Description of the TWSTFT Station at METAS and Presentation of the Calibration Campaign 2006

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***Abstract*— A fully automated two-way satellite time and frequency transfer (TWSTFT) station has been built at METAS. This station has participated in the TWSTFT schedule on a regular basis since January 2005. In the Summer of 2006, the TWSTFT links between METAS, PTB and TUG were calibrated in a specific campaign using the mobile earth station of TUG. In the first part of this communication, technical details on the TWSTFT station at METAS and the data handling are presented. During the setting up of the earth station at METAS, special care was taken to ensure stable environmental conditions for the hardware. Emphasis was also placed on communication interfaces, made independent from the METAS LAN to avoid disruption of the automated TWSTFT station in the event of IT network failures. In the second part of the article, the calibration campaign and its outcome are described. The main result was the determination of the calibration constants of the links involved with combined uncertainties of 0.8 ns (1σ). The calibration data have been reported in the result files since December 2006.**

With a fully automated and calibrated TWSTFT station at METAS, UTC(CH) can now be tied to UTC via TWSTFT measurements.

I. Introduction

Two Way Satellite Time and Frequency Transfer (TWSTFT) has become one of the major means to compare remotely located Primary Frequency Standards (PFS), allowing one to bridge intercontinental distances. The technique is well established and has been described in detail in other publications [1]. Today, in Europe alone, ten laboratories participate in TWSTFT measurements on a regular basis. In particular, all laboratories operating PFS also run TWSTFT-earth stations.

Besides the comparison of state-of-the-art frequency standards, TWSTFT can also be used for time transfer. Laboratories tied to UTC via TWSTFT have a link uncertainty of their local realisation UTC(k) on the monthly bulletin Circular T published by BIPM [2] of less than 1.5 ns. However, this requires all delays be known, *i.e.* links must be calibrated.

The motivation to set up a TWSTFT-station at METAS was twofold. First, the TWSTFT-link was needed to compare the continuous fountains that have been built over the past few years [3], [4] with devices of similar perfomance around the world. Second, METAS also wished to tie its clocks to UTC via TWSTFT, rather than via a GPS Common View (CV) link used heretofore.

While in principle the first goal can be achieved without calibrating delays of the earth stations involved, for the latter one needs to calibrate the link from METAS to the European pivot lab PTB. In the Summer of 2006 a specific calibration campaign was carried out to determine the constants.

This communication reports first on hardware details of the TWSTFT-station at METAS (section II-A) and gives some details on how the data is processed (section II-B). The remaining part of the paper (chapter III) deals with the calibration campaign of 2006 and its results.

II. TWSTFT earth station at METAS

A. Hardware installed

TWSTFT earth stations have become pieces of equipment that can be bought off the shelf. The station installed at METAS is based on a Satre modem, provided by Timetech (Germany). Figure 1 gives an overview of the layout of the subsystems.

The modem modulates the signal of the steering clock into an intermediate frequency (IF) spread spectrum. It is maintained at a well stabilised temperature in the time and frequency control room of METAS. From there, the IF of 70 MHz is carried over 50 m of coaxial cable to the transceiver, installed just beneath the roof. Even though there is no tight temperature control at the location of the transceiver, annual variations do not exceed ± 2 K. The role of the transceiver is to up-convert the signals from the IF to the KU-band (and *vice versa* for the reception part). The cable from the transceiver to the Low Noise Amplifier (LNA) and the Solid State Power Amplifier (SSPA) is 6 m long. Using a long cable introduces additional thermal noise to the signal. However, this extra noise is outweighed by the advantage of installing the transceiver in a protected environment where it does not suffer from large temperature or humidity variations.

Both, LNA and SSPA are mounted directly behind the Feed-Horn of the parabolic antenna. The outside temperature of the SSPA is monitored continuously. The SSPA is controlled via RS485 by the tranceiver which in turn is connected to the Satre modem over the same interface.

The environmental conditions (humidity, air temperature and pressure) are collected about 50 m away from the

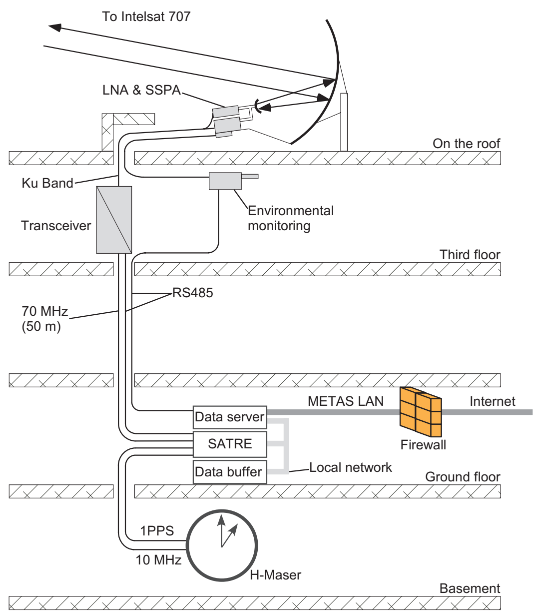

Fig. 1. Overview of the layout of the subsystems of the TWSTFT earth station installed at METAS.

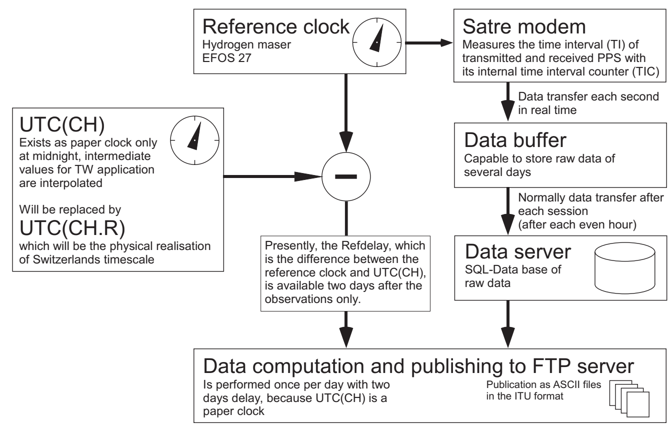

Fig. 2. Block diagram of the processing of the TWSTFT-data at METAS.

TWSTFT-antenna on top of a different building. However, these parameters are not yet reported in our data files.

As reference clock for the TWSTFT system we use an unsteered, free running active Hydrogen maser which is located in the basement of the same building. It provides the 10 MHz and 1 PPS required by the Satre modem. All RF- and time critical connections between the maser and the Satre modem are made with low-temperature-coefficient cables.

The Satre modem includes a time interval counter which is the source of raw TWSTFT data. Every second a set of data is available from the Satre modem. The data thus collected are sent over a local IT network. Besides the modem, only a data buffer and the main data server are connected to this local network (*cf.* Fig. 2). This isolated configuration was chosen for robustness since no other IT service has access to this local area network. The data server plays also the role of a bridge to the METAS LAN. From there, the access internet is granted through a firewall.

METAS is located nearby hills that limit the horizon. The geostationary satellite Intelsat 707, currently used for European and Transatlantic TWSTFT-sessions is located at 53.0°W. To reach this satellite, the antenna operates at an elevation of 22.5° and an azimuthal angle of 247.52°. It turns out that in this particular direction, the elevation of the satellite is very close to the horizon. Indeed, the main beam from the antenna to the satellite passes only 7 m above the trees on the hill.

B. Data processing

From the beginning, the TWSTFT earth station was designed to allow unattended operation. This includes the data processing from the raw data to the ITU-format file on the public FTP server. Figure 2 shows a block diagram of how the data is processed. As already explained in section II-A, the raw time interval measurements are taken by the Satre modem. These data are sent to a buffer which runs under an embedded operating system of National Instruments in real time mode. After each TWSTFT session, *i.e.* currently every even hour, the raw results are automatically transferred to an SQL database located on the data server.

As pointed out previously, the steering clock for the TWSTFT station at METAS is an H-maser free running with respect to UTC(CH). Hence, the difference between the maser and UTC(CH) must be determined for each session and reported in the results. This difference is the so-called REFDELAY. However, at present, UTC(CH) is a paper timescale that is computed once a day at 00:00 UTC only. For all other epochs of the day UTC(CH) does not exist and REFDELAY is obtained by linear interpolation between the current and the following day. Obviously, this calculation is not possible before UTC(CH) has been computed for the day following the TWSTFT measurement. UTC(CH) for day MJD is currently computed on day MJD + 1. The publication of the TWSTFT results is thus also delayed.

To avoid the drawbacks of the system where the TWSTFT results are only available one day later and where REFDELAY is based on an interpolation, METAS is currently in the process of replacing the paper-clock-based UTC(CH) by a physical realisation of the Swiss timescale. More information on this can be found in Ref. [5].

Once the REFDELAY has been estimated, the final data files are compiled daily and published in the ITU format [6] on the public METAS FTP server. The same files are transmitted directly to BIPM, so that timescale differences with other laboratories can be computed.

III. Calibration Campaign

A. Calibration trip 2006

To tie UTC(CH) to UTC via TWSTFT measurements, one needs to calibrate the link UTC(CH01)–UTC(PTB01), the

Fig. 3. Location of the three earth stations involved in the calibration campaign.

Day	*MJD*	*Location*	*Purpose*
1	53881	Graz	1st calibration of TUG
2	53882	∼	
5	53885	Braunschweig	Calibration of PTB01
7	53887	Bern-Wabern	Calibration of CH01
8	53888	∼	
11	53895	Graz	2nd calibration of TUG01

TABLE I

SCHEDULE OF THE CALIBRATION CAMPAING 2006 BETWEEN 26 MAY (MJD 53881) AND 9 JUNE (53895).

connection from METAS to the European pivot laboratory PTB for the calculation of UTC.

There exist different ways to calibrate a TWSTFT link. The method applied here is to co-locate a portable earth station with the ground stations involved in the link. A special calibration campaign was carried out from 26 May to 9 June 2006 with the following partners:

- TUG(TUG01) T&F Laboratory at the Observatory Lustbuehel operated by Technical University of Graz, Dept. IKS and Joanneum Research GmbH,Dept.IAS
- PTB (PTB01) Physikalisch-Technische Bundesanstalt 4.42 Time Dissemination Group Braunschweig, Germany
- METAS (CH01) Federal Office of Metrology METAS Time and Frequency Bern-Wabern, Switzerland

Their relative locations in Europe are shown on the map in Fig. 3. The schedule of the calibration trip is summarized in Table I.

B. Basic equations

To develop the basic equations for a calibration of a TWSTFT-link we start from the general equation for a time transfer as given in Ref. [6]. Equation 1 gives the time scale difference measured with two TWSTFT stations when individual measurements are reported and the corrections for Sagnac effect, ionosphere and satellite delay differences are considered individually. In Ref. [6] this is referred to as a Type 1 measurement with $S = 0$.

$$\begin{aligned} \mathrm{UTC}(k) - \mathrm{UTC}(l) \;=\; & +0.5\,(\mathrm{TI}(k) + \mathrm{ESDVAR}(k)) \\ & + \quad \mathrm{REFDELAY}(k) \\ & -0.5\;\; (\mathrm{TI}(l) + \mathrm{ESDVAR}(l)) \\ & - \quad \mathrm{REFDELAY}(l) \\ & +0.5\; C_{\mathrm{Sagnac}}(k,l) \\ & +0.5\; C_{\mathrm{iono}}(k,l) \\ & +0.5\; \mathrm{CALR}(k) \\ & -0.5\; \mathrm{CALR}(l) \\ & +0.5\; \mathrm{XPNDR}. \end{aligned} \tag{1}$$

In this equation

- $\mathrm{TI}(i)$ is the measured time interval with station i,
- $\mathrm{ESDVAR}(i)$ is the variation of the earth station delay difference with respect to a calibration,
- $\mathrm{REFDELAY}(i)$ is the delay between the Satre modem time reference and $\mathrm{UTC}(i)$,
- $C_{\mathrm{Sagnac}}(k,l)$ is the Sagnac correction for a link between site k and site l,
- C_{iono} is the correction of the difference of the ionospheric delay,
- $\mathrm{CALR}(i)$ is the difference between transmit and receive path of station i,
- XPNDR is the correction for the transponder delay difference of the satellite.

A calibration with a portable earth station (PES) requires two steps. First, the PES is co-located with one of the fixed ground stations of the link to be calibrated (site 1). There, a zero-baseline experiment is carried out using a common clock for both the fixed and the portable TWSTFT station. In a second phase, the PES is transported to the other fixed ground station (site 2) where the same procedure is repeated. In the following, we shall refer to the three TWSTFT-stations involved as 1, 2 and PES, respectively.

For each site, the time transfer experiment between the PES and the fixed earth station is described by the general equation 1. However, due to the co-location and to the common clock, several terms drop out: the timescale difference is zero, the Sagnac effect and the difference of the ionospheric correction can be neglected (the baseline is zero). Also, by definition, the variable $\mathrm{ESDVAR}(i)$ is set to zero, as it is meant to take into account any variation of the earth station delay since the last calibration. Finally, because we use the same transponder, the XPNDR-term vanishes too.

For simplicity, we define a *Common Clock Difference* $\mathrm{CCD}(i)$ for each site:

$$\begin{aligned} \mathrm{CCD}(i) \;=\; & +0.5\;\mathrm{TI}(i) + \mathrm{REFDELAY}(i) \\ & -0.5\;\mathrm{TI(PES)}_i - \mathrm{REFDELAY(PES)}_i. \end{aligned} \tag{2}$$

With this definition, equation 1 for the two sites becomes respectively:

$$0 \;=\; \mathrm{CCD}(1) + 0.5\;\mathrm{CALR}(1) - 0.5\;\mathrm{CALR(PES)} \tag{3}$$

$$0 \;=\; \mathrm{CCD}(2) + 0.5\;\mathrm{CALR}(2) - 0.5\;\mathrm{CALR(PES)}. \tag{4}$$

Station(i)	*MJD*	*CCD*(i) */ ns*	*Std.dev / ns*
PTB01	53885	22.69	0.31
CH01	53887/53888	-137.09	0.31
TUG01 (1st visit)	53881/53882	-20.10	0.16
TUG01 (2nd visit)	53895	-20.10	0.11
TUG01 (overall)		-20.10	0.19
PTB01 (overall)	53664/53684	41.08	0.49

TABLE II

SUMMARY OF THE MEASURED CCD(i) AND THEIR STATISTICAL UNCERTAINTIES.

Even though it can be assumed that CALR(PES) will be the same on sites 1 and 2, this set of two equations has three unknowns: CALR(1) and CALR(2) and CALR(PES). It is therefore not possible to solve for the all unknowns individually. Nevertheless, one can express the two CALR(i) as a function of CCD(i) and CALR(PES). With this substitution, one can then perform a time transfer experiment between two remote sites according to equation 1. It is a property of this calibration technique that in this way the third unknown CALR(PES) cancels from the general equation. The remaining terms can all be determined by other means.

The final result of the calibration is thus a constant for the link between site 1 and site 2 and is expressed by:

$$\begin{aligned} \mathrm{CALR}(1,2) \quad = \quad & +0.5\ C_{\mathrm{Sagnac}}(1,2) \\ & -\mathrm{CCD}(1) \\ & +\mathrm{CCD}(2) \end{aligned} \tag{5}$$

The Sagnac correction for the link between site 1 and site 2 $C_{\mathrm{Sagnac}}(1,2)$ depends on the geometry between earth stations and satellite. It is related to the values given in Table III via

$$0.5\ C_{\mathrm{Sagnac}}(k,l) = D_{\mathrm{Sagnac}}(l) - D_{\mathrm{Sagnac}}(k). \tag{6}$$

More details on how the Sagnac values for a single station are computed can be found in [6].

C. Calibration results

According to Eq. 5 of the previous paragraph, three main ingredients are needed for the computation of the calibration constant of a given link: the CCD of each site and the Sagnac effect correction. The former are obtained experimentally, the latter is obtained by computation.

Fig. 4 represents graphically the CCD-values obtained at PTB, METAS and TUG obtained during of the campaign described above. To check the consistency of the values , the measurement was performed twice at TUG, once at the beginning of the campaign and again at the end. The vertical full scale is identical for the four graphs. We observe that at METAS the spread of the data towards the end of the measurement is much higher than on the other sites. This behavior is not yet fully understood.

From this series of measurements, the standard deviation of the CCD(i) is computed for each site. The final values together with their uncertainties are summarised in Tab. II.

Station	D_{Sagnac} */ ns*
PTB01	119.4
CH01	129.7
TUG01	138.3

TABLE III

SAGNAC CORRECTIONS FOR EACH SITE FOR COMPUTING THE SAGNAC CORRECTION FOR A GIVEN LINK ACCORDING TO EQUATION 6

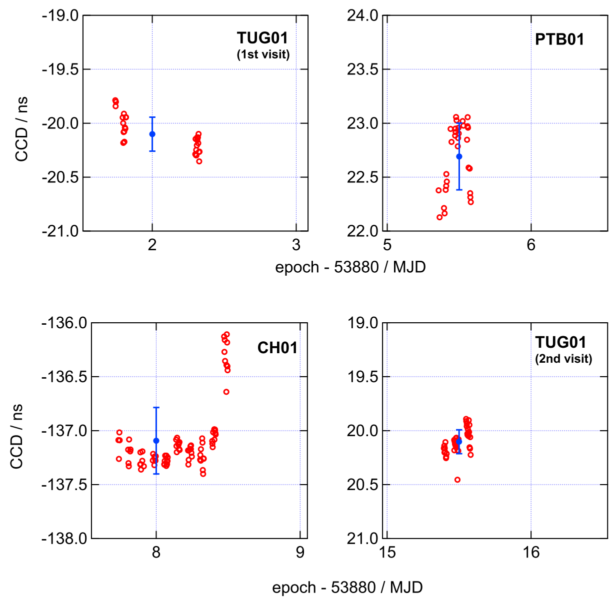

Fig. 4. Measured common clock differences (CCD) on the three sites.

PTB already participated with the same equipment in a calibration campaign in 2005 [7]. The CCD of this previous measrement is also reported in Table II. The newly determined CCD(PTB) differs significantly from the value obtained earlier. The reasons for this discrepancy are still under investigation.

The Sagnac effect for a site, computed on the basis of the position of the station and the position of the satellite, are given in Table III. The values indicated in this table are related to the Sagnac effect correction by Eq. 6

D. Discussion of the uncertainty of the links

Table IV lists the contributions to the uncertainty budget of the calibration constants CALR(k,l). First, the standard deviation of the measured CCD values at each site has to be considered. These two values are type A uncertainties and are obtained directly from the series of measurements on each site (*cf.* Tab. II). Among the type B uncertainties, one has to take into account the closure error of the CCD measurements at TUG at the beginning and end of the campaign. However, as the two CCD values determined at TUG lie very close to each other, this contribution is very small. The uncertainty of the time interval counter is another major contribution. The third type B uncertainty contribution represents all other systematic errors, *e.g.* the stability of the connection to the local UTC,

Contribution	*Value / ns*	*Type*
Standard deviation of CCD(k)	(Tab. II)	A
Standard deviation of CCD(l)	(Tab. II)	A
Combined standard deviation of CCD(TUG)	0.19	B
TIC uncertainty	0.5	B
Other effects	0.37	B

TABLE IV
CONTRIBUTIONS TO THE CALIBRATION CONSTANT UNCERTAINTY

Link	*CALR / ns*	*u / ns*
UTC(CH) - UTC(PTB)	149.5	0.8
UTC(PTB) - UTC(CH)	-149.5	0.8
UTC(CH) - UTC(TUG)	125.6	0.7
UTC(TUG) - UTC(CH)	-125.6	0.7
UTC(PTB) - UTC(TUG)	-23.9	0.8
UTC(TUG) - UTC(PTB)	23.9	0.8

TABLE V
CALIBRATION CONSTANTS FOR ALL LINKS AND CORRESPONDING COMBINED UNCERTAINTIES

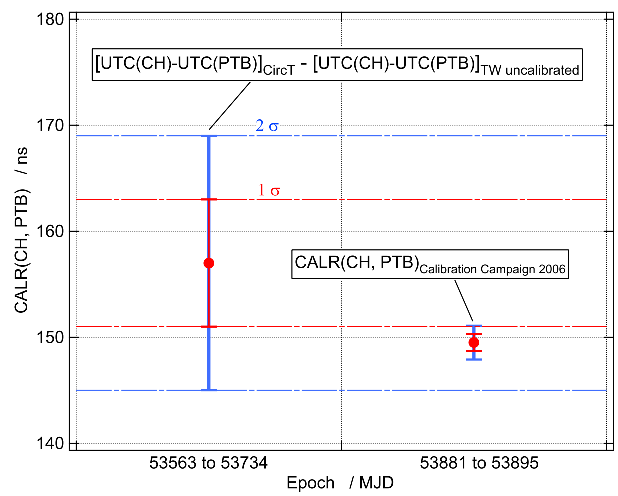

Fig. 5. Comparison between the TWSTFT calibration and GPS measurements.

possible influences of code changes, TX and RX power and C/N_0. The value used here (0.37 ns) was determined in the campaign 2005 [7].

E. Link calibration constants and comparison with GPS

With the CCD values for all sites and the combined uncertainties for all links at hand, one can now calculate the calibration constant CALR(k, l) for the time transfer between site k and l. Table V summarises this final result for the three possible links in both directions.

As this is the first TWSTFT calibration campaign involving METAS, the values obtained can not be compared with earlier results. However, the timescales of PTB and METAS can be compared by means of Circular T, the monthly bulletin published by BIPM [2]. As for now, the METAS results published there are based on GPS CV measurement, *i.e.* a technique completely independent from TWSTFT measurements. One can therefore compare the TWSTFT calibration constant for the link PTB-METAS obtained by this work with the constant that is obtained using Circular T. To this end, we evaluate the double difference $[\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{\mathrm{CircT}} - [\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{\mathrm{TW\ uncalibrated}}$. The suffix *TW uncalibrated* indicates that for this TWSTFT measurement, no calibration constant has been applied. In Circular T, the uncertainty of the local timescale UTC(k) is reported with respect to UTC. To estimate the uncertainty of $[\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{\mathrm{CircT}}$ we add quadratically the uncertainties of UTC(PTB) and UTC(CH). This is a somewhat conservative way to estimate the uncertainty of the time link between these two institutions.

Figure 5 shows the two values obtained with the corresponding uncertainties. One can see, that within the 2σ limits, the two calibration constants are consistent. This gives good confidence in the values obtained from the TWSTFT calibration campaign 2006 and opens the way to tying UTC(CH) to UTC by TWSTFT measurements.

IV. CONCLUSIONS

A TWSTFT station was commissioned at METAS in 2005 and has participated regularly in the European and Transatlantic TWSTFT schedule ever since. In the summer of 2006 a calibration campaign was performed involving three TWSTFT earth stations: TUG, PTB and METAS. For each of these three links the calibration constants were determined with an uncertainty of 0.8 ns (1 σ). The value of the calibration constant for the link between METAS and PTB obtained in the frame of this work is in agreement with that obtained by means of a GPS Common-View-based method. With a calibrated TWSTFT link between METAS and the European pivot lab PTB, the TAI-link, currently based on GPS CV, can be realised by TWSTFT.

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