

## Experimental Study on the Effect of Wind on Pointing Accuracy of Antenna Structures (Post-print)

**Authors:** LiFu, Wang Li, Lingling Wang, WenGuo, Qinghui Liu, Zhiqiang Shen, XuWang, HaimingLiu, Li Fu

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### Abstract

Wind loads have instantaneity and turbulence characteristics that will lead to pointing errors in antenna structures, and these errors cannot be ignored in high-frequency observations. Using the Tianma 65 m radio telescope (TMRT) as an example object, the pointing errors caused by wind loads are investigated using an accelerometer system. First, the resonant frequency range of the antenna structure is used for reference to acquire useful signals through the bandpass filtering method. Then, the direct current (DC) component of these signals is filtered out using the fast discrete Fourier transform method, and the baseline of the acceleration is corrected using the least-squares method. Finally, the acceleration integral is solved approximately using the discrete trapezoidal area method, and the structural vibration displacement of the antenna is determined using a double integral of acceleration. The pointing errors are then obtained based on the displacement relationship between the primary and subreflector surfaces. When the wind speed is 3.2 m/s, the antenna pitch angle is  $61.7^\circ$  and the wind direction angle is  $80^\circ$ , the generated pitch pointing error is  $3.05''$ , and the azimuth pointing error is  $1.14''$ . These results are consistent with those obtained via inclinometer measurements, thus validating the signal processing method and the pointing error calculation method proposed in this paper. The research methods and data analysis results reported here provide a basis for further wind-induced pointing error correction studies.

### Full Text

#### Preamble

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**Article****Open Access****Experimental Study on the Effect of Wind on Pointing Accuracy of Antenna Structures**

Li Fu<sup>1\*</sup>, Wang Li<sup>2</sup>, Lingling Wang<sup>1,3</sup>, Wen Guo<sup>1</sup>, Qinghui Liu<sup>1</sup>, Zhiqiang Shen<sup>1</sup>, Xu Wang<sup>4</sup>, Haiming Liu<sup>5</sup>

<sup>1</sup>Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

<sup>2</sup>Sichuan Institute of Building Research, Chengdu 400074, China

<sup>3</sup>University of Chinese Academy of Sciences, Beijing 101408, China

<sup>4</sup>School of Civil Engineering, Chongqing Jiaotong University, Chongqing 610000, China

<sup>5</sup>Merchants Chongqing Communications Technology Research & Design Institute Co. Ltd., Chongqing 400067, China

\*Correspondence: fuli@shao.ac.cn

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**Abstract**

Wind loads exhibit instantaneous and turbulent characteristics that lead to pointing errors in antenna structures, and these errors cannot be ignored in high-frequency observations. Using the Tianma 65 m radio telescope (TMRT) as a case study, we investigate the pointing errors caused by wind loads using an accelerometer system. First, the resonant frequency range of the antenna structure is used as a reference to acquire useful signals through bandpass filtering. Then, the direct current (DC) component of these signals is filtered out using the fast discrete Fourier transform method, and the baseline of the acceleration is corrected using the least-squares method. Finally, the acceleration integral is solved approximately using the discrete trapezoidal area method, and the structural vibration displacement of the antenna is determined through a double integral of acceleration. The pointing errors are then obtained based on the displacement relationship between the primary and subreflector surfaces. When

the wind speed is 3.2 m/s, the antenna pitch angle is  $61.7^\circ$  and the wind direction angle is  $80^\circ$ , the generated pitch pointing error is 3.05 , and the azimuth pointing error is 1.14 . These results are consistent with those obtained via inclinometer measurements, thus validating the signal processing method and the pointing error calculation method proposed in this paper. The research methods and data analysis results reported here provide a basis for further wind-induced pointing error correction studies.

**Keywords:** Accelerometer; Double integral; Pointing error; Bandpass filtering

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## 1. Introduction

Large aperture sizes and high-frequency operation represent current trends in radio telescope development. As the antenna aperture increases, natural frequency decreases, and the antenna becomes increasingly sensitive to wind loads. At the same time, high-frequency observation places higher demands on antenna pointing accuracy, and the effects of wind loads cannot be ignored.

In recent years, researchers have studied the dynamic behavior of antenna structures induced by wind loads using both simulations and experimental methods. Blough et al. [1] established a structural vibration measurement system on the Nobeyama Radio Observatory (NRO) 45 m radio telescope, which included a total of 44 accelerometers installed at the primary reflector, the subreflector, the quadripods, and the pitch axis, along with a data acquisition system. Smith et al. [2] analyzed the quasi-static and dynamic pointing errors of antenna structures caused by wind loads based on a combination of acceleration measurements and astronomical observations. They concluded that the peak range from 2.6 Hz to 3 Hz in the power spectrum of the pointing errors was caused either by deformation of the primary reflector or by rigid body displacement of the subreflector. Snel et al. [3] used accelerometers to measure and analyze the dynamic characteristics of a 10 m antenna, focusing on calculation methods for antenna pointing accuracy, primary reflector deformation, optical path variations, and antenna structural deformation. It is also possible to derive the dynamic behavior of the performance parameters of an antenna independently of any external sources. Ries et al. [4] analyzed the wind-induced pointing errors on the 100-m-diameter Green Bank Telescope. They determined that the main wind-induced pointing errors, which occurred on timescales of minutes, were caused by the feed arm being blown along the wind vector direction. Yu [5] and Li [6] explored installation issues for the inclinometers used to measure the pointing errors of antennas that occur under wind loads. Zhang et al. [7] proposed a pointing error correction method based on a dynamic model and a pointing model of an antenna structure. The pointing error caused by structural deformation was estimated accurately using displacement information from sampling points located on the reflectors. Liang et al. [8] reconstructed the pointing errors caused by vibration deformation of large reflector antennas using optimized acceleration

measurement points.

These studies of the selection criteria, installation positions, and data analysis methods for acceleration sensors have considerable reference significance for this study. This paper reports on an investigation of wind-induced antenna pointing errors using two triaxial accelerometers installed on the subreflector and the antenna feed cabin. The effectiveness and feasibility of the proposed analysis method are verified by comparing the results obtained with those from an inclinometer measurement system.

This paper is arranged as follows: Section 2 outlines the proposed structural vibration measurement system and the inclinometer measurement system. In Section 3, an analysis of the structural natural vibration characteristics is conducted. Section 4 introduces the theoretical analysis methods, including the acceleration data processing methods, the antenna pointing error calculation methods, and the data processing flow. Section 5 describes the application and experimental verification of the theoretical analysis methods. Finally, in Section 6, conclusions are drawn from the results of this work. The data analysis results provide a basis for further antenna precision control studies.

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## 2. Structural Health Monitoring Measurement System

### 2.1. Structural Vibration Measurement System

The structural vibration measurement system used for the Tianma 65 m radio telescope (TMRT) consists of force balance accelerometers, a data acquisition unit, software (130-SM-GUI and SW-RTI, Trimble), a Global Positioning System (GPS) device, an industrial-type personal computer (PC), and the necessary cables. As shown in [Figure 1: see original paper], two triaxial accelerometers (that measure in a total of six directions) are installed across the subreflector platform and the upper platform of the feed cabin. The sensor's Z-axis is oriented parallel to the optical axis, with the positive direction pointing upward when the antenna is facing the sky. The Y-axis is oriented perpendicular to the elevation axis, with +Y pointing toward true north.

### 2.2. Inclinometer Measurement System

The inclinometer measurement system consists of two Swiss-made Leica Nive1220 dual-axis inclinometers with temperature sensors. The inclinometer interface is an RS485 interface with a resolution of 0.2 and a zero-point stability of  $<0.97$  /°C. The sampling period is 300 ms [9]. The X-axis of the inclinometer is oriented perpendicular to the elevation axis and the Y-axis is oriented parallel to the elevation axis. During installation, it is necessary to level the inclinometers carefully such that the static measurement values in both directions are as close to zero as possible [10] to ensure high accuracy within the measurement range.

The inclinometers are mounted on a plane of the elevation axis in the upper part of the TMRT's alidade, and are positioned as closely as possible to the bearing. They can then be used to measure changes in the pointing accuracy caused by various factors, including track unevenness and pedestal thermal deformation. In this paper, the measurement data acquired from this system are used primarily to verify whether the pointing error determined based on the analysis of the accelerometers is accurate.

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### 3. Analysis of Natural Vibration Characteristics of Antenna Structure

In the antenna structure, different pitch angles can result in different gravity distributions, which may affect the antenna's natural vibration characteristics. However, when the antenna rotates around the azimuth axis, the distribution of the structure remains unchanged, and thus the antenna's natural vibration characteristics also remain the same. To gain an improved understanding of this phenomenon, the self-vibration characteristics of the TMRT structure were analyzed for four different pitch angles (i.e., 5°, 30°, 60°, and 90°) in this study. These analyses were conducted based on an established finite element model, and the results were calculated using the subspace iteration method [11].

Using ANSYS software, modal analyses were performed on the finite element models of the TMRT structure for the four different pitch angles. The results obtained for the first 10 natural frequencies are presented in . Comparison indicates that the natural frequencies obtained from the modal analyses show only minimal differences among the four pitch angles. These values are relatively small and are distributed in the 1.4–4.2 Hz range. This range indicates that, as a whole, the TMRT structure is relatively flexible and is more sensitive to low-frequency fluctuating winds.

When the TMRT structure's vibration response is analyzed, the results show that various interference factors can affect the vibration signals. Significant vibration amplitudes can be found within the sensor's bandwidth range from 0 to 80 Hz by examining the spectrum plot after performing a Fourier transform. However, the frequencies that cause structural vibrations should be concentrated around the natural frequencies, whereas the remaining frequency bands represent interference signals. Before the analysis is conducted, it is important to filter out these interference signals to ensure that the structural vibration signals are identified and analyzed accurately.

## 4. Theoretical Analysis Methods

### 4.1. Acceleration Data Processing Methods

**4.1.1. Acceleration Integration Algorithm** The acceleration integration algorithm method is used to calculate the velocity and displacement of an object. In the vibration measurement system introduced in Section 2.1, the sensors on the subreflector and the feed source have a sampling frequency of 200 Hz, which means that data are collected every 0.005 s, thus ensuring that a continuous distribution of the acceleration is acquired. Therefore, we can approximate the acceleration integration approach using the method of discrete accumulation of trapezoidal areas to obtain the velocity and the displacement with only relatively small errors.

Specifically, we consider consecutive acceleration values as the upper and lower bases of a trapezoid, with the time interval acting as the height. By calculating the area of the trapezoid, we can then obtain the appropriate equations for the velocity and displacement integration, shown here as Equations (1) and (2):

$$v_j = \sum_{i=1}^j \frac{1}{2}(a_i + a_{i+1})\Delta t \quad (1)$$

$$x_j = \sum_{i=1}^j \frac{1}{2}(v_i + v_{i+1})\Delta t \quad (2)$$

In these equations,  $a_i$  represents the acceleration value at the  $i$ -th point,  $v_j$  represents the velocity value at the  $j$ -th point, and  $x_j$  represents the displacement value at the  $j$ -th point.

**4.1.2. DC Component** In recent years, accelerometers have been used increasingly widely in engineering experiments because of the significant role that they play in detecting the dynamic characteristics of structures. However, when using sensors, the detection results often suffer from drift caused by factors such as device construction, instrument characteristics, and environmental conditions. To overcome this issue, the drift component of the non-real signal can be fitted as a straight line, and this process results in the detected signal being a superposition of the real signal and the linear component. This linear component is referred to as the DC component of the signal [12].

To eliminate the DC component in vibration acceleration signals, a fast Fourier transform (FFT) method is used to filter out the DC component in the frequency domain. The specific procedure involves sampling the vibration signal and then storing the sampled signal as time-domain data. The data are then transformed from the time domain to the frequency domain. In the frequency domain, the DC component is located at the zero frequency, and its amplitude can be set to be zero to remove the DC component. After that, the processed data are

subjected to an inverse Fourier transform that converts the signal back into the time domain, thus allowing the vibration acceleration signal to be obtained with the DC component removed. Numerically, this process can be achieved by adding a constant correction value to each time point in the acceleration with the aim of making the algebraic sum of the area enclosed by the acceleration curve and the time axis as close to zero as possible. The processed acceleration time history, which serves as the input for the vibration analysis, effectively addresses the drift phenomenon caused by the deviation of the acceleration mean and also helps to mitigate the relative displacement response of the structure.

#### 4.1.3. Principle of Least-Squares Fitting for Acceleration Baseline

The results show that the velocity and displacement time history curves obtained via double integration of the acceleration signal, which has been filtered and had its DC component removed, still exhibit a slight displacement baseline drift when noise or other complex interference factors are present. To improve the data accuracy, it is necessary to perform an initial baseline fitting operation on the vibration acceleration signal before filtering.

Researchers have previously found that use of a fourth-degree polynomial form in the least-squares method provides a good fitting for the displacement baseline after integration [13]. Equation (3) is the displacement baseline, and Equations (4) and (5) describe the baselines formed for the velocity and the acceleration, which are obtained by taking the first and second derivatives of the displacement baseline, respectively. Those equations are shown here as:

$$u_g(t) = a_{1t}^4 + a_{2t}^3 + a_{3t}^2 + a_{4t} \quad (3)$$

$$v_g(t) = 4a_{1t}^3 + 3a_{2t}^2 + 2a_{3t} + a_4 \quad (4)$$

$$a_g(t) = 12a_{1t}^2 + 6a_{2t} + 2a_3 \quad (5)$$

Where  $u_g$ ,  $v_g$ ,  $a_g$  stand for baseline for displacement, velocity and acceleration, respectively.  $t$  is time and the polynomial coefficients are from  $a_1$  to  $a_4$ .

Equation (5) shows that the baseline form for the acceleration is a quadratic curve. By determining the unknown coefficients in this quadratic curve, the nonzero baseline value can be subtracted from the signal after removal of the DC component. This process eliminates the displacement baseline drift caused by the integration of the acceleration baseline. Additionally, subtracting the quadratic baseline values, as shown in Equation (5), from the original acceleration record is equivalent to application of a high-pass filtering operation to the acceleration time history, which effectively removes the low-frequency components.

Usually, the least-squares method is applied to fit the acceleration signal baseline, which is obtained from discrete acceleration data. The principle behind this procedure is given as follows:

$$\Delta = \min \left\{ \sum_{i=1}^N [a_t(i) - a_g(i)]^2 \right\} = \min \left\{ \sum_{i=1}^N [a_t(i) - (12a_{1t}^2 + 6a_{2t} + 2a_3)]^2 \right\} \quad (6)$$

$$\frac{\partial \Delta}{\partial a_k} = 0 \quad (7)$$

The corrected antenna vibration acceleration can then be given by:

$$a_n(t) = a_t(t) - a_g(t) \quad (8)$$

Where  $a_g$  represents the baseline of acceleration signal,  $a_t$  is acceleration signal removing DC component and  $a_n$  is acceleration signal subtracting non-zero baseline value.

#### 4.1.4. Analysis of Acceleration Signals Based on Bandpass Filtering

As noted in Section 3, the natural frequencies are distributed within the range from 1.4 Hz to 4.2 Hz, which indicates that the dominant vibration frequencies of the structure fall mainly within the range from 1 Hz to 5 Hz. Therefore, bandpass filtering is used to remove noise and any other interference factors from the vibration acceleration signal. In Matlab, the ‘butter’ function can be used to implement bandpass filtering based on the following principle:

- (1) Determine the filter design parameters, including the cutoff frequencies, the filter type, and the filter order. In this work, the lower cutoff frequency of the bandpass filter is set at 1 Hz and the upper cutoff frequency is set at 5 Hz. The ‘butter’ function selected here provides the flattest amplitude-frequency response between the passband and the stopband, and its response curve shows the smoothest slope variation. When a bandpass filter is designed using the ‘butter’ function, determination of the appropriate filter order parameter is crucial. A higher order results in better filter performance and accuracy, but it comes with higher computational costs. Typically, the method used to select the filter order is to choose a higher order initially and then adjust the order by observing the filtered output signal to realize the desired filtering effect. After multiple attempts, a filter order of 2 was found to achieve excellent filtering performance.
- (2) Based on the filter type and order selected, the filter coefficients are computed using the ‘butter’ function. In Matlab, the ‘butter’ function can be used to implement Butterworth filters. Specifically, the ‘butter’ filter function uses an infinite impulse response (IIR) digital filter to implement

the required filtering operation. Based on the filter type specified, the function calculates the poles and zeros of the Butterworth filter and then constructs the IIR filter's transfer function using these poles and zeros.

- (3) The 'filter' function is then used to apply the filter coefficients to the input signal, with the filtered output signal being obtained as a result.

## 4.2. Calculation Method for Antenna Pointing Errors

For the TMRT, there are generally two antenna states. The first state is the antenna's stationary mode, in which the antenna does not undergo azimuthal or elevation rotations. In this mode, the influence of external factors on the antenna vibration behavior is minimal. Therefore, this mode is well-suited for study of the effects of wind because it provides a relatively stable working environment in which to research and optimize the antenna's wind resistance performance. The second state is the radio source tracking mode. In this state, the antenna control system updates the azimuth and elevation positions continuously based on the target position and the current position difference.

In this paper, the accelerometer measurement data are analyzed first in the stationary mode to introduce the calculation method for the antenna pointing error. Then, the method is expanded to analyze the pointing error that occurs at any observation attitude for the antenna.

**4.2.1. Calculation Method for Pointing Error in the Antenna Stationary Mode** The antenna pointing error refers to the deviation of the mechanical axis from its original position under the influence of loads and other factors, which causes a reduction in the antenna's pointing accuracy. In this section, the three-axis accelerometers A1, A2, A3, and A4, A5, A6 shown in [Figure 1: see original paper] that are installed on the feed cabin and the subreflector, respectively, are used to address the pointing errors caused by wind loads. The sensor installation positions are shown in [Figure 1: see original paper]. These sensors are installed parallel to the mechanical axis, thus allowing the deformations in the Y and X directions to be acquired through double integration; the deformations obtained reflect the relative offsets of the mechanical axis.

In the case where the antenna is in the stationary mode, the sensors are in the horizontal state, where the gravitational acceleration direction is oriented perpendicular to each sensor's X and Y axes, and thus does not interfere with their signals. Therefore, the equations used to calculate the elevation and azimuth pointing errors in this state are given as follows:

$$\Delta X_{EL} = \frac{(a_2 - a_5)d}{2t_S} \cdot \frac{180}{\pi} \cdot 3600 \quad (9)$$

$$\Delta EL = \frac{(a_3 - a_6)d}{2t_S} \cdot \frac{180}{\pi} \cdot 3600 \quad (10)$$

Where  $\Delta X_{EL}$  and  $\Delta EL$  represent the pointing errors for the azimuth and the elevation, respectively, as measured in arcseconds (');  $a_2$  and  $a_5$  are the vibration acceleration signals collected by the two sensors in the Y direction (perpendicular to the elevation axis);  $a_3$  and  $a_6$  represent the vibration acceleration signals collected by the two sensors in the X direction (elevation axis); and  $d$  is the distance between the two sensors, which is 14.077 m in this case.

**4.2.2. Calculation Method for Pointing Error in the Antenna Observation Mode** According to the principles of acceleration measurement, when the antenna is in the observation mode, it will have a specific elevation angle and will move at low velocity. At this time, the acceleration sensors will also rotate at the same angle as the antenna. Therefore, the measured acceleration includes two main components: the change in acceleration as the sensor rotates to reach a certain angle and the acceleration variations caused by structural vibrations. To isolate the acceleration data related to these structural vibrations and eliminate the influence of acceleration due to gravity, it is necessary to apply rotation compensation to the data. This process involves determining the sensor's rotation axis during observation, obtaining the real-time rotation angles from the operational data, and then analyzing the relationship between the acceleration due to gravity and the three sensor directions based on the attitude angles. These values are then used to perform compensation.

The schematic diagram of the sensor coordinate directions in [Figure 2: see original paper] shows that the acceleration due to gravity acts perpendicular to the X-axis direction and only affects the signals in the Y-direction and Z-direction. Therefore, in this study, we need only consider the X and Y directions. From [Figure 2: see original paper], the signal correction formula that applies during observation is shown as Equations (11) and (12):

$$a'_2 = a_2 - g \cos(\alpha) \quad (11)$$

$$a'_5 = a_5 - g \cos(\alpha) \quad (12)$$

Where  $\alpha$  is the antenna elevation angle;  $a'_2$  represents the Y-axis acceleration signal from the feed cabin sensor after removal of the influence of gravity; and  $a'_5$  is the Y-axis acceleration signal from the subreflector sensor after removal of the influence of gravity.

After compensating for the deviations, these signals are then substituted into Equations (9) and (10) to produce the following equation for calculation of the antenna pointing errors during observation:

$$\Delta X_{EL} = \frac{(a'_2 - a'_5)d}{2t_S} \cdot \frac{180}{\pi} \cdot 3600 \quad (13)$$

## 5. Analysis of Antenna Pointing Accuracy

This section presents an analysis of the vibration acceleration signals in stationary and observation states, and then compares the results of this analysis with the inclinometer measurement data to validate the proposed method.

### 5.1. Analysis of Antenna Pointing Accuracy in the Stationary State

A total of 20 s of data were selected for analysis from 03:20:00 to 03:20:20 (UTC) on 25 July, 2021. Because of space limitations, only the data processing method used to calculate the elevation pointing error is shown here. The antenna was in the stationary state during this period. The raw acceleration signal is shown in [Figure 3: see original paper] and the measured results obtained from the sensor show drift, thus indicating the presence of a DC component. This drift is caused by various factors, including the sensor's construction, the characteristics of the data acquisition instrument, and environmental interference. Therefore, particularly close attention is required to avoid misjudgments in interpretation of the experimental results being caused by this drift. To allow more accurate analysis of the data, the first step involves removal of the DC component. Two methods are usually applied to perform this process: the first is used for short-duration or uniformly vibrating signals, where it is sufficient to simply subtract the mean value of the signal data from the original signal values; the second is used when the signal time duration is longer and when there are significant vibration intervals, which requires the mean value of the pre-vibration part to be subtracted from the original acceleration time series to provide more accurate analysis results.

In this section, the periods to be analyzed are relatively short and thus the first method is applied to remove the DC component; the resulting signals without the DC component are shown in [Figure 4: see original paper].

We then subtract the acceleration versus time after removal of the DC component, i.e.,  $a_2 - a_5$ , to obtain the differential signal after the same confounding factors have been removed across the entire frequency band. Integrating the differential signal twice allows the velocity and displacement versus time data to be obtained, as shown in [Figure 5: see original paper]. However, it can be seen from the results in the figure that the existence of various confounding factors, including the noise from the feed cabin, mechanical noise, and other elements, will lead to baseline offsets for the recorded acceleration signal. These baseline offsets are then amplified during the secondary integration, thus causing distortion of the velocity and displacement signals, which then cannot reflect the actual vibration situation. Therefore, further processing of the vibration acceleration signal is required to remove the baseline offsets.

After the least-squares correction and filtering processes, the confounding factors across the entire frequency band can be removed effectively to allow more accurate vibration signals to be obtained. Fourier transforms can be used to analyze the frequency domain characteristics of the signals, and the spectra of the

acceleration signals obtained before and after filtering can be used to visualize the filtering effect, as illustrated in [Figure 6: see original paper]. The order of the bandpass filtering can be determined based on the filtering effect shown in the spectrum diagram.

After filtering, the vibration signal is subjected to quadratic integration processing to obtain the velocity and displacement versus time curves. At this point, the results show that the baseline shift behavior of the signal has been greatly improved, with results that are closer to the real vibration situation, as shown in [Figure 7: see original paper]. This processing method can improve the accuracy and reliability of the vibration signals effectively, thereby providing more reliable basic data for use in the subsequent vibration analysis and diagnosis.

Through the processing steps described above, the vibration displacement characteristics of the TMRT mechanical axis in the Y and X directions can be acquired. The elevation pointing error and the azimuth pointing error during this period can be calculated using Equations (9) and (10), with results as shown in [Figure 8: see original paper].

To validate the proposed method and the signal processing procedure used in this paper, the trend of the wind-induced antenna pointing error can be compared with measurement results obtained from the inclinometer. Because of installation location limitations, the accuracy of the data measured using the inclinometer system is only high in the elevation direction, and it is not possible to measure the pointing error in the azimuth direction directly.

We extracted the values at the time points corresponding to the data measured using the inclinometer from the elevation pointing errors calculated in this work, and then compared them. The results are shown in [Figure 9: see original paper], where the acquisition of the inclinometer signal shows a lag of 1–3 s. The figure also shows that the results are very similar in both trend and values to the measured data acquired from the inclinometer, thus verifying the effectiveness of the proposed method. It should also be noted that the inclinometer sampling frequency is relatively low at only 1 Hz, and that interference from other environmental factors is also included in the measured signal from the inclinometer. As a result, a certain deviation between the measured data and the calculated results still exists.

## 5.2. Analysis of Antenna Pointing Accuracy during Observation

A total of 40 s of data were selected for analysis in the time period from 17:33:20 to 17:34:00 (UTC) on 4 April, 2023. The wind speed was 3.2 m/s at this time, and the wind direction angle was 80°. The collection frequency for the real-time elevation angle in the control software is 20 Hz, which differs significantly from the collection frequency used for the accelerometer of 200 Hz. Thus a one-by-one correspondence to the elevation angle in the control software cannot be achieved. This paper uses cubic spline interpolation to supplement the elevation angle at the missing time points. Because there are sufficient numbers of known

elevation angle data points, the cubic spline interpolation method offers high accuracy and high stability.

[Figure 10: see original paper] shows that the signal will present an overall tilt distribution during observation of the antenna that is mainly caused by gravity. When the sensor is in the horizontal state, it can measure the acceleration caused by the structural vibration directly. However, during antenna observation, the sensor is in a tilted state and the mass block in the sensor maintains a force balance. The feedback signal includes the influence of the gravity-related factors at the different elevation angles. Because of the almost constant magnitude and direction of gravity on Earth, gravity generates a reference signal on the acceleration sensor that varies with the elevation angle, and this causes the signal tilt. This influence can be corrected using Equations (11) and (12).

During this 40 s observation process, the elevation angle increased from  $61.69^\circ$  to  $61.72^\circ$  at a speed of approximately  $0.003$  ( $^\circ$ )/s. The average wind speed was  $3.2$  m/s. After the elevation angle at each time point is determined, the signal deviation caused by gravitational acceleration can be removed using Equations (11) and (12). The vibration acceleration signal after correction and removal of the DC component is as shown in [Figure 11: see original paper]. The results show that the signal deviation has improved greatly.

After removal of the signal deviation caused by gravitational acceleration, the velocity and displacement versus time curves before baseline correction are obtained by performing a double integration, with results as shown in [Figure 12: see original paper]. The results in the figure show that there are many instances of interference in the signal without baseline correction processing.

The processing flow in this case is the same as that used in Section 5.1. After the least-squares method is used to perform correction and filtering, the confounding factors within the full frequency band can be removed effectively, ensuring that more accurate vibration signals are obtained. The spectra of the acceleration signal before and after filtering are shown in [Figure 13: see original paper]. The effectiveness of the bandpass filtering order can be verified based on the filtering effect shown in the spectrum diagram. After filtering, the vibration signal is subjected to quadratic integration to produce the velocity and displacement versus time curves, as shown in [Figure 14: see original paper] and [Figure 15: see original paper].

The pointing errors can then be obtained from the displacements in the elevation and azimuth directions, with results as shown in [Figure 16: see original paper].

Inclinometers in the observation state are also affected by factors such as gravity and noise, which can cause differences to occur between the amplitude measured by the inclinometer and the true value, but these values still show high similarity in the time history curve trends. In addition, the peak pointing error in [Figure 17: see original paper] matches well with the simulated results given in reference [11]. A comparison of the errors measured by the two methods is

shown in [Figure 17: see original paper]. The similarity of their trends verifies the effectiveness of the pointing error obtained using the accelerometers.

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## 6. Conclusions

This paper describes experimental research conducted into the vibration behavior of wind-affected antenna structures with a focus on the processing methods for the acceleration data and the calculation methods for the pointing errors. The main conclusions from this research are as follows:

- (1) Through modal analysis of the antenna structure, the first 10 natural frequencies of the TMRT structure were obtained. These frequencies were distributed between 1.4 Hz and 4.2 Hz. This indicates that the TMRT structure is relatively soft overall and is more sensitive to low-frequency fluctuating wind loads.
  - (2) A complete vibration acceleration data processing method has been designed that ensures acquisition of more accurate and reliable signals through application of filtering and baseline correction techniques. By integrating the processed signal twice, the antenna's displacement time history in the elevation and azimuth directions was obtained successfully.
  - (3) For the first time, a triaxial accelerometer was applied to the antenna structure by taking the two states where the stationary antenna is facing the sky and the antenna is tracking the radio source into account. The corresponding calculation formula for wind-induced pointing errors was derived and its accuracy was verified through inclinometer measurements. The calculation method proposed in this study offers the advantages of a high sampling frequency and low signal delay when compared with the inclinometer measurement method. At the same time, this method can compensate for the defect where the inclinometer is unable to measure the pointing error directly in the azimuth direction, and thus provides a more effective and accurate method for correction of the pointing errors of wind-affected antennas.
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of CAS, and the CAS Scholarship.

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## Author Contributions

Li Fu conceived the ideas, designed and implemented the study, and wrote the paper. Wang Li collected and processed the vibration acceleration data and revised the paper. Lingling Wang provided data for the wind speed and direction. Wen Guo did experiments. Qinghui Liu and Zhiqiang Shen revised English expressions. Xu Wang and Haiming Liu instructed Wang Li to process data. All authors read and approved the final manuscript.

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## Declaration of Interests

The authors declare no competing interests.

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## References

- Blough, J. R., Gwaltney, G., Karsen, V., et al. 2001. Gathering operating vibration data on the Nobeyama 45m radio telescope. In *Proceedings of SPIE*.
- Smith, D. R., Weech, K., Blough, J., et al. 2001. Operating data and pointing measurements of a large radio telescope. In *Proceedings of SPIE*.
- Snel, R. C., Mangum, J. G., Baars, J. W. M. 2007. Study of accelerometers. *IEEE Antennas and Propagation Magazine*, 49(4): 84–101.
- Ries, P., Hunter, T. R., Constantikes, K. T., et al. 2011. Measuring and correcting wind-induced pointing errors of the Green Bank Telescope using an optical quadrant detector. *Publications of the Astronomical Society of the Pacific*, 123(904): 682–691.
- Yu, M. Y. 2014. The influence of axial system error on the pointing of 110m-diameter full steerable antenna. Master thesis, Xidian University. (in Chinese)
- Li, S. L. 2014. On key technologies of high-pointing accuracy for 110m-diameter full steerable reflector antenna. Doctor thesis, Xidian University. (in Chinese)
- Zhang, J., Huang, J., Liang, W., et al. 2018. A correction method of estimating the pointing error for reflector antenna. *Shock and Vibration*, 2018(1): 262869.
- Liang, W., Huang, J., Zhang, J., et al. 2019. Reconstruction of vibration-deformation-induced pointing error for large reflector antennas from optimized acceleration measurement points. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 233(10): 3417–3428.

Fu, L., Ling, Q. B., Zhao, R. B., et al. 2016. Settlements of foundation and track of TM65 m and its effect on antenna pointing. *Infrared and Laser Engineering*, 45(11): 183–189. (in Chinese)

Pisanu, T., Buffa, F., Morsiani, M., et al. 2010. Thermal behavior of the Medicina 32-meter radio telescope. In *Proceedings of the Conference on Modern Technologies in Space- and Ground-Based Telescopes and Instrumentation*.

Wang, Y. F. 2018. Research on wind load characteristics and structural response of TM65m radio telescope. Master thesis, Harbin Institute of Technology. (in Chinese)

Chang, J. P., Li, H. L. 2006. *Random Signal Analysis*. Beijing: Science Press. (in Chinese)

Li, J. T., Yang, Q. S. 2010. A correction method for baseline drift of seismic wave. *Journal of Beijing Jiaotong University*, 34(1): 95–99. (in Chinese)

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

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