The time and frequency system of the Tianma 65 m radio telescope (Postprint)

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Full Text

Preamble

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The Time and Frequency System of the Tianma 65 m Radio Telescope

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Abstract: A time and frequency system is a critical component of Very Long Baseline Interferometry (VLBI) stations, providing stable and reliable standards that directly impact data processing quality. At the Tianma 65 m radio telescope (TMRT), this system has been meticulously designed to ensure long-term reliability and high performance. It incorporates high-performance hydrogen atomic clocks, high-precision time standards, automatic signal switching, and robust system software. This comprehensive approach has enabled the system to achieve long-term reliable operation, successfully supporting both major national engineering tasks and daily scientific observations. The effectiveness of the system is evidenced by its consistent delivery of the precision and stability required for radio astronomy. This article provides an in-depth exploration of the design and operation of the time and frequency system at the Tianma 65 m telescope, examining various aspects of its architecture, implementation, and performance. By sharing these insights, we aim to contribute knowledge that could benefit similar systems at other VLBI stations, greatly advancing radio astronomy infrastructure.

Keywords: Time and frequency system; Hydrogen atomic clock; Reliability

1. INTRODUCTION

Time and frequency precision are crucial in radio astronomy observations, particularly in Very Long Baseline Interferometry (VLBI). The essence of VLBI lies in measuring the time difference between radio signals arriving at different antennas from deep space sources. This technique demands high-precision frequency standards, a requirement that becomes evident when considering the basic principles of VLBI. The signals in question are noisy radio emissions from distant cosmic sources, detected by antennas that may be separated by vast distances, even positioned on opposite sides of the Earth. These antennas must accurately record the arrival time of the same wavefront, necessitating strict synchronization between the clocks at each station. Any discrepancy in clock synchronization, no matter how minor, can significantly impact measurement accuracy, potentially compromising the integrity of the observations[**?**].

Accurate timing of signal arrival is crucial, as VLBI measures the minuscule differences in arrival times of radio waves from distant astronomical sources at different antennas, necessitating extremely precise timing at each antenna site. Additionally, precise local oscillators are vital, because the frequency standards serve as references for the local oscillators used to downconvert the received radio signals from radio frequency (RF) to intermediate frequency (IF) and then to baseband frequency (BF) signals. Any instability in this process directly impacts measurement accuracy. Finally, data timestamping is imperative; the recorded data at each telescope must be precisely timestamped to allow proper correlation later, requiring the end system to use high-precision time and frequency references[**?**].

The time and frequency system plays a crucial role in providing precise standards for the station. To meet the stringent requirements of VLBI observations, hydrogen maser atomic clocks are employed as the primary frequency standard reference now. These sophisticated clocks offer dual benefits: exceptional short-term stability, which is essential for maintaining phase coherence during observations, and remarkable long-term stability, crucial for ensuring synchronization over extended observation periods. This combination of short-term precision and long-term reliability makes hydrogen maser atomic clocks ideally suited to the demanding needs of high-precision radio astronomy, particularly in VLBI observations where timing accuracy is paramount.

Typically, the time and frequency system of a VLBI station consists only of a hydrogen clock, Global Positioning System (GPS) receiver, and time interval counter, which provide the frequency standard and time synchronization mentioned above.

In 2012, the TMRT was officially completed under the leadership of the Shanghai Astronomical Observatory, CAS. As the first large-scale radio telescope in China with advanced performance and comprehensive functionality, the TMRT system has achieved advanced levels of performance on par with internationally renowned radio observatories[**?**]. Beyond routine astronomical observations, it has also participated in significant space missions, including lunar and Mars exploration.

The design of the time and frequency system for the TMRT prioritizes stability, reliability, and high performance, which has introduced new construction requirements for the system. To meet these demands, we focused on several key aspects:

(1) **Double backup high-performance atomic frequency standard:** The TMRT employs a high-performance atomic frequency standard in the form of a hydrogen maser atomic clock, which is known for its exceptional stability and precision. Hydrogen masers provide a stable frequency reference with minimal drift, ensuring consistent performance over long observation periods, which is crucial for maintaining the synchronization required for VLBI and other high-precision timing observations.

(2) **High-standard system operating environment:** The operating environment for the time and frequency system at the TMRT is designed to ensure stability and reliability. This includes temperature control, vibration isolation, and electromagnetic shielding to minimize any external

factors that could affect the performance of the frequency standards. This environment is meticulously controlled to maintain the high level of precision required for astronomical observations and space missions.

(3) **Automatic switching of signal output:** The system is able to automatically switch the frequency standard, allowing multiple standards to be used, with smooth switching via a single button. Automatic switching is a faster process, which also reduces the probability of misoperation, greatly improving system reliability[**?**].

(4) **Modular high-reliability system software design:** The software architecture of the TMRT time and frequency system is modular and designed for reliability. This modular approach facilitates easier maintenance, upgrades, and troubleshooting. Each module can be independently tested and verified, ensuring that the overall system remains robust and reliable. The software design also includes features for real-time monitoring and diagnostics, which help in maintaining system performance and quickly addressing any issues that may arise.

Based on these principles, the time and frequency system of the TMRT has been operating continuously since its completion, providing high-performance, reliable frequency and time standards. This continuous operation has significantly contributed to the scientific output of the telescope and the successful completion of space exploration missions.

This paper introduces all aspects of the time and frequency system of the TMRT, from design to operation at the system level, in order to provide a reference for the construction of similar time and frequency systems at other stations.

2.1. Atomic Frequency Standard

In the 1930s, in pursuit of greater precision in time and frequency measurement, scientists shifted their focus from the macroscopic to the microscopic world, seeking a new foundation for timekeeping. This shift led to a breakthrough in the 1950s with the development of the world's first ammonia molecular maser oscillator. Subsequently, various types of atomic clocks emerged, including cesium, rubidium, and hydrogen atomic clocks. This progression has been significant in quantum radio physics, revolutionizing our ability to measure time with unprecedented accuracy[**?**].

Atomic clocks generate stable and accurate frequencies based on the principle of atomic energy level transitions. Different types of atomic clocks, such as cesium, rubidium, and hydrogen atomic clocks, each have their own advantages and disadvantages. Among these, hydrogen atomic clocks are particularly favored by VLBI stations due to their superior stability, which can reach 10^{-14} per second and 10^{-15} or even 10^{-16} per day, making the hydrogen atomic clock the standard for VLBI operations.

The characterization of the frequency standard stability index is usually described by the Allan variance, which generally requires a phase error caused by frequency instability of less than 1 radian in VLBI, that is,

$$2\pi f\tau\sigma_y \leq 1 \text{ radian},$$

where f is the observation frequency, τ is the integration time, and σ_y is the Allan variance. The higher the frequency and the longer the integration time, the smaller the Allan variance value needs to be, which means a higher requirement for stability[**?**, **?**]. Consequently, we choose the hydrogen atomic clock as the frequency source, aiming for its stability index to be as high as possible.

The stability of the primary hydrogen clock we currently use, along with tested values provided by a third-party agency, are presented in Table 1 .

The time and frequency system of the TMRT continuously monitors and measures the offset between second signals from the hydrogen clock and those of the Global Navigation Satellite System (GNSS) over extended periods. Through analysis of this data, the operational status of the hydrogen atomic clock can be assessed. Since the system was established in 2012, four clocks have been employed over 11 years, with each clock generating an average of 920,000 data points annually. The following data represent the performance of two of these clocks over the years, clearly illustrating the distinct operational characteristics of each clock.

Fig. 1 [Figure 1: see original paper] (A) illustrates the clock offset data for the hydrogen clock designated H88 over an eight-year period. Manufactured in 2009, this clock commenced operation in late 2013 and was decommissioned at the end of 2021. The graph reveals multiple instances of anomalous data, several of which can be attributed to hydrogen clock malfunctions. Specifically, the clock experienced three episodes of hydrogen depletion and one ionization source failure. These incidents underscore the crucial role of hydrogen retention in maintaining optimal clock performance. While earlier models relied on hydrogen bottles for storage, recent technological advancements have led to a new process that ensures an adequate hydrogen supply throughout the operational lifespan of the clock, thereby eliminating the need for hydrogen bottle replacements.

Fig. 1 (B) shows the performance of the hydrogen clock designated H0, which has been in continuous operation since its deployment in 2018. Apart from a brief interruption due to a power outage and an air conditioning failure, the data indicate that this clock has been functioning smoothly throughout its operation.

Fig. 1 (C) presents the primary clock data from 2017 to 2022. The graph reveals several distinct changes or transitions in the data, each corresponding to the replacement of different hydrogen clocks during this timeframe. These transitions clearly demarcate the operational periods of successive hydrogen clocks used in the system.

2.2. Automatic Signal Switching

As previously mentioned, hydrogen atomic clocks are crucial to the time and frequency system and the overall functionality of the telescope. A serious failure in these clocks can result in catastrophic data loss. To enhance reliability, each of our stations is equipped with two hydrogen atomic clocks—one as the primary and the other as a backup—to ensure the continuity of observation missions.

However, the initial design of the master-slave switching mechanism is relatively rudimentary. The selection of the active hydrogen clock is based solely on cable connections, necessitating manual intervention for multi-way wiring between devices during a switch. This process leads to prolonged switching times and requires adjustments to the data processing model. In severe cases, this can result in the loss of several hours' worth of valuable data[?].

To achieve more convenient and efficient signal switching while minimizing data loss, we investigate automatic switching methods and develop an automated time and frequency switching system for the VLBI station. Fig. 2 [Figure 2: see original paper] presents a schematic diagram of this system.

The implemented automatic switching system has demonstrated excellent performance during subsequent space exploration missions. It has played a crucial role in managing time-frequency signal transitions necessitated by unexpected failures of the hydrogen atomic clock. This system has been instrumental in ensuring the continuity of related data processing, thereby significantly enhancing the reliability and efficiency of our operations.

2.3. Operating Environment

The time and frequency system includes hydrogen atomic clocks and other time-comparison equipment. Environmental changes can significantly impact the status and performance of this equipment, thereby affecting the entire system. The microwave resonant cavity output frequency of the hydrogen atomic clock, as the most critical component in the system, is particularly susceptible to interference from external environmental changes, such as fluctuations in magnetic fields and temperature. To mitigate these effects, the hydrogen clock requires a highly controlled working environment, including a temperature control accuracy of $±$0.2 °C, and must be kept away from sources of vibration, radiation, and electromagnetic interference. Specific requirements may vary depending on the temperature and magnetic field sensitivity of different hydrogen atomic clocks.

Although hydrogen atomic clocks theoretically exhibit very high stability, practical applications often fall short of these theoretical performance levels. This discrepancy can be attributed to two main factors. First, the lack of higher-performance frequency references for onsite detection makes it challenging to accurately measure the true condition of the clock. Secondly, the working environment in real-world applications often does not meet the same stringent standards maintained in laboratory-based hydrogen atomic clocks.

To ensure the stable operation of the time and frequency system equipment, we provide an optimal working environment with updated air conditioning equipment, renovated insulation walls, provided a continuous and uninterrupted power supply, and focused on ambient temperature control. The hydrogen atomic clock operates in a specially designed shielding room with constant temperature and humidity, while other equipment is housed in a room maintained at a constant temperature and level of humidity. All equipment is supported by an Uninterrupted Power Supply (UPS) system.

Fig. 3 [Figure 3: see original paper] shows an example of the clock room temperature in 2021. The data show noticeable changes at the beginning of the period, caused by the transformation and commissioning maintenance of the air conditioning equipment and power outages. However, the data stabilizes significantly in the later period, indicating a return to optimal operating conditions.

Correspondingly, temperature fluctuations inevitably lead to variations in the data within the hydrogen clock. Fig. 4 [Figure 4: see original paper] presents three datasets from one of the clocks in the same period, demonstrating a strong correlation with changes in ambient temperature. The specific impact of temperature fluctuations depends on the temperature sensitivity of the equipment, which typically ranges from $8 \times 10^{-16}/°C$ to $3 \times 10^{-14}/°C$. At the same time, the clock offset data also changes, showing the significant impact of temperature variation on the atomic clock.

In addition to hydrogen atomic clocks, any device containing a constant temperature crystal oscillator will be sensitive to ambient temperature. Consequently, when installing the device, we must ensure that it is not placed near the air conditioner outlet, that is, the outlet should not be directly facing the device.

Fig. 5 [Figure 5: see original paper] shows clock data from November 26, 2013, containing some obviously abnormal periodic changes. Here, the location of the device was very close to the air conditioner outlet, and the change cycle trended strongly toward the law of air volume change. The device was later covered and protected, and the direction of the air outlet was adjusted, improving the situation rapidly.

To overcome environmental effects, especially thermal and magnetic, the design of the hydrogen atomic clock incorporates magnetic shielding and constant temperature control. For example, multi-layer permalloy shielding and dual-layer constant temperature furnaces are used to maintain temperature control within 1%. Magnetic shields reduce the magnetic sensitivity of the maser, and a multi-level system decreases temperature sensitivity significantly. The magnetic shield uses four layers of shielding and insulation (as shown in Fig. 6 [Figure 6: see original paper]).

2.4. System Software Design

The time and frequency system needs to operate stably for a long time to reliably output high-precision time and frequency standards. In addition to monitoring the operating status of each device, the system software is responsible for collecting and recording clock error information, so it also needs to operate stably and reliably.

Reliability, one of the six key characteristics of software quality, encompasses maturity, fault-tolerance, and recoverability[**?**]. The TMRT time and frequency system software was meticulously designed with these aspects in mind, prioritizing robust and dependable operation.

The system architecture adopts a mature modular design, as illustrated in Fig. 7 [Figure 7: see original paper], with an emphasis on keeping module sizes as small as possible. This approach enhances maintainability and reduces the potential for errors. Each device control and monitoring module operates independently through multi-threading technology, ensuring that issues in one module do not compromise the entire system.

Data integrity and accessibility are ensured through dual storage methods: relational databases and ordinary files. This redundancy facilitates easy querying and processing while safeguarding against data loss. The software is designed to handle communication or data format anomalies gracefully, maintaining normal operation even in the event of device abnormalities. It issues warnings correctly and promptly, and can self-repair in the event of occasional anomalies. Extensive demand analysis and rigorous testing are conducted to account for various functional requirements and potential operational scenarios, ensuring comprehensive coverage of system needs.

To further enhance system reliability and minimize user error, the software interface design prioritizes simplicity and clarity. Important operations require confirmation before execution, adding an extra layer of protection against unintended actions.

In addition to reliability considerations, the modular design adopted by this software also makes it very scalable and widely applicable. For example, the data acquisition module shown in Fig. 7 has the same module architecture for different devices, and the only difference is the communication protocols. For the time and frequency systems of a different VLBI station, the software modules can be easily replaced and installed.

This approach to software design and implementation not only meets the high standards required for the TMRT time and frequency system but also provides a robust, user-friendly, and reliable reference for other astronomical applications.

2.5. Data Analysis

The analysis of clock offset data is crucial for verifying the operational status of hydrogen clocks. However, this data can be influenced by various factors, necessitating meticulous processing to ensure accurate results.

During system operation, data anomalies may occur due to a variety of causes. These can include clock malfunctions, environmental temperature fluctuations, manual adjustments, power interruptions, and sampling irregularities. Each scenario requires appropriate handling based on its specific circumstances, because the nature and extent of the anomaly can significantly impact the interpretation of the data.

Aside from hydrogen atomic clock failure, data discontinuities may also result due to various factors. For instance, acquisition software malfunctions, counter failures in measuring clock offsets, or GNSS reference errors can all lead to gaps or inconsistencies in the data. In these cases, remedial actions are necessary. To maintain data integrity, clock offset values can be manually adjusted to appropriate positions, or missing data can be interpolated to restore continuity.

Considering the methods for preventing and addressing issues related to various factors, we have taken several actions. We ensure the continuous operation of the software by conducting thorough testing to eliminate potential failure risks and maintaining the computer in good working condition. During task execution, we configure a backup computer and establish a personnel monitoring system to regularly check software performance and data recording, allowing us to promptly identify and troubleshoot any issues.

We also focus on ensuring the communication status of devices by selecting reliable network cables and paying special attention to the quality of the connectors. Real-time monitoring of device communication status is implemented, with the software configured to trigger interruption alarms and include reconnection features.

Additionally, we ensure the quality of output signals from devices by regularly using instruments to verify that the output signals meet system requirements. This prevents data measurement failures caused by poor signal quality.

When analyzing hydrogen atomic clock performance, the approach to handling missing data depends on specific analysis goals and the nature of the discontinuity. In some cases, such missing data can be ignored if it does not significantly impact the overall analysis. Alternatively, interpolation methods can be employed to fill these gaps, providing a more complete dataset for analysis. The choice between these approaches depends on factors such as the duration of the missing data, the stability of the clock during the surrounding periods, and the specific requirements of the analysis being conducted[**?**].

As shown in Section 2.1, Fig. 1, which presents data spanning an eight-year period, reveals poor continuity in that clock performance. This lack of consistent data suggests suboptimal operational stability, highlighting the challenges faced in maintaining long-term clock reliability.

Clock offset analysis is a critical process that involves comparing the station's hydrogen atomic clock with the international standard time system, using GNSS as a reference. This comparison is fundamental to understanding clock performance and ensuring synchronization with global time standards. Generally, the clock offset exhibits a linear change over time, with the slope of this change defined as the clock rate. This rate is a key indicator of clock performance, as variations in the clock rate over extended periods reflect the degree of frequency drift in the hydrogen clock. Such drifts are crucial to monitor and understand because they can significantly impact the accuracy of time-sensitive astronomical observations.

In VLBI data processing, the recent clock rate plays a vital role as an initial reference for data preprocessing. This rate is calculated in real-time, typically using data from the most recent ten-day period. However, the calculation period is not fixed and can be adjusted based on observed clock behavior. If the data demonstrates long-term continuity and the hydrogen clock exhibits stable operation, the calculation period may be extended to as long as a month. This flexibility in the calculation period allows for a more accurate representation of the clock's current behavior, balancing the need for recent data with the benefits of a longer-term perspective on clock stability.

Clock offset data are crucial for error modeling in VLBI data processing, in which higher precision facilitates quicker fringe processing. Generally, research in this area focuses on two main approaches: improving equipment output signal performance, such as enhancing 1PPS output synchronization accuracy, and optimizing data acquisition and processing by increasing sampling frequency, optimizing algorithms, and adjusting filtering thresholds.

Through these efforts, our system performance has been greatly improved. Fig. 8 [Figure 8: see original paper] illustrates the difference before and after the system upgrade in 2022, using clock offset residual data. A comparison of pre- and post-upgrade data reveals a five-fold decrease in jitter and a reduction in Mean Square Error (MSE) by several orders of magnitude. These improvements underscore the effectiveness of the upgrade in enhancing measurement precision and stability.

3. CONCLUSIONS

The TMRT time and frequency system has been operational for over a decade, during which time significant efforts have been made to consistently provide high-precision time and frequency standards. These efforts encompass a wide range of improvements, reflecting a comprehensive approach to system enhancement and reliability.

Key areas of focus have included ensuring a high-quality equipment operating environment, implementing automatic signal switching, and applying fault prediction technology. Additionally, we have concentrated on simplifying the system architecture, enhancing equipment performance, streamlining user operations, and optimizing data processing algorithms. This multifaceted approach has not only improved the current system's reliability and precision but has also yielded valuable insights for future development.

The experience gained through these initiatives has proven uniquely useful, providing a solid foundation for the design and construction of next-generation time and frequency systems.

As we look ahead, the advancements made in the TMRT time and frequency system will continue to play a crucial role in the development of new stations. The accumulated knowledge and expertise will inform the design, implementation, and operation of time and frequency systems in future facilities, ensuring that they meet the ever-increasing demands for precision and reliability in scientific observations.

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AUTHOR CONTRIBUTIONS

Lingling Wang conceived the ideas, designed and implemented the study, and wrote the paper. Qinghui Liu provided suggestions for the paper structure. Yong Cai provided details of the hydrogen atomic clock. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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