Measurement and Analysis of Antenna Phase Patterns for the Mingantu Radio Spectral Heliograph (Postprint)

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Abstract

Mingantu Ultrawide SpEctral Radioheliograph (MUSER) is a new generation of solar-dedicated radio telescope with high temporal, spatial, and frequency resolution, which employs the principle of aperture synthesis for imaging; therefore, amplitude and phase are key factors determining the quality of the final images. The antenna phase pattern affects the amplitude and phase output by the radioheliograph. Based on the feed design of the radioheliograph and the principle of aperture synthesis, considering the large number of antennas in MUSER, its outdoor environment, and the requirement for frequent antenna performance testing in astronomical observations, a method for measuring the antenna phase pattern of the radioheliograph based on correlation results is presented. This method can directly use the correlation output results of the radioheliograph to efficiently and accurately obtain the antenna phase pattern. The phase pattern of MUSER-I antennas was measured and analyzed, and the impact of the antenna phase pattern on radioheliograph imaging was also analyzed, providing reference and assurance for obtaining high-quality solar images.

Full Text

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Abstract: The Mingantu Ultrawide SpEctral Radioheliograph (MUSER) is a new generation of solar-dedicated radio telescope capable of imaging the Sun with high temporal, spatial, and frequency resolution simultaneously. As an aperture-synthesis instrument, amplitude and phase are the key factors determining final imaging quality. The antenna phase pattern significantly affects the output amplitude and phase of the radioheliograph. Considering MUSER' s feed design and aperture-synthesis principle, and given the large number of antennas operating in an outdoor environment where frequent performance testing is required for astronomical observations, we present a method for measuring antenna phase patterns based on correlation outputs. This method can efficiently and accurately obtain antenna phase patterns directly from MUSER' s correlation results. We present detailed measurements and analysis of the antenna phase patterns for MUSER-I, and analyze the impact of antenna phase patterns on MUSER imaging, providing a reference and guarantee for obtaining high-quality solar images.

Keywords: phase pattern; correlation; Mingantu Ultrawide SpEctral Radioheliograph (MUSER)

1. Introduction

The antenna pattern is a graphical representation of antenna radiation characteristics as a function of spatial angle, typically forming a three-dimensional spherical surface centered on the antenna' s phase center. By sequentially measuring the antenna' s radiation characteristics at each point on a sufficiently large sphere of radius r, different patterns can be obtained depending on the measured physical quantity: measuring field amplitude yields the field pattern, measuring power yields the power pattern, and measuring phase yields the phase pattern [1]. The phase characteristics of antennas contain crucial information, and phase pattern measurement has become increasingly important, particularly with the development of phased arrays and aperture-synthesis techniques.

Traditional phase pattern measurement methods are similar to those for amplitude patterns, but require measuring the relative phase between the signal under test and a reference signal [2-3]. The measurement principle is analogous to general phase measurement techniques. However, the MUSER antenna array is located on the grasslands of Inner Mongolia in a harsh outdoor environment with numerous antennas [4]. Astronomical observations demand frequent testing of antenna performance, requiring rapid and accurate determination of antenna parameters. Therefore, this paper proposes a method for measuring antenna phase patterns in interferometric arrays based on correlation measurements. According to aperture-synthesis principles, we derive the relationship between array antenna phase and the visibility function, then present a method for measuring MUSER antenna phase patterns based on correlation outputs. We conduct measurements and analysis of the MUSER-I antenna phase patterns, and analyze the impact of antenna phase patterns on MUSER imaging.

2. Overview of the Mingantu Radio Spectral Heliograph

The Mingantu Radio Spectral Heliograph is a dedicated solar radio telescope array that images the Sun with high temporal, spatial, and frequency resolution. MUSER plays an important role in studying transient high-energy phenomena, source characteristics of solar flares and coronal mass ejections, enabling better understanding of solar atmospheric structure and dynamic processes in the corona [5]. Located at the Mingantu Observation Station of the National Astronomical Observatories, approximately 400 km from Beijing, MUSER operates on aperture-synthesis principles and consists of low-frequency and high-frequency arrays. The low-frequency array comprises 40 antennas operating at 400 MHz–2 GHz with 4.5 m diameter dishes, while the high-frequency array comprises 60 antennas operating at 2–15 GHz with 2.0 m diameter dishes. The antennas are distributed along three spiral arms. Solar radio signals received by the antennas are transmitted through equal-length optical fibers to indoor analog receivers, then digitized by digital receivers and processed by a complex correlator to compute complex visibility functions for all baselines. Finally, solar images are obtained through imaging processing [6]. The current primary system specifications are shown in .

** MUSER System Specifications**

Parameter	MUSER-I	MUSER-II
Frequency Range	400 MHz–2 GHz	2 GHz–15 GHz
Number of Antennas	40	60
Number of Baselines	780	1770
Antenna Size	4.5 m	2.0 m
Baseline Range	8 m- 3000 m	4 m- 3000 m
Polarization	Dual circular	Dual circular
Dynamic Range	25 dB	25 dB

3. Phase Pattern Measurement Theory

MUSER is an interferometric system employing aperture-synthesis imaging. The brightness distribution image of a radio source can be obtained by measuring the mutual coherence function of electric fields between pairs of points perpendicular to the source plane. The simplest analysis can be performed using a two-antenna receiving system without down-conversion [8].

Let $\mathbf{s}$ be the unit direction vector pointing toward the radio source, b be the baseline distance between two antennas, and be the angle between the direction vector and the baseline normal. Assuming the antenna receiving system receives a monochromatic signal of frequency f from direction $\mathbf{s}$, the time difference due to the geometric path difference is $= (\mathbf{b} \cdot \mathbf{s})/c = b\cos /c$, where c is the speed of light. Without delay compensation, the input signals before reaching the correlator can be expressed as:

$$V_1(t) = V_{1c}\cos[2\pi f(t-\tau)]$$
$$V_2(t) = V_{2c}\cos(2\pi f t)$$

where $V\ c$ and $V\ c$ are the voltage amplitudes of the two input signals. After correlation and high-frequency component filtering, the correlator output (ignoring link gain) is:

$$R \cong \cos(2\pi f\tau) = \cos\left(\frac{2\pi b\cos\theta}{\lambda}\right)$$

where is the wavelength corresponding to the observation frequency. When the radio source is at the phase center (= 0°), signals from the source arrive at the receiving antennas simultaneously, resulting in zero phase difference at the correlator and maximum output amplitude. This direction is defined as the phase reference direction.

During actual observations, when the antenna pointing deviates from the target source, consider a point source offset from the phase center. The correlation output result is:

$$R \cong \cos\left(\frac{2\pi b\cos\theta}{\lambda} + \Delta\phi\right)$$

where *Δ* is the phase difference when the antenna pointing deviates from the phase center by angle .

In the above calculations, we ignored the influence of antenna pattern lobes. The signal strength received by an antenna is the integral over the source distribution weighted by the antenna pattern. Assuming the brightness distribution of the radiation source is $I(\mathbf{s})$ and the antenna pattern is $A(\mathbf{s})$ (including both power and phase patterns), the signal strength received by the antenna is:

$$\int_{\text{source}} I(\mathbf{s})A(\mathbf{s})d\mathbf{s}$$

4. Phase Pattern Measurement Method

Interferometer calibration and testing typically employ observations of point sources in the sky. For measuring interferometer antenna phase patterns based on correlation results, the procedure is as follows: All antennas are pointed at a calibration source and the visibility function is recorded. Then, keeping one antenna (A) tracking the calibration source, the remaining antennas are gradually moved away in right ascension while recording the visibility function.

Next, keeping antenna A tracking the calibration source, the remaining antennas are gradually moved away in declination while recording the visibility function. The phase variations of antennas other than A are calculated from the visibility functions to obtain the phase patterns in various directions.

For MUSER-I at an observation frequency of 1.7025 GHz, geostationary satellites are suitable calibration sources. The FY-2 satellite is a Chinese geostationary satellite located above the equator with a beacon frequency of 1.7025 GHz, where interference signals are minimal and can be neglected during testing. The satellite' s strong signal and good pointing/tracking accuracy make geostationary satellites excellent calibration sources.

The phase difference between an antenna and the phase center can be calculated from the recorded visibility functions. $\mathit{\Delta}\_RA$ represents the phase difference when antenna pointing deviates from the phase center in right ascension, while $\mathit{\Delta}\_Dec$ represents the phase difference when deviating in declination. Since the Sun' s angular size is approximately 30 , we focus on analyzing the antenna phase pattern within ±1° of the phase center.

5. Measurement Results and Analysis

Following the above procedure, we used the FY-2 satellite to measure the MUSER-I antenna phase patterns. The phase difference between the antenna and phase center remains within approximately ±1° in the ±1° × ±1° imaging range around the Sun. During measurement, satellite motion causes phase variations in MUSER outputs, which must be subtracted from the results during data processing by calculating the phase change due to position variation based on the source' s movement.

Imaging quality depends primarily on the flatness of both the amplitude and phase patterns in the antenna' s main lobe. Since phase errors from pointing deviation are more significant than amplitude errors, we can neglect amplitude errors and focus on analyzing phase error effects on imaging quality. The impact of phase errors on images depends on their effect on the visibility function. Typically, errors in visibility measurements fall into two categories: antenna-based errors and baseline-based errors. Antenna phase patterns belong to antenna-based errors [9-10].

[**Figure 104: see original paper**] Measured phase difference when antenna pointing deviates ±1° in right ascension direction for MUSER-I.

[**Figure 104: see original paper**] Measured phase difference when antenna pointing deviates ±1° in declination direction for MUSER-I.

For MUSER, consider a simple point source with unit flux density at the phase center. For an interferometer with N antennas in snapshot mode, the visibility function is:

$$V(u,v) = \sum_{i=1}^{N} \sum_{j>i}^{N} e^{-i2\pi(ul+vm)}$$

where (*u,v*) are baseline coordinates and (*l,m*) are direction cosines. The interferometer output image can be expressed as:

$$I(l,m) = \sum_{i=1}^{N} \sum_{j>i}^{N} 2\cos[2\pi(ul+vm)]$$

For baselines with errors, this component becomes:

$$I(l,m) = \sum_{i=1}^{N} \sum_{j>i}^{N} [\cos(2\pi(ul+vm)+\phi_e) + \cos(2\pi(ul+vm)-\phi_e)]$$

where is the phase error in the visibility function. The interferometer’ s point spread function can be expressed as:

$$B(l,m) = \sum_{i=1}^{N} \sum_{j>i}^{N} 2\cos[2\pi(ul+vm)]$$

The final output image is:

$$I(l,m) = B(l,m) + R(l,m)$$

where *R(l,m)* represents the error image. Through CLEAN deconvolution, the error image can be obtained as:

$$R(l,m) = I(l,m) - B(l,m) = \sum_{i=1}^{N} \sum_{j>i}^{N} 2\sin[2\pi(ul+vm)]\sin\phi_e$$

This error image is a sinusoidal function. The dynamic range of an image is defined as the ratio of the maximum radiation intensity to the RMS in a source-free region. From the above derivation, for an interferometer with N antennas, if one baseline has a phase error , there are $N/2$ affected visibility functions, yielding a dynamic range of:

$$DR = \frac{N}{2\phi_e}$$

In reality, errors rarely exist on only one baseline. Assuming random phase errors on all baselines that are independent, the dynamic range becomes:

$$DR = \frac{N}{\sqrt{2}\phi_e}$$

If the phase errors are antenna-based (as with antenna phase patterns), each error affects all baselines associated with that antenna, resulting in:

$$DR = \frac{\sqrt{N}}{\phi_e}$$

Assuming all antennas have random antenna-based phase errors , the dynamic range scales with $\sqrt{N}$ and can be expressed as:

$$DR = \frac{1}{\phi_e \sqrt{N}}$$

For MUSER's low-frequency array with $N = 40$ antennas and a technical requirement of dynamic range 25 dB (320:1), the allowable phase error is calculated to be approximately 1.6°. The measured phase differences of MUSER antennas are within ±1° in the solar imaging range, which satisfies the requirement.

6. Conclusion

This paper presents a method for measuring antenna phase patterns based on correlation outputs, tailored to MUSER' s feed design, aperture-synthesis principle, and the need for frequent antenna performance testing in an outdoor environment with numerous antennas. Measurements and analysis of MUSER-I antenna phase patterns demonstrate that MUSER' s antenna phase differences meet the solar imaging dynamic range requirement of 25 dB.

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Abstract: The MUSER (Mingantu Ultrawide SpEctral Radioheliograph) is a new generation of solar dedicated radio telescope for imaging the Sun at high time, high spatial, and high frequency resolutions simultaneously. It is an aperture-synthesis telescope, so the amplitude and phase are the key factors in the final imaging. The phase pattern is an important factor affecting the array' s amplitude and phase. In this paper, allowing for the techniques of MUSER, the method by measuring correlation is adopted to measure phase pattern of feeds for MUSER based on aperture synthesis principle. Since MUSER has numbers of antennas and located in harsh environments and according to the demand of astronomical observations, the performance of the antennas should be measured frequently. This method simplifies the process of phase pattern measurement of the interferometric array and it can obtain accurate results efficiently. The measuring process and analysis of MUSER-I are presented in detail in this paper. In addition, to support future scientific observation, the phase pattern' s effect on the image is further studied.

Keywords: Phase pattern; Correlation; Mingantu Ultrawide SpEctral Radioheliograph

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