

Postprint of Experimental Study on Direction of Arrival of Radio Interference Sources Based on a Four-Antenna Linear Array

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Abstract

This paper addresses the deficiencies in detection methods for the electromagnetic quiet zone surrounding radio astronomy observations and proposes a radio interference monitoring method based on a four-antenna linear array, aiming to real-time monitor the presence of interference sources in the electromagnetic quiet zone and identify their direction of arrival. The method employs a portable four-antenna array configured as a linear array, utilizing the MUSIC algorithm for linear arrays to calculate the direction of arrival of interference sources. Through testing at different distances and under various conditions both indoors and outdoors, the results demonstrate that in a relatively open and quiet environment, the four-antenna array can effectively identify the direction of arrival of interference signals, with a reliability of approximately 87% for measurement angle errors not exceeding 5°. Through comprehensive analysis, this paper concludes that the portable four-antenna linear array approach combined with the MUSIC algorithm can effectively identify the direction of arrival of interference sources in open-area radio astronomy observations, thereby assisting radio telescopes in avoiding interfered channels.

Full Text

Research on Radio Interference Source Direction-of-Arrival Measurement Using a Four-Antenna Linear Array

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Abstract

Radio astronomical observations demand stringent electromagnetic environmental quietness, yet current detection methods for monitoring surrounding electromagnetic environments remain inadequate. This paper proposes a radio interference monitoring method based on a four-antenna linear array to address this limitation, enabling real-time detection of interference sources within electromagnetic quiet zones and identification of their direction-of-arrival (DOA). The approach employs a portable four-antenna linear array configuration combined with the MUSIC (Multiple Signal Classification) algorithm for DOA estimation. Through extensive testing under various indoor and outdoor conditions and distances, results demonstrate that in relatively open and quiet environments, the four-antenna array can effectively identify the DOA of interference signals with approximately 87% reliability for measurement errors within 5°. Comprehensive analysis indicates that the portable four-antenna linear array combined with the MUSIC algorithm can satisfactorily identify interference source directions in open-area radio astronomical observations, thereby assisting radio telescopes in avoiding interfered channels.

Keywords: Electromagnetic environment monitoring; Radio astronomical observations; Radio direction finding; MUSIC direction finding technology

0 Introduction

Radio astronomical observations impose rigorous requirements on electromagnetic environmental quietness. However, with societal development, electromagnetic environments have become increasingly complex, posing significant challenges to radio astronomy. In these complex electromagnetic environments, human-made transmitters represent the primary source of interference. Typical examples include Civil Aviation Signals (CAS), various communication base stations, and high-power signal generators. The emission frequencies of these interference sources often overlap with radio astronomical observation bands, entering receiver systems through antenna sidelobes. This degrades system sensitivity, compromises observation data validity, increases data processing complexity, and in severe cases, directly contaminates observational data within specific frequency bands, rendering large-scale radio scientific instruments incapable of conducting observations during those time periods and sky regions.

Given the growing complexity of electromagnetic environments, radio astronomical observations typically require pre-observation electromagnetic environment monitoring of the target region. By continuously adjusting the observation area of the radio telescope, temporarily effective quiet zones can be achieved within

specific time periods and spatial domains. However, realizing this objective necessitates the use of radio direction finding technology to predict interference source DOA in advance, enabling targeted avoidance strategies.

Radio direction finding technology represents a critical and active area in radio applications. Within the far-field region, DOA can be determined by deploying multiple antennas to construct an array combined with time difference-of-arrival techniques. Employing more antennas in the array configuration can effectively improve measurement accuracy, with numerous studies proposing relevant applications.

For instance, Reference [1] proposed a method that estimates aircraft-to-station distance from aviation signal positions and evaluates power loss to determine the probability of flight path distribution within designated regions, thereby reducing CAS interference effects. Reference [2] utilized a five-element circular array as the receiving antenna, employed a dual-channel interferometer as the receiver to feed signals into a processing unit, and reduced sample library scale through real-time phase difference sample library construction to determine signal DOA. Reference [3] collected and measured electromagnetic signals in air traffic control equipment environments, calculated frequency-domain and time-domain parameter characteristics, combined geographical information data fusion to display signal localization results, analyzed equipment station status, and reflected equipment performance and environmental change trends through data comparison. Reference [4] introduced a radar and radio direction finding fusion localization method employing spatiotemporal calibration, data standardization, and track fusion technologies to achieve multi-source heterogeneous data fusion localization, which was applied in water law enforcement and maritime search and rescue, effectively improving vessel positioning accuracy. Reference [5] developed a maritime personnel search and location device based on combined radio direction finding and satellite positioning technology, enabling radio transmission of drowning victim identification and vital sign information.

The methods described in these references generally require large-scale equipment to achieve satisfactory results. However, bulky equipment introduces mobility constraints. To address this limitation, this paper proposes an interference source direction finding method based on a four-antenna linear array using lightweight and portable equipment suitable for applications requiring repeated relocation. We conducted indoor and outdoor experimental validation of this method's effectiveness, with results presented in the following sections. Section 1 briefly introduces the relevant direction finding algorithms, Section 2 describes equipment parameters and test results, and the final section provides discussion and analysis.

1 Four-Antenna Array Radio Direction Finding System

This study employs a direction finding system based on a four-antenna linear array configuration, consisting of four antennas arranged in a linear array to form the receiving system. The system architecture is illustrated in Figure 1.

The objective of radio direction finding is to determine the direction of radio transmitters by measuring and estimating electromagnetic wave parameters, thereby achieving localization. As shown in Figure 2, the transmitter direction can generally be determined by measuring the azimuth angle α alone. However, for transmitters installed on aircraft and shortwave transmitters, the elevation angle β must also be measured to definitively establish the transmitter's position.

2 MUSIC Direction Finding Algorithm

Consider M identical antenna array elements. If D narrowband signals $s(t)$ impinge from directions θ_k ($k = 1, 2, \dots, D$), the output signal of the i -th array element, accounting for measurement noise and all signal sources, is given by:

$$x_i(t) = \sum_{k=1}^D a_{ik} s(t - \tau_k) + n_i(t)$$

where $n_i(t)$ represents measurement noise, all subscripts i denote the i -th array element, subscripts k denote the k -th signal source, a_{ik} represents the influence of the i -th element on the k -th signal source (assumed identical for all elements in this experiment, i.e., $a_{ik} = 1$), w is the signal's center frequency, and λ is the carrier wavelength.

Assuming mutually independent incident signals and zero-mean Gaussian white noise with variance σ^2 for each array element, uncorrelated with the signals, the vector form of equation (1) yields the array output signal matrix:

$$X(t) = A S(t) + N(t)$$

where: $X(t) = [x_1(t), x_2(t), \dots, x_M(t)]^T$ is the $M \times 1$ output vector — $A(\theta) = [a(\theta\{1\}), a(\theta\{2\}), \dots, a(\theta\{D\})]$ is the $M \times D$ array manifold matrix, whose column vectors represent the array's spatial response — $S(t) = [s\{1\}(t), s\{2\}(t), \dots, s\{D\}(t)]^T$ is the $D \times 1$ signal vector — $N(t) = [n\{1\}(t), n\{2\}(t), \dots, n\{M\}(t)]^T$ is the $M \times 1$ noise vector

The covariance matrix of X is:

$$R = E[X(t)X^H(t)]$$

Performing eigenvalue decomposition on R yields eigenvalues sorted as $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M$, with corresponding eigenvectors $e_1, e_2, \dots, e_M$. Since weak signal eigenvalues are not easily distinguished from noise eigenvalues, the eigenvalues are partitioned as:

$$\Lambda_s = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_D) \text{ (signal eigenvalues)}$$

$$\Lambda_n = \text{diag}(\lambda_{D+1}, \lambda_{D+2}, \dots, \lambda_M) \text{ (noise eigenvalues)}$$

The signal and noise subspaces are correspondingly defined as:

$E = [e_1, e_2, \dots, e_N]$ (signal subspace)

$E_\perp = [e_{N+1}, e_{N+2}, \dots, e_M]$ (noise subspace)

Utilizing the orthogonality between the noise subspace and signal subspace, at the true signal direction we have $E_\perp^H a(\theta) = 0$. In practice, the following function is constructed:

$$P(\theta) = 1 / (a^H(\theta) E E^H a(\theta))$$

The D largest peaks of $P(\theta)$ correspond to the DOA estimates. The fundamental principle of the MUSIC algorithm involves eigen-decomposition of the array output covariance matrix to obtain a signal subspace corresponding to signal components and a noise subspace orthogonal to the signal components, then exploiting the orthogonality between these subspaces to estimate signal parameters (incident direction, polarization information, signal intensity, etc.).

3 Experimental Setup and Results

Experiments were conducted at Yunnan Astronomical Observatory, comprising both indoor near-field and outdoor far-field components. A function generator simulated interference source signals, with an N9020A MXA spectrum analyzer monitoring transmitted signal strength. A four-antenna array received signals, transmitting data to a Raspberry Pi for processing and DOA estimation. The experimental equipment is shown in Figure 3.

Equipment Specifications:

1. Kerberos SDR:

- Frequency range: 24 MHz-1.7 GHz
- ADC sampling rate: 2.4 MSps
- Data precision: 8-bit
- Channels: 4

2. Signal Source:

- Frequency ranges: 10 Hz-100 Hz, 100 Hz-1000 Hz, 1 kHz-10 kHz

3. Raspberry Pi:

- CPU: Broadcom BCM2711, quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5 GHz
- Memory: 2 GB, 4 GB, or 8 GB LPDDR4-3200 SDRAM (model-dependent)
- Wireless: 2.4 GHz and 5.0 GHz IEEE 802.11ac Wi-Fi, Bluetooth 5.0, BLE

3.1 Indoor Testing

Indoor tests were performed in an open indoor space with transmitter-to-receiver distances ranging from 4.8 m to 8.8 m. Multiple test rounds were conducted at

different frequencies and horizontal positions. Results are presented in Table 1.

Assuming the wireless signal wavelength is λ , the spacing between the four KerberosSDR-connected antennas is $s \cdot \lambda$, where s is a scaling parameter. Wavelength equals wave speed divided by frequency (wave speed = 3×10^8 m/s, frequency = 9×10^8 Hz). The spacing parameter s affects the direction finding resolution: larger s values yield higher resolution but require greater physical antenna separation. Higher resolution produces sharper peaks in the DOA Estimation display. Reference [7] uses $s = 0.33$, which served as the basis for our experiments. In all figures, rightward horizontal direction is defined as positive, leftward as negative.

Table 1: Indoor Measurement Data

Frequency	Spacing	Antenna Distance	Straight-line Distance	Transmission Power	Theoretical Angle	Measured Angle
440 Hz	-0.8 m	10 dBm	-9.5°	17° ± 2°	440 Hz —	1.6m 10dBm —
				26.6° ± 4°	440 Hz —	2.4m 10dBm —
				0° ± 5°	550 Hz —	0.8m 10dBm —
				9.5°	—	9.5° —
				6° ± 4°	550 Hz —	1.6m 10dBm —
				34.6°	—	34.6° —
				15° ± 5°	750 Hz —	0.8m 10dBm —
				7° ± 1°	—	7° ± 1° —
				6.3°	750 Hz —	1.6m 10dBm —
				12.5°	—	12.5° —
				18° ± 2°	900 Hz —	0.8m 10dBm —
				18.5°	—	18.5° —
				25° ± 5°	—	25° ± 5° —

3.2 Outdoor Testing

In outdoor environments, the distance between the test antenna and transmitter was increased to over 500 m to evaluate system performance in far-field conditions. Test data at different frequencies and orientations are presented in Tables 2 and 3, with rightward defined as positive and leftward as negative.

Table 2: Far-field Direction Finding (Kerberos SDR)

Frequency	Theoretical Angle	Measured Angle
900 Hz	$2^{\circ} \pm 8^{\circ} 1^{\circ} \pm 5^{\circ} 900 Hz 19^{\circ} \pm 1^{\circ} 13^{\circ} \pm 3^{\circ} 750 Hz 28^{\circ} \pm 2^{\circ}$	
550 Hz		
440 Hz		

Table 3: Far-field Direction Finding (Function Transmitter)

Frequency	Theoretical Angle	Measured Angle
900 Hz	$53^{\circ} \pm 2^{\circ} 16^{\circ} \pm 4^{\circ} 900 Hz -$ $5^{\circ} \pm 1^{\circ} 19^{\circ} \pm 1^{\circ} 750 Hz -$ $5^{\circ} \pm 1^{\circ} -$ $57^{\circ} \pm 2^{\circ} 550 Hz 0^{\circ} \pm 8^{\circ} 19^{\circ} \pm 1^{\circ} 440 Hz -$ $28^{\circ} \pm 2^{\circ} 0^{\circ} \pm 10^{\circ} 440 Hz 15^{\circ} \pm 5^{\circ} -$ $35^{\circ} \pm 5^{\circ}$	

3.3 Results Analysis

In Table 1, 23 tests were conducted. Statistical analysis of measurement dispersion reveals that measurement errors remain within 5° . Considering errors $\leq 5^{\circ}$ as successful, 20 tests succeeded and 3 failed, yielding an approximate success rate of 87%. Two failures occurred at a 2.4 m horizontal distance, possibly due to stronger local interference or insufficient observation strength from excessive distance and limited antenna count. The remaining failure at 0.8 m distance with a 0° measurement may stem from Kerberos SDR's prolonged computation time causing overheating and measurement inaccuracy. Figure 4 illustrates the indoor measurement trend curve, clearly showing the overall pattern.

In Table 2, 13 tests were performed. With statistical dispersion analysis, measurement errors fall within 10° . Using 10° as the maximum acceptable error, 10 tests succeeded and 3 failed, achieving a 77% success rate. Two failures occurred at 440 Hz in outdoor settings, possibly due to nearby electronic device interference. The remaining failure at 550 Hz could result from operational error or reduced Kerberos SDR accuracy from insufficient antenna count. Figure 5 displays the far-field direction finding (Kerberos SDR) trend curve, distinctly revealing the overall pattern.

In Table 3, 14 tests were conducted with all results falling within the actual value ranges, achieving a 100% success rate. This fully demonstrates the accuracy of the N9020A MXA spectrum analyzer and indirectly validates our method's feasibility. Figure 6 presents the far-field direction finding (function transmitter) trend curve, offering clearer experimental result visualization through curve comparison.

Comparison between Tables 2 and 3 suggests that large errors in Table 2 may arise from Kerberos SDR's limited antenna count, making it more susceptible

to interference. Increasing the antenna count could improve measurement accuracy. For the issues in Table 1, cooling measures could be implemented for the Kerberos SDR device, or multiple arrays could be used complementarily to determine the accurate measurement direction.

In summary, using a portable four-antenna array to pre-identify CAS DOA is feasible. Although Kerberos SDR remote direction finding exhibits some errors, further algorithmic improvements are needed to enhance accuracy. Future work should consider real-time data output from Kerberos SDR to cloud servers, leveraging WeChat mini-program functionality to visually display interference signal DOA on mobile phones. This would facilitate staff adjustment of radio telescope observation regions to avoid interference, achieving temporary effective quiet zones.

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