

Article

A High-Precision Frequency Synchronization Method Based on a Novel Geostationary Communication Satellite Phase-Locked Transponder

Xueyi Tang ^{1,2} , Chenhao Yan ^{1,2}, Haiyuan Sun ^{1,2}, Lijiaoyue Meng ^{1,2}, Yibin He ^{1,2}, Rui Liu ^{1,2} , Shiguang Wang ^{1,2,*}  and Lijun Wang ^{1,2,3}

- ¹ Department of Precision Instrument, Tsinghua University, Beijing 100084, China; xy-tang20@mails.tsinghua.edu.cn (X.T.); yanch19@tsinghua.org.cn (C.Y.); shy22@mails.tsinghua.edu.cn (H.S.); mljy21@mails.tsinghua.edu.cn (L.M.); hyb23@mails.tsinghua.edu.cn (Y.H.); liu-r24@mails.tsinghua.edu.cn (R.L.); lwan@tsinghua.edu.cn (L.W.)
² State Key Laboratory of Precision Space-Time Information Sensing Technology, Beijing 100084, China
³ Department of Physics, Tsinghua University, Beijing 100091, China
* Correspondence: wangsg@tsinghua.edu.cn

Abstract: Equipping satellites with a series of high-precision frequency references is essential; however, even advanced active hydrogen masers can often be too heavy and expensive for the current satellite payload constraints. Moreover, in geostationary Earth-orbit communication satellites lacking atomic clocks, onboard oscillators can degrade the performance of time–frequency transmission methods. To address these challenges, this study proposes a novel phase-locked transponder that leverages Einstein’s synchronization theory and real-time carrier-phase compensation to improve the transmission performance of satellite frequency transfer systems while mitigating the noise from onboard satellite oscillators. Notably, this requires only simple modifications to the existing transponder structure. By replicating the high-precision atomic frequency standards from ground stations to satellites, the proposed system achieves enhanced frequency synchronization without additional onboard clocks. The feasibility of the satellite-to-ground link was validated through both a theoretical analysis and an experimental verification. Specifically, ground experiments demonstrated a reproducibility of 6.33 ps (1σ) over a 24 h period, with a long-term frequency stability of 3.36×10^{-16} at an average time of 10,000 s under dynamic conditions, showcasing the potential of this approach for advanced frequency synchronization. This paper presents a cost-effective and scalable solution for enhancing frequency synchronization in geostationary satellites, improving communication reliability, supporting advanced scientific and navigational applications, and enabling the development of high-precision, space-air-ground integrated time–frequency synchronization networks.

Keywords: carrier phase; Einstein synchronization; frequency transfer; geostationary satellite; satellite transponder



Academic Editor: Massimiliano Pieraccini

Received: 13 February 2025

Revised: 28 March 2025

Accepted: 1 April 2025

Published: 3 April 2025

Citation: Tang, X.; Yan, C.; Sun, H.; Meng, L.; He, Y.; Liu, R.; Wang, S.; Wang, L. A High-Precision Frequency Synchronization Method Based on a Novel Geostationary Communication Satellite Phase-Locked Transponder. *Remote Sens.* **2025**, *17*, 1280. <https://doi.org/10.3390/rs17071280>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The importance of artificial satellites in the modern society is increasing owing to their pivotal role in communication, navigation, and remote sensing applications in daily life, industrial production, scientific research, and innumerable other domains [1–4]. To guarantee navigational and scientific operational precision, satellite payloads must be equipped with high-precision frequency or time references [5]. The time–frequency output of the satellite’s onboard clock is a reference for the satellite ephemeris data and various onboard radio

frequency (RF) and digital systems [6]. Currently, the high-precision frequency standards in space contribute considerably to solving astronomical issues pertaining to far-infrared, submillimeter, and millimeter wavelength ranges. This enables astronomers to observe the universe with unparalleled sensitivity and angular resolution [7,8].

A prevalent approach to enhance the performance of spaceborne time and frequency references is to use onboard atomic clocks. Over time, the number of satellites equipped with atomic clocks has increased considerably, particularly for navigational applications [9]. The performance of these onboard atomic clocks directly determines the accuracy of navigational and positioning systems and is crucial for their precision and stability [10–12]. Navigation satellites, such as the Global Positioning System (GPS), GLONASS, BeiDou, and Galileo, are equipped with a cesium frequency standard (CFS), rubidium frequency standard (RFS), and passive hydrogen maser (PHM), which are fundamental to their time–frequency systems [13,14]. The stability of these frequency sources has been evaluated using the Allan variance, a statistical measure for assessing the stability of frequency sources. In this context, the frequency stability of the CFS on GLONASS R17 can reach 3×10^{-14} after averaging for approximately 16 h. The RFS on the GPS yields a 3×10^{-15} 24 h frequency stability. The BeiDou PHM yields a 7×10^{-15} 24 h frequency stability [15].

Despite advances in atomic clock miniaturization technology, balancing performance, size, and power consumption remains a challenge. Active hydrogen masers (AHMs), while offering exceptional short- and medium-term frequency stability—reaching levels such as 1.27×10^{-15} at 10,000 s—are still constrained by their inherent physical size and environmental sensitivity. The microwave cavities in these systems occupy a large portion of the device volume. Although efforts have been made to reduce cavity size using new materials, current compact AHMs currently deployed aboard the Chinese space station still weigh around 35–40 kg and consume approximately 70 W of power [16]. These specifications, while improved over traditional laboratory-grade masers, still limit their integration into standard GEO communication satellite platforms or conventional GNSS satellite platforms.

In contrast, optical clocks have demonstrated superior short- and medium-term frequency stability due to their high interrogation frequencies and ultra-narrow linewidths. They offer promising performance that could exceed that of traditional microwave atomic clocks by one to two orders of magnitude [17]. However, realizing these advantages in space remains challenging. Miniaturized optical clock systems must integrate ultra-stable lasers and thermal control subsystems, all within strict space-qualified SWaP (size, weight, and power) constraints [15]. Further engineering efforts are needed to ensure their long-term stability, mechanical robustness [18], and qualification for GNSS or geostationary satellite deployment.

Satellites equipped with atomic clocks predominantly support navigation satellites, whereas commercial geostationary Earth orbit (GEO) communication satellites typically do not employ atomic clocks. Such satellites are increasingly being utilized as relays for time and frequency synchronization applications through free-space links [19,20]. Nevertheless, existing time–frequency transfer methodologies based on commercial GEO communication satellites face technical challenges stemming from their onboard crystal oscillators [21]. For instance, in satellite two-way time and frequency transfer (TWSTFT)—a critical contribution to realizing Coordinated Universal Time (UTC)—phase jitter in the local oscillators of GEO satellite transponders induces signal phase noise during transmission. This jitter compromises the precision of high-precision carrier-phase measurements [22]. In timing and positioning applications of the Chinese Area Positioning System (CAPS), the limited accuracy and long-term stability of hybrid frequency sources onboard the GEO satellites can adversely affect the stability of downlink carrier frequencies, thereby degrading po-

sitioning precision [23,24]. Regarding our prior work on the Einstein two-way frequency synchronization (SESAR) method [25], the phase drift introduced by the transponder's local oscillators disrupts the phase coherence between uplink and downlink signals, constraining further improvements to frequency comparison accuracy. Even when substituting the crystal oscillators with chip-scale atomic clocks [26], their long-term stability remains limited to the order of 10^{-12} , whereas the daily stability levels of TWSTFT or the SESAR method have already achieved 10^{-15} . This performance gap evidently inhibits emerging high-precision applications.

Meanwhile, other frequency transfer technologies such as fiber-based optical frequency dissemination and free-space optical time–frequency transfer have demonstrated exceptional stability in ground-based systems. However, these methods are difficult to extend to GEO satellite scenarios due to atmospheric turbulence, limited link availability, and complex beam-tracking requirements. As such, scalable RF-based solutions—especially those capable of integrating with the existing GEO platforms—remain essential for the space-time infrastructure.

To address these problems, this study proposed a novel phase-locked transponder designed for GEO communication satellites along with a frequency-synchronization scheme based on carrier-phase active compensation. This scheme eliminates the need for onboard atomic clocks but instead relies on onboard crystals and ground-based high-precision atomic frequency-scale phase locking for remote frequency comparison and distribution. Consequently, a reference clock source locked to the ground's highly stable atomic frequency scale can be recovered from the GEO communication satellites without onboard atomic clocks. The feasibility of this high-precision frequency-synchronization method has been demonstrated through a theoretical analysis and ground experiments. This paper presents a cost-effective and scalable solution for enhancing frequency synchronization in geostationary satellites. By improving the accuracy and stability of satellite frequency references, this method significantly enhances communication reliability, particularly in critical applications that require precise time synchronization. Moreover, the proposed solution supports a wide range of advanced scientific and navigational applications and potentially enables the construction of an integrated space-air-ground time–frequency synchronization network, thus advancing global positioning, navigation, and timing capabilities.

Section 2 introduces a frequency recovery and delivery system using a novel phase-locked transponder. Section 3 models the satellite–ground link, analyzes the ionospheric and relativistic effects and describes the experimental setup, followed by an analysis of the results in Section 4. Section 5 discusses the findings, and Section 6 presents the concluding statements.

2. Scheme Framework

A transponder subsystem connects a satellite's transmitting and receiving antennas. It is one of the most crucial subsystems in the space segment. There are two principal categories of transponders, i.e., single-conversion and regenerative transponders. For GEO communication satellites, the current remote time–frequency comparison uses a single conversion transponder, the principle of which is shown in Figure 1a.

As Figure 1a shows, the onboard oscillator's frequency and phase are included in the signal returned to the ground. Consequently, the received signal always contains this unknown variable, i.e., conventional onboard single-conversion transponders introduce additional transmission errors caused by phase jitter and variations in the onboard local oscillator. As Figure 1b shows, this problem can be solved by a phase-locked frequency conversion method, by which the phases of the uplink and downlink signals are always locked. Once the signal traverses the bandpass filter (BPF), after undergoing a frequency division process, one of the signal paths is selected as the reference for the phase-locked

dielectric resonator oscillator (PDRO). The resulting PDRO output is then mixed with the other path of the original signal and filtered using a low-pass filter to generate the down-converted signal transmitted to the ground station. Concurrently, following the frequency division, the 10 MHz or 100 MHz signal generated by the PDRO output serves as the recovered frequency standard from the ground station to the satellite and from there is provided to other systems.

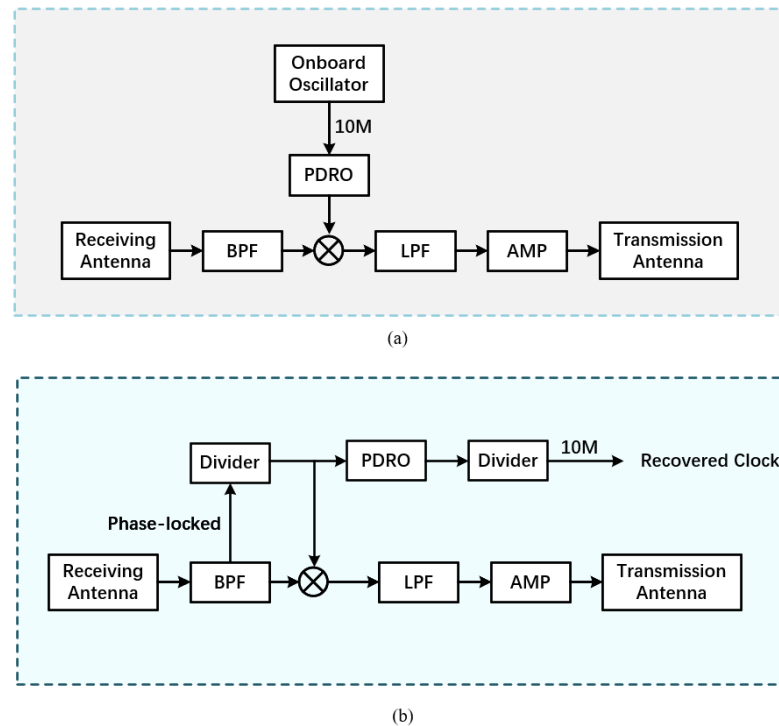


Figure 1. Schematic diagram of a geostationary Earth orbit (GEO) communication satellite transponder. The circle symbol represents a mixer. BPF: bandpass filter; LPF: lowpass filter; PDRO, phase-locked dielectric resonator oscillator. (a) Existing communication satellite transponder structure. (b) Novel GEO communication satellite phase-locked transponder structure.

Compared with the commonly used communication satellite transponders, the phase-locked transponder can eliminate the GEO satellite's onboard crystal oscillator's impact on the ground–satellite bidirectional link. This effectively solves the onboard crystal oscillator's phase drift problem and combines it with the proposed carrier-phase real-time compensation scheme to realize the precise onboard clock recovery (as discussed below).

Figure 2 illustrates the architectural framework of the frequency transfer system based on the proposed GEO communication satellite's phase-locked transponder. The on-orbit payload is servo-controlled and tracked by the main channel over an extended period, with its corresponding ground station, labeled as Station A in the figure, equipped with an ultrahigh-precision atomic frequency standard. A two-way link is established between Station A and the satellite to measure the phase variations across the entire link, evaluated at the carrier signal's phase scale. Using real-time detection, the phase variations in the uplink and downlink are compensated separately to reproduce the terrestrial high-precision atomic frequency standard of Station A on the satellite. The down-converted PDRO of the phase-locked transponder is locked to and reproduces the frequency standard of Station A in real-time. Consequently, any other ground stations within the satellite's coverage area can utilize the proposed transponder as a single conversion transponder without requiring modifications to existing applications. Furthermore, this method supports using any other

ground station within the GEO satellite's coverage area equipped with an atomic clock as the main channel, offering significant flexibility and scalability.

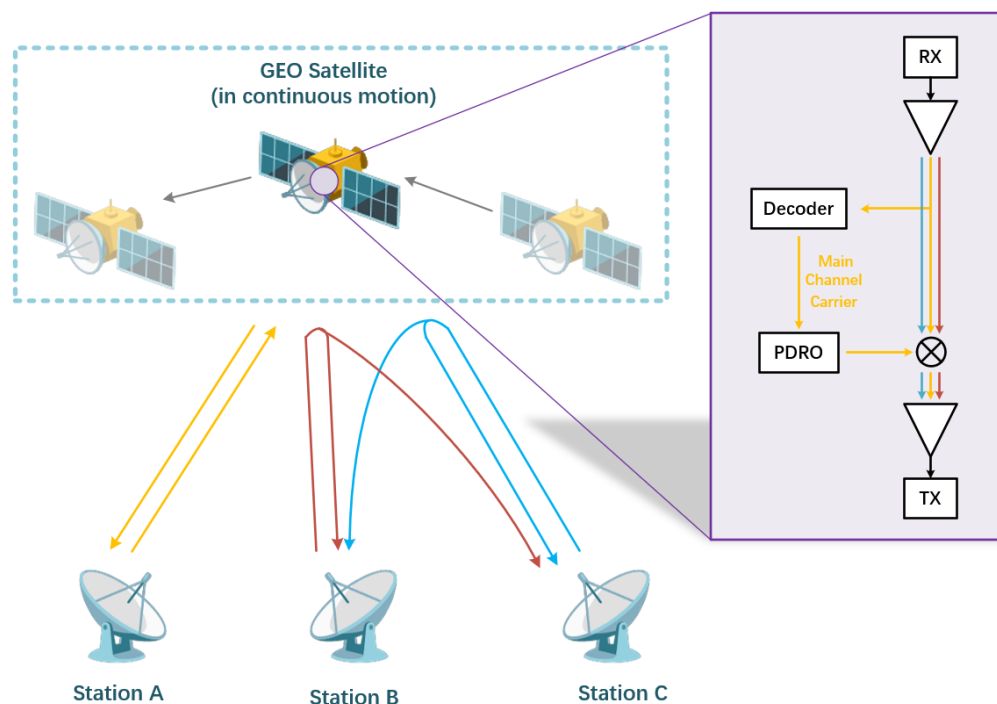


Figure 2. Architecture of the frequency synchronization and comparison system. A, B and C represent multiple future ground stations. The circle symbol represents a mixer.

Moreover, using a compensation approach similar to that of Station A, Stations B and C can each establish a two-way link with the satellite, enabling real-time atomic frequency standard comparisons between the two stations without introducing phase errors from the GEO satellite's oscillator. This two-ground-station remote clock comparison method was experimentally validated in our previous work [25] using conventional commercial communication satellites, demonstrating its feasibility and achieving a 1σ value of 18.06 ps over a 10 km baseline.

3. Materials and Methods

The bidirectional satellite–ground link can be modeled using the carrier phase as a medium for information transfer. Several factors can affect the transmission and reception of a carrier-phase signal generated by a high-precision time and frequency reference at a ground station. These include the changing relative position between the satellite and the ground, phase variations in the onboard oscillator, ionospheric effects, and relativistic effects. All such factors must be considered. When a ground station transmits a signal, it possesses an initial phase. Subsequently, the signal undergoes phase variations during its propagation through the uplink and downlink non-dispersive media. Such phase changes are proportional to both the carrier frequency and the pseudo range. Because the ionosphere is a dispersive medium, its effect requires separate consideration in the equations. The signal forwarded by the synchronized orbit satellite and subsequently received on the ground can be described by the following relationship [25,27]:

$$\begin{aligned} \phi_{AR}(t) = & \phi_{AT}(t) - \frac{\omega_{uA}\rho_{as}(t)}{c} - \phi_S - \frac{\omega_{dA}\rho_{as}(t)}{c} \\ & + K_{\text{iono}} \left(\frac{TEC_A}{\omega_{uA}} + \frac{TEC_A}{\omega_{dA}} \right) + (\omega_{uA} - \omega_{dA})\gamma_A \Sigma_A, \end{aligned} \quad (1)$$

where ϕ_{AT} denotes the signal's phase at the earth station's transmitting end, ϕ_S denotes the additional phases introduced by the satellite transponder, $\rho_{as}(t)$ denotes the pseudo range from Station A to the satellite, and ω_{uA} and ω_{dA} respectively denote the uplink and downlink carrier angular frequencies. The correction coefficient for Station A's proper time is denoted by γ_A , whereas the link asymmetry in Minkowski spacetime is denoted by Σ_A . TEC_A denotes the total electron content along Station A's transmission path, and K_{iono} denotes a constant in the expression for the phase delay caused by the phase refractive index affecting the propagation of electromagnetic waves in the ionosphere, given by

$$K_{iono} = \frac{40.28}{c} \times 4\pi^2 \quad (2)$$

The final two terms of Equation (1) describe the nonlinear time delay introduced by the electromagnetic waves traversing the ionosphere from the viewpoint of the carrier phase and the path asymmetry of the two-way satellite–Earth station link, respectively, which can be analyzed on the basis of special relativity. This is discussed in the following section.

The phase of the signal received by the satellite can be expressed as follows:

$$\phi_{SR}(t) = \phi_{AT}(t) - \frac{\omega_{uA}\rho_{as}(t)}{c} + \frac{K_{iono} TEC_A}{\omega_{uA}} + \omega_{uA}\gamma_A\Sigma_A \quad (3)$$

where ϕ_{SR} denotes the phase of the signal received by the satellite.

The three terms described above must be corrected in real-time at the transmitter to synchronize the signal phase at the ground station with the phase received at the satellite. Consequently, we proposed a frequency-synchronization scheme based on active carrier-phase compensation. The fundamental principles are illustrated in Figure 3.

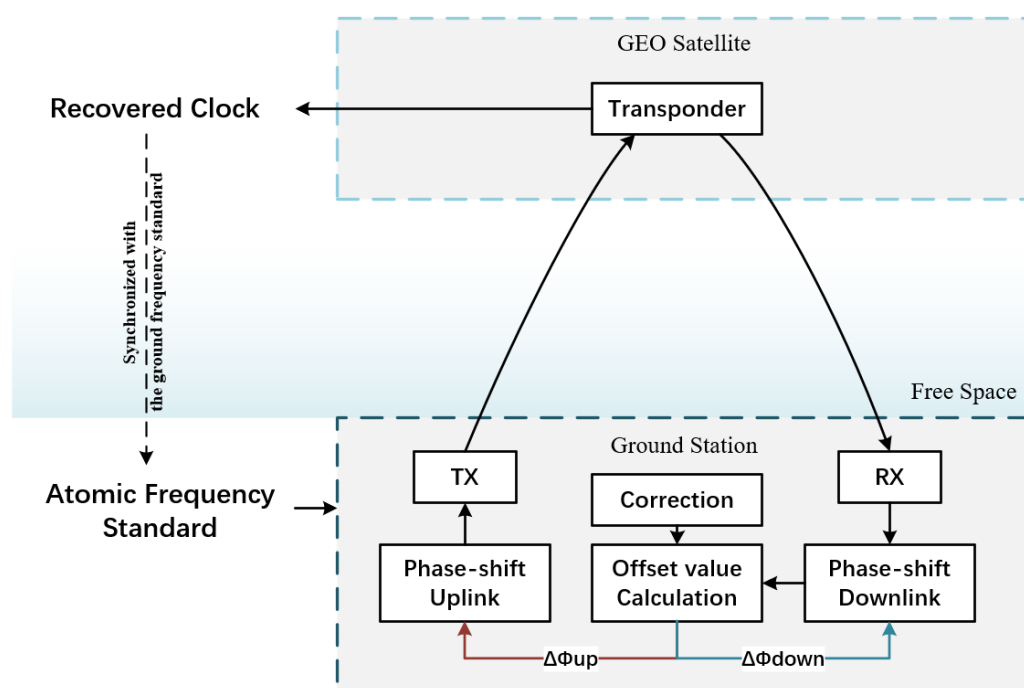


Figure 3. Frequency recovery schematic based on the GEO communication satellite's phase-locked transponder.

The two phase shifters, as shown in the “Phase-shift Uplink” and “Phase-shift Downlink” blocks in Figure 3, can be added before and after the carrier-phase receiver, ensuring that the phase-shifted values of the two phase shifters are maintained at all times by a specific ratio of the uplink and downlink carrier angular frequencies. This linkage, which

compensates for the phase changes in the uplink and downlink is realized by the respective phase shifters, as shown in Figure 3. The “Correction” section in the figure compensates for the nonlinear factors introduced by relativistic effects and the ionosphere in real-time. The final phase shift values, allocated proportionally, are determined by considering phase variations detected in real-time across the entire link combined with the corrections.

Once the phase shifters have been passed at the receiver and the requisite corrections have been made, a closed-loop feedback system maintains the carrier-phase value at approximately zero. The full-path phase noise can be progressively reduced, thereby minimizing the phase difference between the receiver and transmitter and enabling the ground station frequency standard to be recovered at the satellite. Implementing real-time correction and compensation at the ground station depends on knowing all the quantities to be compensated through Equation (3) in real-time at the ground station.

3.1. Recovered Frequency Standard Defined from a Special Relativity Perspective

When ground stations and satellites are in non-inertial motion relative to an inertial frame of reference, clock synchronization requires a definition distinct from that used for inertial or stationary states within the same frame. This synchronization framework should be interpreted in the context of the Minkowski spacetime. Since bidirectional signaling between satellites and ground stations occurs at the speed of light, different coordinate times taken during the uplink and downlink processes result in picosecond-order asymmetry in the bidirectional satellite link. The concept of “satellite Einstein synchronization” has previously been introduced in our work and is briefly explained herein [25,27].

Figure 4 shows the schematic of the bidirectional information exchange between a satellite and a ground station. The ground station antenna’s position vector, projected onto the equatorial plane, interacts dynamically with the Earth’s rotation and the satellite’s synchronized orbit. In the Minkowski spacetime, this creates equidistant spirals, denoted as G (ground station) and S (satellite).

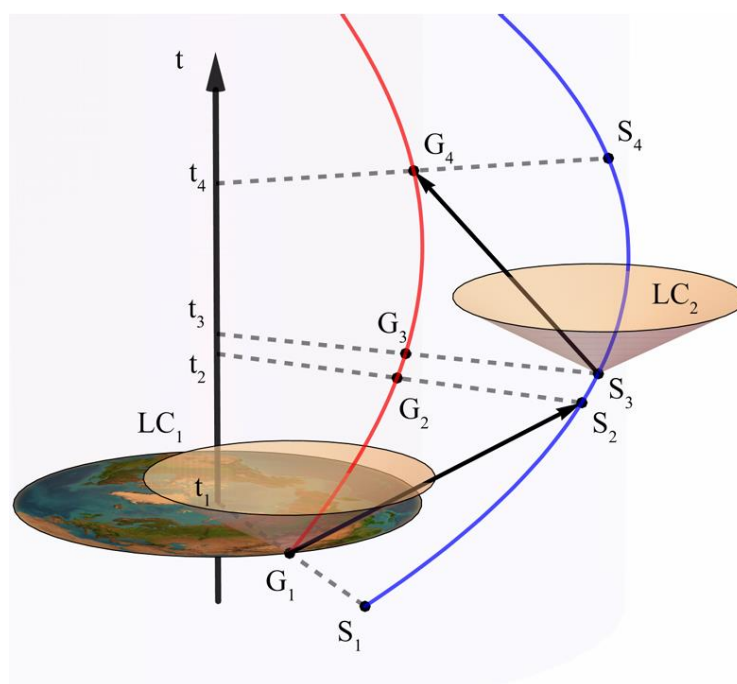


Figure 4. Schematic diagram of round-trip frequency transfer from earth station to satellite.

The signal transmission from the ground station is represented by the coordinates t_1 , G_1 , and S_1 . Here, t_1 denotes the coordinate time of the event, G_1 denotes the ground

station's projection on the two-dimensional spatial plane, and S_1 denotes the position of the GEO satellite within this plane. For the event where the signal arrives at the satellite, we use t_2 , G_2 , and S_2 . The retransmission of the signal by the satellite is denoted by t_3 , G_3 , and S_3 . The time taken for the signal to pass through the satellite's transponder is negligible compared to the transmission time within the satellite link; hence, the reception and retransmission of the signal by the satellite is considered to occur simultaneously. Finally, the event of the signal returning to Earth and being received by the ground station is denoted by t_4 , G_4 , and S_4 .

Assuming that on the GEO satellite a time reference ($\hat{T}^{(s)}$) exists, which is perfectly synchronized with the local time ($T_2^{(g)}$) observed at the ground station whenever the satellite receives a signal, multiple ground stations can independently define their local time references on the satellite. This enables instant determination of the time and frequency comparisons of these local times directly on the satellite. Clearly, the introduced time reference ($\hat{T}^{(s)}$) has a unique significance. This concept is named satellite-based Einstein synchronization. The formula for $\hat{T}^{(s)}$ is derived using approximate geometric calculations based on the principles of special relativity, expressed as follows:

$$\begin{cases} \hat{T}^{(s)} = \frac{1}{2} (T_1^{(g)} + T_4^{(g)}) - \Sigma \cdot \gamma \\ \Sigma = -\frac{\omega_0 \vec{r}_e \times \vec{r}_s}{c^2 - \omega_0^2 \vec{r}_e \cdot \vec{r}_s} \\ \gamma = \frac{\sqrt{c^2 - \omega_0^2 \vec{r}_e \cdot \vec{r}_e}}{c} \end{cases} \quad (4)$$

where $T_1^{(g)}$ and $T_4^{(g)}$ denote the local times recorded at the ground station for the signal emission and reception events during the bidirectional exchange, c denotes the speed of light, ω_0 denotes the angular velocity of Earth's rotation, $\vec{r}_e$ denotes the vector from Earth's center to the ground station projected onto the equatorial plane, and $\vec{r}_s$ denotes the vector from Earth's center to the satellite projected onto the equatorial plane.

This formulation for $\hat{T}^{(s)}$ can be interpreted as a classical Einstein synchronization within an inertial reference frame, supplemented by a term that accounts for the positions of the ground station and satellite. All the necessary parameters can be measured directly at the ground station, avoiding the need to observe the GEO satellite's signal reception within the Earth-centered inertial frame. Consequently, the satellite's onboard time reference can be defined in real-time by the continuous closed-loop tracking of $T_1^{(g)}$ and $T_4^{(g)}$. Accordingly, the constant correction term in Equation (1) associated with the special relativistic effect can be corrected in the uplink and downlink, respectively, provided that the receiver and transmitter frequencies are known.

3.2. Ionospheric Phase Delay Analysis and Correction

The ionosphere introduces nonlinear effects in proportional compensation. For uplink and downlink carriers, the propagation medium is divided into intra- and extra-atmospheric parts. In the extra-atmospheric part, approximated as a vacuum, the refractive index is 1, making time delays carrier frequency-independent.

Within the atmosphere, carriers pass through various layers where the refractive index varies with wavelength due to dispersion effects. As noted in some GNSS textbooks, the troposphere can be approximated as non-dispersive for frequencies up to 15 GHz. Based on this approximation, we have neglected tropospheric dispersion in our modeling, considering only the phase delays proportional to the carrier frequency. However, the ionosphere differs, as it contains free electrons generated by solar ionization. These alter

the refractive index and, due to electron–wave interactions, introduce time delays that are dependent on the carrier frequency.

Proportionally allocating (in real-time) the total ionospheric delay to the upstream and downstream links inevitably introduces errors. For a carrier beam of frequency f , the propagation delay within the ionosphere satisfies the following relationship [28]:

$$\begin{aligned} I_p &= \int_S (n_p - 1) ds = \int_S \frac{a_1}{f^2} ds \\ &= -\frac{40.28}{f^2} \int_S N_e(s) ds = -\frac{40.28 \text{TEC}}{f^2} \end{aligned} \quad (5)$$

where I_p denotes the ionospheric delay in meters, n_p denotes the ionosphere's phase refractive index for electromagnetic waves, and TEC denotes the total electron content, which characterizes the number of free electrons per unit volume of the circular projection. The TEC is usually measured in TECU, with 1 TECU being equivalent to 1×10^{16} el/m². Consequently, we can estimate the level of residual asymmetry after proportional compensation.

Global ionospheric map products based on the International GNSS Service are available from several organizations. The historical ionospheric dataset, sourced from the updated International Reference Ionosphere (IRI) 2016 model (from <https://ccmc.gsfc.nasa.gov/models/IRI~2016/>, accessed on 31 March 2025), was used to calculate the discrepancy between the estimated ionospheric delay using the proportional compensation model and the actual ionospheric delay. This analysis, with Beijing in September 2020 as the case study, determined the discrepancy between the modeled and actual ionospheric delays across multiple bands.

After proportional compensation, the residual ionospheric delay in the uplink was <1 ns for the C-S band and <20 ps for the Ku band, as calculated from the typical satellite–terrestrial radio transmission bands. In the Ka-band, after proportional compensation, in the Beijing area, the residual asymmetric delay was in the order of picoseconds based on historical ionospheric data, as shown in Figure 5.

Meanwhile, using the global ionospheric data corresponding to Xi'an—where our laboratory also operates a ground station—we performed additional calculations, which yielded results of the same order of magnitude, as shown in Figure 6.

Moreover, in future picosecond-level experiments, the ionospheric asymmetry could be measured in real-time using the differential pseudo-code deviation method based on the GNSS constellation and corrected in real-time [29].

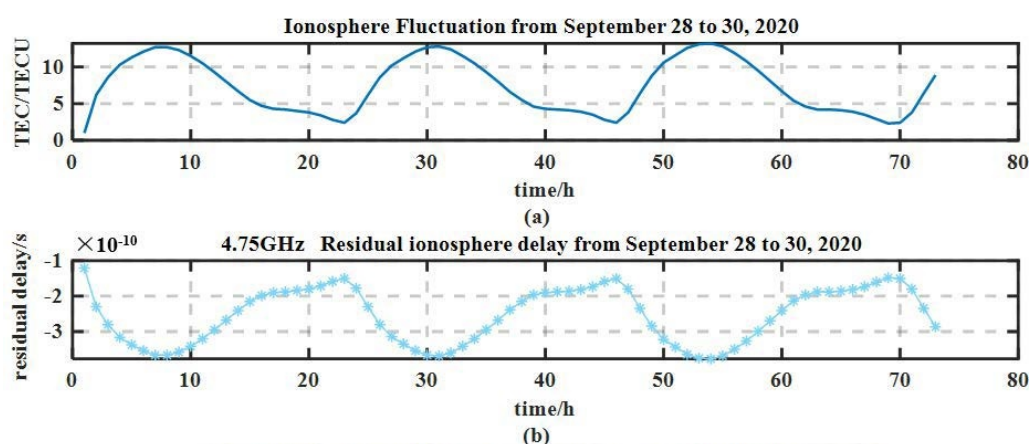


Figure 5. Cont.

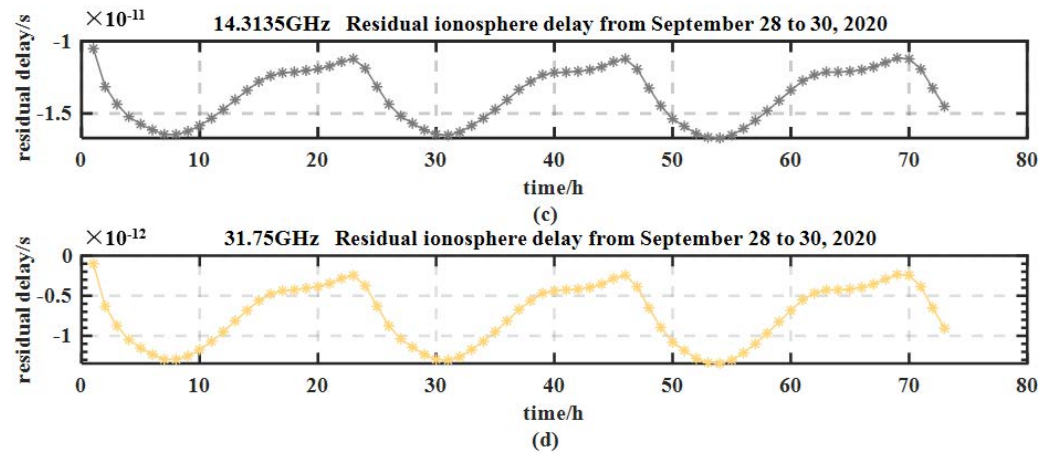


Figure 5. Residual time delays of the signals reproduced on the satellites in the three bands. (a) The electron content (TEC) of the Beijing ionosphere fluctuated over three days. (b) Uplink C-band (4.75 GHz), downlink S-band (3 GHz). (c) Uplink Ku-band (14.3135 GHz), downlink Ku-band (12.5635 GHz). (d) Uplink Ka-band (31.75 GHz), downlink Ka-band (30 GHz).

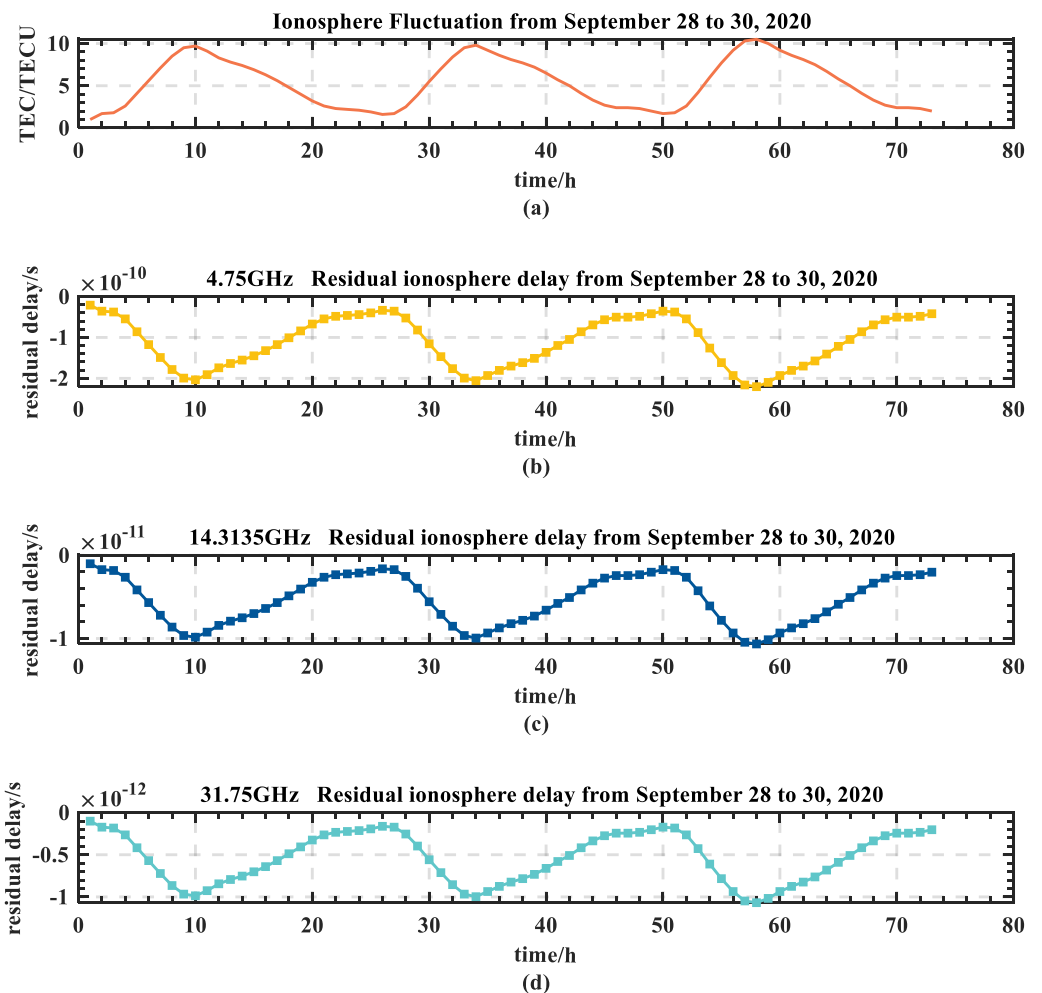


Figure 6. Residual time delays of the signals reproduced on the satellites in the three bands. (a) The electron content (TEC) of the Xi'an ionosphere fluctuated over three days. (b) Uplink C-band (4.75 GHz), downlink S-band (3 GHz). (c) Uplink Ku-band (14.3135 GHz), downlink Ku-band (12.5635 GHz). (d) Uplink Ka-band (31.75 GHz), downlink Ka-band (30 GHz).

3.3. Proportional Compensation Method for Reproducing the Satellite Clock

Considering the aforementioned analysis, the requisite compensation values for Equation (3) can be ascertained using Equation (1). Establishing a real-time active compensation system for the ground station carrier phase enables the phase difference between the transmitter and receiver to be detected after combining the correction values. The all-link phase difference can then be locked to 0 using uplink and downlink phase shifters. By denoting the compensation quantity as $\Delta\phi$, after the system is locked to a steady state, we obtain the following equation:

$$\Delta\phi = \phi_{AR}(t) - \phi_{AT}(t) - K_{\text{iono}} \left(\frac{TEC_A}{\omega_{uA}} + \frac{TEC_A}{\omega_{dA}} \right) - (\omega_{uA} - \omega_{dA})\gamma_A \Sigma_A, \quad (6)$$

where $\Delta\phi$ is the total phase offset given in real-time.

This analysis assumed that a dual-frequency GPS receiver is used to measure the TEC value at Station A in real-time. If the compensation is scaled directly without measurements, the ionosphere-related terms are deleted from the equation and a minor calculated time difference is introduced. All quantities in Equation (6) are known in real-time, and based on Equation (1), we can obtain the relationship between the compensation quantity and the upstream and downstream link delays as follows:

$$\Delta\phi = \frac{\omega_{uA}\rho_{as}(t)}{c} + \phi_S + \frac{\omega_{dA}\rho_{as}(t)}{c}. \quad (7)$$

In this case, owing to the proposed phase-locked forwarding mechanism, the additional S phases (ϕ_S) introduced by the original on-satellite crystal oscillator are eliminated. Then, by allocating the total compensation to the uplink and downlink phase shifters in proportion to the uplink and downlink carrier frequencies and by introducing corrections for the relativistic and ionospheric effects in the uplink, we can obtain the following:

$$\Delta\phi_{up} = \frac{\omega_{uA}}{\omega_{uA} + \omega_{dA}} \Delta\phi + \frac{K_{\text{iono}} TEC_A}{\omega_{uA}} + \omega_{uA} \gamma_A \Sigma_A; \quad (8)$$

$$\Delta\phi_{down} = \frac{\omega_{dA}}{\omega_{uA} + \omega_{dA}} \Delta\phi + \frac{K_{\text{iono}} TEC_A}{\omega_{dA}} - \omega_{dA} \gamma_A \Sigma_A. \quad (9)$$

Therefore, the principle of real-time phase compensation is as follows. First, relativistic corrections are computed based on satellite orbital data, while ionospheric corrections are derived from ionospheric models. Since these two corrections affect the uplink and downlink paths independently, they are applied separately to each link.

After applying these preliminary corrections, the closed-loop feedback system is activated. It measures the phase difference between the received and transmitted signals and adjusts this difference to zero, thereby determining the total compensation value required by the system. According to the theoretical derivation, this total compensation is then proportionally distributed between the uplink and downlink paths based on the carrier phase. To ensure precise and synchronized compensation, two phase shifters are controlled simultaneously: the compensation values are pre-calculated by the host computer according to the carrier frequency and sent to both phase shifters simultaneously, with a common phase-shift enable signal to guarantee synchronous high-precision operation.

Once the compensation amount ($\Delta\phi_{up}$) has been added to the uplink phase shifter, the resulting value can be obtained by combining the terms of Equations (3) and (8) as follows:

$$\phi_{SR}(t) = \phi_{AT}(t). \quad (10)$$

This result confirms that the received signal phase at the satellite matches the phase of the atomic frequency standard at the ground station. This methodology enables the GEO satellites to recover precise and stable atomic frequency standards from ground stations in real-time.

3.4. Experimental Setup

To verify the feasibility of the proposed method, we designed an indoor ground experiment to evaluate its performance. Because the tropospheric and ionospheric path characteristics in the free-space link were lacking, this experiment aimed to evaluate whether the system had demonstrated sufficient dynamic performance for installation on geostationary orbit satellites affected by orbital perturbations, and what levels of accuracy and stability could be obtained. We required a clock with high stability to maintain the frequency standard and ensure that all RF devices and field-programmable gate arrays (FPGAs) could be referenced to it. Therefore, this study used an active hydrogen maser, whose stability is shown in Figure 7.

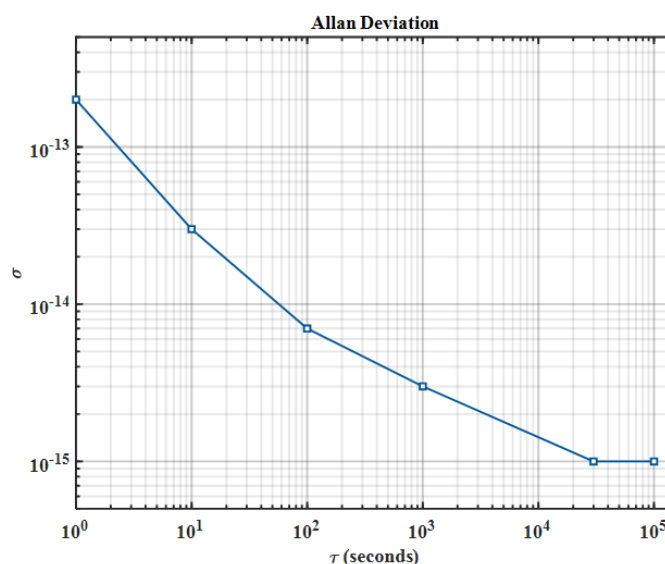


Figure 7. Stability of active hydrogen maser.

In contrast to the 1.8 m parabolic antenna typically used at earth stations, this experiment used two horn antennas, owing to indoor space limitations. In the laboratory, the antennas were placed 20 m apart. As shown in Figure 8, the specific hardware implementation included a moving platform, a C-band transceiver, and baseband processing devices. The C-band was selected to avoid crosstalk with other satellite communication equipment operating in the laboratory during ground experiments, ensuring minimal interference from other signals. The signal was generated by the PDRO, conveyed through a high-precision phase shifter, and subsequently through a bandpass filter and power amplifier before being transmitted through free space to the transponder. The PA used in the experiment had a gain of 35–40 dB, with a 1 dB compression point output power of ≥ 10 dBm. The signal was then converted at the transponder using a phase-locked mechanism, and the downlink frequency was set to 4.5 GHz. At the experimental ground station, the received signal was amplified by LNA and converted from the downlink frequency to an intermediate frequency (IF) using a customized downconverter (D/C), which featured a 4.5 GHz to 1 MHz conversion range. Two identically structured, hardware phase-locked transceivers were placed at the remote and ground ends for the common-mode elimination of additional noise introduced by the devices. Two 1 MHz signals were input into the

baseband processing system realized by the FPGA hardware from National Instruments (NI) Corp. The phase difference extracted from the IQ complex signal in the FPGA was sent to the NI PC controller as an error input.

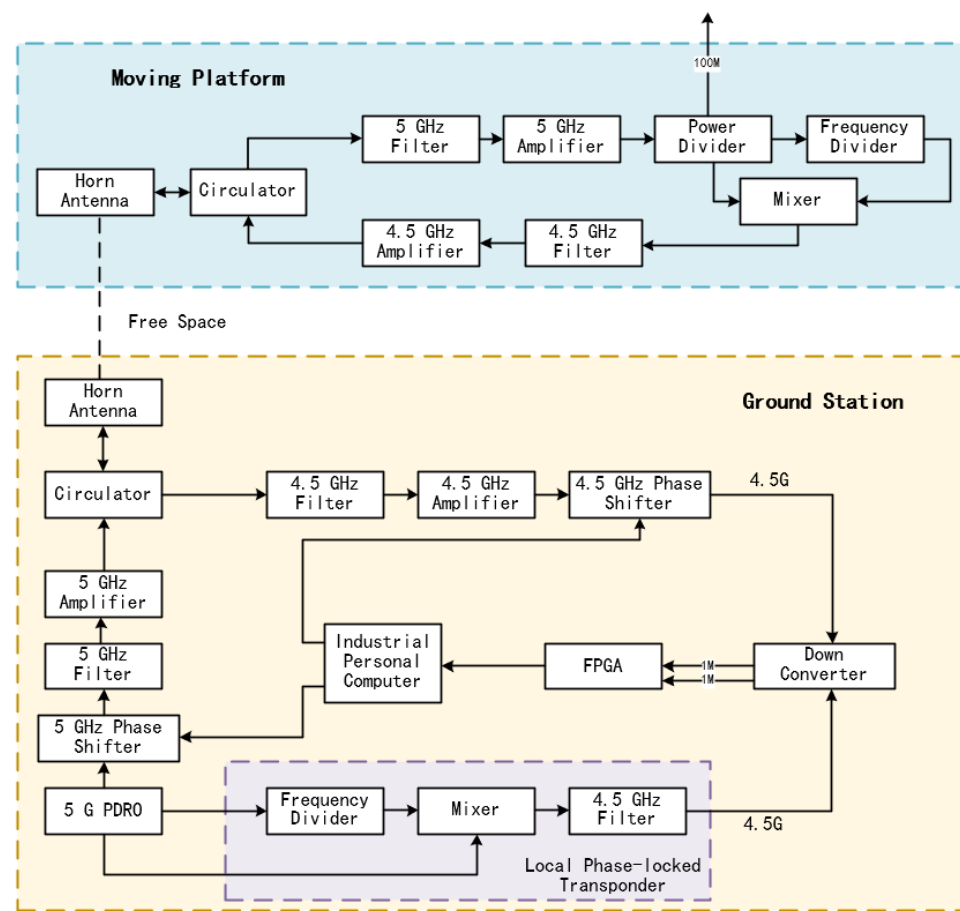


Figure 8. Hardware structure of the ground experimental system.

Given that the carrier phase is used as the frequency transfer medium, the portion of the uplink and downlink that are proportionally compensated can be effectively managed through a phase delay, i.e., a phase shifter. Consequently, as shown in Figure 9, the generated phase control quantity was proportionally distributed and directly applied to the 5G and 4.5G signals through high-precision analog phase shifters. The phase shift rate was 1 kHz with an accuracy of 0.1° . The clock reference for all the RF devices was an active hydrogen maser in a laboratory setting. The FPGA's global clock network also used this hydrogen maser as the input clock source. Data sampling, including A/D conversion, was precisely synchronized with the reference signal through the design of the phase shifter control process, thereby circumventing the host computer's potential clock interference introduced during signal processing. These approaches ensured that all links within the system were referenced to the same active hydrogen maser.

We also designed a dynamic terrestrial experiment to verify whether the system had sufficient dynamic performance to track satellite maneuvers and whether the phase change introduced by the satellite Doppler effect was still proportionally distributed for the uplink and downlink. The synchronous satellite was only theoretically stationary relative to the ground. Information on the radial motion of the Zhongxing-10 communication satellite and the ground station was obtained using real measurements in the previous closed-loop locking experiment of the satellite-ground link. From the ground station perspective, this movement was similar to a sinusoidal motion with a period of 24 h, a maximum speed of

approximately 1–2 m/s, and a maximum change in the distance of approximately 20 km. In the design of the satellite–ground link closed-loop feedback system, to offset the satellite Doppler effect, the host computer must offset a certain frequency on the transmitting end or the receiving end to perform pre-compensation, which counteracts the influence of the satellite’s speed. Consequently, for the designed control system, the closed-loop tracking performance was primarily influenced by the rate of change in the velocity of the GEO satellite relative to the ground station, that is, its acceleration. To address this, we used a stepper motor to control the slide’s reciprocating motion following a sinusoidal pattern. The module is driven by a high-precision servo-controlled stepper motors, capable of sinusoidal motion with a 1000 mm amplitude, 0.05 mm positioning accuracy, and adjustable period. By analyzing the frequency stability before and after compensation, we can quantitatively assess the dynamic clock recovering performance. The maximum acceleration of the motion was identical to the measured acceleration of the radial motion of the communication satellite, relative to the ground station.

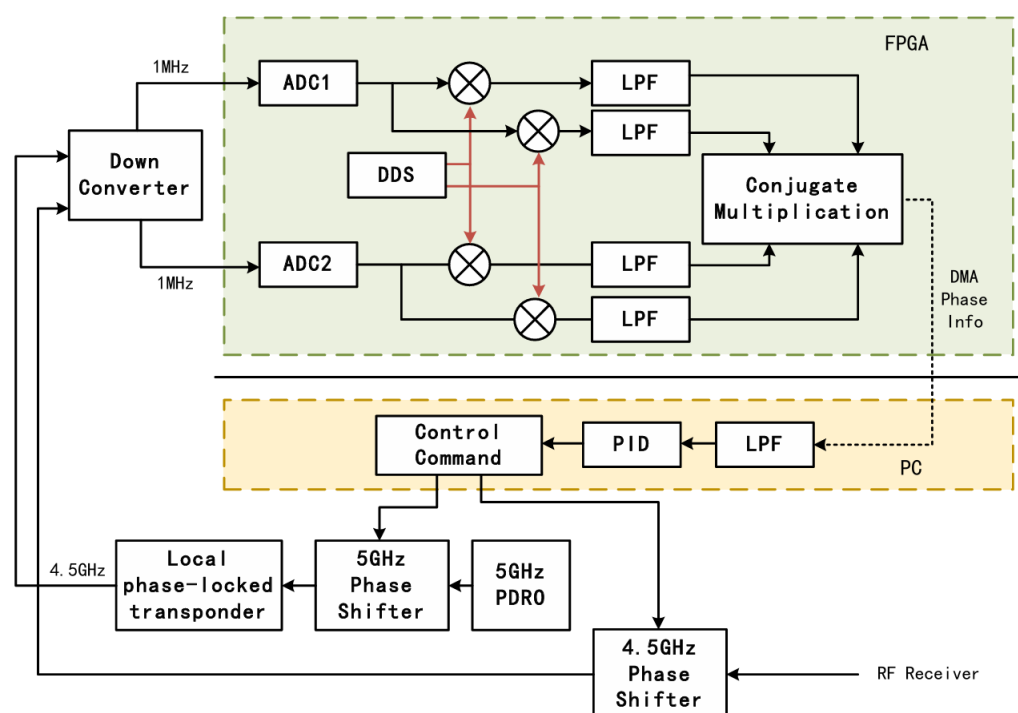


Figure 9. Digital signal processing flow.

Furthermore, we simulated an equivalent 5 km propagation path under dynamic conditions, considering both power attenuation and time delay effects. For the closed-loop delay equivalent simulation of a 5 km bidirectional link, assuming electromagnetic waves propagate at approximately the speed of light, an additional delay of approximately 32 μ s was introduced into the entire closed-loop system.

In the actual implementation, after the signal is sampled by the ADC, it is transferred to the FPGA via Direct Memory Access (DMA). Within the FPGA, the signal undergoes a predefined delay using the Delay Line module, followed by bandpass filtering and quadrature demodulation. The IQ channels of the two demodulation paths are driven by the same decimally zeroed Direct Digital Synthesis (DDS) module. Upon completion of demodulation, two complex baseband signals are generated. By performing a conjugate multiplication of these two complex signals and filtering out the high-frequency components, the phase difference between the two received signals can be obtained.

The architecture and implementation details of the Delay Line module are illustrated in Figure 10. This module consists of a series of cascaded shift registers, operating at a 25 MHz clock rate, to achieve precise and deterministic delay in the digital domain. Since the shift timing of the cascaded registers is entirely determined by the hydrogen maser reference, its accuracy is well ensured. Additionally, to facilitate adjustable delay values in subsequent experiments, each Delay Unit is externally accessible and controlled by a dedicated 8-bit memory cell. When a specific bit is set to 1, the corresponding delay unit is activated. Under ideal conditions, the Delay Line module is capable of introducing a tunable delay, ranging from 0 μ s to 64 μ s, with 8 μ s step resolution.

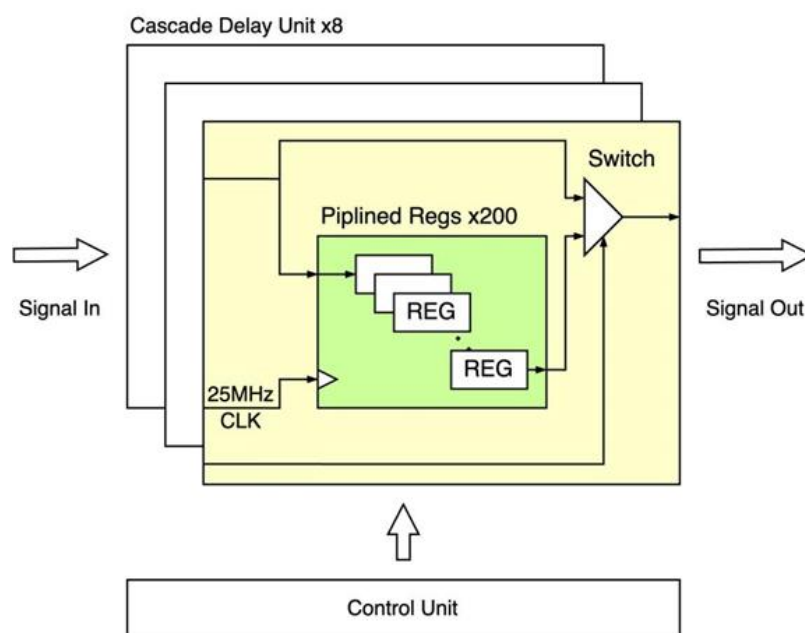


Figure 10. Design of the Delay Line module.

Power attenuation is calculated according to the free-space frequency propagation model, as shown below:

$$PL(dB) = 10\lg \frac{P_T}{P_R} = -10\lg \left[\frac{G_T G_R \lambda^2}{(4\pi)^2 d^2} \right]. \quad (11)$$

where $PL(dB)$ is the power attenuation value, P_T is the transmitting power, P_R is the receiving power, G_T is the transmitting antenna gain, G_R is the receiving antenna gain, λ is the electromagnetic wave wavelength, and d is the transmission distance. Based on the calculation results, the experimental system in the link transceiver ends actually increase the SMA-type fixed attenuator.

4. Results

The frequency-synchronization experiments conducted in the laboratory over a distance of 20 m commenced on 29 July 2024, and were concluded on 30 July 2024. The transfer end corresponds to the TX section in Figure 3, while the receiver end refers to the section after the “Phase-shift Downlink” in the same figure. The phase difference between these two ends represents the overall locking performance of the loop. The recovery clock refers to the clock reproduced at the transponder.

The time domain frequency stabilization and waveforms of the residual phases of the closed-loop compensation experiment are respectively shown in Figure 11, panels (a) and (b). This experiment characterized the precision limits that the system could achieve. Its short-term

and long-term stability reached 2.00×10^{-13} at 1 s and 2.06×10^{-17} at 10,000 s. The phase values obtained in this time domain were statistically analyzed with the data recorded at 0.1 s intervals. The peak-to-peak values were approximately 1.49 ps, with a standard deviation of 0.13 ps, as determined by a statistical analysis.

Regarding the transponder end, Figure 11, panels (c) and (d), respectively, show the frequency stability and time domain waveform of the remaining phase after proportional compensation. Although this method does not have a closed-loop structure for the uplink, as predicted by our theory, the time difference after compensation remained minimal. The peak-to-peak value was approximately 22.36 ps, and the standard deviation was 4.44 ps, as determined by statistical analysis. The system demonstrated short- and long-term stability, with 5.66×10^{-14} at 1 s and 3.56×10^{-16} at 10,000 s.

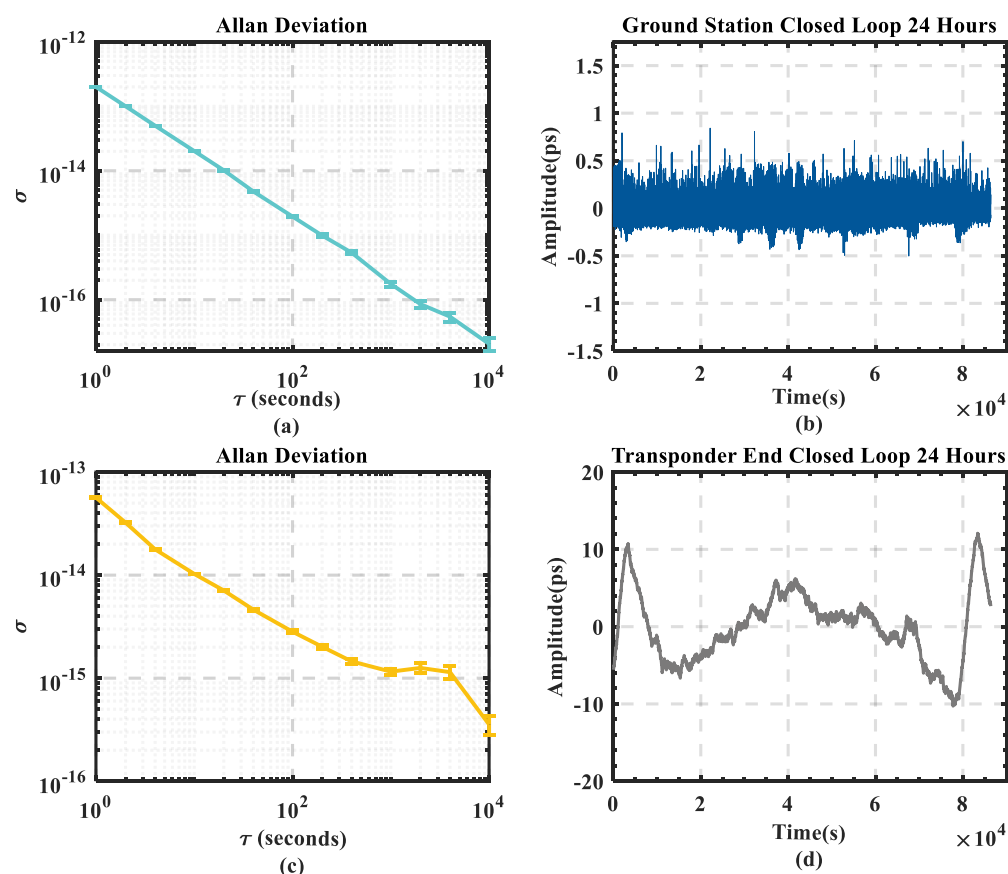


Figure 11. Results of the frequency-synchronization experiments. (a) Allan deviation of the phase difference between the ground station's transfer and receiver ends. (b) Phase differences between the ground station's transfer and receiver ends shown as time-difference changes. (c) Allan deviation of the recovery clock with the local frequency standard. (d) Phase difference in the recovery clock and local frequency standard shown as time-difference changes.

For the dynamic experiment, the receiver end executed a reciprocal motion with a reciprocal distance of approximately 60 cm.

Figure 12a shows the time domain waveforms of the remaining phases of the open- and closed-loop compensation experiments of 24 h for the ground-end. The standard deviation of the closed-loop and open-loop residual phase, converted to time, was calculated to be 1596.55 ps for the open-loop and 0.81 ps for the closed loop. These results demonstrate a considerable improvement in the closed-loop link performance.

Figure 12b shows the time domain waveform and frequency stability of the remaining phase at the transponder end after proportional compensation. A comparison of the

standard deviation of the phase difference converted to time before and after compensation reveals a considerable improvement, with values of 796.02 ps for the open loop and 6.33 ps for the closed loop.

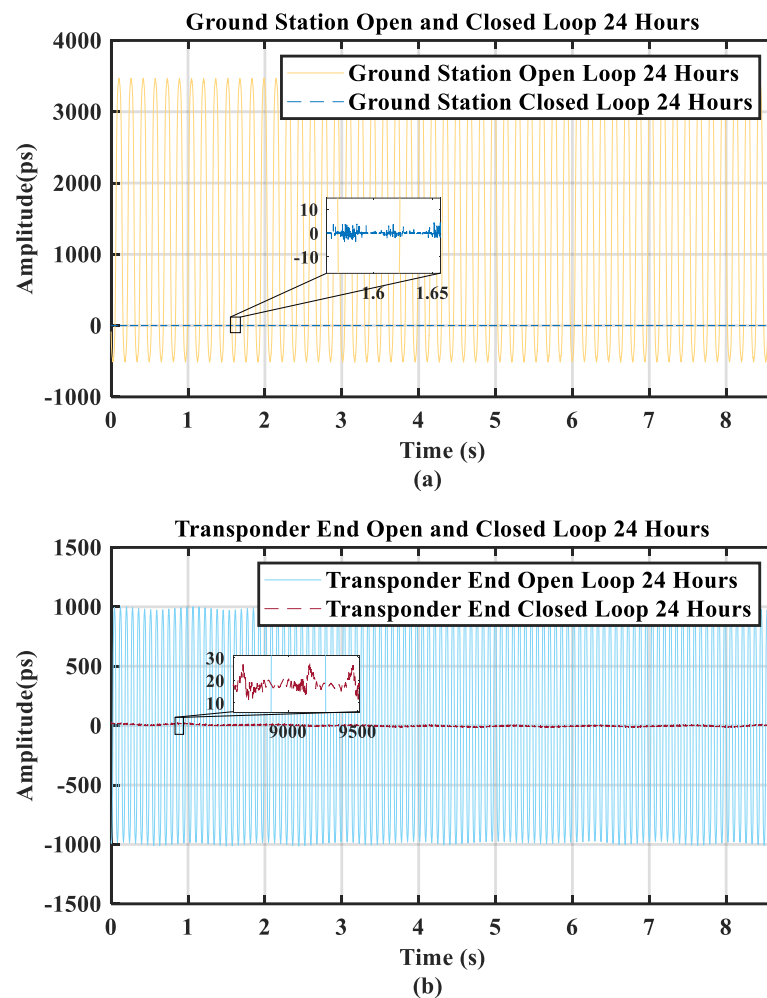


Figure 12. Results of the frequency-synchronization experiments using the moving platform. (a) Open-loop and closed-loop phase differences between the transfer and receiver ends of the ground station, shown as time-difference changes. (b) Open-loop and closed-loop phase differences in the recovery clock at the transponder end and local frequency standard, shown as time-difference changes.

Figure 13 illustrates the closed-loop frequency stability of the dynamic experiment over a 48 h period. The calculations demonstrate that the ground station end's 10,000 s stability reached 9.88×10^{-17} , whereas the transponder end's 10,000 s stability reached 3.36×10^{-16} .

Notably, the ambient temperature in the vicinity of the RF device significantly correlated with the time-varying experimental results at the transponder end. Figure 14 illustrates the temperature fluctuations in the vicinity of the device throughout the experiment and depicts a comparison between the variations in temperature and the phase fluctuations of the recovered clock at the transponder side. The maximum Pearson product moment correlation coefficient (r) was -0.87 , indicative of a strong correlation between the two variables.

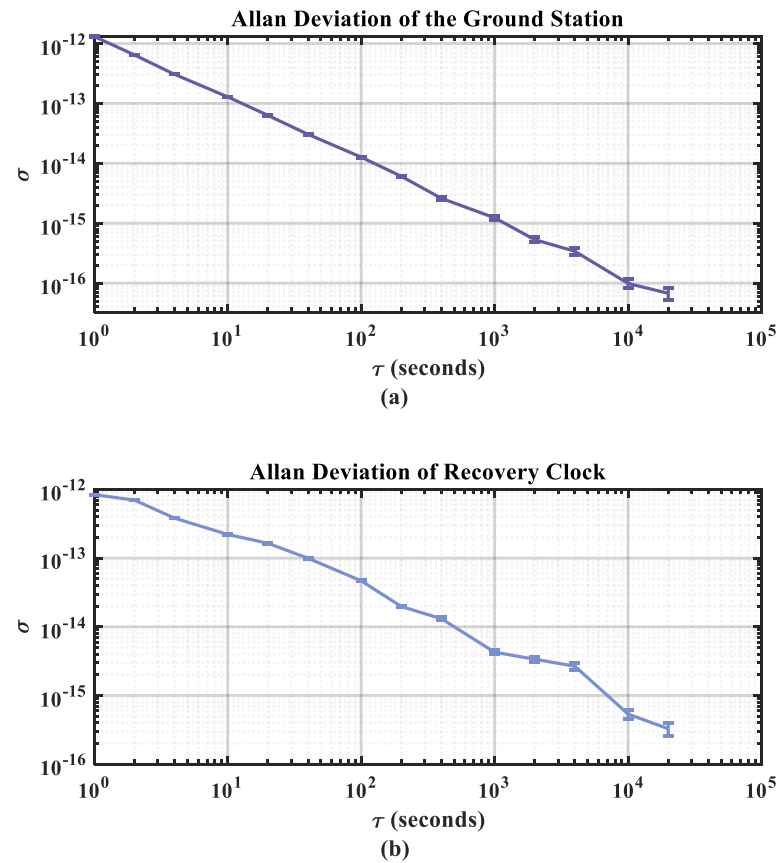


Figure 13. Allan deviation of the frequency-synchronization experiments using the moving platform. (a) Allan deviation of the phase difference between the transfer and receiver end at the ground station. (b) Allan deviation of the recovery clock with local frequency standard.

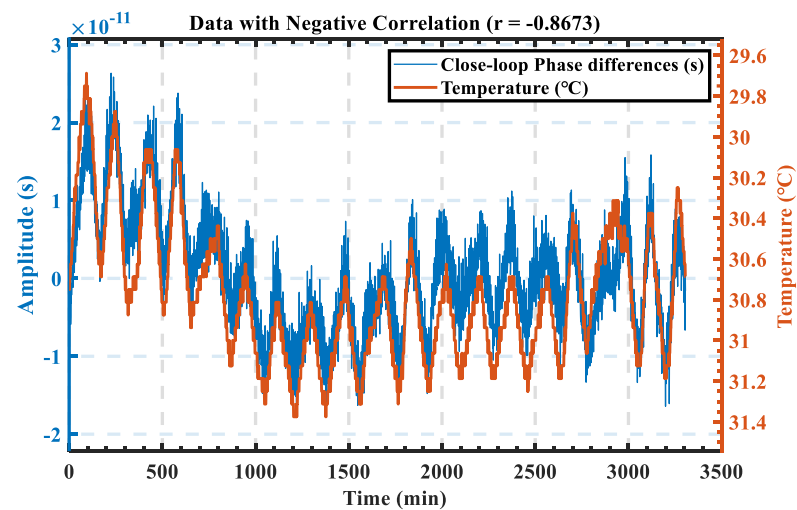


Figure 14. Device temperature fluctuations and transponder recovery clock phase fluctuations.

The corresponding calculation formula is as follows:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}. \quad (12)$$

The Pearson product moment correlation coefficient, denoted by r , measures the degree of correlation between two time series x_i and y_i . The means of these time series are denoted as $\bar{x}$ and $\bar{y}$.

Finally, to verify the repeatability of the experiment, we conducted four sets of dynamic experiments, using a sliding rail, each lasting 12 h. The speed and reciprocation distance settings were identical to those previously described. These experiments commenced on 20 September 2024 and concluded on 22 September 2024.

The findings demonstrate the system's repeatable performance, highlighting its consistent precision and stability throughout multiple trials, as shown in Figure 15. This confirmed the system's reliability for frequency comparisons over extended periods and established its robustness for prolonged operations.

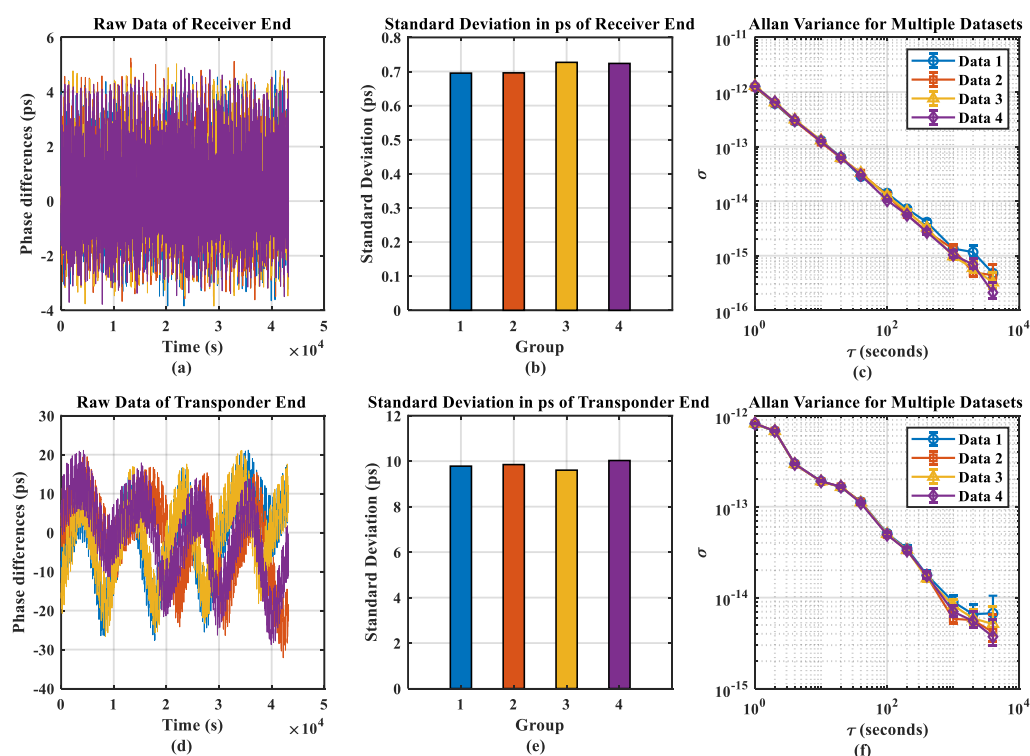


Figure 15. Results of the four groups of frequency-synchronization experiments using the moving platform. (a) Closed-loop phase differences between the ground station's transfer and receiver ends, shown as time-difference changes. (b) Standard deviation of the phase difference between the ground station's transfer and receiver ends for the four groups. (c) Allan deviation of the phase difference between the ground station's transfer and receiver ends. (d) Closed-loop phase differences between the recovery clock and local frequency standard. (e) Standard deviation of the phase difference between the recovery clock and local frequency standard. (f) Allan deviation of the phase difference between the recovery clock and local frequency standard.

Finally, we conducted dynamic experiments lasting 24 h under equivalent 5 km conditions to assess whether the introduction of a certain degree of equivalent distance would have an impact on the experimental results, as shown in Figure 16. Since the standard deviation of the phase difference between the transfer end and receiver end of the ground station was still very small at 0.79 ps, the figure focuses on showing the transponder end.

Figure 16a depicts the time domain waveform and frequency stability of the remaining phase at the transponder end after proportional compensation. The standard deviation of the phase difference were 9.73 ps for the closed loop. Figure 16b illustrates the closed-loop frequency stability of the dynamic experiment over a 24 h period. The calculations demonstrate that the transponder end's 10,000 s stability reached 8.22×10^{-16} . The experi-

mental results are primarily influenced by fluctuations in room temperature, with minimal difference observed in the clock recovery performance before and after the equivalence.

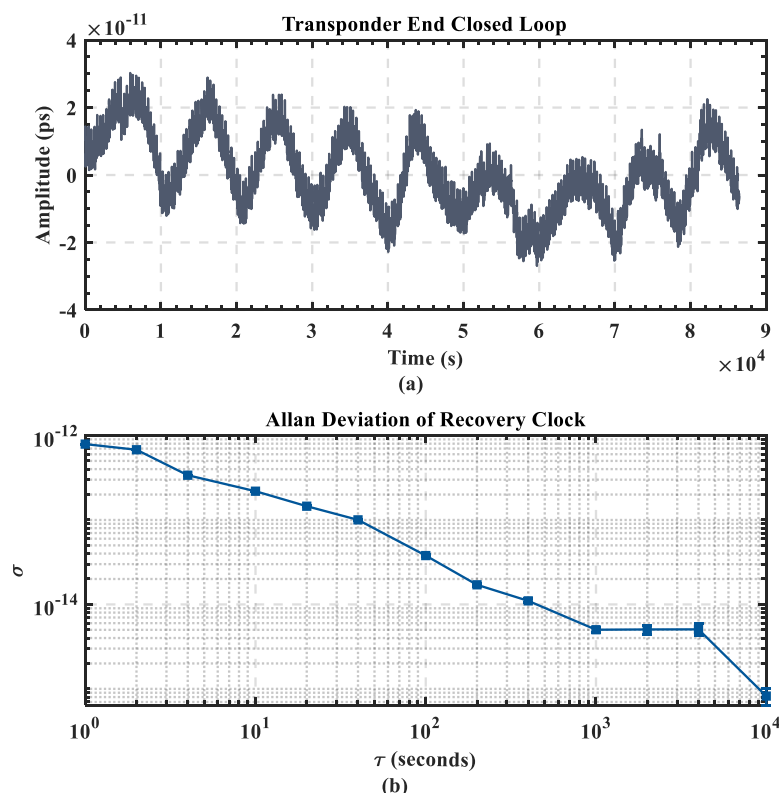


Figure 16. Result of frequency-synchronization experiments with the moving platform under equivalent distance of 5 km. (a) Closed-loop phase differences between the recovery clock and local frequency standard. (b) Allan deviation of the phase difference between the recovery clock and local frequency standard.

5. Discussion

The experimental results demonstrate that the proposed experimental system, constructed using the carrier-phase proportional active compensation method, exhibits the potential to achieve picosecond synchronization accuracy. Moreover, it is comparable to existing satellite-borne atomic clocks regarding short-term stability and exhibited long-term stability an order of magnitude better than existing satellite-borne atomic clocks. The system exhibits a stability level comparable to that of a partially active hydrogen maser. Compared with satellite atomic clocks, which are characterized by their structural complexity and environmental demands, the proposed method requires only the incorporation of a channel into a conventional transparent transponder to facilitate the continuous reproduction of precise and stable terrestrial atomic frequency standards in GEO satellites.

Additionally, the satellite motion data obtained from the compensation amount in this experiment could be roughly used to estimate the radial acceleration level of Zhongxing-10 relative to the ground station. A dynamic platform was constructed based on these data. The results of the satellite–ground link active compensation experiment demonstrated that our proposed method has the potential to achieve picosecond-level accuracy.

The accuracy of the ground experiment characterizes a key factor, namely whether the compensation system has the ability to track satellite motion. Under conditions simulating the acceleration of geostationary satellite motion, the transponder end achieved a picosecond-level reproduction, demonstrating the feasibility of proportional compensation in dynamic scenarios. Since the Ku-band is widely used in satellite communications, and

some of our previous work was also conducted in the Ku-band, we use this band as an example to discuss further extensions of the ground experiment.

Beyond the ground experiments, a crucial aspect yet to be addressed is the extent to which the residual error level of this active compensation method can be reached in an actual satellite–ground link.

In our previous study, we constructed a link between a ground station and a synchronous orbiting satellite, during which we conducted a self-generated and self-received carrier-phase active compensation experiment. The results demonstrated that the phase residual error of the locked satellite–ground link could reach 0.896 ps. The stability performance achieved in this experiment can reach the level of 10^{-12} at 1 s and 10^{-16} at 1 day. The experimental results can be found in Figures 8 and 10 of reference [27]. This demonstrates the noise floor attainable by our system within the ground station-to-satellite link. This also demonstrates that our developed compensation system can function properly under the signal-to-noise ratios (SNRs) present in realistic satellite communication scenarios.

The main difference between the short-distance ground experiment and the long-distance satellite-to-ground link experiment, excluding the ionospheric and relativistic effects which will be considered later, lies in the time delay and the noise introduced by the atmospheric link. In our previous ground experiments, we found that changing the equivalent distance did not significantly affect the precision and stability of the recovery clock. Furthermore, the full-link noise compensation experiment for satellite-to-ground links demonstrated that the control system could compensate for long-distance links with a delay of about 0.25 s. Therefore, the primary influencing factor for the extrapolation of the ground experiment results should be the noise introduced by the atmospheric link.

Regarding the noise introduced by the atmospheric link, while we consider that all media, except for the ionosphere, are non-dispersive, there still exists some frequency dependence, even for lower frequency bands. According to the Liebe model, the German Federal Institute for Physical Technology (PTB) simulated the link delay asymmetry of RF signals below 100 GHz under different atmospheric temperature and humidity conditions. The study, combined with measured data from the ground station, calculated the time delay in the troposphere over 300 days for the Ku-band. The experimental results show that, in the Ku-band used, the propagation delay asymmetry caused by the troposphere between the PTB ground station and the IS-4 geostationary satellite's uplink and downlink varies with humidity, but is always less than 10 ps [30]. This work gives an order of magnitude of the time delay asymmetry of the uplink and downlink. The time delay asymmetry would be even lower in the bands used in the ground experiment.

Next, we further consider the extrapolation effects of the ionospheric and relativistic corrections. For the ionosphere, based on the calculations presented earlier, we estimate that the residual ionospheric delay in the Ku-band under our compensation method without any model-based correction. According to the IGS official website, the accuracy of ionospheric maps is typically within 2–8 TECU. Using this level of accuracy to compute corrections via an ionospheric delay model, the residual ionospheric asymmetry after proportional compensation can be reduced to the tens-of-picoseconds level. While discrepancies exist between the IRI model and actual ionospheric conditions, the prior literature has demonstrated the effectiveness of ionospheric corrections. Specifically, Fujieda et al. investigated the discrepancy between time and frequency transfer results corrected using ionospheric maps and models, and those obtained from GPS CP measurements, within the context of TWSTFT applications [31]. Their findings confirm the efficacy of these model-based corrections, yielding long-term stability performance in the order of 10^{-16} . This demonstrates the feasibility of applying this ionospheric correction model in similar time and frequency

transfer scenarios. If real-time ionospheric measurements are performed using a GNSS dual-frequency receiver, the correction accuracy can be further improved.

As for the relativistic correction of the onboard virtual clock based on Einstein synchronization, the uncertainty of the correction depends on the orbital determination accuracy of the GEO satellite. In the following section, we evaluate the effect of orbit determination errors on the relativistic correction term.

Taking the predicted orbit data of the Zhongxing-10 GEO communication satellite provided by China Satcom as an example, the orbit determination accuracy is approximately on the order of 10 m. Assuming the satellite position in the Earth-Centered Inertial (ECI) frame is (a, b, c) , the ground station position is (x, y, z) , and the Earth's angular velocity is ω_0 , the onboard Einstein-synchronized virtual clock definition (as previously given in Equation (4)) leads to the following expression for the special relativistic asymmetry in uplink and downlink delay:

$$\Sigma = -\frac{\sqrt{a^2 + b^2}\sqrt{x^2 + y^2}\omega_0 \sin\left(\arctan\frac{y-b}{x-a}\right)}{c^2 - \sqrt{a^2 + b^2}\sqrt{x^2 + y^2}\omega_0^2 \cos\left(\arctan\frac{y-b}{x-a}\right)}. \quad (13)$$

By taking the partial derivative of the geostationary satellite coordinates, an uncertainty propagation formula can be derived:

$$\sigma^2 = \gamma \left[\left(\frac{\partial \Sigma}{\partial x} \right)^2 \sigma_x^2 + \left(\frac{\partial \Sigma}{\partial y} \right)^2 \sigma_y^2 \right]. \quad (14)$$

where the definition of γ has been given in Equation (4).

Using the coordinates of the ground station in Tsinghua University and the precise orbit data of the Zhongxing-10 satellite over a 24 h period from September 1 to September 2, 2023 as an example, we calculated that if the satellite orbit determination accuracy is at the 10 m level, the resulting uncertainty introduced into the relativistic correction is approximately 0.04 ps, which is negligible.

Therefore, based on the above analysis, we conclude that when extrapolated to satellite-to-ground links, the performance of the proposed system architecture is primarily limited by the accuracy of ionospheric correction. In the Ku-band, it is expected to reach an accuracy level on the order of several tens of picoseconds, and further improvement is possible when extended to the Ka-band or using a GNSS dual-frequency receiver.

A small nonlinearity exists between the actual output of the phase shifter and the input, which is the reason for the regular spikes in the residual phase difference in the closed loop shown in the enlarged portion of Figure 11d. Moreover, the temperature sensitivity of the device should be further investigated. Using thermostats is expected to enhance the clock recovery performance. The long-term stability of the system is not superior to that of current state-of-the-art active hydrogen masers. Nevertheless, considering the structural design, cost, and realizable precision, the methodology and system outlined in this study retain considerable practical utility.

Notably, in our prior work [24], after applying preliminary relativistic effect corrections and ionospheric compensation, we achieved a simultaneous clock frequency comparison precision of 18.06 ps 1σ and a Allan deviation of $7.67 \times 10^{-15}/1000$ s at a 10 km baseline. This demonstrated the viability of our correction methods at this level of comparative precision. However, these results were obtained using conventional commercial communication satellites and a classic transparent repeater architecture. Therefore, we believe that this architecture and method have the potential to enhance the current frequency comparison precision.

Furthermore, this method can also serve other time and frequency transfer applications and provide a complementary solution to spaceborne time and frequency standards.

6. Conclusions

This study proposed a novel communication satellite phase-locked transponder design based on the satellite-based Einstein synchronization theory and the carrier-phase real-time compensation method. The transponder could replicate the precision of a terrestrial atomic frequency standard in space by modifying the existing transponder's RF structure. Accordingly, this study modeled a satellite–terrestrial link and calculated and analyzed the ionospheric and relativistic effects, demonstrating that the ionospheric error introduced by this method would be at the picosecond level when conducting actual satellite–ground station experiments using the Ka-band. Ground experiments were conducted to evaluate the system's accuracy level and dynamic characteristics. The standard deviation of the recovered clock phase synchronization error was 6.33 ps, with a 10,000 s stability of 3.36×10^{-16} under dynamic conditions. These results demonstrate the potential of the frequency-synchronization method based on a phase-locked transponder. It offers a foundation for developing a synchronous-orbit satellite time–frequency synchronization method.

Moreover, this technology holds strong potential for integration into future large-scale satellite navigation and timing frameworks. By enabling the high-precision frequency synchronization without the need for onboard atomic clocks, it opens new possibilities for space-air-ground integrated timing networks, GNSS augmentation systems, and high-stability time transfer in GNSS-denied environments. Such a system could serve as a complementary time–frequency distribution architecture for existing satellite navigation constellations, contributing to enhanced global synchronization capability and resilience. The proposed approach is not only technically feasible but may also hold significant practical value for next-generation, timing-critical applications in communications, navigation, and scientific observations.

Author Contributions: Conceptualization, X.T., L.W. and S.W.; methodology, X.T. and C.Y.; software, X.T. and C.Y.; validation, X.T., H.S. and L.M.; formal analysis, X.T.; investigation, X.T. and C.Y.; resources, L.W. and S.W.; data curation, X.T., Y.H. and R.L.; writing—original draft preparation, X.T.; writing—review and editing, S.W.; visualization, X.T.; supervision, L.W. and S.W.; project administration, L.W. and S.W.; funding acquisition, L.W. and S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China, grant number 2021YFA1402100.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful to the Xi'an Institute of Space Radio Technology for their help in conducting this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BPF	Bandpass filter
CFS	Cesium frequency standard
FPGA	Field-programmable gate array
GEO	Geostationary Earth orbit
GPS	Global Positioning System

IF	Intermediate frequency
NI	National Instruments
PDRO	Phase-locked dielectric resonator oscillator
PHM	Passive hydrogen maser
RFS	Rubidium frequency standard
TWSTFT	Two-way satellite frequency transfer

References

- Chawla, I.; Karthikeyan, L.; Mishra, A.K. A Review of Remote Sensing Applications for Water Security: Quantity, Quality, and Extremes. *J. Hydrol.* **2020**, *585*, 124826. [\[CrossRef\]](#)
- Koudelka, O.; Schrotter, P. Satellite Services for Disaster Management and Security Applications. *Acta Astronaut.* **2007**, *60*, 986–991. [\[CrossRef\]](#)
- Minnett, P.J.; Alvera-Azcárate, A.; Chin, T.M.; Corlett, G.K.; Gentemann, C.L.; Karagali, I.; Li, X.; Marsouin, A.; Marullo, S.; Maturi, E.; et al. Half a Century of Satellite Remote Sensing of Sea-Surface Temperature. *Remote Sens. Environ.* **2019**, *233*, 111366. [\[CrossRef\]](#)
- Yang, M.; Xu, F.; Ren, J.-G.; Yin, J.; Li, Y.; Cao, Y.; Shen, Q.; Yong, H.-L.; Zhang, L.; Liao, S.-K.; et al. Spaceborne, Low-Noise, Single-Photon Detection for Satellite-Based Quantum Communications. *Opt. Express* **2019**, *27*, 36114–36128. [\[CrossRef\]](#)
- Tavella, P.; Petit, G. Precise Time Scales and Navigation Systems: Mutual Benefits of Timekeeping and Positioning. *Satell. Navig.* **2020**, *1*, 10. [\[CrossRef\]](#)
- Hofmann-Wellenhof, B.; Lichtenegger, H.; Collins, J. *Global Positioning System*; Springer: Vienna, Austria, 2001; ISBN 978-3-211-83534-0.
- Belyaev, A.A.; Demidov, N.A.; Medvedev, S.Y.; Pavlenko, Y.K.; Sakharov, B.A.; Vorontsov, V.G. Russian Hydrogen Masers For Ground And Space Applications. In Proceedings of the 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC), New Delhi, India, 9–15 March 2019; p. 1.
- Wang, Z.-c.; Liu, Q.-h.; Xin, Z.; Juan, Z.; Xie, Y.-h.; Tao, D.; Jiang, J.-h.; Chao, Z.; Wang, L.-l.; Yue, L. The Experiment and Analysis on VLBI Observations of Space Passive Hydrogen Maser. *Chin. Astron. Astrophys.* **2022**, *46*, 297–308. [\[CrossRef\]](#)
- Hao, Q.; Xue, W.; Xu, F.; Wang, K.; Yun, P.; Zhang, S. Efforts towards a Low-Temperature-Sensitive Physics Package for Vapor Cell Atomic Clocks. *Satell. Navig.* **2020**, *1*, 17. [\[CrossRef\]](#)
- Han, C.; Yang, Y.; Cai, Z. BeiDou Navigation Satellite System and Its Time Scales. *Metrologia* **2011**, *48*, S213. [\[CrossRef\]](#)
- Wu, Z.; Zhou, S.; Hu, X.; Liu, L.; Shuai, T.; Xie, Y.; Tang, C.; Pan, J.; Zhu, L.; Chang, Z. Performance of the BDS3 Experimental Satellite Passive Hydrogen Maser. *GPS Solut.* **2018**, *22*, 43. [\[CrossRef\]](#)
- Zhao, Q.; Wang, C.; Guo, J.; Wang, B.; Liu, J. Precise Orbit and Clock Determination for BeiDou-3 Experimental Satellites with Yaw Attitude Analysis. *GPS Solut.* **2017**, *22*, 4. [\[CrossRef\]](#)
- Cernigliaro, A.; Valloreia, S.; Galleani, L.; Tavella, P. GNSS Space Clocks: Performance Analysis. In Proceedings of the 2013 International Conference on Localization and GNSS (ICL-GNSS), Turin, Italy, 25–27 June 2013; pp. 1–5.
- Fabien, D.; Pascal, R.; Sébastien, B.; Batiste, S. GNSS RAFS Latest Improvements. In Proceedings of the 2015 Joint Conference of the IEEE International Frequency Control Symposium & the European Frequency and Time Forum, Denver, CO, USA, 12–16 April 2015; pp. 637–642.
- Jaduszliwer, B.; Camparo, J. Past, Present and Future of Atomic Clocks for GNSS. *GPS Solut.* **2021**, *25*, 27. [\[CrossRef\]](#)
- Xue, X.; Zhou, T.; Wang, N.; Zhang, S.; Ge, J. Recent Progress on Quantum Frequency Standards at BIRMM. *Front. Phys.* **2022**, *10*, 971036. [\[CrossRef\]](#)
- Pizzocaro, M.; Sekido, M.; Takefuji, K.; Ujihara, H.; Hachisu, H.; Nemitz, N.; Tsutsumi, M.; Kondo, T.; Kawai, E.; Ichikawa, R.; et al. Intercontinental Comparison of Optical Atomic Clocks through Very Long Baseline Interferometry. *Nat. Phys.* **2021**, *17*, 223–227. [\[CrossRef\]](#)
- Yun, H.; Liu, L.; Li, Q.; Yang, H. Investigation on Two-Stage Vibration Suppression and Precision Pointing for Space Optical Payloads. *Aerosp. Sci. Technol.* **2020**, *96*, 105543. [\[CrossRef\]](#)
- Rui, P.; Zhang, P.; Tu, R. Discussion on data processing technology about precise time transfer based on GNSS carrier phase observation. *GNSS World China* **2023**, *48*, 1–9. [\[CrossRef\]](#)
- Wu, W.; Dong, S.; Li, H.; Zhang, H. Two-Way Satellite Time and Frequency Transfer: Overview, Recent Developments and Application. In Proceedings of the 2014 European Frequency and Time Forum (EFTF), Neuchatel, Switzerland, 23–26 June 2014; pp. 121–125. [\[CrossRef\]](#)
- Jing, W.; Wang, J.; Zhao, D.; Lu, X.; Wu, J. A Measurement Method of the GEO Satellite Local Oscillator Error. In Proceedings of the 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), Prague, Czech Republic, 21–25 July 2013; pp. 339–342. [\[CrossRef\]](#)

22. Fujieda, M.; Gotoh, T.; Nakagawa, F.; Tabuchi, R.; Aida, M.; Amagai, J. Carrier-Phase-Based Two-Way Satellite Time and Frequency Transfer. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2012**, *59*, 2625–2630. [[CrossRef](#)]
23. Ai, G.-X.; Shi, H.-L.; Wu, H.-T.; Yan, Y.-H.; Bian, Y.-J.; Hu, Y.-H.; Li, Z.-G.; Guo, J.; Cai, X.-D. A Positioning System Based on Communication Satellites and the Chinese Area Positioning System (CAPS). *Chin. J. Astron. Astrophys.* **2008**, *8*, 611. [[CrossRef](#)]
24. Jing, W.; Lu, X. Ground-to-Space Time and Frequency Transfer Based on the “Virtual Clock” Method. In Proceedings of the 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), Besancon, France, 9–13 July 2017; pp. 6–9.
25. Yan, C.; Tang, X.; Meng, L.; Sun, H.; He, Y.; Liu, R.; Wang, S.; Wang, L. A Novel Satellite Frequency Transfer Method Using Einstein Synchronization and Ranging (SESAR) for Advanced Real-Time Coordinated Universal Time (UTC) Generation. *Aerosp. Sci. Technol.* **2025**, *158*, 109870. [[CrossRef](#)]
26. Bagala, T.; Fibich, A.; Stofanik, V. Long-Term Frequency Stability Improvement of OCXO Using CSAC. In Proceedings of the 2016 European Frequency and Time Forum (EFTF), York, UK, 4–7 April 2016; pp. 1–3. [[CrossRef](#)]
27. Yan, C.; Tang, X.; Wang, S.; Meng, L.; Sun, H.; He, Y.; Wang, L. Proposal for a Realtime Einstein-Synchronization-Defined Satellite Virtual Clock. *Chin. Phys. B* **2024**, *33*, 070601. [[CrossRef](#)]
28. Rose, J.A.R.; Watson, R.J.; Allain, D.J.; Mitchell, C.N. Ionospheric Corrections for GPS Time Transfer. *Radio Sci.* **2014**, *49*, 196–206. [[CrossRef](#)]
29. Su, K.; Jin, S. Three Dual-Frequency Precise Point Positioning Models for the Ionospheric Modeling and Satellite Pseudorange Observable-Specific Signal Bias Estimation. *Remote Sens.* **2021**, *13*, 5093. [[CrossRef](#)]
30. Piester, D.; Bauch, A.; Fujieda, M.; Gotoh, T.; Aida, M.; Maeno, H.; Hosokawa, M.; Yang, S. Studies on Instabilities in Long-Baseline Two-Way Satellite Time and Frequency Transfer (TWSTFT) Including a Troposphere Delay Model. In Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Long Beach, CA, USA, 27–29 November 2007; pp. 211–222.
31. Fujieda, M.; Piester, D.; Gotoh, T.; Becker, J.; Aida, M.; Bauch, A. Carrier-Phase Two-Way Satellite Frequency Transfer over a Very Long Baseline. *Metrologia* **2014**, *51*, 253. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.