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TIME TRANSFER BETWEEN USNO AND PTB: OPERATION AND CALIBRATION RESULTS

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Abstract

Two-way satellite time and frequency transfer (TWSTFT) is routinely executed between USNO and PTB via two links, using a connection at Ku-band and X-band. The Ku-band measurements are performed five times per week (in collaboration with several European and American time laboratories). The X-band link is unique: measurements are carried out nominally 24 times per day. By this means, hydrogen masers of both laboratories are compared during 15 minutes each hour. Since June 2003, the X-band results have been evaluated by the BIPM for future use in the production of TAI. Thus, a periodic calibration of the link is strongly desirable. Up to now, three calibration experiments were carried out with a transportable TWSTFT station provided by USNO: in June 2002, January 2003, and July 2003. Because only a few TWSTFT calibrations of civil time laboratories were performed up to now, this first "semiannual" schedule provides a good opportunity to characterize the stability of TWSTFT links. For example, the January 2003 exercise confirmed that the internal delays of the Ku-band as well as of the X-band link were stable within 1 nanosecond. During autumn 2003, the satellite used in the Ku-band link had to be exchanged, which caused a gap in the data of about 3 weeks. Using other time transfer techniques, the gap was bridged with an uncertainty of 1 ns.

1. INTRODUCTION

Satellite time transfer is essential for clock comparisons via long distances, in particular between time laboratories located in America and Europe. These clock comparisons are regularly used by the Bureau International des Poids et Mesures (BIPM) as input for the realization of Coordinated Universal Time (UTC). In particular, it is important to compare the timescale derived from the clock ensemble of the U.S. Naval Observatory (USNO) **[1]** with the primary clocks of the Physikalisch-Technische Bundesanstalt (PTB) **[2]**. USNO's numerous clocks get a large weight in the computation of the International Atomic Time (TAI). The relative weight of the USNO clocks as a whole surpasses 40% of all contributing clocks **[3]**. For many years, the home-built primary clocks of PTB have contributed continuously for adjusting the TAI scale to the SI second. In consequence, there has been a particular motivation to use several time transfer techniques for the connection between both laboratories. Generally speaking, two different methods of time transfer are applied (see Figure 1): Global Positioning System (GPS) common view (CV) [4] and two-way satellite time and frequency transfer (TWSTFT) **[5]** via geostationary satellites. Aside from classic GPS C/A code analysis, which is not a topic in this article, recently installed geodetic GPS receivers allow the so-called P3 code analysis to be made **[6,7]**. Two TWSTFT links have been installed, one with transmit/receive frequencies in the Ku-band (14 GHz /11 GHz) and one in the X-band (8.5 GHz /7.5 GHz). The operation of the X-band link and comparison with the Ku-band link are subjects of the following Section.

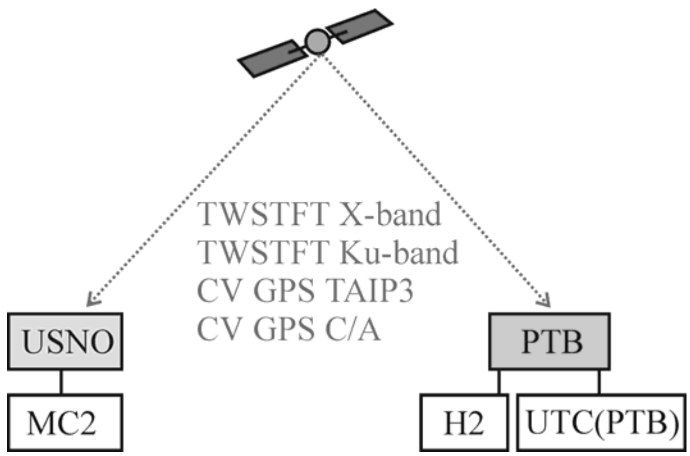

Figure 1. Schematic of the time links between USNO and PTB. The Master Clock 2 (MC2) is a steered hydrogen maser representing UTC (USNO). UTC (PTB) is still based on PTB's primary clock CS2 steered towards UTC. The hydrogen maser H2 delivers the reference frequency for some of PTB's time transfer equipment **[8].** The difference UTC (PTB) – H2 is recorded hourly and is provided for the analysis of the time transfer results.

All links have been calibrated with a transportable TWSTFT station provided by USNO using the same military satellite as the X-band link (see Ref. **[8]** for a brief description of the applied technique). Two calibrations were carried out successfully, the first one in June 2002 **[1]** and the second in January 2003. Unfortunately, a third calibration (July 2003) failed due to hardware problems identified after the fact. The results of the January 2003 and the July 2003 experiments are described in Section 3.

In this contribution, we mainly deal with the TWSTFT links between USNO and PTB. While the Ku-band link has been used as the reference link for timescale comparison in the computation of TAI, the X-band data and the data of the TAIP3 experiment (using the above-mentioned GPS P3 code analysis) have been evaluated to have sufficient backup. This became particularly important when the Ku-band link was disrupted on 25 August 2003. From that day on, the TAIP3 data were used for the TAI computation. When the Ku-band link became available again on 15 September, TAIP3 data were used to bridge the Ku-band link. This was necessary because the link was reinstalled via another satellite, with unknown internal delays and different transponder frequencies. The applied method and results are described in Section 4.

2. TWSTFT OPERATION

A permanent TWSTFT link between USNO and PTB via X-band became operational in summer 2002, made possible by considerable support from USNO. Currently, the hydrogen maser H2 at PTB and

USNO's Master Clock 2 (MC2) that represents UTC (USNO) are compared nominally 24 times per day for 15 minutes with TWSTFT. In Figure 2 (top graph), the number of recorded sessions per day is shown. On most days during the period MJD 52570 to MJD 52870, 23 or 24 sessions were recorded successfully. Sometimes there were fewer sessions due to hardware or software problems. Especially from MJD 52750 until MJD 52850, fewer than 20 sessions per day were recorded. Insufficient cooling during high-temperature periods may have affected the reliability of the outdoor equipment. In the bottom graph of Figure 2, the scatter of the single sessions is represented by the standard deviation of the 1-second data around the session mean (gray dots). Typical values of 0.2 ns or less show the very good intra-session stability. Gaps in the data represent maintenance or repair activities. The slight increase of the scatter during summer 2003 coincides with the above-mentioned decrease of the sessions per day. The scatter of the session means around a daily linear regression shows a different characteristic. It is in good agreement with the standard deviation of the individual sessions only since MJD 52850, and the increase of the scatter of the 1-second data during summer 2003 had no significant influence. But there is a strong increase in the more distant past (before MJD 52750). It would be interesting to know if this was due to undetected outliers or due to diurnal variations.

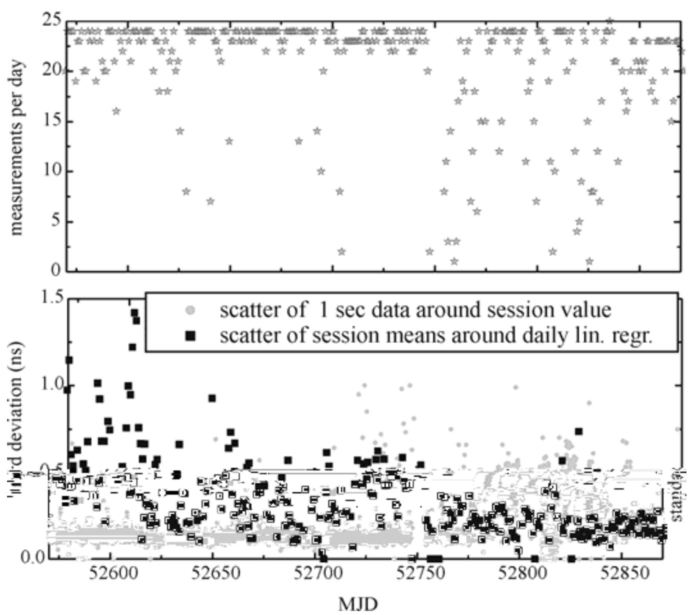

Figure 2. Documentation of PTB – USNO X-band operation. Measurements per day (top graph) and standard deviation (bottom graph) of the data during the period MJD 52570 to MJD 52875 are shown. Gray dots represent the scatter of the 1-second data around the session mean, while black squares represent the scatter of the session means around a daily linear regression.

Ku-band TWSTFT has been routinely performed five times per week (Monday to Friday), each session consisting of 120 measurements, one per second. The reduction of the data is described in Ref. **[8]** and references therein. While at USNO, the 1PPS (one pulse per second) transmit reference is directly derived from MC2, at PTB the reference signal comes from H2. The relation between H2 and UTC (PTB) is reported as REFDELAY. Thus, the TWSTFT data can be used to compare MC2 with UTC (PTB) by including the REFDELAY information or, alternatively for stability studies, to compare two hydrogen masers. In the following, we compare Ku-band and X-band results over an extended period. The X-band data were reduced to a daily mean by applying a linear fit to the sessions of 1 day. The midpoint at 12:00 UTC of the fit represents the daily value of UTC (PTB) – MC2 (USNO), and is depicted in Figure 3, with an offset to reveal the course of both data sets. In Figure 4, the so called double differences $\delta\Delta T$ = [UTC (PTB) – MC2 (USNO)]$_{\text{Ku-band}}$ – [UTC (PTB) – MC2 (USNO)]$_{\text{X-band}}$ are shown, based on the Ku-band individual measurements and the X-band daily mean. The linear fit of the data shows a slight slope -3.0 ± 0.8 ps/day. The standard deviation of the data around the linear regression of 0.78 ns could be explained by a 0.5 ns instability for each link (Ku-band and X-band).

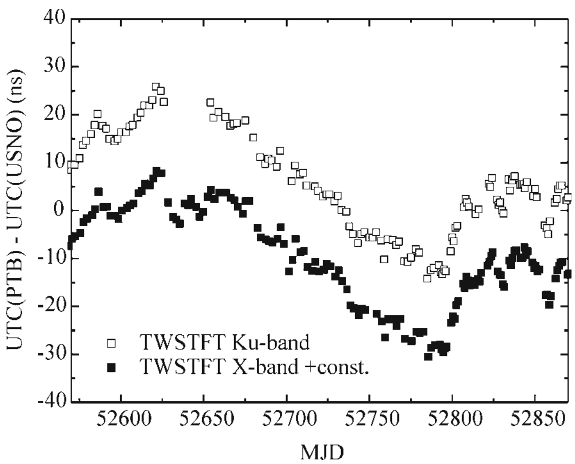

Figure 3. Results of the timescale comparison UTC (PTB) – MC2 (USNO) using TWSTFT in Ku-band (open squares) and X-band (full squares). X-band data are shifted by approximately 16 ns.

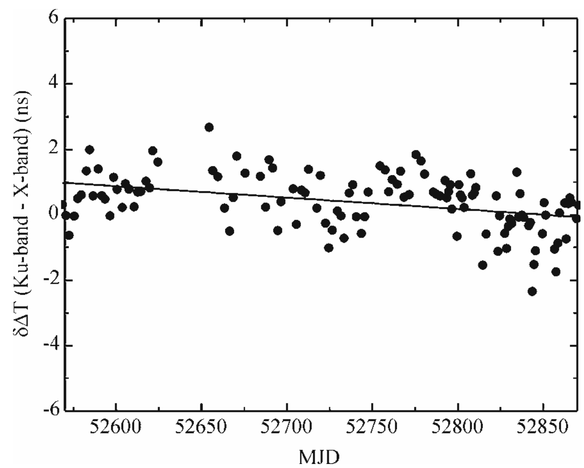

Figure 4. Double differences Ku-band – X-band (dots) and linear fit (line); the zero has been adjusted for MJD 52666, according to calibration results (Table 1).

3. CALIBRATION EXERCISES

In 2003, USNO performed two calibration exercises of the USNO – PTB links. In these exercises, a transportable X-band station was operated at PTB and later connected to MC2 at USNO, giving the station calibration value. Assuming that the internal delays of the transportable station remain the same when the station was operated at PTB, UTC (PTB) – MC2 (USNO) is determined by combining the results obtained at PTB with the station calibration value. The first such experiment was performed in June 2002 (MJD 52435 and MJD 52436). A detailed description of the setup and the applied technique was published in Ref. **[1]**. Following the final evaluation of this first calibration experiment, UTC (PTB) – MC2 (USNO) was determined as 19.33 ns with an estimated total uncertainty of 1.0 ns on MJD 52435. Thus, the calibration value (CALR) in the header of files reporting the Ku-band TWSTFT results was changed as prescribed in the Recommendations ITU-R TF.1153-1 **[9]**.

The subsequent exercises were performed with the same equipment and in the same manner as the June 2002 calibration. In Figure 5, the individual X-band (full squares) and Ku-band (open squares) values of UTC (PTB) – MC2 (USNO) are shown for 27 and 28 January 2003 (MJD 52666 and MJD 52667) when the second calibration was performed. On both days, several additional measurements were recorded via the Ku-band link, explaining the large number of points in the figure. It is obvious that both Ku- and X-band links were in good agreement during the calibration. The results of the travelling station exercise are shown as open diamonds and confirm the formerly achieved results. A comparison of the averages of the measurements UTC (PTB) – MC2 (USNO), depicted in Figure 5, is given in Table 1. While the X-band mean is evaluated from data of about six sessions recorded during the calibration experiment, the

Ku-band and the transportable X-band results are averages over all data recorded on that day. Regarding only the statistical uncertainty of the first calibration (0.15 ns) and the standard deviations of the means, both the Ku- and X-band measurements are in very good agreement with the calibration results on MJD 52666 as well as on MJD 52667. No drift of a single link is observable. Also, no seasonal effect is recognizable by comparing the calibration performed during the winter months with the exercise performed during the summer months. Furthermore, the day-to-day stability of all links represented by the "difference" (see Table 1) is nearly the same for each technique.

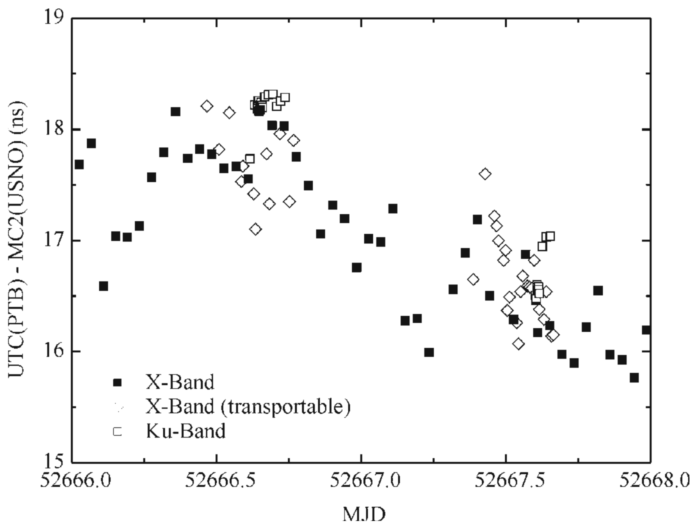

Figure 5. Timescale comparison UTC (PTB) – MC2 (USNO) during the calibration exercise on 27 and 28 January 2003 (MJD 52666 and MJD52667) using Ku-band (open squares), X-band (full squares), and transportable X-band station (diamonds).

In July 2003, a third exercise was carried out between both laboratories. Unfortunately, the evaluated calibration result was 300 ns from the expected value, very probably due to hardware failures in the modem used at that time. Without having a sure explanation, the result was discarded, and a future calibration (March 2004) should hopefully give a clearer picture of the performance of the installed equipment.

Table 1. Averages and standard deviations of excerpts of the timescale comparison UTC (PTB) – MC2 (USNO) during the calibration exercise in January 2003 using Ku-, X-band, and a transportable (fly-away) X-band station. Only measurements recorded during the calibration exercises were taken into account. As a result of the June 2002 calibration, the differences between all comparison channels had been set to zero, and 6 months later the differences were still statistically insignificant.

MJD	**Ku-band (ns)**	**Ku-band minus Reference (ns)**	**X-band (ns)**	**X-band minus Reference (ns)**	**Transportable X-band (ns) Calibration Reference**
52666	18.21 ± 0.13	0.52 ± 0.37	17.80 ± 0.22	0.11 ± 0.41	17.69 ± 0.35
52667	16.66 ± 0.23	0.03 ± 0.44	16.52 ± 0.40	-0.11 ± 0.55	16.63 ± 0.38
difference	1.53 ± 0.26		1.28 ± 0.46		1.06 ± 0.51

In Figure 6, a long-term record of the timescale difference UTC (PTB) – MC2 (USNO) is depicted. The Circular T values published monthly by the BIPM reveal that both timescales do not drift apart by more than 20 ns for most of the time. The course reflects mostly the behavior of UTC (PTB), because UTC (USNO) did not diverge from UTC by more than 6 ns during the last 2 years. The dates and results of the calibration exercises are also indicated in Figure 6.

As published in Circular T, Ku-band data were the basis for TAI computation until 25 August, when the INTELSAT (IS) satellite 706 at position 53° 00' W had to be abandoned, since the satellite no longer provided the required interconnectivity between Europe and America. TWSTFT has been continued using satellite IS 903 (position 34° 50' W). The so-called IS gap was bridged by the BIPM with GPS CV TAIP3 data.

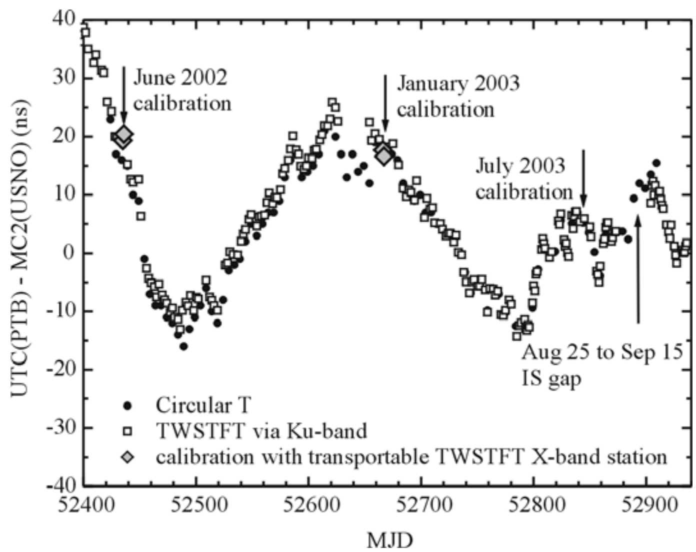

Figure 6. Circular T and Ku-band data of the timescale comparison UTC (PTB) – MC2 (USNO). Calibration dates and results (diamonds) are shown as well as the so-called INTELSAT (IS) gap.

4. SATELLITE CHANGE IN THE TWSTFT KU-BAND LINK

The TWSTFT antenna used for the Ku-band link was directed to the new satellite on MJD 52898 (15 September 2003). No hardware changes in the signal transmission and reception channels were necessary at either site. Therefore, only transponder delay changes between the two satellites and the signal delay differences in the ground stations due to different carrier frequencies used for the up- and downlink can have affected the measurements. In Figure 7, data in the vicinity of the IS gap are shown. As the total delay change was unknown a priori, we had to fall back on a different link to continue the Ku-band link with a well-defined accuracy. The TAIP3 link was continuously in operation and served for that purpose. The method applied is described in the next paragraph.

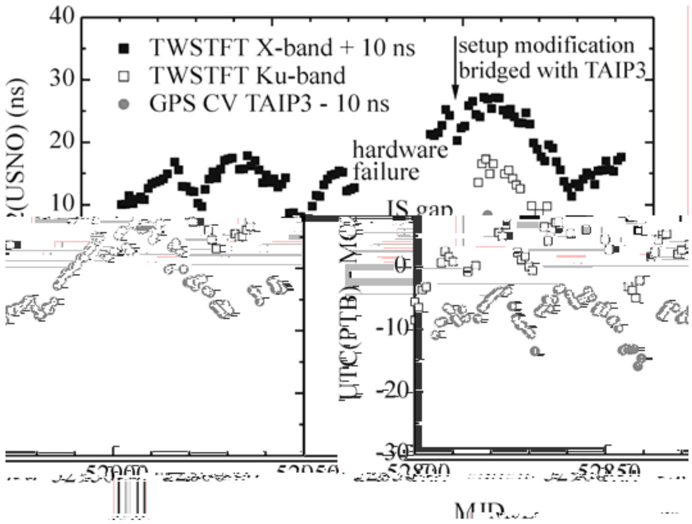

Figure 7. UTC (PTB) – MC2 (USNO) via three links (X-band, Ku-band, and TAIP3) in the vicinity of the so-called IS gap in August/September 2003. To achieve a better visualization, offsets of ± 10 ns were applied to X-band and TAIP3, respectively.

Unfortunately, the X-band link also had to be bridged by TAIP3 data. During the modernization process of the realization of UTC (PTB), new frequency distribution equipment was installed at PTB, and the X-band indoor setup was moved and needed new cabling. Additionally, a hardware failure (a low-noise amplifier in the receive channel had become defective and had to be replaced) that occurred at the PTB site during the IS gap potentially affected the accuracy of the X-band link.

In Figure 8, the measurement results and the adjustments of delays are illustrated. The TAIP3 data, one measurement every 16 minutes, with two to three satellites in common view, are depicted as full circles. Despite previous calibrations of the geodetic GPS receivers, there was initially a few-ns offset with respect to the TWSTFT data (squares). The TAIP3 data were made coincident with the TWSTFT data before the satellite break. In detail, the differences between the daily midpoints of the TAIP3 data and the corresponding TWSTFT data points were determined. Then the sum of the squared differences for all the points (up to MJD 52870) shown in Figure 8 was minimized.

The change of the satellite position has a known effect on the correction due to the Sagnac effect to be applied to the TWSTFT data **[9]**. Having taken only this into account, the TWSTFT data showed a significant difference from the TAIP3 measurements since MJD 52901 (triangles). Now the TAIP3 data were kept fixed, and the TWSTFT were adjusted as described above, shifting them up by 5.5 ns. Thus, an additional correction of ΔCALR = ± 5.5 ns should be applied (the sign depends on the chosen site; see Ref. **[9]** for details) to the calibration value. We estimate that the calibration of the TWSTFT links between PTB and USNO could be maintained that way with an uncertainty of 3 ns. The calibration exercise scheduled for March 2004 will prove this estimate.

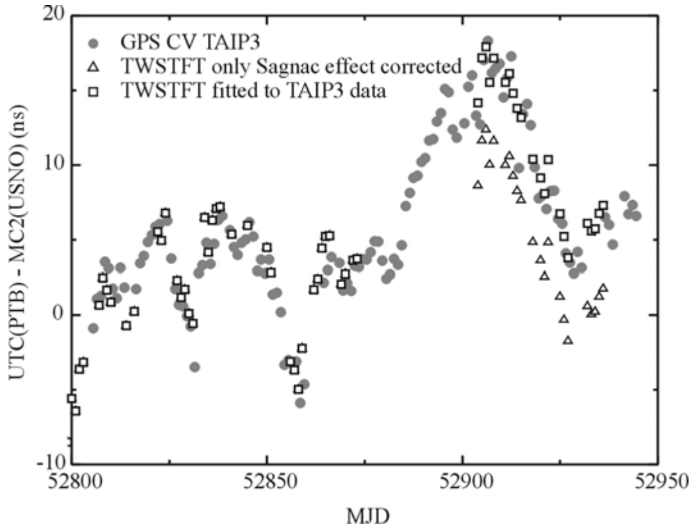

Figure 8. Time comparison UTC (PTB) – MC2 (USNO): full circles: GPS TAIP3 comparison, squares: TWSTFT Ku-band via INTELSAT 706 (before gap) and INTELSAT 903 (after gap, fitted), triangles: TWSTFT if only the Sagnac effect is corrected.

5. CONCLUSION

Time and frequency transfer between USNO and PTB is a key link for the production of TAI. The link stability of TWSTFT Ku-band and X-band links was discussed. A slight drift between the two links of 3 ps/day was observed, which motivates calibration exercises on an annual schedule at least. The results of the calibration exercises in 2003 were discussed. The January 2003 calibration proved the link stability of both Ku- and X-band on the sub-nanosecond level. In mid 2003, a satellite change in the TWSTFT Ku-band link was necessary. When taking only the Sagnac effect into account, an additional offset of 5.5 ns appeared, which is probably due to satellite transponder delays.

6. ACKNOWLEDGMENTS

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