Experimental Study on VLBI Time Transfer Based on GEO Satellite Observation

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***Abstract*—With precise orbits of GEO satellites, the precise time transfer between stations can be realized by VLBI observations of GEO satellite. This can be a new time transfer method independent of GNSS co-view, and can obtain same or even higher time transfer accuracy.**

In this paper, a VLBI time transfer method based on GEO satellite observation is proposed. The time transfer measurement model is established, and the major systematic errors and correction methods are studied. The precise orbits of GEO satelltes which are critical for VLBI measurement model, are determined by GNSS and by the method of Orbit Determination Transfer Tracking (ODTT). The VLBI time transfer experiment was carried out by observing Beidou GEO satellite using Jilin and Sanya stations of the National Time Service Center (NTSC) VLBI network. The GNSS PPP time transfer results are used as a standard for evaluation. The results show that the consistency between VLBI time transfer and GNSS PPP time transfer is consistent within 2 nanoseconds.

Here, we present the preliminary experimental results. Further improvements include: Selection of setellites with larger bandwidth to improve the time transfer accuracy; the correction of satellite antenna phase center to satellite center of mass; the geometric tide correction of stations and other error sources should be investigated in the future.

Keywords—GEO satellite; VLBI; precise time transfer; iGMAS

I. INTRODUCTION

Time is one of the seven basic physical quantities used to describe and study everything. High precision time plays an important role in scientific research, navigation and high-tech industry incluing information, conmunication, transportation, etc. The main technical methods of long-distance time transfer are Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GNSS time and frequency transfer[1,2].

TWSTFT based on the symmetry of the signal transmission path, can largely counteract the impact of the signal path, so it has high accuracy and stability. But this need to rent satellite repeater on communication satellite, causes the limited number of users and high expenses[3]. With the appearance of artificial satellite, especially GNSS, satellite time service has become a new and indispensable means of high precision time transfer. Satellite Common View(CV), All in View(AV), Carrier Phase(CP) and Precise Point Positioning(PPP) technologies has gradually developed. But GNSS time transfer technology is highly dependent on satellite navigation system.

Therefore, it is essential to develop a time transfer technique that independent of TWSTFT and GNSS. The VLBI time transfer based on VLBI observation of GEO satellite was proposed. VLBI is a high accuracy space geodetic technique, that has been widely used in astronomy, astrometry, geodesy, deep space aircraft and near Earth Satellite tracking[4,5,6]. In this paper, we proposed to use VLBI observation of GEO satellites as a tool for time transfer. Here we show the details of this method, and measured results.

II. METHODS

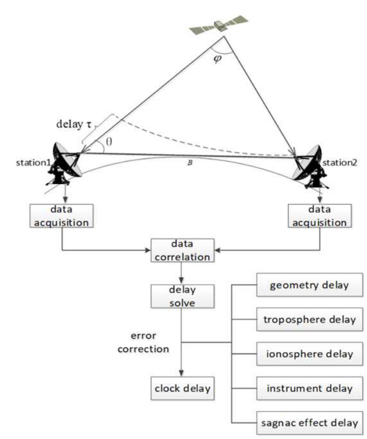

Fig. 1. Schematic diagram of VLBI time transfer method based on GEO satellite observation.

The VLBI time transfer method based on GEO satellite observation can observe any satellite with downlink signal by the passive receiving measurement method of satellite signal, and the observation bandwidth is not limited[7]. The method mainly consists of two steps: Firstly, two antennas are used for interferometric measurement of the satellite, and the time delay observation is obtained through data processing; Then, after error correction, the clock difference between two stations are obtained, realizing the satellite precise time transfer between user stations, as shown in Fig. 1.

II.I Satellite interferometry

As shown in Fig. 1, station1 and station2 both equipped with receiving antennas to receive signal from the same satellite at the same time, collect and record data, then summarize and process the observed data, obtain delay τ.

Assuming that the signal received by the two stations are x(t) and y(t), the cross-correlation function is defined as:

$$c_{xy} = \int_{-\infty}^{\infty} x(t)y(t-\tau)dt \qquad (1)$$

Assuming the frequency is f, transform the time domain functions x(t) and y(t) into the frequency domain by Fourier transform as:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-2\pi f\tau}dt \qquad (2)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t)e^{-2\pi f\tau}dt \qquad (3)$$

Therefore, the cross-power spectrum can be derived as follows:

$$C_{xy}(f) = X(f)Y^*(f) \qquad (4)$$

In (4), Y*(f) is the complex conjugate of Y(f). The inverse Fourier transform of the cross-power spectrum Cxy(f) is the cross-correlation function:

$$c_{xy}(\tau) = \int_{-\infty}^{\infty} X(f)Y^*(f)\, e^{2\pi f\tau}df \qquad (5)$$

Delay τ can be obtained by calculating the maximum value of the cross-power spectrum or cross-correlation function[8].

II.II Error correction

The delay τ of satellite interferometry mainly consists of geometric delay τ_g, clock difference between stations τ_{clk}, instrument delay τ_{inst}, tropospheric delay τ_{trop}, ionospheric delay τ_{iono} and Sagnac effect delay τ_{sag}, as shown in (6) :

$$\tau = \tau_g + \tau_{clk} + \tau_{inst} + \tau_{trop} + \tau_{iono} + \tau_{sag} + \tau_\varepsilon \qquad (6)$$

In (6), τ_ε is random error.

The geometric delay τ_g can be calculated from precision satellite orbit and station coordinates. Since the satellite is close to the Earth, its radio waves are approximated as spherical waves rather than plane waves, as shown in Fig. 1. The delay of signals reaching the two antennas are as follows:

$$\tau_g = B/c \cdot (cos\theta - sin\theta(1 - cos\varphi)/sin\varphi) \qquad (7)$$

In (7), θ is the included angle between the received satellite signal and the baseline, B is the baseline length, c is the speed of light, and φ is the included angle of received satellite signals between two stations.

After the electromagnetic wave arrives at antenna, instrument delay will occur in the transmission process of receiver, RF channels, data acquisition devices and cables. In this paper, our experiment plans to conduct calibration and modeling of instrument delay before formal observation.

Tropospheric delay is the main factor of neutral atmosphere delay, it is mainly composed of dry atmospheric delay and wet atmospheric delay. The contribution of dry and wet atmospheric delay to total tropospheric delay is 90% and 10%. The zenith dry atmospheric delay is usually about 2.3m. Wet atmospheric delay is caused by the presence of water vapor and differs a lot in different areas. The total zenith delay is given by (8), where ε is the observed elevation angle, τ_t is the total zenith delay, τ_{dry} and τ_{wet} are dry and wet atmospheric delays, and M is the mapping function.

$$c\tau_t(\varepsilon) = \tau_{dry}M_{dry}(\varepsilon) + \tau_{wet}M_{wet}(\varepsilon) \qquad (8)$$

The zenith data is modeled to obtain the sight direction data of the station.

Since satellite are usually single frequency observations, The ionospheric delay τ_{iono} in the direction of satellite line of sight is usually calculated by using the global single-layer ionospheric model. The ionospheric delay is calculated by equation (9), where VTEC is the total electron column density in the zenith direction, in unit of TECU (Total Electron Content Unit), f is the signal frequency, $M_i(EL)$ is the mapping function. It can be seen from (9) that the ionospheric delay are related to frequency.

$$\tau_{iono} = 40.28 \times VTEC \times f^{-2} \times M_i(EL) \qquad (9)$$

Sagnac effect is a relativistic effect. When the satellite signal reaches the ground station, the space propagation path of the signal changes due to the rotation of the earth and the movement of the satellite, resulting in sagnac effect. In satellite time transfer, sagnac effect should be considered and corrected. The satellites observed in this experiment are GEO satellites, and the observation stations are not on the equator. The calculation principle of delay caused by Sagnac effect of a single station is shown in Fig. 2.

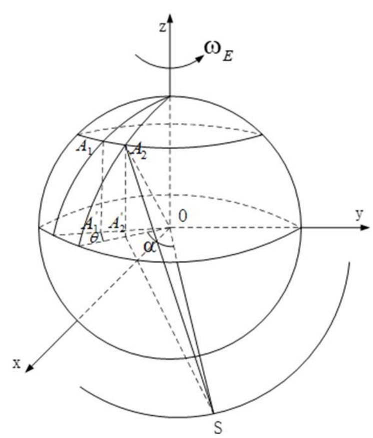

Fig. 2. Sagnac effect calculation schematic diagram of GEO satellite.

As we can see from Fig. 2, due to the influence of relativistic effect, the satellite S sends out a signal at the moment t_0, and the ground station A is at the position A_1. However, when the signal reaches the ground station, the ground station A is already at the position A_2 at the moment t_1. Since the earth station is not on the equator, it is necessary to make a projection of the earth station on the equator. The projections of A_1 and A_2 on the equator are A_1' and A_2', and the latitudes of A_1 and A_2 are φ_A. ω_E is the angular velocity of the earth's rotation; OS is the altitude of the satellite from the earth's center; α is the difference between the longitude of the position of S and station

A; θ is the angle of the earth's rotation during the period from the satellite to the ground station[10,11].

Using sagnac effect calculation model in geocentric inertial system, sagnac effect delay τ_{sag} of station A can be obtained as follows:

$$\tau_{sag} = -\frac{\omega_E}{c^2} \cdot OS \cdot sin\alpha \cdot R \cdot cos\varphi_A \quad (10)$$

In (10), the minus sign indicates that the signal travels in the opposite direction of the earth's rotation, c is the speed of light, and R is the radius of the Earth.

III. RESULTS

We used Jilin(JL) and Sanya(SY) stations of the NTSC(National Time Service Center) VLBI network to carry out the time transfer experiment. Each station is equipped with a 13-meter antenna, a double-circularly polarized wideband refrigerating receiver with a frequency band of 1.2-9GHz, VLBI backends, and a hydrogen clock, etc. In order to evaluate the VLBI time transfer experiment, geodetic GNSS receiver was installed at each station, with the hydrogen clock served as time and frequency source for both VLBI and GNSS system. The GNSS measurement data of each station is transferred online to iGMAS Xi'an Data Center for unified data processing.

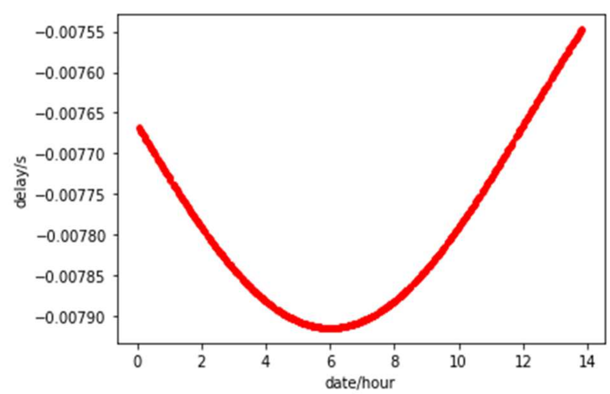

Fig. 3. C02 delay of JL-SY baseline.

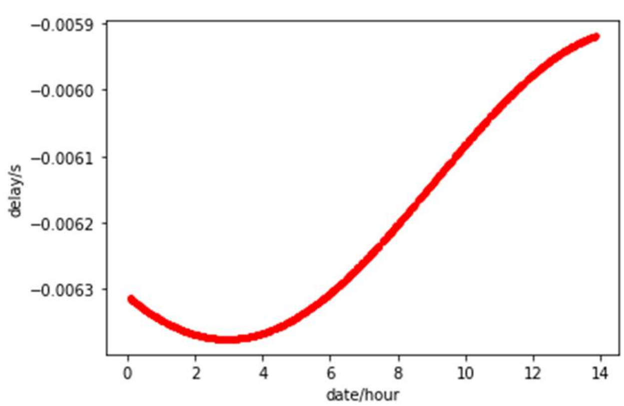

Fig. 4. C03 delay of JL-SY baseline.

On March 23-24, 2021, the Jilin and Sanya stations conducted single-frequency observation of two Beidou GEO satellites named C02 and C03, when March 23 observed C02, and March 24 observed C03. After the observation, we conducted correlation processing on the observation data, and obtained the delay sequences of the two satellites, as shown in Fig. 3 and Fig. 4.

According to (6), the main correction items includes geometric delay correction, instrument delay calibration, ionospheric and tropospheric correction using iGMAS ionospheric and tropospheric products. After error correction, the clock difference between stations is obtained, as shown in Fig. 5 and Fig. 6, realized VLBI time transfer.

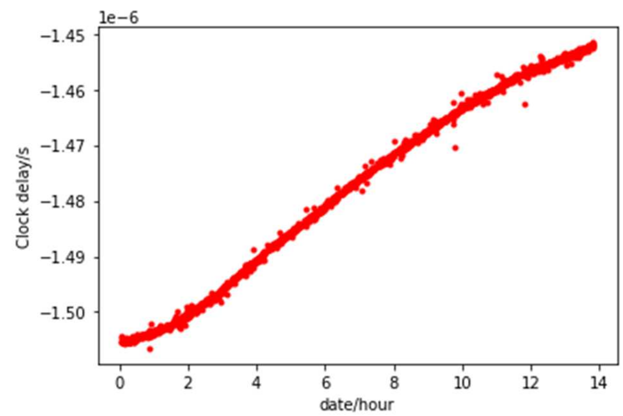

Fig. 5. JL-SY clock difference between stations by C02 observation.

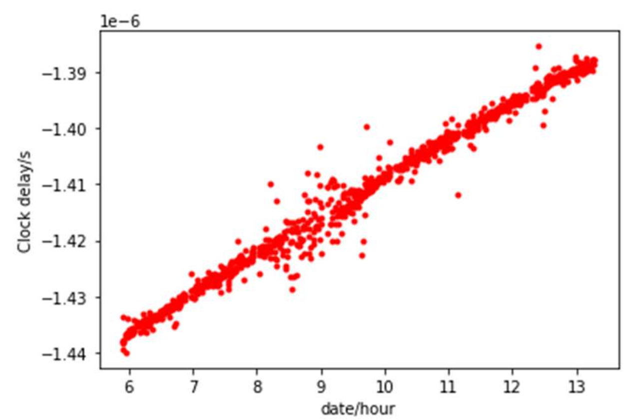

Fig. 6. JL-SY clock difference between stations by C03 observation.

In order to evaluate the accuracy of VLBI time transfer, the VLBI clock difference was compared with GNSS PPP clock difference, and was shown in Fig. 7 and Fig. 8. As can be seen from the figures, the observation results of different satellites are different. C02 satellite has a higher measurement accuracy, and the consistency between VLBI time transfer and GNSS PPP time transfer is consistent within 0.4 nanosecond, where C03 satellite is consistent within 1.8 nanosecond, because the lower SNR.

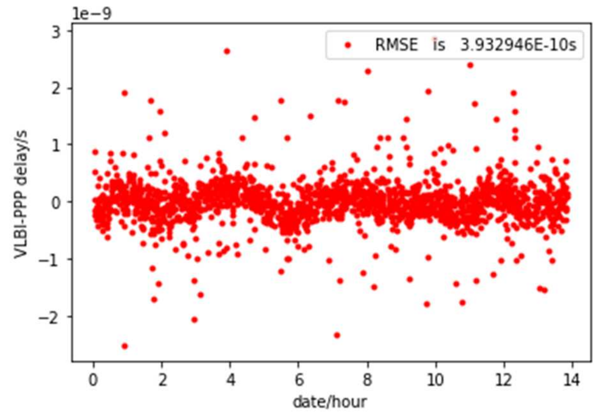

Fig. 7. JL-SY time transfer comparison results by C02 observation.

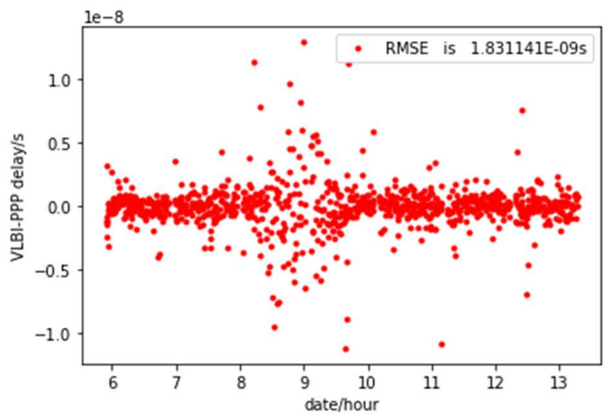

Fig. 8. JL-SY time transfer comparison results by C03 observation.

IV. Conclusions

The experimental results show that it is feasible to use the VLBI technology for time transfer, and VLBI GEO satellite observation can achieve precise time transfer. The consistency between VLBI time transfer and GNSS PPP time transfer is on the order of nanosecond to subnanosecond. In this paper, the existing 13 meter antennas are used for experimental research, and the subsequent research will be carried on small aperture antenna (smaller than 3.7 meter), in order to lower the threshold of VLBI time transfer. The accuracy of time transfer between stations can be further improved by selecting larger bandwidth satellites and improving the accuracy of error correction.

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