Postprint: Detection and Direction Finding of Space Targets Using the Tianlai Radio Array

Authors: Li Jiawei, Gao Pengqi, Shen Ming, Jin Wang, Zhao has 1

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Abstract

The Tianlai radio telescopearray (abbreviated as Tianlai radio array) possesses the dual advantages of a wide field of view and high sensitivity, enabling it to detect relatively small space targets during observations and to simultaneously detect multiple space targets, demonstrating strong space target detection capabilities, and thus can serve as one of the space target monitoring devices. Using the Qujing incoherent scatter radar as the transmitting source, the space target detection capability of the Tianlai radio array is calculated. Subsequently, a space target direction-finding method based on phase difference measurement that can be applied to this system is proposed, and the relationship between direction-finding error and direction-finding angle is investigated.

Full Text

Study on Detection and Direction-Finding Methods for Space Objects Using the Tianlai Radio Array

Jiawei Li[1,2], Pengqi Gao[1], Ming Shen[1], Wang Jin[1,3], You Zhao[1]
[1]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Kunming Radio Wave Observatory, China Research Institute of Radio-Wave Propagation, Qujing, Yunnan 655333, China

Abstract

The Tianlai radio telescope array (hereinafter referred to as the Tianlai array) offers the dual advantages of a wide field of view and high sensitivity, enabling it to detect relatively small space objects during observations and capture multiple space objects simultaneously. These characteristics give it strong space object detection capabilities, making it a viable candidate for space object monitoring equipment. This study calculates the detection capability of the Tianlai array using the Qujing Incoherent Scatter Radar as a transmission source. Subsequently, a direction-finding method based on phase difference measurement is proposed for this system, and the relationship between direction-finding error and angle is investigated.

Keywords: space object detection; Tianlai radio array; phase difference measurement method; direction-finding error

1. Introduction

With the development of aerospace technology, an increasing number of spacecraft have been launched into orbit. As of September 2017, more than 18,700 cataloged space objects larger than 10 cm were in orbit, including active payloads and space debris that threaten the safety of space assets. Space object observation methods primarily include radar, electro-optical detection, satellite laser ranging, and electronic fence systems [1]. Notably, the U.S. Space Fence—officially the Air Force Space Surveillance System (AFSSS)—was an indispensable component of the U.S. Air Force Space Surveillance Network. This system consisted of three transmitter stations and six receiver stations operating at 216 MHz, creating a fan-shaped beam screen that was wide in the east-west direction and narrow in the north-south direction, covering space objects over western longitudes. When a target passed through the screen, the receiver stations captured the scattered signal, enabling space object detection. The system could monitor 40% of Low Earth Orbit (LEO) objects cataloged by the U.S. Space Surveillance Network [2]. Its advantages included a simple operating principle, high system reliability, and broad coverage, theoretically capable of detecting any space object entering the transmitted beam, with continuous operation using fixed transmit and receive beams. However, its narrow beam thickness resulted in short transit times, requiring multiple passes for orbit determination. The fan-shaped beam design enabled simultaneous detection of multiple space objects. The system is currently undergoing upgrades that will increase the operating frequency to S-band, allowing detection of space objects as small as 5 cm in diameter in LEO [3].

[Figure 1: see original paper]

In radio astronomy, using radio interferometer arrays capable of forming fan-shaped beam screens for space object detection has precedent. For example, in 2008, the Medicina Radio Observatory in Italy used the Northern Cross Radio Telescope array in conjunction with radar to detect the U.S. military satellite USA-193, with calculations showing the array could detect space objects as small as 2.2 cm in diameter at 800 km altitude [5-6]. This demonstrates the potential for using such radio interferometer arrays in bistatic radar configurations for space object detection and tracking.

2. Detection Capability Analysis of the Tianlai Array

The Tianlai radio telescope array, located in Balikun, Xinjiang, China, is primarily designed for large-area radio observations of dark energy in the universe. Under certain conditions, the array can be used for space object detection. The array consists of three parabolic cylindrical antennas measuring 40 m × 15 m, with 96 dual-linear polarization feeds, operating at frequencies of 400–1400 MHz. During operation, it forms a fan-shaped beam screen similar to the "electronic fence," which sweeps across large sky areas as the Earth rotates, achieving survey-scanning objectives. The Tianlai array' s high sensitivity and wide field of view enable it to detect multiple space objects simultaneously.

The receiver sensitivity of the Tianlai array can be expressed as:

$$S_{\min} = k_B T_{sys} \sqrt{\frac{1}{N_{ant} \Delta\nu\tau}}$$

where k_B is the Boltzmann constant, $T_{sys} = 50$ K is the system temperature (including ambient temperature and thermal noise), N_{ant} is the number of antennas in the interferometer array, τ is the integration time, and $\Delta\nu = 4$ MHz is the operating bandwidth. With an integration time of 1 s, the receiver sensitivity of the Tianlai array is approximately -168.4 dBm.

The Qujing Incoherent Scatter Radar is a monopulse radar transmitting at 500 MHz, which satisfies the reception frequency requirements of the Tianlai array. Therefore, a bistatic radar system combining the Tianlai array with the Qujing radar can be considered for space object detection. According to reference [7], the Qujing Incoherent Scatter Radar is located at 103.7°E, 25.6°N, with a 29 m antenna aperture, 2 MW peak transmit power, 100 kW average power, 4 MHz bandwidth, 130 K system noise temperature, and 42.7 dB antenna gain. Neglecting system losses and atmospheric attenuation, the detection capability of the Tianlai array can be calculated using the bistatic radar equation [8]:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2}$$

where P_t is the transmit power and P_r is the receiver sensitivity, G_t and G_r are the transmit and receive antenna gains, λ is the operating wavelength, σ is the radar cross-section (RCS) of the space object, and R_t and R_r are the distances from the object to the radar and to the radio array, respectively.

[Figure 3: see original paper]

Due to limited radar transmit power, bistatic radar systems are typically used to observe LEO objects. Therefore, the detection altitude is set to 400–2000 km. Using the Qujing radar' s average transmit power of 100 kW as the system transmit power and 500 MHz operating frequency, the detection capability of the Tianlai array is calculated using equation (2) based on the actual geographic locations of the two stations. The results are shown in Table 1.

Table 1 shows that as the orbital altitude increases, the Tianlai array can detect space objects smaller than 10 cm in diameter across a range of latitudes in LEO.

3. Full-Band Radar Cross-Section Analysis for Space Object Detection

Since the RCS of detection targets depends on the system operating frequency, and the Tianlai array operates at 400-1400 MHz, we can calculate the detectable RCS values within this frequency range. Assuming a radar transmit power of 100 kW, a baseline of 1000 km between the radar and Tianlai array, and other parameters identical to the Qujing Incoherent Scatter Radar (with adjustable frequency to cover the entire Tianlai array operating range), the relationship between operating frequency and RCS at different detection altitudes can be derived using equation (2), as shown in Figure 4.

[Figure 4: see original paper]

At a constant detection altitude, as the bistatic radar system operating frequency increases, the minimum detectable target RCS decreases, enabling detection of smaller debris. Based on current Tianlai array specifications, at 400 MHz the system can detect space debris with diameters of approximately 5.9 cm, 7.9 cm, and 9.8 cm at altitudes of 400 km, 800 km, and 1200 km, respectively. At 1400 MHz, it can detect objects as small as 1.7 cm, 2.3 cm, and 2.8 cm at the same altitudes. This analysis demonstrates that the Tianlai array can detect space objects smaller than 10 cm in diameter, with detection capability improving to objects smaller than 5 cm as operating frequency increases.

4. Detection Efficiency Analysis for Space Objects

The Systems Tool Kit (STK) software was used to analyze the detection efficiency of the Tianlai array. The simulation was run from UTC 2017.05.23 00:00:00 to 2017.05.24 00:00:00, using a random selection of cataloged LEO objects. Detection efficiency was determined by counting the number of beam transits. A total of 1079 space objects were randomly selected for simulation, with results shown in Figures 5 and 6.

[Figure 5: see original paper] [Figure 6: see original paper]

The simulation results show that the Tianlai array could detect 518 out of 1079 LEO objects, yielding a detection efficiency of approximately 48%. Among these 518 detected objects, some were detected multiple times during the period, with 17 objects detected five times. During transit, if the sampling period is set to 1 s, objects with longer transit times can be sampled multiple times in a single pass, with each sample constituting an independent observation. Figure 6 shows that most space objects have transit times concentrated between 3-20 s, allowing for multiple complete detections during transit. The shortest transit time was

0.05 s for object FLOCK-3P38 (NORAD ID: 42037), while the longest was 164.88 s for SWARM-B (NORAD ID: 39451), enabling numerous observations during a single beam crossing. The statistics also indicate that the Tianlai array provides longer observation times for objects with orbital inclinations near 90° and at higher altitudes.

The Tianlai array does not require observation of individual galaxies, so its angular resolution requirement is modest—only 15' is needed to meet its scientific objectives [9]. However, this makes it difficult to locate arcsecond-level space objects through imaging. Since the Tianlai array is a planar array, phase difference measurement can be used for direction finding of space objects.

5. Direction-Finding Method and Error Analysis

5.1 One-Dimensional Interferometer Array Direction-Finding Method When the distance from the transmitter to the radio interferometer array is much greater than the baseline length between feeds, the transmitted signal can be approximated as arriving from parallel directions, generating phase differences due to path length differences. The phase direction-finding formula for a one-dimensional radio array is:

$$\phi = \frac{2\pi D \sin\theta}{\lambda}$$

where ϕ is the baseline phase difference, D is the baseline length, θ is the signal incidence angle measured from the baseline normal, and λ is the signal wavelength.

Radio interferometer arrays observe celestial bodies or space objects, yielding complex data with principal phase values between $-\pi$ and π, so measured phase differences are limited to this range. When the baseline length $D \leq \lambda/2$, the phase difference for any signal direction remains within $[-\pi, \pi]$, allowing the true incidence angle to be determined from measurements. However, when $D > \lambda/2$, the actual phase difference for certain signal directions may exceed this range, making it impossible to deduce the true incidence angle from measurements and resulting in phase ambiguity. The boundary condition $\phi = \pi$ defines the maximum unambiguous field-of-view angle, beyond which phase ambiguity occurs. The relationship between maximum unambiguous field-of-view angle and baseline length D is shown in Figure 7.

[Figure 7: see original paper]

To avoid phase ambiguity, the baseline length D must satisfy $D \leq \lambda/2$. Equation (3) shows that phase difference variation is significantly affected by baseline length, so constraints on baseline length influence both phase difference measurement and direction-finding accuracy, with long baselines having a more pronounced effect. While long baselines provide more precise phase difference information for solving target incidence angles, they also produce multiple possible incidence angles. Therefore, a combination of short and long baselines can be used, leveraging their ratio relationship to obtain precise direction angles and resolve phase ambiguity.

5.2 Two-Dimensional Radio Interferometer Array Direction-Finding Method For a two-dimensional phase interferometer with antennas arranged at the vertices of a right triangle (Figure 8), the direction-finding formulas are:

$$\phi_{AB} = \frac{2\pi D \cos\beta \sin\alpha}{\lambda}$$

$$\phi_{AC} = \frac{2\pi D \cos\beta \cos\alpha}{\lambda}$$

where ϕ_{AB} and ϕ_{AC} are the phase differences on baselines AB and AC, D is the baseline length, α is the signal azimuth angle, β is the signal elevation angle, and λ is the wavelength.

[Figure 8: see original paper]

From equations (4) and (5), the signal azimuth and elevation angles can be derived as:

$$\alpha = \arctan\left(\frac{\phi_{AB}}{\phi_{AC}}\right)$$

$$\beta = \arccos\left(\frac{\lambda\sqrt{\phi_{AB}^2 + \phi_{AC}^2}}{2\pi D}\right)$$

Similar to the one-dimensional case, when the antenna spacing $D \leq \lambda/2$, the phase difference for any signal direction remains within $[-\pi, \pi]$, eliminating multiple possible incidence angles. When $D > \lambda/2$, the phase difference may exceed this range, causing phase ambiguity.

In radio interferometer arrays, feed elements are often arranged irregularly to meet specific observation requirements, resulting in different baseline lengths between feeds. Consider a five-element feed array as shown in Figure 9.

[Figure 9: see original paper]

With four baselines AB, AC, AD, and AE having lengths D_{AB}, D_{AC}, D_{AD}, and D_{AE}, and phase differences ϕ_{AB}, ϕ_{AC}, ϕ_{AD}, and ϕ_{AE}, the geometric relationships yield:

$$\phi_{AB} = \frac{2\pi D_{AB} \cos\beta \sin\alpha}{\lambda}$$

$$\phi_{AC} = \frac{2\pi D_{AC} \cos\beta \sin\alpha}{\lambda}$$

$$\phi_{AD} = \frac{2\pi D_{AD} \cos\beta \cos\alpha}{\lambda}$$

$$\phi_{AE} = \frac{2\pi D_{AE} \cos\beta \cos\alpha}{\lambda}$$

where λ is the incident wavelength, α is the azimuth angle, and β is the elevation angle.

Using multiple feeds to assist in resolving phase ambiguity of long baselines improves direction-finding precision. The target azimuth and elevation angles can be solved using long-baseline phase differences:

$$\alpha = \arctan\left(\frac{D_{AE}\phi_{AB}}{D_{AC}\phi_{AE}}\right)$$

$$\beta = \arccos\left(\frac{\lambda\sqrt{(\phi_{AB}/D_{AB})^2 + (\phi_{AD}/D_{AD})^2}}{2\pi}\right)$$

Phase ambiguity exists between the measured and actual phase differences for long baselines. When baseline lengths satisfy $D_{AB} \leq \lambda/2$ and $D_{AD} \leq \lambda/2$, we have:

$$\phi^m_{AB} = \phi^a_{AB}$$

$$\phi^m_{AD} = \phi^a_{AD}$$

where ϕ^m and ϕ^a denote measured and actual phase difference values. For baselines with $D_{AC} > \lambda/2$ and $D_{AE} > \lambda/2$:

$$\phi^m_{AC} = \phi^a_{AC} - 2\pi N_{AC}$$

$$\phi^m_{AE} = \phi^a_{AE} - 2\pi N_{AE}$$

where N_{AC} and N_{AE} are integers representing the phase ambiguity cycles. Since phase difference is proportional to baseline length, we have:

$$\frac{\phi^a_{AC}}{D_{AC}} = \frac{\phi^a_{AB}}{D_{AB}}$$

$$\frac{\phi_{AE}^a}{D_{AE}} = \frac{\phi_{AD}^a}{D_{AD}}$$

Substituting the measured short-baseline values into the coarse long-baseline values and matching them with precise values yields the cycle numbers N_{AC} and N_{AE}, allowing calculation of the actual phase differences. Substituting these into equations (12) and (13) yields the target signal’ s azimuth and elevation angles, achieving direction finding.

5.3 Error Analysis Using the one-dimensional interferometer direction-finding method from equation (3) as an example, error analysis is performed on the measured incidence angle. Assuming independent variables, taking the total differential of equation (3) with respect to incidence angle, wavelength, and baseline length yields an expression in terms of phase difference measurement error, baseline length measurement error, and signal wavelength measurement error:

$$d\theta = \frac{\lambda}{2\pi D\cos\theta}d\phi - \frac{\phi}{2\pi D\cos\theta}d\lambda - \frac{\phi\lambda}{2\pi D^2\cos\theta}dD$$

According to error propagation theory [10]:

$$\sigma_\theta^2 = \left(\frac{\lambda}{2\pi D\cos\theta}\right)^2\sigma_\phi^2 + \left(\frac{\phi}{2\pi D\cos\theta}\right)^2\sigma_\lambda^2 + \left(\frac{\phi\lambda}{2\pi D^2\cos\theta}\right)^2\sigma_D^2$$

where σ_θ is the standard deviation of the incidence angle, σ_ϕ is the standard deviation of the measured phase difference, σ_λ is the standard deviation of the wavelength measurement, and σ_D is the standard deviation of the baseline length measurement. Typically, baseline length and signal wavelength can be measured accurately, so the primary error source is the first term. The smaller this coefficient, the smaller σ_θ becomes. This coefficient can be expressed as an error ratio.

From equation (24), the incidence angle error depends on wavelength, baseline length, and incidence angle. Setting the wavelength to 0.6 m and baseline lengths to 0.3 m, 0.6 m, and 1.2 m yields the results shown in Figure 10.

[Figure 10: see original paper]

Since equation (24) cannot be evaluated at $\theta = \pm 90°$, calculations are performed for $\theta \in (-90°, 90°)$. Figure 10 shows that for a fixed baseline length, the error ratio increases with azimuth angle when $\theta \in (0°, 90°)$, indicating larger errors for targets at greater actual azimuth angles. Conversely, when $\theta \in (-90°, 0°)$, the error ratio decreases as the incidence angle increases, indicating smaller errors for targets at larger actual incidence angles. Additionally, for a fixed incidence angle, the error ratio decreases with increasing baseline length, demonstrating that long baselines provide higher measurement precision. Finally, the error ratio changes most dramatically as θ approaches 0°, while the variation becomes more gradual near ±90°.

Similarly, the relationship between incidence angle error and frequency can be obtained for a fixed baseline length. For convenience, the frequency range is set to 500–1500 MHz. As shown in Figure 11, the error ratio decreases with increasing incident wave frequency. This indicates that higher incident wave frequencies yield higher azimuth direction-finding precision using phase difference methods. The error ratio variation is more pronounced near the 0° direction, particularly in the low-frequency band, but becomes more gradual as frequency increases. Near the ±90° directions, the error ratio shows relatively less variation with frequency.

[Figure 11: see original paper]

Radio interferometry is a crucial technique in astronomical observations. Beyond observing known or unknown celestial bodies, it can also detect artificial space objects in Earth orbit. The Tianlai array' s wide field of view and high sensitivity make it well-suited for space object capture and detection. This analysis demonstrates that a bistatic radar system combining the Tianlai array with the Qujing Incoherent Scatter Radar can detect space objects smaller than 10 cm in LEO. However, the array' s modest angular resolution makes imaging-based positioning of small objects difficult. This paper proposes using a combination of short and long baselines with phase difference measurement for direction finding, addressing the phase ambiguity problem in measurements and calculations. Error analysis reveals the relationship between direction-finding error and angle. According to reference [11], the Tianlai array has initially demonstrated feasibility for space object detection experiments, and this study provides a theoretical foundation for future space object detection using the Tianlai array.

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Note: Figure translations are in progress. See original paper for figures.