DSRT Three-Axis Low-Frequency Antenna Pointing Error Batch Measurement and Correction Method Postprint

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Abstract

The Daocheng Solar Radio Telescope (DSRT), as an important component of the solar-interplanetary detection subsystem of the Meridian Project Phase II, operates in the 150–450;MHz frequency band and provides high spatial and temporal resolution brightness temperature images of solar bursts. To address the requirements for high-precision pointing measurement of DSRT antennas and batch calibration and correction of pointing errors, we first established a three-parameter encoder zero-point error model for the antenna based on DSRT' s unique three-axis mount system using quaternion rotation transformation. We then proposed a drift-scan method based on radio sources to obtain the power patterns of 16 unit antennas and accurately measured the DSRT antenna pointing errors by determining the beam center from the two-dimensional patterns. Finally, we fitted the model parameters using the least squares method, readjusted the zero points of each axis through the antenna control software, and verified the adjustment results. The results demonstrate that the pointing correction method is reliable and effective: the pointing accuracy of the 16 antennas after correction is within 0.5°, significantly better than the 3.5° pointing error before correction, and meets the requirement that the error be less than 1/10 of the beamwidth at DSRT' s highest operating frequency.

Full Text

Batch Measurement and Calibration of DSRT Three-Axis Low-Frequency Antenna Pointing Errors

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Abstract

The Daocheng Solar Radio Telescope (DSRT) serves as a critical component of the solar-interplanetary exploration subsystem for the second phase of the Chinese Meridian Project. Operating in the 150–450 MHz frequency band, DSRT provides high spatial and temporal resolution brightness temperature images of solar eruptions. To address the need for high-precision pointing measurement and batch calibration of pointing errors for DSRT antennas, this paper first establishes a three-parameter encoder zero-point error model through quaternion rotation transformation based on DSRT' s unique three-axis mount system. We then propose a drift-scanning method using radio sources to obtain power patterns for 16 unit antennas, determining the beam center from two-dimensional patterns to accurately measure DSRT antenna pointing errors. Finally, model parameters are obtained through least-squares fitting, and the zero points of each axis are adjusted via antenna control software, with verification of the adjustment results. The results demonstrate that the pointing calibration method is reliable and effective. After correction, the pointing accuracy of the 16 antennas is within 0.5°, significantly better than the pre-correction error of 3.5°, and meets the requirement that errors be less than one-tenth of the beamwidth at DSRT' s highest operating frequency.

Keywords: radio telescope: pointing error, antenna power pattern; Sun: radio radiation, methods: data analysis

1. Introduction

Beam pointing accuracy represents a crucial performance metric for radio telescope antennas. Ideally, radio telescopes can precisely track known celestial sources through servo drive systems. However, due to installation errors, structural rigidity limitations, geometric imperfections, and environmental conditions, antennas exhibit pointing errors both statically and during motion. These errors include components arising from non-orthogonal axes, gravitational deformation, atmospheric refraction, and other factors. The presence of pointing errors not only degrades the antenna' s ability to track sources but also causes gain loss, making the measurement and correction of pointing errors essential steps for obtaining high-quality data.

Current pointing error correction methods for radio telescopes primarily involve establishing pointing models, fitting model parameters through multi-sample testing to obtain correction coefficients, and compensating for deviations in antenna servo control commands [?, ?]. Alternative hardware-based approaches include installing small star finders or optical telescopes on radio telescopes [?, ?]. Compared with model-based correction methods, hardware approaches incur additional manufacturing and maintenance costs while suffering from significant limitations, such as requiring at least one star in the field of view and being subject to weather conditions.

The Daocheng Solar Radio Telescope (DSRT) is designed primarily for solar activity monitoring while maintaining the capability to detect radio astronomical targets across the entire sky. Consequently, the unit antenna hardware employs a three-axis tracking strategy combining an equatorial mount with an azimuth rotation platform, enabling equatorial or three-axis collaborative observation of all-sky targets. Conventional radio telescope pointing error models are based on equatorial or alt-azimuth mount systems, making them unsuitable for DSRT' s basic parameter model. DSRT operates at 150–450 MHz with unit antenna beamwidths of 19.48°–6.49°. Conventional microwave anechoic chamber measurements and traditional GPS north-finding calibration methods suffer from insufficient precision and low efficiency, necessitating a method capable of batch calibration for all unit antennas in the DSRT system.

To achieve batch calibration of pointing errors for DSRT' s 313 low-frequency antennas and thereby improve system detection performance, this paper measures the power patterns of DSRT's 6 m parabolic circular aperture antennas using the quiet Sun as a target source. Based on DSRT' s unique three-axis mount structure, we innovatively derive a three-axis encoder zero-point error model using quaternion rotation transformation. Utilizing pattern scanning data, we determine antenna pointing errors and employ least-squares fitting to obtain model coefficients. We present a unit antenna pointing error calibration method based on two-dimensional antenna patterns and validate the effectiveness of the pointing error calibration method using actual test data. The results demonstrate that the proposed method enables batch measurement of DSRT unit antenna pointing errors, reducing calibration residuals to within one-tenth of the antenna half-power beamwidth after a single correction round, laying the foundation for improved system detection performance. DSRT' s main technical specifications are shown in Table 1 .

2.1 Principle of Antenna Pointing Error Measurement Based on Two-Dimensional Patterns

Pointing errors in radio telescopes can be measured by scanning celestial radio sources—observing known sources, measuring antenna power patterns, and determining the beam center through beam fitting. Common scanning methods include cross-scanning and five-point methods. However, as celestial objects move relative to ground-based telescopes during scanning, these methods suffer from insufficient sampling points for antennas with pointing errors, resulting in larger errors in fitting the antenna beam center. Therefore, this paper proposes a method for determining pointing errors based on scanning two-dimensional antenna patterns.

Radio sources used for testing antenna patterns and pointing errors should possess the following characteristics: (1) precisely known positions that cover sufficient angular ranges throughout the day; (2) small angular sizes that are unresolved by the antenna under test, allowing treatment as point sources; and (3) high flux density within the observation frequency band to ensure adequate signal-to-noise ratio.

When an antenna scans a radio source with brightness temperature distribution $T_b(x', y')$, the antenna temperature T_A is the convolution integral of the antenna' s normalized power pattern with the source brightness temperature distribution [?], as shown in Equation (1):

$$T_A(x, y) = \Omega_A \iint_{4\pi} P(x - x', y - y') T_b(x', y') dx' dy',$$

where x' and y' are angles relative to the source center, x and y are angles relative to the antenna beam center, η_R represents radiation efficiency expressed as ohmic loss, P is the normalized power pattern, and $\Omega_A = \int_{4\pi} P d\Omega$ denotes the antenna pattern solid angle.

For sources with angular sizes much smaller than the antenna half-power beamwidth (HPBW), i.e., $\theta_s \ll$ HPBW, the source brightness temperature distribution T_b can be approximated as a delta function, and the antenna scan yields the beam shape. For uniformly illuminated circular aperture antennas, the half-power beamwidth [?] is given by Equation (2):

$$\text{HPBW} = 1.02 \frac{\lambda}{D} = 58.442^\circ \frac{\lambda}{D},$$

where λ is the wavelength and D is the antenna aperture.

DSRT operates at 150–450 MHz, with the half-power beamwidth of a uniformly illuminated 6 m circular aperture antenna ranging from 19.48° to 6.49°. The Sun' s angular diameter as observed from Earth is approximately 32 arcminutes, representing 7.7% of the antenna half-power beamwidth at the highest operating frequency. Generally, when a source' s angular size is 10%–20% of the antenna half-power beamwidth, it does not significantly affect scanning results [?]. Therefore, when DSRT scans the quiet Sun to test antenna patterns, it can be approximated as the case $\theta_s \ll$ HPBW, and the measurement error introduced by the Sun' s angular width can be neglected.

The antenna pattern testing process is illustrated in Figure 1 [Figure 1: see original paper]. Using the quiet Sun as the target source with its theoretical position at the origin, scanning is performed along the right ascension direction within a $\pm 3^\circ$ range (assuming pointing errors do not exceed $\pm 3^\circ$). Each scan yields a one-dimensional cut in the right ascension direction. After completing each right ascension scan, the declination axis steps by a fixed 0.5°, and another right ascension scan is performed. This process ultimately produces a two-dimensional power pattern covering a 6° range in both right ascension and declination directions, centered on the Sun' s theoretical coordinates. In Figure 1, (T_s, D_s) represents the target source' s right ascension and declination coordinates at that moment, while (T_i, D_i), $i = 0, 1, \dots, n$ denote the antenna' s scanning coordinates.

The actual scanning trajectory of the DSRT antenna and the motion path of the target source are shown in Figure 2 [Figure 2: see original paper], where the dashed line represents the antenna scanning trajectory and the solid line represents the Sun' s motion path. The first scan requires tracking the target source, with the antenna' s declination matching the source' s declination before beginning the right ascension scan. Consequently, the antenna scanning trajectory in Figure 2 initially deviates positively from the target source in declination, then negatively. Under ideal conditions, the coordinate origin coincides with the antenna beam center. In reality, pointing errors cause deviation between the antenna pattern' s maximum point and the zero point.

2.2 Principle of Antenna Pointing Error Correction

By measuring radio sources with known positions in the sky, an analytical relationship can be established between the true coordinates of the target source and the encoder readings when the antenna response is maximized. This yields a physically meaningful pointing error model. Through multiple measurements, model coefficients are determined and used to correct pointing errors in antenna control commands. Pointing error models include spherical harmonic models [?, ?], basic parameter models [?, ?, ?], and extended error correction models [?]. Among these, the basic parameter model features fewer parameters, clear physical meaning, and easy convergence, making it widely adopted in radio telescope pointing error correction.

The basic parameter model typically has eight free parameters [?], as shown in Equation (3):

$$\Delta A = P_1 + P_3 \cos A \tan E + P_4 \sin A \tan E + P_5 \tan E + P_6 \sec E,$$
$$\Delta E = P_2 - P_3 \sin A + P_4 \cos A + P_7 \cos E + P_8 \cot E,$$

where A and E are the antenna azimuth and elevation angles, ΔA and ΔE are the pointing errors in azimuth and elevation, and P_1 through P_8 are model parameters. The eight-parameter pointing error model for radio telescopes is detailed in Table 2 , which includes error sources such as axis misalignment, gravitational deformation, and atmospheric refraction.

DSRT' s circular array comprises 313 antennas. During batch installation and commissioning, it was found that gravitational deformation errors, axis nonorthogonality errors, and atmospheric refraction errors were not the primary error sources. Instead, errors mainly originated from zero-point errors in the antenna' s three-axis encoders. From an engineering application perspective, this paper considers only the impact of three-axis encoder zero-point errors on pointing accuracy.

3. DSRT Antenna Coordinate System and Encoder Zero-Point Pointing Error Model

Based on the mount structure of DSRT' s 6 m radio telescope, we establish the equatorial hour angle coordinate system (X, Y, Z) and the horizontal coordinate system (X_1, Y_1, Z_1) as shown in Figure 3 [Figure 3: see original paper]. In the figure, D represents declination angle, T represents right ascension angle, ϕ is the station latitude, and the pointing vector is denoted by S. Both coordinate systems are left-handed, with the X_1 axis positive toward north, Y_1 axis positive toward east, Z_1 axis pointing to zenith, and Z axis parallel to Earth' s rotation axis. Azimuth angle is positive clockwise from north, hour angle is positive westward and negative eastward. The azimuth axis coincides with the Z_1 axis, the elevation axis coincides with the Y_1 axis, the right ascension axis coincides with the Z axis, and the declination axis coincides with the Y axis. When hour angle and declination are both 0°, the electrical axis aligns with the X axis.

Finite rotations in three-dimensional space can be conveniently represented by quaternions [?], which consist of three imaginary parts and one real part, expressed as $Q = a + bi + cj + dk$, with magnitude $\|Q\| = \sqrt{a^2 + b^2 + c^2 + d^2}$ and conjugate $Q^* = a - bi - cj - dk$. When a vector rotates by angle θ about axis $\mathbf{u} = (u_x, u_y, u_z)^T$, this rotation can be represented by the quaternion in Equation (4):

$$Q = \cos\frac{\theta}{2} + \sin\frac{\theta}{2}u_x i + \sin\frac{\theta}{2}u_y j + \sin\frac{\theta}{2}u_z k.$$

Any vector $\mathbf{R}$ rotated about unit axis $\mathbf{u}$ by angle θ to obtain new vector $\mathbf{R}'$ can be expressed as the product of three quaternions [?]:

$$\mathbf{R}' = Q\mathbf{R}Q^* = Q\mathbf{R}Q^{-1},$$

where Q is the quaternion constructed in Equation (4) and $\mathbf{R} = (0, \mathbf{V})$ is a pure quaternion with zero real part and imaginary part representing the 3D vector $\mathbf{V}$.

[Figure 3: see original paper]

Assuming the telescope' s initial pointing aligns with the X axis, represented by vector $\mathbf{P}_0 = [1, 0, 0]^T$, and without pointing errors, the antenna points to target S by first rotating about the declination axis by angle D, then about the right ascension axis by angle T. This rotation process is represented by quaternions as:

$$\mathbf{R}_S = \mathbf{R}_T \mathbf{R}_D,$$

$$\mathbf{M}_S = \mathbf{R}_S \mathbf{P}_0 \mathbf{R}_S^{-1} = (\cos D \cos T)i + (-\cos D \sin T)j + (\sin D)k,$$

where $\mathbf{R}_S$ is the constructed quaternion and $\mathbf{M}_S$ is the antenna's pointing vector after rotation. From this we obtain:

$$T = \tan^{-1}\left(-\frac{\mathbf{M}_S(2)}{\mathbf{M}_S(1)}\right),$$

$$D = \sin^{-1}(\mathbf{M}_S(3)),$$

where $\mathbf{M}_S(i)$ $(i = 1, 2, 3)$ denotes the i-th component of $\mathbf{M}_S$.

3.1 Right Ascension and Declination Axis Encoder Zero-Point Errors Antenna axis encoder errors can be categorized into scale errors and zero-point errors. Scale errors are proportional to the encoder reading and result from imprecise scale markings, while zero-point errors occur when the encoder zero point does not coincide with the true zero point when the antenna points to its initial orientation. The presence of three-axis zero-point errors affects measurement accuracy and consequently pointing precision. Right ascension and declination axis encoder zero-point errors represent deviations between encoder zero points and true coordinates when the antenna is oriented at 0° right ascension and 0° declination. These encoder zero-point errors impose stringent requirements on initial antenna installation and adjustment, typically requiring GPS-based calibration of each antenna' s true geographic north direction for storage in the encoders. When antennas form an equatorial system, right ascension and declination axis encoder zero-point errors can be corrected using constant terms.

3.2 Azimuth Axis Encoder Zero-Point Error The DSRT 6 m radio telescope is a three-axis system with a horizontally rotating azimuth axis. When tracking celestial objects using right ascension and declination axes, the azimuth axis is typically rotated to 180° to form an equatorial mount. If a zero-point error exists in the azimuth axis, this is equivalent to the antenna pointing rotating by angle ω about vector $\mathbf{Z}_1 = [\cos\phi, 0, \cos(\frac{\pi}{2} - \phi)]^T$, where ϕ is the angle between the right ascension axis and the horizontal plane (i.e., station latitude). This rotation is represented by the quaternion:

$$\mathbf{R}_{S1} = \mathbf{R}_\omega \mathbf{R}_T \mathbf{R}_D,$$

$$
\begin{aligned}
\mathbf{M}_{S1} &= \mathbf{R}_{S1}\mathbf{P}_0\mathbf{R}_{S1}^{-1} \\
&= [(\cos\phi\sin\phi - \cos\omega\cos\phi\sin\phi)P_3 + (\cos\omega + \cos^2\phi - \cos\omega\cos^2\phi)P_1 - (\sin\omega\sin\phi)P_2]i \\
&\quad + [P_2\cos\omega - (\sin\omega\cos\phi)P_3 + (\sin\omega\sin\phi)P_1]j \\
&\quad + [(\cos\omega\cos^2\phi - \cos^2\phi + 1)P_3 + (\sin\omega\cos\phi)P_2 + (\cos\phi\sin\phi - \cos\omega\cos\phi\sin\phi)P_1]k,
\end{aligned}
$$

where $\mathbf{R}_{S1}$ is the constructed quaternion, $\mathbf{M}_{S1}$ is the antenna' s pointing vector after rotation, and P_1, P_2, P_3 are respectively:

$$
\begin{aligned}
P_1 &= \cos D\cos T, \\
P_2 &= -\cos D\sin T, \\
P_3 &= \sin D.
\end{aligned}
$$

Comparing this expression with Equation (8) for the error-free antenna pointing vector, we derive the pointing errors as:

$$\Delta T = \omega(\cos\phi\tan D\cos T - \sin\phi),$$

$$\Delta D = -\omega\cos\phi\sin T.$$

3.3 Antenna Encoder Zero-Point Pointing Error Model Traditional basic parameter models include only two constant terms for antenna encoder zero-point errors. However, DSRT features a third axis in addition to right ascension and declination rotation axes. The initial positioning coordinates are $(180^\circ, 0^\circ, 0^\circ)$ to form an equatorial mount, meaning the azimuth axis points south, the right ascension axis points to 0° right ascension, and the declination axis points to 0° declination. Therefore, based on DSRT' s unique three-axis system characteristics, this paper establishes a three-parameter encoder zero-point pointing error model, as shown in Equation (13):

$$
\begin{aligned}
\Delta T &= C_1 + C_3(\cos\phi\tan D\cos T - \sin\phi), \\
\Delta D &= C_2 - C_3\cos\phi\sin T,
\end{aligned}
$$

where the newly established three-parameter model better reflects the actual errors in DSRT' s three-axis system. Here, C_1 represents the right ascension axis encoder zero-point error, C_2 the declination axis encoder zero-point error, and C_3 the azimuth axis encoder zero-point error.

3.4 Model Fitting DSRT' s 6 m antennas perform multiple pattern scans of the quiet Sun. By identifying the beam center from the patterns, we obtain the right ascension and declination angles (T_i', D_i') where the antenna response is maximum, along with the corresponding theoretical coordinates of the target source (T_i, D_i) at that moment, thereby determining the antenna pointing errors $(\Delta T, \Delta D)$.

For the antenna main beam within the −20 dB range, the power pattern obtained from scanning radio sources can be well-fitted by a two-dimensional Gaussian function [?], with the Gaussian fitting surface given by:

$$f(x,y) = a_1 \exp\left[-\frac{(x-a_2)^2}{a_3} - \frac{(y-a_4)^2}{a_5}\right],$$

where a_1 through a_5 are coefficients to be fitted. Figures 4(a) and 4(b) [Figure 4: see original paper] show the measured pattern from antenna drift scanning and the two-dimensional Gaussian fitting result, respectively, with contour lines indicating normalized power intensity. The coefficients a_2 and a_4 are determined as the actual beam center, representing the encoder readings when the antenna beam center points to the target source. By calculating the theoretical position of the target source at that moment, the antenna' s right ascension and declination axis pointing errors are obtained. Multiple pattern scanning tests of the target source throughout the day determine pointing error data for different time periods. Least-squares fitting of this pointing error data yields the three parameters C_1 through C_3 in the antenna encoder zero-point pointing error model, enabling compensation of the three-axis encoder zero points.

[Figure 4: see original paper]

4. DSRT Pointing Error Measurement and Correction Results

Based on the structural characteristics of the Daocheng 6 m radio telescope, drift scanning in the right ascension-declination plane was selected for actual testing. DSRT's system capability to simultaneously record received power from all unit antennas allows batch control of antennas for drift scanning, obtaining pattern measurement results for all antennas and enabling batch high-precision calibration of DSRT unit antenna pointing errors using the proposed three-axis zero-point correction method.

Figure 5 [Figure 5: see original paper] presents an example of the three-dimensional patterns obtained from scanning the quiet Sun in the right ascension-declination plane for a DSRT antenna, showing horizontal (Figure 5(a)) and vertical (Figure 5(b)) polarization channels at 445 MHz. Between 9:00 AM and 5:00 PM Beijing time on November 10, 2022, 13 independent drift-scan tests were conducted on the quiet Sun. Under servo drive, 16 antennas scanned at constant angular velocity in the right ascension direction, stepping in declination after each scan. Each drift-scan observation lasted

30 minutes, with 16 scans performed at different hour-angle positions of the source. Antenna encoder data and autocorrelation power data were recorded for each scan. By differencing the antenna movement coordinates with the Sun' s motion trajectory and processing the data, two-dimensional power patterns were constructed for all antennas.

Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper] show the Gaussian-fitted two-dimensional patterns obtained from scanning the quiet Sun by the 16 antennas before and after pointing error correction, respectively. Contour lines indicate normalized power intensity, with the pattern' s maximum point representing the antenna beam center position. The deviation of the beam center from the coordinate origin quantifies the antenna' s pointing error in right ascension and declination. As shown in Figure 6, before pointing correction, all antenna power patterns significantly deviate from the coordinate origin, indicating substantial pointing errors. After pointing correction (Figure 7), all antenna power patterns lie near the origin, demonstrating effective correction of pointing errors across all axes. Two-dimensional Gaussian fitting was used to locate beam centers, determining pointing errors for all 16 antennas. Figure 8 [Figure 8: see original paper] illustrates the variation trends of right ascension and declination axis pointing errors for the 16 antennas before and after correction. According to the established three-axis pointing error model, when an azimuth encoder zero-point deviation exists, the resulting declination axis error term is a function of the source' s hour angle, which explains why most antennas show declination axis pointing errors varying with hour angle in Figure 8.

Based on multiple drift-scan pattern test data, the three encoder zero-point pointing error coefficients for these 16 antennas were solved using least-squares methods and compensated through antenna control software. On November 16, 2022, seven independent drift scans of the Sun were performed using all corrected antennas to determine the post-correction pointing errors. The results show that all antenna pointing errors converged well, with the directional variation trend of pointing errors effectively suppressed through correction.

DSRT antenna pointing errors include right ascension axis error and declination axis error. The root mean square (rms) values η_T and η_D for each of the 16 test antennas were calculated before and after correction using Equation (15), where m represents the number of pointing error measurements, ΔT_i is the right ascension axis pointing error from the i-th measurement, D_i is the declination angle, and ΔD_i is the declination axis pointing error from the i-th measurement:

$$\eta_T = \sqrt{\frac{\sum_{i=1}^{m} (\Delta T_i \cos D_i)^2}{\sum_{i=1}^{m} \cos^2 D_i}},$$

$$\eta_D = \sqrt{\frac{\sum_{i=1}^{m} \Delta D_i^2}{m}}.$$

The combined rms pointing error η for each antenna is then given by Equation (16):

$$\eta = \sqrt{\eta_T^2 + \eta_D^2}.$$

Figure 9 [Figure 9: see original paper] compares the rms pointing errors before and after encoder zero-point correction for the 16 antennas, with Figure 9(a) showing right ascension axis rms errors and Figure 9(b) showing declination axis rms errors. Table 3 presents the rms pointing errors for these 16 unit antennas after correction.

[Figure 5: see original paper] [Figure 6: see original paper] [Figure 7: see original paper] [Figure 8: see original paper] [Figure 9: see original paper]

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