Advances in Laser Scanner Measurement of Antenna Structural Deformation: A Postprint

Authors: Tang Jiansen[1], Fu Li[2], Wang Jinqing[2], Wang Xu[1], Liu Haiming[3], Liu Qinghui[2]

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Abstract

Laser scanning measurement methods exhibit advantages of rapidity, automation, and non-contact operation, yet their measurement accuracy is on the millimeter scale. This paper reviews the application of laser scanners in measuring antenna structural deformation, which can effectively quantify telescope focal length and signal path length variations, VLBI reference point stability, and panel misalignment. Additionally, key technologies for enhancing system measurement accuracy are introduced, encompassing measurement techniques such as two-face measurements and on-site calibration, along with data processing methods including point cloud simplification, correction coefficient incorporation, and orthogonal distance regression. These methods and results can serve as references for efficiently measuring deformation in radio telescope antenna structures.

Full Text

Preamble

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Progress in Research on Antenna Structure Deformation Measurement by Laser Scanning

TANG Jian-sen[1], FU Li[2], WANG Jin-qing[2], WANG Xu[1], LIU Hai-ming[3], LIU Qing-hui[2]
(1. School of Civil Engineering, Chongqing Jiaotong University, Chongqing

400074, China;
2. Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China;
3. China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing 400067, China)

Abstract

Laser scanning measurement methods offer the advantages of being fast, automated, and non-contact, though their measurement accuracy is on the order of millimeters. This paper reviews the application of laser scanners in measuring antenna structure deformation, demonstrating their effectiveness in measuring telescope focal length variations and signal path length changes, VLBI reference point stability, and panel misalignment. The paper also introduces key technologies for improving system measurement accuracy, including measurement techniques such as two-face measurement and in-situ calibration, as well as data processing methods such as point cloud simplification, addition of correction coefficients, and orthogonal distance regression. These methods and results provide valuable references for efficiently measuring the structural deformation of radio telescope antennas.

Keywords: radio telescope; laser scanner; focal length; panel misalignment; signal path length; VLBI

1. Introduction

With the rapid development of China's aerospace industry and astronomical research, increasingly higher demands are being placed on the sensitivity and resolution of radio telescopes. However, antenna structures undergo changes in surface accuracy, focal length, and signal path length under gravitational and other loads, directly leading to degraded telescope performance. Therefore, it is necessary to measure structural deformation, understand its patterns, and perform effective compensation. Current methods for measuring antenna structure deformation include classical surveying, photogrammetry, microwave holography, and laser measurement, each with its own advantages and disadvantages. This paper focuses on reviewing the progress of laser scanning measurement methods, which have been applied to ground-based antenna measurements for just over a decade. Laser scanning offers advantages such as high speed, non-contact operation, high density, and automation, though its measurement accuracy decreases with increasing distance and range, requiring effective measurement and data analysis methods to improve accuracy. This paper aims to address the international research frontier in this field, introducing key technologies, potential solutions, and applications of laser scanning measurement in antenna structure measurement.

2. Laser Scanner Measurement Methods and Data Acquisition

Understanding laser scanner measurement methods enables rational selection of instruments based on antenna structure aperture, measurement distance, and accuracy requirements, and facilitates research on accuracy improvement techniques.

2.1 Laser Scanner Measurement Methods

Laser scanners can be classified by dimension, platform, application range, measurement range, light source, and distance measurement method. For antenna structure deformation measurement, three-dimensional, ground-based, medium-range instruments with semiconductor lasers are typically selected, though the specific distance measurement method must be determined based on actual conditions. The measurement method 主要包括 five aspects: distance measurement, angle measurement, scanning, positioning, and image acquisition.

2.1.1 Distance Measurement Methods The quality of distance measurement directly affects laser scanner accuracy. Scanners can be categorized by distance measurement principle into triangulation, pulse, and phase methods.

(1) Triangulation Method
Triangulation distance measurement is an off-axis method where the laser emission and reception paths are not collinear. It determines the distance from the scanning center to the target using triangular geometric relationships. The laser emission point and reception point are located at both ends of the baseline, forming a spatial planar triangle with the target reflection point. Since the baseline is typically small, the triangulation method is only suitable for short-distance measurement, with accuracy decreasing rapidly as distance increases.

(2) Phase Method
Phase-based distance measurement uses radio frequency to amplitude-modulate the laser beam. By measuring the phase difference of the modulated optical signal traveling back and forth over the measured distance, the round-trip time is indirectly determined, and the distance is calculated. Let ϕ be the phase difference produced by the laser signal's round-trip propagation (in rad), f be the modulation frequency (in Hz), and S be the measured distance (in m):

$$S = \frac{c\phi}{4\pi f}$$

This method can only measure distance with a single frequency. To improve distance measurement accuracy, the modulation frequency f must be increased, which reduces the measurement scale and creates integer ambiguity problems when measuring long-distance targets. Therefore, this method is suitable for medium-range measurement and is mainly applied in precision measurement and medical research.

(3) Pulse Method
Pulse distance measurement calculates the distance to the target by measuring the time difference between emitted and received optical pulse signals. Let S be the target distance, c be the speed of light, and Δt be the measured round-trip time:

$$S = \frac{c\Delta t}{2}$$

As shown in Equation (2), the main factors affecting pulse-based distance measurement are c (in $\mathrm{m \cdot s^{-1}}$) and Δt (in s). The accuracy of c is determined by the atmospheric refractive index n, which can currently be determined with an accuracy of 10^{-6}, having minimal impact on distance measurement. The determination of Δt can be ensured through methods such as leading edge discrimination, high-pass capacitance-resistance discrimination, constant ratio discrimination, or full-waveform detection technology. The pulse method enables longer measurement distances but with lower accuracy. Most current vehicle-mounted and airborne laser scanners use this method, which has good applications in large-scale topographic mapping.

2.1.2 Angle Measurement Method Unlike conventional instruments that use graduated circles for angle measurement, 3D laser scanners obtain scanning angles by altering the laser optical path. Two stepper motors are installed together with a scanning prism to achieve horizontal and vertical scanning. A stepper motor is a control micro-motor that converts pulse signals into angular displacement, enabling precise positioning of the laser scanner. During scanner operation, the subdivision control technology of the stepper motor is used to obtain a stable step angle θ_b:

$$\theta_b = \frac{360^\circ}{N_r \cdot m \cdot b}$$

where N_r is the number of rotor teeth of the motor, m is the number of motor phases, and b is the number of line states and operating modes of various connected windings. Based on θ_b, the rotation angle of the scanning prism can be obtained, and through synchronous measurement with an encoder controlled by a precision clock, the horizontal and vertical scanning angle observations for each laser pulse can be determined.

2.1.3 Scanning Method Laser scanners precisely control the rotation of the scanning prism through mechanical scanning devices, determining the laser beam emission direction and enabling the pulsed laser beam to scan along horizontal and vertical axes. The scanning devices used in laser scanning systems 主

要有 four types: oscillating scanning mirrors, rotating regular polygon scanning mirrors, rotating prism scanning mirrors, and fiber scanning mirrors. Among these, 3D laser scanners mostly use the first two types, while the latter two are more commonly used in airborne laser scanners.

2.1.4 Positioning Method Laser scanners obtain distance S (in m), horizontal angle α (in rad), and vertical angle θ (in rad) through distance and angle measurement. Using polar coordinate principles, the 3D coordinates of the target point in the station's local coordinate system can be obtained:

$$\begin{aligned} X &= S\cos\theta\cos\alpha \\ Y &= S\cos\theta\sin\alpha \\ Z &= S\sin\theta \end{aligned}$$

2.1.5 Image Acquisition Laser scanners can be used with cameras to obtain scene photographs. By calibrating the positional relationship between the two, the transformation relationship between the scanner's station coordinate system and the image space coordinate system can be determined, thereby obtaining RGB values for each scanned point. The massive 3D data points of the object surface obtained by laser scanners are called point clouds. Representing the point cloud with a single color creates a 3D binary image. Laser scanners record not only the spatial geometric information of target points but also information reflecting target material and texture properties, namely echo intensity information. Assigning different colors to the point cloud based on the recorded echo intensity yields a 3D pseudo-color image, which can be used for target recognition and classification. Assigning RGB values obtained from the camera to each point yields a 3D true-color image.

2.2 Data Acquisition and Processing

2.2.1 Data Acquisition Process Laser scanner data acquisition involves five steps: planning, coarse scanning, registration, fine scanning, and photography. The detailed acquisition process is shown in Figure 1 [Figure 1: see original paper].

2.2.2 Data Processing Workflow The entire workflow of a laser scanner system can be divided into field data acquisition and office data processing. Office data processing includes establishing grid structures, filtering and smoothing, hole repair, point cloud resampling, and point cloud simplification, as shown in Figure 2 [Figure 2: see original paper]. For large-aperture radio telescopes, surface measurement must be completed from multiple stations, and the transformation between coordinate systems of different stations—namely, multi-station registration accuracy—is a technical challenge.

In 2009, Sarti et al. [5] first applied laser scanners to measure gravitational deformation of radio telescopes, and subsequent scholars have conducted related research (see Table 1). Studies have found that although laser scanners have advantages such as speed and efficiency, their accuracy is slightly inferior to that of total stations, making them less effective for direct millimeter-wave antenna surface measurement. However, they perform well in measuring focal length and related signal path variations, VLBI antenna reference point stability, and panel misalignment.

In 2009, Sarti et al. [5] used laser scanners to measure and analyze the gravitational deformation of two 32 m radio telescopes located in Medicina and Noto, Italy. The scanner selected was the GS200 from Trimble-Mensi, with a measurement range of less than 100 m and an accuracy of 3 mm. After coordinate transformation and point cloud registration from two stations, a least squares best-fit paraboloid was fitted to obtain the standard deviation of residuals. The results showed that the scanner was not ideal for evaluating the overall performance of the main reflector, but the obtained focal length variation patterns were acceptable.

The paraboloid equation in the design coordinate system is:

$$Z_j = \frac{X_j^2 + Y_j^2}{4f}$$

where X_j, Y_j, and Z_j are the coordinates of points on the designed paraboloid, and f is the focal length (in m).

Next, the transformation between the design coordinate system and the measurement coordinate system is performed:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_y(\phi_y) \cdot R_x(\phi_x) \cdot x_j + X_0$$

where R_x and R_y are transformation matrices, X_0 is the vertex displacement vector, and x_j is the 3D coordinate of the measurement point, calculated as:

$$x_j = \begin{bmatrix} s_j \cos\beta_j \cos t_j \\ s_j \cos\beta_j \sin t_j \\ s_j \sin\beta_j \end{bmatrix}$$

where s_j, β_j, and t_j are the distance, horizontal angle, and vertical angle of the point measured by the laser scanner, respectively.

Finally, the classical least squares (CLS) method is used to obtain parameters including the three-direction displacement X_v, Y_v, Z_v of the main reflector vertex, two-direction rotation angles ϕ_x, ϕ_y, and focal length variation dF.

Furthermore, focal length variation is directly related to signal path length variation, expressed as [1]:

$$\delta dL = \alpha_f dF + \alpha_v dV + \alpha_r dR$$

where δdL is the signal path length variation, dF is the focal length variation, dV is the main reflector vertex movement, dR is the receiver movement, and α_f, α_v, and α_r are coefficients related to the latter three terms. Among them, α_f is the coefficient related to focal length variation, expressed as [6]:

$$\alpha_f = 2\left(1 + \frac{8f^2}{r_0^2}\right)\ln\left(1 + \frac{r_0^2}{4f^2}\right)$$

where f is the focal length and r_0 is the main reflector radius (in m).

Sarti et al. [6] analyzed the signal path variation of the Medicina 32 m radio telescope, measuring focal length variation with a laser scanner, calculating main reflector vertex movement with finite element analysis, and analyzing receiver movement with a combination of finite element and measurement methods. The signal path variation was ultimately calculated using Equation (8). The research results indicated that signal path deviation caused by antenna structural gravitational deformation cannot be ignored.

3.2 VLBI Reference Point Stability

The position of telescope reference points used for VLBI measurements directly affects VLBI measurement accuracy. Holst et al. [8] studied the stability of reference points under gravitational load using the Onsala 20 m radio telescope (see Figure 3 [Figure 3: see original paper]) with a laser scanner. The process consists of four steps: (1) obtaining main reflector vertex parameters at various elevation angles in the scanner coordinate system; (2) transforming vectors at all elevation angles to a common stable reference coordinate system (multi-station registration used overlapping point clouds from each station); (3) analyzing the rotation center to determine reference point stability; and (4) evaluating the accuracy of the rotation center analysis. In practical applications, the measured stability of the Onsala 20 m radio telescope reference point is 0.3 mm.

Note: a) Schematic diagram of VLBI reference point position; b) Schematic diagram of overlapping point cloud positions measured at different elevation angles.

3.3 Panel Misalignment

Holst et al. [8] conducted an in-depth analysis of laser scanning data from the Effelsberg 100 m radio telescope, proposing that post-fitting residuals include three components: random errors, systematic errors, and local deformation of the main reflector. Random and systematic errors are first corrected through averaging residuals of all points on each panel and system calibration. Then, using known panel and sampling point positions, the average value of fitting residuals for each panel is calculated to obtain the offset of each panel. Panel misalignment is verified through measurement results at different elevation angles. Figure 4 [Figure 4: see original paper] shows the actual measurement results. In Figure 4a, six panels show deviations of approximately 5 mm (other panels show deviations within 2 mm), and the deviations remain large at other elevation angles (see Figure 4b), indicating that these panels may have become misaligned. Among them, the four symmetrically distributed points are artificially controlled for holographic measurement, while the two panels in the upper right corner have genuinely become misaligned.

Note: a) 90° elevation angle; b) 45° elevation angle.

3.4 Surface Shape Measurement

Rasha et al. [12] used a FARO laser scanner to measure the surface shape of both the main and sub-reflectors of the Warkworth 30 m radio telescope. The instrument has an accuracy of 1 mm within the range of (0.3–120) m. Principal component analysis (PCA) and least squares methods were employed for data analysis to obtain the surface accuracy of the main and sub-reflectors at different elevation angles (see Table 2). The correlation coefficients between different elevation angles range from 0.972 to 0.986, indicating that the measurement and data processing methods are effective. However, no meaningful surface shape was obtained. According to the Ruze formula, this scanner is suitable for surface shape measurement of centimeter-wave antennas.

4. Key Technologies for Improving Measurement Accuracy

4.1 Installation Position and Method

For the Effelsberg 100 m radio telescope, the laser scanner is installed near the prime focus [9], below the Gregorian sub-reflector, facing downward. Initially, the scanner was rigidly fixed to the structure, rotating with the main reflector. In this configuration, the scanner's measurement range was (30–50) m, enabling single-station measurement of the entire surface. Later, concerns arose that this rigid fixation might damage the scanner or cause measurement biases [10]. An improved approach established a stable hinge allowing the scanner to swing like a pendulum, ensuring it remains vertical. However, due to the instrument's 270° field of view, this improvement has the disadvantage of not being able to scan the complete main reflector at low elevation angles.

For the Onsala 20 m radio telescope, the scanner is installed on the sub-reflector support legs [7] using a similar flexible hinge connection. However, during data analysis, measurement data at certain elevation angles were found to be invalid due to poor hinge stability, leading to measurement errors.

Alternatively, some installations place the laser scanner on the main reflector, completing measurement through multi-station registration. The Medicina 32 m radio telescope is a Cassegrain telescope [5]. The laser scanner is installed at points F1 and F2 near the central feed of the main reflector (see Figure 5 [Figure 5: see original paper]a). The scanner can rotate 360° in azimuth and 60° in elevation, completing full-surface measurement through scanning at F1 and F2 followed by registration. The scanner for the Warkworth 30 m radio telescope is installed on a support structure approximately 10 m from the center of the main reflector (see Figure 5 [Figure 5: see original paper]b), enabling simultaneous measurement of both main and sub-reflectors.

Note: a) Medicina 32 m radio telescope; b) Warkworth 30 m radio telescope.

Installing the scanner on the sub-reflector or support legs enables single-station measurement, but the long lever arm at different elevation angles may be unstable and introduce measurement errors. Installing the scanner on the main reflector avoids these issues but introduces multi-station registration errors. Additionally, scanner installation must consider measurement strategy, ensuring the laser incidence angle is between 10° and 45° to obtain reasonable laser point intensity and guarantee measurement accuracy.

4.2 Measurement Method

Generally, laser scanners are calibrated in a calibration field by scanning targets or planes from different stations to obtain calibration parameters. However, research has found that system errors of equipment calibrated in this manner exceed random errors when measuring antenna structure deformation. Therefore, in-situ calibration is performed at different elevation angles [10] to obtain calibration parameters for each elevation angle, reducing systematic errors.

Additionally, systematic errors can be corrected through two-face measurement: scanning once from 0°–180° and again from 180°–360° [14], merging the two measurements into a single point cloud for data analysis. This method only requires double the measurement time without additional processing.

When measuring the structural deformation of the Onsala 20 m radio telescope antenna, seven parameters sensitive to two-face measurement were first calibrated in-situ (see Equation (10)) [7]. Figure 6 [Figure 6: see original paper] shows the main reflector deformation residuals at 45° elevation angle before and after calibration, demonstrating significant system error correction. However, these seven parameters only apply to this specific field environment and measurement strategy.

$$P_{calib} = [x_{1z}, x_3, x_{5z-7}, x_6, x_{1n+2}, x_4, x_{5n}]^T$$

where x_{1z} is vertical beam deviation, x_3 is mirror deviation, x_{5z-7} is horizontal axis error, x_6 is collimation axis error, x_{1n+2} is horizontal beam deviation, x_4 is vertical deviation, and x_{5n} is horizontal beam tilt.

Note: a) Before calibration; b) After calibration.

4.3 Data Processing

(1) Point Cloud Simplification

Holst et al. [10] proposed a point cloud simplification strategy. The main reflector is separated from the background using laser measurement range and intensity thresholds (empirical values). Points with large deviations are deleted by evaluating point deviation and setting a threshold of 5 cm, such as at locations occluded by sub-reflector support legs. If gaps between panels are too large, points scanned from the panel support structure must be deleted while ensuring uniform distribution of measurement points.

(2) Correction Coefficients

Li Gan [15] used a Riegl VZ400 laser scanner to measure the gravitational deformation of the Shanghai 65 m radio telescope's main reflector backup structure. By introducing additive and multiplicative unknown parameters for distance measurement into the common point transformation model, an 8-parameter least squares model was established. After additive and multiplicative constant corrections, the external coincidence accuracy of point measurement was 1.0 mm and the internal coincidence accuracy was 0.5 mm within a 30 m range.

(3) Orthogonal Distance Regression Method

The least squares method is a classical measurement data analysis approach that linearizes the distance, horizontal angle, and vertical angle of laser scanner measurement points, representing an algebraic fit. Holst et al. [9] proposed the orthogonal distance regression (ODR) method, which directly linearizes the paraboloid itself (i.e., coordinates of points on the paraboloid) when establishing the data analysis model. ODR is a geometric fit with higher fitting accuracy and actual physical meaning, representing real deviation. Furthermore, based on the characteristic that focal length does not change with the spatial position and orientation of the rotating paraboloid [20], the stability of focal length obtained by the two methods is compared.

Figure 7 [Figure 7: see original paper] shows the variation of focal length when the paraboloid rotates 360° around the z-axis at different elevation angles using the CLS method. Table 3 lists the comparison results of the two methods, showing that the focal length obtained by the ODR method is very stable.

Note: The adjustment is performed within both classical least squares (CLS) and ODR.

5. Outlook

Laser scanner measurement of antenna structure deformation represents a primary development direction for future large antenna surface shape measurement methods. However, this method also has issues such as insufficient measurement accuracy, which is the main factor limiting its application in antenna structure deformation measurement. In addition to hoping that equipment manufacturers will improve measurement accuracy through better control of manufacturing processes, system and random errors can be minimized through the following approaches:

(1) **Optimize scanner installation position and method.** The installation position and method of the laser scanner largely determine the magnitude of measurement errors.

(2) **Perform system calibration through two-face measurement at different elevation angles in-situ.** By calibrating the laser scanner system at different elevation angles to obtain calibration parameters for each angle, this method can significantly reduce systematic errors.

(3) **Apply filtering and smoothing to reduce noise and decrease random errors.** During actual measurement, various human or environmental factors introduce noise into measurement results. Reducing or eliminating noise before modeling can improve the efficiency and quality of subsequent data processing.

(4) **Improve multi-station point cloud registration methods.** To obtain complete surface data of an object, multiple measurements from different viewpoints are sometimes required. The process of merging point clouds from various viewpoints into a unified coordinate system is called multi-station registration. Multi-station point cloud registration methods can be categorized into direct methods, feature-based methods, and auxiliary methods. Developing methods with simpler principles and more reliable registration results based on these three approaches will also contribute to improving laser scanner measurement accuracy.

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