The Tianma 65 m Radio Telescope at Shanghai (Postprint)

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Abstract

The Shanghai Tianma 65 m radio telescope (TMRT) is a large, fully steerable radio telescope for multiple scientific applications. The telescope's main structure and four low-frequency receiving systems, including L, C, and S/X bands, were completed between 2008 and 2012. From 2013 to 2017, four high-frequency receiving systems, including Ku, K, Ka, and Q bands, were constructed and their performance comprehensively tested. The project features three major innovations: (1) construction of a fully steerable large radio telescope system with advanced performance and comprehensive functionality; (2) completion of an advanced and reliable main reflector adjustment system that overcomes gravitational deformation, achieving a main reflector surface accuracy of 0.28 mm (root mean square) at any elevation; and (3) development of five innovative technologies enabling high-precision pointing within 3 in any direction. The TMRT has made crucial contributions to the orbital measurement and positioning of China's lunar and deep space probes, significantly enhancing China's capability to participate in international VLBI observations and radio astronomy, and facilitating a series of achievements in observational radio astronomy research in areas such as VLBI, spectral lines, and pulsars.

Full Text

Preamble

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Abstract: The Shanghai Tianma 65 m radio telescope (TMRT) is a large, fully steerable radio telescope designed for multiple scientific purposes. The main telescope structure and four low-frequency receiving systems (L, C, and S/X bands) were completed between 2008 and 2012. From 2013 to 2017, four high-frequency receiving systems (Ku, K, Ka, and Q bands) were constructed and their performance comprehensively tested. The project achieved three main innovations: (1) Construction of a fully steerable large radio telescope system with advanced performance and complete functionality. (2) Development of an advanced, reliable main reflector adjustment system that overcomes gravity deformation, achieving a main reflector surface accuracy of 0.28 mm (root mean square) at any elevation angle. (3) Development of five innovative technologies to achieve high-precision pointing within 3 in any direction. The TMRT has made crucial contributions to the orbital measurement and positioning of China's lunar and deep space probes, significantly enhancing China's participation in international VLBI observations and radio astronomy research, and facilitating a series of achievements in observational radio astronomy across VLBI, spectral lines, and pulsars.

Keywords: Radio telescope; Tianma; Large antenna; Receiving system; Surface accuracy

1. INTRODUCTION

Large radio telescopes are key facilities in fields such as deep space navigation, astrophysics, and astrometry, occasionally leading to Nobel Prize-winning discoveries such as pulsars and the cosmic microwave background. Among all directional, steerable telescopes, major facilities have been constructed worldwide, including the Parkes 64 m telescope in Australia [1], the Effelsberg 100 m telescope in Germany [2], the 110 m Green Bank Telescope (GBT) in the United States [3], and the 64 m Sardinia Radio Telescope (SRT) in Italy [4]. As these international observatories commenced operation, China successively built the Shanghai 25 m, Xinjiang 25 m, Beijing 50 m, and Kunming 40 m telescopes. These four observatories, together with the Shanghai Data Processing Center, form the Very Long Baseline Interferometry (VLBI) Network, which serves as the lunar exploration VLBI orbit measurement subsystem and has made significant contributions to precision orbital measurements for the Chang'e missions. However, compared with the most advanced international observatories at the time, earlier Chinese radio telescopes suffered from small antenna apertures, low observation frequencies, and weak overall performance, which severely constrained China's ability to conduct lunar and deep space observations and undertake original research in radio astronomy.

The Chinese Academy of Sciences (CAS), Shanghai Municipality, and the Lunar Exploration Project jointly funded the development of China's first large-scale radio telescope system, the Shanghai 65 m radio telescope, also known as the TMRT (shown in Fig. 1 [Figure 1: see original paper]). Building a large radio telescope requires overcoming a series of technical challenges, including high-precision pointing, high receiving efficiency, low-temperature broadband reception, a complex and flexible control system, comprehensive performance testing, and gravity deformation correction. In collaboration with several research institutes, CAS successfully created multiple key technologies and built a fully steerable large-scale radio telescope system with advanced performance and complete functionality. The overall performance of the TMRT is on par with other advanced international radio observatories, greatly improving the orbital determination capabilities for China's lunar exploration satellites and deep space probes while providing international VLBI and radio astronomy observation capabilities.

Table 1 presents the main technical specifications of the TMRT. The antenna has a diameter of 65 m and operates across eight frequency bands (L, S, X, C, Ku, K, Ka, and Q) covering 1.25–50 GHz. As shown in Fig. 2 [Figure 2: see original paper], switching between different feed horns is accomplished using a rotating platform that brings the observation feed to the Cassegrain focus within a switching time of 1 minute. The main reflector comprises solid panels whose surface accuracy has been thoroughly measured. The accuracy of individual panels from rings 1 to 12 is better than 0.1 mm (RMS), while panels from rings 13 to 14 achieve better than 0.13 mm (RMS). Using the main reflector adjustment system installed between the antenna's backframe and panels, and based on a pre-established gravity deformation model, the main reflector accuracy can be adjusted to 0.3 mm (RMS) for elevation angles between 10° and 80°. The subreflector achieves better than 0.05 mm (RMS) for individual panels, with total subreflector accuracy of 0.053 mm (RMS). The six-bar parallel mechanism provides 5 degrees of freedom adjustment and, through a pre-established model, compensates for gravity deformation effects on the subreflector position, maintaining high efficiency at any elevation angle. The azimuth wheel track diameter is 42 m with surface unevenness of 0.45 mm, laying the foundation for achieving the final pointing accuracy of 3 .

The efficiency across all eight bands in the 1.25–50 GHz range exceeds 50% at any elevation angle. We have conducted integrated innovative technology research for large-scale radio telescopes, enabling China to fully master the key technologies for large radio telescope research and development. We have built a large-scale, high-performance radio telescope system with complete functionality and developed ten key technologies, including: (1) large-scale cooling antennas, receivers, active adjustment systems for the main reflector, spectral line/pulsar/VLBI observation systems, control software systems, and time-frequency systems; (2) installation of the overall welded track (shown in Fig. 1) on 144 cast-in-place pile foundations with a depth of 65 m, achieving track unevenness better than 0.5 mm on soft soil foundations to facilitate high-precision pointing; (3) simultaneous construction of the antenna mount, large elevation gear, and main reflector with overall lifting, completing large antenna construction within 3 years; (4) use of a six-bar parallel mechanism to precisely adjust the subreflector position and attitude, and development of an active adjustment system for the main reflector using phase reference holography and phase recovery holography to compensate for gravity deformation, ensuring high-precision pointing and high receiving efficiency—a method applicable to other large telescopes.

2. INNOVATION ACHIEVEMENTS

The TMRT has achieved numerous innovative research results during its development. This article highlights three main innovative achievements.

2.1. Successful Development of a Fully Steerable Large Radio Telescope

A fully steerable large radio telescope system with advanced performance and complete functionality has been built. We have solved key technological challenges including large high-precision antennas, active adjustment systems, and advanced control systems. We have developed eight sets of cooling receivers across eight bands with an observation bandwidth of 1.25–50 GHz. The independently developed K, Ka, and Q band dual-beam cooling receivers achieve performance comparable to advanced international radio astronomical facilities. Technical details about the receivers are presented in Table 2 . As shown in Fig. 3 [Figure 3: see original paper], the Shanghai Astronomical Observatory has independently developed L-band single-beam and K, Ka, and Q-band dual-beam circularly polarized cooling receivers operating at 1.25–1.75 GHz, 18–26.5 GHz, 26–40 GHz, and 35–50 GHz, respectively. Cooling components including feed horns, circular waveguide noise injection couplers, phase shifters, orthogonal mode couplers, and low-noise amplifiers to 20 K all work synergistically to greatly improve receiver sensitivity. The noise temperatures of the K, Ka, and Q band full-band receivers are 35 K, 30 K, and 40 K, respectively. The efficiency at high and low elevations exceeds 50%, with key technical indicators reaching the international first-class level. The powerful observation capabilities of the TMRT in the K, Ka, and Q bands have filled China's observation gap in the Q band (35–50 GHz), greatly expanding Chinese researchers' ability to observe spectral lines and participate in international VLBI joint observations.

By adopting advanced software architecture, we have developed a control software system consisting of hundreds of functional modules that facilitate automatic observation and telescope operation. We have implemented large-scale software architecture design, distributed remote control, and high-precision tracking control technologies. By fully utilizing information technology and Internet technology, adopting enterprise-level software design architecture, distributed model-view-controller design patterns, middleware, and other technologies, we independently developed more than 300,000 lines of software code and hundreds of functional modules, culminating in an internationally advanced control and observation software system capable of recording pulsar observations, spectral lines, continuous spectra, VLBI observations, performance measurements, status monitoring, and control functions.

We have developed advanced VLBI, spectral line, and pulsar observation systems, significantly improving China's lunar and deep space exploration VLBI orbital determination capabilities, as well as international VLBI observation and radio astronomical observation capabilities. As shown in Fig. 4 [Figure 4: see original paper], an advanced and complete VLBI observation system has been developed, enabling successful VLBI orbital measurements for the Chang'e-2, -3, -4, -5, -6, and Tianwen-1 space missions. The TMRT has become an important component of the international VLBI network with its ultra-high sensitivity, enhancing the overall observation capability of the international VLBI network. The TMRT has improved the mapping quality of East Asian VLBI by 53%, playing a crucial role in studies of dense celestial bodies such as black hole imaging and spin. We have developed advanced and complete spectral line and pulsar observation systems and independently developed advanced spectral line observation terminals, achieving a series of results in pulsar and spectral line radio astronomy research.

2.2. Developing an Advanced Main Reflector Adjustment System to Overcome Gravity Deformation

An advanced main reflector adjustment system has been built to overcome gravity deformation, achieving a large antenna with a surface accuracy of 0.28 mm (RMS) at any elevation. Adopting a high-precision welding track and six-bar parallel mechanism for subreflector adjustment and developing an active adjustment system for the main reflector of a large radio telescope, a comprehensive gravity deformation correction model was constructed using phase reference holography and phase recovery holography measurement techniques.

We have developed a microwave optical design method for high-sensitivity reflective antennas, including calculation methods for the optimal matching reflection surface of shaped dual-reflector antennas and a multi-band feeding method, solving technical problems related to high efficiency, low sidelobes, low noise, multi-band observation, low-loss feed networks, and high-performance cooling receivers. Performance for all eight bands with the large antenna has been excellent.

In response to the difficulties in designing the structure of a fully steerable ultra-large aperture reflector antenna, modern optimization theory and antenna structure conformal design methods were comprehensively applied to optimize the selection, layout, topology, and other aspects of the antenna backframe and center body. The optimal stiffness distribution and minimum subreflector support occlusion were achieved, reducing the weight of the main reflector backframe structure to 405 tons. The final surface accuracy of the main reflector approaches 0.28 mm (RMS).

A comprehensive method for achieving high pointing accuracy of large antennas has been proposed, which includes conformal design of antenna structure, active adjustment of the main reflector, real-time adjustment of the subreflector, high-precision antenna mount, digital high-precision servo control system, high-precision axis angle information transmission, high-precision design and manufacturing of welded track, high-precision installation and measurement of large antennas, multi-sensor pointing correction, and high-precision pointing calibration, achieving a pointing accuracy of 3 .

We have overcome the technical difficulties in designing and manufacturing antenna panels with large scale, high precision, and high reliability, achieving a surface accuracy better than 0.1 mm (RMS) for a single panel and laying the foundation for achieving 0.28 mm (RMS) surface accuracy for the overall main reflector.

We have developed an active adjustment system for the main reflector of a large radio telescope using phase reference holography and phase recovery holography to precisely measure gravity deformation and enable active correction. This has enabled the TMRT to achieve high efficiency at any elevation angle in all bands. The active adjustment system remotely controls the axial movement of 1,104 actuators distributed under 1,008 main reflector panels, achieving high-precision adjustment positions that compensate for main reflector deformation caused by gravity and significantly improve telescope receiving efficiency. As shown in Fig. 5 [Figure 5: see original paper], in the Q band, efficiency at low and high elevation angles can be reduced to below 20% without the active surface adjustment system due to gravity deformation. By using the active surface adjustment system with a pre-established model to compensate for gravity deformation, and by adopting key measures such as precision design of micrometer-level actuators based on size chain optimization, thermal compensation for actuator return gap based on finite element analysis, thermal error compensation for actuator travel based on a single hidden feedforward neural network, enhanced heat transfer design based on phase change materials, respiratory condensation suppression in enclosed chambers, mechanical probability allocation and designed redundancy based on operations research, and electromagnetic compatibility optimal design based on multi-port network systems, we have achieved breakthroughs in various key technologies for the main reflector active adjustment system. This enables high-precision real-time adjustment of up to 1,104 actuators across full elevation angles with positioning accuracy of 0.015 mm and response time of 1 s. The system has operated steadily for 12 years with a failure rate of approximately 0.3%.

The key technology for high-precision measurement and correction of gravity deformation of the main reflector uses a six-bar parallel mechanism to adjust the position and orientation of the subreflector, with phase reference holographic measurement achieving 0.1 mm accuracy. By inverting geostationary satellite signals and adjusting the main reflector using actuators, the main reflector error at a 52° elevation angle is reduced to 0.28 mm (RMS). The phase recovery holographic measurement system also achieves 0.1 mm accuracy, enabling high-precision compensation for gravity deformation of the main reflector at any elevation angle. The ultimate goal is to achieve reception efficiency exceeding 50% for all bands, including the Q band (35–50 GHz), at any elevation angle. It should be noted that these results were measured on a windy night; mechanical deformation caused by daytime temperature variations will affect high-frequency band receiving efficiency, which can be mitigated by remeasuring and compensating for the main reflector shape at regular intervals, such as once every 2 hours during the day.

2.3. Achieving 3 High-Precision Pointing

Pointing accuracy is a key technical indicator for large radio telescopes. As shown in Fig. 6 [Figure 6: see original paper], the TMRT has achieved a pointing accuracy of 3 through the comprehensive adoption of several innovative methods. We have implemented a fully digital, high-performance, and highly reliable servo control system architecture with multi-motor speed loop digital control clearance technology and advanced composite control strategies, achieving servo control accuracy of 0.54 . High-precision welding track technology has been adopted with track unevenness better than 0.5 mm. Inclinometers and temperature sensors are used to correct pointing errors caused by mechanical thermal deformation of the telescope. By using a six-bar parallel mechanism to adjust the position and attitude of the subreflector, we have achieved high-precision real-time adjustment of the subreflector surface for large-scale heavy loads under complex working conditions. A gravity deformation correction model for the subreflector support leg has been established through precise measurement, and the active adjustment system for the main reflector achieves quasi-real-time adjustment, ensuring high pointing accuracy and significantly reducing pointing errors. It should be noted that the pointing accuracy of 3 was obtained from tests on a windy night; during the day, temperature variations cause mechanical deformation and wind induces antenna shaking, which reduce pointing accuracy.

2.4. Comparison of Principal Properties of Five Telescopes

The performance of the Tianma 65 m, Parkes 64 m, Effelsberg 100 m, GBT 110 m, and SRT 64 m telescopes is compared in Table 3 . Receiving frequencies range from 0.3 to 115 GHz for the GBT, 0.3 to 115 GHz for the SRT, 0.3 to 95 GHz for Effelsberg, 0.7 to 26 GHz for Parkes, and 1.25 to 50 GHz for Tianma. The System Equivalent Flux Density (SEFD) is a comprehensive index for evaluating telescope receiving capability, with smaller SEFD indicating greater sensitivity. The GBT is generally the most sensitive, and Tianma is the second most sensitive in the Q band. The Shanghai Astronomical Observatory is also developing a K/Q/W tri-band cooling receiver for the TMRT, which is expected to enable reception up to 115 GHz.

3. APPLICATIONS

As the most sensitive station in China's VLBI network, the TMRT has completed VLBI observations for orbital determination of Chang'e-2 (Toutatis asteroid exploration), Chang'e-3 (lunar nearside soft landing), Chang'e-4 (lunar farside soft landing), Chang'e-5 (lunar nearside sample return), Chang'e-6 (lunar farside sample return), and Tianwen-1 (Mars exploration), making crucial contributions to the success of these missions. Fig. 7 [Figure 7: see original paper] shows the flight orbits of these spacecraft. The TMRT will continue to perform VLBI orbital determination and positioning for future probes such as Tianwen-2, -3, and -4, as well as Chang'e-7 and -8, serving as an essential facility for China's planned deep space exploration.

As an example, during the approximately 11-month Tianwen-1 mission (July 23, 2020 to June 18, 2021), a total of 198 VLBI observations were conducted. The VLBI residual time delay after each orbital determination is shown in Fig. 8 [Figure 8: see original paper]. During the initial launch period (July 23 to August 6, 2020) and the Mars landing measurement phase (May 7 to 30, 2021), daily VLBI observations began at 10° elevation. Combined with summer observation conditions, the VLBI time delay residuals were relatively large. During the initial launch period, residuals reached 0.64 ns on July 24, 2020, and 0.84 ns on July 26, 2020. The former was mainly caused by Tianwen-1's low-gain antenna transmission, while the latter resulted from attitude maneuvers creating large residuals after orbit determination. On May 30, 2021, after Mars landing, the residual time delay was 0.56 ns because observations were conducted only at low elevation angles of approximately 10°–25°, resulting in significant atmospheric and ionospheric time delay correction errors. The majority of other observations achieved delay residuals of less than 0.2 ns, often below 0.1 ns, after orbit determination. Typical observation durations were 4 hours, while the Mars capture period (February 3–28, 2021) required 8 hours. When scheduling measurements, selecting time periods with elevation angles above 20° greatly reduces atmospheric and ionospheric time delay correction errors. Dominant factors affecting time delay residuals are atmospheric and ionospheric correction errors at low elevation angles, along with weather influences such as wind, rain, snow, and ice. The average residual value for 198 VLBI observations is 0.11 ns, while for high-elevation arcs above 25°, it is generally approximately 0.05 ns, close to NASA's VLBI time delay residual of 0.04 ns.

The TMRT has become an important station in the international VLBI network with its ultra-high sensitivity, significantly improving the overall observation capability of the international VLBI network and China's VLBI visibility. The TMRT has improved the imaging quality of the East Asian VLBI network by 53%, playing a crucial role in studies of dense celestial bodies such as black holes and making significant contributions to the world's first calibration of black hole imaging flux and confirmation of black hole spin. The TMRT has participated in international VLBI joint surveys, obtained unprecedented multi-band synchronous observation results for galaxy M87, played a backbone role in the European VLBI network, and been selected as a reference station multiple times.

Analysis of VLBI observation data from 2000 to 2022 revealed that the black hole jet at the center of the M87 galaxy exhibits periodic precession [8] with a period of approximately 11 years and amplitude of about 10°. This achievement successfully links the dynamics of the black hole jet with the state of the supermassive black hole at the center of the M87 galaxy, providing observational evidence for the existence of spin in the M87 black hole. This work utilized data from 170 observations recorded by multiple international networks, including the East Asian VLBI network, the Very Long Baseline Array from the United States, the Korean VLBI Network (KVN) and Japanese VLBI Exploration of Radio Astrometry (VERA) Joint Array, and the East Asia To Italy: Nearly Global VLBI (EATING VLBI)/Russia joint observation network. The TMRT has made a crucial contribution as the highest-sensitivity component of the East Asian VLBI network, with receiving capacity accounting for 50% of the entire network.

A series of achievements have been made in radio astronomy research on pulsars and spectral lines. In pulsar observations, this has involved recording radio bursts from magnetars near the central black hole of the Milky Way galaxy. For the first time, integrated profiles of 11 pulsars were measured in the X band, and many pulsars have been detected, including the shortest known millisecond pulsar in the northern hemisphere. In spectral line research, spectral line searches have been completed for the Q and Ka bands toward Orion in the largest and most sensitive spectral line survey to date, discovering 21 new astrophysical molecules. The detection of abundant ethanol aldehydes and ethylene glycol at the center of the Milky Way provides direct evidence for complex organic molecules distributed in the galactic center. The most comprehensive methanol maser source catalog to date has also been completed, including 35 new detections.

Preliminary Q-band observations were conducted on the Orion KL celestial body using the TMRT [9], completing spectral line search work for the maximum bandwidth (35–50 GHz) and highest sensitivity (mK level) in this band. Approximately 600 emission lines were detected, with 177 radio recombination lines and 371 molecular spectral lines successfully identified. Among the 53 molecular species detected by the TMRT, 21 were previously undetected in the Q band toward Orion KL. Most of the detected molecular species are complex organic molecules, which are essential precursors in the formation of prebiotic molecules.

Since 2017, the TMRT has been open to the public. Chinese and international scientists have made extensive use of the facility. To further improve the telescope's observational capabilities, the Shanghai Astronomical Observatory is developing the K/Q/W tri-frequency cooling receiver, the K-band 7-beam cooling receiver, and a new spectral line observation terminal.

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AUTHOR CONTRIBUTIONS

Qinghui Liu, Zhiqiang Shen, and Xiaoyu Hong are responsible for the overall telescope technology. Qian Ye developed the active surface system. Bin Li and Weiye Zhong developed the receivers. Jinqing Wang developed the test system. Rongbing Zhao developed the control software. Li Fu studied mechanical systems. Lingling Wang developed time-frequency systems. Juan Li was responsible for spectral line observations. Zhen Yan conducted pulsar observations. Wu Jiang performed VLBI observations. Bo Xia managed observation operations. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

4. CONCLUSION

The TMRT is a large, fully steerable radio telescope for various scientific purposes, with observation capabilities in eight bands: L, C, S, X, Ku, K, Ka, and Q. Innovative achievements have been made in telescope development and application, including fully steerable large radio telescope systems, main reflector adjustment systems, and high-precision pointing. These achievements are also of great significance for the research and development of other large radio telescopes.

The TMRT has completed VLBI orbital measurement and positioning observations for the Chang'e series of spacecraft and the Tianwen-1 Mars lander, making crucial contributions to China's lunar and deep space missions. The TMRT will continue to participate in VLBI orbital measurement and positioning tasks for planned future lunar and deep space probes. To increase frequency coverage and improve observation capabilities, more large multi-band radio telescopes will further enhance China's observational capabilities in the future.

A series of achievements have been made in radio astronomical observations, VLBI, spectral lines, and pulsars, including confirmation of periodic precession of black hole jets in the M87 galaxy and Q-band spectral line searches in Orion. Since 2017, the TMRT has been open to the public, serving as an important facility for both Chinese and international scientists.

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