Measurement of Track Height Difference of the Nanshan 26m Antenna and Its Impact on Pointing Accuracy (Postprint)

Authors: Wen Haoxing[1,2,3], Xu Qian[1,2], Wang Na[1,2]

Date: 2018-06-22T00:00:00+00:00

Abstract

The track of a wheel-rail antenna serves as the foundation bearing the entire weight of the antenna, and its precision directly affects the smoothness of the antenna' s operation in the azimuth direction, thereby causing axial system deviations that impact the antenna' s pointing accuracy. This paper describes the track structure and track height difference measurements of the renovated Urumqi Nanshan 26m antenna (NSRT: Nanshan Radio Telescope), and establishes a mathematical model for the pointing deviations caused by track height differences under different azimuth and elevation angles. Using the "cross-scan" method, pointing data of multiple standard sources at corresponding positions were measured, and pointing deviations were obtained through Gaussian fitting. Through analysis, it is shown that the pointing deviations caused by track height differences can be corrected to improve the antenna' s pointing accuracy.

Full Text

Measurement of NSRT 26m Antenna Track Unevenness and Its Influence on Pointing Accuracy

Wen Haoxing[1,2,3], Xu Qian[1,2], Wang Na[1,2] [1] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China
[2] Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Urumqi 830011, China
[3] University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

The track of a wheel-on-rail antenna serves as the foundational support for the entire antenna structure, and its precision directly affects the stability of azimuth rotation, thereby introducing shafting errors that degrade pointing accuracy. This paper describes the upgraded track structure of the Urumqi Nanshan 26m radio telescope (NSRT) and its track unevenness measurement program, and establishes a mathematical model for antenna pointing errors induced by track unevenness at various azimuth and elevation angles. Using the "cross-scan" method, we measured pointing data for multiple calibration sources at corresponding positions and derived pointing errors through Gaussian fitting. Analysis demonstrates that correcting for pointing errors caused by track unevenness can significantly improve antenna pointing precision.

Keywords: track unevenness; 26m antenna (NSRT); continuous track; cross scanning; pointing error

Introduction

In recent years, as radio antennas have evolved toward larger apertures and higher frequencies, pointing accuracy has become an increasingly critical performance metric. Generally, antenna pointing errors must be less than one-tenth of the beamwidth, but achieving this goal becomes extremely challenging with larger apertures and higher observation frequencies. Consequently, every factor contributing to pointing error must be carefully considered.

For wheel-on-rail azimuth-elevation antennas, track unevenness causes azimuth rotation deviations that introduce shafting errors and degrade pointing accuracy. Early antennas such as the Shanghai 25m and Xinjiang 25m telescopes employed segmented tracks, which caused the antenna to jump at track joints during operation, leading to azimuth deviations. Additionally, segmented tracks experienced stress concentration at joints, reducing track lifespan. Therefore, segmented tracks are typically used only in applications with lower precision requirements. As antenna apertures and observation frequencies have increased, segmented construction can no longer meet requirements, and fully welded high-precision tracks have been implemented in large antennas such as the U.S. GBT 100m [1] and Shanghai TM65m [2]. High-precision track welding technology varies significantly depending on track scale and operating environment. For example, the Xinjiang 110m fully steerable radio telescope (QTT) [3] currently under development by the Chinese Academy of Sciences requires a pointing accuracy of 1.5 arcseconds. To achieve this goal, track precision must be controlled to 0.2 mm (peak-to-peak). Moreover, since the antenna will operate in high-altitude regions with large annual temperature variations, track welding presents new challenges.

The Xinjiang Nanshan 25m telescope was built in 1993 and underwent major upgrades in 2015. After the upgrade, the antenna aperture became 26m, as shown in [Figure 1: see original paper], and adopted fully welded track technology. [Figure 2: see original paper] shows a welded joint on the NSRT antenna track. Three track unevenness measurements were conducted after track welding and during normal antenna operation to verify track precision and reliability.

The measured track precision improved by an order of magnitude compared to pre-upgrade conditions, effectively correcting pointing deviations caused by track unevenness. Both domestic and international researchers have studied the influence of track unevenness on pointing accuracy.

Domestically, Li Yongjiang [4] measured pre-upgrade track unevenness at Nanshan 25m using a digital level and found that track joints were the primary factor affecting pointing accuracy, with pointing errors fitted using four fixed azimuths, resulting in significant fitting errors. Liu Xuan [5] built upon Li' s work by measuring track unevenness on the antenna' s secondary platform after upgrade and correcting pointing errors, though similarly large fitting errors remained. The Miyun 50m telescope considered track irregularity [6] and used finite element simulation to derive azimuth axis tilt errors, establishing a nonlinear pointing correction model, though finite element simulation introduces certain calculation deviations. Shanghai' s Tianma 65m telescope employed a single inclinometer and level [2] to measure track unevenness and studied the influence of track settlement on pointing accuracy. Internationally, the Italian SRT 64m [7] and U.S. DSN 34m [8] measured track unevenness in large radio telescopes using inclinometers to calculate pointing deviations. This paper establishes a model for pointing deviations caused by track unevenness, selects radio sources for actual measurement using the "cross-scan" method to obtain pointing deviations, and compares measured values with those calculated from track unevenness to correct pointing errors.

1.1 Track Unevenness Measurement Scheme

The NSRT antenna track was upgraded to a fully welded construction consisting of 11 curved rail segments with a diameter of 15m and width of 210mm. Throughout the upgrade process, track precision was measured at three critical construction phases: after track installation but before grouting, after grouting the suspended sections beneath the track, and after loading the antenna onto the track for operational testing. The first two measurement phases primarily verified that grouting quality met precision requirements during installation, while the third phase, conducted after the antenna had operated on the track for some time, established the final track precision metrics.

Since large daytime temperature variations significantly affect measurement accuracy, all measurements were conducted after 23:30 at night when ambient temperatures were more uniform, yielding more reliable data. Using a Leica high-precision level and height gauge, we established 220 observation points on the track: 88 points each on the inner and outer rails, and 44 points on the middle rail, as shown in [Figure 3: see original paper].

Using J0 as the reference point and numbering counterclockwise, we marked 77 observation points (single circle) on each of the inner and outer rails. Two additional points were added between each pair of adjacent correction points near weld seams. Weld seams were numbered H1 through H11 counterclockwise, with 11 observation points marked at each seam across inner, middle, and outer rails. Midpoints between weld seams were numbered N1 through N11. To distinguish between rails, letters a, b, and c denote outer, middle, and inner rails respectively, totaling 220 observation points.

1.2.1 Three-Phase Track Unevenness Measurement and Data Analysis

The NSRT antenna track unevenness specification requires 0.45 mm (peak-to-peak). Three measurements were conducted after track welding, after grouting, and after operational loading to monitor each critical construction phase, enabling timely correction of installation errors and ensuring final track precision requirements were met.

(1) Phase 1: Track unevenness measurement before grouting

Phase 1 results are shown in [Figure 4: see original paper]. Before grouting, the peak-to-peak unevenness values for both inner and outer rails were 0.076 mm, with nearly identical profiles between inner and outer rails. Weld seam height differences were comparable to other marked points, indicating good welding quality. The root-mean-square (RMS) errors for inner and outer rail unevenness were calculated as 0.0128 mm and 0.0130 mm, respectively.

(2) Phase 2: Track unevenness measurement after grouting suspended sections

After grouting the suspended sections beneath the track, precision changed. This measurement verified the grouting process and ensured post-grouting unevenness remained within tolerance. Phase 2 results shown in [Figure 5: see original paper] indicate peak-to-peak unevenness of 0.052 mm and 0.062 mm for inner and outer rails, respectively—both lower than the pre-grouting value of 0.076 mm. RMS values were 0.0123 mm (inner) and 0.0132 mm (outer). Analysis shows the inner rail improved slightly after grouting, while the outer rail remained essentially unchanged, demonstrating successful grouting implementation.

(3) Phase 3: Track unevenness measurement under antenna load

After grouting completion, the antenna was placed on the track and operated for some time before measurement. Phase 3 results in [Figure 6: see original paper] show peak-to-peak unevenness of 0.254 mm (inner) and 0.222 mm (outer). RMS values were 0.0578 mm and 0.0562 mm, respectively—significantly higher than in the first two phases. This indicates that loading affected track precision, though still meeting design requirements. Notably, the pre-upgrade segmented track had a peak-to-peak value of 1.200 mm, meaning the fully welded track technology improved precision by nearly an order of magnitude.

[Figure 7: see original paper] displays the average unevenness distribution for inner and outer rails across all three phases, clearly showing changes before grouting, after grouting, and under load. The first two measurements, conducted without load, showed small deformations. Between 0° and 270°, Phase 2 unevenness variation was greater than Phase 1, indicating significant grouting effects on these sections. Between 270° and 360°, Phase 2 variation was smaller than Phase 1, showing that grouting optimized some track sections. Phase 3 showed the largest variation, confirming that loading impacts track precision.

1.2.2 Track Unevenness Data Fitting

Measured track unevenness data are discrete points. To fully analyze the relationship between track unevenness and pointing deviation, continuous variation must be displayed, requiring fitting of Phase 3 unevenness data.

Since track unevenness contains sinusoidal components, we performed eighth-order Fourier and sine function fitting on the average unevenness of inner and outer rails. Coefficients were obtained through nonlinear least-squares fitting, yielding RMSE values of 0.0169 for sine fitting and 0.0172 for Fourier fitting. As shown in [Figure 8: see original paper], sine function fitting captures both large-scale variations (0° to 360°) and small-scale fluctuations, making it closer to actual measurements. This fitted function can therefore estimate unevenness at unmeasured points.

2 Model for Calculating Antenna Pointing Errors from Track Unevenness

[Figure 8: see original paper] NSRT 26m track unevenness fitting

2.1 Calculation of Alidade Rotation Angles About Coordinate Axes Due to Track Unevenness

The antenna alidade contacts the track at four wheel points [9]. Using height differences at these four points, rotation angles about three coordinate axes can be calculated, as shown in [Figure 9: see original paper]. True north (positive Y-axis direction) corresponds to 0° azimuth, with counterclockwise rotation representing 0° to 360° azimuth.

In the three-dimensional coordinate system, points 1, 2, 3, and 4 are numbered counterclockwise, representing the four contact points between alidade and track. Let l denote the distance between points 1-2 or 4-3, h the alidade height, and r the track radius. Right-hand rule is applied for all rotation calculations.

[Figure 9: see original paper] NSRT 26m alidade coordinate system

2.1.1 Rotation About X-Axis To calculate rotation angle a about the X-axis, where h , h , h , h represent height differences at points 1, 2, 3, and 4, respectively. In [Figure 9: see original paper], points 4-1 and 3-2 jointly cause rotation about the X-axis. The angles from these two pairs are calculated and averaged:

4− 1 2 ∗ 3− 2 2 ∗ 2√2∗ ∗ [−1 − 1 1 1] [ ] , (1)

2.1.2 Rotation About Y-Axis To calculate rotation angle a about the Y-axis, points 4-3 and 1-2 jointly cause rotation about the Y-axis. The angles from these two pairs are calculated and averaged:

4− 3 2 ∗ 1− 2 2 ∗ 2√2∗ ∗ [1 − 1 − 1 1] [ ] , (2)

2.1.3 Rotation About Z-Axis To calculate rotation angle a_z about the Z-axis, note that Z-axis rotation is influenced by X-axis rotation. In [Figure 10: see original paper], Δx is caused by height differences between points 4 and 1, and Δx by height differences between points 3 and 2. These cause rotation a_z about the Z-axis:

[Figure 10: see original paper] NSRT 26m alidade Z-rotation angle

41− 32 , (3)

where: 41 ∗ (4− 1 2 ∗) = ∗ (4− 1) , (4) 3− 2 32 ∗ (2 ∗) = ∗ (3− 2 = √2 ∗ , (6) = 2 ∗ cos

Therefore: 4− 1)− ∗(3− 2), (5)

2.2 Calculation of Azimuth and Elevation Pointing Errors

Since the X-axis is parallel to the elevation axis, elevation pointing error a_el equals a . Azimuth pointing error a_az is more complex [10] as it combines effects from rotations a , a , and a_z. As shown in [Figure 11: see original paper], the XEL axis is perpendicular to the pointing plane, $\_el$ is the elevation angle, and a_az is calculated as:

[Figure 11: see original paper] Calculation of azimuth pointing error

= cos ( ) , (8)

where: xel= ∗ cos( ) − ∗ sin ( ), (9)

Therefore: = − ∗ tan ( ), (10)

Since calculations yield values in radians, a conversion factor $k = 180\times3600/$ is applied to obtain arcseconds. The comprehensive formula for pointing deviation caused by track unevenness is:

= √ 2 + 2∗ 2 − tan( ) 2√2∗ 2√2∗ −1 −1]} , (11)

2.3 Results of Pointing Error Calculations from Track Unevenness

Using equation (11) with an elevation angle of 45° and substituting track unevenness data, we calculated azimuth and elevation pointing errors. As shown in [Figure 12: see original paper], the calculated errors contain periodic components. Sine function fitting yielded azimuth pointing errors ranging from

-7.7614 to 7.6544 and elevation errors from -2.0808 to 2.0808 . Azimuth errors are significantly larger because their calculation incorporates alidade rotations about both X and Y axes.

[Figure 12: see original paper] NSRT 26m pointing errors: (a) Azimuth pointing error; (b) Elevation pointing error

Total pointing deviation calculated from equation (12) ranges from 0.4324 to 7.8251 , as shown in [Figure 13: see original paper]. Since pointing deviation is calculated from height differences at four track points, the pattern repeats every 90° of wheel rotation, though with different calculated directions, creating periodicity. Comparing [Figure 13: see original paper] with [FIGURE:6(a)] reveals that locations with large unevenness do not correspond to maximum pointing deviations, because pointing error results from the combined effect of four-point height differences at each antenna position.

[Figure 13: see original paper] NSRT 26m pointing deviation

3 Pointing Deviation Measurement and Analysis

Measurements were conducted during daytime using the “cross-scan” method on multiple standard radio sources. Each azimuth or elevation scan lasted 60 seconds with power readings collected twice per second, yielding high-precision measurements while controlling antenna scanning and recording position information in real time. Each scan produced 120 data points. Gaussian fitting was applied to determine actual pointing deviations, which were compared with model-calculated deviations for correction purposes.

Since cross-scanning performs separate azimuth and elevation scans, the source position continuously changes during each scan. Consequently, when an azimuth scan completes, the fitted azimuth-elevation coordinates differ from those of the subsequent elevation scan. Similarly, after elevation scanning, the fitted coordinates differ from the previous azimuth scan. Using these fitted coordinates, the track unevenness model calculates the corresponding pointing deviations caused by track unevenness. Comparison results between measured and calculated deviations are presented in and .

Measured azimuth pointing errors and calculated errors from track unevenness

Measured elevation pointing errors and calculated errors from track unevenness

The standard sources in Tables 1 and 2 were processed through Gaussian fitting to determine their actual azimuth and elevation positions and corresponding pointing errors. These fitted coordinates were then input into the track unevenness model to calculate the track-induced pointing errors. Correcting measured pointing errors using these calculated values demonstrably improved overall antenna pointing precision.

4 Conclusion

This paper demonstrates that NSRT antenna track peak-to-peak unevenness improved from 1.200 mm pre-upgrade to 0.254 mm after implementing high-precision welded track technology. To correct pointing deviations caused by track unevenness, we established a mathematical model relating track unevenness to pointing errors. Based on cross-scan measurements of NSRT pointing precision, we verified that correcting for track-induced pointing errors improves overall antenna performance.

Antenna pointing deviations result from combined structural, control, and environmental factors, with track unevenness representing only a small portion of structural contributions. Comprehensive error sources including temperature and wind effects must be considered. NSRT has conducted preliminary studies on temperature effects on the antenna alidade [11]. The next step involves constructing a dual-inclinometer shafting deviation measurement system with temperature control and humidity monitoring to measure alidade structural deformation in real time under all weather conditions and develop corresponding correction models.

References

[1] Symmes Arthur, Anderson Robert, Egan Dennis. Improving the service life of the 100-meter green bank telescope azimuth track[J]. Proceedings of SPIE, 2008, V.7012, 701238.

[2] Fu Li, Ling Quanbao, Zhao Rongbing, Qian Zhihan. Settlements of foundation and track of TM65 m and its effect on antenna pointing[J]. Infrared and Laser Engineering, 2016, 45(11): 190-196.

[3] Wang Na. Xinjiang Qitai 110m radio telescope[J]. Sci Sin-Phys Mech Astron, 2014, 44: 783-794.

[4] Li Yongjiang, Aili Yusup, Zhang Zhenglu, Aili Yishamud. Antenna Track Deformation Precise Measurement and Pointing Error Model[J]. Geomatics and Information Science of Wuhan University, 2013, 38(2): 176-180.

[5] Liu Xuan, Aili Yusup, Xiang Binbin, Wang Congsi, Xu Qian, Wang Jun. Analysis and Correction of the Influence of the Track Irregularity on Antenna Pointing[J]. Acta Astronomica Sinica, 2017, 58(4): 47-57.

[6] Jiang Zhengyang, Kong Deqing, Zhang Hongbo, Wang Songgen. A Method to Calibrate Pointing Errors of a Radio Telescope Including Roughness of the Telescope Rail Track[J]. Astronomical Research & Technology, 2015, 12(4): 417-423.

[7] Tonino P, Franco B, Sergio P, et al. The SRT inclinometer for monitoring the rail and the thermal gradient effects on the alidade structure[C]. Proceedings of SPIE, 2014, 9145(28): 72-78.

[8] Wodek Gawronski. Modeling and Control of Antennas and Telescopes[M]. Springer Science+Business Media, 2008, 211-222.

[9] Wu Jiang. The Irregularities of Track and Its Influence on Pointing Accuracy of Fully Steerable Reflector Antenna with the Diameter of 110 Meters[D]. Xidian University, 2016.

[10] W. Gawronski, F. Baher, and O. Quintero. Azimuth-Track-Level Compensation to Reduce Blind-Pointing Errors of the Beam-Waveguide Antennas[R]. The Telecommunications and Mission Operations Progress Report, 1999, 139: 1-18.

[11] Wang Hui, Ning Yunwei, Yan Hao. Temperature Distribution and Deformation Impact Analysis of 26m Antenna Frame[J]. Astronomical Research & Technology, 2018, 15(2): 208-215.

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