Results of the 2008 TWSTFT Calibration of Seven European Stations

Andreas Bauch, Dirk Piester
Time Dissemination Working Group
Physikalisch-Technische Bundesanstalt
Braunschweig, Germany
Andreas.Bauch@ptb.de

Bernd Blanzano, Otto Koudelka
Institute of Applied Systems Technology
Joanneum Research Forschungsgesellschaft m.b.H.
Graz, Austria

Erik Kroon, Erik Dierikx
Van Swinden Laboratory
Delft, The Netherlands

Peter Whibberley
Time, Quantum and Electromagnetics Team
National Physical Laboratory
Teddington , UK

Joseph Achkar, Daniele Rovera
Time Metrology Group
LNE-SYRTE, Observatoire de Paris
Paris, France

Luca Lorini, Franco Cordara
Optics Division
INRiM
Torino, Italy

Christian Schlunegger
Time and Frequency Laboratory
METAS
Bern – Wabern, Switzerland

Abstract— **In 2008, seven European institutes participated in a TWSTFT calibration campaign to determine the internal signal delays of their ground stations relative to the portable reference station of Joanneum Research, Graz. In a second step, the calibration values and their uncertainties for time comparisons of 21 links involving the participating institutes were determined. The following results were obtained. The common clock differences between the two TUG stations measured in October 2007, August 2008 and October 2008, respectively, agreed within 0.5 ns, proving the suitability of the traveling station as a reliable and stable traveling reference. After substantial changes in the hardware, the links connecting to NPL and VSL were calibrated with uncertainties slightly exceeding 1 ns and 2 ns, respectively. The so-called TAI links OP-PTB, INRIM-PTB, and METAS-PTB were recalibrated. Despite hardware changes and a change of the satellite in use in early 2008, the calibration values measured this time agreed with the values determined in 2005 and 2006 well within the calibration uncertainty of slightly above 1 ns.**

I. Introduction

Two-way satellite time and frequency transfer (TWSTFT) using geo-stationary telecommunication satellites has proven to be the most appropriate means of comparing time scales and atomic frequency standards with an uncertainty in time of less than 1 ns and with relative uncertainty for frequency of about 1 part in 10^{15} at averaging times of one day. This is why TWSTFT is widely used in the international network of time keeping institutions supporting the realization of TAI. For the same reasons, TWSTFT has been chosen as the primary means to synchronize the two Precise Timing Facilities (PTF), part of the Galileo Ground Mission Segment. TWSTFT will also be employed for the measurement of the time difference between GPS time and the Galileo System Time (GST).

In order to perform true time comparisons it is necessary to determine the differential signal delays in the stations involved. This is possible in different ways. The method reported in this contribution follows the practice developed in recent years in Europe. A portable earth station is co-located with the ground stations involved in the link. It has been

978-1-4244-3510-4/09/$25.00 ©2009 IEEE

demonstrated before that this method can very likely provide the required calibration uncertainty of 1 ns.

In 2008, seven European institutes, represented by individual authors of this contribution, participated in such a TWSTFT calibration campaign. The portable reference station was provided by Joanneum Research, Graz. This contribution summarizes the Report provided by Joanneum Research [1] and adds further results regarding the temperature stability of the involved equipment. The results are edited for their implementation into the data format described in the Recommendation ITU-R TF.1153-2 [2]. In the following, the theoretical background and uncertainty evaluation are briefly described. The evaluation procedure of the calibration results is equal to the ones used for previous calibration campaigns. In Section V the results are presented. The calibration values for all TWSTFT links are listed and, if applicable, a comparison with the results of previous calibrations [3],[4] is made. The uncertainty for each link is given and finally the exact values to be inserted in the TWSTFT data files are stated.

II. THEORETICAL BACKGROUND

A. TWSTFT basics

TWSTFT between two remote stations 1 and 2 operating clocks CL(1) and CL(2), respectively, is based on two combined coincident measurements at both stations. Each measurement represents the determination of the time of arrival of a radio signal that is transmitted from the remote station and that is phase-coherent with the remote reference clock. The measurement result obtained at site 1, *TW(1,2)*, is the time difference reading from a time interval counter (TIC) at site 1 receiving the signal from site 2. It includes the difference between the two clocks, [*CL(1)-CL(2)*], and also the complete delay along the signal path. For the ground station we distinguish between the transmission (TX) and the receiving (RX) part.

The delay of a signal between its transmission from station 2 and its reception at station 1 consists of the remote site transmitter delay *TX(2)*, the overall signal path delay to the satellite and back to site 1 on Earth *SP(2)* (sum of the uplink delay *SPU(2)*, the transponder delay *SPT(2)*, and the downlink delay *SPD(1)*), the local receiver delay *RX(1)*, and the delay due to the Sagnac effect, which is computed from the positions of the ground stations and the geostationary satellite. We account for the Sagnac effect by introducing corrections for both the uplink to and downlink from the satellite, *SCU(2)* = *-SCD(2)* and *SCD(1)* = *-SCU(1)*, respectively. At site 2, the equivalent measurement is carried out simultaneously, and we obtain two measurement results, *TW(1,2)* and *TW(2,1)*:

$$TW(1,2)=[CL(1)-CL(2)]+TX(2)+SP(2)+RX(1)+ [SCD(1) - SCD(2)] \qquad (1)$$

Calibration of the stations at PTB, NPL, OP, and INRIM took place in the context of the development of the Galileo Time Service Provider Prototype and was financed by GNSS Supervising Authority under contract GJU/05/2419/CTF/FIDELITY, Work Package 3260 of PTB.

$$TW(2,1)=[CL(2) - CL(1)]+TX(1)+SP(1)+RX(2)+ [SCD(2) - SCD(1)] \qquad (2).$$

A detailed theoretical elaboration is given in [5], and the nomenclature follows the one introduced in paper [2].

B. Measurement configuration

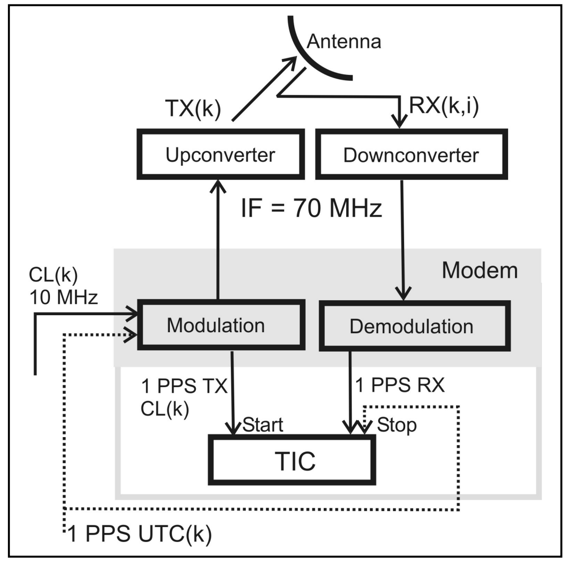

Figure 1. Measurement configuration at a TWSTFT ground station

The configuration of the measurement equipment at each ground station is depicted in Fig. 1. The TIC involved may be a constituent part of the modem or a separate device. The clock (CL) 10 MHz input drives the signal generation of the modem. The 1 PPS TX output is generated from the CL input and represents the epoch of the transmitted signal. Initially, the modem is synchronized with a 1 PPS input from the local time scale. If the physical source of the time scale is identical to CL(k), then the difference between the 1 PPS TX and the time scale is a constant, determined by cable and modem delays. In other cases, CL is an active hydrogen maser, and UTC(k) is derived from another atomic clock, as today at OP and PTB. Then the difference is measured periodically (with the same or a different TIC), and in all cases the value is reported as Reference Delay *RDY(k),* see (3) below.

The comparison between two UTC(k) scales is thus written as

$$[UTC(1) - UTC(2)] = ½ [TW(1,2) - TW(2,1)] + [RDY(1) - RDY(2)] + CAL(1,2) \qquad (3),$$

where we introduce the calibration value for the link between sites 1 and 2, which absorbs the summands *TX*, *SP*, *RX*, and *SCD* in (1) and (2).

C. Calibration practice

In order to determine *CAL(1,2)*, a portable TWSTFT station (PS) is used. In the first step, the PS is operated in parallel to station 1, connected to the same clock. Combining (1) and (2) for this case (common clock, identical site) yields the so called common clock difference *CCD(1, PS)* as

$$CCD(1, PS) = ½[TW(1,PS@1) - TW(PS@1,1)] \quad (4).$$

Thereafter, the PS is transported to station 2 and connected with the reference time scale there. A second CCD measurement is performed, providing

$$CCD(2, PS) = ½[TW(2,PS@2) - TW(PS@2,2)] \quad (5).$$

The calibration value is then determined as

$$CAL(1,2) = CCD(2,PS) – CCD(1,PS) + [SCD(2) – SCD(1)] \quad (6)$$

and later applied in (3).

Based on previous experience, the current calibration campaign has been extended to seven stations, but it was interrupted for one week before the last two stations were visited. It was finished with a closure measurement at site 1 in order to demonstrate that the PS did not change significantly compared to expected uncertainties during the campaign.

III. Calibration Uncertainty

The overall uncertainty of each calibration value is estimated using the following expression, given as 1-σ values if not stated differently:

$$U = \sqrt{u_{A,1}^2 + u_{A,2}^2 + u_{B,1}^2 + u_{B,2}^2 + u_{B,3}^2} \quad (7),$$

where $u_{A,1}$ reflects the statistical uncertainty of the determination of the CCD at site 1 and $u_{A,2}$ reflects the statistical uncertainty of the measurements at site 2. The systematic uncertainty $u_{B,1}$ represents the instability of the PS. It is derived by a comparison of the initial CCD measurements with the second determination during the closure, see [5] for details. Thus, $u_{B,1}$ represents in a strict sense the combined instability of both the PS as well as the collocated ground station at site 1. An additional systematic uncertainty is due to the connection of the PS to the local UTC generation system ($u_{B,2}$). This requires a connection of a local 1 PPS signal to the PS, which is usually done in two steps. First, the delay of the chosen 1 PPS signal to the local UTC(*i*) generation is determined (both signals need not necessarily originate from the same source) with a TIC and the 1 PPS is then connected to the PS, where its rising edge triggers an internal TIC. $u_{B,2}$ is usually estimated based on the specifications of the TIC in use (0.5 ns). In $u_{B,3}$ all other suspected possible systematic effects are included. These effects are, e.g., the instability of the connection to the local UTC (0.1 ns), changes in TX/RX-power and C/N_0 during the campaign, and the use of different PRN codes compared with the operational modes (overall 0.1 ns to 0.2 ns).

As in all previous campaigns, a portable caesium clock was used to connect the PS to UTC(PTB). Thus, an additional 0.3 ns uncertainty has been assumed for links where PTB is involved. No such effect can be expected at all other sites.

IV. Details of the Calibration Campaign 2008

The seven visited institutes, the station designations and the dates when the calibration took place are listed in Table 1. The institutes are part of a larger network of European and two US stations. In this network, TWSTFT is routinely performed 12 times per day during the hours (in UTC) 00:00 to 00:59, 02:00 to 02:59 etc.. using the geostationary satellite IS-3R at 317°E. Calibration measurements were performed mostly during odd hours, occasionally also during the even hours, which required:

- Coordination with the CCTF WG on TWSTFT, announcing the extra measurements and calling from abstention of other stations to use code 15 (assigned to TUG03) during the campaign,
- change of the schedulers (custom written software) driving the TWSTFT station at each institute,
- adapting the scheduler driving the TUG03 station each time.

TABLE I. Summary of the 2008 Calibration Campaign

Institute	Location	TWSTFT Station Code	Date of calibration in 2008
INRIM	Torino, IT	IT02	15. + 16. 09.
METAS	Bern, CH	CH01	24. + 25. 09.
NPL	Teddington, UK	NPL01	08. + 09. 09.
OP	Paris, FR	OP01	11. + 12. 09.
PTB	Braunschweig, DE	PTB04	03. – 05. 09.
VSL	Delft, NL	VSL01	22. – 23. 09.
TUG	Graz, AT	TUG01	31.08., 01. + 02. 10.
TUGcal	traveling station	TUG03	

V. Results

Based on measurement results obtained at each site and using (4), common clock differences were determined. They are thus based on two *TW* measurements (1) and two *RDY* determinations. *RDY* values were either measured individually before each session or interpolated to each measurement epoch. The CCD values form the basic quantities from which the calibration values for each link (6) are calculated. In the following sub-section we show some individual results The upper plots show the CCD values minus their respective mean values. In the lower plot the statistical measurement uncertainty DRMS is shown for the two TW measurements, one obtained from TUG03 (black), one obtained from the visited station (gray). The horizontal axis represents the measurement time in hours from the start of the measurements.

A. Examples of individual results

The TUG results are of particular relevance since the two measurements made at the beginning and at the end of the full campaign are used to determine the uncertainty contribution due to the instability of the traveling station. Only a few measurements had been taken initially on the 31st August before the departure to PTB. The results are given as solid points in the upper part of Fig. 2. The closure data were taken in an overnight run lasting about 24 hours in groups during the odd hours

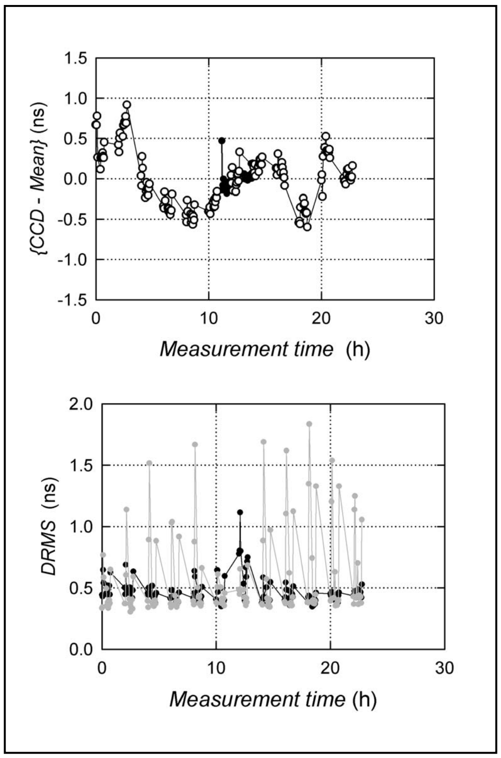

Figure 2. CCD and TW instability obtained at TUG, explanations are given at the beginning of Section V.

Since the data collected in most institutes have a very similar appearance, graphical representations are not presented here. At VSL, a significantly larger variation of CCD values was recorded. Later it turned out that this was likely to be caused by incorrect time-tagging of the 1-s data (1) obtained with VSL01 and its associated operating software. A significantly different pattern of data was collected at OP, and inspection of calibration results of previous years revealed large similarities. The measurements are shown in Fig. 3.

In order to understand what happened while the PS was operated at OP, a similar common clock measurement was later made at OP using the two fixed stations OP01 and OP02. Whereas in the TUG01-OP01 data fluctuations up to 2.5 ns peak-to-peak are observed, the two OP fixed stations vary by less than 0.36 ns over 42 hours. Very likely the excessive noise is related to two facts: the OP site is characterized by a signal path very close to nearby buildings, and the TUG03 antenna is small and has a much reduced efficiency (stronger

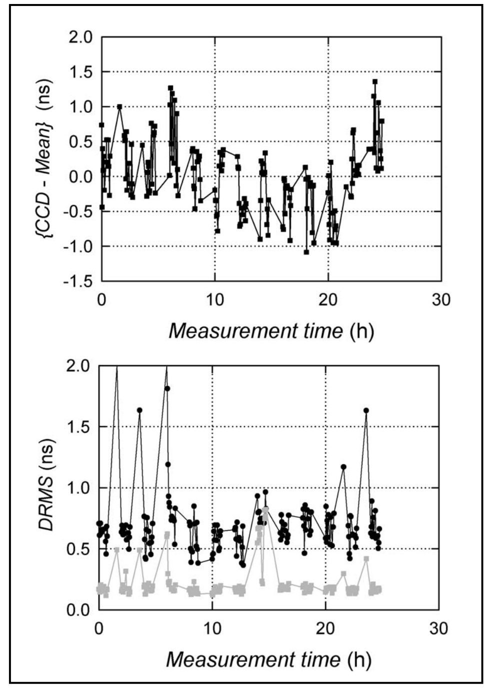

Figure 3. CCD and TW instability obtained at OP, explanations are given at the beginning of Section V.

B. CCD temperature dependence

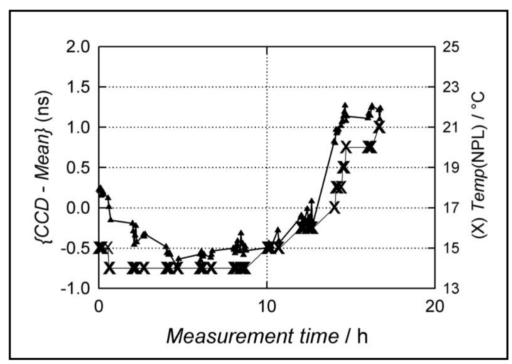

Figure 4. CCD (▲) and recorded temperature (X) at NPL

side lobes in the antenna sensitivity pattern) compared to the high-quality dual-offset antennae used with OP01 and OP02. In the next section we will discuss some further limitations on the achievable calibration uncertainty, which are likely due to the traveling equipment.

A temperature monitoring system is attached to the outdoor part of the traveling station. The temperature recordings as a function of time made at each site have been compared with the variation of the CCD recorded during some twenty hours of data collection. Fig. 4 shows, as an example, the results taken at NPL and reveals a clear correlation between both quantities. Some kind of correlation has been found in all data sets. The sensitivity is not linear but seems instead to be a function of the temperature itself. It is evident that the CCD determination involves the outdoor and indoor equipment of two TWSTFT stations, and the temperature sensitivity of the individual elements remains unknown. In Fig. 5 we present the compilation of the (CCD – Mean) values versus temperature dependence obtained at INRiM, METAS, NPL, and PTB.

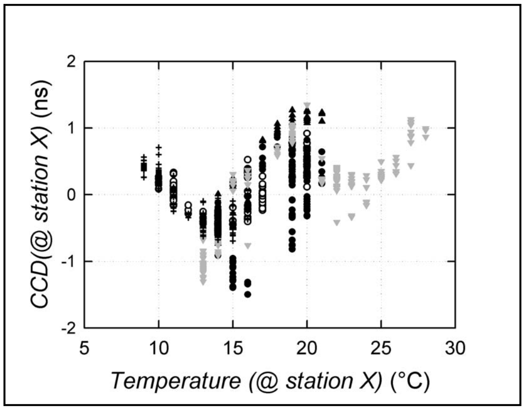

Figure 5. CCD values minus respective means plotted against the recorded temperature for the institutes INRiM (grey), PTB (•), TUG (O), METAS (+), and NPL (▲).

As a consequence of the complicated structure of the data we have refrained from trying to correct the recorded CCD values with respect to temperature. The statistical uncertainty contributions (7) are thus those resulting from the raw data.

C. Summary of results and link calibration uncertainties

In the following, Table II contains the results obtained at each site, (4) and (5), converted to link calibration values (6). All values were rounded to two decimal places. Comparisons are made with the CAL values assumed valid at the time when the calibration exercise was performed, as far as they were available. The Earth Station Delay variation (ESD) values provide known changes to the station delays since the last calibration. If ESD deviates from zero, the comparison of new and old calibration values has to be made against the effective (old) values, named CALeff(k). Table III contains the results of the uncertainty evaluation for each link (see Section III for explanations).

TABLE II. COMPILATION OF CALIBRATION RESULTS OF THE 2008 TWSTFT CALIBRATION, ALL VALUES ARE IN NS.

Link		meas. in 2008-10		Sagnac Correction			old CAL values				Comparison new – old	
k	l	CCD(k)	CCD(l)	SCD(k)	SCD(l)	CAL(k)	CAL(k)	CAL(l)	ESD(k)	ESD(l)	CALeff(k)	new-old
CH01	IT02	-134.73	-28.45	114.94	119.27	110.61	110.86	-110.86	0		110.86	**-0.25**
CH01	NPL01	-134.73	-815.69	114.94	92.14	-703.76						
CH01	OP01	-134.73	6988.39	114.94	102.15	7110.33	7112.13	-7112.13	0		7112.13	**-1.80**
CH01	PTB04	-134.73	-332.62	114.94	107.22	-205.61	-204.55	204.6	0	-0.18	-204.46	**-1.15**
CH01	TUG01	-134.73	-20.66	114.94	126.72	125.86						
CH01	VSL01	-134.73	-157.20	114.94	98.86	-38.55	96.50	-96.50	0	228.85	-17.93	**-20.63**
IT02	NPL01	-28.45	-815.69	119.27	92.14	-814.37						
IT02	OP01	-28.45	6988.39	119.27	102.15	6999.72	7000.41	-7000.41	0		7000.41	**-0.69**
IT02	PTB04	-28.45	-332.62	119.27	107.22	-316.22	-316.10	316.10	0	-0.18	-316.01	**-0.21**
IT02	TUG01	-28.45	-20.66	119.27	126.72	15.25						
IT02	VSL01	-28.45	-157.20	119.27	98.86	-149.16	-14.70	14.70	0	228.85	-129.12	**-20.04**
NPL01	OP01	-815.69	6988.39	92.14	102.15	7814.09			0			
NPL01	PTB04	-815.69	-332.62	92.14	107.22	498.15			0			
NPL01	TUG01	-815.69	-20.66	92.14	126.72	829.62			0			
NPL01	VSL01	-815.69	-157.20	92.14	98.86	665.21			0			
OP01	PTB04	6988.39	-332.62	102.15	107.22	-7315.94	-7316.50	7316.50	0	-0.18	-7316.41	**0.47**
OP01	TUG01	6988.39	-20.66	102.15	126.72	-6984.48						
OP01	VSL01	6988.39	-157.20	102.15	98.86	-7148.89	-7015.43	7015.43	0	228.85	-7129.86	**-19.03**
PTB04	TUG01	-332.62	-20.66	107.22	126.72	331.47			-0.18			
PTB04	VSL01	-332.62	-157.20	107.22	98.86	167.06	298.30	-298.30	-0.18	228.85	183.79	**-16.73**
TUG01	VSL01	-20.66	-157.20	126.72	98.86	-164.41						

When a field in the "old CAL values" columns is empty then no old data were available, e.g. because the station has been rebuilt or is entirely new. The bold values in the last column provide an assessment of the stability of each link, or, from a different viewpoint, of the uncertainty for true time transfer. They should be compared to the uncertainty values stated in Table III. The results involving VSL are unexplained at the time of writing.

TABLE III. COMPILATION OF CONTRIBUTIONS TO THE LINK UNCERTAINTY (7)

Link		uA (ns)		uB (ns)			U (ns)	U (ns)
k	l	1 (k)	2 (l)	1	2	3		rounded
CH01	IT02	0.355	0.69	0.344	0.5	0.22	1.009	1.0
CH01	NPL01	0.355	0.656	0.344	0.5	0.22	0.986	1.0
CH01	OP01	0.355	0.497	0.344	0.5	0.22	0.889	0.9
CH01	PTB04	0.355	0.628	0.344	0.5	0.37	1.013	1.0
CH01	TUG01	0.355	0.367	0.344	0.5	0.22	0.823	0.8
CH01	VSL01	0.355	1.824	0.344	0.5	0.22	1.967	2.0
IT02	NPL01	0.69	0.656	0.344	0.5	0.22	1.150	1.2
IT02	OP01	0.69	0.497	0.344	0.5	0.22	1.068	1.1
IT02	PTB04	0.69	0.628	0.344	0.5	0.37	1.173	1.2
IT02	TUG01	0.69	0.367	0.344	0.5	0.22	1.014	1.0
IT02	VSL01	0.69	1.824	0.344	0.5	0.22	2.054	2.1
NPL01	OP01	0.656	0.497	0.344	0.5	0.22	1.046	1.0
NPL01	PTB04	0.656	0.628	0.344	0.5	0.37	1.153	1.2
NPL01	TUG01	0.656	0.367	0.344	0.5	0.22	0.991	1.0
NPL01	VSL01	0.656	1.824	0.344	0.5	0.22	2.043	2.0
OP01	PTB04	0.497	0.628	0.344	0.5	0.37	1.071	1.1
OP01	TUG01	0.497	0.367	0.344	0.5	0.22	0.894	0.9
OP01	VSL01	0.497	1.824	0.344	0.5	0.22	1.998	2.0
PTB04	TUG01	0.628	0.367	0.344	0.5	0.37	1.017	1.0
PTB04	VSL01	0.628	1.824	0.344	0.5	0.37	2.056	2.1
TUG01	VSL01	0.367	1.824	0.344	0.5	0.22	1.969	2.0

For completeness, we add as Table IV the essence of the two previous tables, namely the data which from 1st April 2009 onwards have been used in the calculation of TAI by BIPM, based on the respective TWSTFT data files of the institutes involved in the current campaign. Here the values are given rounded to 0.1 ns. The results obtained at VSL are currently not used.

VI. CONCLUSIONS

The calibration campaign from 31st August to 2nd October 2008 provided consistent results, which were verified by the good correspondence of the measurements at TUG obtained at the start and at the end of the campaign. Comparisons with the results of previous calibrations, and with determinations of the changes in CAL(k) values due to the change of geostationary satellite in January 2008, indicated that the 2008 TWSTFT calibration achieved its objective.

The immediate conclusion is that TWSTFT can indeed provide true time transfer between remote sites with a 1-σ uncertainty of < 1.3 ns. The uncertainty values stated in Table III represent the combined statistical and estimated systematic uncertainty. The campaign apparently did not, however, confirm the 1.0 ns (1 σ) time transfer uncertainty

TABLE IV. CALR VALUES AND THEIR UNCERTAINTIES FOR USE IN TWSTFT DATA FILES FOR REPORT TO BIPM

Link				
k	l	CALR(k)	CALR(l)	U (ns)
CH01	IT02	110.6	-110.6	1.0
CH01	NPL01	-703.8	703.8	1.0
CH01	OP01	7110.3	-7110.3	0.9
CH01	PTB04	-205.6	205.6	1.0
CH01	TUG01	125.9	-125.9	0.8
IT02	NPL01	-814.4	814.4	1.2
IT02	OP01	6999.7	-6999.7	1.1
IT02	PTB04	-316.2	316.2	1.2
IT02	TUG01	15.2	-15.2	1.0
NPL01	OP01	7814.1	-7814.1	1.0
NPL01	PTB04	498.2	-498.2	1.2
NPL01	TUG01	829.6	-829.6	1.0
OP01	PTB04	-7315.9	7315.9	1.1
OP01	TUG01	-6984.5	6984.5	0.9
PTB04	TUG01	331.5	-331.5	1.0

in each case that has often been expected to be possible. The reason for this is partly understood. The measured CCD values revealed in almost all cases non-white phase modulations. When compared to the temporal variation of the outdoor temperature as recorded with the meteorological sensors attached to the TUG03 station a clear correlation can be seen in three cases (PTB, NPL, INRIM), but a less clear picture is obtained at METAS, TUG and OP. During previous calibration campaigns, data collection has not always spanned a full 24-hour period, and the number of data points obtained was often substantially smaller, so that such a clear signature could not be detected.

In preparations for future TWSTFT calibration campaigns it is proposed that:

- the traveling station should be carefully examined in parallel with a stationary set-up for an extended period;
- the CCD data should be evaluated on-site. This had not happened this time. On-site evaluation of unwanted behavior, such as recorded this time at OP, would require rapid access to the TWSTFT data collected with both set-ups.

More generally, it might be appropriate to design, assemble and test a mobile TWSTFT station which can be used in a more flexible way, and which could reside at each visiting station for at least two full days under automated control.

ACKNOWLEDGMENT

The support of colleagues in the visited institutes, too many to be listed here, is gratefully acknowledged. Without helping hands no such campaign could be carried out successfully.

REFERENCES

[1] O. Koudelka, B. Blanzano: Two-Way-Satellite-Time-Transfer Calibration Campaign 2008 of PTB – NPL – OP – INRIM – VSL – METAS – TUG, Joanneum Research, 2008.

[2] ITU Recommendation TF.1153-2, “The operational use of two-way satellite time and frequency transfer employing PN codes”, May 2003, ITU-R TF.1153-2.

[3] C. Schlunegger, G. Dudle, L.-G. Bernier, D. Piester, J. Becker, B. Blanzano: Description of the TWSTFT Station at METAS and Presentation of the Calibration Campaign 2006; Proc. IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum, Geneva, Switzerland, 29 May – 1 Jun 2007, pp. 918-922, 2007.

[4] D. Piester, J. Achkar, J. Becker, B. Blanzano, K. Jaldehag, G. de Jong, O. Koudelka, L. Lorini, H. Ressler, M. Rost, I. Sesia, P. Whibberley: Calibration of Six European TWSTFT Earth Stations Using a Portable Station; Proc. 20th European Frequency and Time Forum - EFTF 2006, Braunschweig, Germany, 27-30 Mar 2006, pp. 460-467, 2006.

[5] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, O. Koudelka: Time transfer with nanosecond accuracy for the realization of International Atomic Time, Metrologia, 45, (2008), pp. 185 – 198.

.