposed method has the advantages of fast convergence and small training samples requirement. It has greater moving target detection ability especially under the condition for large-scale antenna array and small training samples support than FA and EFA.

1. Introduction

Since Brennan and Reed [1] first jointly exploited spatial and temporal degrees of freedom (DoFs) in the early 1970s, the space-time adaptive processing (STAP) has been receiving much attention and widely applied to the airborne array radar because it can greatly improve the performance of the clutter suppression and moving target detection [2–4]. In particular, the output signal-to-interference-plus-noise-ratio (SINR) can be markedly increased by jointly exploiting spatial and temporal DoFs. Unfortunately, the RMB rule [5] verifies that the full-dimension STAP (will be called f-STAP in short) is impractical in realistic clutter environment since f-STAP requires excessive homogeneous samples. Furthermore, f-STAP that uses NK DOFs leads to an unbearable computational complexity of $O(N^3K^3)$. In other words, f-STAP can hardly work on line in a large-scale antenna array. These two main disadvantages limit the extensive applications of f-STAP and motivate the development of sub-optimal reduced-dimension [6–10] and reduced-rank [11–19] STAP algorithms.

The post-Doppler adaptive processing methods, such as the factored approach (FA, or 1DT) and the extended factored approach (EFA, or mDT) [6,7], can effectively reduce the homogeneous training sample requirement and computational complexity in adaptive processing. They transform the f-STAP, which is actually an NK-dimensional space-time filtering problem, into K separate mN(m is an integer and $m \geq 1$) dimensional adaptive processing problems [7]. According to the RMB rule, the number of homogeneous training samples required for estimating the clutter covariance matrix in post-Doppler adaptive processing is $2mN$, which is less than $2NK$. In addition, the computational complexity of FA and EFA are

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decreased to approximate $O(m^3N^3)$. Less homogeneous training samples requirement and smaller computational complexity increase their applicability in practice.

However, under the condition for large-scale antenna array with numerous elements, post-Doppler adaptive processing methods still have very high adaptive DOFs, which results in that they require excessive homogeneous training samples that cannot be provided in practice. Besides, their clutter suppression and moving target detection ability will be dramatically degraded in this condition since training samples are intrinsically insufficient in real clutter environment. Hence, in order for the post-Doppler adaptive processing methods in large-scale antenna array to effectively enhance their ability for suppressing the clutter and detecting the moving target, we propose the post-Doppler adaptive processing method based on the spatial domain reconstruction to further reduce the dimension. Firstly, this method reconstructs the spatial clutter data vector in FA or EFA as a matrix that has close columns and rows. Secondly, the original cost function of FA or EFA is turned into a bi-quadratic cost function. Thirdly, the cyclic minimizer [20] is applied to find the desired weight vectors. As a matter of fact, our proposed method is two-stage dimension reduced. The Doppler filtering that projects the space-time data vector into a lower dimensional subspace is the first stage dimension reducing while the second stage dimension reducing is performed by reconstructing the original weight vector of the FA or the EFA into two shorter weight vectors. Experimental results verify the clutter suppression and moving target detection ability of this method. Especially, since this method makes the adaptive weight vector in FA or EFA become two considerably smaller weight vectors, it has a much faster convergence rate. Meanwhile, our proposed method has significantly smaller computational complexity than the traditional post-Doppler adaptive processing. Therefore, the proposed method is an effective tool for suppressing clutter and detecting moving targets under the condition for large-scale antenna array with numerous elements in reality.

2. Ground clutter model and the post-Doppler adaptive processing methods

The airborne platform moves parallel to the ground with N antenna array elements. The system processes K pulses in one coherent processing interval (CPI). Then the clutter plus noise data received by the radar system in a range cell are expressed in vector form as [2]

$$\mathbf{x}(l) = [x_{1,1}(l), x_{1,2}(l), \cdots, x_{1,K}(l), x_{2,1}(l), \cdots, x_{N,K}(l)]^T, \tag{1}$$

where $x_{n,k}(l)$ $(n = 1, \cdots, N, k = 1, \cdots, K)$ represents the clutter plus noise data received by the nth antenna at the kth transmitting pulse, the superscript $(\cdot)^T$ represents transpose. The post-Doppler adaptive processing methods perform Doppler filter banks on data of each array element. Adaptive beamforming is then implemented separately within one or several Doppler bins [3]. Let $\mathbf{f}_k$ be the kth $(k = 1, 2, \cdots, K)$ Doppler filter coefficient vector, then the spatial data in the kth Doppler bin are expressed as

$$\tilde{\mathbf{x}}_k(l) = (\mathbf{f}_k \otimes \mathbf{I}_N)^H \mathbf{x}(l), \tag{2}$$

where the superscript $(\cdot)^H$ represents conjugate transpose, $\otimes$ represents Kronecker product, $\mathbf{I}_N$ is an $N \times N$ identity matrix. Let the target steering vector be marked as $\mathbf{s} = [s_{1,1}, s_{1,2}, \cdots, s_{1,K}, s_{2,1}, \cdots, s_{N,K}]^T$. Then the target steering vector in the kth Doppler bin is represented as

$$\tilde{\mathbf{s}}_k = (\mathbf{f}_k \otimes \mathbf{I}_N)^H \mathbf{s}. \tag{3}$$

The objective of FA is to minimize the output energy of clutter plus noise while maintaining that of the target constant in a Doppler bin. This implies that

$$\begin{cases} \min E[|\tilde{\mathbf{w}}_{FA}^H \tilde{\mathbf{x}}_k(l)|^2] \\ s.t. \tilde{\mathbf{w}}_{FA}^H \tilde{\mathbf{s}}_k = 1 \end{cases}. \tag{4}$$

The Lagrange multiplier methodology can be applied to obtain the optimal weight

$$\tilde{\mathbf{w}}_{FA} = \mathbf{R}_{\tilde{x}_k}^{-1} \tilde{\mathbf{s}}_k / (\tilde{\mathbf{s}}_k^H \mathbf{R}_{\tilde{x}_k}^{-1} \tilde{\mathbf{s}}_k), \tag{5}$$

where $\mathbf{R}_{\tilde{x}_k} = E[\tilde{\mathbf{x}}_k(l) \tilde{\mathbf{x}}_k^H(l)]$ is the clutter plus noise covariance matrix in the kth Doppler bin. The symbol $[\bullet]^{-1}$ means the inverse of a matrix. However, as shown in many literatures [2,3], the so-called FA performance is usually poor for most applications. A much better approach is to apply space-time adaptivity to two or more Doppler bins. As similar to FA, EFA is performed by considering the combination of multiple adjacent Doppler bins to improve the clutter suppression ability in the temporal domain. In general, three adjacent Doppler bins are employed. Let $\tilde{\mathbf{y}}_k(l) = [\tilde{\mathbf{x}}_{k-1}^T(l), \tilde{\mathbf{x}}_k^T(l), \tilde{\mathbf{x}}_{k+1}^T(l)]^T$ and $\tilde{\mathbf{p}}_k = [\tilde{\mathbf{s}}_{k-1}^T, \tilde{\mathbf{s}}_k^T, \tilde{\mathbf{s}}_{k+1}^T]^T$. The optimal weight to EFA is

$$\tilde{\mathbf{w}}_{EFA} = \mathbf{R}_{\tilde{y}_k}^{-1} \tilde{\mathbf{p}}_k / (\tilde{\mathbf{p}}_k^H \mathbf{R}_{\tilde{y}_k}^{-1} \tilde{\mathbf{p}}_k), \tag{6}$$

where $\mathbf{R}_{\tilde{y}_k} = E[\tilde{\mathbf{y}}_k(l) \tilde{\mathbf{y}}_k^H(l)]$. In practice, L secondary training samples in adjacent range cells are used for estimating the following clutter pulse noise covariance matrices

$$\hat{\mathbf{R}}_{\tilde{x}_k} = \frac{1}{L} \sum_{l=1}^{L} \tilde{\mathbf{x}}_k(l) \tilde{\mathbf{x}}_k^H(l) \tag{7}$$

$$\hat{\mathbf{R}}_{\tilde{y}_k} = \frac{1}{L} \sum_{l=1}^{L} \tilde{\mathbf{y}}_k(l) \tilde{\mathbf{y}}_k^H(l). \tag{8}$$

We expect $\hat{\mathbf{R}}_{\tilde{x}_k} = \mathbf{R}_{\tilde{x}_k}, \hat{\mathbf{R}}_{\tilde{y}_k} = \mathbf{R}_{\tilde{y}_k}$ when the number of homogeneous training samples tends to infinity, that is, $L \to \infty$. However, in real clutter environment, only finite homogeneous training samples can be acquired. RMB rule shows that, in the Gaussian noise environment, if the number of homogeneous training sample exceeds twice the dimension of the clutter covariance matrix, the normalized output SINR loss will be within $3dB$. Although FA and EFA reduce the sizes of clutter covariance matrices in adaptive processing, their normalized output SINR will still be severely decreased due to the insufficient homogeneous training samples support when the antenna array elements are large.

3. Principle of the proposed method

For simplicity, we illustrate our proposed method by the spatial data in one Doppler bin. The clutter plus noise data in the kth Doppler bin can be described by

$$\tilde{\mathbf{x}}_k(l) = [\mathbf{f}_k^H \otimes \mathbf{I}_N] \mathbf{x}(l) = [\tilde{x}_1(l), \tilde{x}_2(l), \cdots, \tilde{x}_N(l)]^T. \tag{9}$$