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Short communication

A robust STAP method for airborne radar with array steering vector mismatch

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ABSTRACT

In this paper, we consider the problem of space-time adaptive processing (STAP) for airborne radar in the presence of direction-of-arrival (DOA) and Doppler frequency uncertainties, either of which would result in steering vector mismatch. A robust STAP method is devised by introducing an accurate steering vector estimator. In particular, by considering the mismatched DOA and Doppler frequency, a spatial-temporal integral covariance matrix including the actual steering vector component is first constructed. The subspace corresponding to the clutter-plus-noise is then extracted from the so-obtained matrix and used to impose an appropriate constraint to estimate the actual steering vector. The resultant problem is a non-convex quadratically constrained quadratic program (QCQP), which is solved using the semidefinite programming (SDP) relaxation technique. Numerical examples are presented to demonstrate the performance of the proposed approach in different hypothetical scenarios.

1. Introduction

Space-time adaptive processing (STAP) is a two dimensional adaptive beamforming algorithm, which is able to not only suppress wideband interferences [1] but also detect moving targets in the presence of clutter [2–4]. However, a small error in either direction-of-arrival (DOA) or Doppler frequency may result in the mismatch of steering vector and subsequently the cancellation of signal-of-interest (SOI). Then the STAP filter, i.e., the beamformer in the following, misinterprets the SOI as clutter and tries to suppress it [5].

Numerous robust adaptive beamforming (RAB) techniques have been proposed to deal with the steering vector mismatch in the literature [6–19]. The eigenspace-based beamformer method is simple and efficient for strong interferences [6]. However, it would suffer from subspace swap at low signal-to-noise ratio (SNR) levels [7]. Several worst-case optimization beamformers were proposed in [8–10], where constraints on the uncertainty set are utilized to preserve a certain array gain against uncertainties in the steering vector. However, the norm bound of the uncertainty set should be carefully prescribed, otherwise, the performance may be significantly deteriorated. In [11–14], the constraints on the magnitude response, which have the flexibility in controlling the beamwidth and response ripple in the desired direction, are imposed to improve the robustness. However, these methods may reduce the signal-to-interference-plus-noise ratio (SINR) owing to the fact that the noise power is also amplified in the constrained beamwidth accordingly. Contrary to the worst-case optimization and the magnitude response approaches, the robust beamformer in [15,16] firstly correct the mismatched steering vector before the determination of beamformer weight vector. These two algorithms do not make assumptions on either the norm of the mismatch vector or the bounds of magnitude response constraints. However, the iterative quadratic convex optimization in [15] is a tedious process and the upper bound of the constraint in [16] is difficult to determine. More recently, a response vector constrained beamformer, which can yield a lower beampattern sidelobe than that of the traditional linearly constrained minimum variance (LCMV) beamformer [17], was reported in [18,19]. However, its signal-to-clutter-plus-noise ratio (SCNR) loss performance may be considerably degraded when the Doppler frequency of the SOI is close to the clutter ridge.

In this work, the region-of-interest (ROI) in which the DOA and Doppler frequency of the SOI locates is first chosen to construct a spatial-temporal integral covariance matrix. With the so-obtained covariance matrix, the subspace of clutter-plus-noise can be determined, which can be efficiently employed for constraint imposition based on subspace orthogonality. By maximizing the output power of beamformer, the problem of steering vector estimation is formulated as a non-convex quadratically constrained

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quadratic program (QCQP), which can be efficiently solved using the semidefinite programming (SDP) relaxation technique [20]. Unlike the approach in [15], the proposed robust STAP method is free of an iterative procedure. Simulation results illustrate that the proposed robust STAP method can provide superior performance in terms of output SCNR over the state-of-the-art approaches.

2. Array signal model

Consider a side-looking airborne radar system with a uniform linear array (ULA) consisting of N elements, as shown in Fig. 1. Assume that each antenna element transmits M coherent pulses and the inter-element spacing is half wavelength. The spatial-temporal steering vector of echo signal can be expressed as

$$\boldsymbol{a}_{st}(f_d,\theta)=\boldsymbol{a}_s(\theta)\otimes\boldsymbol{a}_t(f_d) \tag{1}$$

where $\otimes$ denotes the Kronecker product, θ denotes the DOA, f_d denotes the Doppler frequency, $\boldsymbol{a}_s(\theta)$ and $\boldsymbol{a}_t(f_d)$ denote, respectively, the spatial and temporal steering vectors, as

$$\boldsymbol{a}_s(\theta)=\left[1e^{j\frac{2\pi}{\lambda}d\,\sin(\theta)}\ldots e^{j\frac{2\pi}{\lambda}(N-1)d\,\sin(\theta)}\right]^T \tag{2}$$

$$\boldsymbol{a}_t(f_d)=\left[1e^{j\frac{2\pi f_d}{f_r}}\ldots e^{j\frac{2\pi(M-1)f_d}{f_r}}\right]^T \tag{3}$$

where f_r is the radar pulse repetition frequency (PRF).

Assume that the DOA and Doppler frequency associated with the desired signal are θ_0 and f_{d_0}, respectively. The array observation $\boldsymbol{x}(k)\in C^{MN\times 1}$ at time k can be expressed as

$$\boldsymbol{x}(k)=s(k)\boldsymbol{a}_{st}(f_{d_0},\theta_0)+\boldsymbol{n}_{cn}(k) \tag{4}$$

where $s(k)$ stands for the desired signal waveform and $\boldsymbol{n}_{cn}(k)$ denotes the clutter-plus-noise component.

In the presence of DOA and Doppler frequency mismatches, the actual steering vector $\boldsymbol{a}_{st}(f_{d_0},\theta_0)$ can be modeled as

$$\boldsymbol{a}_{st}(f_{d_0},\theta_0)=\boldsymbol{a}_{st}(\bar{f}_{d_0},\bar{\theta}_0)+\boldsymbol{\delta} \tag{5}$$

where $\bar{\theta}_0$ and $\bar{f}_{d_0}$ are the nominal DOA and Doppler frequency, respectively, and $\boldsymbol{\delta}$ represents the steering vector mismatch. Assume that the mismatch vector is bounded as $\|\boldsymbol{\delta}\|\le\varepsilon$, where $\|\cdot\|$ denotes the ℓ_2 norm and ε is a certain known constant. It is known that either over or under estimation of the bound may lead to the performance degradation. For notational simplicity, the true and nominal steering vectors are denoted by $\boldsymbol{a}_{st0}$ and $\bar{\boldsymbol{a}}_{st0}$, respectively. The problem at hand is to utilize the nominal steering vector to devise an optimal space-time weight vector in some sense to correct the beampattern.

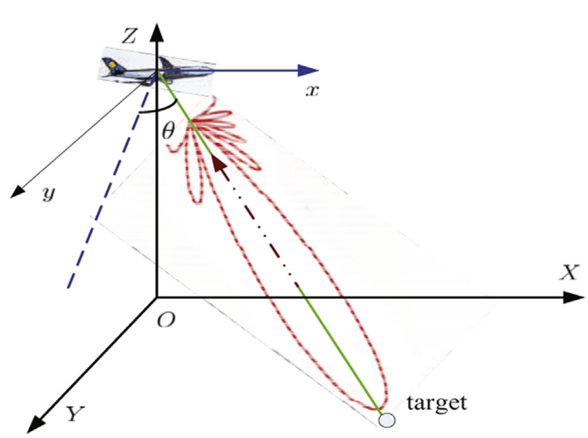

Fig. 1. Geometry of airborne radar system.

3. The proposed robust STAP method

In order to overcome the shortcomings of existing approaches as mentioned earlier, a new robust STAP method for airborne radar is introduced. For ease of illustration, the ROIs of the DOA and Doppler frequency are illustrated in Fig. 2. The nominal position of DOA and Doppler frequency is considered as the center which is not coincident with the actual one. $\boldsymbol{\Theta}$ denotes the spatial region covering the possible target DOA θ and $\mathcal{F}$ denotes the frequency region including the possible target Doppler frequency f_d. $\boldsymbol{\Theta}$ and $\mathcal{F}$ are uniformly sampled with interval θ_{bin} and f_{bin}, respectively. Practically, $\boldsymbol{\Theta}$ and $\mathcal{F}$ can be set according to the estimates of DOA and Doppler frequency obtained by using direction finding and frequency estimation techniques. In this work, they are assumed to be known and distinguishable from clutter location. Then they can be utilized to construct a spatial-temporal integral covariance matrix as

$$\boldsymbol{Q}=\int_{\mathcal{F}}\int_{\boldsymbol{\Theta}}\boldsymbol{a}_{st}(f_d,\theta)\boldsymbol{a}_{st}^H(f_d,\theta)\,d\theta\,df_d. \tag{6}$$

where $(\cdot)^H$ stands for the Hermitian transpose. It can be seen that $\boldsymbol{Q}$ is a positive definite matrix. Let us take the eigendecompositon of the above integral covariance matrix and obtain an orthogonal matrix $\boldsymbol{E}=[\boldsymbol{e}_1,\boldsymbol{e}_2,\ldots,\boldsymbol{e}_P]$ composed of the P dominant eigenvectors $\{\boldsymbol{e}_p\}_{p=1}^P$. Based on subspace property, $\boldsymbol{E}$ can be regarded as the signal subspace in which the actual steering vector $\boldsymbol{a}_{st0}$ lies. The remaining $MN-P$ subdominant eigenvectors form a complementary orthogonal matrix $\tilde{\boldsymbol{E}}$, and hence, we have

$$\tilde{\boldsymbol{E}}^H\boldsymbol{a}_{st0}=\boldsymbol{0}. \tag{7}$$

In what follows, the above property is adopted for robust STAP design.

It is known that, once the clutter has been suppressed, the output power of the beamformer [9], is given by

$$\sigma_{out}=1/(\boldsymbol{a}_{st0}^H\hat{\boldsymbol{R}}^{-1}\boldsymbol{a}_{st0}). \tag{8}$$

Here, $\hat{\boldsymbol{R}}=K^{-1}\sum_{k=1}^K\boldsymbol{x}(k)\boldsymbol{x}^H(k)$ is the sample covariance matrix and K is the number of snapshots. As a result, we propose to estimate the actual steering vector $\boldsymbol{a}_{st0}$ by maximizing the beamformer output power σ_{out} or, equivalently, minimizing $\boldsymbol{a}_{st0}^H\hat{\boldsymbol{R}}^{-1}\boldsymbol{a}_{st0}$. More precisely, the steering vector $\boldsymbol{a}_{st0}$ can be determined by solving the following

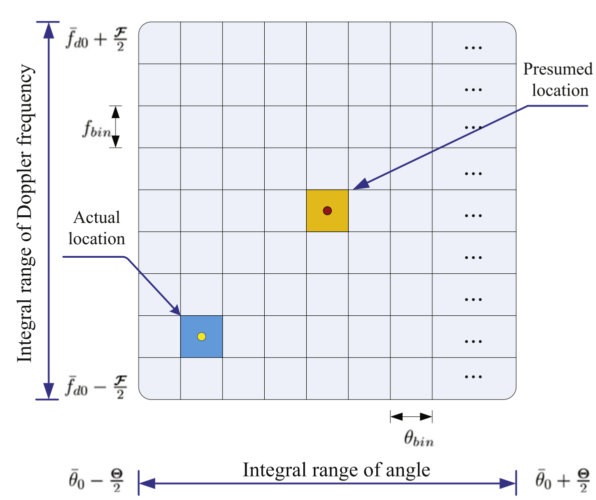

Fig. 2. Illustration of integral range.