K. U. Schreiber et al.: Improving VLBI Station Performance, IVS 2012 General Meeting Proceedings, p.120–127
http://ivscc.gsfc.nasa.gov/publications/gm2012/schreiber.pdf

Improving VLBI Station Performance

K. U. Schreiber [1], J. Kodet [2], C. Plötz [3]

[1)] *1) Bundesamt für Kartographie und Geodäsie and 2) Forschungseinrichtung Satellitengeodäsie (TUM), Geodetic Observatory Wettzell*

[2)] *Forschungseinrichtung Satellitengeodäsie (TUM), Geodetic Observatory Wettzell*

[3)] *Bundesamt für Kartographie und Geodäsie, Geodetic Observatory Wettzell*

Contact author: K. U. Schreiber, e-mail: `schreiber@fs.wettzell.de`

Abstract

Higher bandwidth and a vastly increased number of observed radio sources are basic elements of the roadmap into the future of VLBI. The new twin telescopes at Wettzell is a starting point for these goals. Systematic intra-technique biases are equally important. Modern instrumentation of quantum optics and recent progress in high resolution event timing provide new tools for studying system behavior and the improvement of system stability. Compensated optical fibers may qualify as suitable tools for one-way system delay reduction. This paper introduces current activities for a better system stabilization and inter- and intra- technique bias reductions at Wettzell.

1. Introduction

The major measurement techniques of space geodesy are characterized by a very high measurement sensitivity. It resolves the measured quantities, such as the range to satellites or signal delays, from cosmic sources between radio telescopes to approximately one part in 10^9. While all the different observing stations have an impressive precision, the accuracy still carries biases well in excess of the estimated measurement precision. Within each of the techniques these errors are minimized by a non-linear data fitting process. Fundamental stations on the other side are important because they provide a link from one measurement technique to the other. However, this is also the link where discrepancies between precision and accuracy become evident. The fundamental station Wettzell has repeatedly carried out survey campaigns, which reproduce the geometric relationship between the various geodetic markers at the observatory to well within 2 mm. These measurements also routinely include the geodetic reference points of the laser ranging system and the VLBI system as well as several GNSS receiver antennas. A history of nine consistent campaigns covering more than 20 years was built at Wettzell. Summarizing the results of the local surveys at Wettzell, the conclusions were:

- Referencing the points of the space geodetic techniques shows no significant displacements with respect to the local surveying network.
- There is good repeatability of these measurements, also when a different instrumentation and measurement approach is employed. This can be interpreted as the respective systematic errors being too small.
- The accuracy of the local ties at Wettzell are in the order of 1–2 mm.

- The significance of taking a closer look at the intra-technique biases and undertaking every effort to reduce the effects. This may also mean to devise inter-technique comparisons in order to identify sources of such biases.

The calibration of VLBI and SLR systems can be considered as highly developed. All the necessary procedures have matured substantially over the last thirty years. However, for an observed discrepancy of a few centimeters, equivalent to approximately 100 ps in the time domain, it does not take much of a calibration error or a flaw in the calibration process to generate a bias. Possible candidates are satellite target signature, signal strength variation, an asymmetry between ranging and calibration for SLR, system delay variation, or subtle issues in phase-calibration across the observation bandwidth of the VLBI technique. Two examples can illustrate the type of complications that one has to expect. Figure 1 shows the short-term time evolution of the measured cable signal delay between the detection electronics and the antenna head in the telescope. The measurements of the cable delay were not carried out on the actual VLBI signal line, but on a parallel running cable of the same type and length, which is used to inject the frequency comb for the phase calibration of various VLBI data channels. It is believed that both cables operate the same. A second example is the monitoring of height variations of the reference point of the telescope. Figure 2 shows a measurement series of half a year in length.

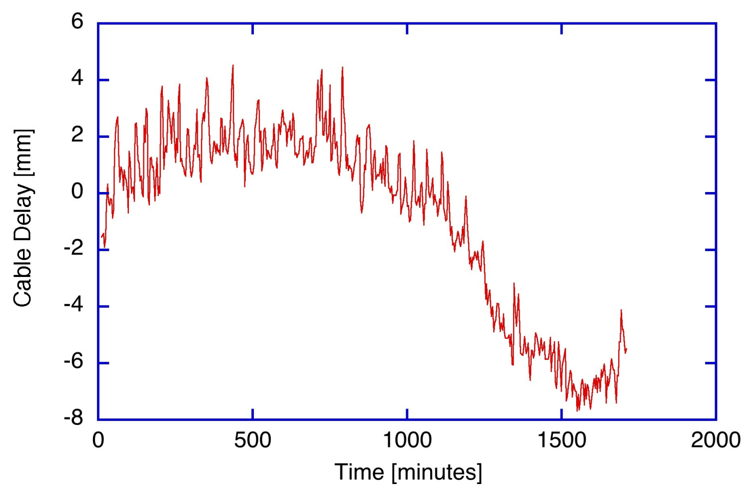

Figure 1. Timeseries of the cable delay measurement at Wettzell over almost 24 hours of measurement. Apart from a diurnal trend there are also short-term fluctuations, which are caused by antenna movements. It is assumed that the actual signal line behaves in an identical fashion.

There is a difference of no more than 2.5 mm in height between summer and winter, while the variation of height over a single day does not exceed 0.5 mm. While the electrical signals cause a variation of more than 8 mm in a day, seasonal variations in ambient temperature do not amount to much change in geometry.

If the case of incomplete or missing local ties at some of the radio telescope sites is excluded from this paper, there is still substantial potential for improvements in the techniques of space geodesy possible when better use is made of the potential of co-location of techniques on the observed satellites. Furthermore it is important to address technique-specific system biases with new

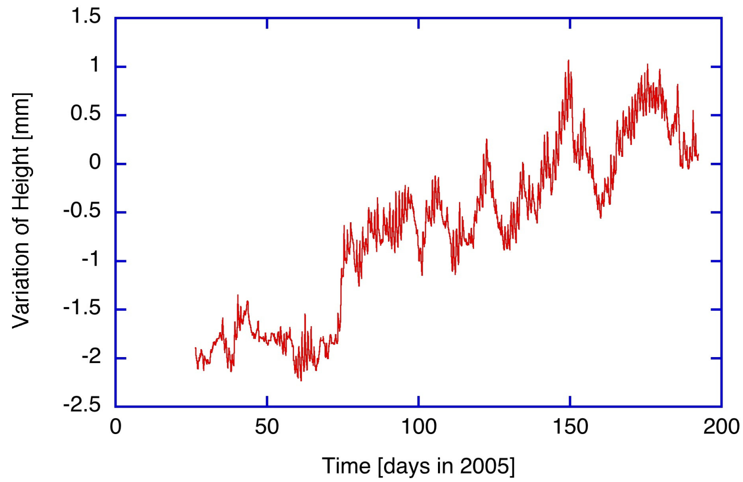

Figure 2. Variation of the height of the radio telescope reference point over a period of half a year. There is a difference in height of approximately 2.5 mm between summer and winter.

concepts. Fundamental stations in geodesy, such as the Geodetic Observatory Wettzell, operate with a certain amount of redundancy. When the twin telescopes at Wettzell are operational, there are three VLBI telescopes, two SLR systems, and approximately five GNSS receivers available for the identification and removal of technique-specific bias sources. It is also intended to apply inter-technique comparisons in order to find the cause of system specific biases.

2. Inter-technique Comparison and Two-way Measurement Concepts

In order to identify systematic measurement biases by inter-technique comparisons, there are several options available. Observing GNSS satellites with the VLBI system has the great advantage (or perhaps disadvantage) that both systems operate in the same regime; i.e., they use microwave frequencies. Measurement errors common to both techniques are therefore difficult to identify. This changes completely, when optical and microwave techniques are compared in an inter-technique verification experiment. For this purpose it may be desirable to place a corner cube reflector right in front of the VLBI antenna feed, next to a broadband, fast-switching avalanche photo diode in Geiger mode [1]. While the short laser pulse coming from the SLR system provides an optical link to the VLBI telescope, the photo-detector generates a signal pulse with a fast rise time of about 35 ps, covering more than 2.5 GHz of bandwidth in the microwave regime. This is at least partially within the reach of the VLBI recording system and can be used to actually track the delay of a microwave signal right through the VLBI detection chain in the time domain. In order to make use of this concept, the timing system of the SLR and the VLBI systems must be synchronized to about 10 ps, which will be possible by running both systems from a common clock. Furthermore, it is necessary to calibrate the conversion delay between the incoming laser pulse and the electrical signal response of the avalanche diode. Last but not least, for this experiment it is desirable to extend the bandwidth of the applied photo-detector in order to cover more from the operation bandwidth of the VLBI system. Signal delays from systematic errors are expected to be 100 ps.

2.1. Event Timers for the Two-way Measurement Concept

The Time of Arrival measurements method based on a transverse surface acoustic wave (SAW) filter excitation was introduced by P. Panek in [2] and [3]. It was shown that the SAW filter can be used as an interpolator, and that the mean interpolation error is zero and the root mean square error is below 1 ps. This allows the investigation and detection of small systematics in propagation delays. Based on this measurement principle an event timer was constructed at the Czech Technical University in Prague, which allows the determination of input pulse arrival times with respect to a local time base. The single shot precision of the registration of synchronously generated time markers with a jitter fewer than 490 fs RMS was achieved. When two equally constructed timers are used and the arrival times of split asynchronous pulses are measured, the resulting single shot precision is found to be 700 fs RMS per channel. In addition, this result contains all the nonlinearity effects of the time interpolation. The nonlinearity effects of the event timers were studied in more detail in [4] and do not exceed 0.2 ps. When operating the device in a laboratory environment without temperature stabilization, a resultant time deviation (TDEV) of less than 4 fs is routinely achieved for averaging times from 300 s to 3000 s [5].

For performance testing purposes and for experiments involving two-way time transfer (TWTT) comparisons, a reference time mark generator was included into the timing device. It generates low jitter pulses synchronously in the local time base. The repetition frequency of these pulses and the number of generated pulses are programmable. The timing jitter of the pulses was found to be below 280 fs RMS. In order to find unknown and variable time delays at locations A and B separated by some distance, a two-way time comparison is most suitable because of the inherent high common mode error rejection. Provided that all the respective delays in this comparison are reciprocal, the offset in time and the drift in time between the two terminals can be estimated with great accuracy. Figure 3 illustrates the procedure. Assume that a frequency source feeds

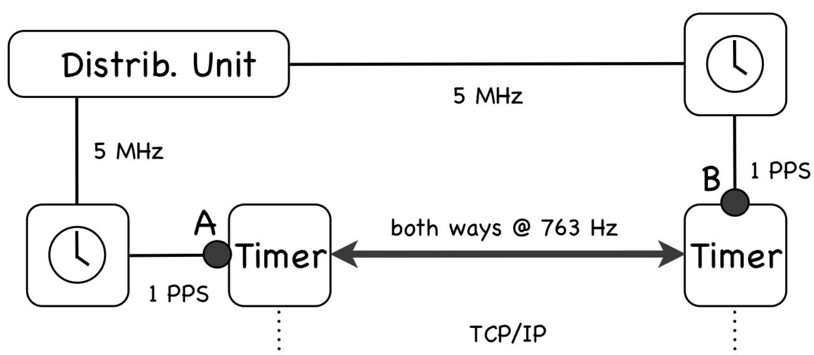

Figure 3. The two-way time comparison allows estimation of the offset and the drift of two clocks separated by a spatial distance of up to several kilometers.

a highly stable frequency of 5 MHz to two clock modules, which are located approximately 100 m apart. Each clock module derives a pulse per second (PPS) from the reference frequency and provides this pulse to a timer for time tagging and clock comparison. In principle, the PPS pulse arriving at point A is split in two equal pulses for which the respective epoch of arrival is recorded by both timers. If one would redo these measurements with the two connecting cables exchanged, the measured delays τ_{AB} and τ_{BA} can then be used to compute the offset between the two timer timescales by averaging the measured delays:

$$\Delta\tau = \frac{1}{2}\left(\tau_{AB} + \tau_{BA}\right). \tag{1}$$

It is important to note that the respective length of the cables involved in the measurement is no longer contributing to the estimated timescale offset. Applying this concept to the arrangement depicted in Figure 3, a pulse generator in timer A generates a pulse which is timed at both devices, using the interconnecting coaxial cable. Then the process is repeated with a pulse generator in timer B passing through the cable in the other direction. From this pair of measurements the timescale offset between the two timers can be derived as

$$\Delta\tau = \frac{1}{2}\left((t_{B1} - t_{A1}) + (t_{B2} - t_{A2})\right). \tag{2}$$

The delay introduced by the length of the connecting cable can also be determined

$$\tau_c = \frac{1}{2}\left((t_{B1} - t_{A1}) - (t_{B2} - t_{A2})\right) \tag{3}$$

and is a valuable quantity to estimating the stability of the measurement setup. For higher statistical resolution the measuremnts are repeated frequently up to 763 times per second. The precision of the resulting time scale difference will obviously depend on the quality of both event timers, the reproducibility of pulses generated by TWTT modules, and the influence of noise induced on the interconnecting cable. Laboratory experiments have demonstrated 3–10 ps consistency of the TWTT technique and a direct comparison of test pulses delivered to two systems operated close to each other and interconnected by a long coaxial cable (ca. 100 m - RG214) [7]. The detailed analysis of the systematic error contributions shows that the resulting accuracy of the two-way time transfer via a coaxial cable as high as 10 ps may be achieved. The maximum separation between the two timing units and the maximum length of the interconnection coaxial cable well exceeds 500 meters. The limiting factor is the transmission bandwidth of the long cable. Both the error analysis and the experiment show that for slew rates faster or equal to 20 ns / 1 V will provide 10 ps of timing accuracy.

2.2. Two-Way Time-Transfer Experimental Results

In order to find small systematic errors in VLBI and SLR coming from small unnoticed changes in system delay, the TWTT technique is applied and a field experiment of TWTT via coaxial cable has been carried out at the fundamental station Wettzell (Germany). The two time scales were formed by two equal timers equipped with TWTT modules as shown in Figure 3. The systems were located in different buildings, namely the time laboratory and the SLR facility. A Heliax LDF4-50 coaxial cable of 170 meters length was used to link the devices together. The timing systems were driven by two different 5 to 200 MHz clock frequency multipliers. A common 5 MHz signal synchronized to the master frequency reference — a Hydrogen maser — was used for both systems. The TWTT measurements were carried out at a repetition rate of 500 Hz. The entire measurement session lasted 16 hours. The results are shown in Figure 4. The time scales offset changed by 300 ps within 16 hours.

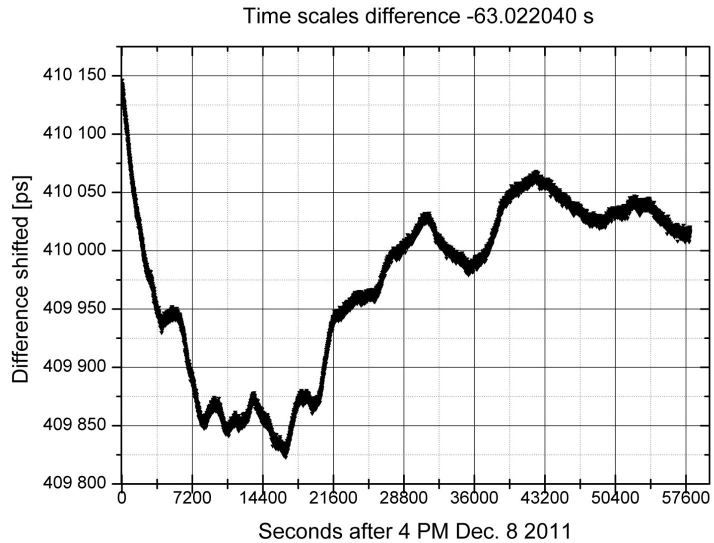

Figure 4. Difference of the two time scales formed by event timers in the field experiment within the master clock room and the SLR building.

2.3. Timescale Stability between the Master Clock and the GNSS Room

The 5 MHz Cesium clock-generated signal is distributed all around the observatory. At each building (SLR, VLBI, and GNSS), the 5 MHz reference frequency is used to form a local timescale by generating 1 pps pulse. Using the TWTT method, these timescales were compared in order to check the stability of the respective clock modules. The timers were driven from 100 MHz sources, which were phase-locked to the 5 MHz clock source. The measurement loop was set up so that one TWTT measurement was performed between two 1 pps signals. The TWTT repetition rate was set to 400 Hz and 100 measurements were reduced to a mean value. The average precision of the means became smaller than 1 ps. The result is shown in Figure 5. The jump of 100 ps after 4.5 days was caused by an air conditioner failure in the GNSS room. System calibration procedures have been developed over the years in order to make the VLBI, SLR, and GNSS measurements at the observatories robust against drifting clocks and signal level variations. However, it cannot be entirely excluded that instabilities occur and small errors degrade the geodetic measurements. Therefore this process of monitoring the general performance of the time and frequency distribution and the propagation delays of signals within the instrumentation must be considered as a work in progress.

3. Modernizing the Time and Frequency Distribution

As the measurement sensitivity and accuracy of the instrumentation of space geodesy improves over the years, higher demands are placed on time and frequency distribution at a fundamental station. While relatively low frequencies at 5 or 10 MHz (which can be distributed with little degradation) have been used in the past as timing references, higher demands for sensor resolution also require higher reference frequency. It is desirable to keep the ratio $\delta f/f$ as small as possible.

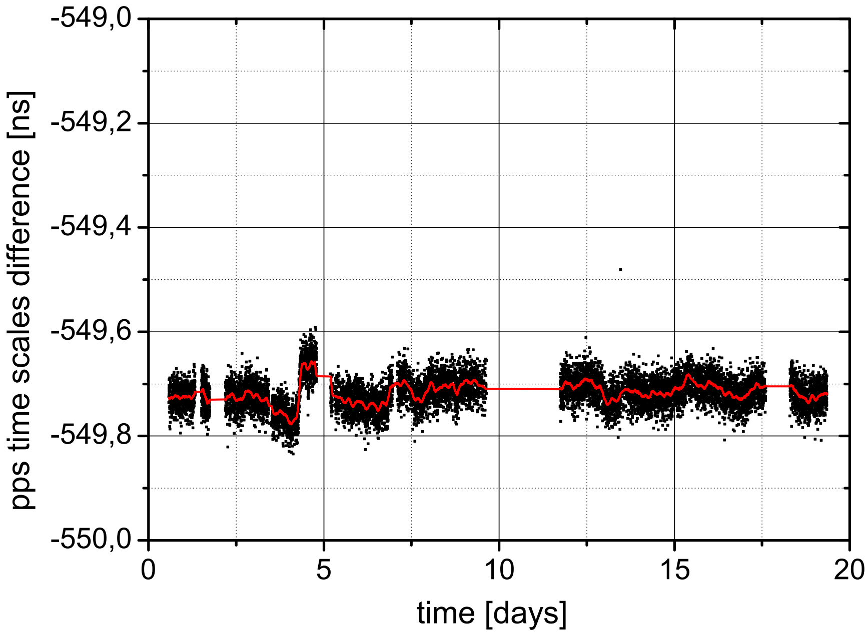

Figure 5. Time scales comparison between GPS and master clock room.

A natural way of improving the resolution is to move to the higher reference frequency f. Clocks, based on narrow- band atomic transitions in the optical regime, are currently forming the high-end regime and reaching accuracies of the order of 10^{-18}; i.e., several orders of magnitudes in excess of hydrogen masers. Over the coming years they are expected to become available for general use. Therefore it becomes important to also address the distribution of time and frequency on the level of an observatory, by implementing appropriate optical time and frequency distribution techniques. Optical frequency combs [8] have bridged the gap between the optical and microwave frequency regime, making precision optical spectroscopy available for exploitation in geodesy.

The loss of an optical frequency transfer via an optical fiber over distances well in excess of 30 km has been demonstrated [9]. This concept also uses a two-way transfer concept to compensate the phase noise introduced to the highly coherent optical frequency transmitted through the fiber. This concept compares a small portion of the laser frequency injected into the fiber with a portion of the same signal, back-reflected from the other end of the fiber. A high bandwidth closed-loop feedback system removes any signal distortions caused by the transport medium. The instability transfer signal was as low as 10^{-17} and can be reduced further. A similar approach has also been demonstrated for the transfer of time as well. Short laser pulses with a width of approximately 10 femto-seconds are transmitted through an optical fiber in a similar two-way approach as it is used for the frequency transfer. Since such short pulses are composed out of mode-locked train laser frequencies covering a broad spectral range, dispersion will quickly degrade the pulse shape. Therefore it is important to compose the entire run of the fiber out of two parts of equal length and conjugate refractive index. While the first half of the fiber disperses the laser pulses, the second half will compress them back to short pulses as they exit the fiber on the other end. Transmitting these pulses back to the fiber allows for the compensation of any variable delay that the fiber introduces to the signal, by a closed-loop feedback system employing a fiber stretcher, and the correlation of the outgoing signal with the back-reflected portion of the transmitted signal. Practical experience shows that an instability of time transfer can be reduced down to below 1 ps. This concept has been demonstrated over distances of several hundred meters and is used for the synchronization of magnets in large-scale free electron lasers [10].

4. Summary

The Global Geodetic Observing System (GGOS) requires both a reduction in measurement errors as well as a considerable reduction of systematic errors within the measurement techniques of space geodesy. At the same time, new demands such as highly accurate time transfer emerge. Current geodetic observatories are not yet equipped for these demands. The Geodetic Observatory Wettzell has embarked on the modernization of the time and frequency distribution for all the techniques of space geodesy. It also applies highly resolving two-way time transfer techniques in order to find and eliminate various systematic errors within VLBI, SLR, and GNSS, assisted by inter- and intra- technique co-locations on ground and in space in response to the ambitious GGOS demands.

References

[1] U. Schreiber, A. Schlicht, and K. H. Haufe; *"Systematic biases in laser ranging measurements"*; Proc. SPIE Vol. 3865, p. 64 – 74, (Dec. 1999)

[2] P. Panek; *"Error Analysis and Bounds in Time Delay Estimation"* Signal Processing, IEEE Transactions on, Vol. 55, p. 3547 – 3549, 2007

[3] P. Panek; *"Time-Interval Measurement Based on SAW Filter Excitation"* Instrumentation and Measurement, IEEE Transactions on, Vol. 57, p. 2582 – 2588, 2008

[4] I. Prochazka, P. Panek; *"Nonlinear effects in the time measurement device based on surface acoustic wave filter excitation"* Review of Scientific Instruments, Vol. 80, p. 076102, 2009

[5] Prochazka, I., Kodet, J., Panek, P., Schreiber, U.; *"Novel concept of sub-picosecond timing system and its applications in fundamental metrology"*. In Proceedings of 2011 Joint Conference of the IEEE International Frequency Control and the European Frequency and Time Forum (FCS), p. 161-164, 2011

[6] Prochazka, I., Kodet, J., Panek, P.; *"Electronic circuit for two way time transfer via a single coaxial cable with picosecond accuracy and precision"* Review of Scientific Instruments, AIP, accepted for publication

[7] Prochazka, I., Blazej, J., Kodet, J.; *"New Technologies for Time Transfer with Picoseconds Precision and Accuracy"* IEEE, p. 1-7. ISBN 978-1-4577-1821-2, 2012

[8] Udem, T., Holzwarth R., Hänsch, T. W.; *"Optical frequency metrology"*; Nature, **416**, (14 MARCH 2002)

[9] Foreman, S., Ludlow, A., de Miranda, M., Stalnaker, J., Diddams, S., Ye, J.; *"Coherent Optical Phase Transfer over a 32-km Fiber with 1 s Instability at* 10^{-17}*"*; Phys. Rev. Lett., **99**, 15, p. 153601, (2007)

[10] Kim, J., Cox, J. A., Chen, J., Kärtner F. X.; *Drift-free femtosecond timing synchronization of remote optical and microwave sources*; Nat. Phot. **2**, 733 – 736, (2008)