



# The Synchronization of Time for VLBI Observations

Lei Liu<sup>1,2,3</sup> , Juan Zhang<sup>1,2,3</sup>, Maoli Ma<sup>1</sup>, and Weimin Zheng<sup>1,2,3,4</sup>

<sup>1</sup> Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; [liulei@shao.ac.cn](mailto:liulei@shao.ac.cn), [zhwm@shao.ac.cn](mailto:zhwm@shao.ac.cn)

<sup>2</sup> Key Laboratory of Radio Astronomy and Technology, Chinese Academy of Sciences, Beijing 100101, China

<sup>3</sup> Shanghai Key Laboratory of Space Navigation and Positioning Techniques, Shanghai 200030, China

<sup>4</sup> National Basic Science Data Center, Beijing 100190, China

Received 2024 September 3; revised 2025 January 7; accepted 2025 January 29; published 2025 February 28

## Abstract

For some space radio telescopes, the orbit determination accuracy is not high enough, the time synchronization accuracy provided by the satellite platforms is low, and GNSS devices are not available. As a result, a traditional method that relies on GNSS devices to obtain an initial clock offset followed by performing correlation with the calibration source may fail to obtain fringes. Moreover, a brutal force search across the 2D clock offset and fringe rate search plane is computationally expensive. In light of these challenges, we propose a novel time synchronization method that utilizes the spacecraft's telemetry tone signal. This method employs frequency polynomials derived from Doppler tracking for fringe rotation during the correlation process. By aligning the frequency of the target station precisely with that of the reference station, it is only necessary to split the clock offset search range into multiple time windows, perform correlation for each window, and identify the window with the highest signal-to-noise ratio (SNR). The precise clock offset is determined by combining the residual delay with the initial offset. To validate the method, we observe the Tianwen-1 telemetry signal with the 4.5 m small telescope in the Tianma campus of Shanghai Astronomical Observatory and 40 m telescope in Kunming. The results demonstrate that our method can accurately determine clock offset for a time range as wide as  $\pm 10$  ms, with an SNR slightly higher than that achieved with the delay model. This method is suitable for wide-range time synchronization for space Very Long Baseline Interferometry observations, especially in scenarios involving small antennas with low sensitivity and poor orbit determination accuracy.

*Key words:* instrumentation: interferometers – methods: data analysis – space vehicles: instruments – techniques: high angular resolution

## 1. Introduction

Very Long Baseline Interferometry (VLBI), renowned for its unparalleled angular resolution (Thompson et al. 2017), is extensively utilized across astrophysics (Event Horizon Telescope Collaboration et al. 2019), astrometry (Schuh & Behrend 2012), and deep space exploration (Duev et al. 2012). Ground-based VLBI faces a natural limitation: the Earth's diameter. To achieve even higher angular resolution, extending baselines beyond Earth becomes essential. This can be accomplished by deploying stations in space and performing either space-ground or space-space VLBI observations. At present, there are two dedicated space VLBI projects that have been implemented: VSOP (Hirabayashi et al. 1998, 2000) and RadioAstron (Kardashev et al. 2012). Numerous countries are actively advancing their own space VLBI projects (Wild et al. 2009; An et al. 2020; Gurvits et al. 2021). In the long run, space VLBI is the trend of VLBI technology (Gurvits 2018).

In the actual VLBI data processing, an accurate clock offset for each station is required. The residual delay derived by fringe fitting combined with the initial clock offset yields the accurate value. For ground stations, initial clock offset is

usually obtained via GNSS devices with an accuracy of microseconds, which guarantees that fringes could be detected for the calibration source. Fringe fitting on the correlation result further improves the accuracy to the level of nanoseconds (Thompson et al. 2017). In this way, time synchronization is performed across stations.

For space VLBI, time synchronization is more challenging. In previous space VLBI projects, for both VSOP and RadioAstron, timestamps of data received by the space antenna were added at the ground tracking station in real time transmission mode. Therefore time synchronization between the space and ground stations was actually not necessary. However, with the development of space radio astronomy technology, for a space VLBI telescope in the near future, the observation bandwidth is expected to be several GHz (Johnson et al. 2024), which leads to a data recording rate of more than ten Gbps. Obviously, it will be more convenient to add a timestamp in space with the onboard data recording system and perform downlink transmission afterwards. As a result, the time synchronization of a space telescope is a problem that must be solved, especially when the space station is outside of the

coverage of GNSS satellites, and the space-ground time synchronization accuracy provided by the satellite platform is only in the order of milliseconds, or even worse. For a typical bandwidth of 32 MHz, to cover such a large delay search window, 1280 K or even higher FFT size is required, which is unreasonably large for VLBI correlation. Moreover, for Earth orbit spacecraft, the typical orbit determination accuracy is several hundred meters for position and tens of centimeters per second for velocity (Likhachev et al. 2017). The corresponding fringe rate uncertainty in the X band is in the order of 10 Hz. To deal with such a large search space, one natural solution is first dividing the delay and delay rate search range into two-dimensional grid points by adjusting the clock offset and rate and then performing correlation and fringe fitting for every grid point. However, to ensure a sufficient signal-to-noise ratio (SNR), the grid size, especially the delay rate interval, must be sufficiently small, which leads to a significant computational burden. Furthermore, as pointed out by Likhachev et al. (2017), data processing of space VLBI must consider the acceleration term, otherwise, the variation in velocity will make the long-term integration impossible. These factors limit the feasibility of brutal force 2D grid search.

In this paper, we propose a novel time synchronization method based on spacecraft’s telemetry signals. The basic idea is: first extracting the accurate frequency of the main carrier tone through Doppler tracking, then performing polynomial fit on the extracted frequencies as a function of time. In the correlation step, performing the fringe rotation by utilizing the frequency polynomial obtained in the previous step. Since frequencies are fully aligned in the fringe rotation stage, it is only necessary to split the whole clock offset search range to a series of search windows, and then perform correlation and fringe fitting for each window. This method only requires a 1D search for clock offset, which significantly reduces the computational burden compared to the 2D search. Moreover, this method avoids the influence of the acceleration term, thus making long-term integration possible.

Compensating for the Doppler shift and then performing long-term integration to enhance SNR is a common treatment for spacecraft signal data processing (Duev et al. 2012, 2016). In the standard two/three-way Doppler measurement for spacecraft, a reference tone signal is transmitted from the ground tracking station to the spacecraft. Then the signal is coherently converted to a new frequency specified by multiplying a fixed factor and is transmitted down to the ground tracking station. Due to the relative motion between the tracking station and the spacecraft, the frequency of the received signal varies with time. One has to realize that this Doppler shift cannot be compensated by the VLBI delay model. As a result, the correlated cross-spectrum is smeared, which severely reduces the SNR of the tone signal. In this sense, Doppler tracking and phase polynomial compensation is the only way to mitigate the frequency smearing and make

long-term integration possible. SFXC (Keimpema et al. 2015) developed by the JIVE perform phase polynomial correction to compensate for the Doppler shift, so as to avoid spacecraft signal’s frequency smearing (Duev et al. 2012). M. Ma & Y. Sun (2024, in preparation) employ a similar approach for the data processing of Tianwen-1 (Zou et al. 2021) signal by CVN observation (Zheng 2015), and perform radio imaging based on that, so as to obtain the high precision angular position of the spacecraft.

This paper is organized as follows: In Section 2, we introduce our spacecraft’s telemetry tone signal-based synchronization method; in Section 3, verification of the method with Tianwen-1 VLBI observation is presented; in Section 4, the whole work is concluded.

## 2. Description of the Method

The data flow of the synchronization method is presented in Figure 1. First of all, frequency polynomials of the main carrier tone for both reference and target stations are derived by Doppler tracking. Meanwhile, the time search window and the corresponding initial clock offset for each window are prepared. Correlation is carried out for the IF that contains the main carrier tone. One special treatment is that in the correlation process, the frequency polynomial derived by Doppler tracking is employed in the fringe rotation step for both target and reference stations. The accurate initial clock offset is determined in the window that yields the highest SNR in the fringe fitting process. Note that the Doppler tracking-derived frequency polynomial can be used for all IFs. However, since the main purpose of this method is to find out the accurate initial clock for time synchronization, in the current demonstration, correlation is performed only for the IF that contains the carrier tone.

### 2.1. Doppler Tracking of the Carrier Tone

We take a similar idea for Doppler tracking as that in STrack (Molera Calvés et al. 2021), but with distinct and independent implementation. In STrack, the whole Doppler tracking procedure is divided into three parts: software spectrometer (SWspec), Multi-tone spacecraft tracker (STrack), and digital Phase Locked Loop (dPLL). Our main purpose for Doppler tracking is to obtain the frequency polynomial, which is implemented in SWspec. One thing we want to point out is, that SWspec obtains the frequency of the spacecraft carrier tone by performing a large number of FFT, which achieves an accuracy of sub-Hz, and so does the frequency polynomial. After that STrack performs phase polynomial correction to compensate for the Doppler shift, and then signal filtering to obtain the narrow band data for each tone. The final micro Hz accuracy is achieved by performing dPLL (Deng et al. 2021) on the narrow band data. Different from Molera Calvés et al. (2021), in our implementation, after

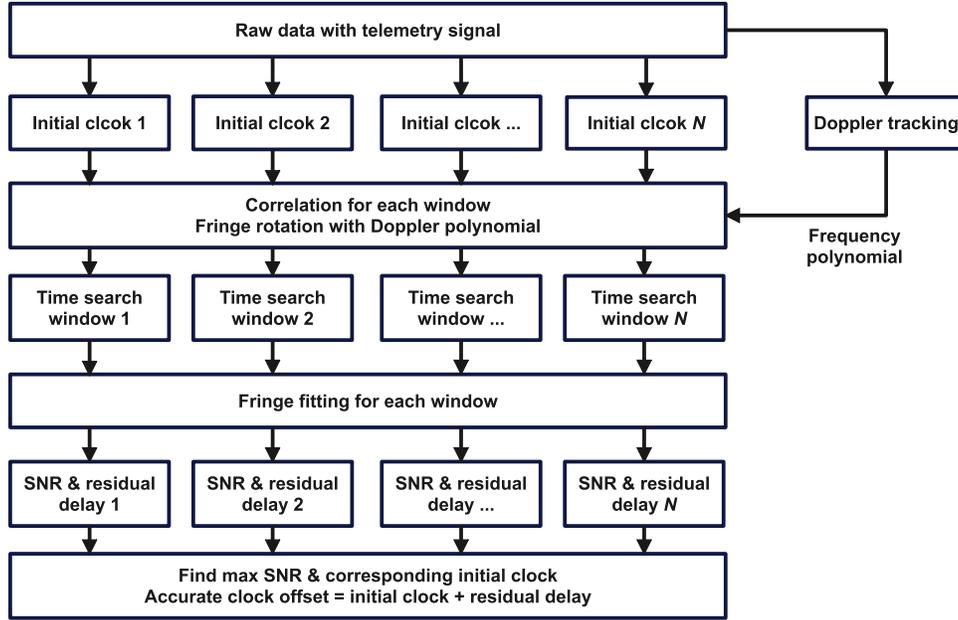


Figure 1. Dataflow of the synchronization method.

obtaining a raw Hz accuracy tone frequency by performing a large number of FFT, the tone is Doppler shifted based on this raw value. dPLL calculation is performed to obtain micro Hz accuracy for this tone. The frequency polynomial is fitted based on these high-accuracy Doppler measurements, which effectively improves the polynomial accuracy.

## 2.2. Determination of Search Window

According to correlation theory, once the sample rate and the FFT number are fixed, the largest delay search range is:  $[-t_{\text{FFT}}/2, t_{\text{FFT}}/2)$ , in which  $t_{\text{FFT}} = t_{\text{sample rate}} \times n_{\text{FFT}}$  is the size of the search window. In the actual implementation, we choose a time window search step of  $t_{\text{FFT}}/4$ , such that the search windows are 3/4 overlapped. As a result, the correct clock offset might be caught in several windows. The highest SNR appears in the window that yields the smallest residual delay.

## 2.3. Correlation and Fringe Fitting

In this work, we perform correlation by utilizing the self-developed CVN software correlator (Zheng et al. 2010). By modifying the correlator, we perform fringe rotation with the frequency polynomial obtained in Section 2.1. In this way, frequencies of distinct stations are aligned, which mitigates the frequency smearing. Other steps are kept unchanged in the correlator. Raw data of the target station with multiple initial clock offsets are correlated with that of the reference station, and the resulting integrated visibility data are saved.

The post-processing step involves fringe fitting for the cross-spectrum generated with multiple initial clock offsets. The time

window that yields the highest SNR is selected. The accurate clock offset is obtained by summing the residual delay with the corresponding initial clock offset.

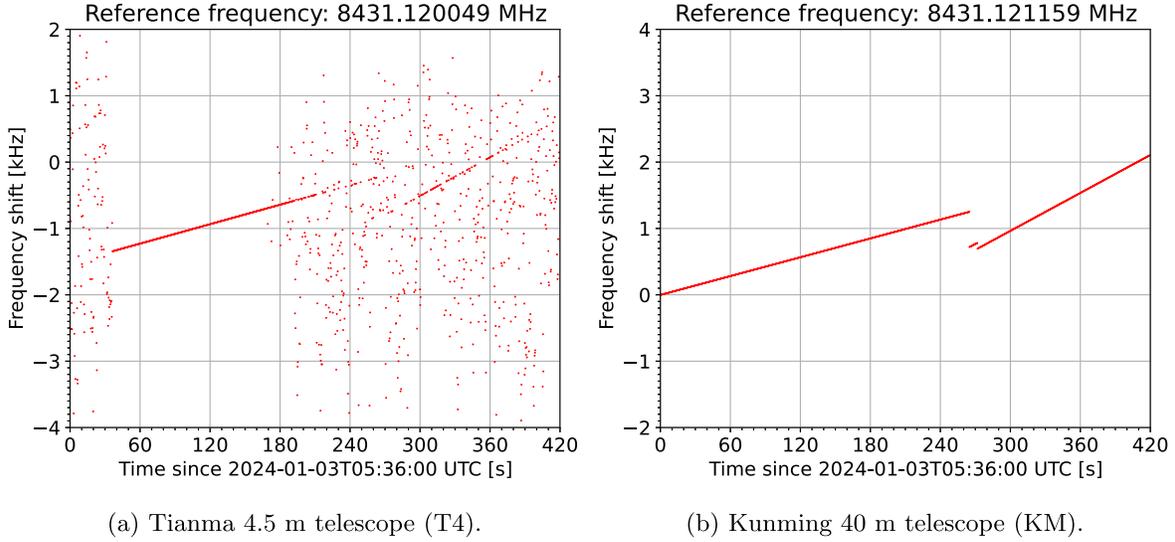
## 3. Verification with Observation

The effectiveness of the synchronization method is verified with actual observation data. In this section, we present the observation setup and make comparisons between the results obtained with Doppler tracking frequency polynomials and regular delay models.

### 3.1. Observation Setup

Due to the constraints of the space environment, the aperture of space telescopes is usually small, which leads to low sensitivity. To improve the baseline SNR, one method is to perform interferometric observation with ground-based large telescopes. To simulate the scenario of joint observations of ground stations with small space telescopes, the Shanghai Astronomical Observatory builds a 4.5 m small telescope at the Tianma Radio Telescope campus and incorporates it into regular CVN observations. We select one of these observations to verify our time synchronization method. The main parameters for the selected observation are presented in Table 1.

The Doppler tracking of Tianwen-1 main carrier tone is performed for T4 and KM stations. Then correlation is done for the T4-KM baseline for the IF that contains the SC's main carrier tone. As a demonstration of our time synchronization



**Figure 2.** Doppler tracking result of Tianma 4.5 and Kunming telescopes. The reference frequency corresponds to the zero-point of frequency shift along the y-axis. Data in the time range of 60–180 s are used for correlation and further processing.

**Table 1**  
Main Parameters of Verification Observation

Parameter	Setting
Code	s4103x
Stations	TM (Tianma 65 m), KM (Kunming), UR (Urumqi), T4 (Tianma 4.5 m)
Frequency setup	X band, 4 IFs, 4 MHz per IF
Time	2024 Jan 3, 5:00 to 7:00 UTC
Target	Tianwen-1

method, 7 minutes of data starting at 05:36 UTC of T4-KM baseline are inspected.

### 3.2. Data Processing Result

For the data taken from the CVN observation, the accurate clock offset is acquired in advance through regular correlation with a large FFT number. We introduce a 7 ms bias to the accurate clock offset of the T4 station in the correlation configuration file, which is used as the initial clock for method validation.

We perform Doppler tracking and polynomial fit for the main carrier tone of Tianwen-1 for T4 and KM. Figure 2 presents the result. The variation of frequency as a function of time is derived using the method described in Section 2.1. In short, first of all, a large number of FFT is performed in the IF that contains the SC's main carrier tone. The raw Hz level accuracy tone frequency is obtained as the frequency point with the highest power. Note that the inspection is performed in a narrow band range ( $\pm 3000$  Hz) around the a priori frequency of

the main carrier tone, so as to avoid selecting the wrong RFI signal. After that, the dPLL is performed to obtain the tone frequency of mHz level accuracy: all sampling points within a given time range (e.g., 1 s) are Doppler shifted according to the raw tone frequency. Then the Doppler-shifted signals are divided into short time segments of length  $\Delta t_{\text{phase}}$  and are coherently summed within each time segment to obtain the varied phases that are caused by the residual Doppler shift (the discrepancy between actual tone frequency and the raw one). The residual Doppler shift is fitted for each longer time segment of length  $\Delta t_f$  that contains several hundred varied phase sampling points. The setting of  $\Delta t_{\text{phase}}$  and  $\Delta t_f$  must be appropriate to sample the maximum residual frequency and track the evolution of the Doppler shift. For the data used in this work, they are set to 0.5 ms and 0.25 s, respectively.

The sensitivity of the 4.5 m telescope (T4) is low, which leads to the large scatter in the time–frequency diagram. As a comparison, the signal quality of KM is much better. Note there is a break at 250 s of KM station, which is due to the change of ground tracking station. Two tracking stations, located at different places on Earth, experience distinct relative velocities with respect to the satellite. This leads to unique Doppler frequency shift trends over time for each station. A similar break is also observed in the T4 data, albeit with a significantly larger scatter. Obviously the data quality of T4 determines whether fringes could be detected for the T4-KM baseline. By inspecting the Doppler tracking result, we select data from 60 to 180 s for correlation and further processing.

According to the actual requirement, the clock offset search range is set to  $\pm 10$  ms, which is obviously too large to be covered by a single pass correlation with a large FFT number

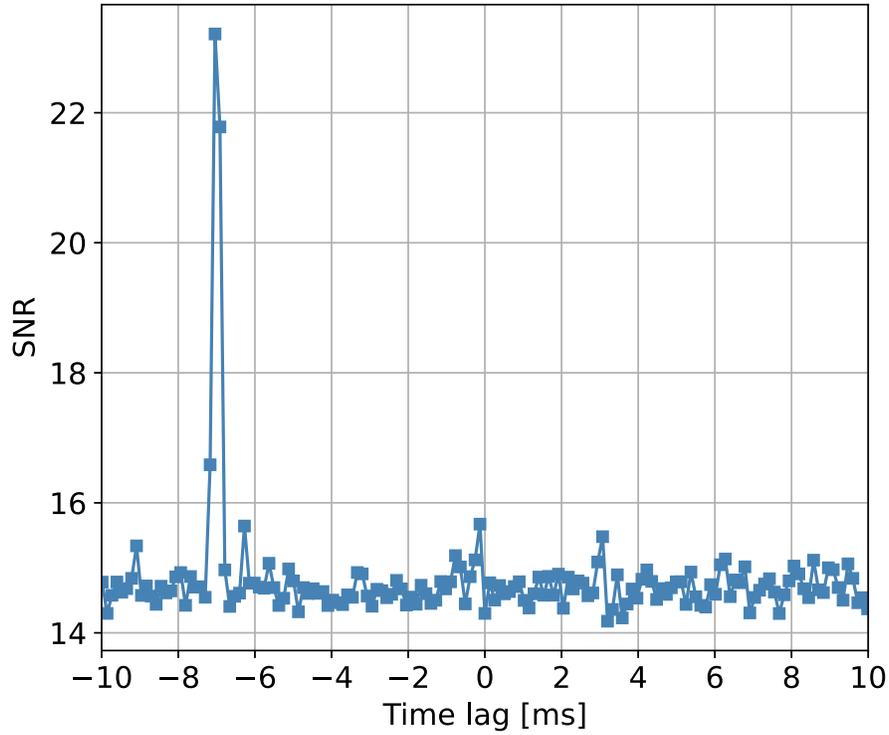
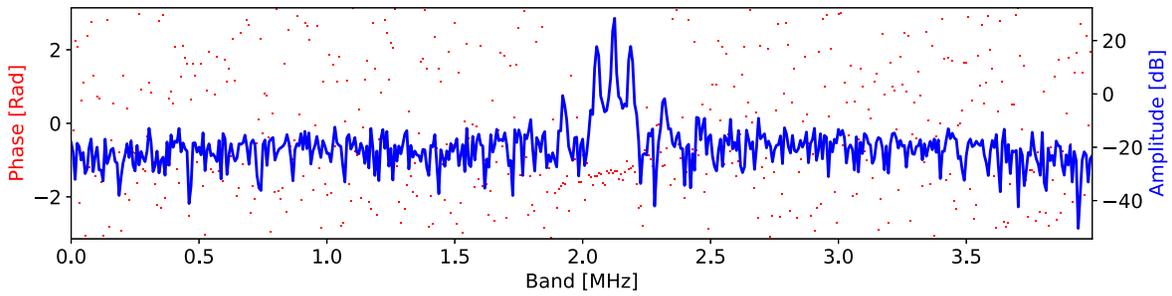
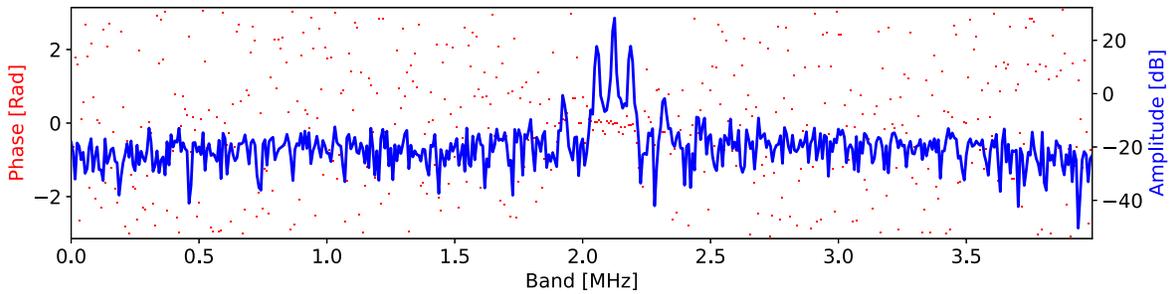


Figure 3. The derived SNR of correlation result as a function of initial clock offset.

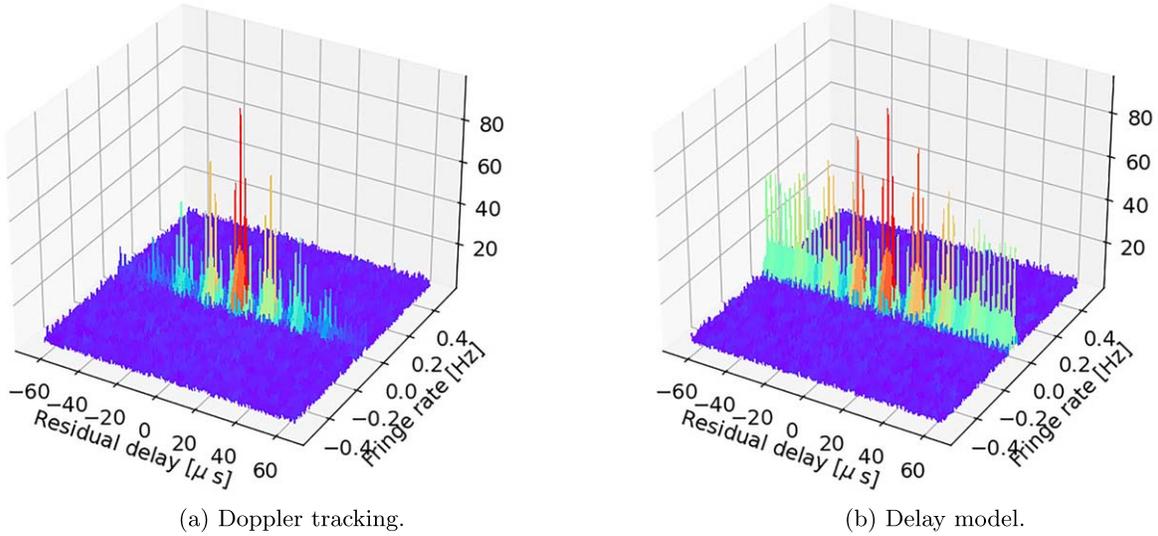


(a) Raw.



(b) Fringe fitted.

Figure 4. The raw and fringe fitted cross-spectrum with accurate clock offset.



**Figure 5.** Fringe fitting results for correlations of 1024 FFT points.

and is, therefore, more suitable for a multiple-time window search. For correlation, the FFT number is set to 4096. According to Section 2.2, a step size of 0.128 ms ( $\frac{1}{4}t_{\text{fft}}$ ) is set for the 4 MHz bandwidth (per IF). For the  $\pm 10$  ms search range, 157 windows are prepared. In each window, raw baseband data are correlated according to its corresponding initial clock.

Figure 3 presents the SNR of the correlation result as a function of the initial clock offset. The highest SNR appears at the offset of  $-7$  ms. This is consistent with our initial offset setup, which suggests that the large clock is correctly identified with our synchronization method.

By adjusting the clock according to the offset found in Figure 3, correlation is performed again to achieve a higher SNR. The result is presented in Figure 4. Fringes are clearly detected in the KM-T4 baseline. One may find that the fringe phase is quite flat before fringe fitting, which indicates the synchronization accuracy is very high, resulting in a small residual delay after correlation.

### 3.3. Comparison with Delay Model

Theoretically, fringe rotation employing frequency polynomial within the correlation process can effectively mitigate frequency smearing, thereby enhancing the SNR. To validate this hypothesis, we perform two sets of correlations utilizing distinct fringe rotation schemes: (a) Doppler Tracking: fringe rotation using frequency polynomial derived from Doppler tracking; (b) Delay Model: fringe rotation using the standard VLBI delay model. The fringe fitting results for the above two data sets are presented in Figure 5. When performing correlation, we realize that the derived SNR in fringe fitting is related to the size of FFT in correlation. Therefore,

**Table 2**  
FFT Size Used in Correlation and the Corresponding SNR for Doppler Tracking and Delay Model

FFT Size	512	1024	2048	4096
Doppler tracking	21.773	29.627	21.286	25.258
Delay model	19.248	20.029	21.314	25.169

relationships between the FFT size and the corresponding SNR are presented in Table 2. According to the result, for three out of four FFT sizes, SNR with frequency polynomials in the fringe rotation step (scheme a) is slightly higher, which can be explained as the frequency of the carrier tone is better aligned. This is consistent with our expectations, although the difference is not so significant. One possible reason might be that the current total integration time is not long enough. However, it is difficult to further increase the total integration time based on the currently available Doppler tracking data of small telescope.

## 4. Conclusion

In VLBI data processing, to detect fringe, the clocks of two stations must be synchronized with high accuracy. However, for some space telescopes, due to the constraints of satellite platforms, the time synchronization accuracy is low. Moreover, compared with ground-based stations, the speed of space stations is much higher, which leads to large Doppler shifting. When the orbit determination accuracy is not high enough, it is difficult to fully compensate for the Doppler shifting with the derived delay model. As a result, even if the onboard clock is fully synchronized, the fringe is still not detectable.

In this paper, we propose a novel time synchronization method, so as to find out the accurate clock offset of a space telescope in a large time search range. The basic idea is: first obtain the frequency polynomial of the spacecraft's telemetry tone signal via Doppler tracking, then perform fringe rotation with this frequency polynomial in the correlation process. Since the frequencies of each station are fully aligned, it is not necessary to search for the delay rate in the following steps. All the computational resources could be devoted to the clock search of the target station relative to the reference station. In this work, the large clock search range is divided into multiple-time search windows based on the sampling rate and FFT size. By performing correlation and fringe fitting in each window, the window that yields the highest SNR is selected. The accurate clock offset is derived by combining the initial clock offset in the corresponding time window and the residual delay.

We use the VLBI observation data from the 4.5 m small antenna in the Tianma campus (T4) and the Kunming (KM) 40 m antenna to verify this method. The results demonstrate that this method is able to accurately determine the clock offset within the predefined time search range  $\pm 10$  ms, and can be applied to scenarios with low sensitivity of small space antennas. Compared with conventional fringe rotation using the delay model, the SNR with our method is slightly higher since the frequency smearing effect is eliminated, which can be regarded as an advantage of the method.

### Acknowledgments

This work is supported by the National Key Research and Development Program of China (grant No. 2022YFC2205203), the National Natural Science Foundation of China (grant No.

42241118), the Strategic Pilot Study Program of the Chinese Academy of Sciences (grant No. XDB0800103), and the Key Incubation Project of Shanghai Astronomical Observatory, CAS.

### ORCID iDs

Lei Liu  <https://orcid.org/0000-0002-2920-1880>

### References

- An, T., Hong, X., Zheng, W., et al. 2020, *AdSpR*, **65**, 850  
 Deng, T., Ma, M.-L., He, Q.-B., et al. 2021, *RAA*, **21**, 220  
 Duev, D. A., Molera Calvés, G., Pogrebenko, S. V., et al. 2012, *A&A*, **541**, A43  
 Duev, D. A., Pogrebenko, S. V., Cimò, G., et al. 2016, *A&A*, **593**, A34  
 Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019, *ApJL*, **875**, L1  
 Gurvits, L. I. 2018, in Proc. 69th Int. Astronautical Congress (IAC 2018)  
 Gurvits, L. I., Paragi, Z., Casasola, V., et al. 2021, *ExA*, **51**, 559  
 Hirabayashi, H., Hirose, H., Kobayashi, H., et al. 1998, *Sci*, **281**, 1825  
 Hirabayashi, H., Hirose, H., Kobayashi, H., et al. 2000, *PASJ*, **52**, 955  
 Johnson, M. D., Akiyama, K., Baturin, R., et al. 2024, *Proc. SPIE*, **13092**, 130922D  
 Kardashev, N. S., Kovalev, Y. Y., & Kellermann, K. I. 2012, *The Radio Science Bulletin*, **343**, 22  
 Keimpema, A., Kettenis, M. M., Pogrebenko, S. V., et al. 2015, *ExA*, **39**, 259  
 Likhachev, S. F., Kostenko, V. I., Girin, I. A., et al. 2017, *JAI*, **6**, 1750004  
 Molera Calvés, G., Pogrebenko, S. V., Wagner, J. F., et al. 2021, *PASA*, **38**, e065  
 Schuh, H., & Behrend, D. 2012, *JGeo*, **61**, 68  
 Thompson, A. R., Moran, J. M., & Swenson, G. W., Jr. 2017, *Interferometry and Synthesis in Radio Astronomy* (3rd ed.; Berlin: Springer)  
 Wild, W., Kardashev, N. S., Likhachev, S. F., et al. 2009, *ExA*, **23**, 221  
 Zheng, W. 2015, *IAUGA*, **22**, 2255896  
 Zheng, W., Quan, Y., Shu, F., et al. 2010, in Sixth Int. VLBI Service for Geodesy and Astronomy. Proc. from the 2010 General Meeting, ed. D. Behrend, **157**  
 Zou, Y., Zhu, Y., Bai, Y., et al. 2021, *AdSpR*, **67**, 812