

Postprint: Modeling of Thermal-Induced Pointing Errors in Radio Telescopes Based on Mount Temperature

Authors: In machine learning, we consider a dataset S generated by a distribution D with parameters θ . Our goal is to learn a model f that minimizes the expected loss on distribution D . Specifically, we define the risk function as $R(f)$. According to [?], deep learning models exhibit excellent performance on this task., Fu Li, Wang Jinqing, Wang Xu, Zhou Lei, Liu Qinghui

Date: 2024-03-22T00:00:00+00:00

Abstract

Temperature is one of the key factors affecting the performance of high-frequency large radio telescopes. Using the Tianma Radio Telescope (TMRT) as a case study, we investigate the relationship between mount node temperature and antenna pointing, and propose a method for constructing a pointing error correction model based on node temperatures. The pointing error is treated as a linear combination of mount node temperatures, with node temperature sensitivity serving as a characteristic condition to optimize the number of independent variables. Pointing test results for the source 2344+8226 near the North Celestial Pole are employed as the sample set to compare the effectiveness of the temperature models before and after independent variable simplification. Both temperature models are also validated through finite element analysis, with the model calculations and finite element analysis results both showing consistency with the sample set. To verify the model's generalizability, the performance of the models before and after simplification is comparatively analyzed across four quarters, with results demonstrating that the simplified temperature model exhibits superior predictive performance. The rapid calculation results from the established node-temperature-based pointing error correction model also provide data support for real-time correction of mount thermal-induced pointing errors.

Full Text

Preamble

ChinaXiv Vol. 42, No. 1

March 2024

PROGRESS IN ASTRONOMY Vol. 42, No. 1, Mar., 2024

doi: 10.3969/j.issn.1000-8349.2024.01.11

Modeling of Thermally Induced Pointing Error for Radio Telescopes Based on Alidade Temperature

TU Biao¹, FU Li^{2;3}, WANG Jin-qing^{2;3}, WANG Xu¹, ZHOU Lei¹, LIU Qing-hui²

(1. School of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China;

2. Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China;

3. Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China)

Abstract

Temperature is one of the key factors influencing the performance of large-scale radio telescopes. Taking the Tianma Radio Telescope (TMRT) as an example, this study investigates the relationship between the temperature of the alidade's nodes and antenna pointing accuracy. A method is proposed for constructing a correction model for pointing errors based on node temperatures. The pointing error is treated as a linear combination of the alidade's node temperatures. The number of independent variables is optimized using the temperature sensitivity of the nodes as feature conditions. The pointing test results of the source 2344+8226 near the North Pole are used as the sample set to compare the effectiveness of the temperature model before and after variable simplification. Both the model calculations and finite element analysis validate the two temperature models, which align with the sample set. Furthermore, to assess model generalization, the performance of the models is compared across four seasons before and after simplification. The results indicate that the simplified temperature model offers improved predictive accuracy. The established node temperature-based pointing error correction model's rapid calculation outcomes provide data for real-time mitigation of thermally induced pointing errors in the mount.

Keywords: radio telescope; temperature sensor; pointing error; temperature model

1 Introduction

Large-aperture radio telescopes are essential equipment for radio astronomy research, enabling astronomers to observe fainter and more distant celestial objects while playing a crucial role in deep space exploration. Pointing accuracy is a critical performance indicator for radio telescopes, directly determining whether the telescope can fully realize its capabilities. Typically, to ensure efficient operation, the pointing accuracy should be better than $1/10$ of the half-power beamwidth [1]. The beamwidth of a telescope is inversely proportional to its aperture size and operating frequency; consequently, as the aperture increases and operating frequency rises, the requirements for pointing accuracy become more stringent.

Conventional telescope pointing correction models compensate for errors caused by structural gravitational deformation but do not correct for pointing errors induced by time-varying thermal deformation of the antenna structure. The structure of an alt-azimuth radio telescope antenna includes the alidade, backup structure, elevation mechanism, and support legs, among which the alidade beams have relatively large cross-sectional dimensions and thickness, resulting in a large thermal time constant and representing the primary source of thermally induced pointing errors [2]. Researchers worldwide have investigated pointing errors caused by thermal deformation of antenna alidades. In 1994, Bayley et al. [3] in the United Kingdom measured temperatures at key positions on the alidade of the 32 m Merlin radio telescope at Cambridge University and analyzed their impact on pointing, implementing thermal compensation corrections. Italian scholars Ambrosini et al. [4] studied thermal effects on the 32 m Medicina radio telescope, analyzing the relationship between alidade beam temperature and elevation axis deformation, and attempted to predict inclinometer readings using finite element analysis. The Sardinia Radio Telescope (SRT) [5] monitored the influence of temperature gradients on the alidade using inclinometers, with measurement results consistent with astronomical observations, demonstrating that pointing errors are primarily caused by alidade temperature gradients. In China, Yi Letian et al. [6] measured key point temperatures on the alidade and solar radiation parameters using a temperature measurement system, simulated the alidade temperature field model, and coupled it with structural analysis; they also combined geometric relationships between antenna structural displacement fields and azimuth axis deviations with measured temperature characteristic data to enable rapid calculation of alidade structural deformation from measured temperatures. Kong Deqing et al. [7] calculated axis angle measurement errors caused by thermal deformation of different alidade components through finite element analysis, demonstrating a strong correlation between axis angle measurement errors and solar radiation temperature gradients, and proposed a correction method for axis angle measurement errors based on antenna structural temperature gradient measurements.

Previous research primarily relied on inclinometer measurements and finite element calculations to analyze alidade thermal deformation. However, the impact

of thermal deformation on telescope pointing varies over time and persists continuously. Inclinometers are susceptible to complex environmental conditions and external vibrations, exhibiting poor anti-interference capability, while finite element analysis requires accurate input of environmental and material parameters and involves substantial computational time. This paper uses the Tianma Radio Telescope (see Figure 1 [Figure 1: see original paper]) as an example to propose a method for constructing and optimizing a pointing model based on alidade node temperatures. Through radio source tracking experiments of source 2344+8226, the performance of the temperature models before and after optimization is compared. Finite element analysis is also employed to verify the performance of the temperature models for TMRT across different seasons.

2.1 Temperature Acquisition System

The temperature acquisition system of the Tianma Radio Telescope includes temperature sensors, a master node controller, power supply, computer, and cables. The system employs DS18B20 digital temperature sensors, which achieve an accuracy of $\pm 0.5^{\circ}\text{C}$ within the temperature range of -10°C to 85°C .

The temperature sensors and their installation positions are shown in Figure 2 [Figure 2: see original paper]. Four sensors numbered 1-4 are installed on each face of the 14 nodes (square beams). For example, the sensors on Node 1 are designated 1-1, 1-2, 1-3, and 1-4. For each node, Sensor No. 1 is defined as the sensor installed on the inner side of the square beam (facing the central pivot), with the other sensors numbered sequentially in a clockwise direction as Nos. 2, 3, and 4. Additionally, one sensor is placed under each of the first and second platforms to measure air temperature, totaling 58 sensors. In this study, the node temperature is taken as the average of the temperatures recorded by the four sensors on each node.

2.2 Temperature Model Construction Principle

Real-time correction of pointing errors caused by alidade thermal deformation is challenging because the impact of alidade thermal deformation on pointing is fluctuating, making it difficult to establish a stable method for real-time detection of thermally induced errors. Moreover, the factors influencing alidade thermal deformation are extremely complex, making it difficult for pointing models to comprehensively account for all factors affecting temperature-induced deformation. Given these circumstances, this study proposes a temperature model construction method for predicting pointing errors by obtaining real-time temperature data from a limited number of nodes in the alidade and investigating the relationship between alidade thermal deformation and pointing errors. For TMRT, the pointing error can be approximated as a linear combination of alidade node temperatures:

$$P = M \cdot T,$$

where P represents the pointing error, T is a column vector composed of temperatures from n nodes, and matrix M is the linear mapping from vector T to P . Specifically, the mapping matrix M can be estimated from experimental datasets as follows: Matrix T consists of column vectors of temperatures from n nodes at s different time instances. Since TMRT has 14 temperature-measured nodes on its alidade, $n = 14$ in this study. The column vector P comprises pointing errors measured at s different time instances. In practice, the pseudoinverse of matrix T is calculated using the Moore-Penrose method. Subsequently, by substituting the pointing error dataset and the node temperatures measured by temperature sensors into the above equation, the mapping matrix M for both the elevation and azimuth models can be computed.

Furthermore, selecting an appropriate number of independent variables helps balance model complexity and performance. This study employs feature selection to identify the most informative independent variables, thereby constructing a concise and efficient model. For the 14 node temperatures on the alidade, the model retains key factors as independent variables based on node temperature sensitivity. Specifically, when isothermal loads are applied to these nodes, those exerting the most significant influence on pointing errors are selected as independent variables. This simplified modeling approach reduces interference from ineffective independent variables in the temperature model while focusing on information-rich nodes during model construction, thereby enhancing model interpretability and applicability.

3.1 Finite Element Analysis

Finite element analysis is a numerical method that simulates and analyzes object structures to obtain stress and deformation distributions. Figure 3 [Figure 3: see original paper] shows the finite element model of the TMRT alidade and elevation mechanism. The coordinate system origin is located at the intersection of the azimuth and elevation axes. The materials for both the alidade and elevation gear are steel, with an elastic modulus of 2.06×10^{11} N/m, Poisson's ratio of 0.3, and density of $7,850$ kg/m³. Boundary constraints consist of two parts: (1) The connection between the elevation axis and alidade is simulated by coupling three displacement components and rotation components about the Y and Z axes, releasing only the rotation component about the X axis to model the elevation mechanism's rotation. (2) For the connection between the azimuth alidade and ground, the azimuth central pivot is constrained in X and Y displacements and rotations, while the alidade roller constraints are applied to X, Y, Z displacements and rotations [10].

When applying temperature loads, since the elevation gear is close to the second platform, the temperature measured on the second platform can be assumed as the temperature load for the elevation gear. In the finite element analysis, the initial reference temperature is set to 20°C [11]. The numbered labels in Figure 3 correspond to the node numbers of temperature sensors. Temperature loads for these 14 nodes are taken from sensor records, and the inverse distance weighting

interpolation method [12] is used to obtain temperatures for the remaining nodes on the alidade. This method calculates weighted averages of all known points within an adjacent region of the interpolation point to determine the value at the interpolation point. Each node's weight is determined by its distance to the interpolation point, with the weight being the inverse of the distance raised to the power k , expressed as:

$$Z_p = \frac{\sum_{i=1}^{n_p} \frac{Z_i}{(d_i + \varepsilon)^k}}{\sum_{i=1}^{n_p} \frac{1}{(d_i + \varepsilon)^k}},$$

where Z_p is the temperature at interpolation point p , Z_i is the temperature of sensor i within the interpolation region, d_i is the distance between interpolation point p and its neighboring sensor i , n_p is the number of sensors in the neighborhood of point p , k is the power of distance, and ε is a small number (0.01) to avoid numerical singularities when d_i becomes too small.

As shown in Figure 4 [Figure 4: see original paper], the influence of alidade thermal deformation on elevation pointing accuracy includes two components [13]: The temperature difference between the sun-facing front leg (A_r) and the shaded rear leg (A_f) of the alidade causes different thermal expansion between the two legs. The resulting error from elevation axis offset is calculated as $\Delta\varepsilon_1 = U_Y/h$, where U_Y is the displacement of node E along the Y axis and h is the alidade height. Additionally, this causes rotation at the top of the "A-frame" ($E \rightarrow E' : \Delta\varepsilon_2$), with elevation axis rotation error $\Delta\varepsilon_2 = ROTX$, where $ROTX$ is the rotation of point E about the X axis [9]. Similarly, the azimuth error $\Delta\phi$ can be expressed as $\Delta\phi_\Sigma = U_X/h + ROTZ$, where U_X is the displacement of node E along the X axis and $ROTZ$ is the rotation of point E about the Z axis. Therefore, the total tilt angle perpendicular to the elevation axis is $\Delta\varepsilon_\Sigma = \Delta\varepsilon_1 + \Delta\varepsilon_2$.

3.2 Experimental Results

To determine which nodes on the alidade have the greatest impact on pointing errors, this study conducted a finite element analysis of alidade node temperature sensitivity. Initially, all node temperature loads were set to 0; then, a 5°C temperature load was applied to different nodes individually, and the resulting pointing errors caused by alidade deformation were calculated for each case. These results were compared to identify which node temperature loads produce greater effects on pointing errors.

In the finite element model, considering its central symmetry, only nodes 1, 6, 7, 12, and 14 were selected for comparative analysis (see Table 1). Analysis of the experimental data revealed that the temperature load applied to node 7 had the most significant influence on pointing errors in both azimuth and elevation. Based on this result, node 7 and its symmetric nodes 8, 10, and 11 were selected as independent variables for the temperature model.

4.1 Radio Source Method

The radio source method is widely used for detecting antenna pointing errors. Using satellite or strong radio source scanning, the antenna performs azimuth and elevation scans of the radio signal while detecting the received power. The pointing error corresponding to each scan can then be accurately determined using the signal maximum, the source's theoretical position, and the antenna's actual position [14].

To investigate the patterns of telescope pointing variation and alidade thermal deformation, we selected source 2344+8226 near the North Pole for observation. As it is visible throughout the day, TMRT's azimuth and elevation spans are 20° and 15° , respectively (see Figure 5 [Figure 5: see original paper]). Within this small range, pointing errors are relatively minor, allowing maximum resolution of temperature-induced pointing errors [15]. On a clear day, March 7, 2023, we conducted 8 hours of continuous cross-scanning of source 2344+8226 while recording alidade node temperature sensor data. Two temperature models were fitted: Temperature Model A uses all measurable nodes as independent variables, while Temperature Model B uses only the characteristic nodes identified through temperature sensitivity analysis. The results from both models were compared and validated against finite element analysis using alidade temperature data to verify the accuracy and reliability of the established temperature models.

Figure 6 [Figure 6: see original paper] shows the variation of alidade node temperatures during the radio source tracking process. Comparison with the pointing error variations in Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] clearly reveals that when alidade node temperatures peak during the 14:00-15:00 period, both elevation and azimuth errors also reach their maximum, showing highly consistent trends. This indicates a significant correlation between alidade temperature and pointing errors.

For more objective verification of this correlation and comparison of different temperature models, pointing errors and node temperature data were combined with Equations (1) and (2) to calculate the following two temperature models:

$$\begin{cases} DEL_A = -3.51T_1 + 1.9T_2 - 1.28T_3 - 0.53T_4 - 6T_5 + 5.93T_6 + 3.38T_7 + 4.04T_8 - 0.75T_9 + 0.3T_{10} + 6.88T_{11} \\ DAZ_A = -2.761T_1 + 0.2T_2 - 0.82T_3 - 0.4T_4 - 1.26T_5 + 1.02T_6 + 0.62T_7 - 5.48T_8 - 4.7T_9 + 2.79T_{10} - 6.6T_{11} \end{cases}$$

$$\begin{cases} DEL_B = 6.87T_7 - 0.24T_8 - 0.96T_{10} - 5.46T_{11} \\ DAZ_B = 0.82T_7 - 0.8T_8 - 2.08T_{10} - 3.58T_{11} \end{cases}$$

where DEL_A and DEL_B are the elevation models for temperature models A and B, respectively; DAZ_A and DAZ_B are the azimuth models for temperature models A and B, respectively; and T_i is the measured temperature at node i (with 14 measured nodes, so $i \leq 14$).

The data in Figures 7 and 8 show that both calculated temperature models exhibit trends similar to those measured by the radio source method for both elevation and azimuth errors. Within the same day, both temperature models demonstrate excellent predictive accuracy. To ensure experimental credibility, finite element analysis was used for validation. By simulating alidade deformation under different temperature conditions in the simulation environment, consistency among finite element analysis, temperature models, and radio source measurements was verified. These results confirm that the established temperature models can adequately explain the sample set.

5 Model Generalization Verification

The preceding analysis of pointing tests on source 2344+8226 confirmed that both proposed temperature models can effectively fit the sample set. Subsequently, to verify the generalization capability of these models, data from randomly selected days in each of the four seasons over the past two years were used as test samples. The effectiveness of the models across different seasons was evaluated using finite element analysis.

Node temperature data from the test samples were substituted into temperature models A and B and compared with finite element analysis results. Figure 9 [Figure 9: see original paper] shows that in predicting elevation errors, both temperature models agree well with finite element analysis results, but Model B's predictions deviate less from the finite element results than Model A. However, in predicting azimuth errors, Model A shows significant deviation and inconsistent trends compared with finite element analysis, whereas Model B generally aligns well with finite element results, albeit with some temporal lag.

These results demonstrate that temperature model B can effectively reflect trends in thermally induced alidade pointing errors across different seasons, while model A performs poorly in predicting azimuth errors in the test samples, showing obvious deviation trends. Overall, model B's predictive accuracy is superior to model A in all experiments. This validation further supports the effectiveness and optimality of the temperature model simplification method, providing a reliable approach for alidade pointing error compensation across different seasons and environmental conditions.

6 Conclusion

This study investigated the influence of TMRT alidade temperature on pointing performance and proposed a method for constructing and optimizing a pointing error correction model based on node temperatures. Experiments confirmed the feasibility of both the original and simplified temperature models in fitting the sample set. However, analysis across different seasons revealed that the temperature model based on characteristic variable simplification provides more accurate predictions than the pre-optimization model, validating the optimality of the simplification approach. This provides a reliable method for compensating

thermally induced alidade pointing errors, supporting efficient TMRT observations across various seasons and environments. Alidade thermal deformation is the primary factor affecting antenna structure-induced pointing errors; future research will consider thermal deformation effects from the backup structure and subreflector support legs on antenna pointing accuracy. Further work will optimize the temperature model to enhance pointing performance stability and accuracy.

We thank the engineers at the Shanghai Astronomical Observatory' s Tianma Radio Telescope facility for their assistance and technical support.

References

- [1] Levy R. Structural Engineering of Microwave Antennas. New York: IEEE Press, 1996: 52
- [2] Yu L F, Wang J Q, Jiang Y B, et al. Sci Sin-Phys Mech Astron, 2019, 49(12): 151
- [3] Bayley A M, Davis R J, Haggis J S, et al. A&A, 1994, 283: 1051
- [4] Ambrosini R, Grueff G, Morsiani M, et al. Ap&SS, 1996, 239: 247
- [5] Pisanu T, Buffa F, Poppi S, et al. SPIE, 2014, 9145: 1670
- [6] Yi L T, Xu Q, Li L, et al. Astronomical Research & Technology, 2022, 19(05): 438
- [7] Kong D Q, Jiang Z Y, Zhang H B, et al. Sci Sin Tech, 2019, 49(11): 1331
- [8] Fu L, Ling Q B, Geng X G, et al. SPIE, 2016, 9912: 1408
- [9] Fu L, Wang J, Jiang Y, et al. Experimental Astronomy, 2019, 48(1): 49
- [10] Fu L, Dong J, Ling Q B, et al. Journal of Electronics & Information Technology, 2017, 32(03): 314
- [11] Fu L, Yu L, Tang J, et al. Research in Astronomy and Astrophysics, 2022, 22(10): 5011
- [12] Li W, Fu L, Wang X, et al. Progress in Astronomy, 2023, 41(02): 292
- [13] Greve A, Bremer M. Thermal design and thermal behaviour of radio telescopes and their enclosures, Berlin: Springer Science & Business Media, 2010: 180
- [14] Yu L F, Wang J Q, Zhao R B, et al. Acta Astronomica Sinica, 2015, 56(2): 165
- [15] Wang J Q, Yu L F, Zhao R B, et al. Sci Sin-Phys Mech Astron, 2017, 47(12): 125

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

Source: ChinaXiv –Machine translation. Verify with original.