A Passive Direction Finding Algorithm Based on Baselines Selected from Phased Array

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Abstract. In view of the increasing scale and poor concealment of existing electronic reconnaissance satellites, this paper proposes a passive direction finding algorithm based on baseline selection of communication load phased array. The algorithm performs direction finding by selecting part of array elements in the phased array to form a two-dimensional interferometer. Then the direction finding result of interferometer is used as the basis to determine the spatial domain search range of the MUSIC algorithm. Finally the fast and high precision estimation of elevation angle and azimuth angle is completed by MUSIC algorithm. The algorithm can realize fast and high-precision direction finding under communication concealment. At the same time, multi-scale direction finding results can guide the beamforming of phased array and enhance the communication. This algorithm provides a new solution for the integrated payload of miniaturized concealed electronic reconnaissance and communication.

Keywords: Electronic reconnaissance · Phased array · Direction finding of interferometer · Communication enhancement · Integrated payload

1 Introduction

In the existing passive direction finding algorithms [1], the passive direction finding algorithm based on large phased array [2–5] can improve the direction finding accuracy and anti-interference ability of electronic reconnaissance satellites [6–8]. However, the increasing scale of reconnaissance antennas further increases the economic cost and cycle cost of satellite research and development. In the meantime, the electronic reconnaissance satellites based on large antennas have poor concealment and invulnerability.

According to the above analysis, our country's electronic reconnaissance satellites have the development needs for multi-functionality, practicability, wide adaptability, and concealed anti-destruction. Aiming at the problem of poor concealment, high R&D cost and long period caused by large-scale antennas, there is a need for a novel algorithm to achieve covert and efficient electronic reconnaissance. The algorithm is based on the wide application of phased array antennas in communication satellites. Phased array elements of the communication payload are selected to form an interferometer [9, 10] to achieve fast estimation of target angles and complete reconnaissance tasks under

M. Jia et al. (Eds.): WiSATS 2019, LNICST 281, pp. 587–595, 2019.
https://doi.org/10.1007/978-3-030-19156-6_55

communication concealment. Based on this, according to the task needs, the interferometer direction finding result can be used as priori information, and the spatial search range is narrowed, which can reduce the calculation of spatial spectrum estimation and achieve fast and accurate estimation of the target position. At the same time, the interferometer and spatial spectrum estimation provide angle information of multi-scale resolution, which can guide beamforming and enhance communication. A new solution is provided for a flexible integrated payload system with communication and reconnaissance.

This paper is organized as follow: Firstly, the passive direction finding algorithm based on baselines selected from phased array is introduced in Sect. 2, followed by simulation results in Sect. 3. Finally, conclusions are drawn in Sect. 4.

2 Direction Finding Algorithm Based on Baselines Selected from Phased Array

2.1 Introduction of the Algorithm

The phased array is arranged as shown in Fig. 1, which is a 5 × 5 square array. Six of the array elements are selected to form four baselines. That is, array element 3 and 8, array element 14 and 15 form a two-dimensional short baseline, respectively. Array element 3 and 23, and array element 11 and 15 form a two-dimensional long baseline, respectively.

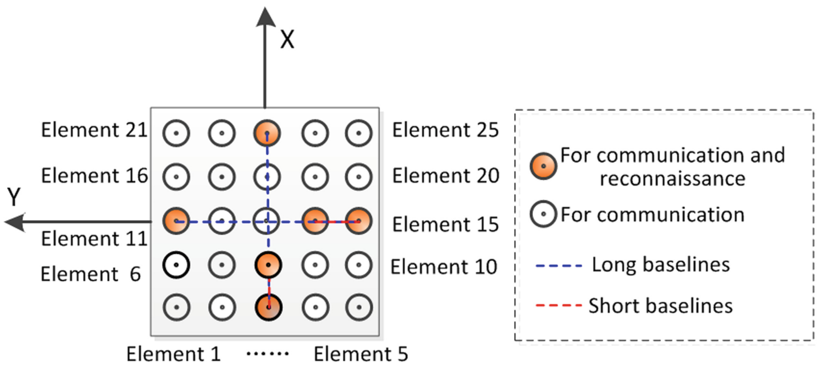

Fig. 1. Arrangement of array and selection of baselines

We define the central array element of the phased array, i.e., the array element 13 as the phase reference point and a Cartesian coordinate system is established. So the short baseline formed by the array element 3 and 8 on the x-axis can obtain the unambiguous phase difference corresponding to the baseline:

$$\Delta\varphi_{3-8} = \frac{2\pi}{\lambda} D_{3-8} \sin\theta \cdot \cos\varphi = \frac{2\pi}{\lambda} d \sin\theta \cdot \cos\varphi \tag{1}$$

Since the element interval is less than half wavelength, the phase difference between the array element 3 and the array element 8 is within the main value section (−π, +π). And the measurement result of phase $\Delta\varphi'_{3-8}$ obtained by the phase detector is also located in the main value section, which indicates that the phase difference corresponding to the short baseline does not include phase multi-valued ambiguity, i.e.:

$$\Delta\varphi_{3-8} = \Delta\varphi'_{3-8} = \frac{2\pi}{\lambda} d \sin\theta \cdot \cos\varphi \tag{2}$$

The short baseline formed by element 15 and 14 on the y-axis gives the unambiguous phase difference corresponding to the baseline:

$$\Delta\varphi_{15-14} = \frac{2\pi}{\lambda} D_{15-14} \sin\theta \cdot \sin\varphi = \frac{2\pi}{\lambda} d \sin\theta \cdot \sin\varphi \tag{3}$$

Similarly, the phase difference corresponding to the short baseline does not include the multi-valued ambiguity. That is, it satisfies:

$$\Delta\varphi_{15-14} = \Delta\varphi'_{15-14} = \frac{2\pi}{\lambda} d \sin\theta \cdot \sin\varphi \tag{4}$$

Where $\Delta\varphi'_{15-14}$ is obtained by the phase detector.

Estimation of elevation $\hat{\theta}_0$ and azimuth angle $\hat{\varphi}_0$ can be obtained from Eqs. (2) and (4).

$$\hat{\varphi}_0 = \arctan\left(\frac{\Delta\varphi'_{15-14}}{\Delta\varphi'_{3-8}}\right) \tag{5}$$

$$\hat{\theta}_0 = \arcsin\left(\frac{\lambda\sqrt{\left(\Delta\varphi'_{3-8}\right)^2 + \left(\Delta\varphi'_{15-14}\right)^2}}{2\pi d}\right) \tag{6}$$

The elevation and azimuth estimates obtained with short baselines often do not meet the requirement for accuracy. To reduce the error of direction finding, the length of baseline should be increased as much as possible to increase the baseline to wavelength ratio. Therefore, the two-dimensional angles can be estimated again in combination with the phase difference corresponding to the long baseline, and the highly accurate angle measurement is obtained.

$\hat{\theta}_0$ and $\hat{\varphi}_0$ are used to search for the fuzzy numbers p and q of the phase difference corresponding to the two-dimensional long baseline. Each set of fuzzy numbers (p, q) can calculate a set of corresponding angle estimates. And the closest angle values to $\hat{\theta}_0$ and $\hat{\varphi}_0$ are the target's direction of arrival, which are denoted by $\hat{\theta}_1$, $\hat{\varphi}_1$. Unambiguous and higher precision elevation and azimuth estimates are achieved.

The long baseline formed by the array element 23 and 3 on the x-axis gives the phase difference corresponding to the baseline:

$$\Delta\varphi_{23-3} = \frac{2\pi}{\lambda} D_{23-3} \sin\theta \cdot \cos\varphi = -\frac{2\pi}{\lambda} 4d \sin\theta \cdot \cos\varphi \quad (7)$$

The interval between the array element 23 and the array element 3 is greater than half a wavelength, so the corresponding phase difference has the following relationship with the phase measurement result of the phase detector:

$$\Delta\varphi_{23-3} = \Delta\varphi'_{23-3} + p \cdot 2\pi \quad (8)$$

Where $\Delta\varphi_{23-3}$ is the phase difference corresponding to the long baseline, $\Delta\varphi'_{23-3}$ is the phase measurement result of the phase detector, and p is the full-cycle ambiguous multiple.

Combining Eqs. (7) and (8), we get:

$$-\frac{2\pi}{\lambda} 4d \sin\theta \cdot \cos\varphi = \Delta\varphi'_{23-3} + p \cdot 2\pi \quad (9)$$

Further organizing the above formula, it can be expressed as follows:

$$p = -\frac{4d}{\lambda} \sin\theta \cdot \cos\varphi - \frac{\Delta\varphi'_{23-3}}{2\pi} \quad (10)$$

By performing the inequality operation on the Eq. (10), the search range of p can be obtained. The maximum and minimum values of p are expressed as follows:

$$p_{\min} = -\frac{4d}{\lambda} - \frac{\Delta\varphi'_{23-3}}{2\pi} \quad p_{\max} = \frac{4d}{\lambda} - \frac{\Delta\varphi'_{23-3}}{2\pi} \quad (11)$$

It is known that the measurement value of phase difference is located at (−π, +π), and the above formulas are rounded to obtain the range of p:

$$p \in [\mathrm{ceil}(-\frac{4d}{\lambda}), \mathrm{floor}(\frac{4d}{\lambda})] \quad (12)$$

Where p is an integer, ceil() means rounding towards positive infinity, and floor() means rounding towards negative infinity.

Similarly, the long baseline formed by the array element 11 and 15 on the y-axis can obtain the phase difference corresponding to the baseline:

$$\Delta\varphi_{11-15} = \frac{2\pi}{\lambda} D_{11-15} \sin\theta \cdot \sin\varphi = -\frac{2\pi}{\lambda} 4d \sin\theta \cdot \sin\varphi \quad (13)$$

The interval between the array element 11 and the array element 15 is greater than half a wavelength, and the corresponding phase difference has the following relationship with the phase measurement result of the phase detector:

$$\Delta\varphi_{11-15} = \Delta\varphi'_{11-15} + q \cdot 2\pi \tag{14}$$

Where $\Delta\varphi_{11-15}$ is the phase difference corresponding to the long baseline, $\Delta\varphi'_{11-15}$ is the phase measurement result of the phase detector, and q is the full-cycle ambiguous multiple.

Combining Eqs. (13) and (14), we get:

$$-\frac{2\pi}{\lambda} 4d \sin\theta \cdot \sin\varphi = \Delta\varphi'_{11-15} + q \cdot 2\pi \tag{15}$$

Further organizing the above formula, it can be expressed as follows:

$$q = -\frac{4d}{\lambda} \sin\theta \cdot \sin\varphi - \frac{\Delta\varphi'_{11-15}}{2\pi} \tag{16}$$

By performing the inequality operation on the Eq. (16), the search range of q can be obtained. The maximum and minimum values of q are expressed as follows:

$$q_{\min} = -\frac{4d}{\lambda} - \frac{\Delta\varphi'_{11-15}}{2\pi} \quad q_{\max} = \frac{4d}{\lambda} - \frac{\Delta\varphi'_{11-15}}{2\pi} \tag{17}$$

It is known that the phase difference measurement value is located at ($-\pi$, $+\pi$), and the above formulas are rounded to obtain the range of q:

$$q \in [\mathrm{ceil}(-\frac{4d}{\lambda}), \mathrm{floor}(\frac{4d}{\lambda})] \tag{18}$$

Where q is an integer, ceil() means rounding towards positive infinity, and floor() means rounding towards negative infinity.

Bring the possible value of p into Eq. (9) and the possible value of q into Eq. (15), we can calculate a set of corresponding estimates. The closest angle values to $\hat{\theta}_0$ and $\hat{\varphi}_0$ are the target's direction of arrival.

When the above-mentioned direction finding method based on interferometer still has insufficient angular resolution and the direction finding accuracy does not meet the actual demand, the array antenna can be used to achieve high resolution spatial spectrum estimation. The MUSIC algorithm is the most classic high-resolution DOA estimation algorithm. Its core idea is to decompose the signal and noise subspaces of the covariance matrix of received data. Then according to the intersection feature between the signal and the noise subspaces, a cost function can be constructed to estimate the angles. However, in practical applications, its complex matrix calculation and huge computational complexity make it very hard to apply to the existing practical systems. And there are fewer effective applications on small and medium-sized arrays.

The direction finding accuracy of the MUSIC algorithm is related to the step size of the search. In the case of sufficiently high SNR, the smaller the step size, the higher the accuracy. However, the smaller the step size is selected, the greater the computational complexity on the satellite. The method utilizes the two-dimensional long and short baseline interferometer to provide a priori information, which can significantly reduce the spatial search range of the MUSIC algorithm. The method makes it possible to adopt a smaller search step size, and improves the direction finding accuracy while reducing the computation load. The fast and accurate estimates of the angles are implemented.

The search range determined for the MUSIC's spatial spectrum estimation is as follows:

$$\theta_{search} = \left[\hat{\theta}_1 - \Delta\theta, \hat{\theta}_1 + \Delta\theta\right] \tag{19}$$

$$\varphi_{search} = [\hat{\varphi}_1 - \Delta\varphi, \hat{\varphi}_1 + \Delta\varphi] \tag{20}$$

Thus, the spectral expression of MUSIC is

$$P_{MUSIC}(\theta_{search}, \varphi_{search}) = \frac{1}{a(\theta_{search}, \varphi_{search})^H \cdot U_N \cdot U_N^H \cdot a(\theta_{search}, \varphi_{search})} \tag{21}$$

Where U_N is the noise subspace, $a(\theta_{search}, \varphi_{search})$ is the steering vector, and $(\cdot)^H$ denotes conjugate transpose. The two-dimensional angles corresponding to the peak are the elevation and azimuth of the target.

2.2 Algorithm Flow

The flow of passive direction finding algorithm based on baseline selected from phased array is as follows:

(1) Selecting part of array elements in the phased array to form a two-dimensional interferometer with long and short baselines;
(2) Obtaining the elementary direction finding results and by two-dimensional interferometer;
(3) Using direction finding result of interferometer as the basis to determine the spatial domain search range of the MUSIC algorithm;
(4) Completing the fast and high precision estimation of elevation angle and azimuth angle by MUSIC algorithm;
(5) Multi-scale direction finding results can guide the beamforming of phased array and enhance the communication.

3 Simulation Analysis

Parameter Setting: Carrier frequency, Fc = 3 GHz. Elevation angle = 10.04°. Azimuth angle = 15.07°. Element interval, d = λ/2. Length of long baseline = 4d. Length of short baseline = d. SNR = 10:5:40.

3.1 Direction Finding Results of Short Baselines

It can be seen from Fig. 2 that the estimation errors of angles are quite large when solving the angles only with short baselines.

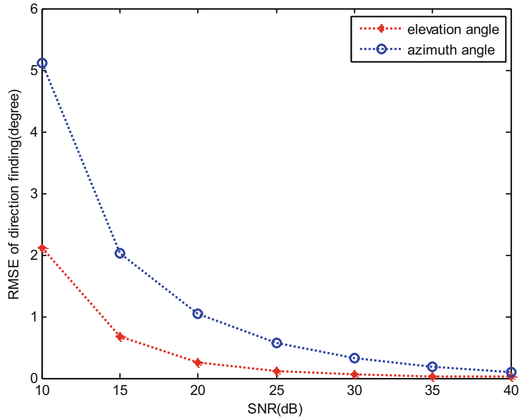

Fig. 2. Direction-finding RMSEs by two-dimensional short baselines versus SNR

3.2 Direction Finding Results of Combining Long and Short Baseline

It can be seen from Fig. 3 that the estimation errors of angles can be reduced after combining long baseline to solve the angles.

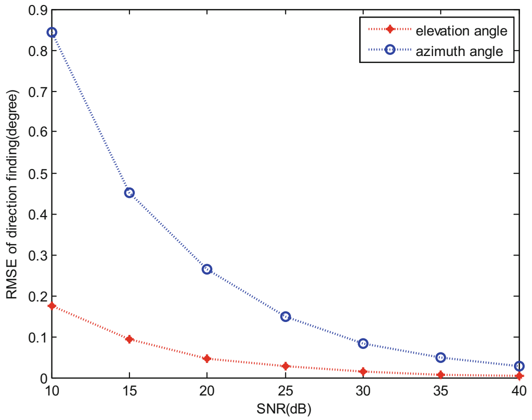

Fig. 3. Direction-finding RMSEs by two-dimensional long and short baselines versus SNR

3.3 Direction Finding Results of MUSIC

As can be seen from the above Fig. 4, the two-dimensional angle estimates are: elevation angle = 10.04°, azimuth angle = 15.07°.

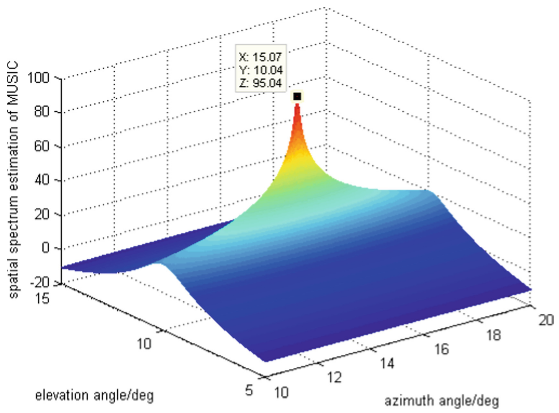

Fig. 4. Direction-finding of MUSIC based on interferometer (SNR = 40 dB)

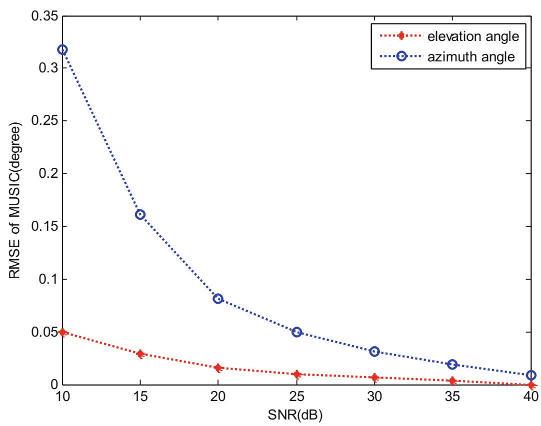

Fig. 5. RMSE of MUSIC versus SNR

It can be seen from Fig. 5 that the estimation errors of angles can be significantly reduced after utilizing MUSIC. Then the fast and high-precision estimates of angles are completed by MUSIC based on interferometer.

4 Conclusion

The algorithm utilizes the array elements of the communication load' phased array to complete direction finding based on the interferometer, which narrows the range of MUSIC spectral search. The fast and accurate estimation of the target' angle and the efficient electronic reconnaissance under the communication' concealment can be realized. In the meantime, the two-scale results of direction finding based on the interferometer and MUSIC method can guide the beamforming of the phased array, which can realize the enhancement of communication with the ground station, and design a flexible payload integrated with communication and electronic reconnaissance.

Acknowledgments. This work was partly supported by National Nature Science Foundation Program of China (No. 61601295), Shanghai Sailing Program (16YF1411000), National Key R&D Program of China (2017YFB0502902) and Autonomous Deployment Program of IAMC (ZZBS17DZ01).

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