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Successive DSPE-based coherently distributed sources parameters estimation for unmanned aerial vehicle equipped with antennas array

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ABSTRACT

In electronic countermeasures and reconnaissance, unmanned aerial vehicle (UAV) has played a more and more significant role. Usually when UAV conducts low altitude reconnaissance, due to the complicated environment, the reflected signals of the same source through different propagation paths will produce multipath signals. In this paper, we construct the received multipath signals of UAV with antennas array as coherently distributed (CD) sources model and propose a successive distributed signal parameter estimation (S-DSPE) algorithm to estimate its nominal direction of arrival (DOA) and angular spread. The proposed algorithm simplifies two-dimensional (2D) spectral peak searching within the conventional DSPE algorithm to one-dimensional spectral peak searching, which remarkably reduces the computational complexity of conventional DSPE algorithm. Furthermore, the parameters estimation performance of the proposed algorithm is close to the conventional DSPE algorithm, and outperforms the estimation of signal parameters via rotational invariance technique (ESPIRT) algorithm and propagator method (PM). The simulations results verify the usefulness of the proposed algorithm.

1. Introduction

In recent decades, with the development of science and technology, the applications of unmanned aerial vehicle (UAV) have become more and more extensive, which including electronic countermeasures, geological survey, logistics transportation, rescue inspection and so on [1–7]. For UAV reconnaissance system, how to obtain the direction of arrival (DOA) of received signals from the reconnaissance area has played a significant role [8–14]. Till now, based on array signal processing, many traditional DOA estimation algorithms like multiple signals classification (MUSIC) algorithm [15] and estimation of signal parameters via rotational invariance technique (ESPIRT) algorithm [16] have been developed for far-field point source model. However, in many practical low altitude reconnaissance of UAV, due to the compound ground environment like big city with kinds of high buildings, the reflected signals of the same sources through different propagation paths will produce multipath signals. In addition, the effect of angular spread of the received signals also should be taken into account. In this case, the traditional far-field point source model is not suitable to describe the received signals of UAV and the algorithms in [12–16] may fail to provide significant results.

The distributed sources model, which also referred to as the angle spread signal with distributive property, can find applications in wireless localization, mobile radio channel modeling and downlink beamforming [13] design for wireless networks [17–20], where the received signal is characterized by two angular parameters: the nominal DOA (defined as the mean value of DOAs of multiple rays) and the angular spread (defined as the standard deviation of angular distribution around the nominal DOA) [19]. Generally, the distributed source can be classified into two categories: coherently distributed (CD) source and incoherently distributed (ID) source [21,22]. For the CD source, the signals arriving from different directions are correlated. Whereas for the ID source, all signals coming from different directions are assumed to be completely uncorrelated. For UAV, the CD sources model is more appropriate to be applied to estimate the parameters of the received data.

Till now, many algorithms have been developed for the parameters estimation of coherently distributed (CD) source [23–33]. In [23], the distributed source parameter estimator (DSPE) algorithm for CD source was proposed to estimate the angular parameters. And [24] proposed an algorithm for angular parameter estimation of CD source based on TLS-ESPRIT algorithm which required two identical and closely separated subarrays. This algorithm obtained the nominal DOAs via ESPIRT method, and the angular spread of each source was estimated via DSPE algorithm. The DSPE algorithm has good parameters estimation performance, however it suffered from heavy computational load due to the

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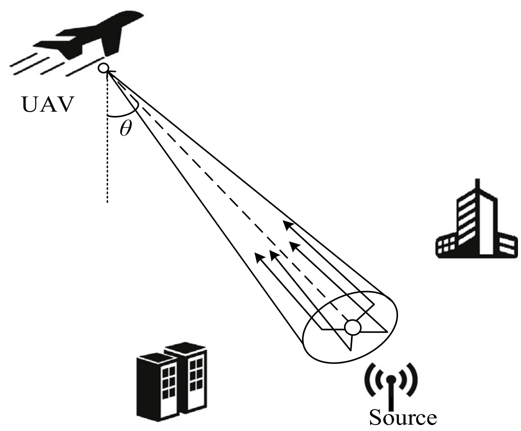

Fig. 1. The scene diagram of UAV reconnaissance.

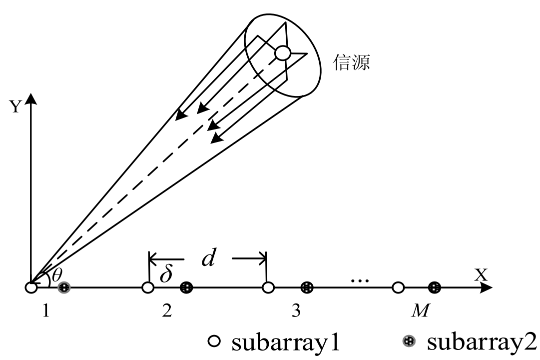

Fig. 2. The structure of the signal receiving array.

complicated multi-dimensional peak searching. While [32] proposed a search-free Root-MUSIC algorithm. But it could only be applied to the case of single source.

In this paper, we improved the traditional DSPE algorithm and propose a successive DSPE (S-DSPE) algorithm for the parameters estimation of the received signals of UAV, which only contains one-dimensional spectral peak searching and significantly reduces the computational complexity with an acceptable parameters estimation performance. Compared with the conventional DSPE algorithm [23] which obtains the parameters estimation via two-dimensional global spectral peak searching, the proposed algorithm first utilizes the ESPIRT algorithm to make the preliminary estimation of the nominal DOAs, then the more accurate estimation of the nominal DOAs and the angular spreads can be estimated through three times one-dimensional local peak searching, which effectively reduces the complexity of the parameters estimation process. The main contributions of this paper can be concluded as follows:

(1) For the low altitude reconnaissance of UAV equipped with antennas array, we construct the received data as CD sources model, which is more appropriate for the parameters estimation of UAV.

(2) We combine DSPE-CD [23] and ESPIRT-CD [24] to propose a successive DSPE algorithm which owns close parameters estimation performance to DSPE.

(3) The proposed algorithm exploits three one-dimensional spectral peak searching to replace the more complicated 2D spectral peak searching within DSPE, which remarkably reduces the computational complexity.

(4) The proposed algorithm can exhibit more precise parameters estimation performance than the ESPIRT-CD [24] algorithm and PM-CD [25] algorithm.

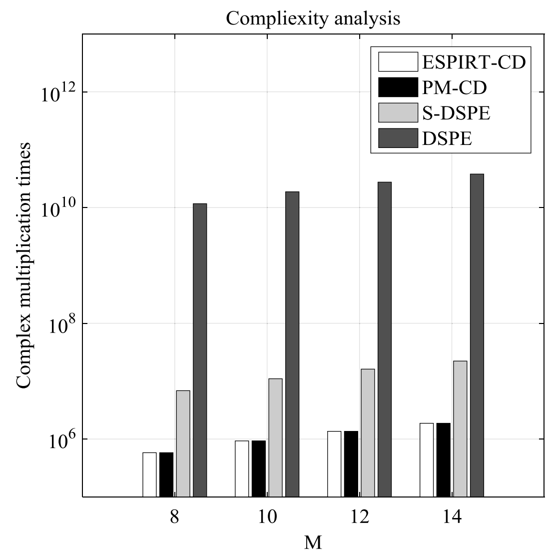

Fig. 3. Complexity comparison with different number of sensors.

The remainder of our paper is structured as follows: Section 2 presents the received data model of CD received sources of UAV. Based on this model, Section 3 shows a description of the conventional DSPE algorithm while the proposed S-DSPE algorithm is derived in Section 4. Section 5 provides the advantages as well as the complexity analysis. Numerical simulations are exhibited in Section 6 to demonstrate the performance of the proposed approach and we conclude this paper in Section 7.

Notations: Matrices and vectors are represented by boldfaced capital letters and lower case letters respectively. $\otimes$, $\circ$ and $\oplus$ stand for *Kronecker* product, *Khatri–Rao* product and *Hadamard* product, respectively. $(.)^*$, $(.)^T$, $(.)^H$, $(.)^{-1}$ and $(.)^\dagger$ denote the operations of complex conjugation, transpose, conjugate–transpose, inverse, and Moore–Penrose pseudoinverse, respectively. $E(\bullet)$ denotes the expectation operator.

2. Data model

We assume that a UAV is conducting a low altitude reconnaissance missions in a big city with high buildings and have received K narrowband far-field sources from the reconnaissance area. The sources are located at $\{\theta_k|k = 1, 2, \ldots, K\}$, where θ_k is the center elevation angle of the kth source. The scene diagram is shown in Fig. 1.

The array antenna on the UAV equipped with two uniform linear arrays with the same structure. As shown in Fig. 2, the distance between the two linear arrays is δ and each subarray has M sensors. The distance between each sensor in the same subarray is d and satisfies $\delta \ll d$. The number of CD sources has been assumed to be known or can be estimated via the method in [34,35].

According to [23], the received signal at each subarray can be expressed as

$$\mathbf{x_1}(t) = \sum_{i=1}^{K} \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta) s_i(\theta, t; \boldsymbol{\psi}_i) d\theta + \mathbf{n}_1(t), \tag{1}$$

$$\mathbf{x_2}(t) = \sum_{i=1}^{K} \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta) s_i(\theta, t; \boldsymbol{\psi}_i) e^{-j2\pi \frac{\delta}{\lambda} \sin\theta} d\theta + \mathbf{n}_2(t), \tag{2}$$

where $\mathbf{a}(\theta)$ is the location vector of the array, $s_i(\theta, t; \boldsymbol{\psi}_i)$ is the angular signal density of the ith source in the direction $\theta \in [-\pi/2, \pi/2]$, $\boldsymbol{\psi}_i = (\theta_i, \sigma_{\theta_i})$. θ_i is the nominal DOA of the ith CD source and σ_{θ_i} is the angular spread of the ith CD source. $\mathbf{n}_1(t)$ and

$\mathbf{n}_2(t)$ are complex-valued additive noise vectors with zero mean and variance σ_n^2, which are independent of signals. λ represents the wavelength.

For CD source, the received signal components from the source at different angles can be regarded as the delayed and scaled replicas of the same signal, so the angular signal density $s_i(\theta, t; \boldsymbol{\psi}_i)$ can be represented as [23]

$$s_i(\theta, t; \boldsymbol{\psi}_i) = s_i(t)\rho(\theta; \boldsymbol{\psi}_i), \tag{3}$$

where $s_i(t)$ denotes the ith signal and $\rho(\theta; \boldsymbol{\psi}_i)$ is deterministic angular signal density satisfied [23]

$$\int_{-\pi/2}^{\pi/2} \rho(\theta; \boldsymbol{\psi}_i) d\theta = 1. \tag{4}$$

Thus for the CD source, the received signal at each subarray can be written as

$$\begin{aligned}\mathbf{x_1}(t) &= \sum_{i=1}^{K} s_i(t) \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta)\rho(\theta; \boldsymbol{\psi}_i)d\theta + \mathbf{n}_1(t) \\ &= \sum_{i=1}^{K} s_i(t)\mathbf{b_1}(\boldsymbol{\psi}_i) + \mathbf{n}_1(t),\end{aligned} \tag{5}$$

$$\begin{aligned}\mathbf{x_2}(t) &= \sum_{i=1}^{K} s_i(t) \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta)\rho(\theta; \boldsymbol{\psi}_i)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta} d\theta + \mathbf{n}_2(t) \\ &= \sum_{i=1}^{K} s_i(t)\mathbf{b_2}(\boldsymbol{\psi}_i) + \mathbf{n}_2(t),\end{aligned} \tag{6}$$

where the generalized direction vector of the ith CD source can be respectively defined as

$$\mathbf{b_1}(\boldsymbol{\psi}_i) = \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta)\rho(\theta; \boldsymbol{\psi}_i)d\theta, \tag{7}$$

$$\mathbf{b_2}(\boldsymbol{\psi}_i) = \int_{-\pi/2}^{\pi/2} \mathbf{a}(\theta)\rho(\theta; \boldsymbol{\psi}_i)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta} d\theta. \tag{8}$$

Let each array manifold of the CD sources be

$$\mathbf{B}_1 = \left[\mathbf{b}_1(\boldsymbol{\psi}_1), \mathbf{b}_1(\boldsymbol{\psi}_2), \ldots, \mathbf{b}_1(\boldsymbol{\psi}_K)\right], \tag{9}$$

$$\mathbf{B}_2 = \left[\mathbf{b}_2(\boldsymbol{\psi}_1), \mathbf{b}_2(\boldsymbol{\psi}_2), \ldots, \mathbf{b}_2(\boldsymbol{\psi}_K)\right]. \tag{10}$$

Then (5) and (6) can be rewritten as

$$\mathbf{x_1}(t) = \mathbf{B_1}\mathbf{s}(t) + \mathbf{n}_1(t), \tag{11}$$

$$\mathbf{x_2}(t) = \mathbf{B_2}\mathbf{s}(t) + \mathbf{n}_2(t), \tag{12}$$

where $\mathbf{s}(t) = [s_1(t), s_2(t), \ldots, s_K(t)]^T$. Combining the received data of two subarrays, we have

$$\mathbf{x}(t) = \begin{bmatrix}\mathbf{x}_1(t) \\ \mathbf{x}_2(t)\end{bmatrix} = \begin{bmatrix}\mathbf{B_1} \\ \mathbf{B_2}\end{bmatrix}\mathbf{s}(t) + \begin{bmatrix}\mathbf{n}_1(t) \\ \mathbf{n}_2(t)\end{bmatrix} = \mathbf{B}\mathbf{s}(t) + \mathbf{n}(t), \tag{13}$$

where

$$\mathbf{B} = \begin{bmatrix}\mathbf{B_1} \\ \mathbf{B_2}\end{bmatrix} = \begin{bmatrix}\mathbf{b}(\boldsymbol{\psi}_1) & \mathbf{b}(\boldsymbol{\psi}_2) & \cdots & \mathbf{b}(\boldsymbol{\psi}_K)\end{bmatrix}, \tag{14}$$

$$\mathbf{n}(t) = \begin{bmatrix}\mathbf{n}_1(t) \\ \mathbf{n}_2(t)\end{bmatrix}, \tag{15}$$

where $\mathbf{b}(\boldsymbol{\psi}_k) = \begin{bmatrix}\mathbf{b}_1(\boldsymbol{\psi}_k) \\ \mathbf{b}_2(\boldsymbol{\psi}_k)\end{bmatrix}$.

3. Conventional method: the DSPE algorithm

In the finite sample case, the covariance matrix $\mathbf{R}_x$ can be estimated as

$$\hat{\mathbf{R}}_x = \frac{1}{L}\sum_{t=1}^{L} \mathbf{x}(t)\mathbf{x}^H(t). \tag{16}$$

where L denotes the number of snapshots. Then the Eigen -decomposition of the covariance matrix $\mathbf{R_x}$ can be presented as

$$\mathbf{R}_x = E[\mathbf{x}(t)\mathbf{x}^H(t)] = \mathbf{E}_s\boldsymbol{\Lambda}_s\mathbf{E}_s^H + \sigma_n{}^2\mathbf{E}_n\mathbf{E}_n^H, \tag{17}$$

where the eigenvalues satisfy $\lambda_1 \geq \cdots \geq \lambda_K > \lambda_{K+1} = \cdots \lambda_{2M} = \sigma_n^2$. And $\mathbf{E}_s$ is the signal subspace consists of the eigenvectors corresponding to the K largest eigenvalues, and $\mathbf{E}_n$ is the noise subspace consists of the eigenvectors of the $2M - K$ smallest eigenvalues.

The DSPE algorithm [23] is a MUSIC-type algorithm in the case of distribution source model. For the parameters estimation of the CD source, DSPE algorithm mainly uses the orthogonality between noise subspace and generalized direction vector.

For the CD source, we have [23]

$$\mathbf{E_n}\mathbf{b}(\boldsymbol{\psi}_i) = \mathbf{0}, \quad i = 1, \ldots, K, \tag{18}$$

Hence, the spatial spectrum function can be defined as [20]

$$f_{DSPE}(\boldsymbol{\psi}) = \frac{1}{\mathbf{b}^H(\boldsymbol{\psi})\mathbf{E}_n\mathbf{E}_n^H\mathbf{b}(\boldsymbol{\psi})}. \tag{19}$$

Now, the nominal DOAs and the angular spreads can be obtained through a 2D peak searching of (19). However, the 2D peak searching of DSPE-CD algorithm brings much burden computational complexity. To resolve this drawback, we improve the conventional DSPE algorithm and propose a successive-DSPE algorithm which can efficiently avoid the two-dimensional peak searching process.

4. The proposed S-DSPE algorithm

4.1. Initial estimation

In the case of CD sources, we can get an approximately invariant structure [24] between the two subspaces spanned by $\mathbf{b}_1(\boldsymbol{\psi}_i)$ and $\mathbf{b}_2(\boldsymbol{\psi}_i)$. Then use the Taylor series expansion of $\mathbf{a}(\theta)$ around $\theta = \theta_i$, we can denote $\mathbf{b}_1(\boldsymbol{\psi}_i)$ as

$$\mathbf{b_1}(\boldsymbol{\psi}_i) = \int_{-\pi/2}^{\pi/2} \sum_{n=0}^{\infty} \frac{\mathbf{a}^{(n)}(\theta_i)}{n!}(\theta - \theta_i)^n \rho_i(\theta; \boldsymbol{\psi}_i)d\theta, \tag{20}$$

where $\mathbf{a}^{(n)}(\theta_i)$ is the nth derivative of $\mathbf{a}(\theta)$ at $\theta = \theta_i$.

Denote the nth moment of $\rho_i(\theta; \boldsymbol{\psi}_i)$ at $\theta = \theta_i$ as

$$\mathbf{M}_i^n = \int_{-\pi/2}^{\pi/2} (\theta - \theta_i)^n \rho_i(\theta; \boldsymbol{\psi}_i)d\theta, \tag{21}$$

then $\mathbf{b}_1(\boldsymbol{\psi}_i)$ can be simply expressed as

$$\mathbf{b_1}(\boldsymbol{\psi}_i) = \sum_{n=0}^{\infty} \frac{\mathbf{a}^{(n)}(\theta_i)}{n!}\mathbf{M}_i^n. \tag{22}$$

Similarly, $\mathbf{b}_2(\boldsymbol{\psi}_i)$ can be written as

$$\mathbf{b_2}(\boldsymbol{\psi}_i) = \sum_{n=0}^{\infty} \frac{(\mathbf{a}(\theta_i)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta_i})^n}{n!}\mathbf{M}_i^n. \tag{23}$$

Then, the first-order derivative of $\mathbf{a}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}$ with respect of θ is

$$\begin{aligned}&\frac{\partial}{\partial\theta}(\mathbf{a}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}) \\ &= \mathbf{a}'(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta} - j2\pi\frac{\delta}{\lambda}\cos\theta\,\mathbf{a}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}.\end{aligned} \tag{24}$$

Note that for $\delta \ll d$, we can get

$$\frac{\partial}{\partial\theta}(\mathbf{a}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}) \approx \mathbf{a}'(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}. \tag{25}$$

Hence, we have

$$\frac{\partial^n}{\partial\theta^n}(\mathbf{a}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}) \approx \mathbf{a}^{(n)}(\theta)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta}. \tag{26}$$

Similarly, $\mathbf{b_2}(\boldsymbol{\psi}_i)$ can be approximately denoted as

$$\mathbf{b_2}(\boldsymbol{\psi}_i) \approx \sum_{n=0}^{\infty}\frac{\mathbf{a}^n(\theta_i)\mathrm{e}^{-j2\pi\frac{\delta}{\lambda}\sin\theta_i}}{n!}\mathbf{M}_i^n. \tag{27}$$

According to (22) and (27), $\mathbf{b}_1(\boldsymbol{\psi}_i)$ and $\mathbf{b_2}(\boldsymbol{\psi}_i)$ approximately satisfy rotation invariance as

$$\mathbf{b_2}(\boldsymbol{\psi}_i) \approx \mathbf{b_1}(\boldsymbol{\psi}_i)e^{-j2\pi\frac{\delta}{\lambda}\sin\theta_i}. \tag{28}$$

In matrix form we have

$$\mathbf{B_2} \approx \mathbf{B_1}\boldsymbol{\Phi}_r, \tag{29}$$

where $\boldsymbol{\Phi}_r = diag(e^{-j2\pi\frac{\delta}{\lambda}\sin\theta_1}, e^{-j2\pi\frac{\delta}{\lambda}\sin\theta_2}, \ldots, e^{-j2\pi\frac{\delta}{\lambda}\sin\theta_K})$.

Under noiseless case, there exist a full rank matrix $\mathbf{T} \in \mathbb{R}^{K\times K}$ satisfies

$$\mathbf{E}_s = \mathbf{BT}. \tag{30}$$

We partition the subspace $\mathbf{E}_s$ as follows.

$$\mathbf{E}_s = \begin{bmatrix}\mathbf{E}_{s_1}\\ \mathbf{E}_{s_2}\end{bmatrix} = \begin{bmatrix}\mathbf{B}_1\mathbf{T}\\ \mathbf{B}_2\mathbf{T}\end{bmatrix} = \begin{bmatrix}\mathbf{B}_1\mathbf{T}\\ \mathbf{B_1}\boldsymbol{\Phi}_r\mathbf{T}\end{bmatrix}, \tag{31}$$

where $\mathbf{E}_{B_1} \in \mathbb{C}^{M\times K}$, $\mathbf{E}_{B_2} \in \mathbb{C}^{M\times K}$. Then from (31), we have

$$\mathbf{E}_{s_2} = \mathbf{E}_{s_1}\mathbf{T}^{-1}\boldsymbol{\Phi}_r\mathbf{T}. \tag{32}$$

And we can get

$$\mathbf{E}_{s1}^{+}\mathbf{E}_{s_2} = \mathbf{T}^{-1}\boldsymbol{\Phi}_r\mathbf{T}. \tag{33}$$

Now, by performing eigenvalue decomposition on $\mathbf{E}_{s1}^{+}\mathbf{E}_{s_2}$, we can obtain the value of $\boldsymbol{\Phi}_r$ via the eigenvalues of $\mathbf{E}_{s1}^{+}\mathbf{E}_{s_2}$. The initial nominal DOAs $\hat{\boldsymbol{\theta}}_{ini} = [\hat{\theta}_{c1}, \hat{\theta}_{c2}, \ldots, \hat{\theta}_{cK}]$ can be estimated by

$$\hat{\theta}_{ck} = -\arcsin\{\lambda \cdot angle(\lambda_k)/(2\pi\delta)\}k = 1, 2, \ldots, K. \tag{34}$$

where λ_k is the kth value of $\boldsymbol{\Phi}_r$.

4.2. The successive processing

4.2.1. The first one-dimensional search

In this section, we utilize the initial nominal DOAs $\hat{\boldsymbol{\theta}}_{ini} = [\hat{\theta}_1^{ini}, \hat{\theta}_2^{ini}, \ldots, \hat{\theta}_K^{ini}]$ to implement the first one-dimensional spectral peak searching. The spatial spectrum function is given by

$$f_{DSPE}(\sigma) = \frac{1}{\mathbf{b}^H(\hat{\theta}_i^{ini}, \sigma)\mathbf{E}_n\mathbf{E}_n^H\mathbf{b}(\hat{\theta}_i^{ini}, \sigma)}, i = 1, \ldots, K, \tag{35}$$

where

$$\mathbf{b}(\hat{\theta}_i^{ini}, \sigma) = \begin{bmatrix}\mathbf{b}_1(\hat{\theta}_i^{ini}, \sigma)\\ \mathbf{b}_2(\hat{\theta}_i^{ini}, \sigma)\end{bmatrix}. \tag{36}$$

By one-dimensional peak searching of σ, we can obtain the initial estimation of the angular spreads $\hat{\boldsymbol{\sigma}}_{ini} = [\hat{\sigma}_1^{ini}, \hat{\sigma}_2^{ini}, \ldots, \hat{\sigma}_K^{ini}]$.

4.2.2. The second one-dimensional search

In this section, we utilize the estimation of the angular spreads $\hat{\boldsymbol{\sigma}}_{ini} = [\hat{\sigma}_1^{ini}, \hat{\sigma}_2^{ini}, \ldots, \hat{\sigma}_K^{ini}]$ in *subsection A* to implement the second one-dimensional searching. Then the spatial spectrum function can be expressed as

$$f_{DSPE}(\theta) = \frac{1}{\mathbf{b}^H(\theta, \hat{\sigma}_i^{ini})\mathbf{E}_n\mathbf{E}_n^H\mathbf{b}(\theta, \hat{\sigma}_i^{ini})}, i = 1, \ldots, K, \tag{37}$$

where

$$\mathbf{b}(\theta, \hat{\sigma}_i^{ini}) = \begin{bmatrix}\mathbf{b_1}(\theta, \hat{\sigma}_i^{ini})\\ \mathbf{b_2}(\theta, \hat{\sigma}_i^{ini})\end{bmatrix}. \tag{38}$$

Then the second estimation of nominal DOAs $\hat{\boldsymbol{\theta}}_{\mathrm{sec}} = [\hat{\theta}_1^{\mathrm{sec}}, \hat{\theta}_2^{\mathrm{sec}}, \ldots, \hat{\theta}_K^{\mathrm{sec}}]$ can be obtained by one-dimensional peak searching of θ.

4.2.3. The third one-dimensional search

Based on the aforementioned works, we can utilize the second estimation of nominal DOAs $\hat{\boldsymbol{\theta}}_{\mathrm{sec}} = [\hat{\theta}_1^{\mathrm{sec}}, \hat{\theta}_2^{\mathrm{sec}}, \ldots, \hat{\theta}_K^{\mathrm{sec}}]$ in *subsection B* to implement the third one-dimensional peak searching. The spatial spectrum function can be presented as

$$f_{DSPE}(\sigma) = \frac{1}{\mathbf{b}^H(\hat{\theta}_i^{\mathrm{sec}}, \sigma)\mathbf{E}_n\mathbf{E}_n^H\mathbf{b}(\hat{\theta}_i^{\mathrm{sec}}, \sigma)}, i = 1, \ldots, K, \tag{39}$$

where

$$\mathbf{b}(\hat{\theta}_i^{\mathrm{sec}}, \sigma) = \begin{bmatrix}\mathbf{b}_1(\hat{\theta}_i^{\mathrm{sec}}, \sigma)\\ \mathbf{b}_2(\hat{\theta}_i^{\mathrm{sec}}, \sigma)\end{bmatrix}. \tag{40}$$

By searching σ, we can obtain the second estimation of the angular spreads $\hat{\boldsymbol{\sigma}}_{\mathrm{sec}} = [\hat{\sigma}_1^{\mathrm{sec}}, \hat{\sigma}_2^{\mathrm{sec}}, \ldots, \hat{\sigma}_K^{\mathrm{sec}}]$.

Till now, we have presented the detailed derivation of the proposed algorithm, and the major steps are concluded as follows:

Algorithm: The proposed S-DSPE algorithm

Step 1. Compute the sample covariance matrix $\hat{\mathbf{R}}_x$ via (17);
Step 2. Perform eigenvalue decomposition on $\hat{\mathbf{R}}_x$ and obtain the signal subspace;
Step 3. Calculate the eigenvalues of $\mathbf{E}_{s1}^{+}\mathbf{E}_{s_2}$ and estimate the initial nominal DOAs via (34);
Step 4. Estimate the initial angular spreads $\hat{\boldsymbol{\sigma}}_{ini} = [\hat{\sigma}_1^{ini}, \hat{\sigma}_2^{ini}, \ldots, \hat{\sigma}_K^{ini}]$ via (35);
Step 5. Calculate the second estimation of the nominal DOAs $\hat{\boldsymbol{\theta}}_{\mathrm{sec}} = [\hat{\theta}_1^{\mathrm{sec}}, \hat{\theta}_2^{\mathrm{sec}}, \ldots, \hat{\theta}_K^{\mathrm{sec}}]$ via (37);
Step 6. Get the second estimation of the angular spreads $\hat{\boldsymbol{\sigma}}_{\mathrm{sec}} = [\hat{\sigma}_1^{\mathrm{sec}}, \hat{\sigma}_2^{\mathrm{sec}}, \ldots, \hat{\sigma}_K^{\mathrm{sec}}]$ via (39);

5. Complexity analysis and the advantages

5.1. Complexity analysis

In this subsection, we discuss the complexity of the proposed algorithm. In terms of complex number multiplication, the computational complexity of the proposed S-DSPE algorithm is $O(4M^2L + 8M^3 + 7MK^2 + 2MK(2M-K) + K^3 + (l_1+l_2+l_3)(2M(2M-K)))$, where $l_i (i = 1, 2, 3)$ denotes the number of search time. In contrast, the conventional DSPE-CD [23] algorithm costs $O(4M^2L + 8M^3 + l_1l_2(2M(2M-K)))$ to implement the two-dimensional spectral peak searching. The complexity comparison of each algorithm versus sensors number is presented in Fig. 3. For intuitive illustration, we consider $K = 2$ CD sources impinging on the antennas array. The other parameters are set as $L = 500$, $l_1 = 5000$, $l_2 = 35000$, $l_3 = 5000$. As is shown in Fig. 3, The computational complexity of the proposed algorithm is much lower than that of the conventional DSPE method. For the sake of clarify, Table 1 gives the actual running time with $M = 10$ of the four algorithms, which also shows clearly that the proposed algorithm outperforms the other methods in complexity.

In addition, from the perspective of data storage space, the proposed algorithm also outperforms the traditional DSPE algorithm. As during the spectral peak searching process, the proposed S-DSPE algorithm only need to save $l_1 + l_2 + l_3$ spectral function numbers, while for the traditional DSPE algorithm, it should save l_1l_2 spectral function numbers, usually l_1l_2 is much larger than $l_1 + l_2 + l_3$.

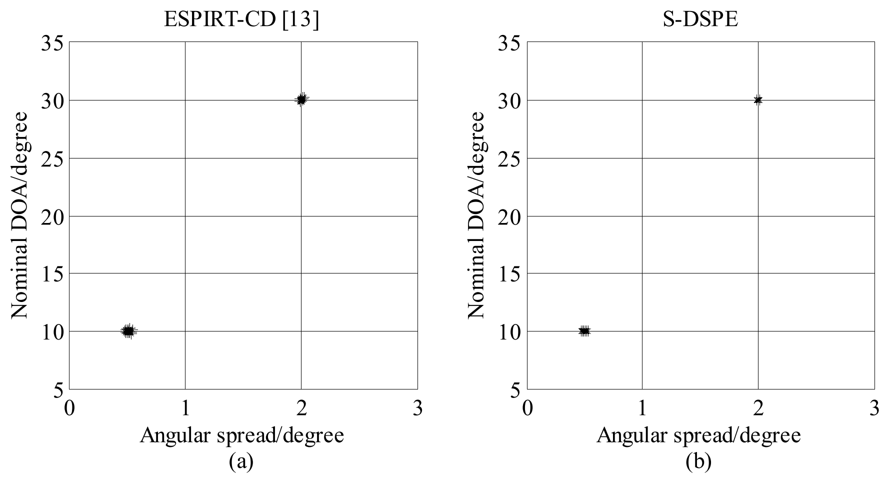

Fig. 4. Estimation results of 500 Monte-Carlo trials.

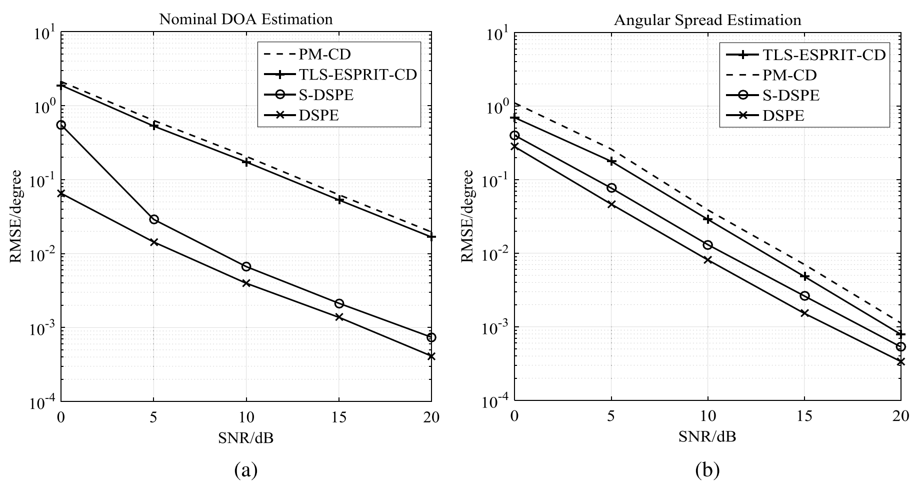

Fig. 5. RMSEs of different algorithm versus SNR.

Table 1
Running time of relevant methods.

	Complexity	Time/s
ESPRIT-CD	$O(4M^2L + 8M^3 + 4MK^2 + 11K^3 + l_1(2M(2M - K)))$	0.0519
PM-CD	$O(4M^2(K + L) + 5MK^2 + 2K^3 + l_1(2M(2M - K)))$	0.0448
S-DSPE	$O(4M^2L + 8M^3 + 7MK^2 + 2MK(2M - K) + K^3 + (l_1 + l_2 + l_3)(2M(2M - K)))$	2.7114
DSPE	$O(4M^2L + 8M^3 + l_1l_2(2M(2M - K)))$	1235.8596

5.2. Advantages of the proposed algorithm

The advantages of the proposed algorithm can be summarized as follows:

(1) The proposed algorithm can avoid the high-complexity 2D spectral peak searching, while has close parameters estimation performance to DSPE method which is proved in the simulations.

(2) The proposed algorithm combines DSPE-CD [23] and ESPIRT-CD [24], and exploiting three one-dimensional spectral peak searching to replace the more complicated 2D spectral peak searching. And the complexity analysis indicates that the only three times one-dimensional local peak-searching dramatically reduces the complexity of the proposed algorithm.

(3) The parameters estimation performance of the proposed algorithm outperforms ESPIRT-CD [24] algorithm and PM-CD [25] algorithm, which is proved in the simulation result Section 6.

6. Simulation results

In this section, we illustrate the parameters estimation performance of the proposed S-DSPE algorithm. Suppose that two CD sources located at $(\theta_1, \sigma_{\theta 1}) = (10°, 0.5°)$ and $(\theta_2, \sigma_{\theta 2}) = (30°, 2°)$ impinging on the antennas array of UAV. The root mean square

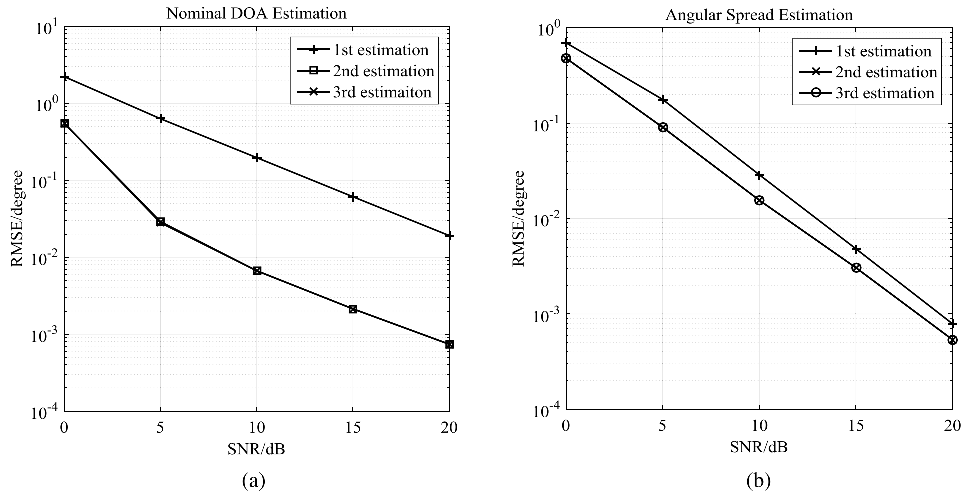

Fig. 6. RMSEs versus SNR of the 1st, 2nd, 3rd estimation.

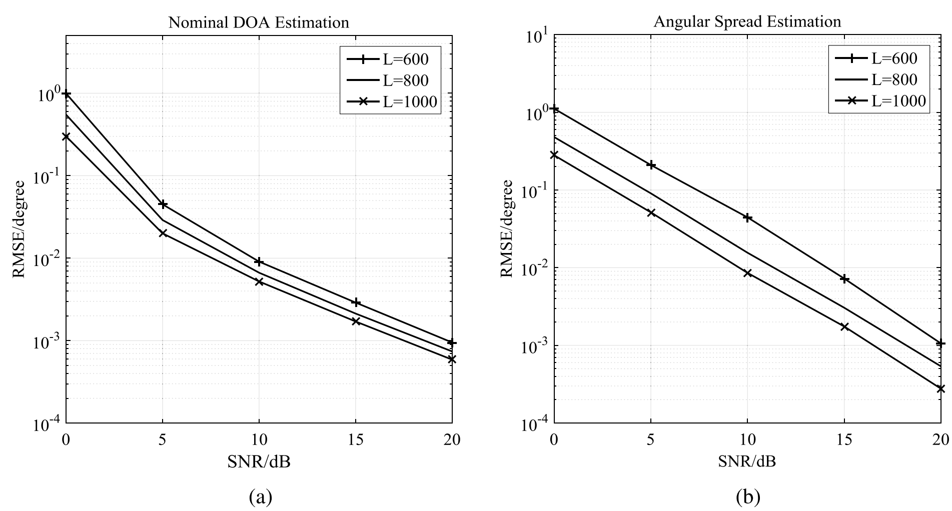

Fig. 7. RMSEs versus different number of snapshots.

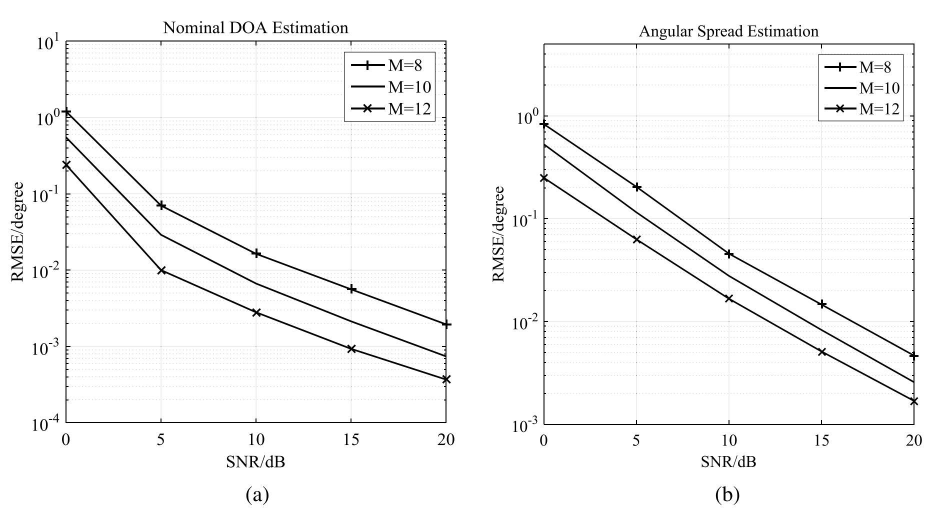

Fig. 8. RMSEs versus different number of sensors.

error(RMSE) is defined as

$$RMSE = \sqrt{\frac{1}{NK}\sum_{n=1}^{N}\sum_{i=1}^{K}(a_i - \hat{a}_{i,n})^2} \tag{41}$$

where N denotes the times of Monte-Carlo simulations, a_i is the theoretical value of the ith angular parameter and $\hat{a}_{i,n}$ is the estimation of the ith angular parameter for the nth trial.

Fig. 4(a) and (b) are the angle estimations result of different algorithms, where $M = 10$, $K = 2$, $L = 500$ are considered. The results indicate that the proposed S-DSPE algorithm is effective for the angle estimation of received signals.

Fig. 5(a) and (b) show the RMSEs of angular parameters versus SNR of the proposed algorithm, PM-CD [25], ESPIRT-CD [24] and DSPE-CD [23] algorithm, where $M = 10$, $K = 2$, $L = 500$ are considered. It indicates that the parameters estimation performance of the S-DSPE algorithm is better than ESPIRT-CD and PM-CD algorithm and close to DSPE-CD algorithm.

As shown in Fig. 6(a) and (b), we compare the angular parametric estimation performances of the first, second, and third successive procedure. It can be clearly observed that with the times of the successive procedure increasing, the estimation results have no improvements from the second successive procedure. Thus, it is sufficient to implement three one-dimensional peak searching to obtain the effective angular parameter estimations.

Fig. 7 shows the angle estimation performance of the proposed algorithm with $K = 2$, $M = 12$ with different values of L. It clearly indicates that the performance of proposed algorithm is getting better with the increasing number of snapshots, as the larger number of snapshots can more efficient to restrain the signal noise and brings more accurate covariance matrix.

Then in Fig. 8 we vary the number of sensors with $K = 2$, $L = 500$. It can be observed that with the increase of the number of sensors, the estimations of the Nominal DOA and angular spreads get more precise. This is very reasonable because more sensors provide more received data, and in addition the diversity gain also brings more accurate parameters estimation.

7. Conclusion

In this paper, a successive DSPE algorithm which combines DSPE-CD [23] and ESPIRT-CD [24] is developed for the parameters estimation of CD sources for UAV reconnaissance system. The proposed algorithm dramatically reduces the computational complexity of the conventional DSPE algorithm with three one-dimensional spectral peak searching. The simulation result demonstrates that when comparing with the DSPE-CD [23] algorithm, the proposed algorithm has close parameters estimation performance and meanwhile, the S-DSPE algorithm for CD source can exhibit more precise estimation than the ESPIRT-CD [24] and PM-CD [25] algorithm.

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