The Synchronization of Time for VLBI Observations (Postprint)

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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 \$±\$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.

Full Text

The Synchronization of Time for VLBI Observations

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Abstract

For some space radio telescopes, orbit determination accuracy is insufficient, time synchronization accuracy provided by satellite platforms is low, and GNSS devices are unavailable. Consequently, traditional methods that rely on GNSS devices to obtain an initial clock offset followed by correlation with a calibration source may fail to detect fringes. Moreover, brute-force searching across the two-dimensional clock offset and fringe rate plane is computationally expensive. To address these challenges, we propose a novel synchronization method that utilizes the spacecraft's telemetry tone signal. This method employs frequency polynomials derived from Doppler tracking for fringe rotation during correlation. By precisely aligning the frequency of the target station with that of the reference station, it becomes necessary only to divide 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 observed the Tianwen-1 telemetry signal with the 4.5 m small telescope at the Tianma campus of Shanghai Astronomical Observatory and the 40 m telescope in Kunming. The results demonstrate that our method can accurately determine clock offsets across a time range as wide as \$±\$10 ms, with an SNR slightly higher than that achieved with the delay model. This method is suitable for wide-range time synchronization in space Very Long Baseline Interferometry observations, particularly for 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 is limited by 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. Currently, two dedicated space VLBI projects 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 term, space VLBI represents the future of VLBI technology (Gurvits 2018).

In actual VLBI data processing, accurate clock offsets for each station are required. The residual delay derived through fringe fitting, combined with the initial clock offset, yields the precise value. For ground stations, the initial clock offset is typically obtained via GNSS devices with microsecond accuracy, which guarantees that fringes can be detected for the calibration source. Fringe fitting on the correlation result further improves accuracy to the nanosecond level (Thompson et al. 2017). This process achieves time synchronization across stations. For space VLBI, time synchronization is more challenging.

In previous space VLBI projects, including both VSOP and RadioAstron, timestamps of data received by the space antenna were added in real-time at transmission. Therefore, time synchronization between space and ground stations was not actually necessary. However, with the development of space radio astronomy technology, future space VLBI telescopes are expected to have observation bandwidths of several GHz (Johnson et al. 2024), leading to data recording rates exceeding ten Gbps. Obviously, it will be more convenient to add timestamps in space using the onboard data recording system and perform downlink transmission afterward. Consequently, time synchronization of a space telescope becomes a problem that must be solved, particularly when the space station is outside the coverage of GNSS satellites and the space-ground time synchronization accuracy provided by the satellite platform is only on the order of milliseconds or worse. For a typical bandwidth of 32 MHz, covering such a large delay search window requires an FFT size of 1280 K or even larger, which is unreasonably large for VLBI correlation. Moreover, for Earth-orbiting spacecraft, 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 on the order of 10 Hz. To address such a large search space, one natural solution is to first divide the delay and delay rate search range into a two-dimensional grid by adjusting the clock offset and rate, then perform correlation and fringe fitting for every grid point to ensure a sufficient signal-to-noise ratio (SNR). However, the grid size, especially the delay rate interval, must be sufficiently small, leading to significant computational burden. Furthermore, as pointed out by Likhachev et al. (2017), space VLBI data processing must consider the acceleration term; otherwise, velocity variations will make long-term integration impossible. These factors limit the feasibility of brute-force 2D grid search.

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

Compensating for Doppler shift and performing long-term integration to enhance SNR is a common approach in spacecraft signal data processing (Duev et al. 2012, 2016). In standard two/three-way Doppler measurement for spacecraft, a reference tone signal is transmitted from the ground tracking station to the spacecraft. The signal is then coherently converted to a new frequency specified by multiplying a fixed factor and transmitted down to the ground tracking station. Due to relative motion between the tracking station and spacecraft, the received signal varies with time. One must realize that this Doppler shift cannot be compensated by the VLBI delay model. Consequently, the correlated cross-spectrum is smeared, severely reducing the SNR of the tone signal. In this sense, Doppler tracking and phase polynomial compensation are the only ways to mitigate frequency smearing and enable long-term integration. SFXC (Keimpema et al. 2015), developed by JIVE, performs phase polynomial correction to compensate for Doppler shift, thereby avoiding frequency smearing of spacecraft signals (Duev et al. 2012). M. Ma & Y. Sun (2024, in preparation) employ a similar approach for processing Tianwen-1 (Zou et al. 2021) signal from CVN observations (Zheng 2015), performing radio imaging to obtain high-precision angular positions of the spacecraft.

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

2. Description of the Method

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

2.1. Doppler Tracking of the Carrier Tone

We adopt a similar approach to Doppler tracking as SCtrack (Molera Calvés et al. 2021), but with distinct and independent implementation. In SCtrack, the Doppler tracking procedure is divided into three parts: software spectrometer (SWspec), Multi-tone tracker (SCtrack), and digital Phase Locked Loop (dPLL). Our main purpose for Doppler tracking is to obtain the frequency polynomial, which is implemented in SWspec. We note that SWspec obtains the frequency of the spacecraft carrier tone by performing a large number of FFTs, achieving sub-Hz accuracy, as does the frequency polynomial. SCtrack then performs phase polynomial correction to compensate for Doppler shift and signal filtering to obtain narrowband data for each tone. Final micro-Hz accuracy is achieved by performing dPLL (Deng et al. 2021) on the narrowband data. Unlike Molera Calvés et al. (2021), in our implementation, after obtaining raw Hz-level accuracy tone frequency by performing numerous FFTs, 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 polynomial accuracy.

2.2. Determination of Search Window

According to correlation theory, once the sample rate and FFT number are fixed, the largest delay search range is $[-\text{tFFT}/2, \text{tFFT}/2)$, where $\text{tFFT} = \text{tsamplerate} \times \text{nFFT}$ is the size of the search window. In actual implementation, we choose a time window search step of tFFT/4, such that the search windows are 3/4 overlapped. Consequently, the correct clock offset might be captured in several windows, with the highest SNR appearing in the window that yields the smallest residual delay.

2.3. Correlation and Fringe Fitting

In this work, we perform correlation using our 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. This aligns frequencies of distinct stations, mitigating frequency smearing. Other steps remain 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 yielding the highest SNR is selected, and 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 compare results obtained with Doppler tracking frequency polynomials versus regular delay models.

3.1. Observation Setup

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

Doppler tracking of the Tianwen-1 main carrier tone was performed for T4 and KM stations. Correlation was then performed for the T4-KM baseline for the IF containing the spacecraft's main carrier tone. As a demonstration of our time synchronization method, 7 minutes of data starting at 05:36 UTC of T4-KM baseline were inspected.

3.2. Data Processing Result

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

We performed Doppler tracking and polynomial fitting for Tianwen-1's main carrier tone for T4 and KM. Figure 2 [Figure 2: see original paper] presents the results. The variation of frequency as a function of time was derived using the method described in Section 2.1. In short, numerous FFTs were first performed in the IF containing the spacecraft's main carrier tone. Raw Hz-level accuracy tone frequency was obtained as the frequency point with highest power. Note that inspection was performed in a narrow band range ($±$3000 Hz) around the a priori frequency of the main carrier tone to avoid selecting incorrect RFI signals. Afterward, dPLL was performed to obtain tone frequency with mHz-level accuracy: all sampling points within a given time range (e.g., 1 s) were Doppler-shifted according to the raw tone frequency. The Doppler-shifted signals were divided into short time segments of length Δtphase and coherently summed within each segment to obtain varied phases caused by residual Doppler shift (the discrepancy between actual and raw tone frequency). The residual Doppler shift was fitted for each longer time segment of length Δtf containing several hundred varied phase sampling points. Settings for Δtphase and Δtf must be appropriate to sample the maximum residual frequency and track Doppler shift evolution. For the data used in this work, they were set to 0.5 ms and 0.25 s, respectively.

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

According to actual requirements, the clock offset search range was set to \$±\$10 ms, which is too large to be covered by single-pass correlation with a large FFT number and is therefore more suitable for a multiple-time window search. For correlation, the FFT number was set to 4096. According to Section 2.2, a step size of 0.128 ms (tFFT/4) was set for the 4 MHz bandwidth (per IF). For the \$±\$10 ms search range, 157 windows were prepared. Baseband data were correlated according to their corresponding initial clock.

Figure 3 [Figure 3: see original paper] presents the SNR of the correlation result as a function of initial clock offset. The highest SNR appears at an offset of −7 ms, consistent with our initial offset setup, suggesting that the large clock offset is correctly identified with our synchronization method.

By adjusting the clock according to the offset found in Figure 3, correlation was performed again to achieve higher SNR. The result is presented in Figure 4 [Figure 4: see original paper]. Fringes are clearly detected in the KM-T4 baseline. One may notice that the fringe phase is quite flat before fringe fitting, indicating very high synchronization accuracy and resulting in 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 SNR. To validate this hypothesis, we performed 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. Fringe fitting results for these two datasets are presented in Figure 5 [Figure 5: see original paper]. When performing correlation, we observed that the derived SNR in fringe fitting relates to FFT size in correlation. Therefore, relationships between FFT size and corresponding SNR are presented in Table 2 . According to the results, 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 by better alignment of the carrier tone frequency. This is consistent with expectations, although the difference is not significant. One possible reason is that the current total integration time is not long enough. However, it is difficult to further increase total integration time based on currently available Doppler tracking data from the small telescope.

4. Conclusion

In VLBI data processing, detecting fringes requires high-accuracy clock synchronization between stations. However, for some space telescopes, satellite platform constraints result in low time synchronization accuracy. Moreover, compared with ground-based stations, space stations have much higher velocities, leading to large Doppler shifts. When orbit determination accuracy is insufficient, it is difficult to fully compensate for Doppler shifts using the derived delay model. Consequently, even if the onboard clock is fully synchronized, fringes may still be undetectable.

In this paper, we propose a novel time synchronization method to determine accurate clock offsets for space telescopes across large time search ranges. The basic idea is to first obtain the frequency polynomial of the spacecraft's telemetry tone signal via Doppler tracking, then perform fringe rotation with this frequency polynomial during correlation. Since frequencies of each station are fully aligned, it is unnecessary to search for delay rate in subsequent steps. All computational resources can be devoted to clock search for the target station relative to the reference station. In this work, the large clock search range is divided into multiple time windows based on sampling rate and FFT size. By performing correlation and fringe fitting in each window, the window yielding the highest SNR is selected. The accurate clock offset is derived by combining the initial clock offset in the corresponding time window with the residual delay.

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

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