Research on Digital Beamforming Technology for Interplanetary Scintillation (IPS) Telescopes (Postprint)

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Abstract

For the Mingantu Interplanetary Scintillation Telescope in the proposed Meridian Project Phase II, digital beamforming technology constitutes one of the key technologies. Addressing the inability of existing digital beamforming algorithms to satisfy the application requirements of IPS telescopes and their high computational complexity, this paper presents improvements and optimizations to existing digital beamforming algorithms, proposing a beamforming algorithm tailored for the Mingantu IPS telescope. Simulation results demonstrate that the algorithm can well satisfy the requirements of IPS telescopes. Additionally, building upon the single-beam foundation, this paper also proposes a multi-beam synthesis algorithm and performs algorithmic simulations.

Full Text

Research on Digital Beamforming Technology for Interplanetary Scintillation (IPS) Telescope

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Abstract: Digital beamforming technology represents a key enabling technology for the Mingantu Interplanetary Scintillation Telescope, a major instrument under development for the Meridian Project Phase II. Existing digital beamforming algorithms fail to meet the application requirements of IPS telescopes and suffer from high computational complexity. This paper presents improvements and optimizations to conventional digital beamforming algorithms, proposing a novel beamforming algorithm tailored specifically for the Mingantu IPS telescope. Simulation results demonstrate that the algorithm successfully satisfies the stringent requirements of IPS observations. Building upon the single-beam framework, we further propose and validate a multi-beam synthesis algorithm through comprehensive simulations.

Keywords: Interplanetary Scintillation (IPS) telescope; Digital beamforming algorithm; Linearly Constrained Minimum Variance (LCMV) algorithm

0 Introduction

The Meridian Project Phase II, a major national scientific research equipment development initiative, has been designated as one of ten priority projects supported by China' s National Development and Reform Commission. This comprehensive observatory system provides continuous monitoring of critical parameters throughout Earth' s space environment, extending from the upper atmosphere at 20–30 km altitude through the ionosphere and magnetosphere to the interplanetary medium at distances exceeding ten Earth radii. The network measures electromagnetic fields, electric fields, upper atmospheric wind fields, density and composition, ionospheric characteristics, and magnetospheric and interplanetary space parameters.

Interplanetary Scintillation (IPS) refers to the random fluctuations in intensity and phase of radio waves from distant compact radio sources as they propagate through the solar wind plasma in interplanetary space. This scattering phenomenon enables researchers to investigate the angular structure of compact sources while simultaneously measuring solar wind velocity and characterizing the power spectrum of electron density irregularities in the solar wind plasma. IPS observations thus provide valuable data for both theoretical research and practical applications. Ground-based IPS measurements represent an economical and effective remote sensing technique for monitoring interplanetary space. By utilizing natural radio sources or satellite downlink signals as radio beacons and receiving these signals through single or networked ground-based telescopes, researchers can analyze how the interplanetary medium affects radio propagation characteristics. Measurements of signal intensity fluctuations, propagation delays, and phase variations, combined with inversion calculations when necessary, enable remote sensing of interplanetary spatial structures and their temporal evolution.

Currently, several countries have conducted IPS studies using existing telescopes. In China, the Meridian Project Phase II IPS observation facility, led by the Space Center of the Chinese Academy of Sciences, is undergoing technical development. Through coordinated three-station observations and data analysis, this system is expected to achieve significant scientific advances in mapping the three-dimensional large-scale distribution of background solar wind velocity, tracking the evolution of solar activity cycles, performing three-dimensional tomographic inversion and temporal monitoring of Coronal Mass Ejections (CMEs) in interplanetary space, and investigating kinetic turbulence amplitudes in the solar wind.

For IPS telescopes, digital multi-beam synthesis represents a critical enabling technology. Digital multi-beam synthesis, also known as spatial filtering, constitutes a primary technique in array signal processing with widespread applications in radio astronomy, radar, sonar, navigation, wireless communications, and seismic monitoring. This paper focuses specifically on its application to radio telescopes. Digital beamforming fundamentally exploits spatial signal information acquired by array elements at different positions, applying weights to each element to enhance desired signals while suppressing interference. Key advantages include: the ability to form single or multiple independently controllable beams without signal-to-noise ratio degradation; flexible beam characteristics controlled through weight vectors; excellent self-calibration and low sidelobe capabilities; and facilitation of subsequent array signal processing for superior performance. This technology enables the formation of multiple main beams, allowing simultaneous observation of multiple radio sources across the sky.

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1 Interplanetary Scintillation (IPS) Telescope

In the design of the Meridian Project Phase II IPS telescope, we analyzed and compared the IPS design approaches and observational experience of Japan’ s Nagoya four-station system and India’ s Ooty single-station system to propose a novel “one master station with two auxiliary stations” configuration. The master station, located in Mingantu Town, Zhengxiangbai Banner, Inner Mongolia, employs a large steerable parabolic cylindrical antenna. The two auxiliary stations, situated in Abaga and Hexigten respectively, utilize fully steerable parabolic antennas. The three stations form an approximately equilateral triangle geographically, with baseline lengths of approximately 200 km between any two stations. The IPS instrumentation primarily measures time series of intensity scintillation from radio sources, employing power spectrum fitting from single-station observations and cross-correlation time delays from three-station joint measurements to rapidly obtain physical parameters including solar wind velocity and the non-normalized power spectrum of electron density perturbations in different spatial regions. This approach enables tracking of solar wind and CME disturbances as they accelerate, propagate, and evolve through interplanetary space.

[Figure 1: see original paper] shows the configuration of the IPS telescope. The master station consists of three parabolic cylindrical antennas placed side by side, each measuring 140 meters in the north-south (N-S) direction and 40 meters in the east-west (E-W) direction, as illustrated in [Figure 2: see original paper]. To enable rapid sky scanning and facilitate observations of other scientific targets, the cylindrical antennas are designed to rotate in the E-W direction without tracking specific sources. Through rotation, the system can point to different sky regions at different times, achieving rapid scanning coverage of the entire sky. Additionally, the master station includes a 20-meter parabolic antenna that can also be used for IPS observations. Each auxiliary station is equipped with a ~20-meter parabolic antenna.

At each site, the antennas can operate independently in dual-frequency mode for single-station observations or work jointly across multiple stations in dual-frequency mode. This dual approach leverages the high sensitivity of the master station' s antennas to observe more radio sources across the sky while simultaneously employing multi-station correlation of strong sources to obtain more accurate solar wind velocity information, thereby enabling better three-dimensional reconstruction of solar wind structures.

Each cylindrical antenna features a focal line along which 304 feed elements are positioned to receive radio signals, capable of operating simultaneously or independently at 327 MHz and 654 MHz. Each feed connects to a low-noise amplifier (LNA); after amplification and bandpass filtering, the signal is digitized by an AD converter. The digital signals are transmitted via optical fiber to indoor receivers for digital multi-beam synthesis, ultimately producing observation signals for multiple radio sources in different directions. This paper focuses on investigating the digital multi-beam synthesis technology for the cylindrical antennas at the IPS telescope master station. The main specifications and technical indicators of the IPS telescope array are summarized in .

Table 1 Main Specifications and Technical Indicators of IPS Telescope Array

Parameter	Specification
Antenna Configuration	Cylindrical: 3×140m×40m; Parabolic: 1×20m and 2×~20m
Frequency Bands	327 MHz, 654 MHz, 1420 MHz*
Frequency Resolution	40 MHz
Frequency Resolution	39 kHz
Beam Synthesis	Master station: 3×12 beams, sidelobes below -20 dB
Sensitivity	Master station: ~4.4 mJy; Sub-stations: ~261 mJy

*Note: Only auxiliary parabolic antennas operate at 1420 MHz.

2 Array Signal Modeling

Consider a radio source in space and a uniform linear array (ULA) consisting of N elements receiving its signal. With the first element positioned at the coordinate origin serving as the reference element, and under the narrowband signal assumption, if the signal received by the reference element is represented as $s(t)e^{j\omega t}$, then the signal received by the i-th element can be expressed as $s(t)e^{j\omega t} \cdot e^{-j\omega\tau_i}$. The received signal model for a uniform linear array is shown in [Figure 4: see original paper].

Let the steering vector be denoted as $a(\theta)$. Then $a(\theta) = [1, e^{-j\omega\tau_1}, \dots, e^{-j\omega\tau_i}, \dots, e^{-j\omega\tau_{N-1}}]^T$, where the time delay τ_i of the i-th element relative to the reference element is given by $\tau_i = \frac{d \sin\theta_i}{c}$. Interference and desired signals are narrowband signals at the same frequency but with different incident angles and are uncorrelated with the desired signal. The noise signal is stationary, zero-mean Gaussian white noise with variance σ^2, with noise received at each element being mutually uncorrelated and uncorrelated with the desired signal.

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3 Array Pattern Definition

The array antenna pattern represents the array response of a weighted antenna array to signals arriving from different spatial directions. The array pattern function can be expressed as:

$$F(\theta) = W^H a(\theta) \quad (1)$$

where W is the weight vector obtained from the beamforming algorithm. The pattern function characterizes the gain of the antenna array to signals arriving from various directions after beamforming. By taking the absolute value, normalizing, and applying logarithmic processing, the array pattern can be expressed as:

$$P(\theta) = 20\log_{10}\frac{|F(\theta)|}{\max(|F(\theta)|)} \quad (2)$$

From equations (1) and (2), we can see that when the array' s weight vector changes, the response to spatial signals from different directions varies accordingly, thereby altering the pointing direction of the formed array pattern.

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4 Digital Beamforming Algorithm

Digital beamforming algorithms enhance desired signals and suppress interference by applying weights to array elements at different positions, aligning the main lobe of the array pattern with the desired signal' s incident direction while positioning low sidelobes toward interference directions. These algorithms include conventional digital beamforming and adaptive digital beamforming approaches.

4.1 Conventional Digital Beamforming Algorithm

The conventional digital beamforming algorithm employs fixed weights independent of the input signal. The weights equal the steering vector of the desired signal, yielding a response in the desired signal direction of $F(\theta_0) = a^H(\theta_0)a(\theta_0) = N$, where θ_0 is the desired signal' s incident angle and N is the number of array elements. Under these conditions, signals from all channels add coherently in phase, maximizing the array' s signal gain in the desired signal direction.

4.2 Adaptive Digital Beamforming Algorithm

Adaptive digital beamforming algorithms adjust the array' s weight vector based on prior knowledge of the signal environment and specific optimization criteria, creating a main beam in the desired direction while forming nulls in interference directions to suppress unwanted signals. Adaptive beamforming weights depend on the input signal and adaptively adjust as the electromagnetic environment changes, enabling tracking of desired signals. The block diagram of an adaptive beamforming system is shown in [Figure 5: see original paper].

The Linearly Constrained Minimum Variance (LCMV) algorithm represents an optimal adaptive digital beamforming approach. The LCMV principle minimizes array output power while constraining the gain in the desired signal direction to unity and the gain in interference directions to zero. The constraint expression is:

$$C^H W = f$$

where C is an $N \times 2$ constraint matrix $[a(\theta_0), a(\theta_1)]$, with θ_0 representing the desired signal direction and θ_1 the interference signal direction, and f is a 2×1 response vector $[1, 0]^T$.

The mathematical formulation of the LCMV algorithm is:

$$\min_W W^H R_x W \quad \text{s.t.} \quad C^H W = f$$

where R_x is the covariance matrix of the received signal (including desired signal, interference, and noise). Using the Lagrange multiplier method, the optimal weight vector is:

$$W_{opt} = R_x^{-1} C [C^H R_x^{-1} C]^{-1} f$$

Due to system amplitude and phase errors, the received signal' s covariance matrix R_x differs from the actual signal covariance matrix, degrading algorithm performance. This error manifests as errors in both the desired signal and interference components. To mitigate these effects, we preprocess R_x by subtracting the desired signal component. Since the LCMV algorithm minimizes the power of desired signal, interference, and noise (effectively minimizing interference and noise power) while maintaining unit response in the desired signal direction, we can decompose the received signal as:

$$X = X_s + X_{i+n}$$

where X is the total received signal, X_s is the desired signal component, and X_{i+n} represents interference plus noise. The covariance matrix of interference plus noise is $R_{i+n} = E[X_{i+n}X_{i+n}^H]$. The optimal weight vector then becomes:

$$W_{opt} = R_{i+n}^{-1}C[C^H R_{i+n}^{-1}C]^{-1}f$$

This preprocessing ensures that the error between the received covariance matrix and the actual covariance matrix is limited to the difference between received and actual interference components.

4.3 Matlab Simulation and Results Analysis

For the parabolic cylindrical antennas at the IPS telescope master station, each cylindrical antenna contains 304 feed elements spaced at half-wavelength intervals. IPS observations require beamforming processing of all feed element signals to enable antenna pointing toward different radio sources. These feeds can be treated as a linear feed array with $N = 304$ elements and element spacing $d = 0.5\lambda$. To evaluate digital beamforming algorithm performance, we conducted the following simulations:

1. **Conventional Beamforming**: Assuming a desired signal arrival angle of 10°, the resulting array pattern is shown in [Figure 6: see original paper].
2. **LCMV Beamforming**: With desired signal at 10°, interference at 50°, snapshot number of 1000, SNR = 30 dB, INR = 30 dB, and 5% amplitude-phase error added to interference, the LCMV array pattern is shown in [Figure 7: see original paper].

Simulation results demonstrate that the LCMV algorithm successfully suppresses interference, whereas the conventional beamforming algorithm cannot. However, both algorithms exhibit relatively high first sidelobe levels of approximately -13.4 dB, failing to meet the IPS telescope’ s technical requirement of -20 dB sidelobe suppression (Table 1). During observations, interference could enter the receiving system through these high sidelobes, compromising observational results.

5 Improved Digital Multi-Beamforming Algorithm

Conventional beamforming algorithms can achieve the IPS telescope’ s sidelobe specifications through windowing methods, but such approaches sacrifice antenna sensitivity. This paper proposes an improved algorithm based on LCMV that reduces sidelobes without sensitivity loss to meet IPS telescope requirements.

5.1 Improved LCMV Algorithm

The LCMV algorithm naturally forms deep nulls in interference directions. We leverage this capability by introducing virtual interference sources to suppress sidelobes. After obtaining the LCMV result, we identify angular positions of sidelobe peaks exceeding a threshold (e.g., -25 dB) and designate these as virtual interference directions. While standard LCMV forces zero response at interference directions (creating deep nulls), this severely elevates responses in adjacent directions. Our improved algorithm instead constrains virtual interference responses to a small non-zero value (e.g., 0.05), thereby reducing sidelobe heights at virtual interference directions without significantly increasing sidelobe levels in neighboring regions.

The improved LCMV constraint expression becomes:

$$C^H W = f$$

where C is an $N \times (m+1)$ constraint matrix $[a(\theta_0), a(\theta_1), a(\theta_2), \dots, a(\theta_m)]$, with θ_0 representing the desired signal direction, θ_1 the actual interference direction, and $\theta_2 \dots \theta_m$ the virtual interference directions. The response vector f is an $(m+1) \times 1$ vector $[1, 0, 0.05, \dots, 0.05]^T$.

The improved LCMV algorithm is formulated as:

$$\min_W W^H R_x W \quad \text{s.t.} \quad C^H W = f$$

The optimal weight vector obtained via Lagrange multiplier method is:

$$W_{opt} = R_x^{-1} C [C^H R_x^{-1} C]^{-1} f$$

5.2 Matlab Simulation and Results Analysis

Under identical conditions (desired signal at 10°, interference at 50°, 1000 snapshots, SNR = 30 dB, INR = 30 dB, 5% amplitude-phase error), we set angles with responses above -25 dB as virtual interference directions. The improved LCMV algorithm simulation result is shown in [Figure 8: see original paper].

The simulation employs the improved LCMV algorithm, constraining angles above -25 dB in the original LCMV pattern to virtual interference directions with response 0.05. Results show that sidelobe heights near the main beam that originally exceeded -25 dB are reduced below this threshold. Due to the additional constraint on virtual interference responses, sidelobe amplitudes in regions adjacent to virtual interference directions increase slightly, but remain below -20 dB. Consequently, the improved LCMV algorithm successfully meets the IPS telescope' s technical specification of -20 dB sidelobe suppression.

6 Subarray-Based Improved Digital Beamforming Algorithm

If each array element corresponds to a dedicated receiving channel, the array achieves optimal response and maximum beam steering flexibility. However, for large arrays such as ours, this results in high-dimensional weight vectors and computationally intensive digital beamforming algorithms. Moreover, each channel requires hardware components including AD converters and filters, leading to a complex system with high costs. To reduce system complexity and hardware costs while maintaining satisfactory array response, we employ a subarray approach where each subarray corresponds to a single receiving channel. We therefore propose a subarray-based digital beamforming algorithm, with its principle block diagram shown in [Figure 9: see original paper].

Table 2 Comparison of Complexity Between Element-Level and Subarray-Level Processing

Component	Element-Level	Subarray Scheme I (4 elements)	Subarray Scheme II (8 elements)
Array Elements	304	304	304
Analog Phase Shifters	0	304×3	304×7
AD Converters	304×1	76×1	38×1
Data Rate	304×100 MB	76×100 MB	38×100 MB
Weight Vector Dimension	304×1	76×1	38×1

The table compares complexity between element-level and subarray-level processing. The subarray-based approach significantly reduces the number of AD converters, data rate, and weight vector dimension by factors proportional to the number of elements per subarray. While increasing elements per subarray yields greater reductions in hardware complexity, it simultaneously decreases beam steering flexibility. Therefore, to maintain adequate array response, we cannot arbitrarily increase subarray size.

6.1 Matlab Simulation and Results Analysis

For a 304-element linear array with subarray sizes of 19 and 38 elements (non-overlapping), assuming a desired signal arrival angle of 10° and interference at 50°, with 1000 snapshots, SNR = 30 dB, INR = 30 dB, and 5% amplitude-phase error, we set angles above -25 dB as virtual interference directions. Phase shifters align elements within each subarray coherently, while the improved LCMV algorithm processes signals between subarrays. Simulation results for different subarray sizes are shown in [Figure 10: see original paper] and [Figure 11: see original paper].

Results demonstrate that the improved LCMV algorithm based on subarrays (with 19 or 38 elements per subarray) meets the IPS telescope' s sidelobe specifications while substantially reducing computational complexity compared to element-level processing. However, the 38-element subarray configuration fails to form deep nulls in the interference direction and exhibits higher first sidelobe levels, indicating noticeable performance degradation. Additional simulations with subarray sizes of 2, 4, 8, and 16 elements also satisfied the sidelobe requirements. Performance degrades as subarray size increases, establishing 19 as the maximum practical subarray size among divisors of 304.

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7 Multi-Beam Synthesis

Previous sections addressed single-beam synthesis, but simultaneous observation of multiple radio sources requires formation of multiple main beams. As established earlier, array weights determine beam pointing directions. Multi-beam synthesis therefore requires generating multiple distinct weight sets, each providing different phase compensation and amplitude adjustments to form separate main beams. The principle block diagram for multi-beam synthesis is shown in [Figure 12: see original paper].

7.1 Matlab Simulation and Results Analysis

Simulation conditions: $N = 304$ elements, $d = 0.5\lambda$ spacing, 19 elements per subarray (non-overlapping), multiple desired signals at -20°, 0°, 10°, and 30°, interference at 50°, 1000 snapshots, SNR = 30 dB, INR = 30 dB, 5% amplitude-phase error, angles above -25 dB designated as virtual interference directions, intra-subarray phase alignment via phase shifters, and improved LCMV algorithm for inter-subarray processing. Results are shown in [Figure 13: see original paper].

The simulation successfully forms four main beams at -20°, 0°, 10°, and 30°, with sidelobe levels meeting IPS telescope technical specifications.

This paper investigates digital beamforming technology—a key technology for the Meridian Project Phase II IPS telescope—proposing a digital beamforming algorithm specifically adapted for the telescope' s cylindrical antennas. The algorithm employs virtual interference techniques based on LCMV to achieve synthesized beams meeting IPS requirements. Subarray processing reduces computational complexity and implementation difficulty. Finally, building upon single-beam synthesis, we propose a multi-beam synthesis algorithm enabling simultaneous observation of multiple radio sources across the sky.

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