Thermal Expansion Study of the Tianma VGOS Telescope Based on an Automatic Real-Time Monitoring System: Postprint

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Abstract

Thermal expansion of radio telescopes constitutes a non-negligible factor in the data analysis of geodetic and astrometric VLBI (Very Long Baseline Interferometry). To investigate the thermal expansion of the Tianma 13.2 m VGOS (VLBI Global Observing System) radio telescope, a monitoring system was developed to automatically and in real-time monitor the thermal deformation of the antenna structure. Through continuous observation of a target installed on the antenna's azimuth axis, 1.5 m directly below the reference point, the monitoring system can determine the three-dimensional position variations of the prism. Continuous monitoring from November 10, 2020, to August 31, 2021, revealed that the maximum change in prism height was 2.6 mm over ten months, with a maximum variation of 0.2 mm within a single day; the horizontal displacement of the prism over ten months was 0.1 mm. Finally, the IERS (International Earth Rotation Service) thermal expansion model was validated using the height thermal deformation of Tianma VGOS, with results indicating that the residuals between them were less than 1.5 mm and the RMS of the residuals was 0.43 mm. This result can satisfy current conventional VLBI measurements but cannot meet the precision requirements of VGOS. Therefore, the IERS thermal expansion model needs to be reconsidered for VGOS antennas.

Full Text

Study on Thermal Expansion of Tianma 13.2-m VGOS Radio Telescope Based on Automatic and Real-time Monitoring System

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Abstract

The thermal expansion of radio telescopes is a non-negligible factor in geodetic and astrometric VLBI (Very Long Baseline Interferometry) data analysis. To investigate the thermal expansion of the Tianma 13.2-m VGOS (VLBI Global Observing System) radio telescope, we developed an automatic, real-time monitoring system for thermal deformation of the antenna structure. By continuously observing a prism mounted on the antenna azimuth axis 1.5 m directly below the reference point, the system determines three-dimensional position variations of the prism. Continuous monitoring from November 10, 2020, to August 31, 2021, revealed a maximum height change of 2.6 mm over ten months and 0.2 mm within a single day, while horizontal displacement remained at 0.1 mm over the same period. Finally, we validated the IERS (International Earth Rotation and Reference Systems Service) thermal expansion model using the Tianma VGOS height deformation data. The residuals between the model and observations are less than 1.5 mm, with an RMS of 0.43 mm. While this satisfies current conventional VLBI measurements, it fails to meet VGOS accuracy requirements, necessitating reconsideration of the IERS thermal expansion model for VGOS antennas.

Key words: VGOS; thermal expansion; monitoring system; correlation

1 Introduction

For conventional IVS (International VLBI Service for Geodesy and Astrometry) antennas (approximately 20 m aperture), thermal expansion causes an annual variation of 4–6 mm in the reference point height, while for the 100 m Effelsberg antenna, this reaches 20 mm [1]. Current geodetic and astrometric VLBI data analysis primarily relies on models to mitigate antenna thermal expansion effects. The IERS Conventions 2010 recommended thermal expansion model maintains reference point height deformation accuracy at the millimeter level [2]. Established by Nothnagel in 1995 based on measured thermal deformation data from the Hartebeesthoek (HartRAO) radio telescope, the IERS thermal expansion model derives its parameters from correlation analysis between temperature and reference point height time series, particularly the time lag parameter representing the delay between temperature changes and structural thermal deformation. In 2013, Bail et al. fixed time lags from 0 to 9 hours (incrementing by 1 hour) in the thermal expansion model and computed baselines for 19 global VLBI stations, finding that WRMS values were minimized and comparable for time lags of 0, 1, or 2 hours [3]. This multiplicity of solutions may stem from limitations in contemporary observation technology, low precision of time lag parameters, or inherent errors in the IERS thermal expansion model itself. Consequently, Altamimi has issued four calls in the ITRF2020 (International Terrestrial Reference Frame 2020) participation requirements to validate or improve the current thermal expansion model [4].

Real-time monitoring of antenna reference point height represents an alternative method for estimating and correcting structural thermal deformation. For instance, the Onsala 20 m [5] and Wettzell 20 m [6] radio telescopes monitor reference point height variations with temperature in real time using invar wires (or rods) installed near the reference point. Invar wires can observe seasonal and diurnal reference point height changes with better than 0.1 mm precision, yet most VLBI stations lack such infrastructure. Moreover, invar wires cannot measure horizontal thermal deformation of antenna structures.

Beyond these two approaches, Wresnik et al. (2005) modeled temperatures of steel and concrete structures using reference point height measurements from Onsala 20 m's invar rod, thereby addressing the time lag issue between ambient air temperature and antenna structural temperature [7]. This method accounted for environmental heating and cooling effects on antenna structures as well as thermal memory effects, applying digital filtering to measured reference point heights to solve for model coefficients. However, its complexity prevented widespread adoption.

Current research on antenna thermal expansion has focused exclusively on reference point height, with few studies addressing horizontal deformation due to the difficulty of obtaining sufficient time series of reference point horizontal positions. Since a VLBI antenna's reference point is not a physical location but rather the intersection between the fixed rotation axis (azimuth axis) and a plane perpendicular to this axis passing through the moving axis (elevation axis) [8], indirect methods such as three-dimensional circle fitting [9–11] and transformation methods [12] are required to measure its three-dimensional position. These indirect approaches determine azimuth and elevation axes by observing targets attached to and moving with the antenna structure, thereby locating the reference point. Such methods demand good spatial coverage of targets to achieve better than 1 mm precision, necessitating over one day of observations to determine the reference point position. Because the reference point lies on the antenna's symmetry axis (the azimuth axis), its effective length in the horizontal direction is minimal, making millimeter- or submillimeter-level observation of horizontal thermal deformation impractical. Indirect methods are thus inadequate for monitoring horizontal thermal deformation in both precision and data volume, being primarily used to determine local ties—vectors between collocated stations.

To achieve the VLBI2010 goal of 1 mm positioning accuracy within 24 hours [8], the three-dimensional position RMS of VGOS telescope reference points must be stable or modeled to 0.3 mm. Consequently, we developed a monitoring system to automatically and continuously measure thermal deformation of the Tianma 13.2 m VGOS radio telescope. Ten months of monitoring revealed a maximum height change of 2.6 mm (0.2 mm diurnal) and horizontal displacement of 0.1 mm. Correlation analysis between reference point height deformation and ambient temperature showed identical frequency components in both time series. Since the prism is mounted on the antenna azimuth axis—the structural symmetry axis—its corresponding effective length for thermal expansion is nearly zero, rendering horizontal thermal deformation insignificant. The observed horizontal deformation may be small and susceptible to interference (e.g., wind), correlating with temperature only in long-term trends.

2 Methods

The Tianma VGOS monitoring system operates on two principles: (1) A prism mounted on the antenna azimuth axis is unaffected by gravitational deformation [13], meaning its position changes primarily result from thermal expansion [1]; (2) The IERS thermal expansion model assumes symmetric expansion or contraction of antenna structures with temperature. Therefore, the prism's position time series, installed near the reference point on the azimuth axis, can reflect reference point position variations.

The system comprises three components: a control system, observation system, and storage system. The control system is the RocBox controller developed by Information Engineering University (Zhengzhou), an embedded system that sends commands to the observation and storage systems according to observation schedules. As shown in [Figure 1: see original paper], the observation system consists of a Topcon DS101AC total station and AK11 reflecting prism. The DS101AC high-precision total station features: angular accuracy of 1 , distance measurement accuracy of $(1.5 + 2 \times 10^{-6}\mathrm{D})$ mm, precision measurement time of 0.9 s, and operating temperature range of −20°C to +50°C. Distance error increases with D; for our case with $\mathrm{D} = 8$ m, this error is negligible.

The storage system includes two modes: (1) local storage via cable transmission; (2) wireless storage via network transmission.

To monitor prism position changes, we collected observations from November 10, 2020, to August 31, 2021. The total station operates in automatic recognition mode, automatically sighting and observing the prism. To detect outliers, the total station performs two consecutive observations per cycle, with one cycle per minute. Since antenna thermal deformation is a relative quantity, we used single-face (face left) measurement mode. Because the total station center, prism center, and reference point are nearly collinear, and the Tianma VGOS telescope remained stationary except during system testing, instrument errors in observations can be considered constant, which does not affect relative thermal deformation measurements. Differencing the two consecutive observations per cycle (including horizontal angle, zenith distance, and slope distance) provides preliminary outlier identification. Based on differential errors and error propagation law, we derived standard errors of 113.6 , 0.7 , and 0.1 mm for horizontal angle, zenith distance, and slope distance, respectively. The large horizontal angle error arises because the prism is near zenith, where horizontal angles approach singularity. Calculations show that with a horizontal distance of 1 cm from total station to prism, the 113.6 horizontal angle error corresponds to only 6 m of horizontal thermal deformation, sufficient for monitoring prism horizontal position changes.

We divided antenna structural thermal deformation into horizontal and vertical components. Since we monitor thermal deformation by observing prism position changes, the effective antenna structure in the vertical direction includes the portion from the base pier bottom to the prism center.

2.1 Two-Dimensional Transformation Model

Due to installation error, the prism is not perfectly located on the antenna azimuth axis. We define the center of the circular trajectory traced by the prism during antenna rotation as the approximate reference point. Changes in the horizontal distance from prism to this approximate reference point thus describe horizontal thermal deformation. In practice, this distance is small (<0.2 mm), so reference point horizontal deformation can be inferred from the prism.

We introduce two coordinate systems: the total station observation coordinate system and the VGOS antenna coordinate system. The observation system originates at the total station center; after backsight orientation, the x-axis aligns with the total station's horizontal axis, the z-axis with the local vertical, and the y-axis completes the right-handed system. The antenna coordinate system originates at the approximate reference point; its y-axis parallels the VGOS antenna's initial pointing (0° direction), the z-axis aligns with the antenna azimuth axis, and the x-axis completes the right-handed system. The two-dimensional transformation model is given by Equation (1):

$$P_{total} = R(A) \cdot E + T$$

where P_{total} represents the prism's horizontal position in the observation coordinate system, A is the telescope azimuth angle, R is a two-dimensional rotation matrix, E denotes the prism's initial coordinates in the antenna coordinate system, and T represents the antenna coordinate system origin in the observation coordinate system. Equation (1) describes the coordinate transformation relationship as the prism rotates with the antenna.

Since we are only interested in distance changes from prism to approximate reference point, we transform Equation (1) into:

$$\|E\|^2 = \|P_{total} - T\|^2$$

For convenience, we replace the two-norm $\|E\|^2$ with r.

To determine the relative position between prism and approximate reference point, we conducted two experiments on November 10, 2020, and August 31, 2021, designated Experiment 1 and Experiment 2. As shown in [Figure 2: see original paper], the VGOS antenna was rotated through azimuth angles 0°–360°, pausing every 20° for 2 minutes; three complete circles were performed at elevation angles of 0°, 45°, and 89.9°. The prism moved with the antenna, its position varying with azimuth angle.

Substituting data into Equation (1) and using least squares estimation yielded the two-dimensional transformation model parameters shown in . In the table, $(T_x; T_y)$ represent estimates of T, and $(E_x; E_y)$ represent estimates of E. From T estimates, the distance from approximate reference point to total station center is about 1 cm. From E estimates, the distance from prism to approximate reference point is about 0.2 mm. Note that the standard errors in represent formal precision only. Since thermal deformation is a relative quantity, we are primarily concerned with relative changes in prism position.

Each total station observation of the prism yields a coordinate P_{total}. Substituting observations and results from into Equation (2) gives the distance from prism to approximate reference point. Long-term continuous monitoring produces a time series of prism horizontal displacement. Since we only care about relative horizontal position changes, we use only the August 31, 2021, observation results from when solving the horizontal displacement time series. This describes the principle for real-time monitoring of antenna horizontal thermal deformation.

2.2 Antenna Reference Point Height Monitoring Method

Because the prism is only 0.2 mm from the approximate reference point, its circular trajectory during rotation effectively approximates a point, preventing the total station from detecting tilt of this trajectory relative to the horizontal plane. Assuming a 1° azimuth axis tilt, the impact on distance measurement within a 0.2 mm range does not exceed 4 m. Since actual azimuth axis tilt cannot exceed 1°, we need not consider its effect on slope distance observations.

As the prism rotates with the antenna, zenith distance variations cause changes in slope distance, described by:

$$\Delta sd = h \sin z \cos^2 z$$

where h is prism height, z is prism zenith distance, Δz is zenith distance change, and Δsd is slope distance change. Calculations show Δsd maxima are less than 1 m, indicating slope distance variation is independent of antenna rotation. The relationship between prism height and slope distance is given by Equation (4):

$$sd - h = sd(1 - \cos z)$$

Calculations show $sd - h$ maxima are 7 m, meaning prism slope distance essentially equals its height. Based on this analysis, we use prism slope distance variations to describe antenna reference point height thermal deformation.

3 Results

3.1 Horizontal Thermal Deformation

During the observation period, construction activities near the Tianma VGOS antenna caused slight vibrations. Calculations confirmed that construction only affected prism horizontal position, not height. [Figure 3: see original paper] shows observations from May 21 to August 9, 2021, with blue points during construction shutdowns and red points during active construction. During this period, the antenna was under maintenance, with prism horizontal position affected by both thermal deformation and construction activity, showing approximately 0.1 mm horizontal offset due to construction.

To investigate antenna structural horizontal thermal deformation, we used only observations during shutdown periods. To reduce observation noise, we applied Gaussian filtering to both temperature and r time series with a 1-hour window to preserve diurnal signals. [Figure 4: see original paper] presents results from May 21 to July 18, 2021, showing no significant correlation between temperature and horizontal thermal deformation at the 24-hour period, though they share the same long-term trend. This may occur because the effective structural length corresponding to the prism is short (0.2 mm), yielding small horizontal thermal deformation magnitude (approximately 0.05 mm for 20°C temperature difference), making it susceptible to interference such as wind.

3.2 Height Thermal Deformation

Since construction did not affect prism height, we used all observation data to study antenna height variation with temperature. For clear correlation demonstration, [Figure 5: see original paper] shows only 30 days of observations (November 10–December 10, 2020). Fast Fourier Transform of both height and temperature time series revealed identical periods in both datasets, with the largest amplitudes in the long-term (infinite period) and 24-hour periodic signals. The Pearson correlation coefficient between reference point height variation and temperature is 0.8. [Figure 6: see original paper] shows decomposition of both datasets into long-term trends and periodic components: (a) for antenna height data, (b) for temperature data. Both periodic signals and long-term trends show significant correlation between antenna height thermal deformation and temperature.

Finally, we validated the IERS thermal expansion model using observed antenna height deformation. Since the monitoring system only measures vertical components, we adapted the IERS thermal expansion model [1] as:

$$\Delta h = \mathbf{f}(T(t-\Delta t_f)-T_0)h_f + \mathbf{a}(T(t-\Delta t_a)-T_0)h_a$$

where Δh is antenna height thermal deformation, **a** and **f** are thermal expansion coefficients for steel and concrete structures, Δt_a and Δt_f are time lags for steel and concrete, h_a and h_f are effective lengths for steel and concrete structures, T is ambient temperature of the antenna structure, and T_0 is the antenna reference temperature. The IERS model specifies steel and concrete thermal expansion coefficients as $\mathbf{a} = 12\times10^{-6}$ m/(°C) and $\mathbf{f} = 10\times10^{-6}$ m/(°C), with time lags of 2 h and 6 h, respectively [1]. Substituting the Tianma VGOS antenna's effective thermal expansion lengths into the IERS model and comparing with monitoring system measurements yields the results shown in [Figure 7: see original paper]. The residuals between the IERS model and measured data are less than 1.5 mm, with an RMS of 0.43 mm. The IERS thermal expansion model can eliminate most annual variations, consistent with results in [1].

4 Conclusion

The Tianma VGOS monitoring system can monitor both real-time reference point height variation with temperature and horizontal thermal deformation. Because the reference point lies on the antenna's symmetry axis with minimal effective length in the horizontal direction, horizontal thermal deformation is very small. Current monitoring results indicate annual horizontal deformation does not exceed 0.1 mm. However, VGOS height deformation cannot be ignored; the current IERS thermal expansion model only reduces RMS to 0.43 mm, which fails to meet VLBI2010 requirements. While the IERS model's precision satisfies current conventional VLBI geodetic and astrometric applications, it should be reconsidered for VGOS antennas.

Calculations demonstrate significant correlation between antenna thermal height and ambient temperature, with identical frequency components in the frequency domain. Future work will reconsider the thermal expansion model in the frequency domain.

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