CALIBRATION OF THE IEN-PTB TWSTFT LINK WITH A PORTABLE REFERENCE STATION

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Abstract

During 2003 the IEN-PTB Two-Way Satellite Time and Frequency Transfer (TWSTFT) link was calibrated using a portable reference station. The calibration activity was conducted in the framework of the Galileo System Test Bed Version 1 (GSTB V1), under a contract with Joanneum Research G.m.b.H. (Austria). The calibration constant was determined with an uncertainty lower than 1 ns.
Only few months after the calibration, the satellite provider moved the TWSTFT service to a different satellite; this caused changes non-reciprocal delays of the link (Sagnac and earth stations delays) and the calibration constant had to be re-evaluated. A recalculation of the Sagnac delays is presented together with a re-evaluation of earth stations delays with different measurements techniques.

1 Introduction

In the last decade the Two-Way Satellite Time and Frequency Transfer (TWSTFT) demonstrated to be one of the most powerful tools for time and frequency transfer [1].
When TWSTFT is used for remote time scale comparisons, an absolute calibration of the synchronization link is required. In fact non-reciprocal delays in the transmitting-receiving equipment can amount to few hundreds of nanoseconds.
Different approaches are available for a TWSTFT link calibration: the comparison with a parallel calibrated time link (e.g. a GPS link), the direct measurement of ground station non-reciprocal delays with a satellite simulator, or the differential delay measurement with a portable reference station [2].
The portable reference station approach has demonstrated up to now the best performances (accuracy at the 1-ns-level) for an absolute TWSTFT link calibration [2]. However, this is a very challenging activity, mainly by the logistic point of view.

1.1 The calibration activity

The GSTB V1 is the first experimental phase of the Galileo project, funded by the European Space Agency (ESA). One of the main GSTB V1 products is an experimental time scale (Experimental Galileo System Time, E-GST) with optimized features for navigation and time-dissemination purposes.
The infrastructure devoted to E-GST generation is the experimental precise timing station (E-PTS) which is located at IEN, Italy, and reuses part of the IEN infrastructure, namely the clocks and the time transfer equipment. The E-GST time scale has to be steered to TAI with a quite demanding performance [3], and the calibration of time transfer links connecting IEN with external laboratories (PTB and NPL) involved in GSTB V1 is requested for this purpose.
In this framework, dedicated funding were provided by ESA for high accuracy calibration of remote time transfers with external UTC laboratories participating in the project. The calibration of the TWSTFT link between the IEN and PTB, which is the pivot laboratory in Europe for TAI [4], with a portable station, was decided.
The calibration activity was performed under a contract with Joanneum Research G.m.b.H. and the Institute of Applied System Technology of Technische Universitaet Graz – TUG. The Joanneum Research G.m.b.H. had the possibility to use the portable station identified as TUG02 which was already used in a calibration experiment between European TWSTFT stations. Reported accuracy of that calibration was about 1 ns [2].
The calibration activity was carried out during May-June 2003.

1.2 Link recalibration after the satellite change

In September 2003 the satellite provider moved the TWSTFT service for the European laboratories to a different satellite.

This caused a change of the IEN-PTB non-reciprocal delays of the link, making the calibration value, calculated as the result of the calibration activity with the TUG02 portable station, no more valid. To save this high accuracy calibration, the delay change due to the satellite switch was evaluated with a work in close cooperation between IEN, PTB and VSL

2 The IEN-PTB link calibration

2.1 Principle of operations

The calibration of a TWSTFT link with a portable station relies on two common clock experiments between the portable station and the local station at both sides of the link. A mandatory condition for a correct calibration is that the intrinsic non-reciprocal delays of the portable station equipment stay constant during the calibration trip. An evaluation of possible delay changes of the portable station during the calibration activity is usually performed starting and ending the trip at the same location with a closure measurement. This calibration procedure requires, that the TX and RX satellite spots are overlapping. Otherwise, if the TX and RX spots are separated, a slightly different calibration technique has to be applied [5].
The common clock experiment at each location provides a differential delay between the local and the portable station. Link calibration is calculated using the S = 0 formula defined by the ITU recommendation ITU-R TF.1153 [6], which combines the two calibration constants determined with the same reference station at both link sides and the position dependent delays (e.g. Sagnac delay).

2.2 The TUG02 portable station

The TUG02 portable station is a complete TWSTFT measurement system, developed for calibration purpose, that can be transported hosted in a car trailer. It is composed by a specially modified VSAT 1.8 m antenna (details reported in [2]), a Ku-band transceiver and a local delay monitor device (satellite simulator). The set-up can be assembled in a few hours by two people.
The indoor equipment is made of a SATRE modem (no. 036), a portable PC for measurement automation and data acquisition, and distribution amplifiers for delivering the reference frequencies and 1PPS signals. Cable connections between outdoor and indoor devices are possible up to 50 m length, ensuring various installation possibilities with the same cable configuration.
Phase coherent frequency and 1PPS signals, related to those driving the local TWSTFT station, should be provided to the indoor equipment of the portable station.

2.3 The calibration trip

The calibration trip was organized in three stages with two installations at IEN, including the closure measurement, and one at PTB.
As the journey from Torino to Braunschweig needs more than one day of car travel, the calibration measurements took place on Friday 30th and Saturday 31th May 2003 (MJD 52789 and 52790) in Torino, on Monday 2nd and Tuesday 3rd June (MJD 52792 and 52793) in Braunschweig, and on Friday 6th June (MJD 52796) again in Torino.
The portable station used the MITREX code 3, which was not used in the European session at the moment of the calibration. This allowed the portable station to participate to the regular schedule (Monday, Wednesday, Friday, form 14:00 to 14:30 UTC at the moment of the calibration); however the satellite provider gave the possibility to use the satellite channel also outside the schedule and some additional measurements were taken.

2.4 Installation and operation at IEN

The IEN location offered a quite clear visibility to the satellite Intelsat 706 (IS706), so it was possible to accommodate the outdoor equipment of the travelling station on the green, just in front of the Time and Frequency laboratory. The IEN01 TWSTFT antenna and transceiver are located on the roof of the building hosting the Time and Frequency laboratory; the distance between the two antennas was not more than 10 m.
Using the 50 m cable assembly of TUG02, the indoor equipment of the portable station was installed inside the IEN time and frequency laboratory.

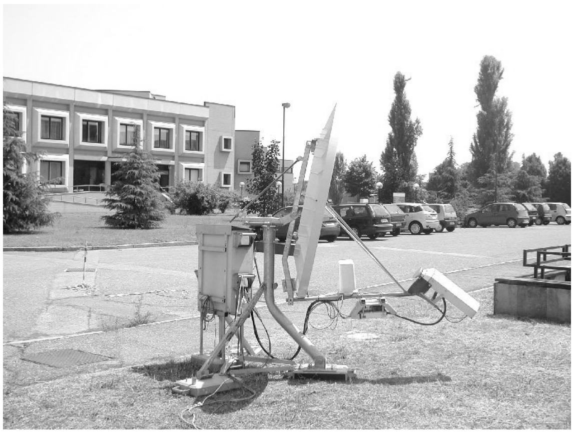

Figure 1. The TUG02 portable station installed at IEN

Both stations (IEN01 and TUG02) were driven by the IEN H maser M1(IEN) frequency and 1PPS signals and internal delay measurements related the modems outputs to both UTC(IEN) and M1(IEN) reference signals. Although the internal measurements allowed to use both M1(IEN) and UTC(IEN) as the common clock reference, the data reduction was performed using M1(IEN), which allowed for a simpler measurement scheme and a better stability.

2.5 Installation and operation at PTB

To achieve a good visibility of IS706, the PTB01 TWSTFT antenna and transceiver are located on a roof top in a distance of about 400 m to the time and frequency laboratory where the modem and automation systems are located. The TUG02 antenna and transceiver were mounted side by side to the PTB outdoor equipment. The indoor set-up was located in the same building (in a room below the antenna).

Because no reference frequency and 1PPS were available at the TUG02 set-up, 1PPS and frequency were supplied by a caesium clock (model HP5071A, ID C9) from the PTB clock ensemble, which was brought to the TUG02 set-up only for the duration of the experiment. Usually, the clock is hosted in the time and frequency laboratory and continuously measured versus UTC(PTB) which was used as the common time scale in the calibration experiment. UTC(PTB) – C9 is shown in the lower part of Figure 2. In the upper part the residuals to a linear fit is represented. The arrows indicate when the clock was moved from the time and frequency laboratory to the TUG01 set-up.

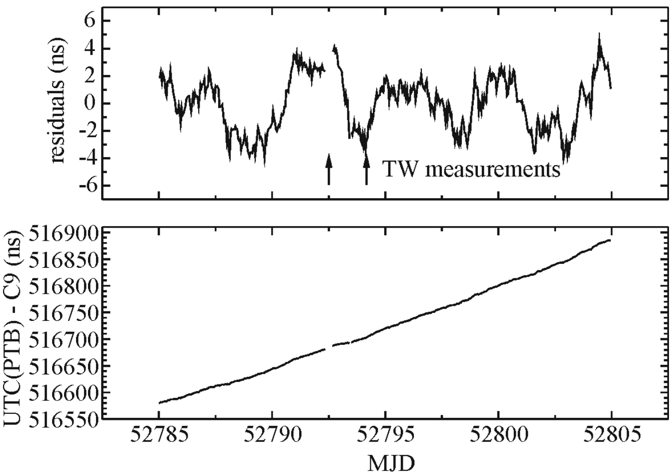

Figure 2. UTC(PTB)-C9 time differences measurements and residuals after a linear fit.

The TUG02 modem output was compared to UTC(PTB) by a linear interpolation of UTC(PTB)-C9 data during the calibration periods.

2.6 Calibration results

The station calibration constant (defined as CALR in [6]) was calculated as the average of the common clock TWSTFT measurements, taking into account the delays of the modem reference with respect to the common clock reference (defined as REFDELAY in [6]).

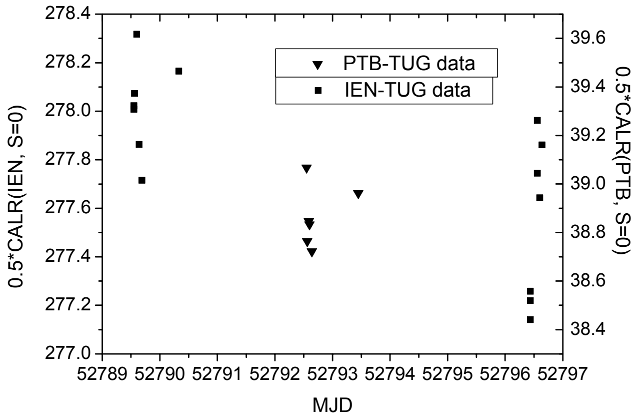

Figure 3. Calibration measurement data used for CALR(IEN) and CALR(PTB) calculation

The CALR(IEN) was obtained as the average of 14 measurements (6 on MJD 52789, 1 on MJD 52790, 6 on MJD 52796); its value is [7]:

$$\mathrm{CALR(IEN)} = -555.6 \text{ ns} \pm 0.7 \text{ ns } (1\sigma). \quad (1)$$

The uncertainty was limited by the REFDELAY(IEN) evaluation. The source of the instability was identified in the high thermal sensitivity of MITREX modem used in the IEN01 set-up. In fact, the TUG02 equipment, installed nearby the IEN01 modem, caused some thermal instabilities [7].

The CALR(PTB) value was calculated as the average of six measurements (5 on MJD 52792, 1 on MJD 52793); its value is [7]:

$$\mathrm{CALR(PTB)} = -77.7 \text{ ns} \pm 0.3 \text{ ns } (1\sigma). \quad (2)$$

The uncertainty was limited by the TWSTFT measurement instability and is the standard deviation of the six recorded measurements at PTB [7].

As the calibration constants come from co-location experiments, to calculate the actual calibrated TW differences for the IEN-PTB link the contribution of Sagnac delays has to be explicitly taken into account. The complete formula which has to be used in this case is reported in [6] and specified in the TW measurement file with the S = 0 (Calibration Switch).

2.7 Comparison with Circular T calibration of the IEN-PTB TWSTFT link

At the beginning of the year 2002 (MJD 52297), with the aim of using the IEN-PTB TWSTFT link for TAI, the BIPM had calculated a calibration constant using the Circular T.

The comparison between the TWSTFT link and another calibrated link provides a CALR value which includes all contributions to the link delay calibration. The formula which has to be used in this case for the calculation of the calibrated TWSTFT differences is different from the S = 0 case, and is specified with S = 1 [6].

The calibration value obtained with Circular T at MJD 52297 was:

CALR(IEN01) = – CALR(PTB01) = – 253 ns ± 5 ns (1σ). (3)

To compare the link calibration value obtained with the portable station, which provides a CALR with S = 0 and the calibration value obtained with Circular T, which provides a CALR with S =1, the following relation has to be used:

$$\text{CALR(IEN01, S=1)} = 0.5\cdot[\text{CALR(IEN01, S=0)} - \text{CALR(PTB01, S=0)}] + \text{SAGNAC (IEN-PTB)}. \quad (4)$$

Using the Sagnac delay calculated for the IEN-PTB link through the IS706 satellite, which was used at the epoch of both calibrations:

SAGNAC(IEN-PTB) = –15.090 ns (5)

the comparison shows a very good agreement between the two methods:

CALR(IEN01, S=1) = – 253 ns ± 5 ns (1σ) with Circ.T
CALR(IEN01, S=1) = – 254.0 ns ± 0.4 ns (1σ) with TUG02.

3 Satellite change

During August 2003 the satellite provider (Intelsat) dismissed the service on the Transatlantic Two Way link with the satellite IS706. After a few weeks, Intelsat moved the TWSTFT service to a different satellite namely the IS903 at position 34° 30' W. During the whole period of non-operation of the transatlantic link, the European link on IS706 was kept operating and the TW community eventually decided to switch both European and Transatlantic link to IS903 on MJD 52798.
At both laboratories (PTB and IEN), the visibility of the new satellite is good and the satellite could easily be pointed. However the switch to the new satellite required the recalculation of the link calibration constant; in fact, the Sagnac delay changed due to the different satellite position and earth station delays could change due to different transmitting (TX) and receiving (RX) frequencies used on the new satellite; moreover at PTB the RX frequency change on the European link required a replacement of the downlink hardware.
The Sagnac delay change can be accurately recalculated (with uncertainties of few picoseconds), using theoretical formulas, meanwhile the earth station delay change has to be evaluated with experimental measurements.

3.1 Sagnac delay recalculation for the satellite IS903

The new Sagnac delay can be calculated using the satellite position and the coordinates of the earth stations. In the table below the Sagnac delay changes are reported for each active TWSTFT link where VSL, PTB and IEN are involved.

LAB	Sagnac Change (ns) VSL-LAB	Sagnac Change (ns) PTB-LAB	Sagnac Change (ns) IEN-LAB
VSL	0.000	-3.736	2.121
PTB	3.736	0.000	5.858
NPL	-3.029	-6.765	-0.908
IEN	-2.121	-5.858	0.000
OCA	-3.294	-7.030	-1.172
ROA	-15.906	-19.642	-13.784
OP	-3.200	-6.936	-1.079
USNO	-16.782	-20.518	-14.660
NIST	3.187	-0.550	5.308

Table 1. Sagnac delay change at the satellite switch for TWSTFT links involving IEN, PTB and VSL

The Sagnac delay change affects the CALR value when it is expressed using the calibration switch S = 1. In this case it becomes

CALR(IEN01, S=1) = – 247.15 ns ± 0.4 ns (1σ) (6)

after the satellite change.

3.2 ESDVAR calculation at the satellite change

Following the prescriptions in [6], the earth station delay variation has to be reported in the TWSTFT measurement file in the ESDVAR column. As the ESDVAR is defined as an incremental value, the delay change due to the satellite switch from IS706 to IS903 will be reported in this work as ΔESDVAR.
At VSL the earth station delay change due to the different TX and RX frequencies between the satellites IS706 and IS903 was evaluated using a satellite simulator (SATSIM) [8]. In this case the SATSIM device is very suitable to evaluate possible delay changes; in fact the knowledge of the SATSIM absolute delay is not required because the ΔESDVAR measurement relies on the stability of the SATSIM delay itself.
The ΔESDVAR(VSL) value evaluated with the SATSIM is:

ΔESDVAR(VSL) = 0.2 ns. (7)

Because neither at IEN nor at PTB a SATSIM device is installed, additional TWSTFT measurements between IEN, PTB, and VSL were recorded just before and after the satellite switch (MJD 52898 at 14:00 UTC).
The differential earth station delay for the IEN-PTB link is:

$$0.5\cdot[\Delta ESDVAR(IEN) - \Delta ESDVAR(PTB)]\,. \quad (8)$$

Itcan be evaluated with different methods, but the contribution due to the single station (the ΔESDVAR(IEN) or the ΔESDVAR(PTB)) can be calculated only with respect to VSL.

Triangulation measurement provides in fact two independent equation sets and three ΔESDVAR unknowns, therefore the solution requires the ΔESDVAR(VSL) value evaluated with the SATSIM technique.
Solving the triangulation equations we achieve to:

ΔESDVAR(IEN) = - 0.1 ns ± 1.0 ns
ΔESDVAR(PTB) = + 64.2 ns ± 1.0 ns. (9)

The main limit of this approach is the stability of the reference time scales and the possibility that closing errors can affect the results. Using a conservative approach a uncertainty of 1 ns was therefore assigned to IEN and PTB ESDVAR(IEN) and ESDVAR(PTB) values with this method.
As it is become clear from this calculation, the time step introduced by the change in the TX and RX frequencies at IEN and VSL is well below the uncertainty . On the contrary, at PTB the time step introduced by the RX hardware replacement is notably higher.
The differential earth station delay change 0.5·[ESDVAR(IEN) - ΔESDVAR(PTB)] can be evaluated with an higher accuracy by using high stability H-masers as references or by comparing TWSTFT with high performance GPS-based time transfer tools.

3.3 Differential earth station delay change evaluation using H-masers comparison

Both IEN and PTB drive their TWSTFT modems using the frequency delivered by their H-masers. The link to UTC(IEN) and UTC(PTB) is made with a second measurement and reported as the REFDELAY.
Disregarding the REFDELAY values one can access to the comparison between the two time scales generated by the H-masers, which have a very good short/medium-term stability. Thus, it is possible to use the H-masers as frequency flywheel to evaluate the time step at the satellite switch.

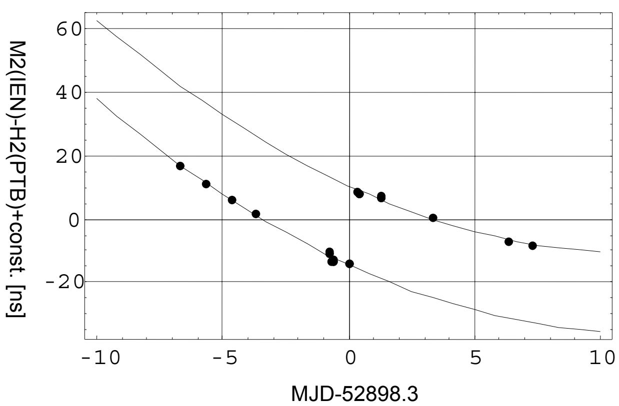

Figure 4. M2(IEN)-H2(PTB) measurements via TWSTFT. The lines represents the fitting functions (10)

Measurement data spanning up to 20 days have been fitted (using a linear least square model) with the following equation set, which also accounts for the masers frequency drift:

$$\begin{cases} At_i^2 + Bt_i + C = x(IS706)_i \\ At_i^2 + Bt_i + C' = x(IS903)_i \end{cases} \tag{10}$$

where t_i are the epochs of the measurement data, $x(IS706)_i$ and $x(IS903)_i$ are the TWSTFT measurement data with IS706 and IS903, respectively, A and B estimates the frequency drift and offset between the two masers and C'-C estimates the time jump at the satellite change.
The estimated earth stations differential delays is

$$0.5 \cdot [\Delta ESDVAR(IEN) - \Delta ESDVAR(PTB)] = -31.0ns \pm 0.9ns \tag{11}$$

Differences in fit values obtained with slightly different (longer or shorter) periods are not relevant.
The uncertainty was evaluated as a result of the least square analysis; the resulting uncertainty would have taken advantage by alternating the measurements with the two different satellites; unfortunately it was not possible (PTB needed to change the receiving hardware) and the resulting uncertainty is quite large.

3.4 Differential earth station delay change evaluation using TAIP3

TAIP3 is a pilot experiment, promoted by the BIPM, to test the use of the GPS P3 code measurements for remote clock comparisons using geodetic GPS receivers as an input to TAI [9]. P3 is the ionosphere-free combination of the P1 and P2 codes available on the two frequencies L1 and L2 in use by the GPS system.
We consider the difference between UTC(IEN) and H2(PTB) which were the time scales driving the geodetic receivers at IEN and PTB at that time. One can easily evaluate H2(PTB)-UTC(IEN) also from the TW measurements taking into account only the REFDELAY(IEN), whereas the REFDELAY(PTB) is left out of consideration (for detailed information see [6]). H2(PTB)-UTC(IEN) differences coming from TWSTFT measurements (spanning the period MJD 52890-52906) were compared to corresponding GPS data evaluated with the TAIP3 algorithm.
The TAIP3 algorithm provides one measurement every 16 minutes consisting of data from 4-6 satellites in common view (depicted as full circles in Figure 5). The data were adjusted to the TWSTFT data collected before the satellite change (dashed vertical line) in the following way. The 11 data points around each TWSTFT epoch were fitted using a linear regression model and the difference of the midpoint to the corresponding TWSTFT data (open circles) was determined.

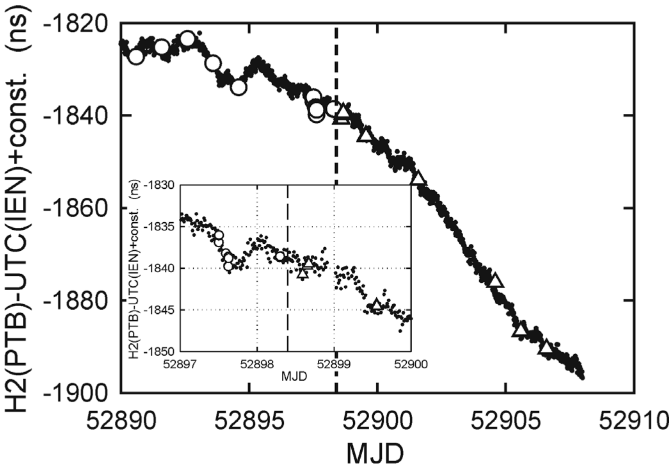

Figure 5. H2(PTB)-UTC(IEN) as evaluated with TWSTFT and GPS TAIP3. The vertical dashed line separates the IS706 and IS906 activity periods

The time step at the satellite change was calculated minimizing the sum of the squared differences between the TWSTFT and the TAIP3 averaged data. The TWSTFT data after the satellite change (triangles) were adjusted to the GPS data in the same way.

The earth station differential delay obtained by this calculation is:

$$0.5 \cdot [\Delta ESDVAR(IEN) - \Delta ESDVAR(PTB)] = -30.6 \pm 0.3\, ns \quad (12)$$

3.5 Differential earth station delay change evaluation using Precise Point Positioning

The Precise Point Positioning (PPP) is a post-processing approach using un-differenced dual frequency pseudo-range and carrier phase observations coming from a single geodetic GPS receiver, together with the high-quality GPS products such as those provided by the International GPS Service (IGS). Taking advantage of the precise satellite clock estimates as well as of the precise satellite coordinates in the IGS products, the PPP is able to allow stand-alone receiver clock offset estimates with sub-nanosecond uncertainty.

RINEX files coming out of the IEN and PTB receivers, together with the IGS final products, were processed with the PPP algorithm, providing the time differences between the GPS time (as provided by the IGS products) and UTC(IEN) and H2(PTB), respectively.

The PPP software version used for this work was implemented by the Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) and its used was granted to IEN [10].

As the PPP algorithm provides clock differences with respect to the same reference (a GPS based time scale) for both UTC(IEN) and H2(PTB), the time differences UTC(IEN)-H2(PTB) can be easily calculated. These time differences are spaced by 30 seconds, which is the sample rate of the receivers.

Afterwards, the UTC(IEN)-H2(PTB) time differences are hourly averaged, around the TWSTFT measurement epoch, and compared with the data coming from the TWSTFT measurements themselves. For the PPP-TWSTFT comparison a 4 days period across the satellite switch was selected.

Looking at the data reported in Figure 6 the constant C-C', which represents the time step due to the satellite change, was adjusted minimizing the sum of the squared differences between GPS and TWSTFT data.

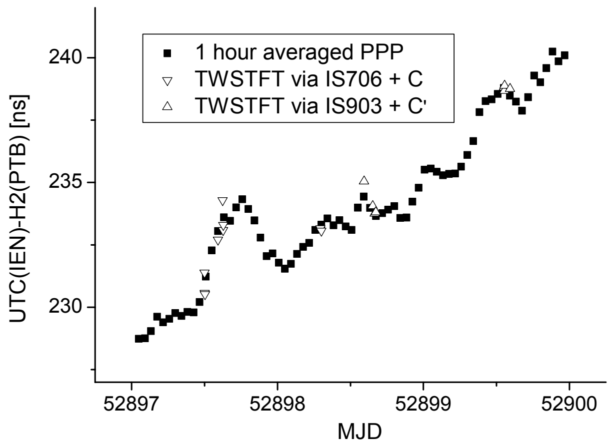

Figure 6. H2(PTB)-UTC(IEN) as evaluated with TWSTFT and PPP.
Squares: PPP data.
Triangles: TWSTFT data, already corrected for the constants C and C'

The estimated earth stations differential delay with this method is

$$0.5 \cdot [\Delta ESDVAR(IEN) - \Delta ESDVAR(PTB)] = -31.1 ns \pm 0.2\, ns \quad (13)$$

3.6 Results comparison

The comparison between 0.5·[ΔESDVAR(IEN)-ΔESDVAR(PTB)] values obtained with three accurate methods, shows that the results (see Figure 7) are in agreement within 500 ps. This implies that the quality of the IEN-PTB calibration with TUG02 is only slightly degraded and the actual uncertainty can be evaluated to be as low as 1 ns after the satellite switch.

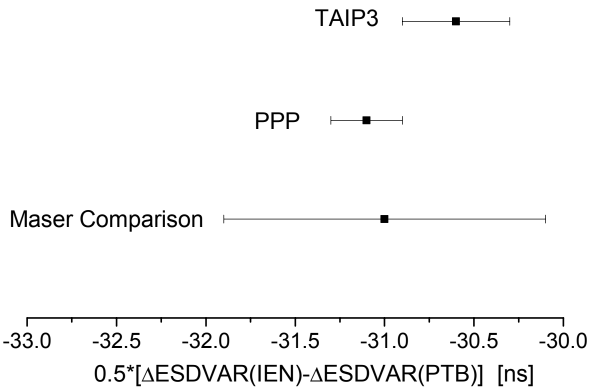

Figure 7. Comparison between the earth station differential value obtained with three different methods

However, as PTB and IEN are involved in TWSTFT links with other European laboratories, for the evaluation of the time step due to the satellite switch involving these links the ΔESDVAR(IEN) and ΔESDVAR(PTB) values are required.
Taking advantage from the evaluations reported in the previous sections, since the March 2nd, 2003 (MJD 53066) the following values were adopted to update the ESDVAR values in the ITU files:

$$\begin{aligned} \Delta ESDVAR(VSL) &= +0.2 \text{ ns} \\ \Delta ESDVAR(IEN) &= -0.1 \text{ ns} \\ \Delta ESDVAR(PTB) &= +61.1 \text{ ns} \end{aligned} \tag{14}$$

where the ΔESDVAR(VSL) comes from the measurements with the SATSIM, the ΔESDVAR(IEN) value from the UTC(IEN)-UTC(VSL) comparison (see equation (9)) and the ΔESDVAR(PTB) value from the comparison with TAIP3 (see equation (12)), combined with the ΔESDVAR(IEN) value.

4 Conclusions

The calibration with the TUG02 portable station provided a calibration of the IEN-PTB link differential delay with an uncertainty of less than 1 ns. After the satellite change, an accurate analysis was required to evaluate the Sagnac and the earth stations delay changes which could have affected the link calibration. Using three different methods the link calibration after the satellite change was re-evaluated with 1 ns uncertainty.
The calibrated TWSTFT IEN-PTB link is currently used for the E-GST generation algorithm, in the frame of the GSTB V1 experiment.
As the IEN-PTB TWSTFT link is also involved in TAI computation, the uncertainty of the link calibration with TUG02 is reported in the BIPM Circular T bulletin since April 2004 [11].

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