European TWSTFT Calibration Campaign 2016

--- Calibration Report ---

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Abstract

This report presents part of the results of the 2016 campaign intended for the calibration of the time transfer links established via TWSTFT between the Galileo Precise Timing Facilities PTF1 and PTF2, and five UTC(k) laboratories associated to the Galileo Full Operational Capability Time and Geodetic Validation Facility (hereinafter referred to as UTC(k) labs). This report is restricted to provide the calibration results for links between these involved UTC(k) laboratories: INRIM, OP, PTB, ROA and SP. In the case of INRIM, the time links were calibrated involving two TWSTFT stations: the currently operational and the IT01, after its repair and setting up.

This calibration exercise was performed during the deployment and operations ("FOC") phase of the Galileo Program, according to the Time Validation Facility (TVF) Statement of Work, issued by the TVF industrial prime GMV, Tres Cantos, Spain. The calibration, involving a traveling TWSTFT station subcontracted to TimeTech, GmbH, Stuttgart, Germany, took place in spring 2016 (from April 4th to June 3rd).

As a result of the visit of five UTC(k) laboratories (besides the two Galileo Control Centers, and the fixed station at TimeTech), after about 10000 km of distance travelled, and 740 hours of effective measurements, this document includes the calibration results of 14 time links using the baseline method.

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1 Introduction

1.1 Scope of the Document

This document presents part of the results of the 2016 campaign intended for the calibration of the time transfer links established via TWSTFT between the Galileo Precise Timing Facilities PTF1 and PTF2, and five UTC(k) laboratories associated to the Galileo Full Operational Capability Time and Geodetic Validation Facility (hereinafter referred to as UTC(k) labs). This report is restricted to provide the calibration results for links between these involved UTC(k) laboratories: INRIM, OP, PTB, ROA and SP (see acronyms explained in Table 1-2). In the case of INRIM, the time links were calibrated involving two TWSTFT stations: the currently operational and the IT01, after its repair and setting up.

1.2 Document Structure

Section 1 of this document gives the introduction, comprising the scope of the document, document structure and a document baseline (in terms of applicable and reference documents and used acronyms).

Section 2 describes the current contractual relation between UTC(k) laboratories and the provider of the satellite transponder capacity used in the time transfer via TWSTFT.

Section 3 describes the calibration campaign undertaken in April / June 2016 and lists the involved institutes and relevant parameters.

Section 4 presents the theoretical framework for a calibration of TWSTFT links involving a mobile station.

Section 5 illustrates the installation of the mobile station used and contains the measurement schedule adhered to.

Section 6 states the main problems encountered during the campaign and shows the collection of raw results obtained.

Section 7 explains how the determined CALR value shall be introduced in TWSTFT results reports.

1.3 Documents

1.3.1 Reference Documents

The following documents are used as reference in this document.

Table 1-1 List of Reference Documents

Ref.	Title	Code	Version	Issue
RD01	Directive for operational use and data handling in two-way satellite time and frequency transfer (TWSTFT)	Rapport BIPM-2011/01, Bureau International des Poids et Mesures, Sèvres, 25 pp.		2011
RD02	The operational use of two-way satellite time and frequency transfer employing PN codes	ITU Radiocommunication Sector, Recommendation ITU-R TF.1153-4, Geneva, Switzerland.		2015
RD03	Time transfer with nanosecond accuracy for the realization of International Atomic Time	Metrologia, 45, (2008), pp. 185 – 198		2008
RD04	TWSTFT Calibration Guidelines for UTC Time Links		1.0	2015
RD05	European TWSTFT Calibration Campaign 2014 Calibration Report			2015-03-06
RD06	TVFFOC TWSTFT Calibration: Site Preparation document checklist	GAL-TN-PTB-TGVFFOC-20049	2.3	2016-05-24
RD07	MODEL SR620 Universal Time Interval Counter, Stanford Research Systems, Revision 2.7 (2006).		2.7	2006

1.3.2 Acronyms and Abbreviations

Table 1-2 List of Acronyms and Abbreviations

Acronym	Definition
BIPM	Bureau International des Poids et Mesures
CCTF	Consultative Committee for Time and Frequency
CSD	Combined Standard Deviation
C/N0	Carrier-to-noise ratio
EPS	European Participating Stations (in TWSTFT)
ESXi	Is an enterprise-class, type-1 hypervisor developed for deploying and serving virtual computers. The name ESXi originated as an abbreviation of Elastic Sky X "integrated"
FDIS	Frequency Distribution Amplifier
FOC	Full Operational Capacity
GEO	Geo-stationary satellite
IIOTIC	Intelligent In/Out and Time Interval Counter
INRIM	Istituto Nazionale di Ricerca Metrologica
ITU	International Telecommunication Union
MJD	Modified Julian Date
NMI	National Metrology Institute
OP	LNE-SYRTE, Observatoire de Paris, Paris, France
PDIS	Pulse distribution amplifier
PTB	Physikalisch-Technische Bundesanstalt, Germany
PTF	Precise Timing Facility
PTF1, PTF2	Galileo Precise Timing Facilities
ROA	Real Instituto y Observatorio de la Armada en San Fernando, San Fernando, Spain
SOW	Statement of Work
SP	Technical Research Institute of Sweden, Borås, Sweden
TDEV	Time Deviation. Is a measure of time stability based on the modified Allan variance
TGVF	Timing and Geodetic Validation Facility
TIC	Time Interval Counter
TIM	TimeTech GmbH, Stuttgart, Germany. Also the fixed station at TimeTech, used in calibration experiments
TVF	Timing Validation Facility
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UTC	Coordinated Universal Time
UTC(k)	Version of UTC realized at each of the contributing NMI(k)s
WG	Working Group
	TWSTFT specific acronyms
ADUO	Additional diurnal of unknown origin
CALR(i, k)/CALR	Calibration value, which has to be added to the raw TWSTFT measurement result between stations (i, k) to yield the true time difference between the time scale maintained at stations i and k.
CC	Common clock.
CCD(i, k)	Common-clock difference, TWSTFT measurement result between two TWSTFT setups (i, k) at one site, connected to the same clock.
CI	Calibration Identification
DLD(i)	Difference of signal propagation delay through the transmit and receive path of station i, Tx(i) – Rx(i).
ESDVAR(k)	Earth station delay variation, with respect to the Earth station delay at the time of calibration (if available).
MOB	Mobile station, short form for a transportable TWSTFT ground station used in calibration experiments.
PRN	Dedicated pseudorandom noise code used by each station in the transmitted signal
REFDELAY	Reference delay, time difference between the local time scale and the modem 1PPS output synchronous with the Tx signal.
Rx(i)	Signal delay in the receive path of TWSTFT station i.
SCD(i)	Sagnac delay for a signal propagating from the GEO satellite to station i.
SCU(i)	Sagnac delay for a signal propagating from the station i to the GEO satellite.
SP(i)	Complete signal path delay from station i to station k, SPU(k) + SPT(k) + SPD(i)
SPD(i)	Signal path downlink delay
SPT(i)	Signal path delay through the transponder from station i to station k.
SPU(i)	Signal path uplink delay
TS(i)	Local time scale, physically represented by the 1PPSTX signal generated by the modem, i being 1 for station 1 and 2 for station 2.
TW(i)	Counter reading in TWSTFT station i.
TX(i)	Signal delay in the transmit path of the TWSTFT station i.

2 Contractual TWSTFT Operation Status

2.1 TWSTFT Operation Status

Satellite transponder capacity with the required connectivity between Europe (extending to Poland and Sweden) and the US (extending to Boulder, Colorado, in the West), is very scarce. From summer 2009 onwards, the Telesat owned satellite T-11N at the location 37.5 degrees West longitude has been used. The access to the satellite was initially managed by Americom Government Services (AGS). 13 institutes - 2 in the US, and 11 in Europe, including TimeTech GmbH, Stuttgart, Germany (in short TimeTech) as industrial partner - agreed on the contract with AGS. The two Galileo PTFs were integrated into the network at a later stage. The European participating stations (EPS), among them the TVF partners mentioned above, signed an Agreement with PTB dealing with the cost sharing, the practice of invoicing, and other administrative issues. Since July 2011 the lease agent for the transponder capacity on the same satellite was changed to RiteNet, MD. The contract in force during the campaign was prolonged until November 2016, and since the 27th November a new contract for one year is operational.

The technical parameters of the satellite as of April-June 2016 were:

Beacon frequency: 11699.5 MHz

For the Europe to Europe link:
Carrier ID, 112677
Uplink, 14260.150 MHz, horizontal polarization
Downlink, 10960.150 MHz, vertical polarization

For the transatlantic link:

In Europe:
Carrier ID, 112673
Uplink, 14046.5900 MHz, horizontal polarization
Downlink, 11489.060 MHz, vertical polarization

In USA:
Carrier ID, 112701
Uplink, 14289.060 MHz, horizontal polarization
Downlink, 11746.590 MHz, vertical polarization

2.2 Contractual arrangements for the FOC TVF TWSTFT calibrations

A calibration exercise involving a traveling TWSTFT station and comprising PTF1, PTF2, INRIM, OP, PTB, ROA, and SP, had to be organized and evaluated by ROA in 2016 according to contractual obligations, and it took place in the spring of 2016 (April 4th to June 3rd).

The provision of the mobile TWSTFT station which is designated as MOB in this report and its operation was directly subcontracted to TimeTech GmbH, Stuttgart, by the FOC TVF industrial prime GMV, Tres Cantos, Spain.

3 Organization of the April/June 2016 campaign

3.1 Travel Schedule and measurement periods

3.1.1 Travel Schedule

Table 3-1 Travel Schedule adhered to by the mobile TWSTFT station (MOB)

From	To	Distance	Time to travel	Start Date and Time (Local time)	Reach Date and Time (Local time)
Stuttgart	Torino	612 km	7 hrs	09 Apr, 13:00	10 Apr, 20:00
Torino	San Fernando	1985 km	21 hrs	16 Apr, 13:00	18 Apr, 12:00
San Fernando	Paris	1864 km	24 hrs	21 Apr, 18:00	24 Apr, 17:00
Paris	Boras	1540 km	17 hrs	28 Apr, 13:00	1 May, 18:00
Boras	Braunschweig	844 km	10 hrs	5 May, 12:00	6 May, 13:00
Braunschweig	Oberpfaffenhofen	725 km	10 hrs	14 May, 10:00	16 May, 20:00
Oberpfaffenhofen	Ortuccio	997 km	13 hrs	20 May, 15:00	22 May, 20:00
Ortuccio	Stuttgart	1163 km	13 hrs	27 May, 12:00	28 May, 12:00

3.1.2 Effective measurement schedule

Table 3-2 Periods of data taking of MOB while installed at the various sites

MOB at	Week	From Date and Time (UTC)	To Date and Time (UTC)	MJD
TIM	14	Mon, 04 Apr 2016 00:00	Fri, 08 Apr 2016 08:30	57482 – 57486
INRIM	15	Wed, 13 Apr 2016 16:30	Sat, 16 Apr 2016 09:00	57491 – 57494
ROA	16	Mon, 18 Apr 2016 13:30	Thu, 21 Apr 2016 15:00	57496 – 57499
OP	17	Mon, 25 Apr 2016 10:30	Thu, 28 Apr 2016 09:30	57503 – 57506
SP	18	Mon, 02 May 2016 10:30	Thu, 05 May 2016 09:30	57510 – 57513
PTB	19	Mon, 09 May 2016 11:30	Fri, 13 May 2016 12:00	57517 – 57521
TIM	22	Mon, 30 May 2016 13:00	Fri, 03 Jun 2016 12:30	57538 – 57542

3.2 TWSTFT Station Information

Table 3-3 Designation and location of TWSTFT stations involved

T&F Lab. Code	Location	TWSTFT St code even hours	TWSTFT St code odd hours	Position deg: min: sec
INRIM	Torino IT	IT02	IT12	LA: N 45:00:53.987 LO: E 007:38:20.686 HT: 306.6 m
			IT11	LA: N 45:00:53.987 LO: E 007:38:20.686 HT: 306.6 m
ROA	San Fernando ES	ROA01	ROA11	LA: N 36:27:51.530 LO: W 006:12:22.333 HT: 74.7 m
LNE-SYRTE (OP)	Paris FR	OP01	OP11	LA: N 48:50:09.236 LO: E 002:20:05.873 HT: 78.0 m
SP	Boras SE	SP01	SP11	LA: N 57:42:55.000 LO: E 012:53:27.000 HT: 225.0 m
PTB	Braunschweig DE	PTB01	PTB11	LA: N 52:17:49.787 LO: E 010:27:37.966 HT: 143.4 m
TIM	Stuttgart DE	TIM01	TIM11	LA: N 48:44.16.272 LO: E 009:06:45.106 HT: 529.0 m
MOB	Stuttgart DE	MOB02	MOB12	Mobile

Table 3-3 summarizes the TWSTFT stations involved, including MOB which was shipped in sequence between TimeTech (TIM), INRIM, ROA, OP, SP, and PTB. The station code (columns 3 and 4 in Table 3-3) is part of the designation of data lines [RD01, RD02] in which measurement results are reported. According to the practice in the TWSTFT community it is changed between regular sessions – during even hours, 00:00 to 01:00 ff – and extra sessions – during odd hours, 01:00 to 02:00 ff (in UTC).

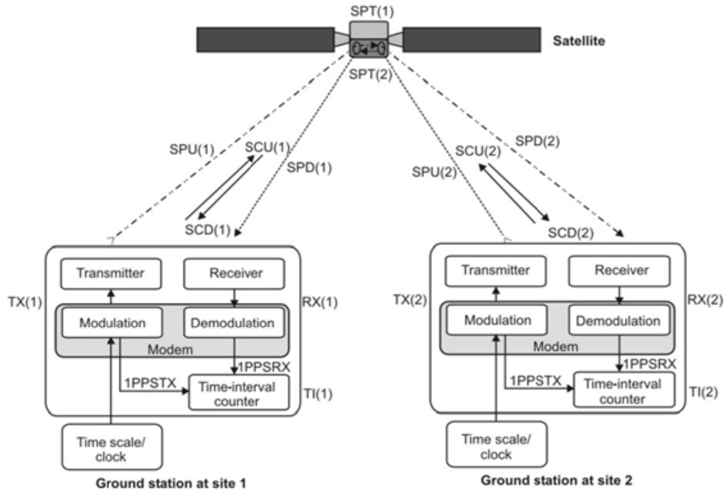
4 Information on TWSTFT

4.1 Quantities determined in a TWSTFT Calibration

In this section, we recall the theoretical background and derive the equations necessary for the determination of calibration constants. We follow, when possible and expedient, the description and naming of the ITU-R Recommendation TF.1153-4 [RD02] and extend or deviate thereof only if necessary. In particular, we use some of the common abbreviating acronyms in the text and in equations, which are listed in Table 1-2.

TWSTFT between two remote stations 1 and 2 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 phase coherent to the remote atomic time scale and transmitted from the remote station with respect to the local time scale. The measurement result obtained at one site, e.g. TW(1), is the time difference reading from a time-interval counter (TIC). It comprises the difference between the two time scales involved and also the complete delay along the signal path from station 2 to station 1. For the ground station, we distinguish only between the transmission (TX) and receiving (RX) part. We use Figure 4-1 to describe the individual signal delay components, e. g., for the signal received at site 1.

Figure 4-1 Schematics of a TWSTFT set-up, including the designation of the various signal delays [RD03]



The signal delay 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 signal path uplink delay SPU(2), the satellite path delay through the transponder SPT(2), and the signal path 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 according to [RD02] by introducing Sagnac corrections for both the uplink and downlink to and from the satellite, SCU(2) = -SCD(2) and SCD(1) = -SCU(1), respectively, which have to be determined separately from the positions of the stations and the satellite. The new version of [RD02], in force since august 2015, considers that the earth is not perfectly spherical. Instead, it is considered as an ellipsoid at first approximation, and takes into account the transformation from geodetic to geocentric coordinates.

At site 2, the equivalent measurement is carried out simultaneously, and we obtain two measurement results, TW(1) and TW(2):

(1) $$\mathrm{TW(1) = TS(1)\text{-}TS(2)} + \underbrace{\mathrm{TX(2) + SP(2) + RX(1) + SCD(1)\text{-}SCD(2)}}_{\text{signal delay on site 1}}.$$

(2) $$\mathrm{TW(2) = TS(2)\text{-}TS(1)} + \underbrace{\mathrm{TX(1) + SP(1) + RX(2) + SCD(2)\text{-}SCD(1)}}_{\text{signal delay on site 2}}.$$

We assume at this stage a complete reciprocity of the signal path: SP(1) = SP(2). As mentioned above, the signal path consists of three components, SPU, SPT, and SPD. The satellite transponder delay cancels only if both ground stations transmit to the respective partner via the same transponder on the satellite, which requires that both stations are within the same antenna footprint of the satellite. This is the situation prevailing for all links within Europe and thus valid in this campaign.

The timescale difference can be computed by subtraction of (2) from (1):

(3) $$\mathrm{TS(1) - TS(2)} = 0.5 * [\mathrm{TW(1) - TW(2)}] + $$
$$+\{0.5 * [\mathrm{DLD(1) - DLD(2)}] - [\mathrm{SCD(1) - SCD(2)}]\}.$$

Here, $\mathrm{DLD(i)}$ is the signal-delay difference between the transmitter and the receiver part of station i, $\mathrm{DLD(i)} = \mathrm{TX(i)} - \mathrm{RX(i)}$. The calibration value for the link between sites 1 and 2 is defined as the terms in curly brackets in eq. 3:

(4) $$\mathrm{CALR(1,2)} = +0.5 * [\mathrm{DLD(1) - DLD(2)}] - [\mathrm{SCD(1) - SCD(2)}].$$

For its determination by using a mobile TWSTFT station (MOB), two different approaches are in principle possible, the so-called site-based TW calibration method, which requires pure common clock TWSTFT measurements taken at each site and the baseline-based TW calibration method, which avoids that. In order not to perturb the operations of PTF1 and PTF2, the baseline mode was used during the current campaign for the calibration of the links between PTF1/PTF2 and INRIM, ROA, OP, SP, and PTB respectively. In this mode, the application of a dedicate schedule for the PTF1 and PTF2 TW stations just for a few days is avoided, i.e. PTF1 and PTF2 have been operating undisturbed.

For links between UTC(k) labs, it was also decided to use the baseline-based TW calibration method in a broader sense as will be explained below. The key benefit of this method is the link calibration while using the TWSTFT modems in their operational configuration. Baseline mode was used during an expanded timetable, including an extended schedule besides the regular one.

In the site mode, the MOB is operated in parallel to the station 1, both connected to a single clock. Eq. 3 is, thus, simplified to:

$$(5) \qquad 0 = 0.5 * [\mathrm{TW}(1) - \mathrm{TW}(\mathrm{MOB@1})] \; + \; \{0.5 * [\mathrm{DLD}(1) - \mathrm{DLD}(\mathrm{MOB})]\}.$$

We define the common-clock difference, CCD(MOB@1,1), as the last addend in (5), and determine it consequently from a TWSTFT measurement between 1 and MOB as:

$$(6) \qquad \mathrm{CCD}(\mathrm{MOB@1,1}) = 0.5 * [\mathrm{TW}(\mathrm{MOB@1}) - \mathrm{TW}(1)] = 0.5 * [\mathrm{DLD}(1) - \mathrm{DLD}(\mathrm{MOB})].$$

Note that DLD(MOB) is a term that is assumed to be constant during the whole campaign and thus independent of the location where MOB is operated. This assumption cannot be proven during the campaign. Only at its end a second common-clock measurement at the station where the campaign started may give evidence.

From site 1 the MOB is transported to site 2 and connected to the corresponding time scale TS(2). A new common-clock difference, CCD(MOB@2,2) can be measured at this site. Subtracting (6) from itself particularized for site 2, and considering (4), a calibration value can be computed:

$$(7) \qquad \mathrm{CALR}(1,2) = \; [\mathrm{CCD}(\mathrm{MOB@1},1) - \mathrm{CCD}(\mathrm{MOB@2},2)] - [\mathrm{SCD}(1) - \; \mathrm{SCD}(2)].$$

In the baseline mode, the MOB is operated in parallel to station 1, both connected to a single clock. Eq. 5 and 6 remain valid.

From site 1 the MOB is transported to site 2 and connected to the corresponding time scale TS(2). The time-scale difference $\mathrm{TS}(1) - \mathrm{TS}(2)$ is measured by performing TWSTFT measurements between the MOB, located at site 2, and the site 1, in addition to the regular configuration of two fixed stations. Eq. 3 can thus be written twice, and the difference of both expressions leads to:

$$(8) \qquad 0 = 0.5 * \left[\left(\mathrm{TW}(2) - \mathrm{TW}(1)\right) - \left(\mathrm{TW}(\mathrm{MOB@2}) - \mathrm{TW}(1)\right)\right] + \\ + \{0.5 * [\mathrm{DLD}(2) - \mathrm{DLD}(\mathrm{MOB})]\}.$$

Subtracting (8) from (5), and considering (4), the calibration value will be given by:

$$(9) \qquad \mathrm{CALR}(1,2) = \; \mathrm{CCD}(\mathrm{MOB@1},1) + \\ +0.5 * \left[\left(\mathrm{TW}(1) - \mathrm{TW}(\mathrm{MOB@2})\right) - \left(\mathrm{TW}(1) - \mathrm{TW}(2)\right)\right] + \\ - \mathrm{SCD}(1) + \; \mathrm{SCD}(2).$$

Notice that the mathematical expression $-0.5 * \left[\left(\mathrm{TW}(1) - \mathrm{TW}(\mathrm{MOB@2})\right) - \left(\mathrm{TW}(1) - \mathrm{TW}(2)\right)\right]$ in eq. 8 and 9 seems to be identical to $\mathrm{CCD}(\mathrm{MOB@2},2)$. This is, however, not the case due to the way of involving the pseudorandom noise codes. To be more precise, $\mathrm{CCD}(\mathrm{MOB@k},\mathrm{k})$ in eq. 6 in fact refers to a CCD when the station at site "k" transmits with PRN "k" and receives with the PRN allocated to the mobile station. When $\mathrm{CCD}(\mathrm{MOB@1,1})$ and $\mathrm{CCD}(\mathrm{MOB@2,2})$ are combined in eq. 7, any delay dependence in reception and transmission on the PRN would vary the DLD of the stations involved as well as the estimated CALR.

As the first step in the baseline method, station "1" transmits with PRN "1" and receives with the PRN allocated to the mobile station (for instance "3"). In a second step, station "2" transmits with PRN "1" and receives with PRN "2", while the mobile station transmits with PRN "3" and receives with PRN "1". The effect on the delays caused by using PRN "1" and "3" between station "1" and mobile station are cancelled, and only remains the effect of PRN "1" and "2" between stations "1" and "2", i.e. those that will be present in normal operation and must be included in the estimation of the CALR value.

Hereafter, we will also refer to the expression $-0.5 * \left[\left(\mathrm{TW}(1) - \mathrm{TW}(\mathrm{MOB@2})\right) - \left(\mathrm{TW}(1) - \mathrm{TW}(2)\right)\right]$ as CCD result (in a more general sense).

A greater generalization of the baseline-based TW calibration method would consist in the application of this approach to both sites involved in the time link, i.e. exchanging the sites 1 and 2 and repeating the same steps (eq. 5, 6, 8 and 9). Both estimations of $\mathrm{CALR}(1,2)$, with their uncertainties, can be combined to provide a best estimation of such parameter. This generalization is possible for the UTC(k) laboratories, as true common-clock measurements were taken at each site.

4.2 The REFDELAY issue

At this point it is necessary to introduce the quantity REFDELAY. According to [RD01, RD02] it represents the time difference between the local reference point for time scale TS(k) and the physical signal involved in the measurement process, 1PPSTX(k). It is reported in a separate column in the standard ITU file according to [RD02]. Software adhering to the standard includes it in the calculation, e.g. when CCD shall be calculated. The physical connections between the local time scale reference points and the two TWSTFT ground stations involved differ in general. As an example, Figure 5-1 depicts the situation where the 10 MHz and the two 1 PPS signals connected to the TWSTFT ground station, here in particular the MOB, are from the same physical source. In this case, REFDELAY is just a constant that would change only if cable connections are changed.

More specific than (6), one has to consider

(10) $$\begin{aligned}\mathrm{CCD}(\mathrm{MOB@k,k})_{\mathrm{true}} &= 0.5*\Big(\mathrm{TW}(\mathrm{MOB@k})-\ \mathrm{TW}(\mathrm{k})\Big)+\\ &\quad +\mathrm{REFDELAY}(\mathrm{MOB@k})-\ \mathrm{REFDELAY}(\mathrm{k})=\\ &= 0.5*\Big(\mathrm{TW}(\mathrm{MOB@k})-\mathrm{TW}(\mathrm{k})\Big)+\mathrm{REFDLYdiff}(\mathrm{MOB@k,k})\\ &= 0.5*\Big(\mathrm{TW}(\mathrm{MOB@k})-\ \mathrm{TW}(\mathrm{k})\Big)_{\mathrm{true}}.\end{aligned}$$

We note that the calculation involves only differences of REFDELAY values, mobile station minus fixed station. At each site, these differences were constant. This facilitated the evaluation since the ITU files for the station MOB do not automatically contain the correct REFDELAY values. The use of (10) is appropriate for all links involved. The delay between the local reference point for time scale TS(k) and the physical signal connected to MOB was determined using the same time interval counter at all stations, such that this counter's systematic time-interval measurement uncertainty involved in the measurement process was negligible. The values REFDLYdiff and the Sagnac Corrections are reported in Table 4-1.

Table 4-1 Correction of ITU files provided by MOB, and Sagnac Corrections

Location of MOB installation, ID station	**REFDLYdiff(MOB@k, k)** to be used in calculations, [ns]	**SCD(Loc)** Sagnac Correction, [ns]
TIM1 (*)	25.565	104.78
INRIM (IT02)	-657.449	109.52
INRIM (IT01)	-736.505	109.52
ROA	-689.927	91.26
OP	-755.963	92.18
SP	-714.767	90.01
PTB	-732.704	99.32
TIM2(*)	25.922	104.78

(*) The difference of $\mathrm{REFDLYdiff}(\mathrm{MOB@k,k})$ at TIM premises before and after the trip also took into account the delay variation in the optical cable of the mobile station connecting the indoor equipment to the trailer; this cable was unconsciously damaged during the visit to INRIM, and subsequently repaired. The impact on the calibration will be explained further on.

Combining equations 7 and 10 for the site mode approach, we get:

(11) $$\begin{aligned}\mathrm{CALR}(1,2) = &\ \mathrm{CCD}(\mathrm{MOB@1},1)+\mathrm{REFDLYdiff}(\mathrm{MOB@1},1)+\\ &-\mathrm{CCD}(\mathrm{MOB@2},2)-\mathrm{REFDLYdiff}(\mathrm{MOB@2},2)+\\ &-\mathrm{SCD}(1)+\ \mathrm{SCD}(2).\end{aligned}$$

Likewise, combining equations 9 and 10 for the baseline mode, we get:

(12) $$\begin{aligned}\mathrm{CALR}(1,2) = &\ \mathrm{CCD}(\mathrm{MOB@1},1)+\mathrm{REFDLYdiff}(\mathrm{MOB@1},1)+\\ &+0.5*\Big[\big(\mathrm{TW}(1)-\mathrm{TW}(\mathrm{MOB@2})\big)-\big(\mathrm{TW}(1)-\mathrm{TW}(2)\big)\Big]+\\ &-\mathrm{REFDLYdiff}(\mathrm{MOB@2},2)-\mathrm{SCD}(1)+\ \mathrm{SCD}(2).\end{aligned}$$

Finally, eq. 13 shows how the calibration value enters in the calculation of time scale differences (simplified from [RD01]):

(13) $$\mathrm{TS}(1)-\mathrm{TS}(2)\ =$$

$$+0.5*[TW(1)-TW(2)]+[REFDELAY(1)-REFDELAY(2)]+CALR(1,2).$$

4.3 The ESDVAR issue

According to [RD01, RD02], the ESDVAR represents any intentionally introduced change in the signal delays in the TX and / or RX path of a TWSTFT station. [RD02] suggests that each TWSTFT network decides whether the ESDVAR is re-set or not when a delay calibration has taken place. It is usual practice for TWSTFT calibrations in Europe to do so, therefore the "final" CALR values given below were calculated with ESDVAR set to zero (if applicable). It is, however, convenient to compare new against old CALR values when the ESDVAR is left unchanged, as this gives a clue on the stability with time (resp. the unintentional delay changes) of the installations at the stations which are connected. We report thus such $CALR_{interim}$ values – ESDVAR value unchanged – as well as the final values – ESDVAR set to zero.

4.4 Least-Squares fitting for the baseline-based TW calibration method

Like during the preceding TWSTFT campaign, we have used the approach designed at the time for the statistical analysis in the case that the baseline method was used.

In this section, we recall the foundation of this approach and the resulting equations, of which stems the solution.

In general, the trends of TS(1) and TS(2) are different, and so the differences between TW(1) and TW(MOB@2) (or between TW(1) and TW(2)) are not stationary (see eq. 12). On the other hand, the result of the expression in squared brackets in eq. 12 should be a constant. But this value cannot be estimated directly from the set of TW data because there are series of data taken in different sessions or time windows, and consequently data are not strictly contemporaneous.

There are contemporaneous values of TW(1) with TW(MOB@2), and there are additionally contemporaneous values of TW(1) with TW(2).

The approximation consists of finding the best straight lines to fit two series of experimental points (linear regression or least-squares fit for each line), with the condition that both lines have the same slope "a".

Calling $0.5*(TW(1)-TW(MOB@2))=X_{1o}(t)$, and $0.5*(TW(1)-TW(2))=X_{2o}(t)$, we search for the straight lines $X_{1e}=a*t+b_1$ and $X_{2e}=a*t+b_2$ that best fit the measurements, that is, to search for the best estimates for the constants a, b_1 and b_2 based on the data $X_{1o}(t)$ and $X_{2o}(t)$. Once these three parameters have been estimated, the value b_1-b_2 provides the estimation of the expression in squared brackets in (12).

For the calculation of the three constants a, b_1 and b_2, we formulate the expression of the residual sum of squares:

$$E^2=\sum_i(X_{1o}-X_{1e})^2+\sum_j(X_{2o}-X_{2e})^2$$

Differentiating E^2 with respect to a, b_1 and b_2 and set the derivatives equal to zero, we get three equations that can be rewritten as simultaneous equations for a, b_1 and b_2:

$$a*\sum t^2+b_1*\sum_i t_i+b_2*\sum_j t_j=\sum t*X$$
$$a*\sum_i t_i+N_1*b_1=\sum_i X_{01i}$$
$$a*\sum_j t_j+ \qquad +N_2*b_2=\sum_j X_{02j}$$

Here, N_1 and N_2 mean the number of data X_{1o} and X_{2o} respectively.

Note that the summation symbol without subscript refers to the sum of both summations, those for the series i and j.

The solution of this equation system provides the three parameters, and specifically b_1 and b_2.

For the estimation of the uncertainty in the difference of ordinates b_1-b_2, a linear interpolation, applied on the series of data j to estimate values at every instant of series i, has been used. The uncertainty was derived from the estimation of residuals at instant i. Based on the estimation of the uncertainty, a 3-σ filter was used to remove outliers. The fit procedure is iterative, as often as necessary, though in practice, rarely a second iteration was needed.

5 Operation of MOB

5.1 Signal Scheme

In Figure 5-1 below, UTC(k) designates the reference time scale of the visited k laboratory.

The optical link (cable #5) connecting the indoor equipment to the trailer of the mobile station refers all TWSTFT measurements to the 1 PPS(Aux) input, independent of the phase of the reference frequency. The operation of the optical link has the additional effect that it presents coherent and phase stable 10 MHz and 1 PPS signals to the SATRE modem in the mobile station. Hence the frequency input to that SATRE follows the phase of the local 1 PPS(Aux) signal. Three cables connecting the local station to the Optical Master have been provided. Note: The cable #4 is a test cable used to verify the 1PPS of Slave with the auxiliary 1PPS provided locally. This cable is used to check there is no error of outdoor synchronization w.r.t. 1 PPS(Aux).

Figure 5-1 Interfaces to the MOB station – Cable Identification

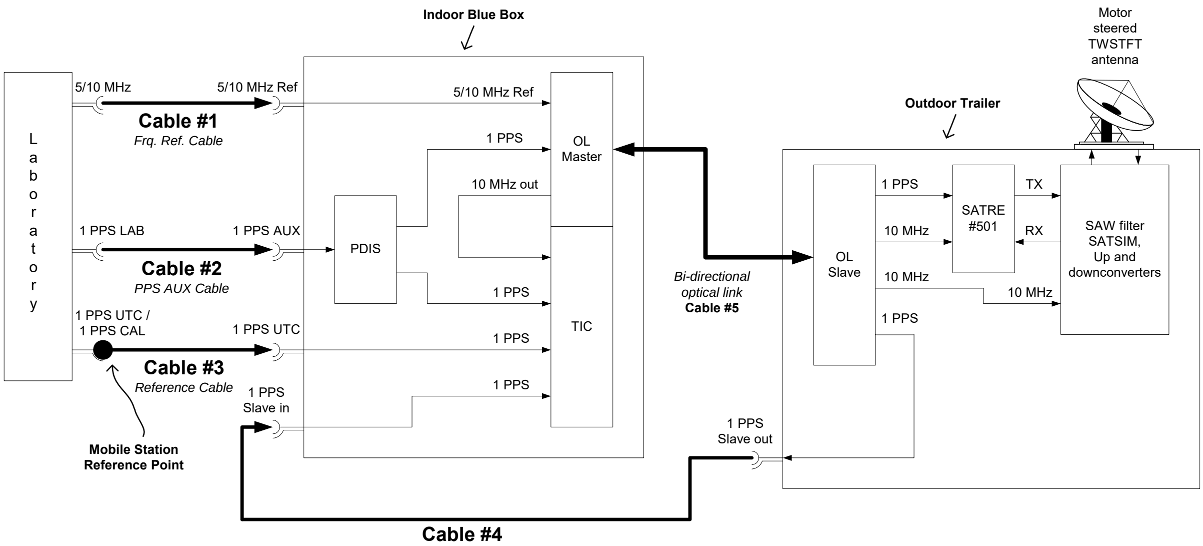


Table 5-1 Description of cables used

Cable #	Signal name	Cable Length	Cable Type	Cable diameter	Connectors	Connector diameter
Cable #1	5/10 MHz Ref	7.5 m	RG223	5.40 mm	N(M) - N(M)	19 mm
Cable #2	1 PPS AUX	7.5 m	RG223	5.40 mm	N(M) - N(M)	19 mm
Cable #3	1 PPS UTC	7.5 m	Sucotest	4.60 mm	N(M) - N(M)	19 mm
Cable #4	1 PPS return	200 m	LMR240	6.40 mm	N(M) - N(M)	19 mm
Cable #5	Optical cable	200 m	LWL-4HMC	6.00 mm	HMC - HMC	23 mm

All 5 cables are provided with the traveling equipment. In particular, the use of cables 3, 4, 5 is mandatory. Cables 1 and 2 can be chosen at will in each laboratory, taking care, however, not to choose them in a way that the 1 PPS AUX rising edge is earlier than the rising edge of 1 PPS UTC.

5.2 OPLINK principle of operation

The optical link (OPLINK) connecting the indoor “Master” with the outdoor “Slave” in the mobile station refers all time interval measurements to the 1 PPS AUX input, independent of the phase of the reference frequency. The TIC that is integral part of the Master replaces the external counter that was used to be shipped around in the 2014 calibration campaign. It measures the 1 PPS signal from PDIS inside Blue Box to Master Oplink, 1 PPS from Oplink Slave (via cable #4) and 1 PPS UTC signal with respect to 1 PPS AUX. In case that 1 PPS UTC cannot be provided continuously to the input of cable #3, it should be connected at start-up of the blue box, and some 1 PPS signal, potentially offset from UTC(k), should if available, be connected to #3 at all times. The 1 PPS Auxiliary signal from the laboratory to the Blue Box is regenerated in the trailer. This signal is verified by connecting it to the TIC in the Blue Box using cable #4. The installation of this cable is mandatory and is needed for assessment of the proper function of OPLINK. The measurement results are recorded and should give the same value at each site.

The operation of the optical link has the additional effect that it provides coherent and phase stable 10 MHz & 1 PPS signals to the SATRE modem in the mobile station, hence the frequency input to that SATRE modem follows the phase of the local 1 PPS AUX signal. The IIOTIC in the SATRE modem that is part of the mobile station measures a constant value and this value need not be applied as a correction. This is in contrast to normal SATRE modem operation, where the difference between the TX 1 PPS and the local 1 PPS connected to the SATRE modem is measured with the built-in IIOTIC, and the measurement result has to be applied in the data evaluation (known as REFDELAY).

5.3 TWSTFT Measurement Schedule during the campaign

The operation schedule shown as Table 5-2 was implemented from early April to the beginning of June, irrespective of the actual installation of the mobile station. This allowed long-term monitoring of all links involved. In this Report, measurements involving the fixed station at TimeTech (TIM01, TIM11) are discussed only in the context with the repeated common-clock measurement made that demonstrated the stability of the MOB during the exercise. The schedule below does not show the other TWSTFT links established during even hours by the TWSTFT stations participating in this campaign.

Table 5-2 TWSTFT schedule implemented during the campaign, even hour sessions

First	Last	Action	Length	OP01		SP01		PTB01		IT02		ROA01		PTF101		PTF201		TIM01		MOB02		Lab
				TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	
				a		d		e		i		k		r		s		t		v		file Char
hhmmss	hhmmss		s	-20		-40		40		-60		-100		-50		50		-30		-70		offset kHz
UTC	UTC			0		3		4		6		7		12		13		14		31		TX code
		U/D link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	
0:00:00	0:00:59	Prep.time	60																			
0:01:00	0:02:59	CC	120																			
0:03:00	0:03:59	Prep.time	60	0	0	3	12	4	14	6	6	7	7	12	3			14	4			
0:04:00	0:05:59	Measure	120	0	0	3	12	4	14	6	6	7	7	12	3			14	4			
0:06:00	0:06:59	Prep.time	60	0	0	3	3	4	4	6	6	7	7	12	12	13	13	14	14			
0:07:00	0:08:59	Measure	120	0	0	3	3	4	4	6	6	7	7	12	12	13	13	14	14			
0:09:00	0:09:59	Prep.time	60							6	7	7	6	12	13	13	12					
0:10:00	0:11:59	Measure	120							6	7	7	6	12	13	13	12					
0:12:00	0:12:59	Prep.time	60					4	6	6	4											
0:13:00	0:14:59	Measure	120					4	6	6	4											
0:15:00	0:15:59	Prep.time	60	0	3	3	0	4	7			7	4									
0:16:00	0:17:59	Measure	120	0	3	3	0	4	7			7	4									
0:18:00	0:18:59	Prep.time	60	0	4	3	7	4	0			7	3					14	31	31	14	
0:19:00	0:20:59	Measure	120	0	4	3	7	4	0			7	3					14	31	31	14	
0:21:00	0:21:59	Prep.time	60			3	6			6	3											
0:22:00	0:23:59	Measure	120			3	6			6	3											
0:24:00	0:24:59	Prep.time	60	0	6					6	0											
0:25:00	0:26:59	Measure	120	0	6					6	0											
0:27:00	0:27:59	Prep.time	60	0	7	3	4	4	3			7	0									
0:28:00	0:29:59	Measure	120	0	7	3	4	4	3			7	0									
0:33:00	0:33:59	Prep.time	60					4	31											31	4	
0:34:00	0:35:59	Measure	120					4	31											31	4	
0:36:00	0:36:59	Prep.time	60			3	14											14	3			
0:37:00	0:38:59	Measure	120			3	14											14	3			
0:39:00	0:39:59	Prep.time	60	0	12	3	13			6	31			12	0	13	3			31	6	
0:40:00	0:41:59	Measure	120	0	12	3	13			6	31			12	0	13	3			31	6	
0:42:00	0:42:59	Prep.time	60	0	13							7	31			13	0			31	7	
0:43:00	0:44:59	Measure	120	0	13							7	31			13	0			31	7	
0:45:00	0:45:59	Prep.time	60							6	12	7	13	12	6	13	7					
0:46:00	0:47:59	Measure	120							6	12	7	13	12	6	13	7					
0:48:00	0:48:59	Prep.time	60							6	13	7	12	12	7	13	6					
0:49:00	0:50:59	Measure	120							6	13	7	12	12	7	13	6					
0:51:00	0:51:59	Prep.time	60	0	31			4	12					12	4					31	0	
0:52:00	0:53:59	Measure	120	0	31			4	12					12	4					31	0	
0:54:00	0:54:59	Prep.time	60			3	31	4	13							13	4			31	3	
0:55:00	0:56:59	Measure	120			3	31	4	13							13	4			31	3	
0:57:00	0:57:59	Prep.time	60	0	0	3	3	4	4	6	6	7	14					14	7			
0:58:00	0:59:59	Measure	120	0	0	3	3	4	4	6	6	7	14					14	7			

CC: Clean Carrier

Table 5-3 TWSTFT schedule implemented during the campaign, odd hour sessions

First	Last	Action	Length	OP11		SP11		PTB11		IT12		ROA11		TIM11		IT11		MOB12		Lab
				TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	
				a		d		e		i		k		t		j		v		file Char
hhmmss	hhmmss		s	-20		-40		40		-60		-100		-30		90		-70		offset kHz
UTC	UTC			0		3		4		6		7		14		17		31		TX code
		U/D link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	
1:00:00	1:00:59	Prep.time	60																	
1:01:00	1:02:59	CC	120																	
1:03:00	1:03:59	Prep.time	60	0	0	3	3	4	4	6	6	7	7	14	14	17	17	31	31	
1:04:00	1:05:59	Measure	120	0	0	3	3	4	4	6	6	7	7	14	14	17	17	31	31	
1:06:00	1:06:59	Prep.time	60	0	14	3	31	4	6	6	4	7	17	14	0	17	7	31	3	
1:07:00	1:08:59	Measure	120	0	14	3	31	4	6	6	4	7	17	14	0	17	7	31	3	
1:09:00	1:09:59	Prep.time	60	0	31	3	14	4	7	6	17	7	4	14	3	17	6	31	0	
1:10:00	1:11:59	Measure	120	0	31	3	14	4	7	6	17	7	4	14	3	17	6	31	0	
1:12:00	1:12:59	Prep.time	60	0	3	3	0	4	17	6	14	7	31	14	6	17	4	31	7	
1:13:00	1:14:59	Measure	120	0	3	3	0	4	17	6	14	7	31	14	6	17	4	31	7	
1:15:00	1:15:59	Prep.time	60	0	4	3	17	4	0	6	7	7	6	14	31	17	3	31	14	
1:16:00	1:17:59	Measure	120	0	4	3	17	4	0	6	7	7	6	14	31	17	3	31	14	
1:18:00	1:18:59	Prep.time	60	0	6	3	7	4	14	6	0	7	3	14	4	17	31	31	17	
1:19:00	1:20:59	Measure	120	0	6	3	7	4	14	6	0	7	3	14	4	17	31	31	17	
1:21:00	1:21:59	Prep.time	60	0	7	3	6	4	31	6	3	7	0	14	17	17	14	31	4	
1:22:00	1:23:59	Measure	120	0	7	3	6	4	31	6	3	7	0	14	17	17	14	31	4	
1:24:00	1:24:59	Prep.time	60	0	17	3	4	4	3	6	31	7	14	14	7	17	0	31	6	
1:25:00	1:26:59	Measure	120	0	17	3	4	4	3	6	31	7	14	14	7	17	0	31	6	
1:27:00	1:27:59	Prep.time	60																	
1:28:00	1:29:59	Measure	120																	
		U/D link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	
1:30:00	1:30:59	Prep.time	60																	
1:31:00	1:32:59	CC	120																	
1:33:00	1:33:59	Prep.time	60	0	0	3	3	4	4	6	6	7	7	14	14	17	17	31	31	
1:34:00	1:35:59	Measure	120	0	0	3	3	4	4	6	6	7	7	14	14	17	17	31	31	
1:36:00	1:36:59	Prep.time	60	0	14	3	31	4	6	6	4	7	17	14	0	17	7	31	3	
1:37:00	1:38:59	Measure	120	0	14	3	31	4	6	6	4	7	17	14	0	17	7	31	3	
1:39:00	1:39:59	Prep.time	60	0	31	3	14	4	7	6	17	7	4	14	3	17	6	31	0	
1:40:00	1:41:59	Measure	120	0	31	3	14	4	7	6	17	7	4	14	3	17	6	31	0	
1:42:00	1:42:59	Prep.time	60	0	3	3	0	4	17	6	14	7	31	14	6	17	4	31	7	
1:43:00	1:44:59	Measure	120	0	3	3	0	4	17	6	14	7	31	14	6	17	4	31	7	
1:45:00	1:45:59	Prep.time	60	0	4	3	17	4	0	6	7	7	6	14	31	17	3	31	14	
1:46:00	1:47:59	Measure	120	0	4	3	17	4	0	6	7	7	6	14	31	17	3	31	14	
1:48:00	1:48:59	Prep.time	60	0	6	3	7	4	14	6	0	7	3	14	4	17	31	31	17	
1:49:00	1:50:59	Measure	120	0	6	3	7	4	14	6	0	7	3	14	4	17	31	31	17	
1:51:00	1:51:59	Prep.time	60	0	7	3	6	4	31	6	3	7	0	14	17	17	14	31	4	
1:52:00	1:53:59	Measure	120	0	7	3	6	4	31	6	3	7	0	14	17	17	14	31	4	
1:54:00	1:54:59	Prep.time	60	0	17	3	4	4	3	6	31	7	14	14	7	17	0	31	6	
1:55:00	1:56:59	Measure	120	0	17	3	4	4	3	6	31	7	14	14	7	17	0	31	6	
1:57:00	1:57:59	Prep.time	60																	
1:58:00	1:59:59	CAL	120																	

CC: Clean Carrier
CAL: Calibration

As it appears in the Table 5-3, the schedule for odd hours included the second TWSTFT station at INRIM (IT11). This station was not taking part in the regular TWSTFT operations scheduled by CCTF WG on TWSTFT, therefore even hour sessions involving IT01 were not performed.

6 Documentation of data collection and results

CC measurements were made at each visited UTC(k) laboratory. Here, as in all cases we distinguish first between data collected in even and odd hours, respectively. An average was made separately to each of the data sets and the ordinate value determined for an abscissa value about in the middle of the data set, including its uncertainty which is about equal to the standard deviation of the individual data points around the mean divided by square-root on the number of data points. The uncertainty values were found in some cases significantly smaller than the ordinate difference between even and odd hour data. This actually points to some systematic effects in the modems involved, namely that the measurement results obtained for a link between two stations depends on the other signals present that are transmitted by other stations at the same time. We thus estimate the statistical uncertainty of each CC value based on the worst TDEV value obtained for the range of useful averaging time (range from 2 to 8 hours), and we include a contribution to the uncertainty budget based on the findings.

The linear fit method is particularly suitable when the two time scales compared have a large relative rate and at the same time the data show gaps. In these cases, the method presented in section 4.4 was employed to solve the eq. 12: The summands $0.5 * [(\mathrm{TW}(1) - \mathrm{TW}(\mathrm{MOB@2})) - (\mathrm{TW}(1) - \mathrm{TW}(2))]$ in that equation represent two TW data taken nominally at the same time, but data from MOB@2 need not perfectly cover the same period as data from the fixed station at laboratory 2 as was stated in section 4.4.

In total, just over 95 pairs of link data for each time link and even and odd hours were taken (The only exceptions to this were the smaller number of link data involving IT01, of about 60, as a result of its operation restricted to odd hours).

Usually, diurnal variations in the TWSTFT data were noted. The cause of the diurnals is not understood, and they might prevent from reaching a 1 ns-uncertainty for the CALR values in some cases, but this was not the case in the current campaign.

6.1 Data collection and individual results relative to MOB Station

6.1.1 MOB at TIM – closure measurement

The fixed TWSTFT installation operated by TimeTech served as reference for the assessment of the performance of the mobile station during the trip. To this end, CC measurements were made before and after the trip. The following results, illustrated in Figure 6-1, were obtained:

CCD(MOB@TIM, TIM)_1: mean = -58.26 ns
sigma = 0.22 ns, TDEV 0.15 ns
N: 152 values

CCD(MOB@TIM, TIM)_2: mean = -58.11 ns
sigma = 0.18 ns, TDEV 0.11 ns
N: 134 values

As will be explained below in section 6.2.2, the accidental and unforeseen break down of the optical cable connecting the indoor equipment to the trailer forced to use an optical cable different from the original, from then on. The estimated delay variation of the optical cable after its repair was entered as a correction to the calculation of the mobile reference delay at TIM before the trip. The green line in Figure 6-1 represents the mean CCD value after applying that correction (fit to the left-hand data). The red line depicts the mean CCD value after the trip (fit to the right-hand data). Both CCD values refer to the repaired optical cable. Dotted lines represent the extrapolated data (back and forth).

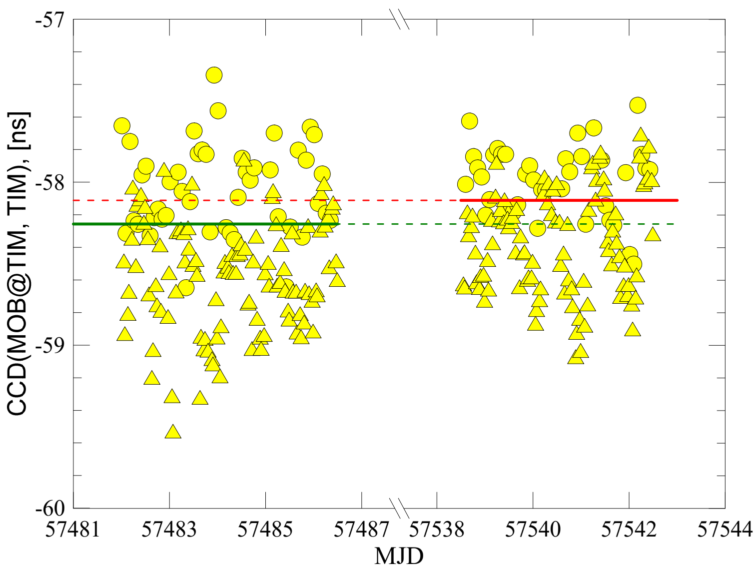
Consider here and hereafter that CCD refers to the "true" value, i.e. that it includes the REFDLYdiff value as was defined in eq. 10.

Also, note that sigma represents the standard deviation from the average or arithmetic mean (hereafter "mean") of individual data points. The statistical measurement uncertainty is estimated by the worst TDEV value observed rather than by $\mathrm{sigma}/\sqrt{\mathrm{N}}$. The latter statement applies for all subsequent data sets.

For the closure measurement estimation, the TDEV values are combined with the corresponding statistical uncertainty associated to the estimation of every REFDLYdiff value, providing the uncertainty u_{CCDi} ; i = 1, 2.

Since the combined standard deviation $\mathrm{CSD} = \sqrt{(u_{CCD1})^2 + (u_{CCD2})^2} = 0.19$ ns was slightly higher than the change in the CCD value along the trip ($\mathrm{CCD}_1 - \mathrm{CCD}_2 = 0.15$ ns), the uncertainty is estimated to be the CSD value, reflecting the estimated instability of the mobile station throughout the campaign.

Figure 6-1 Result of common-clock measurements MOB at TimeTech, circles: data taken at even hours, triangles: data taken at odd hours



6.1.2 MOB at INRIM

As explained above, in the case of INRIM, the time links were calibrated involving two TW stations: the IT02 currently operational and the IT01, after its repair and setting up. CCD involving IT0**1** was calculated using only odd hour sessions data because this station does not take part in the regular TWSTFT operations.

The picture of the Figure 6-2 shows the trailer while was installed at INRIM.

Figure 6-2 View of the mobile station at INRIM

6.1.2.1 MOB at INRIM CCD measurement involving IT02

After considering the REFDLYdiff(MOB@IT, IT02) on the combination of TWSTFT measurement data, the results in Table 6-1 below, were obtained for the CCD measurement involving IT02 station at INRIM. Note that as was stated in section 4.1, we refer to the expression $-0.5 * \left[\left(\text{TW}(1) - \text{TW}(\text{MOB@2})\right) - \left(\text{TW}(1) - \text{TW}(2)\right)\right]$ as $\text{CCD}(\text{MOB@2,2})$ bridged through the station "1".

For the baseline mode, the results were obtained bridging MOB to IT02 by each UTC(k) laboratory taking part in the campaign.

Table 6-1 Result of CCD measurements MOB at INRIM, IT02

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@IT-IT2	97	-920.55	0.44	0.29
Bridged CCD				
MOB2@IT-IT2 thru ROA	94	-921.70	0.65	0.29
MOB2@IT-IT2 thru OP	96	-921.46	0.92	0.46
MOB2@IT-IT2 thru PTB	97	-921.47	0.53	0.18
MOB2@IT-IT2 thru SP	85	-920.65	0.73	0.37
MOB2@IT-IT2 thru IT1	62	-921.66	0.66	0.36

6.1.2.2 MOB at INRIM CCD measurement involving IT01

Similarly, the following results were obtained for the CCD measurement involving IT01 station at INRIM:

Table 6-2 Result of CCD measurements MOB at INRIM, IT01

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@IT-IT1	62	-648.66	0.49	0.30
Bridged CCD				
MOB2@IT-IT1 thru ROA	32	-648.95	0.60	0.54
MOB2@IT-IT1 thru OP	66	-648.50	0.37	0.20
MOB2@IT-IT1 thru PTB	34	-648.25	0.48	0.44
MOB2@IT-IT1 thru SP	63	-648.91	0.52	0.28
MOB2@IT-IT1 thru IT2	63	-647.56	0.44	0.26

With regard to the TWSTFT involving ROA and IT1, further investigations should be carried out because a diurnal modulation of about 90 ns of amplitude was observed during the calibration campaign. Those results were discarded.

6.1.3 MOB at ROA

The photography of the Figure 6-3 shows the mobile and ROA fixed stations antennas during the visit to ROA.

Figure 6-3 Foreground view of the mobile station antenna and ROA fixed station antennas in the background

Following a procedure similar to the one used for INRIM, the results obtained were:

Table 6-3 Result of CCD measurements MOB at ROA

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@ROA-ROA1	106	-633.26	0.21	0.15
Bridged CCD				
MOB2@ROA-ROA1 thru IT2	108	-632.69	0.53	0.22
MOB2@ROA-ROA1 thru OP	66	-633.59	0.50	0.22
MOB2@ROA-ROA1 thru PTB	107	-633.21	0.34	0.15
MOB2@ROA-ROA1 thru SP	98	-633.52	0.40	0.24
MOB2@ROA-ROA1 thru IT1	36	-633.11	0.32	0.27

6.1.4 MOB at OP

Figure 6-4 shows a photograph of the trailer while was installed at OP.

Figure 6-4 View of the mobile station at OP

The following results were obtained:

Table 6-4 Result of CCD measurements MOB at OP

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@OP-OP1	107	-7778.08	0.35	0.22
Bridged CCD				
MOB2@OP-OP1 thru IT2	106	-7776.84	0.66	0.27
MOB2@OP-OP1 thru ROA	107	-7778.09	0.49	0.22
MOB2@OP-OP1 thru PTB	92	-7777.83	0.35	0.20
MOB2@OP-OP1 thru SP	73	-7778.42	0.39	0.17
MOB2@OP-OP1 thru IT1	67	-7778.05	0.40	0.20

6.1.5 MOB at SP

The picture of the Figure 6-5 shows the trailer during pre-operation preparations at SP.

Figure 6-5 View of the mobile station at SP

The following results were obtained:

Table 6-5 Result of CCD measurements MOB at SP

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@SP-SP1	103	-668.21	0.34	0.28
Bridged CCD				
MOB2@SP-SP1 thru IT2	64	-668.17	0.69	0.32
MOB2@SP-SP1 thru ROA	101	-668.30	0.78	0.34
MOB2@SP-SP1 thru OP	101	-668.20	0.47	0.20
MOB2@SP-SP1 thru PTB	91	-667.80	0.72	0.33
MOB2@SP-SP1 thru IT1	66	-667.72	0.77	0.45

6.1.6 MOB at PTB

The following results were obtained:

Table 6-6 Result of CCD measurements MOB at PTB

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
Common-clock difference				
MOB2@PTB-PTB1	134	-656.81	0.43	0.31
Bridged CCD				
MOB2@PTB-PTB1 thru IT2	123	-655.61	1.11	0.62
MOB2@PTB-PTB1 thru ROA	124	-656.80	0.73	0.36
MOB2@PTB-PTB1 thru OP	123	-657.17	0.54	0.25
MOB2@PTB-PTB1 thru SP	125	-657.43	0.66	0.29

	N. of values	CCD, [ns]	sigma, [ns]	Worse TDEV, [ns]
MOB2@PTB-PTB1 thru IT1	48	-657.09	0.68	0.58

6.2 Main problems encountered during the campaign

6.2.1 Failure of ESXI server

Just the first day of campaign at INRIM (MJD 57489), the ESXI server failed: The core operating system did not boot. This server is an essential device for controlling the operation of SATRE modem and optical link, and collecting the measurement data.

The faulty unit was returned to TimeTech premises for retrieving the contents of the built-in hard disk in the replacement unit, prior to shipment to INRIM.

The spare unit was delivered to the mobile team in the late afternoon of the next day.

6.2.2 Break down of optical link (cable #5) at INRIM

The campaign was just starting to take off with its first visit at INRIM, when the optical cable of the mobile station connecting the indoor equipment to the trailer was unconsciously damaged in a mishap during the preparations for TW operations.

The calibration activity was interrupted until the optical link was repaired or replaced. From that moment begins a feverish activity. On the one hand, TimeTech people was behind the preparation and shipping of a new optical cable of similar metrological characteristics, and on the other hand, INRIM fibre optic experts worked to recover the accidentally damaged cable. Thanks to the good predisposition and excellent work done, the optical link was restored and the calibration resumed without significant delays.

The next figure shows a picture of INRIM fibre optic experts working after the mishap.

Figure 6-6 INRIM fibre optic experts working to recover the accidentally damaged cable

During the next visits, the repaired optical cable was used. That means that all the laboratories visited used the same setup. All the calculations in this exercise were referred to the original optical cable after its repair.

The impact of the fibre damaged on the closure measurement was estimated by comparing the delay with the original fibre, against the mean delay with the repaired fibre (data gathered during the visit to the five UTC(k) laboratories).

This value was entered as a correction to the calculation of the mobile reference delay at TIM (REFDELAY(MOB@TIM)) before the trip.

Delay variation: Delay of Original Fibre – Delay of Repaired Fibre = 0.14 ns ± 0.06 ns (1-σ)

6.2.3 Unforeseen failure of MOB station at PTB

After a successful start the mobile station stopped working early evening of 9th May (MJD 57517) because of a power failure and a blown fuse.

The cause was not fully understood. The next morning, it was noted that the AC supply voltage to the trailer was below 210 V, likely due to a too long cabling between the power socket in the building and the location of the trailer. So, once the length of the power cable was shortened, the operation was restored.

6.3 TWSTFT link calibration values

From now on, all values reported in tables are stated in ns.

6.3.1 Links between UTC(k) TWSTFT stations

We make use of baseline mode in its most general version (baseline mode on both sides of each link), as already explained above, getting two possible solutions for each link. The weighted average of both solutions provides the desired result. Common clock data were reported in Sections 6.1.2 to 6.1.6.

In Table 6-7 odd rows show the differences of CCD (ΔCCD) results, as well as the combined ΔCCD obtained for each couple of UTC(k) labs: INRIM (IT1 and IT2), OP, ROA, PTB and SP. Even rows show the associated statistical uncertainties, which were based on the TDEV values:

Table 6-7 Differences of CCD for pairs of UTC(k) stations participating in TWSTFT calibration campaign

	CCD(MOB@1, 1)	Bridged CCD(MOB@2, 2)	**ΔCCD1**	Bridged CCD(MOB@1, 1)	CCD(MOB@2, 2)	**ΔCCD2**	**ΔCCD**
ΔCCD(IT02, OP01)	-920.55	-7776.84	**6856.29**	-921.46	-7778.08	**6856.62**	**6856.41**
$u_{\Delta CCD(IT02, OP01)}$	0.29	0.27	**0.40**	0.46	0.22	**0.51**	**0.31**
ΔCCD (IT02, PTB01)	-920.55	-655.61	**-264.94**	-921.47	-656.81	**-264.66**	**-264.72**
$u_{\Delta CCD (IT02, PTB01)}$	0.29	0.62	**0.68**	0.18	0.31	**0.36**	**0.32**
ΔCCD (IT02, ROA01)	-920.55	-632.69	**-287.86**	-921.7	-633.26	**-288.44**	**-288.18**
$u_{\Delta CCD (IT02, ROA01)}$	0.29	0.22	**0.36**	0.29	0.15	**0.33**	**0.24**
ΔCCD (IT02, SP01)	-920.55	-668.17	**-252.38**	-920.65	-668.21	**-252.44**	**-252.41**
$u_{\Delta CCD (IT02, SP01)}$	0.29	0.32	**0.43**	0.37	0.28	**0.46**	**0.32**
ΔCCD (OP01, PTB01)	-7778.08	-657.17	**-7120.91**	-7777.83	-656.81	**-7121.02**	**-7120.96**
$u_{\Delta CCD (OP01, PTB01)}$	0.22	0.25	**0.33**	0.2	0.31	**0.37**	**0.25**
ΔCCD (OP01, ROA01)	-7778.08	-633.59	**-7144.49**	-7778.09	-633.26	**-7144.83**	**-7144.69**
$u_{\Delta CCD (OP01, ROA01)}$	0.22	0.22	**0.31**	0.22	0.15	**0.27**	**0.20**
ΔCCD (OP01, SP01)	-7778.08	-668.2	**-7109.88**	-7778.42	-668.21	**-7110.21**	**-7110.03**
$u_{\Delta CCD (OP01, SP01)}$	0.22	0.2	**0.30**	0.17	0.28	**0.33**	**0.22**
ΔCCD (PTB01, ROA01)	-656.81	-633.21	**-23.60**	-656.8	-633.26	**-23.54**	**-23.57**
$u_{\Delta CCD (PTB01, ROA01)}$	0.31	0.15	**0.34**	0.36	0.15	**0.39**	**0.26**
ΔCCD (PTB01, SP01)	-656.81	-667.8	**10.99**	-657.43	-668.21	**10.78**	**10.87**
$u_{\Delta CCD (PTB01, SP01)}$	0.31	0.33	**0.45**	0.29	0.28	**0.40**	**0.30**
ΔCCD (ROA01, SP01)	-633.26	-668.3	**35.04**	-633.52	-668.21	**34.69**	**34.86**
$u_{\Delta CCD (ROA01, SP01)}$	0.15	0.34	**0.37**	0.24	0.28	**0.37**	**0.26**
ΔCCD (IT01, OP01)	-648.66	-7778.05	**7129.39**	-648.5	-7778.08	**7129.58**	**7129.50**
$u_{\Delta CCD (IT01, OP01)}$	0.30	0.2	**0.36**	0.2	0.22	**0.30**	**0.23**
ΔCCD (IT01, PTB01)	-648.66	-657.09	**8.43**	-648.25	-656.81	**8.56**	**8.51**
$u_{\Delta CCD (IT01, PTB01)}$	0.30	0.58	**0.65**	0.44	0.31	**0.54**	**0.42**
ΔCCD (IT01, ROA01)	-648.66	-633.11	**-15.55**	-648.95	-633.26	**-15.69**	**-15.60**
$u_{\Delta CCD (IT01, ROA01)}$	0.30	0.27	**0.40**	0.54	0.15	**0.56**	**0.33**
ΔCCD (IT01, SP01)	-648.66	-667.72	**19.06**	-648.91	-668.21	**19.30**	**19.22**
$u_{\Delta CCD (IT01, SP01)}$	0.30	0.45	**0.54**	0.28	0.28	**0.40**	**0.32**

Table 6-8 contains the results obtained for each couple of UTC(k) labs: INRIM (IT1 and IT2), OP, ROA, PTB and SP.

We make use of eq. 12, the Sagnac Corrections reported in Table 4-1, and the differences of common clock data reported in Table 6-7. Subsequently CALR values are reported in two tables, with the motivation given in Section 4-3. Table 6-8 contains the final values to be applied further on (with ESDVAR set to zero), and interim values, intended for comparisons old-new in Table 6-9 (ESDVAR values kept unchanged).

Table 6-8 CALR values (in ns) for pairs of UTC(k) stations participating in TWSTFT calibration campaign

New CALR, ESDVAR set to zero				
	ΔCCD	SCD(1)	SCD(2)	CALR
CALR*(IT02, OP01)	6856.41	109.52	92.18	**+6839.07**
CALR*(IT02, PTB01)	-264.72	109.52	99.32	**-274.92**
CALR*(IT02, ROA01)	-288.18	109.52	91.26	**-306.44**
CALR*(IT02, SP01)	-252.41	109.52	90.01	**-271.92**
CALR*(OP01, PTB01)	-7120.96	92.18	99.32	**-7113.82**
CALR*(OP01, ROA01)	-7144.69	92.18	91.26	**-7145.61**
CALR*(OP01, SP01)	-7110.03	92.18	90.01	**-7112.2**
CALR*(PTB01, ROA01)	-23.57	99.32	91.26	**-31.63**
CALR*(PTB01, SP01)	10.87	99.32	90.01	**+1.56**
CALR*(ROA01, SP01)	34.86	91.26	90.01	**+33.61**
CALR*(IT01, OP01)	7129.5	109.52	92.18	**+7112.16**
CALR*(IT01, PTB01)	8.51	109.52	99.32	**-1.69**
CALR*(IT01, ROA01)	-15.60	109.52	91.26	**-33.86**
CALR*(IT01, SP01)	19.22	109.52	90.01	**-0.29**

The calibration values in Table 6-8 (CALR*) take into account that the earth stations delay variations (ESDVAR) will be reset to zero after the calibration. [RD02] suggests that each TWSTFT network decides whether the ESDVAR is re-set or not when a delay calibration takes place. It is usual practice for TWSTFT calibrations in Europe to do so, therefore the "final" CALR values are given with ESDVAR set to zero (if applicable). It is, however, more instructive to compare new against old ones when the ESDVAR is left unchanged, as this gives a clue on the stability with time of the installations at the stations which are connected. We report thus such $CALR_{interim}$ subsequently in Table 6-9.

Table 6-9 $CALR_{interim}$ values (in ns) for pairs of UTC(k) stations participating in TWSTFT calibration campaign

$CALR_{interim}$, ESDVAR unchanged			
	ESDVAR(1)	ESDVAR(2)	CALR*(1, 2) – 0.5*[ESDVAR(1) - ESDVAR(2)]
CALR(IT02, OP01)	0	0	**+6839.07**
CALR(IT02, PTB01)	0	-1412.656	**-981.25**
CALR(IT02, ROA01)	0	0	**-306.44**
CALR(IT02, SP01)	0	0	**-271.92**
CALR(OP01, PTB01)	0	-1412.656	**-7820.15**
CALR(OP01, ROA01)	0	0	**-7145.61**
CALR(OP01, SP01)	0	0	**-7112.2**
CALR(PTB01, ROA01)	-1412.656	0	**+674.7**
CALR(PTB01, SP01)	-1412.656	0	**+707.89**
CALR(ROA01, SP01)	0	0	**+33.61**
CALR(IT01, OP01)	0	0	**+7112.16**
CALR(IT01, PTB01)	0	-1412.656	**-708.02**
CALR(IT01, ROA01)	0	0	**-33.86**
CALR(IT01, SP01)	0	0	**-0.29**

Notice that $\mathrm{CALR}(1,2) = -\mathrm{CALR}(2,1)$, therefore changing the sign of the last column in tables 6-8 and 6-9 gives the CALR values for the second station.

6.3.2 Summary and discussion of uncertainty contributions

A large part of this section is based on the reasoning and conclusions of annex I in [RD04].

The combined standard uncertainty u_c is given by the geometric sum of components coming from statistical analysis, or type "a" (u_a), and components type "b" or evaluated by means other than the statistical analysis of series of observations (u_b). The total calibration uncertainty U is obtained by multiplying the combined uncertainty by a coverage factor $k = 2$, providing an interval about the result of the measurement with a level of confidence of approximately 95 %.

The following statistical uncertainty component was identified:

u_a reflects the statistical uncertainty associated to the time link, as reported in Table 6-7.

As explained in section 6.1.1, the statistical measurement uncertainty was stated by the worst TDEV value estimated for the range of useful averaging time rather than by $\mathrm{sigma}/\sqrt{N}$ (with sigma the standard deviation of the CCD data, N = number of data points).

This approach takes into account some systematic effects observed occasionally in the modems involved, namely that the measurement results obtained for a link between two stations depends on the signals present that are transmitted by other stations at the same time. It also takes into account diurnal variations noted in the TWSTFT data.

The various contributions to the uncertainty type "b" were classified into the following groups: Mobile TWSTFT station and related equipment (I), Laboratory station and related equipment (II), Interface mobile TWSTFT station and local UTC(k) realization (III) and the satellite link and environment (IV).

I) Mobile TWSTFT station and related equipment

During the campaign the internal delays of the mobile station might differ due to different environmental conditions at the different sites and mechanical stress on components and cabling during traveling. This group of uncertainty components takes into account changes of environmental parameters during the period of installation at a given site and the differences encountered between different sites.

u_b,1 – uncertainty due to the impact of temperature variations.

The impact of the environmental temperature is estimated assuming that the indoor equipment is located in a temperature controlled environment at standard 23 °C +/- 2 K rms (the root mean square) at all sites. The equipment in the trailer is controlled to be within 4 K rms at all sites.

To take into account the impact after visiting two labs, the uncertainty at one site is then multiplied by $\sqrt{2}$. In the table below the uncertainty due to temperature changes is listed.

Table 6-10 Uncertainty due to the impact of temperature variations

location	device	Temp coef.	unit	variation	unit	Contribution to u_b,1 (ps)
indoor	PDIS	6	ps/K	2	K	12
	TIC	2	ps/K	2	K	4
	OPLINK master	25	ps/K	2	K	50
outdoor	OPLINK slave	10	ps/K	4	K	40
	modem	30	ps/K	4	K	120
				u_b,1 (ps) =		**136× $\sqrt{2}$ =192**

u_b,2 – uncertainty due to other contributions related to the mobile TWSTFT station.

Other uncertainty contributions in this equipment are:

Table 6-11 Uncertainty due to other contributions related to the mobile TWSTFT station

device	Contribution to u_b,2 (ps)		comment
OPLINK master	PPS uncertainty	10	Specification
OPLINK slave	PPS uncertainty	20	Specification
modem	Meas. resolution	10	Specification
	u_b,2 (ps) =	**25× $\sqrt{2}$ =35**	

u_b,3 – instability of the portable station.

The third contribution is the difference between the initial CCD between the mobile station and a fixed reference station and measured closure after the campaign (see section 6.1.1):

u_b,3 = 0.19 ns

The quadratic sum of these three contributions to the uncertainty provides the next value for the uncertainty encompassing contributions group I:

u_b,I = 0.27 ns

u_b,I and subsequent uncertainties defined by groups, represent the 1-σ uncertainty, rounded to 0.01 ns.

II) Laboratory station and related equipment

u_b,4 – uncertainty due to the impact of temperature variations.

The stability due to temperature variations of the fixed stations can be estimated in a similar way as set out in Table 6-10.

Table 6-12 Uncertainty due to the impact of temperature variations

location	device	Temp coef.	unit	variation	unit	Contribution to u_b,4 (ps)
Site 1	modem	30	ps/K	2	K	60
Site 2	modem	30	ps/K	2	K	60
				u_b,4 (ps) =		**85**

u_b,5 – uncertainty due to other contributions in laboratory stations.

This uncertainty contribution resulting from the instabilities of the fixed stations and signal distribution systems has been estimated considering the measurement resolution of modems.

For each link calibrated according to the baseline-mode approach, this contribution was estimated as:

u_b,5 = 0.020 ns

The quadratic sum of both contributions to the uncertainty provides the uncertainty contribution group II:

u_b,II = 0.09 ns

III) Interface mobile TWSTFT station and UTC(k) realization

u_b,6(i) – contribution derived from statistical uncertainty already calculated (statistical uncertainty associated to the estimation of the REFDLYdiff value).

u_b,7 – uncertainty due to contributions in equipment related to laboratory stations.

This uncertainty contribution, resulting from the instabilities of signal distribution systems, has been estimated considering the instability of PDIS/FDIS.

For each link calibrated according to the baseline-mode approach, this contribution was estimated in:

u_b,7 = 0.200 ns

u_b,8 – uncertainty due to TIC resolution.

According to the description in the manual of the widely used TIC SR620 [RD07], u_b,8 is the measurement resolution, or the smallest statistically significant change which can be measured.

This uncertainty component is effectively reduced by averaging to be < 25 ps, or < 36 ps for both sites. Taking a sufficiently high number of samples averaged N, this contribution decreases becoming negligible.

u_b,9 – uncertainty due to TIC systematic contributions.

Systematic contribution coming from the time base error (negligible value), the start and stop trigger level errors, and the internal delay asymmetry (predominant component, of about 0.5 ns).

Since the TIC was used in a relative mode [RD07], i.e. a single TIC was used at all labs to connect the mobile TWSTFT station to the local time reference UTC(k), the internal delay asymmetry ("systematic error") was substituted by the differential non-linearity (50 ps).

In such circumstances, u_b,9 was estimated in 130 ps for each link.

Table 6-13 summarizes the group III uncertainty contribution values. All values are in ns.

Table 6-13 Uncertainty contributions and combined uncertainty - Group III

Case	u_b,6(1)	u_b,6(2)	u_b,7	u_b,8	u_b,9	u_b,III
CALR(IT02, OP01)	0.59	0.02	0.20	-	0.13	**0.64**
CALR(IT02, PTB01)	0.59	0.23	0.20	-	0.13	**0.68**
CALR(IT02, ROA01)	0.59	0.15	0.20	-	0.13	**0.65**
CALR(IT02, SP01)	0.59	0.21	0.20	-	0.13	**0.67**
CALR(OP01, PTB01)	0.02	0.23	0.20	-	0.13	**0.33**
CALR(OP01, ROA01)	0.02	0.15	0.20	-	0.13	**0.28**
CALR(OP01, SP01)	0.02	0.21	0.20	-	0.13	**0.32**
CALR(PTB01, ROA01)	0.23	0.15	0.20	-	0.13	**0.36**

Case	$u_{b},6(1)$	$u_{b},6(2)$	$u_{b},7$	$u_{b},8$	$u_{b},9$	u_{b},III
CALR(PTB01, SP01)	0.23	0.21	0.20	-	0.13	**0.39**
CALR(ROA01, SP01)	0.15	0.21	0.20	-	0.13	**0.35**
CALR(IT01, OP01)	0.59	0.02	0.20	-	0.13	**0.64**
CALR(IT01, PTB01)	0.59	0.23	0.20	-	0.13	**0.68**
CALR(IT01, ROA01)	0.59	0.15	0.20	-	0.13	**0.65**
CALR(IT01, SP01)	0.59	0.21	0.20	-	0.13	**0.67**

IV) Satellite link and environment

This group of uncertainties summarizes all effects attributed to the satellite link and outdoor environment. They comprise the instability of satellite communication parameters (signal power, C/N0, codes), atmospheric parameters (ionosphere, troposphere), and satellite motion (residual diurnals, residual Sagnac, path delay difference).

Previous studies have revealed that the causes of diurnal variations in the time transfer results are related to satellite motion, causing a residual Sagnac effect (A) and the path delay difference between the two ground stations to the satellite (B), respectively. In many cases, however, diurnal variations are observed that are substantially larger than could be explained with the two effects. In particular, it has been noted that the two mentioned effects are almost identical for all inner-European links (due to the very similar geometry of stations and satellite), but the amplitude of diurnal variations is quite different in magnitude and it seems to "come and go" in the course of time by an unknown root cause. Because of this, it is proposed to include a term "additional diurnal of unknown origin (ADUO)". This value has been estimated considering that: 1) the diurnal has a sinusoidal wave form, 2) the minimum measurement time interval was about three days, 3) CCD in this exercise showed a maximum amplitude (peak value) of about 2.1 ns, and 4) the worst-case scenario may occur, when the measurement time interval extends to 3 ¼ days and the six additional hours of data are close to a peak or trough. Based on these assumptions, the average value may deviate by 0.34 ns from an average over n full days. This potential deviation is considered as the ADUO uncertainty contribution, rounded up to 0.4 ns.

The table 6-14 contains the uncertainties budget that matches findings in this campaign quite well.

Table 6-14 Uncertainty contributions and combined uncertainty - Group IV

sub group	source	Contribution to u_{b},IV (ns)
sat com	Tx power, C/N0	0.150
	PN codes	0.150
atmosphere	Ionosphere	0.030
	Troposphere	0.001
	Temperature variations on ground station	0.100
	Humidity changes	0.010
satellite motion	ADUO	0.400
	residual Sagnac (A)	0.250
	path delay difference (B)	0.002
	u_{b},IV =	**0.53**

The combined uncertainty u_c is estimated as the square-root of the sum of squares of all contributions.

Table 6-15 summarizes the uncertainty contribution case by case. All values are in ns, U represents the 2-σ uncertainty, or the expanded uncertainty ($k = 2$), rounded to 0.1 ns.

Table 6-15 Uncertainty contributions and expanded U, ($\boldsymbol{k = 2}$)

Case	u_a	u_{b},I	u_{b},II	u_{b},III	u_{b},IV	u_c	U
CALR(IT02, OP01)	0.31	0.27	0.09	0.64	0.53	**0.93**	**1.9**
CALR(IT02, PTB01)	0.32	0.27	0.09	0.68	0.53	**0.96**	**1.9**
CALR(IT02, ROA01)	0.24	0.27	0.09	0.65	0.53	**0.92**	**1.8**
CALR(IT02, SP01)	0.32	0.27	0.09	0.67	0.53	**0.96**	**1.9**
CALR(OP01, PTB01)	0.25	0.27	0.09	0.33	0.53	**0.73**	**1.5**
CALR(OP01, ROA01)	0.20	0.27	0.09	0.28	0.53	**0.69**	**1.4**
CALR(OP01, SP01)	0.22	0.27	0.09	0.32	0.53	**0.72**	**1.4**
CALR(PTB01, ROA01)	0.26	0.27	0.09	0.36	0.53	**0.75**	**1.5**

Case	u_a	u_b,I	u_b,II	u_b,III	u_b,IV	u_c	U
CALR(PTB01, SP01)	0.3	0.27	0.09	0.39	0.53	**0.78**	**1.6**
CALR(ROA01, SP01)	0.26	0.27	0.09	0.35	0.53	**0.74**	**1.5**
CALR(IT01, OP01)	0.23	0.27	0.09	0.64	0.53	**0.91**	**1.8**
CALR(IT01, PTB01)	0.42	0.27	0.09	0.68	0.53	**1.00**	**2.0**
CALR(IT01, ROA01)	0.33	0.27	0.09	0.65	0.53	**0.95**	**1.9**
CALR(IT01, SP01)	0.32	0.27	0.09	0.67	0.53	**0.96**	**1.9**

In Table 6-16 the results obtained hitherto are contrasted with the previously assumed CALR values and their assigned uncertainties [RD05].

Here the performance assessment is based on the absolute value of the CALR difference, relative to the geometric sum of uncertainties:

$$E_n = \frac{|\text{CALRinterim} - \text{CALR(old)}|}{\sqrt{(\text{U\_CALR}^2 + \text{U\_CALR\_old}^2)}}$$

The discrepancy is considered not to be significant when this expression is ≤ 1, and significant otherwise.

$E_n = 1$ is the boundary condition for a level of confidence of approximately 95 %.

Table 6-16 $CALR_{interim}$ values (in ns) obtained during the campaign, compared to old values

Link	CALR(old)	U_CALR_old	$CALR_{interim}$	U_CALR	CALR variation	E_n
IT02–OP01	+6837.3	1.8	+6839.07	1.9	+1.77	**0.68**
IT02–PTB01	-982.9	1.6	-981.25	1.9	+1.65	**0.66**
IT02–ROA01	-307.7	1.6	-306.44	1.8	+1.26	**0.52**
IT02–SP01	-275.6	1.6	-271.92	1.9	+3.68	**1.48**
OP01–PTB01	-7820.2	1.6	-7820.15	1.5	+0.05	**0.02**
OP01–ROA01	-7145.0	1.6	-7145.61	1.4	-0.61	**0.29**
OP01–SP01	-7112.9	1.6	-7112.2	1.4	+0.70	**0.33**
PTB01–ROA01	+675.2	1.6	+674.7	1.5	-0.50	**0.23**
PTB01–SP01	+707.3	1.6	+707.89	1.6	+0.59	**0.26**
ROA01–SP01	+32.1	1.6	+33.61	1.5	+1.51	**0.69**
IT01–OP01	-	-	+7112.16	1.8	-	-
IT01–PTB01	-	-	-708.02	2.0	-	-
IT01–ROA01	-	-	-33.86	1.9	-	-
IT01–SP01	-	-	-0.29	1.9	-	-

Table 6-17 summarizes the consistency of new CALR values against the old ones. In orange are measures of CALR variation whose absolute value is higher than the geometric sum of old and new expanded uncertainties ($E_n > 1$), and in green are values lower than the abovementioned geometric sum ($E_n \leq 1$):

Table 6-17 CALR variation for TWSTFT links, ESDVAR left unchanged

CALR Variation	**IT02**	**OP01**	**PTB01**	**ROA01**	**SP01**
IT02		+1.77	+1.65	+1.26	+3.68
OP01	-1.77		+0.05	-0.61	+0.70
PTB01	-1.65	-0.05		-0.50	+0.59
ROA01	-1.26	+0.61	+0.50		+1.51
SP01	-3.68	-0.70	-0.59	-1.51	

6.4 *Discussion of results*

During the campaign, new CALR values were determined with expanded uncertainties of 2.0 ns and below (combined 1-σ uncertainties lower than 1.0 ns). These uncertainties are of similar order as those obtained in previous campaigns [RD03, RD05] (see Table 6-15). Data collected at each site were of excellent quality, and only occasionally data were removed (by applying a 3-σ filter). The measurement noise was at the standard level.

Calibration values for links involving IT02 seem to indicate a delay variation related to such station and/or their interfaces with UTC(IT) realization. This variation seems to be within the range of 1.5 and 2.0 ns, and may be linked to the reconfiguration of the interface IT02 station – UTC(IT) after the last TWSTFT calibration performed in summer 2014. The variation becomes even more evident for the link with SP01 (SP01 shows a small delay variation in opposite direction).

However, it is considered that part of the discrepancies noted are related to the fact that, unlike the previous calibration campaign in 2014, this time was used the baseline-based TWSTFT calibration method. Baseline mode allows performing the calibration under conditions as close as possible to those found under usual operation and might justify the observed delay variations. This calibration should be used as a starting point for future calibration exercises, in order to gain more in-depth knowledge about the impact of baseline mode use, as well as for assessing the quality assurance of the final results (CALR values computed) and the long term stability of TWSTFT links.

It is thus proposed to apply the new values of CALR as is explained in the following section.

7 Application of CALR values in TWSTFT ITU files

In order to be compliant with [RD01], the result of the current TWSTFT calibration has to be introduced into the TWSTFT report files as shown below. It is adopted that the ESDVAR be set to zero. The calibration identifiers 433 - 446 were provided by BIPM.

IT02

```
* CAL   433 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns
* CAL   434 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns
* CAL   435 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns
* CAL   436 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns

                CI S    CALR
  IT02   OP01  433 1  6839.100
  IT02  PTB01  434 1  -274.900
  IT02  ROA01  435 1  -306.400
  IT02   SP01  436 1  -271.900
```

OP01

```
* CAL   433 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns
* CAL   437 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   438 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   439 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   443 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns

                CI S    CALR
  OP01   IT02  433 1 -6839.100
  OP01  PTB01  437 1 -7113.800
  OP01  ROA01  438 1 -7145.600
  OP01   SP01  439 1 -7112.200
  OP01   IT01  443 1 -7112.200
```

PTB01

```
* CAL   434 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns
* CAL   437 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   440 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.800 ns
* CAL   441 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.800 ns
* CAL   444 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns

                CI S    CALR
 PTB01   IT02  434 1   274.900
 PTB01   OP01  437 1  7113.800
 PTB01  ROA01  440 1   -31.600
 PTB01   SP01  441 1     1.600
 PTB01   IT01  444 1     1.700
```

ROA01

```
* CAL   435 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns
* CAL   438 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   440 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.800 ns
* CAL   442 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   445 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns

                CI S    CALR
 ROA01   IT02  435 1   306.400
 ROA01   OP01  438 1  7145.600
 ROA01  PTB01  440 1    31.600
 ROA01   SP01  442 1    33.600
 ROA01   IT01  445 1    33.900
```

SP01

```
* CAL   436 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns
* CAL   439 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   441 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.800 ns
* CAL   442 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   446 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns

                CI S    CALR
  SP01   IT02  436 1   271.900
  SP01   OP01  439 1  7112.200
  SP01  PTB01  441 1    -1.600
  SP01  ROA01  442 1   -33.600
  SP01   IT01  446 1    +0.300
```

IT01

```
* CAL   443 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.900 ns
* CAL   444 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns
* CAL   445 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    0.700 ns
* CAL   446 TYPE: PORT ES REL        MJD: 57542  EST. UNCERT.:    1.000 ns

                CI S    CALR
  IT01   OP01  443 1  7112.200
  IT01  PTB01  444 1    -1.700
  IT01  ROA01  445 1   -33.900
  IT01   SP01  446 1    -0.300
```

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