Review of Surface Accuracy Measurement Methods for Large Radio Telescopes (Postprint)

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Abstract

Radio telescopes are essential equipment for astronomical observation and deep space exploration, currently developing toward large aperture and high-frequency bands. The surface accuracy of large radio telescopes is a critical metric affecting receiving performance. To clarify the characteristics of various surface accuracy measurement methods for large radio telescopes, these methods are categorized into four types: classical measurement, laser measurement, photogrammetry, and microwave holography; the principles and applications of each method are elaborated in detail, and their respective advantages and disadvantages are comparatively analyzed; finally, the development trends of surface accuracy measurement methods for large radio telescopes are discussed and prospected, providing inspiration for the continuous exploration and innovation of telescope surface accuracy measurement methods.

Full Text

A Review of Surface Accuracy Measurement Methods for Large Radio Telescopes

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Abstract: Radio telescopes are essential instruments for astronomical observation and deep space exploration, currently evolving toward larger apertures and higher operating frequencies. The surface accuracy of large radio telescopes is a critical parameter that directly affects receiving performance. To clarify the characteristics of various surface accuracy measurement methods for large radio telescopes, this paper categorizes these methods into four groups: classical measurement methods, laser measurement methods, photogrammetric methods, and microwave holography methods. The principles and applications of each surface measurement method are elaborated in detail, followed by a comparative analysis of their respective advantages and disadvantages. Finally, the development trends of surface accuracy measurement methods for large radio telescopes are discussed and 展望, providing inspiration for the continuous exploration and innovation of telescope surface measurement techniques.

Keywords: large radio telescope; surface accuracy; measurement method
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0 Introduction

Surface accuracy is a key performance indicator for radio telescopes, determining both antenna efficiency and the shortest observable wavelength. The relationship between observation wavelength , antenna efficiency , and surface accuracy is given by = exp[-(4 /)^2] [?]. For high-performance radio telescopes, surface accuracy typically must be less than 1/15 to 1/20 of the shortest observable wavelength [?], while measurement accuracy should reach 1/3 to 1/5 of the surface accuracy [?]. Clearly, shorter observation wavelengths and higher antenna efficiency requirements demand increasingly stringent surface measurement capabilities.

As radio telescope apertures continue to expand and operating frequencies rise, surface measurement methods have evolved to meet the growing demands of radio astronomy and deep space exploration. Early large radio telescopes such as the UK' s Lovell 76 m [?], Australia' s Parkes 64 m [?], Germany' s Effelsberg 100 m [?], and the Spanish-French MRT 30 m [?] initially employed theodolite-tape methods or their variants for surface measurement. Japan' s Nobeyama 45 m millimeter-wave radio telescope [?] began utilizing advanced total stations. More recent telescopes including the US GBT 100 m [?], Arecibo 305 m [?, ?], and China' s Miyun 50 m [?], Tianma 65 m [?], and FAST 500 m [?] have adopted more advanced techniques such as laser measurement, photogrammetry, or microwave holography for surface measurement and adjustment.

Reviewing the development history of surface measurement methods, approaches for large radio telescopes with apertures of 25 m or larger can be classified into four categories: classical measurement methods, laser measurement methods, photogrammetric methods, and microwave holography methods. This paper summarizes and analyzes the principles and applications of these four categories to provide insights for the ongoing exploration and innovation of telescope surface measurement techniques.

1.1 Classical Measurement Methods

Classical measurement methods primarily include theodolite-tape methods, theodolite system measurement methods, total station measurement methods, distance intersection measurement methods, and others. These methods are commonly employed during the initial installation of reflector surfaces for large radio telescopes both domestically and internationally.

1.1.1 Theodolite-Tape Method

The measurement principle is illustrated in [Figure 1: see original paper]. Metal tape scales with drilled holes are placed on the reflector surface with targets positioned at these holes. A theodolite placed at the vertex of the reflector then measures the angular positions of each target, enabling calculation of the spatial coordinate deviations of target points from the ideal paraboloid [?]. Through point-by-point measurement and subsequent data reduction, the root-mean-square (RMS) error of the reflector surface can be obtained. For large radio telescopes requiring hundreds or even thousands of target measurements, a complete survey typically takes 8–10 hours, making the measurement process extremely labor-intensive.

The MRT 30 m telescope at the International Radio Astronomy Institute achieved a single panel manufacturing accuracy of 0.03 mm [?], and using an improved theodolite-tape method, the overall reflector surface accuracy was measured to be 0.12 mm [?]. In the early 1970s, Germany completed the Effelsberg 100 m telescope, then the world’ s largest steerable radio telescope, which also initially employed the theodolite-tape method for surface measurement, achieving accuracy better than 1 mm within the central 80 m region [?].

1.1.2 Theodolite System Measurement Method

This method utilizes multiple high-precision electronic theodolites combined with various accessories and software systems to determine spatial point coordinates based on the principle of spatial forward intersection. [Figure 2: see original paper] shows the layout of a measurement system for a large antenna with a surface area of approximately 600 m^2, divided into two zones and surveyed by four T3000A theodolites. Before measurement, the spatial relative positions and orientations of the four theodolites are calibrated. After system orientation, theodolites 1 and 2 measure zone 1 while theodolites 3 and 4 measure zone 2. Based on the measured angles i and i, three-dimensional coordinates of points P1 and P2 can be obtained through data processing. The reflector surface adjusted using this method can achieve accuracy better than 0.5 mm [?].

When developing China’ s first multi-beam antenna, the 54th Research Institute of China Electronics Technology Group Corporation constructed a theodolite measurement system comprising T3000A and T2000S electronic theodolites, reference scales, data transmission cables, and portable computers, controlling the antenna surface accuracy to approximately 0.67 mm [?]. The Information Engineering University developed the MetroIn software for theodolite system measurement and applied it to real-time processing and analysis of measurement data during large radome installation to guide on-site assembly [?]. Reference [?] employed this method to measure gravitational deformation of a 25 m antenna reflector, obtaining a surface RMS of 0.5 mm.

1.1.3 Total Station Measurement Method

Total station measurement methods are widely applied in large antenna deformation measurement. Compared with theodolite system measurement methods, a single total station can perform all general measurement functions at lower cost. Additionally, this approach offers advantages including rapid system setup, short measurement time, and simple operation. The measurement principle is shown in [Figure 3: see original paper], where the three-dimensional coordinates of a point P on the antenna paraboloid are calculated by measuring the horizontal angle , vertical angle , and slope distance s (x = s cos sin , y = s cos cos , z = s sin).

During the installation and adjustment of Japan' s 45 m Nobeyama millimeter-wave radio telescope, total stations were used to control antenna surface accuracy to approximately 0.2 mm [?]. The Arecibo 305 m telescope, the world' s largest fixed radio telescope when constructed in the 1960s, also employed total stations for initial installation measurement, achieving an absolute control network accuracy of 1 mm [?]. In the early 21st century, the National Radio Astronomy Observatory constructed the 100 m GBT steerable radio telescope in Green Bank, which used a combination of total stations and theodolites during initial installation to achieve a surface accuracy of approximately 1.1 mm [?].

1.1.4 Distance Intersection Measurement Method

While theodolite systems and total stations are based on angular intersection measurement, the distance intersection method is based on distance intersection. Since angular errors affect results proportionally with measurement distance whereas distance errors do not, distance intersection methods generally achieve slightly higher precision. The principle is illustrated in [Figure 4: see original paper], where the measured point on the paraboloid does not lie on the plane formed by measurement points 1, 2, and 3. Using point 1 as the coordinate origin, the line connecting points 1 and 2 as the x-axis, and the normal to the plane formed by points 1, 2, and 3 passing through point 1 as the z-axis, the system is first calibrated. Observation equations are then established: measuring n points ($n > 6$) yields 4n observation equations with 3n+6 unknowns, which can be solved using least squares methods.

The National Radio Astronomy Observatory previously used three rangefinders for distance intersection measurement of GBT' s active surface, achieving absolute surface measurement accuracy better than 1 mm [?]. To understand deformation during antenna elevation rotation, engineers subsequently installed 12 specially designed rangefinders on the antenna foundation ground, as shown in [Figure 4: see original paper], improving ranging accuracy to 0.05 mm and controlling surface accuracy within 0.3 mm [?].

1.2 Laser Measurement Methods

Classical measurement methods are time-consuming and labor-intensive, with results heavily dependent on operator skill and emotional state. Laser measurement methods, along with photogrammetric and microwave holography methods, eliminate human factors from surface measurement and significantly improve measurement speed.

1.2.1 Laser Tracking Measurement Method

Laser trackers share the same measurement principle as total stations but differ in distance measurement, tracking methods, and structural design. A laser tracking measurement system consists of a laser tracker and a portable computer. A single laser tracker comprises five major components: angle measurement unit, distance measurement unit, tracking control unit, control unit, and support structure. Laser tracking measurement systems offer high precision, fast measurement speed, and minimal human influence.

The University of Science and Technology of China employed an API LTS-3000 laser tracking system to measure an antenna, achieving repeatability of 5 m/m within the measurement range and approximately 10 m/m when using absolute coordinate measurement [?]. The Information Engineering University developed secondary control software for Leica laser trackers based on the EmScon platform, solving the problem of automatic and rapid precise positioning of measurement points, and verified its accuracy and efficiency through simulation experiments [?]. In the 1970s, the Arecibo 305 m telescope attempted to use laser tracking measurement, but due to technical limitations at the time, measuring a single target position and its error required approximately 60 seconds, with achieved target position accuracy ranging from 0.8 mm to 2.7 mm [?].

1.2.2 Laser Scanning Measurement Method

Laser scanning measurement is essentially a distance measurement technique that can be categorized as either incoherent or coherent based on measurement principles. Incoherent methods measure laser time-of-flight, while coherent methods measure laser phase differences. Due to the extremely high speed of light, incoherent ranging has relatively low resolution for short to medium distances, whereas coherent ranging offers higher accuracy. Unlike laser tracking measurement, laser scanning does not require targets as cooperative objects, making it a non-contact measurement technique.

Several laser scanning products have been developed internationally, including Focus S350, IMAGER 5010C, and RIEGL VZ400. Reference [?] used RIEGL VZ400 to measure bridge deflection, achieving 1 cm accuracy when the farthest scanned bridge bottom was within 400 m of the instrument. Reference [?] investigated the application of 3D laser scanning technology to deformation monitoring and analysis of ancient buildings. Reference [?] studied the current status and development of 3D laser scanning technology, scanner principles, error sources, and point cloud registration, proposing that using identical points for point cloud registration with indirect adjustment can yield registration coordinates meeting accuracy requirements. Reference [?] attempted to use Riegl VZ400 to measure the backup structure of Tianma 65 m radio telescope, achieving good results within 30 m range. Although practical applications of laser scanners for large antenna surface measurement remain limited, the performance characteristics of developed products (as shown in) demonstrate significant potential for antenna measurement applications.

1.3 Photogrammetric Method

Photogrammetry is a universal method for deformation measurement of large structures and equipment. When applied to large radio telescope reflector measurement, the process involves: first, using one or two industrial cameras to capture two or more images of the antenna reflector from different positions, forming a stereo image pair [?]; second, employing image processing techniques to extract image plane information of the antenna reflector; and third, using coordinate transformation methods such as direct linear transformation, space resection-intersection, relative-absolute orientation, and bundle adjustment to determine the absolute positions of image points in the object space coordinate system, thereby reconstructing the three-dimensional information of the antenna reflector. [Figure 5: see original paper] illustrates the spatial coordinate transformation relationships in antenna reflector deformation detection based on close-range photogrammetry, showing the relationship between the photographed antenna reflector image (largest rectangular frame) and the actual deformed surface (curved portion).

The United States first applied photogrammetric technology to antenna measurement. During the Arecibo telescope upgrade, three photogrammetric surveys were conducted. The initial measurement was unsatisfactory, yielding a surface accuracy of 15 mm, significantly exceeding the estimated 3.2 mm [?]. Subsequent measurements using CRC1 industrial cameras achieved coordinate measurement accuracy of 0.25 mm [?]. In China, Wang Yong et al. applied photogrammetry to millimeter-wave and submillimeter-wave antenna surface measurement, achieving adjusted surface accuracies of 0.083 mm and 0.0055 mm, respectively [?]. Ma Kaifeng investigated close-range photogrammetry and data processing techniques for satellite antenna surface deformation under high and low temperature environments [?]. Li Zongchun et al. proposed using simulation data to verify photogrammetric accuracy, taking photography distance, station ring number, station interval, and image point error as input parameters and point position error as output to determine the optimal configuration for Tianma 65 m antenna photogrammetry [?]. Reference [?] employed photogrammetry to measure and adjust the Miyun 50 m antenna reflector surface at elevation angles of 7° and 30°, achieving adjusted surface accuracies within 2 mm.

1.4 Microwave Holography Method

Microwave holography is a systematic measurement approach that can eliminate other system errors, offering large measurement range, high precision, relatively fast measurement speed, and high automation. The principle for measuring antenna surface accuracy is illustrated in [Figure 6: see original paper]. For an ideal paraboloid, signals emitted from a source at the focal point reflect off the paraboloid and reach the aperture plane with equal optical path lengths (FP + P T = FP + P T). However, actual antenna reflectors are not ideal paraboloids, and a small normal error exists between the tangent plane of the ideal surface and that of the actual deformed surface at corresponding points. By measuring the phase or phase difference of signals from the emission source reaching various points on the aperture plane, the small differences between the actual antenna surface and the ideal paraboloid can be determined.

Research shows that phase values on the aperture plane can be measured indirectly based on the physical fact that a two-dimensional Fourier transform relationship exists between the aperture field and far-field of a paraboloid antenna [?]. Knowing the amplitude and phase of the antenna far-field in the complex plane allows theoretical derivation of the aperture field amplitude and phase, and vice versa. The mathematical relationship between far-field radiation T and small surface deformation is given by:

$$\varepsilon(x,y) = \frac{F^{-1}\left[\left\{1 + \frac{j\lambda}{4\pi}\text{Phase}\left[e^{-j2kF}\right]\right\} \cdot T(u,v)\right]}{2} \qquad (式\ 1)$$

where $F^{-1}[\cdot]$ denotes the two-dimensional inverse Fourier transform.

The theoretical measurement precision of microwave holography can be evaluated through the signal-to-noise ratio after cross-correlation [?]:

$$\varepsilon = \frac{\lambda}{4\pi} \cdot \frac{1}{\sqrt{N \cdot \text{SNR}_O}} \qquad (式\ 2)$$

where N is the square root of the number of points in the antenna grid scan, and SNR_O is the cross-correlation output signal-to-noise ratio when both the test antenna and reference antenna point toward the signal source.

Phase difference acquisition methods include phase-correlation and phase-retrieval approaches. The former requires far-field amplitude and phase distribution data, with the reference antenna continuously aligned to the signal source during measurement. The latter requires only far-field amplitude data without a reference antenna, with aperture field phase distribution iteratively derived from far-field amplitude characteristics through radiation models. Measurement quality depends on the phase-retrieval algorithm, with the Misell algorithm being commonly used [?]. This algorithm demonstrated excellent performance in MRT 30 m reflector surface measurement, achieving 0.02 mm accuracy [?]. Simulation analysis indicates that the surface accuracy recovered by the Misell algorithm can basically meet the requirements for the 110 m radio telescope under construction in Qitai, Xinjiang [?].

Microwave holography was proposed in the 1960s but was not applied to antenna surface measurement until 1977 when Scott et al. used it to measure a 5 km radio astronomy interferometer array antenna, achieving 0.1 mm surface accuracy [?]. Nishibori et al. applied this method to measure and adjust the UDSC 64 m radio telescope reflector, obtaining 0.54 mm surface accuracy [?]. In China, Wang Jinqing et al. used phase-correlation holography to measure the primary reflector of the Sheshan 25 m radio telescope, achieving 0.52 mm surface accuracy after panel adjustment [?], and subsequently applied the method to measure and adjust the active surface of Tianma 65 m radio telescope, improving surface RMS from 0.58 mm to 0.28 mm [?].

A summary of the measurable range, accuracy, measurement speed, and other characteristics of the four surface measurement method categories is presented in . Classical measurement methods are feasible for initial reflector installation but show significant limitations for subsequent panel adjustment and maintenance. Laser measurement, photogrammetry, and microwave holography partially or completely overcome the disadvantages of classical methods such as limited measurement range, low accuracy, slow speed, and target requirements. Among these, laser scanning offers the fastest measurement speed and enables full-elevation-angle measurement, while microwave holography provides systematic measurement (capable of correcting subreflector accuracy) with the largest measurement range, both showing promising application prospects.

2.2 Development Trend Analysis

Laser scanning, photogrammetry, and microwave holography represent the main development directions for large antenna surface measurement methods, yet several issues require resolution. The feasibility of laser scanning for large antenna surface measurement needs experimental verification. Photogrammetry typically requires photography distances within 100 m, making manual shooting and subsequent image mosaic processing complex for large-aperture antennas, while high accuracy demands numerous targets, increasing measurement preparation workload. Microwave holography typically uses geostationary satellites as signal sources, limiting antenna elevation angles, and its resolution is affected by signal source strength and reference antenna aperture. Additionally, all these methods are influenced by environmental factors including light, wind, temperature, and dust.

Future surface measurement methods will inevitably develop toward real-time or near-real-time, high-precision, automated systems with minimal environmental susceptibility. Photogrammetry can overcome shooting difficulties by employing industrial cameras carried by unmanned aerial vehicles. Microwave holography can achieve full-elevation measurement using broadband signals from specific radio sources, compensating for limitations of narrowband geostationary satellite signals. Integration of laser measurement with microwave holography can combine the advantages of both methods to further improve antenna surface measurement accuracy.

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