CALIBRATION OF FOUR EUROPEAN TWSTFT EARTH STATIONS WITH A PORTABLE STATION THROUGH INTELSAT 903

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Keywords: TWSTFT, time transfer, calibration, uncertainty evaluation, Galileo.

ABSTRACT

The differential delays of four two-way satellite time and frequency transfer (TWSTFT) earth stations were determined by using a portable TWSTFT station. This station was assembled by TUG and visited the time laboratories of PTB, OP, NPL, and VSL from 5th to 16th July 2004. A number of calibration measurements was performed during a four hours slot at each location. These measurements were supplemented by differential measurements between the portable and the co-located local stations. Differential delays between the portable and co-located earth stations show a statistical uncertainty below 0.6 ns for a standard TWSTFT measurement. The final closure measurement at PTB allows a stability analysis of the differential delay between the portable and the local station. The deviation between the two co-locations is only 0.4 ns. We achieved total estimated uncertainties down to 0.9 ns. As a further test the results were checked for closing errors and also against previous calibration results.

1. INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) is one of the leading techniques for remote frequency standards and time scales comparison [1, 2]. Accuracies in the sub-nanosecond regime are achievable. Many systematic errors which are present in receive-only methods, such as GPS common-view time transfer, are negligible small. While unknown delay differences between the earth stations' transmitting and receiving path do not hamper comparisons of remote frequency standards it is observed that time scale comparisons even on the level of hundreds of nanoseconds are impossible without a proper calibration of the participating ground stations.

TWSTFT is being used by the Bureau International des Poids et Mesures (BIPM) to relate the Coordinated Universal Time UTC(i) scales realized in the institutes i. Up to now, most of the TWSTFT time links have been calibrated using GPS common-view measurement results which limit the attainable uncertainty to several nanoseconds. This can be clearly seen in the uncertainty values of UTC - UTC(i) published for the first time in BIPM Circular T 205 [3]. Consequently, the CCTF Working Group on TWSTFT stimulated to perform calibrations of TWSTFT links using an adequate technique. The most convenient way is the use of a portable TWSTFT station.

Beside the extensive calibration activities of the U.S. Naval Observatory (USNO) [4], in 1998 and 2003 European calibration trips were carried out by two persons visiting three or two European stations, respectively [5, 6]. We report on the calibration of four TWSTFT earth stations during a two-week schedule. The portable station needed to be conducted by only one person as the invited stations were well prepared and supported the activity. We report on the evaluation concept of the calibration and describe the execution and results of the exercise in detail, including a discussion of the uncertainty budget estimation. Finally, the possible influence of so-called closing errors is discussed.

2. THE CALIBRATION TRIP

Four European institutes agreed to have the differential earth station delays of their TWSTFT systems in Ku-band determined in a way which was successfully demonstrated one year ago for the IEN – PTB link [6]. Pseudo-random noise (PRN) phase-modulated signals were exchanged via the geostationary satellite INTELSAT 903 at 325.5°E with uplink and downlink frequencies of 14170.5975 MHz and 11120.5975 MHz, respectively. Each station transmits a pre-determined characteristic PRN signal at 2.5 MChip with Mitrex compatible codes. A standard session consists of nominal 120 time difference values (one measurement each second). The midpoint of a quadratic fit function is calculated at each station i, named TW(i) further down, and exchanged among the stations, as recommended in the ITU-R documents [7]. The travelling portable reference station (TS), designated TUG01 and first used in 1998 [5], was provided and operated by Joanneum Research on contract basis [8]. The campaign is illustrated in Fig. 1. The TS was sequentially operated at four different European time laboratories (the Physikalisch-Technische Bundesanstalt – PTB in Germany, the Bureau National de Métrologie, Systèmes de Référence Temps Espace - BNM-SYRTE (in the following named Observatoire de Paris - OP) in France, the National Physical Laboratory – NPL in the United Kingdom, and the National Metrology Institute Van Swinden Laboratorium B. V. – VSL in the Netherlands) during a two-week schedule. The initial measurements at PTB were verified by a second series concluding the campaign.

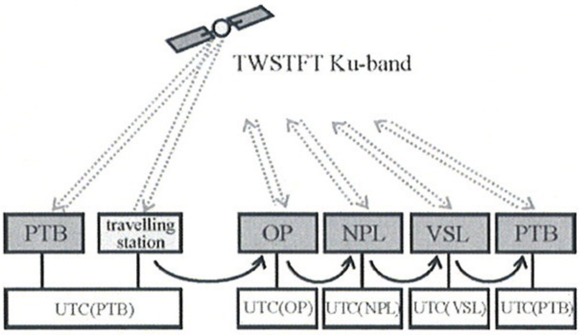

Figure 1: Schematic set-up representation of the travelling TWSTFT station (TUG01) sequentially operated at PTB, OP, NPL, VSL, and back at PTB.

The campaign was carried out from 5th to 16th July 2004. The TS was supplied with a new 4-segment antenna (diameter 1.2 m) to facilitate transport and deployment by one engineer. Most of the outdoor and indoor equipment including cables were the same as in previous calibration exercises [5, 6]. The TS modem was SATRE 036. Since the last campaign some microwave components (LNB, filter) have been replaced due to a change of the geostationary satellite and its transponder frequencies. Thus, comparisons with previous results are hampered by the unknown delay change due to the exchange of these components.

The measurements started on 6th July (MJD 53192) at PTB, followed by measurements at OP (9th July, MJD 53195), NPL (12th July, MJD 53198), VSL (14th July, MJD 53200), and again at PTB (16th July, MJD 53202). In Fig. 2 photographs of the TS beside the local outdoor equipment are depicted (a to d). There were normal weather conditions (cloudy and sometimes rainy, temperature ranging from 10° C to 22 °C) during the whole trip which had no noticable impact on the results of the campaign.

A half hour time-table was arranged between all sites and the TS to enable TWSTFT measurements in all possible combinations. This time-table was repeated seven times to a total schedule lasting four hours from 10:00 UTC to 14:00 UTC. Additional measurements before and after the schedule were recorded at all sites between the TS and the local station. At VSL the schedule was enhanced by using otherwise idle time slots of the schedule.

In Fig. 2 (e to h) the indoor setup at each site is shown. At OP, NPL, and VSL the TS indoor equipment was installed inside the respective time and frequency laboratory. At PTB, the TWSTFT antenna and transceiver of the local station are mounted on a roof top in a distance of about 200 m from the time and frequency laboratory where the local modem and automation systems are located. The TS antenna and transceiver were mounted side by side to the local outdoor equipment and the indoor set-up was located in the same building (in a office two floors below). Because no reference frequency and 1PPS were available at the TS set-up, 1 PPS and 10 MHz frequency were supplied by a caesium clock (model HP5071A, ID C9) from the PTB clock ensemble, which was brought to the TS set-up for the duration of the experiment.

3. CALIBRATION TECHNIQUE

To determine the permanent stations' individual differential delays at each side, the TWSTFT equipment was measured versus the TS, both connected to the local realization of UTC(*i*). This relative delay difference is called the common clock difference between the local station of laboratory *i* and the TS and given by

$$\begin{aligned}\mathrm{CCD}(i,\mathrm{TS}) = {} & \tfrac{1}{2}\mathrm{TW}(i) - \tfrac{1}{2}\mathrm{TW}(\mathrm{TS}) \\ & + \mathrm{REFDLY}(i) - \mathrm{REFDLY}(\mathrm{TS}),\end{aligned} \tag{1}$$

REFDLY(TS) is the connection of the TS's modem TX 1PPS (PPSTX(TS)) to the local UTC(*i*) and determined using

$$\begin{aligned}\mathrm{REFDLY}(\mathrm{TS}) = {} & [\mathrm{UTC}(i) - \mathrm{CLK}(i)] \\ & + [\mathrm{CLK}(i) - \mathrm{REF}(\mathrm{TS})] \\ & + \tfrac{1}{2}[\mathrm{REF}(\mathrm{TS}) - \mathrm{PPSTX}(\mathrm{TS})]\end{aligned}, \tag{2}$$

where CLK(*i*) is the input reference clock for the TS's modem. The difference to UTC(*i*) has to be determined. REF(TS) is a 1PPS generated by the indoor unit of the TS and related to the modem reference frequency. Thus, REF(TS) is phase coherent to the PPSTX which is the transmission output of the modem. In the TS measurement configuration the start input of the time interval counter is not triggered by the PPSTX but by the REF(TS). This configuration introduces the factor ½ in eq. (2) and differs from the normal practise in the laboratories. In a second step, link calibration constants were computed from the differential earth station delays. Generally, delay differences between the transmission and reception paths of both, the local station and the TS, are leading to a non-zero result of the CCD.

After determination of the CCD(*i*,TS) at at least two sites *k* and *l*, a calibration constant for a time comparison between them can be computed using

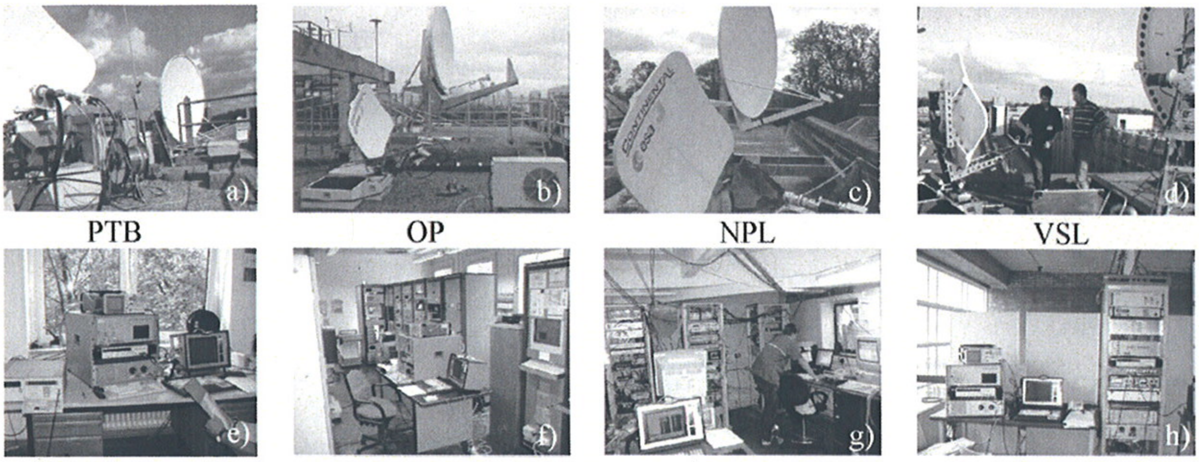

Figure 2: The TUG portable station collocated at four European TWSTFT earth stations. The upper photographs show the outdoor the lower photographs the indoor setup at PTB (a, e), OP (b, f), NPL (c, g), and VSL (d, h), respectively.

$$\mathrm{CALR}(k,l) = \mathrm{CCD}(k,TS) - \mathrm{CCD}(l,\mathrm{TS}) + \mathrm{TCD}(l) - \mathrm{TCD}(k) , \quad (3)$$

where TCD(i) is the earth rotation correction (Sagnac effect) for the one-way path from the satellite to station i, calculated following Ref. [7]. Having completed this exercise, the difference of the time scales UTC(k) and UTC(l) can be further on determined in routine operations according to

$$\begin{aligned}\mathrm{UTC}(k) - \mathrm{UTC}(l) = &\tfrac{1}{2}[\mathrm{TW}(k) + \mathrm{ESDVAR}(k)] \\ &- \tfrac{1}{2}[\mathrm{TW}(l) + \mathrm{ESDVAR}(l)] \\ &+ \mathrm{REFDLY}(k) \\ &- \mathrm{REFDLY}(l) \\ &+ \mathrm{CALR}(k,l)\end{aligned} . \quad (4)$$

ESDVAR(i) is the monitored differential earth station delay variation due to changes in cabling, etc. This value is set to zero at the moment when a new calibration value is applied.

4. RESULTS

The results of single calibration measurements between the TS and the collocated station are shown in Fig. 3. In the upper part the REFDLY(TS) measurements (label **I** to **IV**) are shown in detail:

$$\begin{aligned}&\mathrm{I}: && \mathrm{UTC}(i) - \mathrm{CLK}(i) + C_{\mathrm{I}} \\ &\mathrm{II}: && \mathrm{CLK}(i) - \mathrm{REF}(\mathrm{TS}) + C_{\mathrm{II}} \\ &\mathrm{III}: && \mathrm{REF}(\mathrm{TS}) - \mathrm{PPSTX}(\mathrm{TS}) + C_{\mathrm{III}} \\ &\mathrm{IV}: && \mathrm{REFDLY}(\mathrm{TS}) + C_{\mathrm{IV}}\end{aligned} . \quad (5)$$

Constants C_{I} - C_{IV} have been applied for a better visualization of the data and are summarized in Table 1. **I** represents the relation between UTC(i) and the modem reference CLK(i). At OP, NPL, and VSL both signals were phase coherent, while at PTB the use of the clock C9 introduced additional noise. The corresponding time differences between UTC(PTB) and C9 during the TW sessions were calculated by using a linear regression for the first co-location (MJD 53192) and the mean value for the closure (MJD 53202).

Table 1: Constants applied in eq. (5)

	PTB_1	OP	NPL	VSL	PTB_2
C_{I} (ns)	-48660	-360	-8361	-26	-48773
C_{II} (ns)	-41	-46	-95	-92	-41
C_{III} (ns)	-731	-724	-723	-769	-731
C_{IV} (ns)	-49074	-775	-8824	-510	-49187

Measurements **II** and **III** were ideally phase coherent. Especially the data of the first visit at PTB reveal a significant slope, which we attribute to warm up processes in the modem. One may recognize the same but very slight slope in the second PTB data. **IV** is the REFDLY(i) (see eq. (4)) taken to calculate the CCD(i) after eq. (1). CCD(i) is shown in the lower part of Fig. 3. The black dots represent the results of the individual measurements, the grey dots are the mean over all data of one day. The error bars represent the standard deviation. PTB_1, OP, and VSL data show slight drifts over the total measurement time, which do not exceed one nanosecond at least for PTB_1 and VSL. The data of OP and NPL show a little bit more noise. The PTB_2 data reveal a local minimum which may be due to clock drifts of the TS reference. The calibration results shown in Fig. 3 are summarized in Table 2. The standard deviation (sigma) of the CCD(i) is always below 0.6 ns. In the last column the Sagnac correction TCD(i) is given.

Table 2: Calibration campaign results

Laboratory	CCD (ns)	sigma (ns)	TCD (ns)
NPL	-824.08	0.57	76.298
OP	6998.16	0.43	86.103
PTB	+7.20	0.31	94.295
VSL	-29.12	0.23	84.324

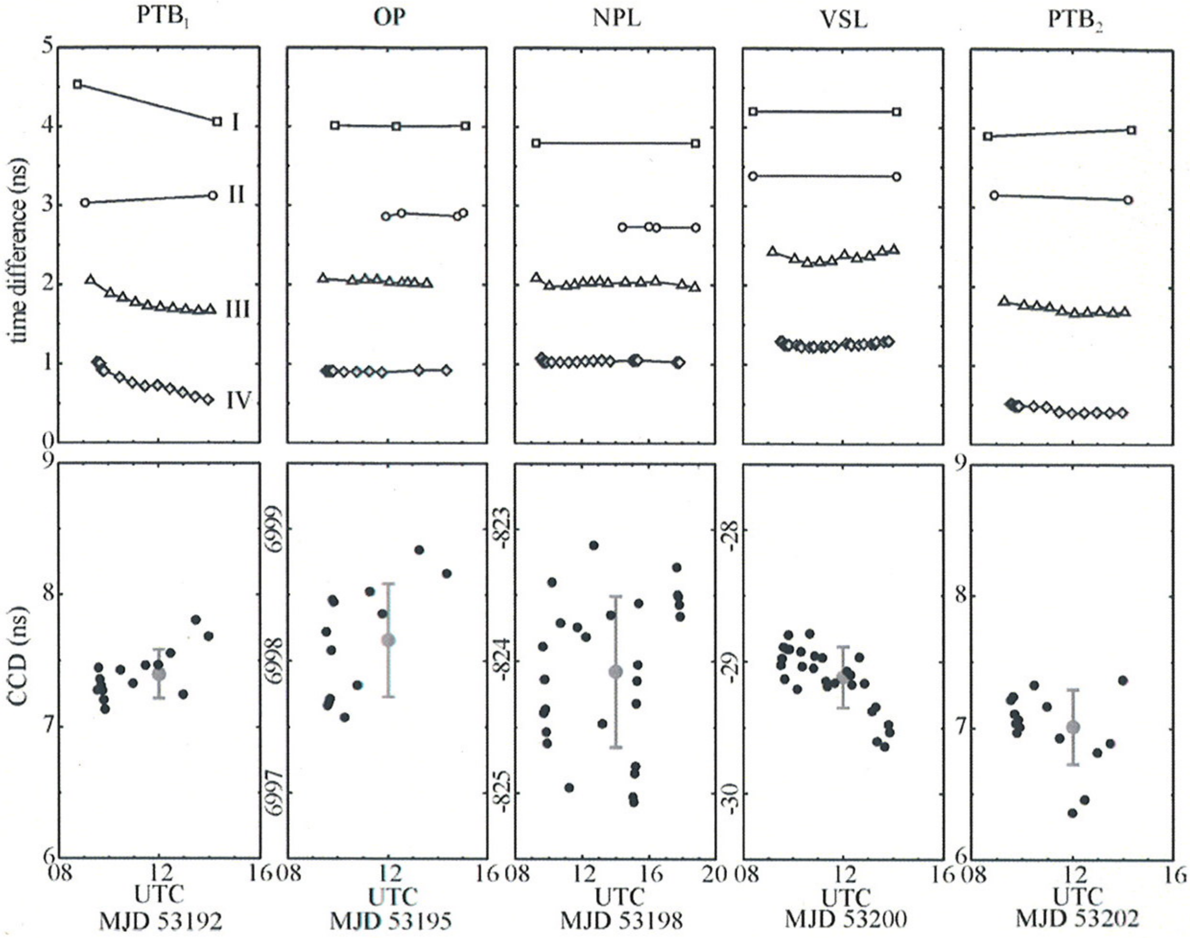

Figure 3: REFDLY measurements of the TS (upper part, for details see the text) during the calibration trip from the 1st visit at PTB (left) to the 2nd (right). In between the measurements recorded at OP, NPL, and VSL. The lower part shows the single measurements (black dots) as well as the means and standard deviation (grey symbols) of the common clock difference CCD between the TS and the local station.

The resulting calibration constants are shown in Table 3. The overall uncertainty of the calibration constants can be calculated using the following equation:

$$U = \sqrt{u_{\mathrm{A},k}^2 + u_{\mathrm{A},l}^2 + u_{\mathrm{B},1}^2 + u_{\mathrm{B},2}^2 + u_{\mathrm{B},3}^2}\ . \qquad (6)$$

$u_{\mathrm{A},i}$ is the standard deviation of CCD(i) determined at laboratory i. Ideally the determination of the two CCD(i) for one link calibration should be performed simultaneously. In practice this is not possible. To account for potential delay variations of the three stations, which are involved for one link calibration, we estimate them from the two experiments TS at PTB, the initial and the closure. The difference between both measurements is 0.39 ns. If this difference is shared equally between both stations every single station shows the same instability, and thus contributes with 0.28 ns. Because three stations are involved for one link calibration the total amount is $u_{\mathrm{B},1} = 0.48$ ns. The TS has to be related to the local UTC(i) which requires a measurement of the UTC(i) reference with the TS's time interval counter for REFDLY(i) determination. We have to account for this by applying $u_{\mathrm{B},2} = 0.5$ ns according to the time interval counter specifications. $u_{\mathrm{B},3}$ reflects all other systematic errors, e.g. the stability of the connection to the local UTC (0.1 ns), influence of code changes, Tx and Rx power, C/N$_0$ (overall 0.2 ns). PTB used a portable clock C9 to connect the TS to UTC(PTB). Thus additional 0.3 ns should be assumed for links where PTB is involved. The total estimated uncertainty is just at the border to the sub-nanosecond region (see Table 3).

5. COMPARISONS WITH PREVIOUS CALIBRATIONS

Except the links including OP, which TWSTFT equipment was recently established and thus had not been calibrated, all others had been initially calibrated with Circular T (i.e. relaying on GPS measurement and calibration) [9]. To compare the present CALR values (column 2 in Table 3) with old ones, one has to take into account the values of the monitored differential earth

Table 3: Applied calibration constants and uncertainty budget evaluation. For details see the text.

Link	CALR(k,l) (ns)	$u_{A,k}$ (ns)	$u_{A,l}$ (ns)	$u_{B,1}$ (ns)	$u_{B,2}$ (ns)	$u_{B,3}$ (ns)	U (ns)
NPL - OP	7832.05	0.57	0.43	0.48	0.50	0.22	1.02
NPL - PTB	849.28	0.57	0.31	0.48	0.50	0.37	1.02
NPL - VSL	802.99	0.57	0.23	0.48	0.50	0.22	0.95
OP- PTB	-6982.77	0.43	0.31	0.48	0.50	0.37	0.95
OP - VSL	-7029.06	0.43	0.23	0.48	0.50	0.22	0.88
PTB - VSL	-46.29	0.31	0.23	0.48	0.50	0.37	0.88

station delay variations ESDVAR (see Ref. [7]) which may introduce additional uncertainties. We neglect these uncertainties here.

The NPL-PTB link had been calibrated with Circular T on MJD 52434 with an estimated uncertainty of 5.0 ns. The expectation calibration value is 853.36 ns. The offset of 4.1 ns to the new calibration is within the estimated uncertainty of the previous calibration. The link NPL-VSL had been calibrated on MJD 51434 with Circular T with an estimated uncertainty of 5.0 ns. We expected a calibration result of 818.93 ns which is 15.9 ns off in comparison with the actual result. The link PTB-VSL had been calibrated with Circular T on MJD 51017 (July 1998) with an estimated uncertainty of 5.0 ns. The new calibration deviates significantly from the old constant (-34.59 ns). In summer 2002 (MJD 52416), an Agilent 5071 Opt001 clock was transported from PTB to VSL and back [10]. The result of the clock transportation was that the TWSTFT calibration constant of the PTB should be reduced by 7.8 ns. But this shift was never applied until now. Considering this observation, fictively the expected calibration value is –34.59 ns – 7.8 ns = -42.39 ns. The difference to the actual calibration is reduced to only 3.9 ns. This is still a little bit larger than the reported total estimated uncertainty of the clock transport of 1.5 ns.

6. CLOSING ERRORS

In the data evaluation of this report we assumed that the delays of the receiving paths of all participating stations are constant, i.e. not dependent on the station which transmits a dedicated signal. Generally, the receive path delay depends on the received spectrum. Because different earth stations transmit different spectra, the delay difference in the local earth station k determined relatively with respect to a TS is generally different from the delay difference during time transfer between station k and l. Those delay differences may cause so-called closing errors [11], which can be observed if two time scales are compared via different TWSTFT measurement paths, i.e. direct measuring UTC(k) – UTC(l), and using a third "relay" station m measuring [UTC(k) – UTC(m)] + [UTC(m) – UTC(l)] [12, 13]. A non-zero difference is called the closing error, whose origin is not well understood. In previous studies, no significant relations between delay variations and operating parameters were detected [13]. Furthermore, instabilities in the closing error, e.g. jumps of the same magnitude as the effect itself, were observed [12]. In a theoretical analysis [11] J. Davis showed that closing errors may deteriorate the accuracy of a calibration experiment as presented in this report. In the ITU-R documents [7] this technique is characterized by the key words: Portable earth station used in a relative mode (REL). To circumvent possible closing errors Davis proposed to use a portable earth station as an independent time-transfer system (IND). Both techniques are illustrated in Fig. 4. However, additional stations can be easily calibrated only by using the same TS in the REL mode. If the CCD of an additional station is determined all links to the previously visited stations would be calibrated assuming the TS has not changed its internal delays.

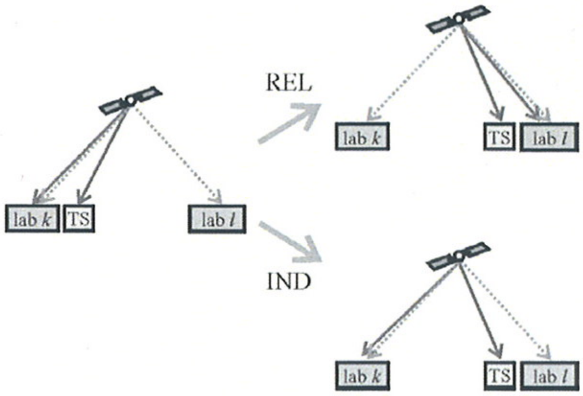

Figure 4: Different calibration techniques employing a portable travelling earth station (TS): TS used in a relative mode (REL) and as an independent time-transfer system (IND). The dotted arrows indicate the link to be calibrated, the red ones indicate the TWSTFT measurements to be evaluated for calibration.

The technique REL is usually applied by TUG campaigns, while IND is usually used by the USNO in their calibration campaigns e.g. for the link USNO-PTB [14]. We recorded data of all possible measurement combinations between the participating stations to enable a comparison between the REL- and IND-technique for the current campaign. In Fig. 5, results of both calibration techniques are compared. Each link between the four sites was investigated by analyzing the measurements of one day when the TS was located at one site of the link. The error bars reflect the combined standard deviation of the two techniques. The standard deviation of $[\mathrm{UTC}(k)-\mathrm{UTC}(l)]_{\mathrm{REL}}$ consists of the statistical uncertainty of both common clock experiments at station k and l which are necessary for calibration, as well as the TWSTFT measurement of the calibrated link. Only two measurements contribute to the statistical uncertainty of $[\mathrm{UTC}(k)-\mathrm{UTC}(l)]_{\mathrm{IND}}$, the common clock measurement at k and the remote measurement between TS located at site l, and k.

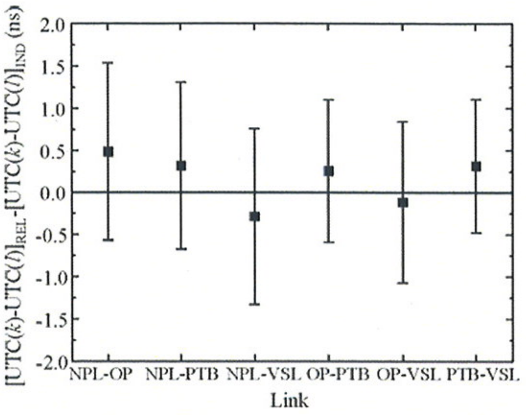

Figure 5: Analysis of possible common clock errors, by comparing the two different calibration techniques REL and IND.

No result shows a significant deviation from zero. Thus, we expect that there is no appreciable deterioration of the REL results. Nevertheless, a future detailed analysis may reveal systematic phenomena which probably lead forward to a better understanding of TWSTFT.

7. CONCLUSION

The differential delays of four European TWSTFT earth stations were determined by using a portable TWSTFT station. Calibration constants with a total estimated uncertainty down to 0.9 ns were achieved. A test for closing errors showed no significant deterioration of the accuracy of the calibration. The exercise demonstrates that a two-week schedule is sufficient for the calibration of four TWSTFT earth stations and only one person is needed to conduct the portable station during travelling, provided that the invited stations are well prepared and support the activity. This is important because in the future low cost high accuracy procedures are necessary to calibrate TWSTFT equipment of time laboratories contributing to the Galileo System Time.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of A. Bauch T. Polewka, C. Richter (PTB), D. Valat (SYRTE) during assembling and operating the TS at the respective home laboratories and for helpful discussions. The support of INTELSAT for providing satellite transponder time for scientific purposes is gratefully acknowledged.

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