

Towards Clock Ties for a Global Geodetic Observing System

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Abstract

International reference frames play a pivotal role in metrological applications related to the Earth sciences, covering critical areas such as geodetic reference frames, global change research, deformation processes, and global mass transport. Despite substantial advancements in measurement precision over the past two decades, there are still discrepancies at the centimeter level presenting a persistent challenge. In this paper, we investigate a promising approach to address these subtle error sources, affecting critical parts of the measurement equipment despite the presence of calibration methods.

We have built a novel measurement constraint, based on a precise clock and active time delay compensation. By comparing the timing signals in a geodetic measurement system constantly against a precisely controlled optical ruler, we can identify variable system delays that were previously inaccessible. In this way, we introduce a novel tie to the geodetic measurement techniques that can even capture instrumental delay variations over several months.

Keywords

Common clock · GNSS · Multi-technique combination · SLR · Time in geodesy · VLBI

1 Introduction

The combination of the space geodetic techniques is essential in defining both the International Terrestrial and Celestial Reference Frames. Fundamental stations, integrating multiple space geodetic techniques, play a pivotal role in this matter as they provide geometric reference points, which allow the connection of these techniques (Seitz et al. 2022). A particular challenge arises when systematic biases of unknown origin occur between the large measurement sys-

tems, especially when the geodetic reference point doesn't align with the signal reference point.

To overcome this challenge and enhance measurement consistency, our main objective is to tie these points together. We have developed an innovative Optical Time and Frequency Distribution System at the Geodetic Observatory Wettzell (GOW). This system provides actively delay-compensated timing signals, which are unaffected by variable propagation delays and environmental changes. It thus provides a common clock to all measurement systems, which is stable to ± 1 ps. The system generates ultra-stable and low-noise electric timing signals at the end of each link terminal. The mode-locked laser is the central component housed in the TWIN radio-telescope building and serves as a stable time and frequency reference for all the instrumentation of space geodesy. The timing system provides phase coherence over long distances, which enables tight control over systematic measurement errors in instruments as large as a telescope in closure over time.

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The overarching goal is the realization of a long-term stable system reference, which recovers variable biases.

2 Optical Timing System

The optical time and frequency distribution system is the critical component for the geodetic measurement systems, providing a solution for the reduction of systematic biases. It provides a reference scale against which variations show up.

The design features a mode-locked fs-pulse laser referenced to a hydrogen maser. The ultrashort optical pulse train is distributed to the measurement system via an active delay-compensated optical fiber (Schreiber and Kodet 2018; Kodet et al. 2018), providing a fixed relationship for the time markers, with a stability of 1 ps over many days across the entire observatory. In 2022, the installation was completed, solving the most challenging problem of including the moving VLBI antennas, where the cable twister introduces considerable delay variations. The core component of the active delay compensation is an optical-microwave phase detector (BOMPD) transferring the radio frequency (RF) based reference frequency from a hydrogen maser to the optical domain. This allows the locking of a femtosecond laser source without compromising the RF quality of the source (Peng et al. 2014).

The BOMPD's fundamental function lies in precisely measuring the phase delay between optical and microwave signals. This is achieved through the conversion of optical into electrical signals, ensuring continuous alignment of the phases in both domains. The system achieves an impressive low drift of 10 fs over several days. This tight synchroniza-

tion is vital for continuous high coherence at each endpoint of the time and frequency distribution system.

Such a laser pulse train is further distributed around the observatory using delay-compensated and drift-free optical links. The active stabilization of link delays is achieved through interferometry. The pulse train is split into two parts, with one part serving as a short reference arm installed in a temperature-stabilized front end. The signal arm includes the optical fiber and delivers the optical pulses to the measurement systems. A mirror at the end of the line reflects most of the light back to the interferometer. The pulse traverses first a dispersion-compensated fiber, ensuring that the pulse width at the optical cross-correlator remains unaffected by optical fiber dispersion. The optical cross-correlator performs an interferometric comparison, as depicted in Fig. 1, gauging the delay between a pulse from the reference arm and the link pulse. A feedback loop drives the fiber stretcher to ensure a precise overlap of 150 fs pulses in width. The stabilization has a bandwidth from DC to approximately 1 kHz, allowing it to cancel out any fiber delay fluctuations within this range.

The result is an exact copy of the input signal at the end of the fiber with a constant phase offset. However, the signals of interest are electrical signals, namely, 1 pulse per second (PPS) and typical reference frequencies, i.e., 10 and 100 MHz. To obtain high delay stability, it is crucial to generate signals with extremely low-temperature coefficients. This is because temperature variations have a significant impact on timing stability. While it is often claimed that sufficient temperature stabilization of electronics is possible, this is not fully accurate. In fact, a large temperature coefficient of the electronic components can result in unrealistic high requirements for temperature stabilization. For instance, the temperature coefficients of filters used in frequency multipliers can easily reach 50 ps/K. In order to achieve 1 ps stability

Fig. 1 Design of fiber-link stabilization unit utilizing optical cross-correlator and a feedback loop operating a fiber stretcher

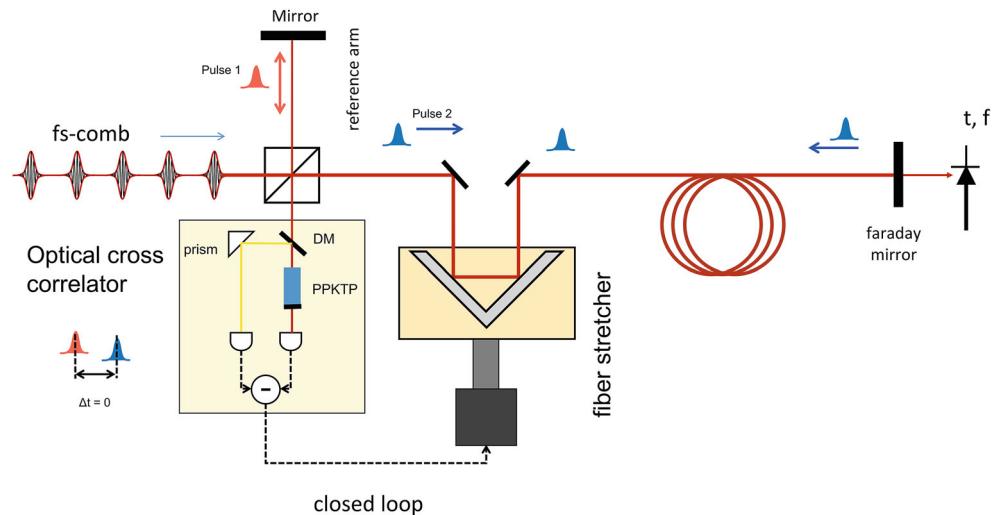
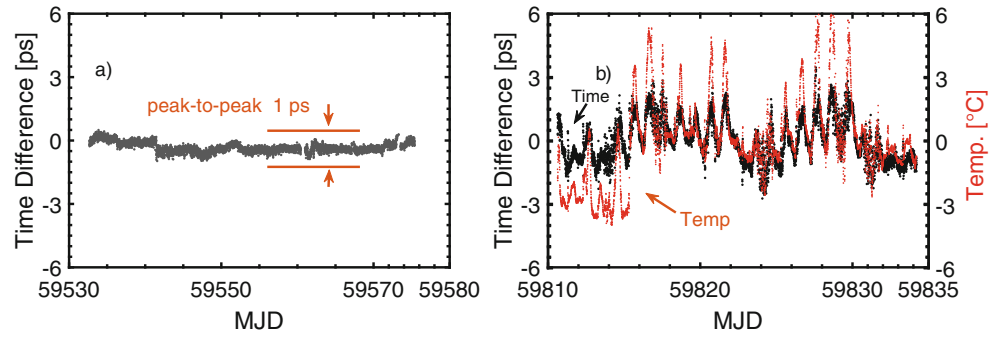


Fig. 2 Timing difference of electrical signals generated at the end of two stationary links (a), and time difference measured between two radiotelescopes, Radiotelescope Wettzell (Wz) and TWIN Wettzell-North (Wn) (b). 59,530 corresponds to 11.12.2021, and 59,810 corresponds to 19.08.2022



for long-term operations, a temperature stability of 20 mK would be required. Therefore, we have invested a significant effort into designing electronics with very low-temperature coefficients to achieve the desired high performance. A typical temperature coefficient of electrical signals provided by the electronic at each link end (back-end) is 1 ps/K.

To validate the quality of the time distribution units, two event timers implementing a two-way time transfer concept (TWOTT) for widely separated locations were employed (Kodet et al. 2016a, b). This technique achieves sub-picosecond timing jitter and timing stability, obtained from the time deviation evaluation (TDEV), reaching 50 fs.

We conducted an extensive investigation involving two types of links in operation at the GOW. The first type involves the assessment of link stability for a stationary link installed in a rack mount within a laboratory. Figure 2a illustrates the delay stability observed over a period exceeding 1 month. Notably, the stability of electrical signals between the front-end and back-end exhibited a negligible increase, staying within the 1 ps range.

The evaluation of the signal delay for terminals installed inside the elevation cabinets of the radiotelescopes is more difficult due to temperature variations. The advantage of low-temperature coefficients turned out to be very important since the temperature difference between the two radio telescopes reached up to 8 K.

In Fig. 2b, we observe residual timing variations that are highly correlated with temperature. Based on the underlying data set, the temperature coefficient was determined to be 0.42 ps/K, and we must consider three sources for these variations: the back-end of the timing system, the TWOTT event timing modules, and the interconnecting RF cables. The back-end electronics are additionally temperature stabilized within a fractional degree of Celsius, so any temperature variations in this component are expected to be attenuated. The TWOTT timers have a temperature coefficient of 1.4 ps/K, and the interconnecting RF cables type LMR-240 have a temperature coefficient of 0.5 ps/K per meter. A notable aspect is the system's capability to achieve precise

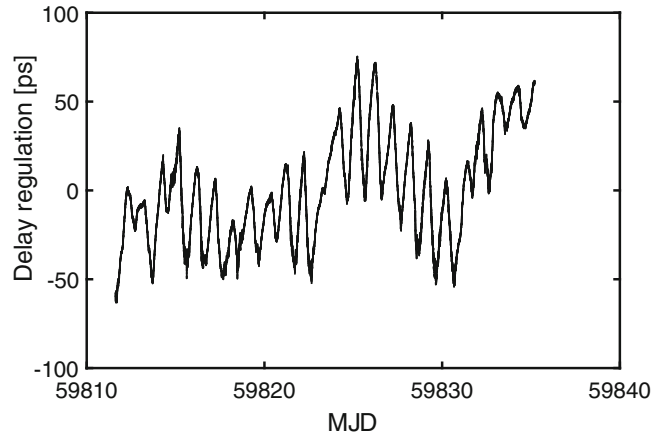


Fig. 3 The optical link delay is actively controlled; the figure illustrates the amount of adjustment required to achieve 1 ps stability

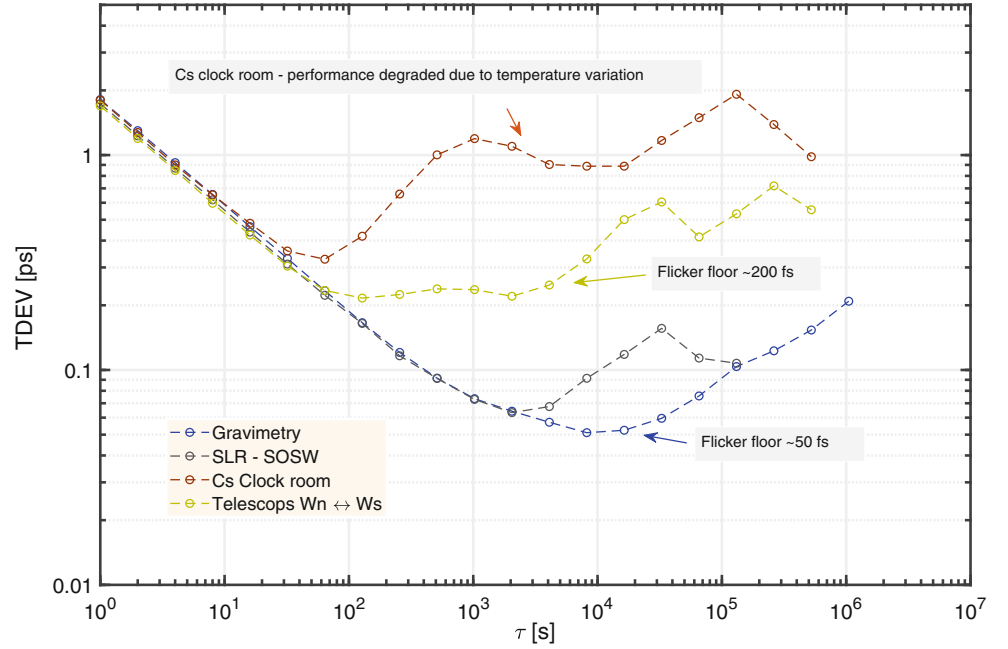
timing even in dynamic conditions, as demonstrated by links in radiotelescopes experiencing telescope movements and temperature variations. Figure 3 illustrates the effectiveness of the delay compensation by showing the error signal for a measurement over several days.

The precision of timing signals is presented through TDEV values, revealing that, in most links, the precision is close to 50 fs, likely limited by TWOTT measurements. The comparison is depicted in Fig. 4.

Radiotelescope links, which are subject to dynamic regulation, have achieved a time deviation (TDEV) as low as 200 fs. Among all the links, the one located in the Cesium clock room is the worst, with the highest TDEV. This is due to poor thermal stability. To address this issue, plans are in place to relocate the Cesium clock facility to a more stable room, considering the impact of environmental factors on timing signals.

In summary, the optical timing system delivers unprecedented timing stability, especially in challenging conditions. The TDEV analysis and comparisons highlights the system's capability to provide high time coherence right at the locations where critical system calibrations are performed.

Fig. 4 A TDEV analysis demonstrates link stability of 50 fs for a laboratory measurement and 200 fs between the radiotelescopes



3 Application of the Optical Timing System in VLBI

This section explores the practical application of the optical timing system in VLBI and shows the case where more stable clock distribution improves VLBI products. In the initial stages of developing the optical timing system in 2015, we could synchronize two local radiotelescopes in the following way. The 20 m Radiotelescope Wettzell (Wz) was locally referenced to hydrogen masers and equipped with a phase calibration unit and cable calibration unit. In contrast, the Wn (TTW1) telescope, while referenced to another maser, lacked these calibration units. Synchronization of both masers was achieved using the TWOTT technique, connecting close to a maser as a synchronization point. Therefore, not all delays were properly captured during the observation. The baseline between these radio-telescopes spanned 123 m and over 100 days, TWOTT measurement data covered 18 R1 and R4 VLBI sessions in the period of (Sep 2015–Feb 2016).

The Levika software (Schüler et al. 2015) was employed for the VLBI analysis, solving for the local VLBI baseline. The local tie measurements provided the coordinates for the positions of both telescopes. Additional constraints were put on the ionosphere and troposphere, considering they are the same for both telescopes. This approach facilitated the estimation of VLBI clock differences from each quasar observation, providing a unique opportunity to analyze VLBI clocks with high resolution during 24-h sessions.

The distinctions between a VLBI clock estimation and the TWOTT measurements are described in (Kodet et al. 2016a, b). Here, we can take a different perspective on

these measurements. According to (Whitney 1974) precision, determined by observing the group delay between two telescopes can be expressed as:

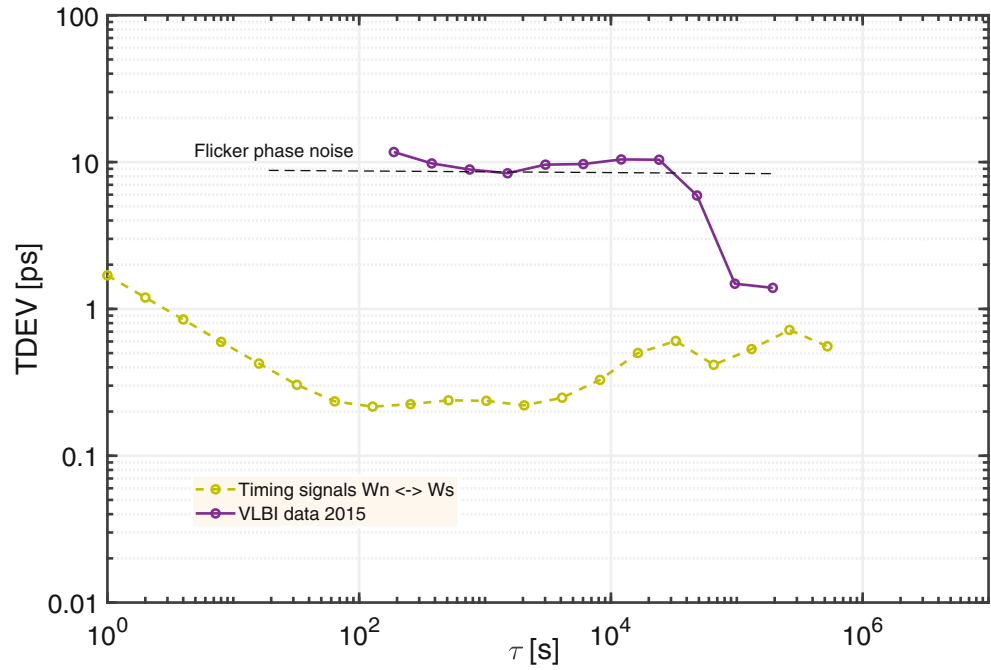
$$\sigma_{\tau_g} = \frac{1.24 * 10^3}{B_s J d_1 d_2} \sqrt{\frac{T_{s1} T_{s2}}{\varepsilon_1 \varepsilon_2 W T}}, \quad (1)$$

where ε_i is antenna efficiency, d_i is antenna diameter, B_s is spanned bandwidth, W is channel bandwidth, T_{si} is total system noise temperature, and T is integration time. Typical values for VGOS or S/X observations yield a 10–30 ps precision. The above formula assumes only white-phase noise of the observable group delay between the telescopes, which is given (Nothnagel et al. 2018) as

$$\tau_{obs} = \tau_{geom} + \tau_{iono} + \tau_{atm} + \tau_{clk} + \tau_{inst} + \tau_{def} + \epsilon. \quad (2)$$

Here, we focus on τ_{clk} and τ_{inst} only, since the rest of the variables are constrained for this specific data set. τ_{clk} should contain the phase difference of the reference frequency generated by involved stations clocks and τ_{inst} contains instrumental delays, which should be calibrated. While the antenna moves from one source to another, the antenna delay may change and must be well-calibrated. In classical VLBI analyses the clock delay is parameterized and estimated using piece-wise linear functions with a resolution of 20 min to 1 h. Challenges arise when other noise sources interfere with white-phase noise averaging. This could be well observed in our data set, where each quasar observation was used for the τ_{clk} and τ_{inst} estimation.

Fig. 5 Clock offsets expressed as TDEV between Wz and Wn antennas were obtained from a VLBI analysis in 2015, including TWOTT measurements. The flicker floor limits the VLBI instrumental resolution much earlier than the clocks. The TDEV of timing signals difference from optical time and frequency distribution as measured in 2022 is plotted for comparison



We used this dataset from 2015, which allowed us to look at these results from the perspective of TDEV analyses and determine which type of noise dominates VLBI observation. Figure 5 illustrates the results, offering insight into the limitations of white-phase noise averaging. The VLBI data starts averaging at around 13 ps, aligned with the formula (1), but the group delay does not improve with increasing averaging time. The precision reaches the flicker floor and levels off at around 10 ps, suggesting that increasing the number of observations or integration time does not provide higher resolution for the baselines. Points beyond a 24-h integration time exhibit a downward step, which appears to be an artifact from the TDEV analysis due to an insufficient number of observations. Therefore, any enhancement achieved through the use of averaging cannot be implemented. It appears that the VLBI flicker floor limitation is mainly due to variable instrumental delays, which are not adequately addressed in the calibration during the experiment. This finding motivated the development of the coherent optical time and frequency distribution system. In 2022, we completed the installation of the delay-compensated terminals in all three radio telescopes at GOW.

4 First VLBI Local Experiments with the Optical Timing System

In a test run in 2022, we conducted two local experiments utilizing Wz and Wn radiotelescopes in this new setup. In these experiments, each digitizer was locked to its own optical time distribution terminal, while the Local Oscillators (LO) and

phase calibration units (pCal) in the antenna were connected to another delay-compensated back-end. The experimental setup is sketched up in Fig. 6.

For verification purposes, we evaluated TWOTT during a 1-h experiment. It is necessary to point out that these experiments were primarily focused on compatibility checks of VLBI instruments with all relevant signals generated from the optical time and frequency distribution system. While VLBI provides the delay between radiotelescopes, Fig. 7 illustrates the signal differences. The amount of delay removed by active stabilization is together with the stability of the difference between the 100 MHz local oscillator generation and the phase calibration injection point, as measured by TWOTT.

We observed 31 radio sources in a 1-h experiment. That does not provide sufficient data for a full statistical analysis of the group delay estimation. Nevertheless, it provides important evidence, if all instrumental delays are sufficiently

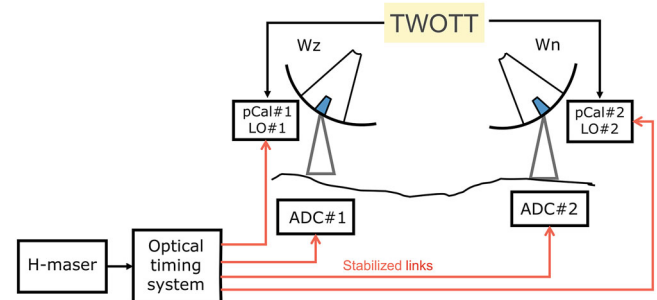
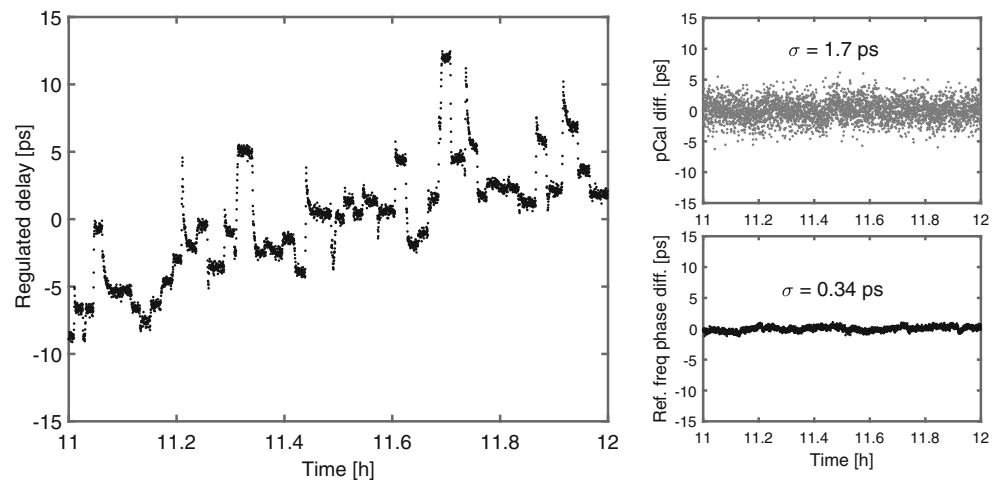


Fig. 6 Local experimental setup for the Wz and Wn radiotelescopes, utilizing 4 stable delay-compensated back-ends

Fig. 7 The active stabilization aims to bring a stable phase of the reference frequency as the timing signal for pCal generation into the radiotelesopes elevation cabins. As an example, the figure illustrates for the duration of 1 h the amount of delay difference (Wn-Wz), which was actively regulated (left side), as well as the difference of pCal and reference frequency phase difference between the antennas (right side)



well calibrated and whether the VLBI delay estimation is contaminated by an additional noise source. A noticeable difference in the TDEV is observed when a phase calibration signal is applied to the measurement. Figure 4 supports the argument that the timing signals to which the telescopes are referenced do not increase the VLBI flicker floor. However, TDEV computed from VLBI clocks offsets does not exhibit the $1/\sqrt{\tau}$ slope, which is indicative of the presence of white phase noise. This could originate from the application of pCal phase calibration in the fringe fit after correlation, as detailed in (Nothnagel 2023). The phase calibration correction is applied as a single value for the duration of one observation, meaning that each quasar observation has its unique instrumental phase delay correction. The pCal phase delay estimation is used to equalize different observation channels. However, it is not used to relate individual scans to the same phase reference. Therefore, when the antenna shifts position to point to another source, the changes in instrumental delay, and consequently, the phase delay is estimated with respect to another phase reference. This aspect is currently not contained in the fringe-fitting process. It is currently assumed that the delay change behaves as white-phase noise which will be absorbed during parameter estimation. This appears to be not the case.

5 Conclusions and Outlook

In accordance with the overarching objectives of the Global Geodetic Observing System (GGOS) to provide high-accuracy reference frames. Our research effort focuses on reducing systematic errors, which influence geodetic measurements from fundamental stations. We introduce active delay compensation to increase the stability of the measurement systems. At the same time, we operate the instrumentation with a common clock and a very tight phase relationship. From this actively controlled delay,

the goal is to establish an additional tie between the different instruments, which is based on time coherence. Measurements on the VLBI systems in Wettzell allow us to observe biases caused inside the instrumentation, which limit the performance of the technique and, hence, its long-term stability.

Early experiences with the newly implemented time and frequency distribution system are promising. The delay compensation system provides exceptional stability, achieving levels well below 1 mm when interpreting time delay as a distance. The successful performance of VLBI experiments further underscores the potential of deriving common clocks through delay drift-free links in VLBI applications. While the initial VLBI experiments were conducted over a relatively short duration only, they have provided valuable insights. Currently, we still have to resolve a technical issue, which causes the presence of low-level spurious frequencies in the calibration signal.

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