Rapid High-Precision VLBI Positioning Observations of GEO Satellites (Postprint)

Authors: Li Ting, Tong Fengxian, Zheng Weimin, Zhang Juan

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Abstract

The rapid development of satellite Earth observation and navigation positioning has created a demand for meter-level or even higher orbit determination accuracy for Geostationary Earth Orbit (GEO) satellites. This paper investigates a method for rapid positioning of GEO satellites using Very Long Baseline Interferometry (VLBI) delay data. First, a theoretical accuracy analysis of VLBI delays is conducted, followed by GEO satellite observation experiments and data correlation processing using the Chinese VLBI Network, and finally positioning calculations for GEO satellites are completed using short-duration VLBI delay data. To address the problem of outliers in the delays that are related to stations and baselines, this paper proposes corresponding detection and correction methods. After the data is corrected and reprocessed, the VLBI residual delay measurement accuracy is approximately 0.16 ns, equivalent to a satellite transverse position error of approximately 0.58 meters. The research in this paper can be applied to rapid high-precision positioning and rapid orbit recovery of GEO satellites.

Full Text

Fast High-Accuracy Positioning of GEO Satellites Using VLBI Observations

Li Ting[1,2], **Tong Fengxian**[1,3], **Zheng Weimin**[1,3,4,5], **Zhang Juan**[1,3]

[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China
[4]National Public Science Data Center for Basic Disciplines, Beijing 100190, China

[5]Shanghai Key Laboratory of Space Navigation and Positioning Techniques, Shanghai 200030, China

Abstract

The rapid development of satellite Earth observation and navigation positioning has created a demand for Geostationary Earth Orbit (GEO) satellite orbit determination accuracy at the meter level or even higher. This paper investigates a method for rapid GEO satellite positioning using Very Long Baseline Interferometry (VLBI) delay data. We begin with a theoretical accuracy analysis of VLBI delays, then conduct GEO satellite observation experiments and data correlation processing using the Chinese VLBI Network (CVN), and finally perform positioning calculations for GEO satellites using short-duration VLBI delay data. To address the problem of outliers related to stations and baselines in the delay data, we propose corresponding detection and correction methods. After data correction and reprocessing, the VLBI residual delay measurement accuracy reaches approximately 0.16 ns, equivalent to a satellite transverse position error of about 0.58 meters. This research can be applied to fast, high-precision positioning and rapid orbit recovery of GEO satellites.

Keywords: differential VLBI; GEO satellite; accuracy analysis; delay correction; fast high-accuracy positioning

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Geostationary Earth Orbit (GEO) satellites orbit at an altitude of approximately 36,000 km with an orbital period matching Earth' s rotation, making them appear stationary relative to ground points within a certain range. These satellites play crucial roles in geodesy, navigation, positioning, and disaster monitoring. However, GEO satellites are subject to various perturbation forces during operation, particularly significant solar radiation pressure on their solar panels, which causes orbital drift and deviation from equilibrium points [1]. To reduce the impact of orbital errors on user positioning accuracy, it is essential to obtain accurate satellite position information as quickly as possible, making research on rapid position measurement methods after GEO satellite maneuvers highly significant.

Currently, line-of-sight position measurement of GEO satellites primarily relies on ranging techniques, including pseudorange and carrier phase measurements, transponder ranging, and laser ranging. High-precision ranging requires satellite-borne transponder signals and represents active measurement, achieving orbit determination accuracy at the hundred-meter level [2]. Factors limiting ranging orbit determination accuracy relate to GEO satellite characteristics: the high orbital altitude and relatively small ground tracking network result in poor observational geometry; the relatively stationary nature weakens dynamic and geometric constraints between satellite and stations, making systematic errors such as clock offsets and station biases difficult to resolve; and frequent orbital maneuvers required to maintain synchronous orbit are challenging to model, complicating subsequent orbit recovery and prediction [2]-[4].

For measuring GEO satellite orbital plane positions, passive methods such as optical imaging or radio interferometry can be employed. These methods offer the advantage of only requiring reception of satellite downlink signals without consuming satellite resources. Very Long Baseline Interferometry (VLBI), with independent local oscillators, is a radio interferometric technique that has been widely applied to deep space probe tracking due to its ultra-high angular resolution and sensitivity [5]. VLBI exhibits high sensitivity for determining satellite transverse positions (perpendicular to the orbital radial plane) and provides geometric constraints on the observed target' s angular position. Differential VLBI technology alternately observes the target spacecraft and nearby compact radio sources, effectively reducing measurement errors from media delays, instrumental delays, and station clock offsets through signal differencing, achieving angular accuracy better than milliarcseconds [6]-[7].

Combining VLBI with ranging techniques can further improve three-dimensional position determination accuracy for GEO satellites. In 1984, Tadashi Shiomi used differential VLBI combined with radio ranging for GEO satellite joint orbit determination experiments, achieving orbital accuracy of approximately 100 meters [8]. In recent years, domestic scholars have conducted simulation experiments and actual measurements on GEO satellites. In 2003, Shu Fengchun utilized two differential VLBI techniques—Delta Differential One-way Ranging (ΔDOR) and Delta Differential One-way Velocity—to conduct China's first GEO satellite VLBI observation experiment, obtaining satellite signal interference fringes but without actual positioning calculations. The experiment' s ΔDOR total error was approximately 41 cm, theoretically equivalent to an 8-meter position error when observing geosynchronous targets with a 2000 km baseline [9]. In 2006, Du Lan' s numerical simulation experiments showed that adding VLBI auxiliary observation data to ranging observations could theoretically improve GEO satellite orbit accuracy to the meter level [3], though no actual experiments were conducted. In 2011, Huang Yong used C-band transponder ranging data and VLBI delay data for integrated orbit determination experiments, achieving post-fit delay data residuals with an RMS of approximately 3.6 ns and delay rate of 0.4 ps/s, equivalent to a transverse orbital position error of about 10 meters [10]. In 2017, Gong Jianjun observed GEO satellites using a broadband VLBI system combined with orbit tracking and two-way range determination, obtaining delay formal errors of approximately 0.14 ns, with repeated orbit determination results showing meter-level standard deviations within the same time period [11], representing internal precision evaluation. None of these experimental results were compared with post-mission precise orbits, so their accuracy could not be assessed.

Given the long recovery time and large deviations after satellite orbital maneuvers, and increasingly higher requirements for GEO satellite orbit determination accuracy, research on rapid, high-precision measurement technology for GEO satellite positions holds significant practical importance. We organized observations of GEO satellites by four stations of the Chinese VLBI Network (CVN) and performed positioning calculations using short-duration VLBI delay measurement data. CVN consists of four observing stations—Tianma (Tm), Beijing (Bj), Kunming (Km), and Urumqi (Ur)—and a data processing center in Shanghai, comprising six observation baselines. This paper first theoretically analyzes the VLBI delay observation accuracy for GEO satellites, then uses approximately four hours of S-band VLBI delay data for satellite positioning calculations. Additionally, we describe in detail the outlier detection and correction methods for VLBI delay results and reprocess the GEO satellite positioning using corrected VLBI delay data and newly developed post-processing software. Comparing the results with post-mission precise orbit data from the International Global Navigation Satellite Systems Service (IGS) provides an external accuracy estimate.

Satellite Differential VLBI Observation Principle and Accuracy Analysis

1.1 Principle of Satellite Differential VLBI Observation

VLBI observables include delay and delay rate—the time delay and its rate of change between signals received by two ground antennas from the same source —including group delay (rate) and phase delay (rate). Differential VLBI technology selects compact radio sources with precisely known positions near the target spacecraft as reference sources, alternately observing the reference source and target spacecraft. Generally, the angular separation is required to be less than 10° [12], with higher observation frequencies allowing larger usable angular separations. Through signal differencing, delay measurement errors can be effectively reduced. Figure 1 [Figure 1: see original paper] illustrates the differential VLBI geometry. In the diagram, 1 and 2 are two observation stations, $\vec{B}$ is the baseline vector formed by the two stations, $\hat{s}$ is the station' s observation direction vector toward the radio source, $\hat{r}_1$ and $\hat{r}_2$ are the station' s observation direction vectors toward the satellite, and τ_g^s is the radio source observation delay.

During measurement, observations follow a "reference source-target satellite-reference source" sequence, with VLBI delay values at times t_1, t_2, and t_3 being $\tau(t_1)$, $\tau(t_2)$, and $\tau(t_3)$, respectively, where superscript s denotes reference source observation and r denotes satellite observation. Through interpolation, the reference source observation at time t_2 can be obtained as $\tau^s(t_2)$. At time t_2, the following relationship holds:

$$\tau^r(t_2) = \tau_g^r(t_2) + \tau_{err}^r(t_2) = \tau_g^r(t_2) + \tau_{err}^r \quad (1)$$

where τ_g is the geometric delay, calculable from a priori values including station coordinates, source coordinates, and Earth orientation parameters. τ_{err} represents the sum of systematic and random errors in observation, including media delay, clock offsets, instrumental delay, and observation noise. The differential VLBI delay observable is:

$$\Delta\tau = \tau^r(t_2) - \tau^s(t_2) = \tau_g^r(t_2) - \tau_g^s(t_2) + \varepsilon_\tau \tag{2}$$

$\varepsilon_\tau(t_2)$ represents the error value at the same observation time. Clock offsets and instrumental delays can be considered approximately equal, and because the observation interval is short and the angular separation between reference source and target is small, media delays differ minimally. Therefore, the differenced ε_τ is an extremely small error term, eliminating the influence of common error sources in VLBI observations that cannot be precisely modeled. The actual VLBI delay value for the satellite is obtained as:

$$\tau_g^r(t_2) = \tau^r(t_2) - \tau_{err}^r(t_2) = \tau^r(t_2) - \tau_{err}^s(t_2) + \varepsilon_\tau \tag{3}$$

Since $\tau_{err}^s(t_2) \approx \tau_{err}^r(t_2)$, we have:

$$\tau_g^r(t_2) \approx \tau^r(t_2) + \Delta\tau \tag{4}$$

$\tau_g^r(t_2)$ contains satellite position information that can be used for positioning.

1.2 Delay Accuracy and Satellite Position Error Analysis

To evaluate satellite position solution accuracy, theoretical analysis of VLBI measurement precision is required. VLBI delay measurement errors mainly include systematic errors from radio source position, station position, Earth rotation parameters, and media, as well as random errors from observation source noise, hydrogen maser clock instability, media fluctuations, and instrumental phase jitter [13].

Radio Source Position Error: VLBI observations select point sources with high positional accuracy from the International Celestial Reference Frame, making the source position delay error in systematic errors an extremely small quantity related to the source' s position accuracy and projected baseline length. The estimation formula is [13]:

$$\varepsilon_{\Delta\tau} = \frac{p \cdot \varepsilon_\vartheta}{c} \tag{5}$$

where p is the projected baseline length in the sky plane, ε_ϑ is the extragalactic source position error, and c is the speed of light. Most source position accuracies are 0.5-2.0 nrad. For a baseline with 3000 km projected length and a source position error of 0.75 nrad, the resulting delay error is approximately 0.0075 ns.

Station Position Error: The station position delay error can be expressed as baseline projection error on the celestial sphere, related to the angle between the radio source and satellite:

$$\varepsilon_{\Delta\tau} = (\Delta\theta) \cdot \frac{\varepsilon_{BL}}{c} \tag{6}$$

where $\Delta\theta$ is the angle between the radio source and satellite, and ε_{BL} is the baseline projection error. Assuming a 0.2 rad separation angle and 0.02 m baseline projection error, the resulting delay error is approximately 0.0067 ns.

Earth Orientation Parameter Error: The effect of Earth orientation parameters on delay is mainly introduced during coordinate system conversion in model calculations, depending on UT1 and polar motion parameter accuracy and proportional to the angle between satellite and reference source:

$$\varepsilon_{\Delta\tau} = (\Delta\theta) \cdot \frac{\varepsilon_{UTPM}}{c} \tag{7}$$

where ε_{UTPM} is the error in UT1 and polar motion Earth orientation parameters, an extremely small value. Assuming a 0.2 rad separation angle and 0.02 m Earth orientation parameter error, the resulting delay error is approximately 0.0067 ns.

Neutral Atmosphere Systematic Error: This error relates to dry and wet tropospheric errors in the zenith direction and the station's observation elevation angle:

$$\varepsilon_{\Delta\tau} = \frac{\sin\gamma_r}{\sin\gamma_s} \cdot \rho_z + 0.015 \cdot \frac{\sin\gamma_r}{\sin\gamma_s} + 0.015 \tag{8}$$

where γ_r and γ_s are the elevation angles of satellite and radio source observations, respectively, and ρ_z is the zenith dry/wet tropospheric error. Assuming a 40° satellite elevation angle, 39° radio source elevation angle, 0.002 m zenith dry tropospheric error, and 0.005 m zenith wet tropospheric error, the delay error from both stations' tropospheric effects is approximately 0.0075 ns.

Ionospheric Systematic Error: Ionospheric systematic error effects on delay error are complex and can be roughly calculated using the Klobuchar model. More accurate station ionospheric information can be obtained if dual-frequency GPS receivers are deployed around observation stations. The typical value for VLBI observation ionospheric delay error is 0.02 ns.

Satellite Thermal Noise Error: GEO satellite thermal noise relates to signal-to-noise ratio, observation channel bandwidth, and integration time:

$$\varepsilon_{\Delta\tau} = \frac{1}{2\pi\Delta f_{BW}} \cdot \frac{1}{SNR} \tag{9}$$

where Δf_{BW} is the satellite observation bandwidth and SNR is the satellite signal-to-noise ratio. GEO satellite data transmission signals typically use single-channel observations with 10 MHz bandwidth. Assuming an SNR of 1000, the resulting delay error is approximately 0.0551 ns.

Station Clock Instability Error: Error from hydrogen maser instability can be expressed as station clock frequency stability during the alternating observation interval:

$$\varepsilon_{\Delta\tau} = T_{r-s} \cdot \frac{\varepsilon_{\Delta f}}{f} \tag{10}$$

where T_{r-s} is the alternating observation time between radio source and satellite, and $\varepsilon_{\Delta f}/f$ is the clock frequency stability. With a 600 s observation interval and clock frequency stability of 10^{-14}, the delay impact is 0.0060 ns.

Instrumental Phase Jitter Error: Delay error from instrumental phase jitter is approximately inversely proportional to total signal bandwidth:

$$\varepsilon_{\Delta\tau} = \frac{\sqrt{2}\varepsilon_{\varphi}}{2\pi f_{BW}} \tag{11}$$

where ε_{φ} is the instrumental phase error and f_{BW} is the total observation bandwidth. Assuming 0.2° phase jitter and 40 MHz total bandwidth, the delay error is 0.0278 ns.

Media Fluctuation Error: Random errors from troposphere and ionosphere relate to fluctuation uncertainties in respective observation directions and the angle between satellite and reference source. These cannot be eliminated through differencing:

$$\varepsilon_{\Delta\tau} = (\Delta\theta) \cdot \frac{\rho_{fluct}}{c} \tag{12}$$

where ρ_{fluct} is the tropospheric or ionospheric fluctuation uncertainty for a 10° separation angle. If both tropospheric and ionospheric fluctuation uncertainties are 0.01 m, their impact on delay is 0.0191 ns each.

The statistical results of these error terms are shown in Figure 2 [Figure 2: see original paper], where red items represent systematic errors, blue items represent random errors, and black items represent the Root Sum Square (RSS) of all error terms. The total RSS error is approximately 0.0720 ns.

The relationship between differential VLBI delay measurement error $\varepsilon_{\Delta\tau}$ and satellite position error ε_{pos} perpendicular to the radial orbital plane satisfies [2]:

$$\varepsilon_{pos} = \frac{L}{B} \cdot c \cdot \varepsilon_{\Delta\tau} \tag{13}$$

where B is the projected baseline length in the sky plane and L is approximately the distance from station to satellite. For GEO satellites, L is about 36,000 km. With a projected baseline length of 3000 km and differential VLBI delay measurement accuracy of 0.0720 ns, the transverse orbital position accuracy is approximately 0.26 meters.

To intuitively evaluate positioning result reliability, experimental results can be compared with post-mission precise orbit data from IGS. Different institutions' GEO precise orbit results inherently show certain differences. Currently, the German Research Centre for Geosciences (GeoForschungsZentrum, GFZ) and Wuhan University (WHU) publicly provide GEO satellite precise orbits with a latency of about ten days. Figure 3 [Figure 3: see original paper] shows the comparison of precise orbit data for Beidou navigation satellite C03 from these two institutions. The horizontal axis represents observation time, and the vertical axis shows coordinate differences between the two institutions' precise orbits. Blue, orange, green, and black scatter points represent differences in X, Y, Z components and three-dimensional coordinates, respectively, with RMS values of 1.09 m, 0.64 m, 0.17 m, and 1.27 m. The maximum three-dimensional coordinate difference is about 1.45 m, indicating that precise orbit data from different institutions contains meter-level discrepancies.

Data Processing and Analysis

2.1 Observation Configuration

We conducted a differential VLBI observation campaign of approximately 4 hours on GEO satellites on January 13, 2018 (UTC), with a beacon frequency of 2.217 GHz. Detailed observation parameters are listed in Table 1 .

Four CVN stations participated in the observations. The longest baseline was the east-west Urumqi-Tianma baseline (Ur-Tm) at approximately 3249 km, while the shortest was the Beijing-Tianma baseline (Bj-Tm) at about 1114 km. Due to GEO satellites' lower altitude compared to extragalactic radio sources and their relative motion of about 15 degrees per hour along the celestial equator, the parallax angles between satellite and nearby reference sources differ among stations and vary with time. To improve observation accuracy, six compact radio sources near C03 satellite were selected from the International Celestial Reference Frame as reference sources. The celestial positions and trajectories of radio sources and satellites are shown in Figure 4 [Figure 4: see original paper].

2.2 Data Processing

After correlation processing of raw observation data using the CVN software correlator scorr, corrected observation delays were obtained [14]. During correlation processing, model delays calculated in advance were used to compensate signals received at two stations, yielding residual delays [15]. Radio source model delays use a far-field model, while satellite model delays use a near-field model based on the satellite' s predicted orbit, both calculated by the Shanghai Astronomical Observatory VLBI Center.

The Fourier transform point number was set to 1024 during correlation processing. The cross-correlation power phase spectrum results for 512 data points in the satellite frequency domain are shown in Figure 5 [Figure 5: see original paper]. The six subplots represent Beijing-Kunming (Bj-Km), Beijing-Urumqi (Bj-Ur), Beijing-Tianma (Bj-Tm), Kunming-Urumqi (Km-Ur), Kunming-Tianma (Km-Tm), and Urumqi-Tianma (Ur-Tm) baselines. The horizontal axis shows frequency in kHz, while the vertical axis shows amplitude spectrum in dB (blue) and phase spectrum in degrees (orange). The correlation processing results demonstrate that all six baselines obtained good interference fringes.

Post-processing results after fitting, clock offset correction, and media correction of the delay data are shown in Figure 6 [Figure 6: see original paper], where the horizontal axis represents observation time and the vertical axis shows residual delay values for six baselines in ns. The post-fit residual RMS values for the six baselines are 2.35 ns, 1.15 ns, 0.39 ns, 0.75 ns, 0.70 ns, and 0.86 ns, respectively, with a mean of 1.03 ns. The figure shows missing values and jumps in residual delay results during certain periods, related to errors introduced by station data and data processing. The sum of residual delay results and model delays constitutes total delay data. Since VLBI is insensitive to satellite radial position, using only total delay data for position solution yields poor accuracy. Therefore, a range constraint method can be applied, assuming the satellite' s geocentric distance equals that calculated from its predicted orbit, with the a priori error of the geocentric distance constraint given by the predicted orbit error [16]. This equation, combined with VLBI observation equations, forms an error equation system to solve for satellite position. Comparison with IGS precise orbit data yields three-dimensional coordinate differences shown in Figure 7 [Figure 7: see original paper]. The coordinate differences are less than 35 meters, with an RMS error of about 16.76 meters. Some time periods in Figure 7 show jumps in satellite positioning results, consistent with periods showing jumps in residual delay results, marked by blue, red, and green circles in both figures.

2.3 Residual Delay Improvement Methods

Delay outliers directly affect final satellite positioning results. To improve satellite position solution accuracy, outlier detection and correction of VLBI residual delay data are necessary to address delay jumps. Outlier causes fall into two categories: (1) station-related errors, such as those introduced by station measurement/recording equipment or residual clock correction components; (2) baseline-related errors introduced during data processing.

Since residual delay data are time series, outlier detection cannot treat samples as isolated points. Polynomial fitting methods and the constraint that theoretical delay closure errors for baselines should be zero are used to detect both outlier types. Fitted residual values for each baseline serve as outlier detection data, with values deviating from the mean by a certain multiple of standard deviation identified as outliers. Flowcharts for station-related and baseline-related outlier detection and correction methods are shown in Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper], respectively, with main steps including: (1) identifying outliers, (2) determining if station- or baseline-related, and (3) calculating and applying correction values.

For station-related outlier detection, we use fitted residual values with a 1-sigma threshold as the outlier detection criterion. If all baselines related to a particular station are marked with outliers during the same time period, the data anomaly is considered station-related. After identifying station-related outliers, station data during anomalous periods are corrected by testing correction values from 0 to the maximum deviation at small intervals (e.g., 0.01 ns), calculating the sum of squared differences between corrected delay measurements and fitted values for all baselines, and selecting the correction value that minimizes this sum.

For baseline-related errors introduced during data processing, the detection and correction method primarily relies on the condition that theoretical delay closure errors for multiple baselines equal zero. With four stations and six baselines, there are four combination methods, such as BK-KU-BU representing Bj-Km, Km-Ur, and Bj-Ur baseline combinations. Delay closure errors are calculated for different baseline combinations, and the average closure error for each scan (scan closure error mean) is computed. With a threshold of 1.25 ns, time periods where scan closure error means exceed the threshold require correction. The correction value is taken as the average of absolute values of baseline combination closure errors. The sign is determined by the scan closure error mean sign and the baseline' s position in the combination. For example, if both BK-KU-BU and BK-KT-BT baseline combinations are marked in a scan, the common baseline BK (Bj-Km) requires correction. If both combination closure error means are positive, BK baseline needs to subtract the correction value; otherwise, it needs to add the correction value. Missing station recording data causes baseline data gaps, and large differences in closure errors among baseline combinations may prevent identification of specific baselines requiring correction, which can be addressed by adjusting the closure error threshold.

Comparison of baseline combination delay closure errors before and after correction is shown in Figure 10 [Figure 10: see original paper], where the horizontal axis represents observation time and the vertical axis shows closure errors in ns. Blue scatter points represent pre-correction closure errors, with poor results in some periods, while red scatter points represent post-correction results that are closer to the theoretical zero value. Pre- and post-correction residual delays are shown as blue asterisks and green circles in Figure 11 [Figure 11: see original paper], respectively, demonstrating that residual delay values become smoother after correction. Post-correction residual delay post-fit RMS values for the six baselines are 0.56 ns, 0.53 ns, 0.31 ns, 0.66 ns, 0.50 ns, and 0.70 ns, respectively, with a mean of 0.54 ns.

2.4 Results Analysis

To further improve satellite positioning accuracy, data were reprocessed, making residual delay data smoother (red line in Figure 11 [Figure 11: see original paper]). Fifth-order polynomial fitting was applied to VLBI residual delay data, with delay accuracy represented by post-fit residual RMS values. The final post-fit residual RMS values for six baselines are 0.16 ns, 0.23 ns, 0.14 ns, 0.14 ns, 0.14 ns, and 0.13 ns, respectively, with a mean of 0.16 ns, equivalent to a transverse orbital position error of about 0.58 meters.

GEO satellite positioning was performed using both corrected and reprocessed total delay data. Comparison of positioning results with precise orbit coordinates is shown in Figure 12 [Figure 12: see original paper], where red asterisks represent pre-correction results, green plus signs represent post-correction results, and blue circles represent new processing program results. After baseline and station delay correction, satellite positioning accuracy improved, particularly for the three time periods with outliers marked in Figure 6. The RMS error of orbit positioning results compared with precise orbits after new post-processing is about 6.61 meters. Statistics for mean residual delay and satellite coordinate RMS errors from the three processing stages are listed in Table 2 .

Experimental results demonstrate that using only 4 hours of short-duration VLBI delay data can achieve meter-level external coincidence accuracy for GEO satellite positioning, facilitating rapid orbit recovery. Comparison with historical experimental results is shown in Table 3 , indicating that this experiment' s narrowband observation delay measurement accuracy shows significant improvement over historical narrowband results and approaches broadband observation accuracy. Moreover, this study is the first to calculate external coincidence accuracy, providing better evaluation of positioning result accuracy. Although differences remain compared with precise orbits, the ability to quickly provide relatively high-precision satellite position information after GEO satellite maneuvers remains significant for reducing orbit error impacts.

Conclusion

VLBI technology for GEO satellite observation leverages VLBI' s high-precision constraint on satellite transverse positions to improve short-term positioning accuracy and facilitate rapid orbit recovery after maneuvers. This paper first theoretically analyzed VLBI delay accuracy, including systematic errors from radio source positions, station positions, Earth rotation parameters, and media, as well as random errors from observation source noise, hydrogen maser instability, media fluctuations, and instrumental phase jitter. The analysis yielded a theoretical differential VLBI delay measurement accuracy of 0.0720 ns, equivalent to a satellite plane position error of about 0.26 meters.

The actual experiment used four CVN stations to observe GEO satellites, obtaining 4 hours of VLBI residual delay data with a post-fit residual RMS mean of 1.03 ns. Visual analysis revealed missing values and jumps in residual delays that affected measurement accuracy. Consequently, we proposed outlier detection and correction methods addressing both station-related and baseline-related anomalies. Reprocessing the corrected data yielded a post-fit residual RMS mean of 0.16 ns. Satellite positioning calculations further validated the correction effectiveness, reducing differences with IGS precise orbits from 16.76 meters to 6.61 meters. This research enables rapid, high-precision GEO satellite positioning using short-duration VLBI observations, promising application for rapid orbit recovery.

Future work may utilize VLBI delay and delay rate data to predict short-term VLBI delay values for subsequent GEO satellite position forecasting research. As the global VLBI observation system continues to improve, more stations and baseline combinations will become available for GEO satellite tracking. Additionally, implementing dedicated DOR beacons or broadband beacons could further improve short-term measurement accuracy and enhance GEO satellite orbit monitoring capabilities.

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