Two-Way Satellite Time Transfer Between USNO and PTB

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Abstract—**Two completely independent two-way time and frequency transfer (TWSTFT) links have been established between the institutions of USNO and PTB, with transponder frequencies in the Ku-band and X-band, respectively. The Ku-band link has some strategic importance, since currently it connects almost one half of the atomic clocks in the BIPM network that are employed for the realization of TAI. The X-band data are provided as a backup. To reach the full potential of TWSTFT, especially for time scale comparisons, repetitive calibrations of the links are necessary. Since 2002, USNO has scheduled semiannual calibration exercises. We report on the three calibration campaigns in 2004 and early 2005. New calibration values were determined in 2004 and 2005. For the first time, combined uncertainties below 1.0 ns for both links were achieved. A change of the TWSTFT transmission frequencies or satellite changes in general cause discontinuities in the series of time transfer data and render the previous calibration useless. We describe how we coped with two such events by bridging with X-band and GPS carrier phase data. The previous calibration could be preserved with sufficient accuracy of about a few tenths of a nanosecond.**

I. INTRODUCTION

One of the most accurate and precise techniques for remote time scale and clock comparisons is two-way satellite time and frequency transfer (TWSTFT) [1,2]. It is independent of GPS, the second widely used technique, and features low noise for short averaging times and has the potential to allow frequency comparisons below 10^{-15} at averaging times of 1 day [3]. This aim may be safely reached in the near future by exploiting the carrier phase of the transmitted signals [4]. Already similar performance has been demonstrated in a 3-week-long campaign during which TWSTFT was performed on an intensive schedule [5]. Furthermore, only TWSTFT has shown in operational use that combined uncertainties for true *time transfer* below 1 ns can be achieved by carrying out TWSTFT calibration campaigns at regular intervals [6].

Comparing the time scale derived from the clock ensemble of the U.S. Naval Observatory (USNO) with the primary clocks of the Physikalisch-Technische Bundesanstalt (PTB) is of special interest. USNO's numerous clocks typically get a large weight in the computation of the Temp Atomique International (TAI), and for many years the home-built primary clocks of PTB have contributed continuously in adjusting the TAI scale unit to the SI second. Furthermore, the link between both institutions connects almost half of the clocks contributing to the realization of TAI.

Consequently, there is a special motivation to maintain different independent time transfer setups to provide sufficient redundancy. Beside classical GPS common view (CV), which is not discussed in this contribution, three completely independent links have been established, through geodetic GPS receivers as part of the IGS network [7], and two TWSTFT links, 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). While the Ku-band link has been used as the reference link for time scale comparison in the computation of TAI by the BIPM, the X-band data are provided monthly as a backup. The geodetic GPS data have been used only occasionally; see Section IV as an example. Redundant operation of two TWSTFT links allows one to monitor the link stability and helps to generate continuous time series even in case that maintenance work or equipment failures affect one link. In order to get true *time* differences from TWSTFT, repetitive calibration campaigns using a TWSTFT portable station have to be performed. Since 2002 USNO has scheduled semiannual calibration exercises [8,9] to allow regular monitoring of both TWSTFT link stabilities.

In this contribution we report the calibration campaigns of the USNO – PTB link performed by USNO during 2004 and 2005 by circulating a portable station. These calibration campaigns are part of an extensive schedule operated by USNO for TWSTFT calibrations of timing stations and laboratories worldwide [6]. The applied calibration technique
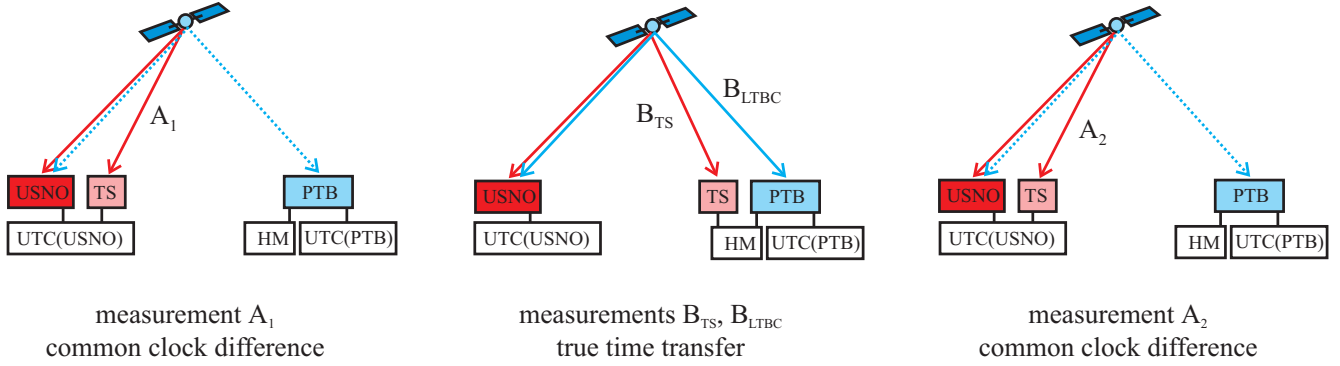
Figure 1. Schematic representation of the setup of a travelling TWSTFT station (TS) sequentially operated at USNO and PTB in three steps; the red arrows indicate the time transfer performed during the calibration with the TS. The blue line indicates the permanent TWSTFT links that are calibrated that way. Full lines indicate the measurements that are necessary for calibration.

is described in Section II. Thereafter (Section III), the data evaluation and the resulting calibration constants are discussed. In between the calibration exercises, measurement setup changes and changes in the satellite configuration happened and made application of data bridging procedures necessary. Their results and uncertainties are described in Section IV. The uncertainty evaluation of the calibration exercises is reported in Section V. Finally, all TWSTFT calibrations since 2002 and their impact on the two permanent links are discussed.

II. CALIBRATION TECHNIQUE

The purpose of the TWSTFT calibration exercises described in this contribution is to determine the sum of the differential station delays and the transponder delay applied in the evaluation of time scale comparisons via two independent TWSTFT links between USNO and PTB in the Ku- and X-bands. This is achieved by using portable and calibrated TWSTFT equipment, the so-called travelling station (TS), working also in the X-band, to measure the differences between the time scales of USNO and PTB. Such an exercise is carried out in two steps.

The first step is the parallel operation of the travelling station side by side to the stationary X-band setup at USNO, both connected to the same clock representing UTC(USNO). The result is the Common Clock Difference (measurement A_1 in Fig. 1),

$$\begin{aligned} CCD(USNO, TS) = {} & 0.5 \cdot TW(USNO) \\ & - 0.5 \cdot TW(TS@USNO) \, , \\ & + DLY(TS) \end{aligned} \quad (1)$$

where $0.5\,TW(USNO) - 0.5\,TW(TS@USNO)$ is determined by averaging over about 5 to 10 minutes the second-by-second recordings of the so-called clock offset value provided in the data output of a dedicated time transfer modem (SATRE) which is used for generating and processing the TWSTFT signals. The clock offset data are computed every second combining the second by second

data of the local measurement with the extrapolation of transmitted fit functions of the remote site data. The principle of the TWSTFT technique is described in [10]. DLY(TS) represents the connection of the TS's modem TX 1PPS to UTC(USNO). In several cases CCD values were determined with different hardware setup configurations so that the subsequent calibration trip could be successfully completed even in the case of failure of single components meanwhile. To verify the stability of the TS during the calibration trip, a second CCD measurement should be carried out after returning from the visit of the remote site (measurement A_2 in Fig. 1).

Assuming that the internal delays of the TS remain unchanged when, in a second step, the station is operated at PTB, the true time difference UTC(PTB) – UTC(USNO) is determined, combining CCD with the results obtained at PTB (measurement B_{TS} in Fig. 1):

$$\begin{aligned} UTC(PTB) - UTC(USNO) = {} & 0.5 \cdot TW(TS@PTB) \\ & - 0.5 \cdot TW(USNO) \\ & + REFDLY(TS) \\ & - CCD(USNO, TS) \\ & + SAGNAC(USNO, PTB) \end{aligned} \quad (2)$$

where $0.5\,TW(TS\,@\,PTB) - 0.5\,TW(USNO)$ is determined as described earlier . Because the TS is connected to a hydrogen maser (H4) while UTC(PTB) is derived from the primary clock CS2 [11], the difference between both clocks has to be recorded separately; REFDLY(TS) represents this connection of the TS to UTC(PTB). SAGNAC(USNO, PTB) is the so-called Earth rotation correction [10], here -205.14 ns. Any independent time transfer technique that is operated in parallel to the TS can in principle be calibrated that way, since the calibration value CALR(USNO, PTB) can be determined by subtracting the true time difference from the time difference given by the link to be calibrated (LTBC) (measurement B_{LTBC} in Fig. 1):

$$CALR(USNO, PTB) = [UTC(PTB) - UTC(USNO)]_{LTBC} \\ - [UTC(PTB) - UTC(USNO)]_{TS} \quad .(3)$$

Note that the calibration setup and one LTBC (X-band) make use of the same hardware at USNO site. This is neither necessary nor recommended. However, the use of hardware for both purposes may reduce time-dependent instabilities otherwise unavoidable between completely independent hardware.

III. CALIBRATION EXERCISES IN 2004 AND 2005

Three calibration exercises were carried out by USNO in March and September 2004 and May 2005 (hereafter Mar'04, Sep'04, and May'05, respectively). In the following the results are summarized. In Section III-A the precalibration, i.e. the determination of the CCD and its influence on the estimated uncertainty of the calibration is discussed. Thereafter, the calibration measurements at PTB are described. Note, in between both consecutive calibration exercises the continuity of at least one TWSTFT link had to be preserved by bridging the data using data of the other operated TWSTFT link. The procedures are described in Section IV.

A. Determination of the CCD

Before shipment of the TS to a remote site, the CCD is determined according to (1). Only the measurement of the CCD enables the true time transfer to a station to be calibrated, assuming that the internal delays of the calibration device do not change during the whole trip. This can be tested by comparing CCD measurements before and after the trip. At present, this is the only practical way to estimate internal delay changes of the hardware during the trip. The difference between both measurements indicates the possible delay changes of the calibration setup to be considered in estimating the calibration uncertainty. A rather bad example is depicted in Fig. 2, in which the results of the initial and the closure measurements of the Mar'04 calibration are shown. Note that the date of the calibration is not close to the middle of the two measurements at USNO. Nevertheless, the interpolated CCD has been used to determine the differences between TS and stationary X-band and Ku-band measurements.

Repeated calibration exercises of USNO in the USA have proven that closure errors are well below 1 ns, if no hardware failure happened. For example, the SUV, a dedicated van hosting the travelling station, including full temperature control of the "indoor" equipment, enabled closures below 0.4 ns in most exercises to be reached [6]. The same level was achieved in a European calibration campaign using the portable station of the Technical University of Graz [14]. The travelling station used here was shipped several times, and an average closure of 0.48 ns was noted [6]. However, a closure measurement was not carried out after all calibration trips discussed here. It was done only if doubts about the achieved results arose. In other cases, the stability of the TS had to be derived from earlier experience. We estimate the
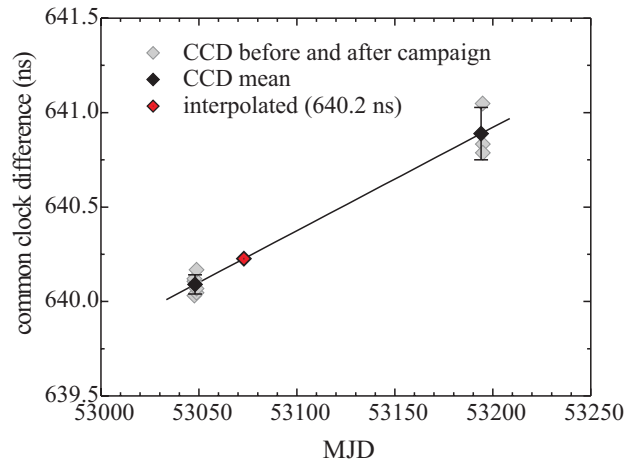

Figure 2. Initial (February 13) and closure (July 8) measurements for the Mar'04 calibration at USNO. Gray diamonds represent single measurements, and black diamonds and error bars represent the mean and standard deviation, respectively. Interpolation of both results (red diamond) provides the common clock difference between permanent and the travelling station (TS) of USNO for the epoch of the TS operation at PTB.

instability during the Mar'04 exercise from the closure depicted in Fig. 2 to be 0.8 ns. The same value is assumed for the Sep'04 trip. After the evaluation of several calibration trips, we assume 0.6 ns for the 1-sigma uncertainty for the May'05 exercise.

B. True Time Transfer

Two calibrations were carried out in 2004. The second, Sep'04, calibration became especially important because in the Ku-band link an unexpectedly large time step of about 14 ns was noticed after a rather small change of the transmission frequencies. The Ku-band data gap of a few days was bridged with X-band data, and the delay change was afterwards verified during the Sep'04 calibration. Just a few days before the May'05 calibration was carried out, Intelsat requested a switch to another satellite for TWSTFT activities, which introduced an unknown delay-change in the transponder configuration of the satellite. Fortunately, the applied bridging procedure could be soon verified.

1) Calibration Exercise Mar'04

In Fig. 3 the time difference UTC(PTB) – UTC(USNO) is shown using both TWSTFT links and the TS during the visit from 8 to 10 March. Ku-band (blue squares) was operated 24 sessions per day while TS was in operation at PTB. The permanent X-band link (open red squares) had a break (1 day) due to a modem synchronization problem at PTB. From noon of MJD 53073 on, the PTB station was operated with a new low-noise amplifier (LNA) (yellow filled diamonds), and additional sessions were recorded. The black lines/arrows are just guides for the eye.

The sessions with the transportable station were grouped into five data sets. Set 1: TS was linked directly to UTC(PTB); both the frequency reference and the 1PPS were related to the caesium clock CS2 steered in frequency. Sets 2 to 4: the primary modem SATRE 87 (S87) was connected to
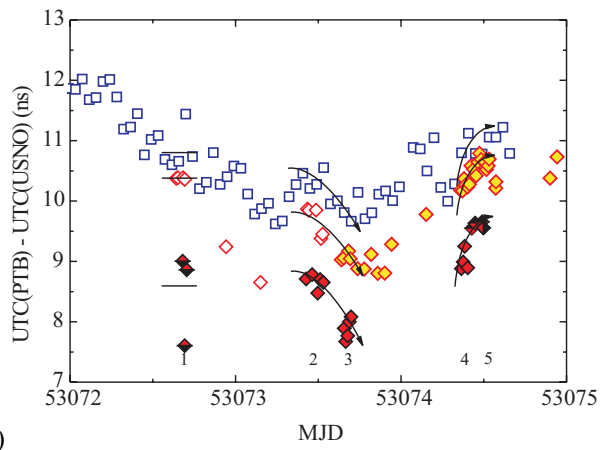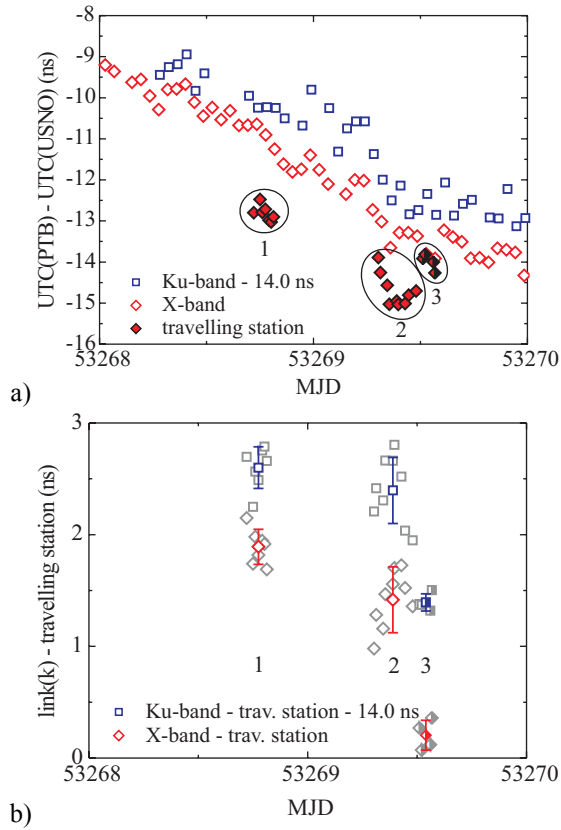
a)
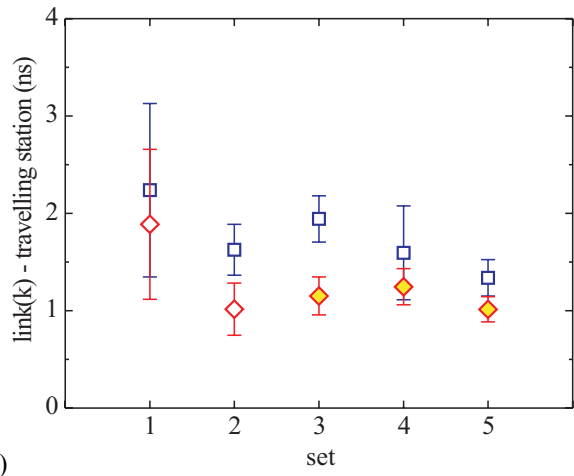
b)

Figure 4. September 2004: a) Comparison of the time scales UTC(USNO) and UTC(PTB) using three TWSTFT links during the calibration campaign in September 2004: Ku-band (blue squares), X-band (red diamonds), and TS (full symbols). Here we distinguish between sets 1 and 2, when the TS standard configuration including primary modem S87 was used, and set 3, when the backup modem S268 was used. b) Double-differences between regular links (Ku-band, X-band) and the link via the travelling station (TS). Gray symbols represent the single differences, while the colored symbols represent the average over each set of data (colorcode as above).
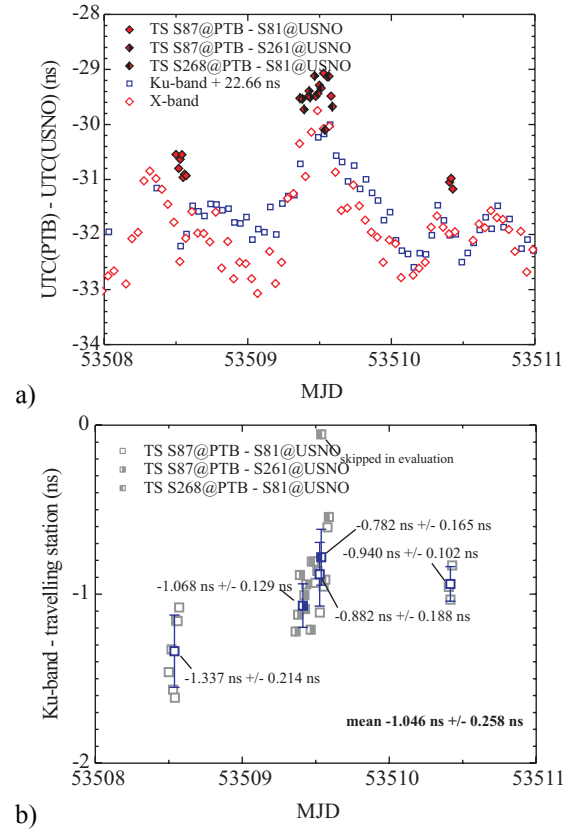

Figure 5. May 2005: a) Comparison of the time scales UTC(USNO) and UTC(PTB) using three TWSTFT links during the calibration campaign in Sep'05: Ku-band (blue squares), X-band (red diamonds), and TS (full symbols). b) Double-differences between regular links (Ku-band, X-band) and the link via the travelling station (TS). Gray symbols represent individual measurements, whereas the colored symbols represent the average over each set of data.

the previous exercise during March, and the difference between them is given. The evaluation was done without a closure measurement at USNO. But taking into account the excellent agreement between both calibration trips, the September experiment should not be affected by instabilities. Taking into account the results of data bridging of the Ku-band (14.2 ns; see Section IV), the effective differential correction is only 0.6 ns for the Ku-band link and 0.4 ns for the X-band link.

TABLE II. Calibration results and differential corrections to be applied. For details see the text.

	δΔT (ns) Mar'04	δΔT (ns) Sep'04	differential correction (ns)
X-band – TS	1.2	1.6	+0.4
Ku-band – TS	1.7	16.5	+0.6[1]

[1]For the differential correction a 14.2 ns jump in the data derived from data bridging (see Section IV) is taken into account.

3) Calibration Exercise May'05

From 18 to 20 May 2005 the TS was again operated at PTB. As in previous calibrations, the number of Ku-band measurements was increased from the nominal four to 24 sessions per day. The TS was operated on 3 days with the primary setup, while on day 2 different hardware configurations were employed aiming at sufficient redundancy in verification of the results. In Fig. 5a), the true time transfer of the TS is depicted, together with the results of the X-band and the Ku-band data recorded during the calibration days. As an example, the double-differences Ku-band - TS are shown in Fig. 5b). The single measurements were grouped with respect to the recording day and to the hardware setup employed. A comparison of the mean values of all groups, including the X-band double-differences which are not shown here, proves that the day-to-day instability is less than 0.7 ns in both links calibrated. The mean over all recorded data points (only one outlier was removed) results in differential corrections to the Ku-band link of -1.05 ns and to the X-band of −1.00 ns, respectively. The standard deviations are 0.26 ns and 0.37 ns, respectively.

configuration, including the frequency change of some MHz. However, the magnitude of the jump was unexpectedly large and is still not understood. Fortunately, the unaffected X-band link was in full operation during the break. Thus, a comparison of H4(PTB) – UTC(USNO) via Ku-band and X-band before and after the jump allowed the determination of the true magnitude of the jump by computation

UTC(USNO)]$_{Ku-band}$ – [H4(PTB) - UTC(USNO)] . The results are shown in Fig. 6 a). 317 and 176 data points averaged over a period of 38 days and of 53 days after the jump respectively. The standard deviations are 0.54 ns and 0.55 ns respectively. The combined statistical uncertainty is thus 0.77 ns. The difference between both values of 4.18 ns is considered as entirely due to the jump in the Ku-band, and thus represents the recalibration value to be applied to the Ku-band data evaluation. This is in good agreement with the value of 4.0 ns computed by the BIM independently [12].

The second example was carried out to account for a complete satellite change in the Ku-band TWSTFT network. In this framework the Astronomical Institute of the University of Bern (AIUB) supported the TWSTFT community with GPS CP data computed using the Bernese GPS software [5,13]. The result of the bridging is depicted in Fig. 6b), together with the result from the bridging analysis using X-band data. The double-difference Ku-band – GPS CP gives –22.88 ns, while Ku-band – X-band gives – 22.66 ns. The differences are well within the standard deviation of the X-band related data, amounting to 0.87 ns and of the GPS CP related data, amounting to 0.44 ns. They are also consistent with the uncertainties of the means of 0.21 dividing the standard deviation by the square-root of the number of the measurements, assuming a normal distribution of the individual measurements.

tively, which are calculated ns and 0.09

IV. B DATA JUMPS AND AND 2005

A calibrated TWSTFT link is susceptible to delay changes due to equipment replacement or even up- and downlink frequency changes requested by the satellite provider. In such cases, discontinuities and data steps or jumps deteriorate the calibration accuracy. To minimize the impact of such actions, the data of the affected link can be bridged with data of another low-noise link that is operated in parallel. A minimum loss of accuracy can be achieved by employing GPS carrier phase (CP) data or even a second TWSTFT link. Two examples are given in the following.

On 8 July 2004 (MJD 53194) Intelsat disconnected the transponder configuration of IS 903 used for the transatlantic Ku-band link between the US (affecting the National Institute of Standards and Technology (NIST) and USNO) and several European time laboratories (among them PTB). Using new transmit/receive frequencies, the link was reestablished on 27 July (MJD 53216). An analysis revealed a jump of approximately 14 ns in all transatlantic links, which could be attributed to the new transponder

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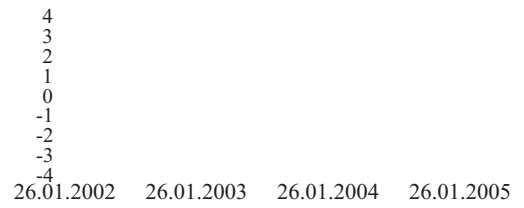
A.1

A.2

TS   LTBC
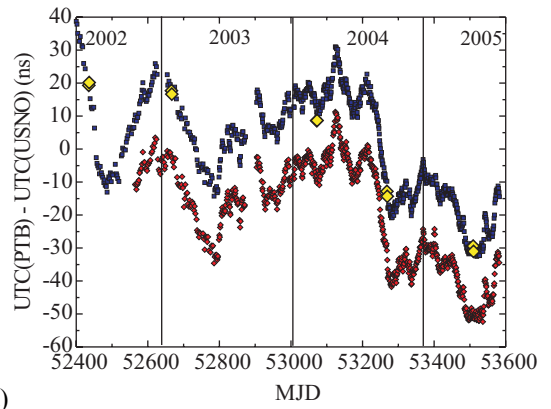
a)

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TABLE III.   UNCERTAINTY BUDGET EVALUATION OF THE CALIBRATION EXERCISES. FOR DETAILS SEE THE TEXT.

	$u_{A,1}$ (ns)	$u_{A,2}$ (ns)	u_A (ns)	$u_{B,1}$ (ns)	$u_{B,2}$ (ns)	$u_{B,3}$ (ns)	u_B (ns)	U (ns)
Mar'04 Ku	0.095	0.327	0.341	0.799	0.5	0.141	0.953	1.012
Mar'04 X	0.095	0.191	0.213	0.799	0.5	0.141	0.953	0.977
Sep'04 Ku	0.072	0.267	0.277	0.799	0.5	0.141	0.953	0.992
Sep'04 X	0.072	0.318	0.326	0.799	0.5	0.141	0.953	1.007
May'05 Ku	0.211	0.258	0.333	0.586	0.5	0.141	0.783	0.851
May'05 X	0.211	0.373	0.429	0.586	0.5	0.141	0.783	0.892

Ku-band and X-band links at the same level as the current calibration uncertainty. Future improvements of the link stabilities may be achieved by a detailed investigation of environmental conditions like temperature or humidity or the stability of single components of the time transfer equipment, including the frequency distribution equipment in the participating institutions.

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