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Calibration of Six European TWSTFT Earth Stations Using a Portable Station

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Two-way satellite time and frequency transfer (TWSTFT) has become an important component in the international network for comparing time scales. To employ the full potential of the technique a calibration of the internal delay of each ground station is necessary. Only a few calibration campaigns have previously been carried out in the European network of TWSTFT links. We report on the first recalibration of TWSTFT links during a campaign involving six European time institutes. The campaign was performed using a portable ground station assembled and operated by TUG/Joanneum Research, Graz, that visited the sites of INRIM, NPL, OP, PTB, SP, and VSL, travelling a total distance over 7000 km during a three-week period in October/November 2005. Differential delays of earth stations were determined in the common clock mode relative to the portable station. Combined uncertainties ranging from 0.9 ns to 1.3 ns for all calibrated links were achieved in this campaign.

Keywords: calibration, TAI, two-way satellite time and frequency transfer, TWSTFT, uncertainty budget

I. INTRODUCTION

During the last decade time transfer via geostationary satellites has been developed into a widely used method for remote clock comparisons [1,2]. The two-way technique provides a method of cancelling out unknown delay variations on the signal path. While two-way satellite time and frequency transfer (TWSTFT) has been in operational use it has been shown that remote clocks can be compared at the 10^{-15} level (using a dense measurement schedule) [3] and time scales can be compared with nanosecond accuracy [4]. The latter requires a measurement of the internal delays of the earth stations. This can be done by means of a portable station (PS) which is operated in consecutive experiments side-by-side with the participating earth stations in a common clock set-up. Worldwide only three institutes perform TWSTFT calibration campaigns. These include the United States Naval Observatory (USNO) [5] and the National Institute for Information and Communications Technology (NICT) in Tokyo [6], covering North America and Asia respectively. In Europe, TWSTFT calibrations have been conducted by Joanneum Research, a spin-off of the Technical University of Graz in Austria (TUG). Including the exercise reported here four calibration campaigns have been carried out since 1997 in Europe. The calibration campaigns and the visited institutes are listed in Table 1. The institutes participating in one or more campaigns were the Deutsche Telekom AG (DTAG), the Italian Istituto Nationale di Ricerca Metrologica (INRIM, formerly Istituto Elettrotechnico Nazionale – IEN), the National Physical Laboratory (NPL) of the UK, the French National Metrology Institute for Time and Frequency LNE-SYRTE Observatoire de Paris (OP), the German Physikalisch-Technische Bundesanstalt (PTB), the Swedish National Testing and Research Institute (SP), and the National Metrology Institute Van Swinden Laboratorium B. V. (VSL) in the Netherlands.

In each campaign the measurements at the first site were repeated after visiting all other participating institutes to verify the stability of the portable station during the trip.

Since in every one of the first three campaigns no link was calibrated twice, the 2005 campaign was the first repetition of a TWSTFT link calibration by means of the same technique. Furthermore, the calibration of six earth stations and thus 15 individual links in a single campaign is a record.

After a brief description of the calibration technique (references for a detailed study are given in the text below) and the course of the trip, the results of the single common clock experiments are presented. Thereafter, we discuss the uncertainty budget evaluation including a short analysis of a possible uncertainty impact of PRN code changes which are necessary for the technique used in this work. Finally, we compare the new results with previous calibrations.

II. CALIBRATION TECHNIQUE

The internal delays in TWSTFT earth stations can be observed and measured by suitable equipment and procedures. Because a local absolute calibration of a complete TWSTFT ground station set-up – providing knowledge of the overall internal delay - has not yet been demonstrated, different approaches to measuring the internal delays of ground stations relative to a dedicated standard are in use at present. Three different methods are employed to calibrate TWSTFT links which are part of the worldwide network established for the production of “Temps Atomique International” (TAI) and supervised by the BIPM. One is the use of independent and calibrated time transfer equipment such as GPS receivers. The others make use of a portable TWSTFT station (PS), either as an independent time transfer technique (similar to GPS) (IND) or as a reference to determine the relative delays of the earth stations to be calibrated with respect to the PS (REL). However, only the use of portable TWSTFT equipment has up to now allowed time transfer with nanosecond accuracy. Details of the measurement techniques are described elsewhere: for IND see [4] and for REL see e.g. [9].

Here we give only a rough sketch of the REL method applied in the current campaign. As depicted in Fig. 1, the PS is operated at two different sites *k* and *l*. At each site both stations, the PS and the station to be calibrated, are connected to the same clock. The result of a TWSTFT experiment between the collocated stations (exchanging pseudo-random noise (PRN) signals via a geostationary communication satellite, as described e.g. in Ref. [1]) is the difference of the internal delays of both stations operated in the common clock mode, which is named the common clock difference CCD. After determination of the CCD at at least two sites *k* and *l*, a calibration constant CALR(*k*,*l*) for a time comparison between *k* and *l* can be computed using

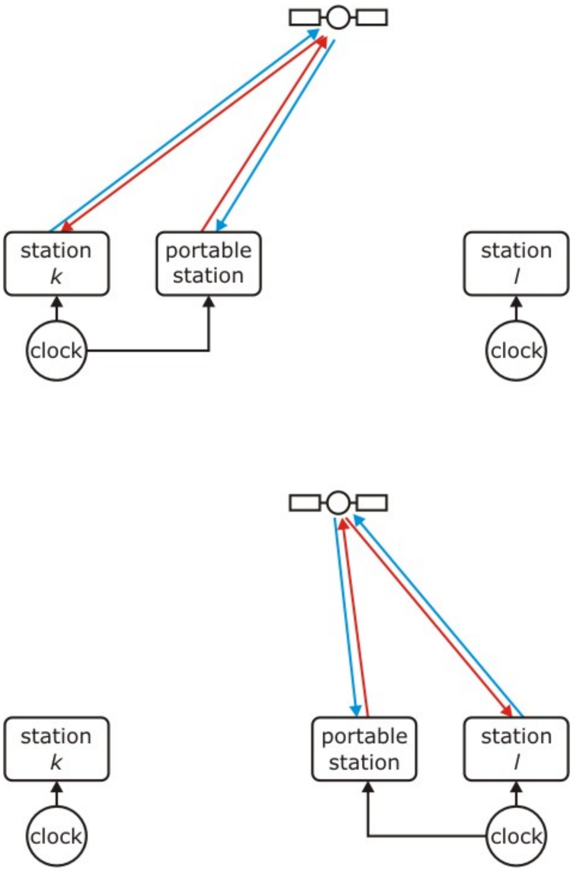

Fig. 1: Schematic of the set-up of the portable station sequentially operated at two different sites *k* (top) and *l* (bottom) to determine the common clock difference (CCD) at each site.

Table 1: History of European TWSTFT calibration trips using the portable station of TUG

No.	Year	Participating Institutes	Reference	
#1	1997	TUG-DTAG-PTB-TUG	Kirchner et al.	[7]
#2	2003	IEN-PTB-IEN	Cordara et al.	[8]
#3	2004	PTB-VSL-OP-NPL-PTB	Piester et al.	[9]
#4	2005	PTB-SP-VSL-NPL-OP-INRIM-PTB	this work	

$$\begin{aligned}\mathrm{CALR}(k,l) = {} & \mathrm{CCD}(l,\mathrm{PS}) - \mathrm{CCD}(k,\mathrm{PS}) \\ & + \mathrm{TCD}(l) - \mathrm{TCD}(k)\end{aligned} , \qquad (1)$$

where TCD(i) is the Earth rotation correction (Sagnac effect) for the one-way signal path from the satellite to station i, calculated as described in [10]. Having completed this exercise, the difference between the time scales UTC(k) and UTC(l) can be later determined by routine TWSTFT operations according to

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

where TW(k) is the result of time-of-arrival measurements at station k of signals transmitted by l and vice versa. ESDVAR(i) is the monitored differential earth station delay variation due to changes in the cabling, etc. This value is set to zero at the moment when a new calibration value is applied. REFDLY(i) represents the relation between the modem time reference and the clock representing UTC(i).

III. THE 2005 CALIBRATION TRIP

The CCDs between six European earth stations and the PS were determined during the campaign described in the following. The campaign started on 19th October 2005 at Graz with measurements on 21st October (MJD 53664) at PTB in Braunschweig, followed by measurements at SP in Borås (24th-25th October, MJD 53667-8), VSL in Delft (28th-29th October, MJD 53671-2), NPL in Teddington (31st October-1st November, MJD 53674-5), OP in Paris (3rd-4th November, MJD 53677-8), INRIM in Torino (6th-7th November, MJD 53680-1), and again at PTB (10th November, MJD 53684). The PS was transported in a van and accompanied by one engineer. However, installation at the laboratories required the support of the local staff. In Figure 2 the route of the van is depicted. A total distance of more than 7000 km required additional overnight stops (open symbols in Figure 2) and days off rest. The campaign was thus completed on 12th November in Graz after 25 days of travelling.

The set-up of the portable station [11] was generally the same as used for previous calibration campaigns. For the set-up and modifications see Ref. [7] and [8,9], respectively. As an example, in Fig. 3 the PS at SP is shown. In the foreground of Fig. 3 a) the outdoor equipment is installed on the roof top of SP just beside the outdoor parts of the TWSTFT station to be calibrated. The indoor set-up is shown in Fig 3 b).

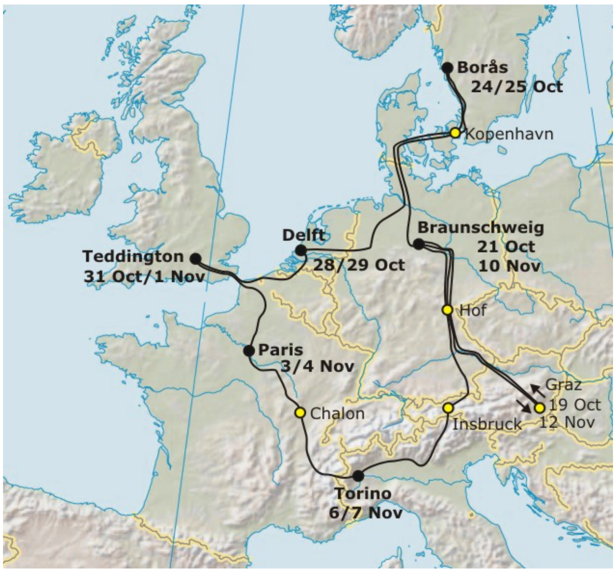

Fig. 2: Route of the calibration trip. Calibration locations and dates are indicated by bold letters, overnight stops by open symbols.

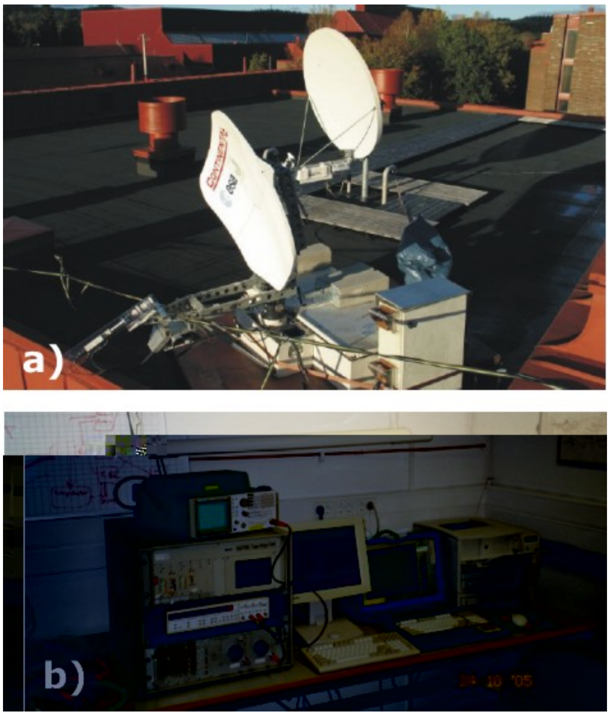

Fig. 3: The TUG portable station collocated at the SP TWSTFT earth station. Photograph a) shows the outdoor set-up and b) shows the indoor set-up.

To determine the CCD(i) at each site, pseudo-random noise (PRN) phase-modulated spread-spectrum signals

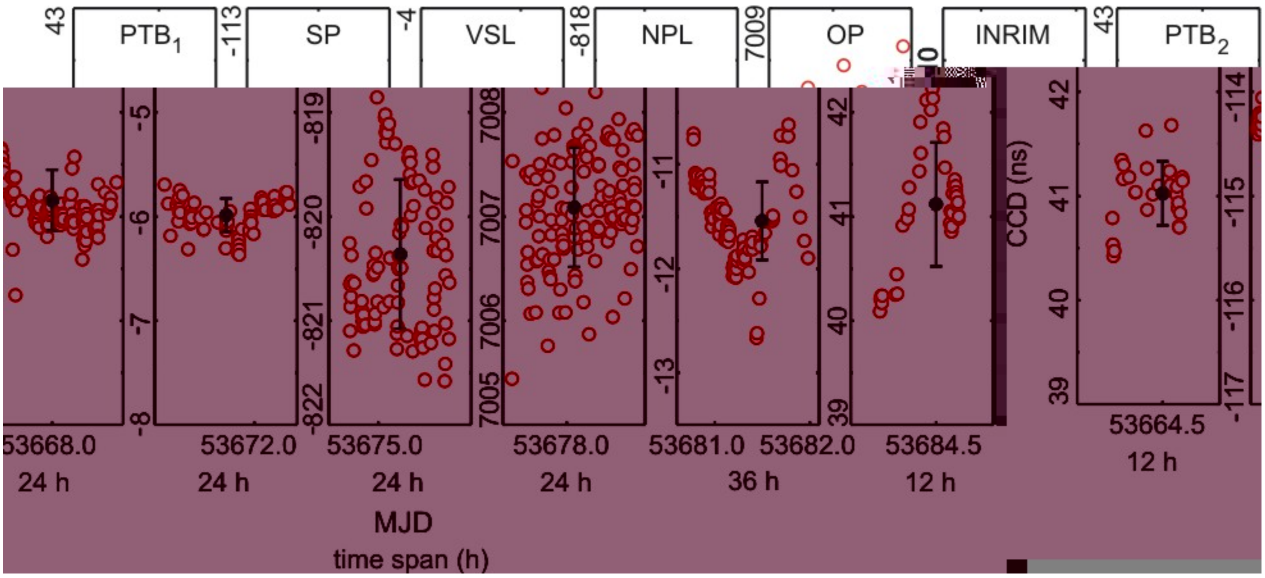

Figure 4: Single CCD measurements (open dots), mean values (solid dots) and standard deviations (bars) of the single CCDs between the PS and the local station.

were exchanged via the Intelsat geostationary satellite IS 707 at 307°E with up- and downlink frequencies of 14013.2 MHz and 12518.2 MHz, respectively. Each station transmitted a predetermined characteristic PRN signal at 2.5 MChip (one of the MITREX compatible codes 0 to 7 [12]), and locked its receiver to the PRN-coded signal of the collocated stations following a predetermined schedule which was added to the routine TWSTFT schedule. A standard session in this schedule consists of 120 time difference values (one measurement each second). The midpoint of a quadratic fit function is calculated at each station *i* and exchanged among the stations, as proposed in the ITU-R recommendations [10]. While every station to be calibrated has its own designated transmission code, the PS switched between several codes following a predetermined schedule. For example, at INRIM the PS transmitted with four different codes, with the MITREX code numbers 0, 2, 3, and 5.

In total 15 TWSTFT links between European time laboratories were calibrated, representing 5 links used by the BIPM in the production of TAI.

IV. RESULTS

Determination of the CCD was done in the same way as in all previous calibration campaigns listed in Table 1. A detailed description is given in Ref. [9]. In the following, only the TAI links are discussed in the text but the results regarding all links are summarised in Tables 2 and 3 to enable future retrospective evaluations of all links. In Fig. 4 the results are depicted. Open dots represent single CCD measurements; the mean values and standard deviations around the mean are depicted as full dots with error bars. The standard deviation is a useful measure of the data scatter if they are randomly distributed. However, some measurement series (INRIM, PTB$_2$ and to some extent SP, VSL) show significant drifts. These drifts are not visible in the internal REFDLY measurements of the PS and do not occur at every site and must therefore be attributed to instabilities in the local 1pps distribution or frequency distribution system or the local TWSTFT station being calibrated. For example, the course of the CCD values measured at INRIM correlates with the environment temperature. However, the origin of the drifts as well as the difference in the data scatter is not well understood at present and should be investigated in future calibration exercises.

Table 2: Results of the common clock differences (CCD) and standard deviations (SD) together with the station-associated Sagnac "downlink" correction (TCD).

station	CCD (ns)	SD (ns)	TCD (ns)
IEN01	279.528	0.304	134.441
IEN02	-11.543	0.375	134.441
NPL01	-820.363	0.716	108.152
OP01	7007.088	0.573	118.128
PTB01	41.071	0.495	119.383
SP01	-114.844	0.294	106.383
VSL01	-5.988	0.158	113.149

The calibration results shown in Fig. 2 are summarized in Table 2. Note that INRIM calibrated two stations: IEN01 and IEN02. If the link to INRIM is discussed in the following, only the station IEN02 is referred to. The highest standard deviation (SD) of the CCD(*i*) is 0.7 ns; the average SD is 0.416 ns.

The resulting calibration constants CALR(*k*,*l*) appearing in Eq. 2 are listed in Table 3. For completeness all link combinations and the associated uncertainty budgets are given. The overall uncertainty *U* for one link is the geometric sum of the single uncertainty contributions listed in the table. $u_{A,i}$ is the standard deviation of the single CCD(*i*) from its mean. Ideally the determination of the two CCD(*i*) for one link calibration should be performed simultaneously. In practice this is not possible. An estimate of the stability of the stations involved can be derived from the two measurements at PTB, the initial and the closure. The mean values of both measurements show excellent agreement, 41.025 ns and 41.116 ns respectively. However there is a significant drift in CCD values, especially during the closure measurements, and thus the standard deviation of the second data set is much bigger than the difference between both mean values. We account for this by applying the “combined” SD of the initial and the closure measurement $u_{B,1} = 0.671$ ns. The PS has to be related to the local UTC(*i*) which requires a measurement of the UTC(*i*) reference with the PS’s time interval counter (TIC) for REFDLY(*i*) determination. We take this into account by applying $u_{B,2} = 0.5$ ns according to the TIC specifications. $u_{B,3}$ reflects all other systematic errors, e.g. the stability of the connection to the local UTC (0.1 ns), possible influence of code changes, Tx and Rx power, C/N_0 (overall 0.2 ns). PTB used a portable caesium clock to connect the PS to UTC(PTB). Thus an additional 0.3 ns uncertainty is assumed for links where PTB is involved. The total estimated 1-σ uncertainty ranges from 0.9 ns to 1.3 ns.

As mentioned, the TWSTFT calibration in the REL mode requires the use of additional PRN codes compared with the routine link operation between the ground stations. In principle, a time transfer measurement should be independent of the PRN code used. However, delay changes of up to 0.5 ns coinciding with code changes were reported [13]. We tested whether a significant delay change occurred if the PRN codes in use were changed. The test measurements were part of the predetermined schedule which was repeated every two hours. Thus, the code sequence was repeated

Table 3: Calibration constants and uncertainty budget (1-σ) of all links between two stations *k* and *l*. CALR and *U* values are applied in the data files according to Ref. [10], rounded to one decimal place.

Link *k*-*l*	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)
IEN01 – NPL01	-1126.180	0.304	0.716	0.671	0.5	0.22	1.163
IEN01 – OP01	6711.247	0.304	0.573	0.671	0.5	0.22	1.081
IEN01 – PTB01	-253.515	0.304	0.495	0.671	0.5	0.37	1.084
IEN01 – SP01	-422.430	0.304	0.294	0.671	0.5	0.22	0.963
IEN01 – VSL01	-306.808	0.304	0.158	0.671	0.5	0.22	0.931
IEN02 – NPL01	-835.109	0.375	0.716	0.671	0.5	0.22	1.184
IEN02 – OP01	7002.318	0.375	0.573	0.671	0.5	0.22	1.103
IEN02 – PTB01	37.556	0.375	0.495	0.671	0.5	0.37	1.106
IEN02 – SP01	-131.359	0.375	0.294	0.671	0.5	0.22	0.988
IEN02 – VSL01	-15.737	0.375	0.158	0.671	0.5	0.22	0.956
NPL01 – OP01	7837.427	0.716	0.573	0.671	0.5	0.22	1.261
NPL01 – PTB01	872.665	0.716	0.495	0.671	0.5	0.37	1.263
NPL01 – SP01	703.750	0.716	0.294	0.671	0.5	0.22	1.161
NPL01 – VSL01	819.372	0.716	0.158	0.671	0.5	0.22	1.134
OP01 – PTB01	-6964.762	0.573	0.495	0.671	0.5	0.37	1.188
OP01 – SP01	-7133.677	0.573	0.294	0.671	0.5	0.22	1.079
OP01 – VSL01	-7018.055	0.573	0.158	0.671	0.5	0.22	1.050
PTB01 – SP01	-168.915	0.495	0.294	0.671	0.5	0.37	1.081
PTB01 – VSL01	-53.294	0.495	0.158	0.671	0.5	0.37	1.052
SP01 – VSL01	115.622	0.294	0.158	0.671	0.5	0.22	0.927

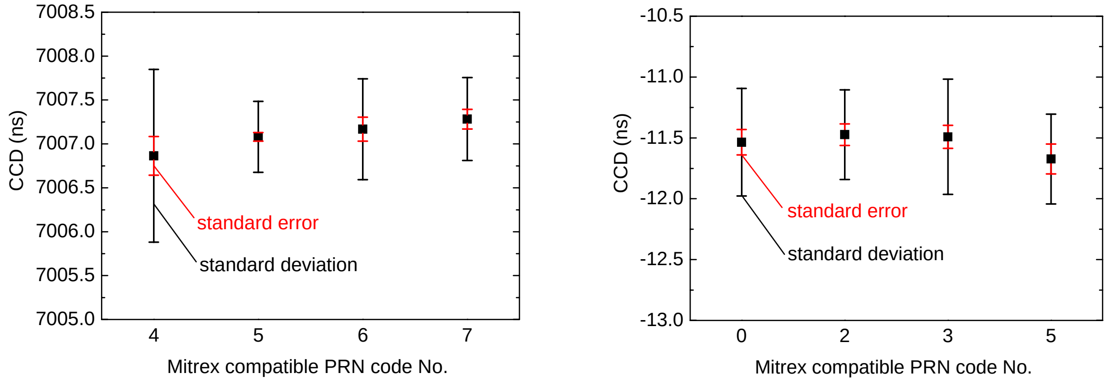

Figure 5: Two examples of using different codes at the Tx channel of the PS. The left (right) graph CCD measurements at OP (INRIM) arranged according to the codes used by the PS.

several times when the PS was operated for around one day at some sites. In Figure 5 two examples of the CCDs sorted by the associated PS codes are shown. For example, when the PS was operated at OP, MITREX codes 4, 5, 6, and 7 were used (see left graph) while at INRIM (right graph) the codes 0, 2, 3, and 5 were employed. No significant dependency of the CCD(*i*) on the code used is observed. If we take the deviation of the mean, the so-called standard error (SE), instead of the SD, it can be seen that the 1-σ error bars of code 4 and 7 (left graph) do not overlap. However, SE reflects the uncertainty of the mean only if the single measurements are normally distributed.

V. HISTORY OF EUROPEAN TWSTFT TAI-LINKS

Except for the links to SP, whose TWSTFT equipment was recently installed and thus had not been calibrated, all other links had been calibrated before by means of TWSTFT. However, various events may have degraded the calibration uncertainties achieved previously, e.g. the change of the satellite used affected all links, and major setup changes happened at VSL. Comparison of the present CALR values (column 2 in Table 3) with previous ones requires some caution. The uncertainty of the CALR(*i*) values had to be adjusted after satellite or even transponder frequency changes and the uncertainty was increased as a result (see e.g. Ref. [4]). The earth station delay variations ESDVAR(*i*) (see Ref. [10]) changed due to equipment modifications which may have introduced additional uncertainty.

In Fig. 6 the long term records of the differential corrections of the European TAI links UTC(*i*) – UTC(PTB) are depicted. The links to INRIM, NPL, and OP were initially calibrated using Circular T (i.e. relying on GPS measurements and calibration), and were calibrated with the TWSTFT technique in 2003 (INRIM) and 2004 (NPL, OP). For each link the left coloured bar (± 5 ns) reflects the uncertainty of the GPS calibration. In the case of VSL the uncertainty of a clock transportation from PTB to VSL is shown which was never applied in the TWSTFT evaluation (see Ref. [9,14] for details). The differential corrections of the 2003 and 2004 campaigns are labelled with the “serial” number as given in Table 1. Each time a new calibration is applied the time transfer uncertainty is estimated at the nanosecond level. This uncertainty is increased whenever an occurrence renders continuous TWSTFT operations impossible. Increased error bars and labels indicate the date and what had happened (e.g. IS706 – IS903 for a satellite change and IEN01-IEN02 for a station change).

The actual calibration values deviate only slightly from previous values in the case of the links IEN01 – PTB01 (-0.76 ns), NPL01-PTB01 (-0.62 ns), and OP01-PTB01 (-1.53 ns). The mean of these changes, -0.97 ns, indicates a potential instability of the PTB01 earth station. The differential correction of the links IEN02-PTB01 (+2.5 ns) and VSL01-PTB01 (+12.1 ns) are unexpectedly large. However, the change from IEN01 to IEN02 was necessary due to a failure of hardware components of IEN01 and thus happened without sufficient time to determine the CALR for IEN02. In the case of VSL the setup was disassembled and rebuilt due to the move of the whole time laboratory to a different building over a distance of about 3 km. Both experiences prove that it is highly desirable to recalibrate a TWSTFT earth station after major setup changes to keep the uncertainty at the 1 ns level. The link SP01-PTB01 (+7.9 ns) had not been calibrated before but a comparison with Circular T (i.e. with GPS CV time transfer) shows very good agreement, within the estimated uncertainty of the GPS calibration

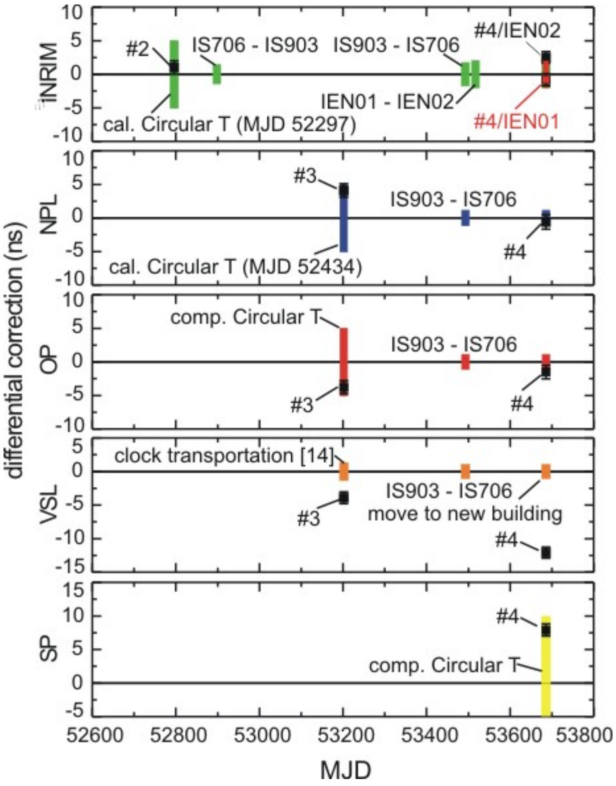

Figure 6: Differential corrections applied to the European TWSTFT links UTC(*i*) – UTC(PTB) contributing to TAI from MJD 52600 (Nov 2002) to MJD 53800 (Mar 2006). The error bars reflect the estimated uncertainty of the calibration; the coloured bars represent the estimated uncertainty of the link at the day of calibration including uncertainties due to possible bridging procedures.

($u_B = \pm 10$ ns) [15]. Note that the calibration was performed back in 1997 using a single channel single frequency GPS receiver.

VI. CONCLUSION

The differential delays of six European TWSTFT earth stations were determined by using a portable TWSTFT station. The whole campaign spanned over 7000 km and was conducted by one engineer during 24 days of travelling. Calibration constants with estimated uncertainties down to 0.9 ns were achieved. In this first recalibration of TWSTFT calibrated time links an average reproducibility of 0.97 ns is consistent with the estimated uncertainties of the links and of the calibration values.

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