

Summary for the 2019 SDR TWSTFT OP-PTB calibration report

F. Meynadier

This document summarizes the report of the 2019 calibration of the TW link between OP51 and PTB55 stations, i.e. using a SATRE modem for Tx and a SDR module for Rx.

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Results

The following tables reproduce the final pages of the report containing the CALR values and CI to be used for each calibrated link, as well as the lines to be inserted in the ITU format files.

The complete report is appended to this summary as an appendix, as well as a manual describing the operation of the SDR-enabled mobile station.

PTB55

* CAL 517 TYPE: PORT ES REL MJD: 58617 EST. UNCERT.: 0.500 ns

	CI	S	CALR
PTB55 OP51 517 1			2034.672

OP51

* CAL 517 TYPE: PORT ES REL MJD: 58617 EST. UNCERT.: 0.500 ns

	CI	S	CALR	ESDVAR	ESIG
OP51 PTB55 517 1			-2034.672	18.166	0.156

First Calibration of the UTC TWSTFT Link between OP and PTB Using a Travelling SDR Receiver

--- Calibration Report ---

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Abstract

For more than 15 years, Two-Way Satellite Time and Frequency Transfer (TWSTFT) has been a major technique operated continuously and regularly in about 20 timing laboratories worldwide. Processed data are used for the generation of Coordinated Universal Time (UTC). The technique relies on a protocol for transmitting and receiving clock signals via a telecommunication satellite using carrier frequencies in the Ku band. For this purpose, Satellite Time and Ranging Equipment (SATRE) modems, developed and marketed by TimeTech GmbH, are being operated in the earth stations of the contributing laboratories. The precision of TWSTFT as observed today (with its financial restrictions on the lease of satellite transponder bandwidth) is limited by an apparent daily variation pattern (diurnal) in the TWSTFT results. In consequence, calibrations using a mobile TWSTFT station are usually limited by the same effect. Recent developments of Software-Defined Radio (SDR) receivers for TWSTFT have demonstrated superior performance in terms of stability, and thus the BIPM processes the SDR measurements of the TWSTFT link between OP (LNE-SYRTE) and PTB as a UTC backup link since the end of 2017. However, the accuracy in time remains limited to date because the SDR TWSTFT link is calibrated by alignment with the corresponding SATRE TWSTFT link. In this report we present the first calibration of the SDR TWSTFT link between OP and PTB using a travelling SDR receiver developed in OP driven by a calibration software developed by OP in collaboration with TL. This work is aimed to improve the calibration accuracy and thus the uncertainty of operational time links, e.g. to improve the generation of UTC and the Galileo ground segment timing infrastructure. We present in detail the calibration method used, the achieved results and the associated measurement uncertainties for the SDR TWSTFT link between OP and PTB. The estimated combined standard uncertainty for the calibration is 0.5 ns. This corresponds to an expanded uncertainty of 1 ns ($k = 2$).

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1. Introduction

1.1 Scope of the document

This report describes the calibration method of TWSTFT stations for the OP-PTB link equipped with SDR receivers using a travelling SDR receiver and presents the results of this calibration.

1.2 Document structure

Section 1 of the calibration report 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 gives the TWSTFT operation status.

Section 3 describes the calibration campaign undertaken in March / April 2019 and lists the involved institutes and relevant parameters.

Section 4 presents the theoretical framework for a calibration of TWSTFT links with stations operating an SDR receiver involving a portable earth station equipped with a SATRE modem and a travelling SDR receiver.

Section 5 illustrates the operation of the portable earth station and the SDR travelling receiver used and contains the agreed measurement schedule.

Section 6 reports the data acquisition and processing and provides the calibration results and related uncertainty budget.

Section 7 explains how the determined CALR value may be introduced in the SDR TWSTFT data files.

Section 8 gives some recommendations for improvement.

General note: in this report, the decimal separator used for numbers is "." except in Excel tables where it is ",".

1.3 Reference documents

The following documents are used as reference in this report:

- [1] The operational use of two-way satellite time and frequency transfer employing pseudorandom noise codes. *Recommendation* ITU-R TF.1153-4, Geneva 2015. <https://www.itu.int/rec/R-REC-TF.1153/en>
- [2] TWSTFT Calibration Guidelines for UTC Time Links. BIPM 2016.
- [3] F J Galindo, A Bauch, D Piester, H Esteban, I Sesia, J Achkar, K Jaldehag. European TWSTFT calibration campaign 2016. *Calibration Report* issued on 2017-01-31, 2017.
- [4] Z Jiang, V Zhang, Y-J Huang, J Achkar, D Piester, S-Y Lin, W Wu, A Naumov, S-H Yang, J Nawrocki, I Sesia, C Schlunegger, Z Yang, M Fujieda, A Czubla, H Esteban, C Rieck, P Whibberley. Use of software-defined radio receivers in two-way satellite time and frequency transfers for UTC computation. *Metrologia* **55** 685, 2018. <https://doi.org/10.1088/1681-7575/aacbe6>

- [5] Y-J Huang, J Achkar. Calibration Manual using LNE-SYRTE SDR TWSTFT Travelling Equipment, v1.1, 2019.
- [6] H Esteban. TWSTFT Calibration Report. GAL-TN-ROA-GSOP-20191001 v3, 2019.
- [7] Directive for operational use and data handling in TWSTFT. Rapport BIPM-2011/01, 2011.
- [8] D Piester, A Bauch, L Breakiron, D Matsakis, B Blanzano, and O Koudelka. Time transfer with nanosecond accuracy for the realization of International Atomic Time. *Metrologia*, **45**, 185-198, 2008. <https://doi.org/10.1088/0026-1394/45/2/008>

1.4 Acronyms, Abbreviations or Definitions

BIPM	Bureau international des poids et mesures (Sèvres, France)
ITU	International Telecommunication Union
LNE-SYRTE (OP)	French national metrology institute for time and frequency, also known as OP (Paris, France)
PTB	Physikalisch-Technische Bundesanstalt (Braunschweig, Germany)
ROA	Real Instituto y Observatorio de la Armada (San Fernando, Spain)
TimeTech GmbH	Company manufacturing SATRE modems for TWSTFT and carrying out TWSTFT calibration services using a portable earth station (Stuttgart, Germany)
TL	Telecommunication Laboratories (Taoyuan, Taiwan)
CALR (l,r)	CALibration Result parameter for a link relating station (l) and station (r)
CCD (m,i)	Common Clock Difference parameter at one site between fixed station (i = l,r) and mobile station (m)
CI	Calibration Identifier
CRP	Common Reference Point defined for calibration purposes
C/N ₀	Carrier-to-Noise density ratio
DDM	Differential Delays Measurement
DLK (m,l,r)	Difference Link parameter between the mobile station (m) at site (l) and two-way measurements of station (m) and station (l) with a remote station (r)
DUT	Device Under Test
ES	Earth Station
ESDVAR	Earth Station Delay VARIation
KCDB	Key Comparison Data Base
MODEM	MODulator-DEModulator
PORT ES	PORTable Earth Station, also known as mobile station
PPS	Pulse Per Second
PRN	PseudoRandom-Noise
REFCAL	Delay of the reference with respect to a CRP for calibration purposes
REFDELAY	Delay of the reference with respect to UTC(k)
RSIG	Standard measurement uncertainty of the REFDELAY
Rx	Reception (power or signal)
SATRE	SATellite Time and Ranging Equipment manufactured by TimeTech GmbH
SDR	Software-Defined Radio
T-11N	Satellite Telstar 11N

TIC	Time Interval Counter
TWSTFT	Two-Way Satellite Time and Frequency Transfer
Tx	Transmission (power or signal)
UTC	Coordinated Universal Time
UTC(k)	UTC as realized by laboratory k
MOB02	TimeTech portable earth station equipped with a SATRE modem (Tx, Rx)
MOB52	TimeTech portable earth station equipped with a SATRE modem (Tx) and temporary with OP SDR receiver (Rx)
OP01	OP TWSTFT station equipped with a SATRE modem (Tx, Rx), operated regularly in the even UTC hours
OP11	OP TWSTFT station equipped with a SATRE modem (Tx, Rx), operated temporary in the odd UTC hours
OP51	OP TWSTFT station equipped with a SATRE modem (Tx) and an SDR receiver (Rx), operated regularly in the even UTC hours
PTB05	PTB TWSTFT station equipped with a SATRE modem (Tx, Rx), operated regularly in the even UTC hours
PTB15	PTB TWSTFT station equipped with a SATRE modem (Tx, Rx), operated temporary in the odd UTC hours
PTB55	PTB TWSTFT station equipped with a SATRE modem (Tx) and an SDR receiver (Rx), operated regularly in the even UTC hours

2. TWSTFT Operation Status

Satellite transponder capacity with the required connectivity between Europe (extending to Poland and Sweden) and the USA (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 American Government Services (AGS). 14 institutes - 2 in the USA, and 12 in Europe, including TimeTech GmbH, Stuttgart, Germany (in short TimeTech) as industrial partner - agreed on the contract with AGS. The two Galileo Precise Timing Facilities (GPTFs) were integrated into the network at a later stage. The European participating stations (EPS), among them the Galileo Time Service Provider (GTSP) partners that participated in the 2019 SATRE calibration exercise under TSP contract [6], signed an Agreement with PTB dealing with the satellite transponders cost sharing, the practice of invoicing, and other administrative issues. Since July 2011 the lease agent for the satellite transponder capacity was changed to RiteNet, MD. The current contract runs from November 2016 to May 2021, with one year renewal options to cope with all the necessary changes. Early this year the contract was renewed to cover until May 2020.

The technical parameters of the satellite as of April-June 2019 were:

Beacon frequency: 11 699.500 MHz

For the Europe to Europe link:

Carrier ID, 112677

Uplink, 14 260.150 MHz, horizontal polarization

Downlink, 10 960.150 MHz, vertical polarization

For the transatlantic link:

In Europe:

Carrier ID, 112673

Uplink, 14 046.590 MHz, horizontal polarization

Downlink, 11 489.060 MHz, vertical polarization

In USA:

Carrier ID, 112701

Uplink, 14 289,060 MHz, horizontal polarization

Downlink, 11 746,590 MHz, vertical polarization

3. Organization of the Calibration Campaign

This section gathers the measurement periods and specific information of the TWSTFT stations participating in this calibration campaign.

3.1 Measurement period

Table 3.1 - Periods of data collecting of portable earth station and SDR travelling receiver installed at the various sites

MOB02 and MOB52 at	Week#	From Date and Time (UTC)	To Date and Time (UTC)	MJD
PTB	10	2019-03-12T10:00:00	2019-03-15T10:00:00	58554 - 58557
OP	16	2019-04-23T10:30:00	2019-04-26T10:30:00	58596 - 58599

3.2 TWSTFT Station Information

Table 3.2 - Designation and location of TWSTFT SATRE and SDR stations involved

UTC(k)	Location	TWSTFT Station ID (even hours)	TWSTFT Station ID (odd hours)	SDR TWSTFT Station ID	Position deg: min: sec
PTB	Braunschweig, DE	PTB05	PTB15	PTB55	LA: N 52:17:49,787 LO: E 010:27:37,966 HT: 143.4 m
LNE-SYRTE (OP)	Paris, FR	OP01	OP11	OP51	LA: N 48:50:09,236 LO: E 002:20:05,873 HT: 78.0 m

4. Description of the TWSTFT calibration method

4.1 TWSTFT equation in the use of calibration and time-scale comparison

In this section, we recall the theoretical background in [1] and derive the equations necessary for the determination of calibration result values and finally we use the result to compare time scales.

4.1.1 TWSTFT equation for calibration purpose: determination of CALR values

$$TW(1) = \{1ppsTx(1) - 1ppsTx(2) + Tx(2) + SCU(2) + [SPU(2) + SPT(2) + SPD(1)] + SCD(1) + Rx(1)\}$$

$$TW(2) = \{1ppsTx(2) - 1ppsTx(1) + Tx(1) + SCU(1) + [SPU(1) + SPT(1) + SPD(2)] + SCD(2) + Rx(2)\}$$

$$\begin{aligned} 1ppsTx(1) - 1ppsTx(2) &= \frac{1}{2} [TW(1) - TW(2)] \\ &+ \frac{1}{2} \{[SPU(1) - SPD(1)] - [SPU(2) - SPD(2)]\} \\ &+ \frac{1}{2} \{[SCU(1) - SCD(1)] - [SCU(2) - SCD(2)]\} \\ &+ \frac{1}{2} [SPT(1) - SPT(2)] \\ &+ \frac{1}{2} \{[Tx(1) - Rx(1)] - [Tx(2) - Rx(2)]\} \end{aligned}$$

Considering that the parameters introduced on the above five lines, composing the equation represent, respectively:

- *time interval measurements at sites 1 and 2*
- *propagation delay in the atmosphere*
- *Sagnac correction delay*
- *Satellite transponder delay*
- *Stations delay differences*

The CALR parameter includes all the above two-way delays, except the time interval measurement (Figure 4.1)

$$\begin{aligned} 1ppsTx(1) - 1ppsTx(2) &= \frac{1}{2} [TW(1) - TW(2)] && \rightarrow \text{time interval measurement} \\ &- [SCD(1) - SCD(2)] && \rightarrow \text{Sagnac correction delay} \\ &+ \frac{1}{2} [SDD(1) - SDD(2)] && \rightarrow \text{Stations delay differences,} \end{aligned}$$

where the equalities

$SCD(1) = -SCU(1)$ and $SCU(2) = -SCD(2)$ were used, and the quantities $SDD(1) = [Tx(1) - Rx(1)]$ and $SDD(2) = [Tx(2) - Rx(2)]$ have been introduced.

The propagation delay in the atmosphere and the satellite transponder delay are in the current context considered as cancelled due to reciprocity of the signal path (SPU, SPD and SPT). For SPT this is fully justified for the prevailing case in Europe, and second-order propagation delay differences can be neglected.

$$1ppsTx(1) - 1ppsTx(2) = \frac{1}{2} [TW(1) - TW(2)] \quad \rightarrow \quad \text{time interval measurement}$$

$$+ CALR(1,2) \quad \rightarrow \quad \text{calibration result}$$

Where

$$CALR(1,2) = \left\{ \frac{1}{2} [SDD(1) - SDD(2)] - [SCD(1) - SCD(2)] \right\} \text{ and thus } CALR(1,2) = -CALR(2,1)$$

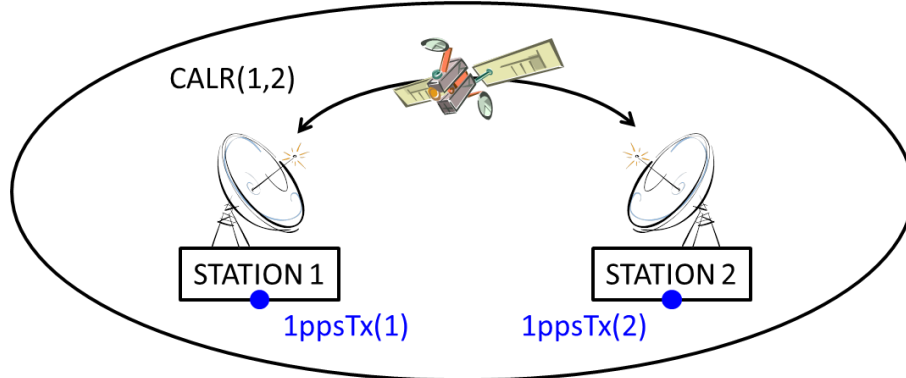


Figure 4.1 - Conceptual diagram of a TWSTFT system. CALR is a parameter of the two-way system and it is independent of other parameters, e.g. REFDELAY and ESDVAR

4.1.2 TWSTFT equation for time-scale comparison: introduction of the REFDELAY and ESDVAR parameters

$$REFDELAY(1) = [UTC(1) - 1ppsTx(1)]$$

and

$$REFDELAY(2) = [UTC(2) - 1ppsTx(2)]$$

Thus

$$UTC(1) - UTC(2) = \frac{1}{2} [TW(1) - TW(2)] \quad \rightarrow \quad \text{time interval measurement}$$

$$+ \frac{1}{2} \{ [SPU(1) - SPD(1)] - [SPU(2) - SPD(2)] \} \quad \rightarrow \quad \text{propagation delay}$$

$$+ \frac{1}{2} \{ [SCU(1) - SCD(1)] - [SCU(2) - SCD(2)] \} \quad \rightarrow \quad \text{Sagnac correction}$$

$$+ \frac{1}{2} [SPT(1) - SPT(2)] \quad \rightarrow \quad \text{Satellite delay}$$

$$+ \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(2) - Rx(2)] \} \quad \rightarrow \quad \text{Stations delay}$$

$$+ [Refdelay(1) - Refdelay(2)] \quad \rightarrow \quad \text{UTC(k)s Reference delay}$$

The CALR parameter includes all the above two-way delays, except the time interval measurement and the (one-way) Refdelay parameter (Figure 4.2).

According to [1], the time-scales difference can be deduced from the equation above by introducing intrinsic parameters closely related to the calibration process, and more precisely CALR and ESDVAR parameters (associated with specific indicators, CI and S):

By introducing these quantities, in two-steps, we obtain,

$$\begin{aligned}
UTC(1) - UTC(2) &= \frac{1}{2} [TW(1) - TW(2)] \\
&+ \frac{1}{2} \{ [SPU(1) - SPD(1)] - [SPU(2) - SPD(2)] \} \\
&+ \frac{1}{2} \{ [SCU(1) - SCD(1)] - [SCU(2) - SCD(2)] \} \\
&+ \frac{1}{2} [Esdvar(1) - Esdvar(2)] \\
&+ \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(2) - Rx(2)] \} \\
&+ [Refdelay(1) - Refdelay(2)]
\end{aligned}$$

Considering that the parameters introduced on the above six lines, composing the equation represent, respectively:

- *time interval measurement, not included in CALR*
- *propagation delay in the atmosphere, included in CALR*
- *Sagnac correction delay, included in CALR*
- *Earth station delay variation, to be reset after calibration*
- *Stations delay, included in CALR*
- *UTC(k) Reference delay, not included in CALR*

With the same assumptions as introduced before, we get for $S = 1$ (ITU-R TF.1153-4),

$$\begin{aligned}
UTC(1) - UTC(2) &= \frac{1}{2} [TW(1) + Esdvar(1)] + Refdelay(1) \\
&- \frac{1}{2} [TW(2) + Esdvar(2)] - Refdelay(2) \\
&+ \frac{1}{2} [CALR(1,2) - CALR(2,1)]
\end{aligned}$$

Considering that the parameters introduced on the above three lines, composing the equation represent, respectively:

- *Station 1 delay (time interval, refdelay, delay variation sets to 0 after cal)*
- *Station 2 delay (time interval, refdelay, delay variation sets to 0 after cal)*
- *CALR calibration result for stations 1 and 2 (excluding time interval and Refdelay)*

Setting ESDVAR to zero after a new calibration is a good convention introduced some years ago and respected within the European TWSTFT network.

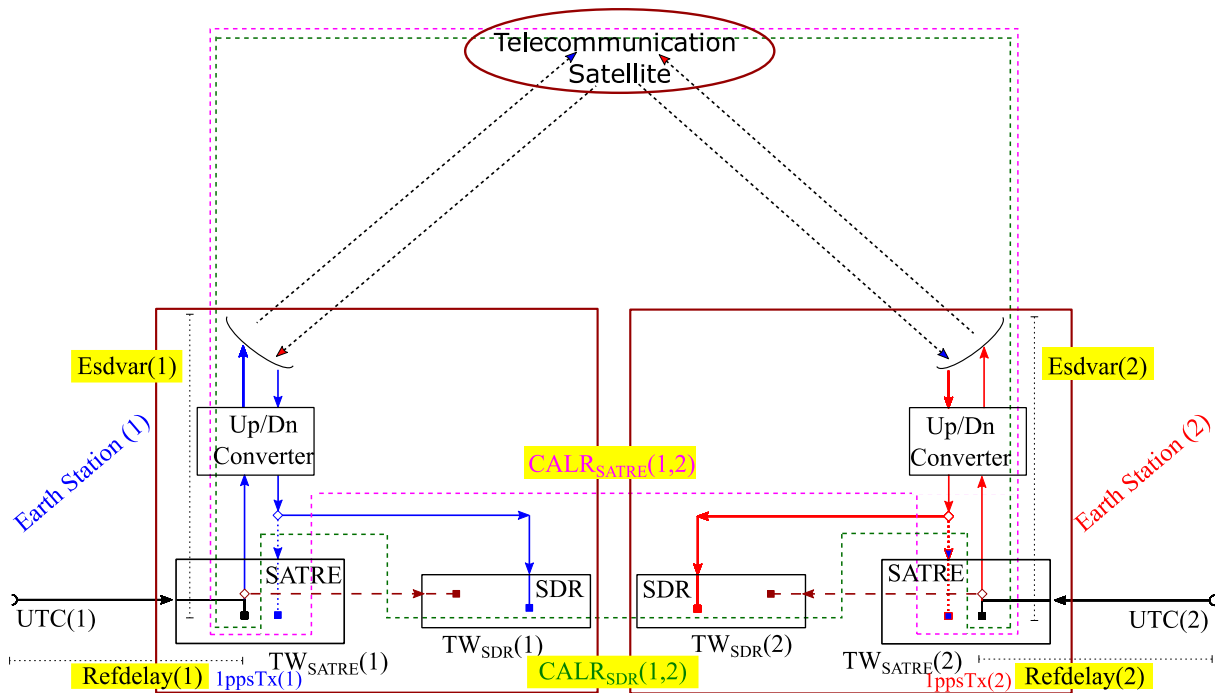


Figure 4.2 - Illustration of the main signal paths of a TWSTFT link based on the combination of SATRE modems with SDR receivers to compare UTC(k)s. After the calibration, any update in the two-way earth stations will be accounted in the values of ESDVAR

4.1.3 TWSTFT equation for determining CALR value in site mode – introduction of the CCD parameter

In the calibration protocol annexed to the BIPM calibration guide [2], in Section 4.2 a mixture of one-way and two-way quantities has been made. Deviating from the ITU-R Recommendation, the CALR value seems to depend on the Refdelay values, which is not justified. The following suggestions shall be applicable in case of a mobile station *m* being operated at sites 1 and 2 in sequence. The term (*m*,1) refers to *m* operated at site 1, etc.

It is proposed to define at each site a common point Refcal, which is physically located between the local on-time reference point and the input to the fixed station. The quantities Refcal(1) and Refcal(*m*,1) are then the delays between this point and the input to stations 1 and *m*, respectively. Note that the Refcal point can in principle coincide with the local on-time point or with the input to the fixed station. In all cases, the two quantities Refcal(*i*) and Refcal(*m*,*i*) have to be measured at *i* = 1, 2.

Using this definition, in the common clock mode between the fixed station and the mobile station (Figure 4.3), the above equations are modified to:

$$\begin{aligned}
 UTC(1) - UTC(1) &= \frac{1}{2} [TW(1) - TW(m, 1)] \\
 &+ \frac{1}{2} \{ [SPU(1) - SPD(1)] - [SPU(1) - SPD(1)] \} \\
 &+ \frac{1}{2} \{ [SCU(1) - SCD(1)] - [SCU(1) - SCD(1)] \} \\
 &+ \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(m) - Rx(m)] \} \\
 &+ [Refcal(1) - Refcal(m, 1)]
 \end{aligned}$$

The five lines of the equation above represent respectively:

- *time interval measurement*
- *propagation delay in the atmosphere*
- *Sagnac correction delay*
- *Stations delay difference*
- *Common reference point delay for station 1 and mobile station at 1*

Equalizing the equation to zero,

$$0 = \frac{1}{2} [TW(1) - TW(m, 1)] + \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(m) - Rx(m)] \} + [Refcal(1) - Refcal(m, 1)]$$

The above three lines represent respectively:

- *time interval measurement*
- *Stations delay difference*
- *Common reference point delay for station 1 and mobile station at 1*

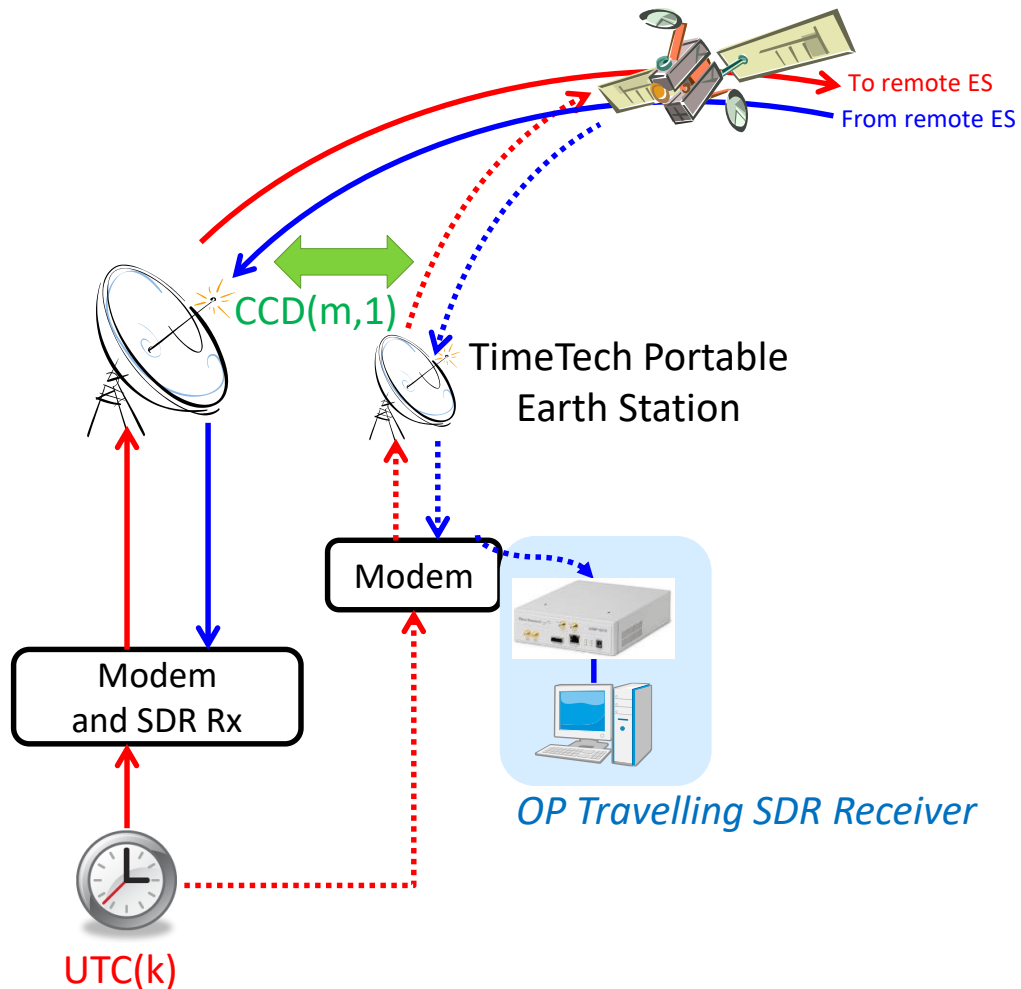


Figure 4.3 – Calibration process in a site-mode configuration involving a fixed station and a mobile station, both equipped with SATRE modems and SDR receivers

At Site 1:

$$\begin{aligned}
 CCD(m, 1) &= \frac{1}{2} [TW(m, 1) - TW(1)] && \rightarrow \text{time interval measurement} \\
 &+ [Refcal(m, 1) - Refcal(1)] && \rightarrow \text{Common reference point difference delay} \\
 &= \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(m) - Rx(m)] \} && \rightarrow \text{Stations delay difference}
 \end{aligned}$$

At Site 2:

$$\begin{aligned}
 CCD(m, 2) &= \frac{1}{2} [TW(m, 2) - TW(2)] && \rightarrow \text{time interval measurement} \\
 &+ [Refcal(m, 2) - Refcal(2)] && \rightarrow \text{Common reference point difference delay} \\
 &= \frac{1}{2} \{ [Tx(2) - Rx(2)] - [Tx(m) - Rx(m)] \} && \rightarrow \text{Stations delay difference}
 \end{aligned}$$

By combining the measurements of both sites:

$$\begin{aligned}
 CALR(1,2) &= [CCD(m, 1) - CCD(m, 2)] && \rightarrow \text{common clock difference measurement} \\
 &- \frac{1}{2} \{ [SCU(1) - SCD(1)] - [SCU(2) - SCD(2)] \} && \rightarrow \text{Sagnac correction delay} \\
 &= [CCD(m, 1) - CCD(m, 2)] \\
 &- [SCD(1) - SCD(2)] \\
 &= \left\{ \frac{1}{2} [TW(m, 1) - TW(1)] + [Refcal(m, 1) - Refcal(1)] - \frac{1}{2} [TW(m, 2) - \right. \\
 &TW(2)] - [Refcal(m, 2) - Refcal(2)] \left. \right\} \\
 &- [SCD(1) - SCD(2)] \\
 &= \left\{ \left(\frac{1}{2} [TW(m, 1) - TW(1)] - \frac{1}{2} [TW(m, 2) - TW(2)] \right) + [Refcal(m, 1) - \right. \\
 &Refcal(m, 2)] - [Refcal(1) - Refcal(2)] \left. \right\} \\
 &- [SCD(1) - SCD(2)]
 \end{aligned}$$

From the above equation, the differential delay, $Tx(m) - Rx(m)$, of the mobile station is cancelled (in theory).

4.1.4 TWSTFT equation for determining CALR in both link and two-link modes – introduction of the DLK parameter

In the case where the site mode cannot be performed on the two sites involved in the calibration process (case of a two-way station of the Galileo ground segment), an approach introduced in [6, 8] consists in using a combined method based on the application of the site mode for one station (Figure 4.3) and the link mode for the remote station (Figure 4.4). So, we introduce another parameter here called Difference Link (DLK). The aim is to consider the different possible configurations and to determine the calibration value as the optimum average value in order to better estimate the measurement uncertainties and ultimately contribute to the reduction of the final calibration uncertainty. During the calibration, we can measure time links with a remote station using mobile and fixed stations at local site. The DLK, known also as bridged CCD in [3], is the difference of the two links. Using DLK values, the calibration can be performed in both Link mode (CCD at local site, DLK at remote site) and Two-Link mode (DLK at both sites).

At Site 1 (mobile station equipped with modem and SDR receiver co-located at site 1):

$$\begin{aligned}
 CCD(m, 1) &= \frac{1}{2} [TW(m, 1) - TW(1, m)] && \rightarrow \text{time interval measurement} \\
 &+ [Refcal(m, 1) - Refcal(1)] && \rightarrow \text{Common reference point difference delay} \\
 &= \frac{1}{2} \{ [Tx(1) - Rx(1)] - [Tx(m) - Rx(m)] \} && \rightarrow \text{Stations delay difference}
 \end{aligned}$$

At Site 2 (mobile station equipped with modem and SDR receiver located at site 2):

$$\begin{aligned}
 DLK(m, 2, 1) &= \frac{1}{2} [TW(1, 2) - TW(2, 1)] && \rightarrow \text{time interval measurement} \\
 &- \frac{1}{2} [TW(1, m) - TW(m, 1)] && \rightarrow \text{time interval measurement} \\
 &+ [Refcal(m, 2) - Refcal(2)] && \rightarrow \text{Common reference point difference delay} \\
 &= \frac{1}{2} \{ [Tx(2) - Rx(2)] - [Tx(m) - Rx(m)] \} && \rightarrow \text{Stations delay difference}
 \end{aligned}$$

Where,

$TW(1,2)$ and $TW(2,1)$ are time intervals 1ppsTx(1)-1ppsTx(2) measured for the two-way link between station 1 (site 1) and station 2 (site 2) and,

$TW(1,m)$ and $TW(m,1)$ are time intervals 1ppsTx(1)-1ppsTx(m) measured for the two-way link between station 1 (site 1) and mobile station (site 2)

By combining the measurements of both sites:

$$\begin{aligned}
 CALR(1,2) &= [CCD(m, 1) - DLK(m, 2, 1)] \\
 &- [SCD(1) - SCD(2)]
 \end{aligned}$$

The two lines of the equation above represent respectively:

- *common clock difference measurement for both site and link modes*
- *Sagnac correction delay*

While $DLK(m,2,1) \neq -DLK(m,1,2)$ because both are individual measurements $\rightarrow CALR(1,2) = -CALR(2,1)$ for site mode and $CALR(1,2) \neq -CALR(2,1)$ for link mode. In link mode and $S = 1$, the averaged value is considered in CALR in order to be sure that $CALR(1,2) = -CALR(2,1)$.

Alternatively, we can determine the CALR value by combining two DLK measurements:

$$\begin{aligned}
 CALR(1,2) &= [DLK(m, 1,2) - DLK(m, 2, 1)] && \rightarrow \text{common clock difference measurement} \\
 &- [SCD(1) - SCD(2)] && \rightarrow \text{Sagnac correction delay}
 \end{aligned}$$

So, we define this equation relationship as TWO-LINK mode calibration.

Notes:

- Site mode *means* CCD at both sites
- Link mode *means* CCD at one site, DLK at other site
- Two-Link mode *means* DLK at both sites
- DLK (letter m , number 1, number 2) *means* station m at site 1, two-way link measurement 1 - 2

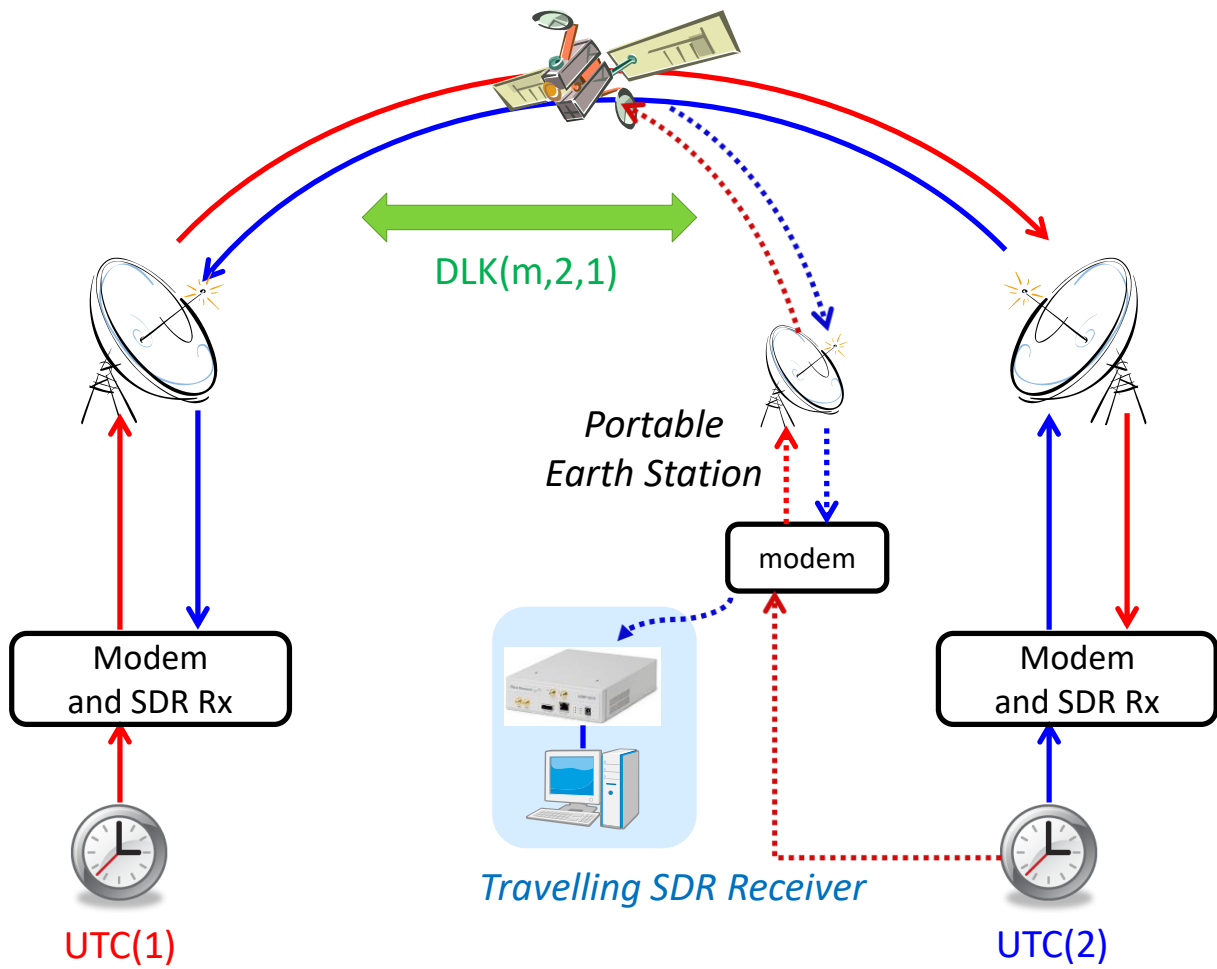


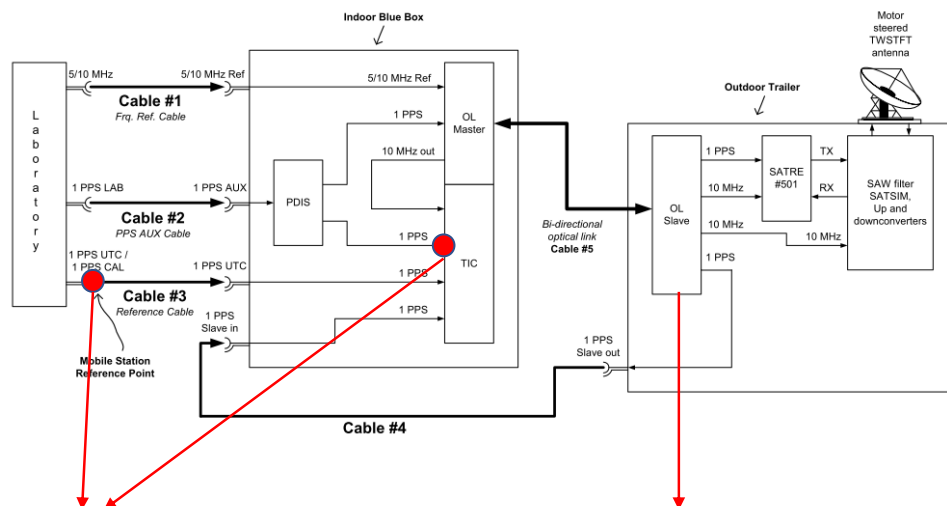
Figure 4.4 – Calibration process in a link-mode configuration involving a fixed station (at local site) and a mobile station (at remote site), both equipped with SATRE modems and SDR receivers

4.2 Common Reference Point

This section introduces the new concept of considering a common reference point for calibration purposes. The new concept was applied only on the OP side during this calibration. It may be applied in future calibration campaigns for all sites visited, wherever possible.

4.2.1 Common reference point and determination of reference calibration delay at PTB

PTB selected UTC(PTB) as the CRP. Thus Refcal of PTB05 is identical to REFDELAY (Figure 4.5). During the calibration campaign, the Refcal values used are 736.13 ns (value extracted from a twptb file) and 63.22 ns (measured value on site) for the fixed station PTB05 and the mobile station MOB02, respectively. The REFDELAY at PTB was determined by relating the input 1pps to the SATRE modem to UTC(PTB). This practice is not strictly compliant with the definitions in [1]. A measurement of the REFDELAY during the campaign obtained a value of 735.36 ns, which is considered here as option 2.



$UTC'(PTB) - 1pps\ AUX = ca. 63.2\ ns$
as measured by TIC of Indoor Blue Box

Here we connect the SDR box with a defined cable. All delays are fixed.

Figure 4.5 - Common Reference Point considered for calibration at PTB

4.2.2 Common reference point and determination of reference calibration delay at OP

Two approaches are considered for the reference point during the calibration process of the differential delays of TWSTFT stations (Figure 4.6):

- Option 1 [CRP at 1pps-UTC(OP)] is regularly used which consists of defining the reference point as the UTC (k) point or more precisely, the point for which the refdelay parameter as defined in [1] is determined and used.

In this case: $refcal(OP01) = refdelay(OP01)$ and $refcal(MOB02 \text{ at } OP)$ is measured w.r.t. 1pps UTC(OP) reference point.

This approach is valid if this parameter is measured during calibration [3]. The advantage of this method is to minimize the error related to a possible offset from the value applied in the TWSTFT equation, however an additional measure is generally a source of additional error to be taken into account. Contrary to what is indicated here, and to be consistent with the calibration of SATRE TWSTFT links realized by ROA [6], we have adopted as option 1 the value of $refdelay$, measured by a local TIC type SR620, as reported in the twop files.

- Option 2 [CRP at OP01 1ppsTx] is proposed here when the 1ppsTx point is explicitly defined. The advantage of this approach is twofold: a single Time Interval Counter is used for all TWSTFT stations to be calibrated, namely that of the mobile station (reduction of measurement errors due to reduction of equipment used), to avoid taking into account the $refdelay$ parameter (even in differential mode) which fully respects the definitions in [1]. In this case, the CALR parameter unambiguously represents the delay specific to a given two-way link.

In this case: $refcal(OP01) = 0 \text{ ns}$ and $refcal(MOB02 \text{ at } OP)$ is measured w.r.t. OP01 1ppsTx reference point.

Figure 4.6 summarizes the two options described.

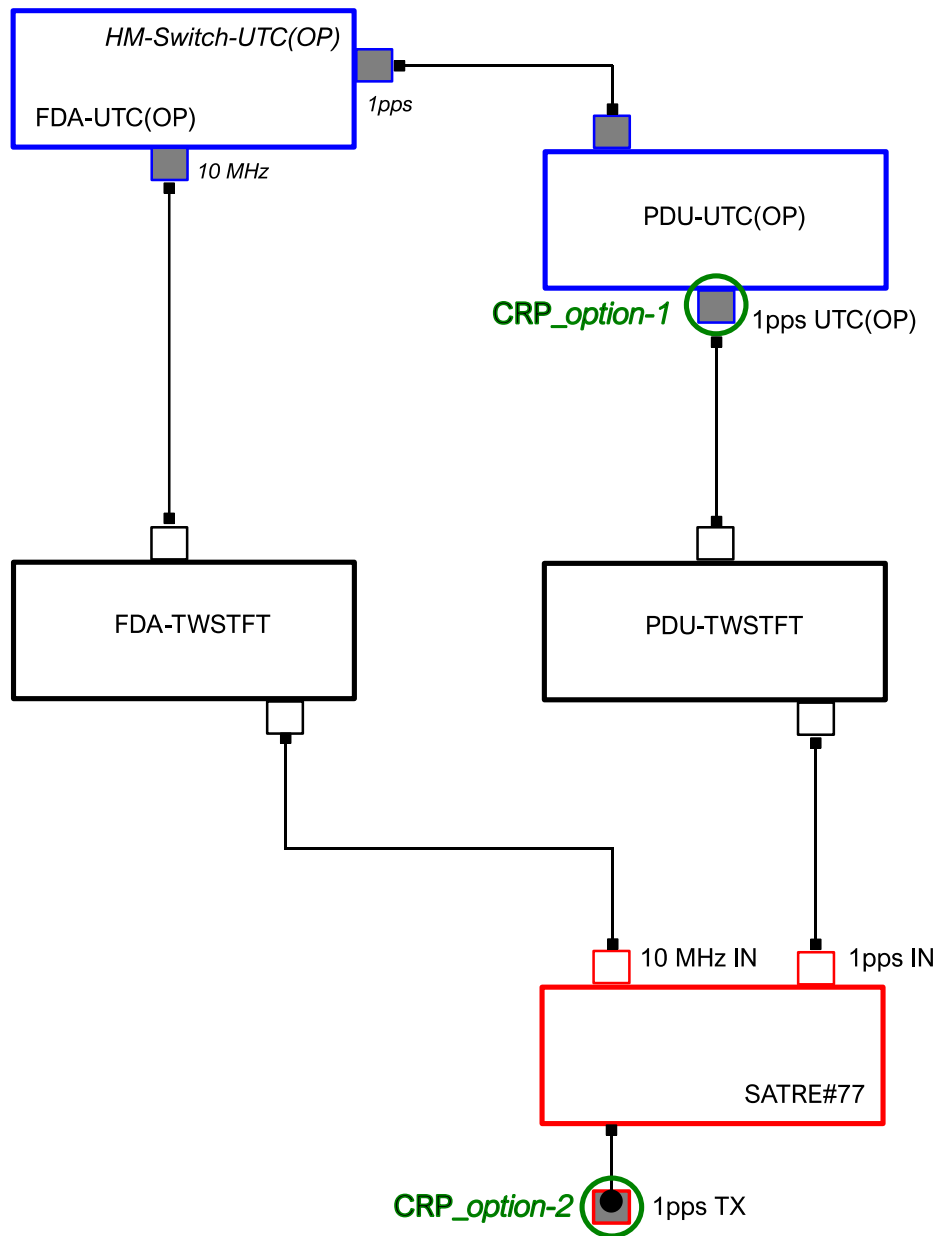
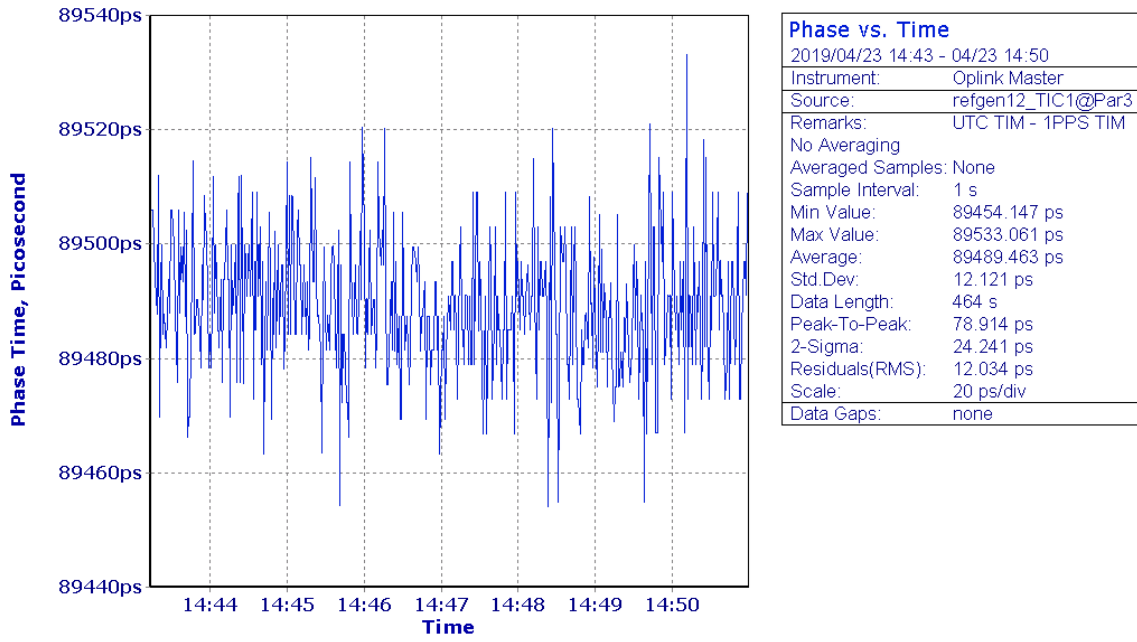


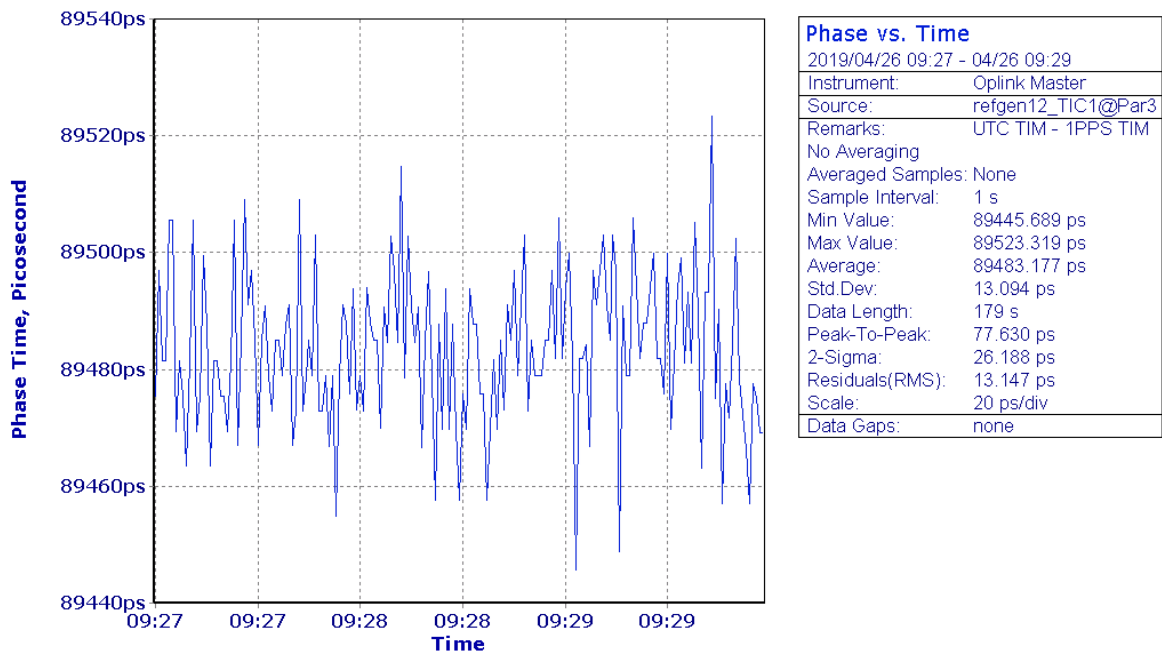
Figure 4.6 - Common Reference Point options considered for calibration at OP

4.2.3 Correction values used in calibration calculations

The Refcal value is determined according to the two approaches selected in OP (Figures 4.7 and 4.8). The discrepancy is 0.13 ns, larger than the statistical uncertainty 0.03 ns. It is caused by using two different types of time interval counter in Option 1. Nevertheless, whichever option is used, the uncertainty on the measurement of the refdelay must be estimated and entered in the RSIG column according to [1]. This uncertainty contributes to that of CALR to the overall uncertainty of the two-way link, and therefore of the time-scales difference.

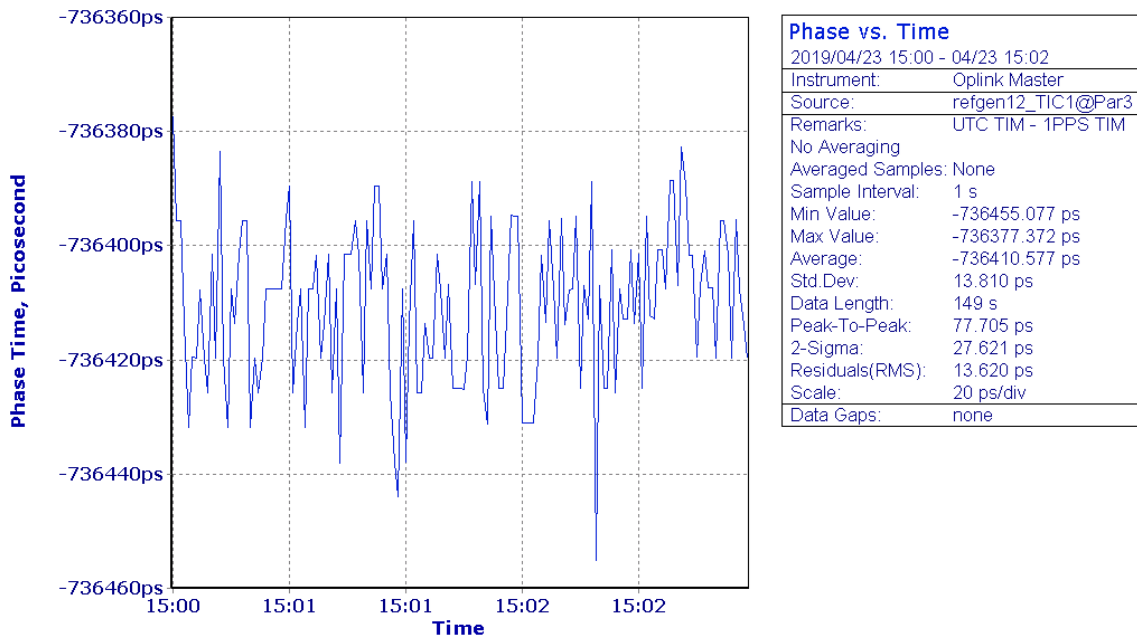


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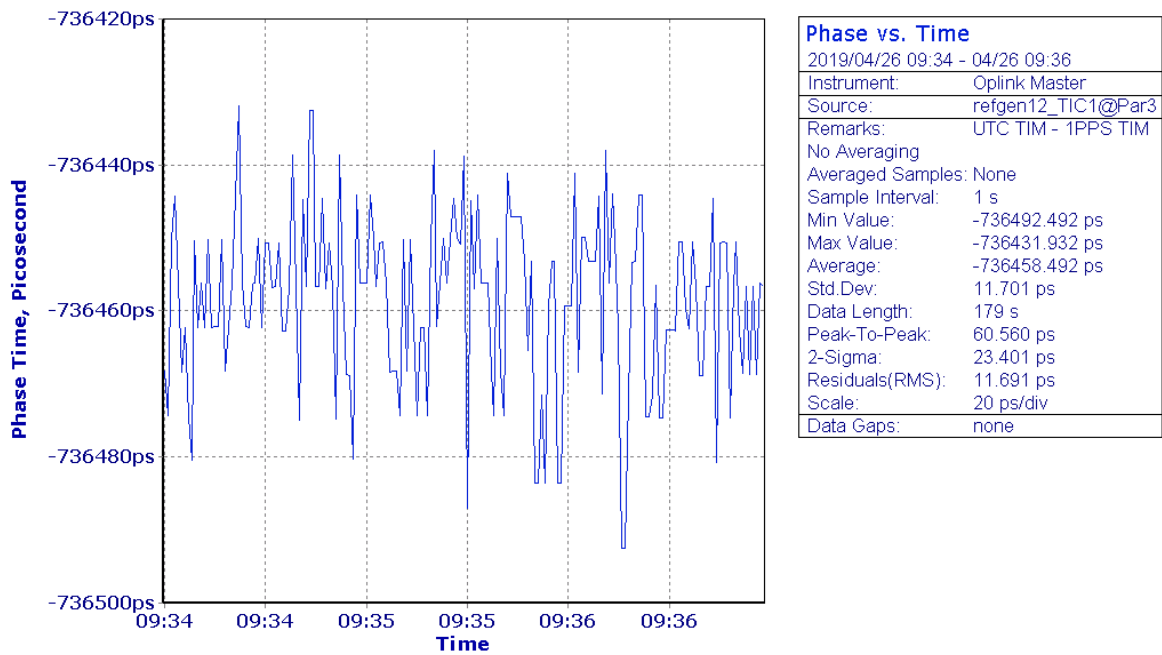


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Figure 4.7 - Measurement of the Refcal parameter of the portable earth station relative to UTC(OP) at the beginning and at the end of the measurement campaign in OP



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Figure 4.8 - Measurement of the Refcal parameter of the portable earth station relative to 1ppsTx (OP01) at the beginning and at the end of the measurement campaign in OP

Table 4.1 – Correction values used in the calculations

Location	OP (opt. 1)	Std. Dev. (ns)	OP (opt. 2)	Std. Dev. (ns)	PTB (opt. 1)	Std. Dev. (ns)	PTB (opt. 2)	Std. Dev. (ns)
Refcal(m,k) (ns)	89,48	0,04	-736,43	0,02	63,22	0,04	63,22	0,04
Refcal(k) (ns)	826,04	0,04	0,00	-	736,13	0,04	735,36	0,04
Refcal(m,k) - Refcal(k) (ns)	-736,56	0,05	-736,43	0,02	-672,91	0,05	-672,14	0,05
SCD(Loc) Sagnac correction (ns)	92,18	-	92,18	-	99,32	-	99,32	-

In this report, the calibration result (CALR) was calculated by considering as CRP for OP, the 1 ppsTx (option 2 column in Table 4.1) and for PTB, UTC (PTB) [option 1 column in table 4.1).

4.3 ESDVAR values consideration

The ESDVAR values are set to zero during the calibration for both fixed stations. Once the calibration result is approved and shall be implemented, all changes of station delay from the date of calibration to the date of implementation will be taken into account in the ESDVAR parameter.

4.4 Least-squares fitting for the link-based TWSTFT calibration method

A least-squares fitting is needed if the two TWSTFT links with the fixed station and with the mobile station are not measured at the same time [3, 6]. This is the case in the regular TWSTFT calibration because the SATRE modems have only one reception channel in operation, so the measurements must be time-sharing. The method uses first-order polynomials to model the time links and assumes them at the same frequency. If either clock is unstable, the links will have a large residual and the calibration uncertainty will be increased.

The SDR TWSTFT technique does not require the fitting because the two TWSTFT links can be measured simultaneously due to multiple channels in the SDR receiver. So, the calibration uncertainty is independent of clock stability.

5. Operation of the Portable earth station and the SDR travelling receiver

5.1 Signal scheme of the Portable earth station

Please refer to the detailed description in reference [6].

5.2 OPLINK principle of operation

Please refer to the detailed description in reference [6].

5.3 Configuration of the SDR travelling receiver

The SDR travelling receiver is made by an Analog-to-Digital Sampler, a GPU-enabled computer and some intermediate-frequency (IF) components, protected by a rigid box and equipped with a trailer. Four signals are needed to operate the SDR receiver. Two of them are shared from the IF input and output of SATRE modem in the mobile station. Their cabling must be kept the same during the campaign. The other two signals are 1 PPS and 10 MHz external frequency. They can be connected to arbitrary points that comes from the UTC(k) source. The time stamps of measurement values are given manually. One should observe the offset from the UTC to the time stamp of the running software, and configure this value in order to generate the correct ITU files. Please refer to the detailed description in Annex-1 or in [5].

5.4 TWSTFT measurement schedule during the campaign

The schedule is made for regular TWSTFT. For SDR TWSTFT, the station names change: OP51 replaces OP01 and OP11, PTB55 replaces PTB05 and PTB15, and MOB52 replaces MOB02 and MOB12. If the signals of OP51, PTB55 and MOB52 are in the air, they will be measured simultaneously and the ITU files will contain as many sessions as possible. To calibrate and compare with regular TWSTFT, the nominal tracking length of the SDR TWSTFT is set to be 2 min, instead of the 5 min tracking length used by the regular SDR TWSTFT.

Table 5.2 - TWSTFT schedule implemented during the campaign, odd UTC hours sessions

TWSTFT Schedule		Europe <-> Europe		+ Europe <-> USA												Starting at hh: UTC:		01h													
First	Last	Action	Length	OP11 TX	SP11 RX	PTB15 TX	IT12 RX	ROA11 TX	TIM11 RX	ROA12 TX	MOB12 TX	IT11 TX	Lab	OP11 RX	SP11 TX	PTB15 RX	IT12 TX	ROA11 RX	TIM11 TX	ROA12 RX	MOB12 RX	IT11 RX	file Char								
hhmmss	hhmmss		s	a	d	e	i	k	t	w	v	j		-20	-40	40	-60	-100	-30	100	-70		offset kHz								
UTC	UTC			0	3	4	6	7	14	18	31	17		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	TX code								
01:00:00	01:00:59	Prep.time	60																												
01:01:00	01:02:59	CC	120																												
01:03:00	01:03:59	Prep.time	60	0	0	3	17	4	31	6	18	7	3	7	14	14	7	18	6	31	4	17	3								
01:04:00	01:05:59	Ranging	120	0	0	3	17	4	31	6	18	7	3	7	14	14	7	18	6	31	4	17	3								
01:06:00	01:06:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	7	18	14	14	18	7	31	6	17	4								
01:07:00	01:08:59	Measure	120	0	3	3	0	4	17	6	31	7	18	7	18	14	14	18	7	31	6	17	4								
01:09:00	01:09:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	7	31	14	17	18	14	31	7	17	6								
01:10:00	01:11:59	Measure	120	0	4	3	3	4	0	6	17	7	31	7	31	14	17	18	14	31	7	17	6								
01:12:00	01:12:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	7	17	14	31	18	18	31	14	17	7								
01:13:00	01:14:59	Measure	120	0	6	3	4	4	3	6	0	7	17	7	17	14	31	18	18	31	14	17	7								
01:15:00	01:15:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	7	0	14	17	18	31	31	18	17	14								
01:16:00	01:17:59	Measure	120	0	7	3	6	4	4	6	3	7	0	7	0	14	17	18	31	31	18	17	14								
01:18:00	01:18:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	7	3	14	0	18	17	31	31	17	18								
01:19:00	01:20:59	Measure	120	0	14	3	7	4	6	6	4	7	3	7	3	14	0	18	17	31	31	17	18								
01:21:00	01:21:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	7	4	14	3	18	0	31	17	17	31								
01:22:00	01:23:59	Measure	120	0	18	3	14	4	7	6	6	7	4	7	4	14	3	18	0	31	17	17	31								
01:24:00	01:24:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	7	6	14	4	18	3	31	0	17	17								
01:25:00	01:26:59	Measure	120	0	31	3	18	4	14	6	7	7	6	7	6	14	4	18	3	31	0	17	17								
01:27:00	01:27:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	7	7	14	6	18	4	31	3	17	0								
01:28:00	01:29:59	Measure	120	0	17	3	31	4	18	6	14	7	7	7	7	14	6	18	4	31	3	17	0								
		UD link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR								
01:30:00	01:30:59	Prep.time	60																												
01:31:00	01:32:59	CC	120																												
01:33:00	01:33:59	Prep.time	60	0	0	3	17	4	31	6	18	7	3	7	14	14	7	18	6	31	4	17	3								
01:34:00	01:35:59	Measure	120	0	0	3	17	4	31	6	18	7	3	7	14	14	7	18	6	31	4	17	3								
01:36:00	01:36:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	7	18	14	14	18	7	31	6	17	4								
01:37:00	01:38:59	Measure	120	0	3	3	0	4	17	6	31	7	18	7	18	14	14	18	7	31	6	17	4								
01:39:00	01:39:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	7	31	14	18	18	14	31	7	17	6								
01:40:00	01:41:59	Measure	120	0	4	3	3	4	0	6	17	7	31	7	31	14	18	18	14	31	7	17	6								
01:42:00	01:42:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	7	17	14	31	18	18	31	14	17	7								
01:43:00	01:44:59	Measure	120	0	6	3	4	4	3	6	0	7	17	7	17	14	31	18	18	31	14	17	7								
01:45:00	01:45:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	7	0	14	17	18	31	31	18	17	14								
01:46:00	01:47:59	Measure	120	0	7	3	6	4	4	6	3	7	0	7	0	14	17	18	31	31	18	17	14								
01:48:00	01:48:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	7	3	14	0	18	17	31	31	17	18								
01:49:00	01:50:59	Measure	120	0	14	3	7	4	6	6	4	7	3	7	3	14	0	18	17	31	31	17	18								
01:51:00	01:51:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	7	4	14	3	18	0	31	17	17	31								
01:52:00	01:53:59	Measure	120	0	18	3	14	4	7	6	6	7	4	7	4	14	3	18	0	31	17	17	31								
01:54:00	01:54:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	7	6	14	4	18	3	31	0	17	17								
01:55:00	01:55:59	Measure	120	0	31	3	18	4	14	6	7	7	6	7	6	14	4	18	3	31	0	17	17								
01:57:00	01:57:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	7	7	14	6	18	4	31	3	17	0								
01:58:00	01:59:59	CAL	120	0	17	3	31	4	18	6	14	7	7	7	7	14	6	18	4	31	3	17	0								
CC:	Clean Carrier			EUR:	EUR:	EUR:	EUR:	EUR:	EUR:	EUR:	EUR:	EUR:	EUR:	TRA:	TRA:	TRA:	TRA:	TRA:	TRA:	TRA:	TRA:	TRA:	TRA:								
CAL:	Calibration			USA:	USA:	USA:	USA:	USA:	USA:	USA:	USA:	USA:	USA:																		

6. Data acquisition and processing

6.1 TWSTFT data collection

6.1.1 Portable earth station and SDR travelling receiver at PTB

Figures 6.1 and 6.2 show a photograph of the TimeTech Trailer with the Portable earth station during the operation at PTB. Also the installation of the OP SDR travelling receiver (type N210) at PTB is shown.



Figure 6.1 - TimeTech portable earth station and OP SDR travelling receiver installed at PTB in March 2019 during the calibration campaign

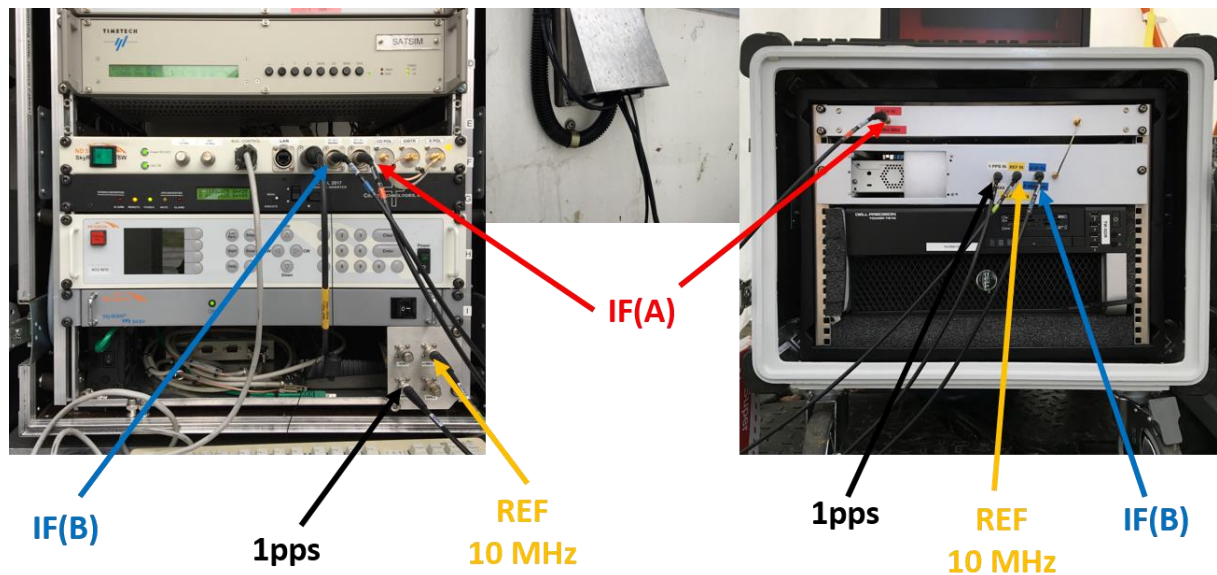


Figure 6.2 - Cabling of the SDR travelling receiver with the Portable earth station at PTB (March 2019)

The following results were obtained:

Table 6.1 - Result of CCD and DLK measurements for MOB52 at PTB

	Number of meas. points	CCD or DLK (ns)	σ (ns)
Site Mode Calibration Method (CCD)			
(MOB52, PTB) - PTB	1 088	-1 719,739	0,203
Link Mode Calibration Method (DLK)			
(MOB52, PTB) - PTB thru OP	1 020	-1 719,826	0,215
Two-Link Mode Calibration Method (DLK)			
(MOB52, PTB) - PTB thru OP	1 020	-1 719,826	0,215

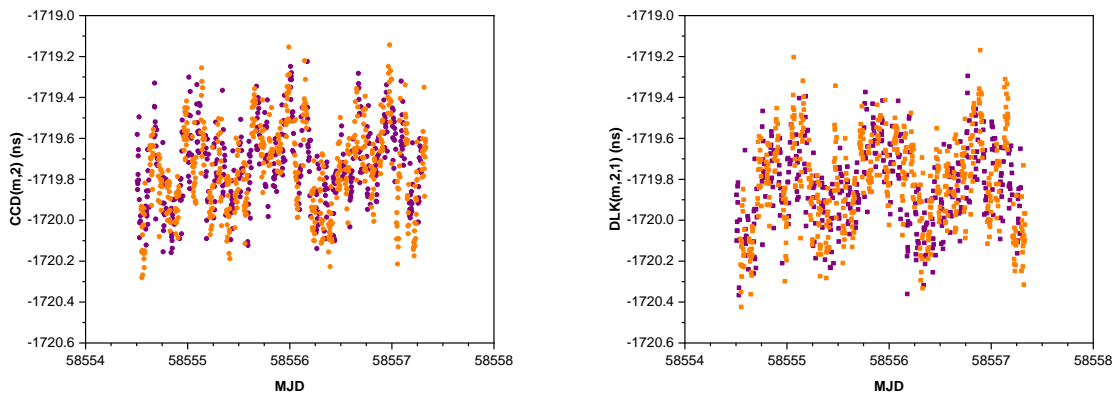


Figure 6.3 - CCD and DLK measurements for MOB52 at PTB. *Purple* and *orange* measurement points are plotted and correspond to measurements made at even and odd UTC hours, respectively

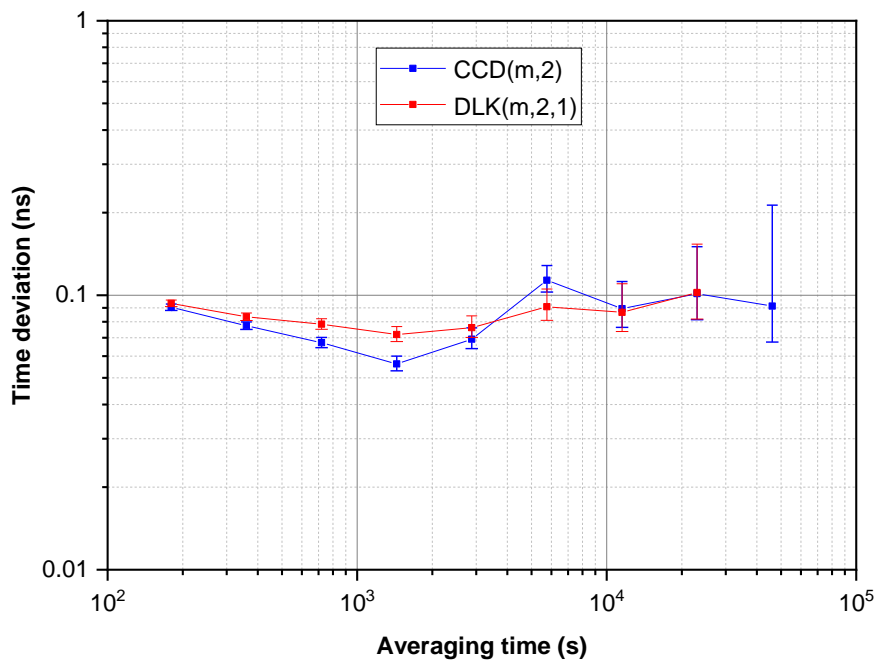


Figure 6.4 - Time deviation of the CCD and DLK measurements at PTB

6.1.2 Portable earth station and SDR travelling receiver at LNE-SYRTE

Figure 6.5 shows a photograph of the TimeTech Trailer and Portable earth station while were installed at OP. On the right picture is mounted the OP51 SDR receiver (type X310) of the OP fixed station.

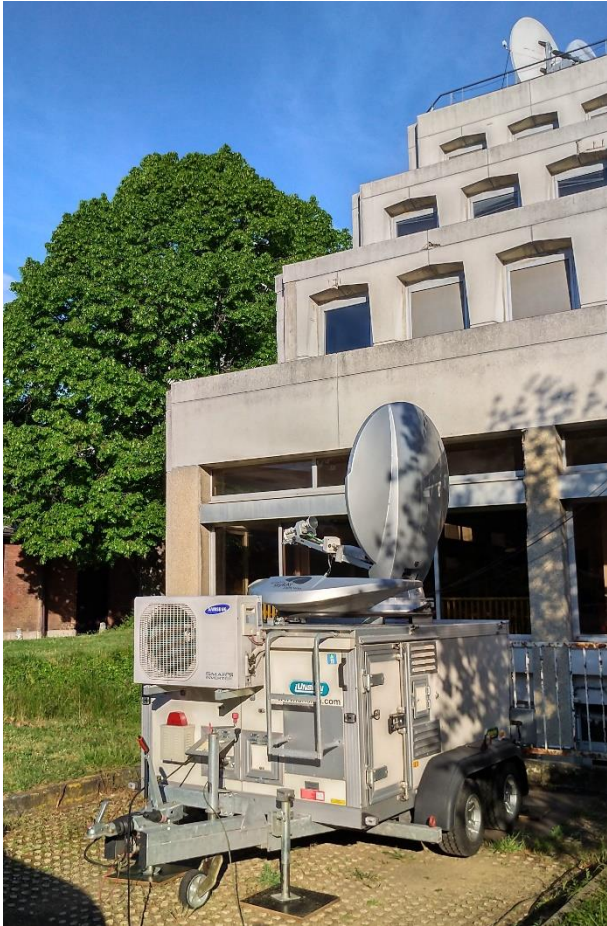


Figure 6.5 - TimeTech portable earth station installed at OP in April 2019 during the calibration campaign. The OP SDR fixed operational receiver is also shown on the right

The following results were obtained:

Table 6.2 - Result of CCD and DLK measurements for MOB52 at OP

	Number of meas. points	CCD or DLK (ns)	σ (ns)
Site Mode Calibration Method (CCD)			
(MOB52, OP) - OP	1 096	-3 761,651	0,220
Link Mode Calibration Method (DLK)			
(MOB52, OP) - OP thru PTB	1 028	-3 761,545	0,206
Two-Link Mode Calibration Method (DLK)			
(MOB52, OP) - OP thru PTB	1 028	-3 761,545	0,206

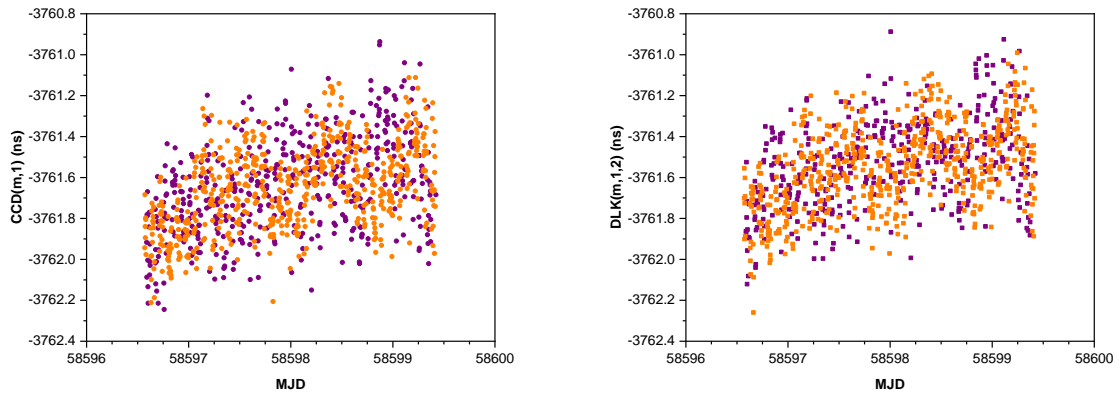


Figure 6.6 - CCD and DLK measurements for MOB52 at OP. Purple and orange measurement points are plotted and correspond to measurements made at even and odd UTC hours, respectively

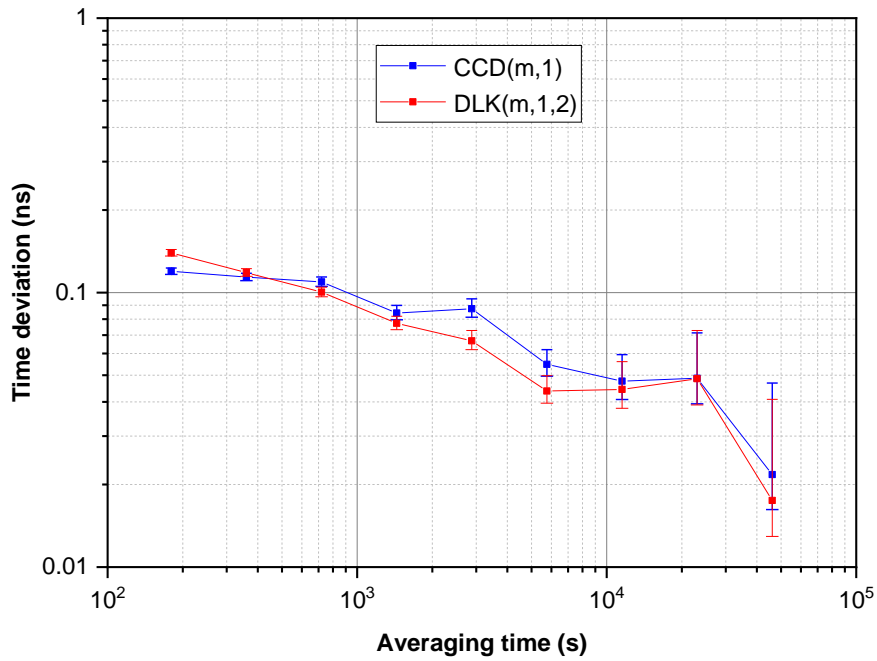


Figure 6.7 - Time deviation of the CCD and DLK measurements at OP

6.2 TWSTFT link calibration values

6.2.1 Determination of the calibration value

In considering the different possible configurations related to the TWSTFT link calibration method using a portable earth station equipped with SATRE modem and SDR receiver, we determined for each configuration the calibration value of the SDR link. Table 6.3 shows the different calibration values obtained and gives the average calibration value considered with its related standard deviation.

Table 6.3 - Calculation of CALR values w.r.t. Table 4.1

Station 1	Station 2	Calibration Method	CALR (1,2) (ns)
OP51	PTB55	Site Mode	-2 034,768
OP51	PTB55	Link Mode $DLK(m,2,1)$, CCD at Station 1	-2 034,681
OP51	PTB55	Link Mode $DLK(m,1,2)$, CCD at Station 2	-2 034,662
OP51	PTB55	Two-Link Mode	-2 034,575
OP51	PTB55	Average	-2 034,672
OP51	PTB55	Standard deviation	0,079

6.2.2 Calibration uncertainty budget

The uncertainty budget is evaluated in the same way as in [3, 6]. We consider the variation of SDR receivers and the closure of the SDR travelling equipment to be additional items. We will discuss the impact of using the Refcal parameter instead of the Refdelay parameter.

6.2.2.1 Statistical uncertainty

Measurement uncertainty is evaluated by using TDEV value of the CCD and DLK measurements shown in Sec. 6.1.1 and Sec. 6.1.2. The detailed calculations are given in Table 6.4.

Table 6.4 – CCD and DLK values and their statistics where m: MOB51, 1: OP51 and 2: PTB55. The TDEV value is considered the maximum value over the averaging time longer than 10^4 s

	Value (ns)	Std. deviation (ns)	Time deviation (ns)
CCD(m,1)	-3 761,651	0,220	0,050
CCD(m,2)	-1 719,739	0,203	0,100
DLK(m,1,2)	-3 761,545	0,206	0,050
DLK(m,2,1)	-1 719,826	0,215	0,100
SCD(1)	92,180	-	-
SCD(2)	99,320	-	-
CALR(1,2), site mode	-2 034,768	0,299	0,118
CALR(1,2), two-link mode	-2 034,575	0,298	0,118
CALR(1,2), link mode, CCD at Station 1	-2 034,681	0,308	0,118
CALR(1,2), link mode, CCD at Station 2	-2 034,662	0,289	0,118
CALR(1,2) in average, links mode, μA	-2 034,672	0,211	0,08

6.2.2.2 Contribution of the SDR-based TWSTFT Portable earth station

To calculate the CALR parameter, we assume that the equipment delay is unchanged during calibration. Any variation in this delay must be considered as a source of error contributing to the uncertainty budget. To evaluate this variation, we connect MOB52 to the monitor port of the OP51 and we perform, in parallel, measurements of two-way time intervals of a specific signal. Thus the value measured by MOB52 is then subtracted from that obtained by OP51. As shown in Table 6.5, the resulting value varies by 0.04 ns on average after calibration. We therefore take as uncertainty value half of 0.04 ns, i.e. 0.02 ns because in the TWSTFT equation, the delay of the receiver contributes half, to the CALR (Table 6.6).

Table 6.5 - "Common view" results between MOB52 and OP51 for some selected signals

Signal to be measured code (source station)	MJD 58592 – 58596 (19 – 23 April 2019)	MJD 58613 – 58617 (10 – 14 May 2019)	TW(2) – TW(1) (ns)
	TW(1) (ns)	TW(2) (ns)	
PN #0 (OP01)	6 182,16	6 182,08	-0,08
PN #1 (NPL02)	6 182,04	6 182,00	-0,04
PN #2 (VSL01)	6 181,75	6 181,71	-0,04
PN #3 (SP01)	6 181,74	6 181,75	0,01
PN #4 (PTB05)	6 181,64	6 181,60	-0,04
PN #6 (IT02)	6 182,56	6 182,52	-0,04
PN #7 (ROA01)	6 182,65	6 182,60	-0,05
PN #9 (CH01)	6 181,80	6 181,75	-0,05
PN #14 (TIM01)	6 182,30	6 182,27	-0,03
PN #17 (IT01)	6 181,31	6 181,26	-0,05
PN #18 (ROA02)	6 181,01	6 180,99	-0,02
Average	-	-	-0,04

In the same way, we take as uncertainty value half of 0.35 ns [6] for closure measurement of MOB02; i.e. 0.175 ns as a conservative value. The other contributions to the uncertainty (temperature variation impact and equipment resolution of portable ES) are kept identical (as conservative values) to those evaluated for the portable earth station [6]. All of the contributions to this uncertainty component are summarized in Table 6.6.

Table 6.6 - Contribution of the SDR-based TWSTFT portable earth station

	Temperature variation impact (ns)	Resolution (ns)	MOB02 Closure (ns)	MOB52 Closure (ns)	uB_1 (ns)
Portable earth station, uB_1	0,193	0,035	0,175	0,020	0,26

6.2.2.3 Contribution of the UTC(k) SDR TWSTFT station

The contribution to the uncertainty budget in terms of temperature variation and equipment resolution in the laboratory earth station [6] is estimated as shown in Table 6.7.

Table 6.7 - Contribution of the laboratory earth station in terms of temperature and resolution

	Temperature variation impact (ns)	Resolution (ns)	Δ LAB (ns)
Lab. earth station, uB_2	0,085	0,020	0,09

6.2.2.4 Contribution of the differential delays measurement

The approach applied is similar to that considered in [6], except that the CRP defined at OP is the 1ppsTx so that the contribution $\cdot \sigma_{\text{refcal}}(\text{OP})$ becomes negligible or not applicable. Therefore, the contribution to the uncertainty budget of the local equipment delays measurement, by considering Differential Delays Measurement (DDM), is given in Table 6.8.

Table 6.8 - Contribution of the local equipment delays measurement

	σ_{refcal} at OP (ns)	σ_{refcal} at PTB (ns)	FDA/PDU instability (ns)	TIC Resolution (ns)	TIC systematic error (ns)	DDM uncertainty (ns)
uB_3	-	0,050	0,200	-	0,130	0,24

6.2.2.5 Contribution of the satellite link and environment

The approach applied is similar to that considered in [6]. We observed that the diurnal patterns in CCD(m,2) and DLK(m,2,1) measurements have a maximum amplitude of about 0.5 ns, and thus we give a value 0.1 ns for the term "additional diurnal". However, Table 6.9 distinguishes between data collected in even and odd UTC hours, and the average is calculated separately for each data set.

Table 6.9 – Difference between results in even and odd UTC hours

	Even UTC hours		Odd UTC hours		Even - Odd
	Average (ns)	Nb. of meas. points	Average (ns)	Nb. of meas. points	Difference (ns)
CCD(m,1)	-3 761,639	477	-3 761,653	619	0,014
CCD(m,2)	-1 719,734	476	-1 719,744	612	0,010
DLK(m,1,2)	-3 761,528	409	-3 761,550	619	0,022
DLK(m,2,1)	-1 719,837	408	-1 719,819	612	-0,018
CALR (1,2) for Site mode	2 034,765		2 034,769		-0,004
CALR (1,2) for Two-Link mode	2 034,551		2 034,591		-0,040
CALR (1,2) for Link mode, CCD at 1	2 034,662		2 034,694		-0,032
CALR (1,2) for Link mode, CCD at 2	2 034,654		2 034,666		-0,012

The contribution to the uncertainty was found for a value of 0.04 ns, estimated from the largest value of these differences. Table 6.10 provides the detailed contribution of the satellite link and environment.

Table 6.10 - Contribution of the satellite link and environment

	Source	Uncertainty (ns)
Satellite communication	Tx power, C/N ₀	0,150
Atmosphere	Ionosphere	0,030
	Troposphere	0,001
	Temperature variation on ground station	0,100
	Humidity change	0,010
Satellite motion	Additional Diurnal	0,100
	Residual Sagnac (A)	0,250
	Path delay difference (B)	0,002
Even and odd UTC hours measure	Possible interference between PRN codes	0,040
<i>uB₄</i>		0,33

6.2.2.6 Summary of the various contributions to the uncertainty budget

Table 6.11 summarizes the different contributions to the uncertainty budget and gives the combined standard uncertainty u and the expanded uncertainty U ($k = 2$), which are determined as follows:

$$u = \sqrt{uA^2 + uB_1^2 + uB_2^2 + uB_3^2 + uB_4^2}$$

and

$$U = 2 \cdot u$$

Table 6.11 - Summary of the various contributions to the uncertainty budget

UTC Link	uA (ns)	uB_1 (ns)	uB_2 (ns)	uB_3 (ns)	uB_4 (ns)	u (ns)	U (ns) $k = 2$
U_CALR (OP51, PTB55)	0,08	0,26	0,09	0,24	0,33	0,50	1,00

6.3 Discussion of results

In the 2016 calibration campaign [3], we noticed that the most significant contributions to the uncertainty were: "additional diurnal" (0.4 ns), time interval counter measurement (0.23 ns) and statistical uncertainty (0.25 ns). In order to reduce the calibration uncertainties, we performed a calibration using a travelling SDR receiver and introducing the "Refcal" measurement. As a result, uncertainty components related to "additional diurnal", TIC and statistics were significantly reduced to 0.10 ns, 0.16 ns and 0.08 ns, respectively. We also noticed that in the latest calibration campaign carried out in 2019 [6], the most significant contribution to uncertainty was the "Possible interferences

between PRN codes" estimated at 0.5 ns. This has been significantly reduced to 0.04 ns by using the travelling SDR receiver.

The ambient temperature of the travelling equipment was not well controlled when it was put in operation. This led to unstable results for CCD and DLK measurements. When the measurement was performed in PTB, the variation had an amplitude of about ± 0.5 ns. When the equipment was in OP, the results have a slope of about 0.1 ns per day. Stability can be further improved if the equipment, including cabling, is put inside the temperature-controlled space, e.g. the mobile station trailer.

The 2019 SDR TWSTFT link calibration result CALR for OP-PTB using a travelling SDR receiver is plotted in Figure 6.8. We used this SDR method to calibrate the SATRE TWSTFT link whose result is given in the same figure. As a comparison, we present other two-way calibration results obtained over the last three years on the same two-way link: the 2019 SATRE TWSTFT link calibration result performed by SATRE [6], and the calibration results obtained in 2016 and 2017 for the SATRE [3] and SDR links respectively. For the latter, it was an SDR link alignment technique using the calibrated SATRE link [4].

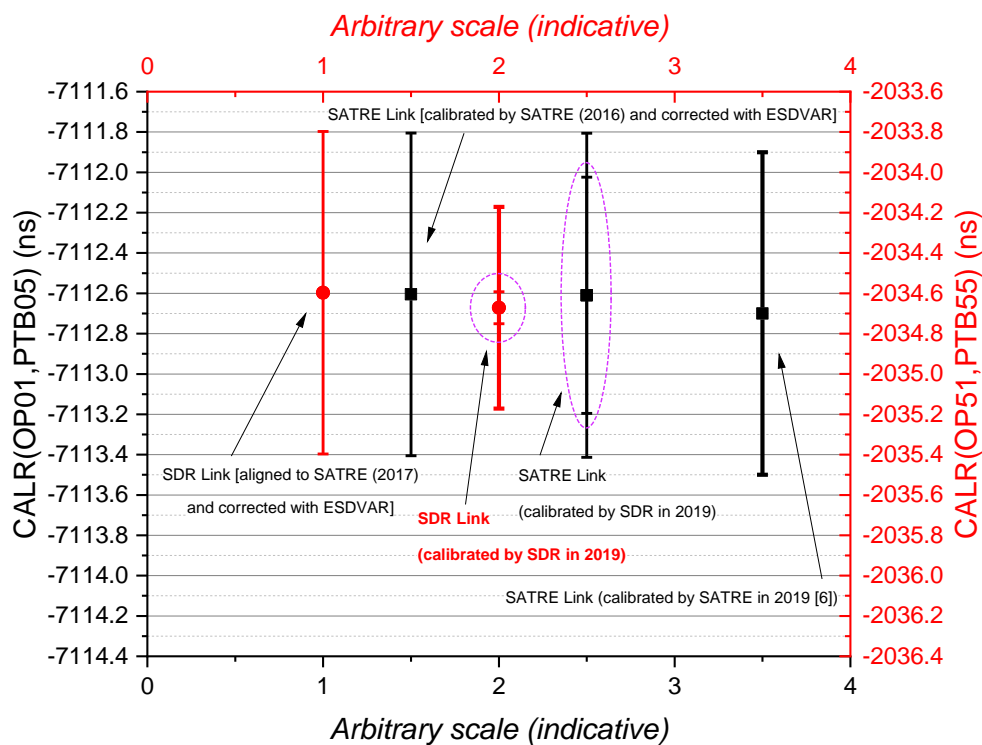


Figure 6.8 – SDR and SATRE TWSTFT OP-PTB links calibration results performed in 2019 using a travelling SDR receiver. Comparison with calibration (SATRE) and alignment (SDR) results achieved in 2016 [3], 2017 [4] and 2019 [6], and corrected with ESDVAR values; the respective error bars represent the combined uncertainties resulted from calibration or alignment. For 2019 values calibrated by SDR, two types of error bars are shown: large error bars represent the combined uncertainties while the reduced error bars represent the standard deviation on the mean of the calculated values by considering different calibration configurations (site mode, link modes and two-link mode)

To conclude, the calibration of the SDR TWSTFT OP-PTB link using a travelling SDR receiver provides relevant results for all possible configurations (site mode, link modes and two-link mode), leading to an average CALR value of -2 034.672 ns with a standard deviation of 79 ps and a combined standard uncertainty of 0.500 ns. The deviation from the value before calibration is 75 ps (Figure 6.8). With the very interesting results obtained, the time link OP-PTB by SDR can become the main link in the UTC computation by the BIPM, while the current time link by SATRE will thus become a backup link.

7. Application of CALR values in SDR TWSTFT ITU files

In order to be compliant with [7], the result of the current SDR TWSTFT calibration has to be introduced into the SDR TWSTFT report files as shown below. It is proposed that the ESDVAR be set to zero. The Calibration Identifier (CI) 517 was provided by BIPM.

On the OP side, following a change in a UTC(OP) distribution unit and a hardware change in the configuration of OP01, both produced on 7 October 2019 (MJD 58763), corrections were made in the SDR measurement files (from MJD 58767) to take these changes into account. As a result, the values of the Refdelay, Esdvar, and Esig parameters have been corrected. Since these corrections occur only after calibration, they should be taken into account again once the new calibration result has been applied.

PTB55

* CAL 517 TYPE: PORT ES REL MJD: 58617 EST. UNCERT.: 0.500 ns

	CI	S	CALR
PTB55 OP51	517	1	2034.672

OP51

* CAL 517 TYPE: PORT ES REL MJD: 58617 EST. UNCERT.: 0.500 ns

	CI	S	CALR	ESDVAR	ESIG
OP51 PTB55	517	1	-2034.672	18.166	0.156

Note: all parameters of the OP-PTB link by SDR must be filled in after the calibration has been applied. This mainly concerns the following columns: CI, S, calr, esdvar and esig. For those where there are no particular values, replace 9 ... 9 with 0 ... 0.

8. Recommendations for Improvement

The calibration exercise thus carried out for the first time with a calibration kit based on a travelling SDR receiver accompanying a TWSTFT portable earth station equipped with a SATRE modem allowed to put into practice and also to identify some tracks of improvement:

- a) To follow exactly the definitions of the recommendation ITU-R TF.1153-4 (2015) in its Annex 1, section 8.1 for $S = 1$;
- b) To consider, where possible, $1ppsTx$ as best CRP for calibration purposes. When this is not possible for some reason, systematically measure the *RefCal* or *RefDelay* parameter during a calibration campaign;
- c) A major advantage of considering the $1ppsTx$ as the CRP is to limit the use of time interval counters to the single counter of the mobile station. The associated uncertainty component is thus reduced;
- d) Another major advantage of systematically measuring the *RefCal* or *RefDelay* parameter during a calibration process is to ensure that a CRP has been applied both to the fixed station as the DUT and to the mobile station connected in common clock mode. Thus a bias can be clearly discarded;
- e) Finally, placing the SDR travelling kit in a place regulated in temperature and humidity is strongly recommended, at each visited site.

Acknowledgment

The authors thank Wolfgang Schäfer and Thorsten Feldmann (TimeTech GmbH) for their collaboration providing gracefully access to the portable earth station on the two visited sites in Braunschweig and Paris. We further thank Héctor Esteban (ROA) for the organization of the TWSTFT calibration campaign among several European institutes and Galileo timing facilities. We also thank Andreas Bauch (PTB) for the interesting discussions on the subject and for having provided a critical and constructive look at the drafting of this report.

ANNEX-1: Calibration Manual using LNE-SYRTE SDR TWSTFT Travelling Equipment

Annex 1 is provided in a separate document.

End of Document

Calibration Manual using LNE-SYRTE SDR TWSTFT Travelling Equipment

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Acronyms

Acronym	Definition
BIPM	Bureau International des Poids et Mesures
BPSK	Binary Phase Shift Keying
CCD	Common-Clock Difference
CCTF	Consultative Committee for Time and Frequency
C/N ₀	Carrier-to-Noise-density ratio
CRP	Common Reference Point
DLK	Difference between two time LinKs
IF	Intermediate Frequency
ITU	International Telecommunication Union
LNE-SYRTE	Laboratoire National de métrologie et d'Essais - SYstème de Références Temps-Espace
MJD	Modified Julian Date
MOB	MOBile station, manufactured by TimeTech GmbH
NMI	National Metrology Institute
OP	LNE-SYRTE, Observatoire de Paris, Paris, France
PRN	PseudoRandom Noise
PPS	Pulse Per Second
PS	Portable Station
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
SNR	Signal-to-Noise Ratio
SDR	Software-Defined Radio
SATRE	SATellite Tracking and Ranging Equipment, manufactured by TimeTech GmbH
TOA	Time Of Arrival
TL	Telecommunication Laboratories, Chunghwa Telecom Co., Ltd., Taoyuan, Taiwan
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UTC	Coordinated Universal Time
UTC(k)	UTC realization of the laboratory k
WG	Working Group

I. Getting Started

This SDR TWSTFT travelling equipment is intended to work with a TWSTFT portable station. It collects signal's TOA at the same time as the modem in the portable station. This data can be used to generate ITU-format time transfer files and then to calibrate the SDR TWSTFT links.

Section II describes the hardware of the travelling equipment. Before the calibration campaign, every visited laboratory should follow Section III to configure the fixed SDR receiver. At the same time, the coordinator should follow Section IV to configure the travelling equipment. Upon the portable station and the travelling equipment arrive, you can follow the steps in Section V to make cabling and collect data. Section VI provides a method to obtain calibration results.

In the TWSTFT calibration campaign in 2019, a mobile station equipped with a SATRE modem is used as the portable station.

II. LNE-SYRTE SDR travelling equipment

Table 1 lists the components which are included in the travelling equipment. All items described in the table are for scientific use and have no commercial value.



Figure 1 The LNE-SYRTE SDR travelling equipment

Table 1 Components of the SDR travelling equipment

Item	Description	Identification
1. Box	Size: 71 cm (L) x 64 cm (W) x 64 cm (H) Weight: 41 kg Socket type: E 4 wheels with brakes	MOB52
1.1. A/D Sampler	NI USRP N210	-
1.2. computer	DELL Precision 7920 Coin cell battery CR2032, 3.0 V	-
1.3. microwave box	Amplifiers	-
1.4. cable	RG58, BNC(M)-BNC(M), 15 m	IF(A)
1.5. cable	RG58, BNC(M)-BNC(M), 15 m	IF(B)
1.6. cable	RG58, BNC(M)-BNC(M), 15 m	REF
1.7. cable	RG58, BNC(M)-BNC(M), 15 m	PPS

Pay attention to as described below when you use the travelling equipment.

1. Do not put the equipment in the area exposed to temperature extremes, excessively humid air, strong magnet and electromagnet, strong vibration or where it might experience heavy impact
2. Operate the equipment in an environment with temperature between 0 °C and 40 °C and relative humidity less than 95 %
3. Only authorized persons can touch the equipment

III. Preparation in the visited laboratory

Before the campaign, the visited laboratory should follow the steps below to provide necessary information to the coordinator and to prepare the calibration.

1. The SATRE modems transmit PRN-coded and BPSK-modulated signals in the Ku band. The code rate is 1.0 Mcps. Make sure the information in **Table 2** is correct.
2. Update the transmission plan in Annex I
3. According to the plan, put the IF value and range of the mobile station's signal into **Table 3**. Then, configure your fixed SDR receiver for it to receive the signal.
4. Make a diagram like **Figure 2** to show the hardware connection of your fixed station
5. Prepare a VGA or DVI monitor, a USB or PS/2 keyboard and a mouse

Table 2 Earth station parameters

Laboratory	Earth Station ID	PRN ID	Uplink Frequency apart from 14 260.15 MHz (kHz)	Location: latitude, longitude and height in WGS84
LNE-SYRTE	OP51	0	-8.944	N 48:50:09.236 E 002:20:05.873 78.00 m
PTB	PTB55	4	+17.889	N 52:17:49.787 E 010:27:37.966 143.41 m
-	MOB52	31	-31.305	mobile station

Table 3 Received signal information

Received by	Transmitted by	SDR channel	PRN ID	IF value \pm dynamic range / Hz
OP51	MOB52	A	31	69995395 \pm 4096
OP51	PTB55	A	4	70044920 \pm 4096
PTB55	MOB52	A	31	69966685 \pm 4096
PTB55	OP51	A	0	69989039 \pm 4096

To configure the SDR receiver, e.g. for OP51, to be able to receive the signal of mobile station, one additional line should be appended in the configuration file "satre.param" as follows according to **Table 2** and **Table 3**.

A N 4 70044920 1000 1000 4096 256 -18
A N 31 69995395 1000 1000 4096 256 -18

To report the measurements in ITU files, you need to append a few additional lines between [RX] and [END] in the configuration file “ITU.param” according to the measurement sessions of the transmission plan in Annex I. As shown below, 36 (= 2 x 18) additional lines will be appended since there are 2 remote stations and 18 sessions in each hour.

```
[RX]
A OP51 PTB55 4 4 1000 70044920 119 14 999 9 999999999 999999999 99999
A OP51 MOB52 4 31 1000 69995395 119 14 999 9 999999999 999999999 99999
A OP51 PTB55 7 4 1000 70044920 119 14 999 9 999999999 999999999 99999
A OP51 MOB52 7 31 1000 69995395 119 14 999 9 999999999 999999999 99999
...
A OP51 PTB55 XX 4 1000 70044920 119 14 999 9 999999999 999999999 99999
A OP51 MOB52 XX 31 1000 69995395 119 14 999 9 999999999 999999999 99999
...
A OP51 PTB55 58 4 1000 70044920 119 14 999 9 999999999 999999999 99999
A OP51 MOB52 58 31 1000 69995395 119 14 999 9 999999999 999999999 99999
[END]
```

XX is filled with 04, 07, 10, 13, 16, 19, 22, 25, 28, 34, 37, 40, 43, 46, 49, 52, 55, and 58 (total 18 sessions).

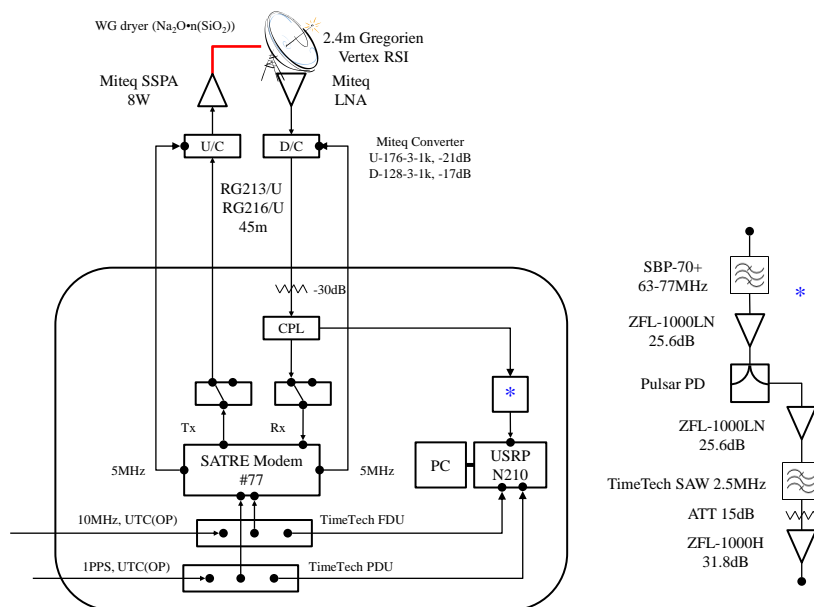


Figure 2 Block diagram of the fixed station OP51

IV. Configuration of the SDR travelling equipment

The role of the coordinator is to configure the SDR travelling equipment. The coordinator should ask mobile station provider and each visited laboratory for providing the sources in **Table 4** that will be connected to the SDR travelling equipment.

Table 4 Required sources for the SDR travelling equipment

Item	Source	Source description
1	RF # IN Monitor	On the rear panel of the SATRE RX module in the mobile station
2	RF OUT Monitor	On the rear panel of the SATRE TX module in the mobile station
3	1 PPS	From laboratory or through portable station
4	10 MHz	From laboratory or through portable station
5	AC Power	220 – 240V AC; Socket type E

The coordinator should ask mobile station provider about received signal parameters and then configure the SDR travelling equipment for it to receive the signals. The coordinator will put the code ID, the IF value and its dynamic range of each laboratory in **Table 5**, and put the code ID and IF value of the signal transmitted by the mobile station in **Table 6**.

Table 5 Signal parameters of each laboratory received by mobile station. These signals should be received by the SDR travelling equipment channel A

Received by	Transmitted by	SDR channel	PRN ID	IF value \pm dynamic range / Hz
MOB52	OP51	A	0	70142756 \pm 4096
MOB52	PTB55	A	4	70169589 \pm 4096

Table 6 Transmitted signal by the mobile station. The signal should be received in channel B

Received by	Transmitted by	SDR channel	PRN ID	IF value / Hz
MOB52	MOB52	B	31	70118695

Below are the contents of the configuration file “satre.param” according to **Table 5** and **Table 6**.

A	N	0	70142756	1000	1000	4096	256	-18
A	N	4	70169589	1000	1000	4096	256	-18
B	N	31	70118695	1000	1000	32	4	0

To report the measurements in ITU files, a few lines should be inserted between [RX] and [END] in the configuration file “ITU.param” according to the measurement sessions of the transmission plan in Annex I. As shown below, 36 (= 2 x 18) lines are inserted since there are 2 remote signals and 18 sessions in each hour. When going through the operation procedure in Section V, you will be asked to modify the values followed by [REFDELAY_ns] and [UTC-PC_s].

```
[1PPSTX]
B 31 1000
[END]

[RX]
A MOB52 OP51 4 0 1000 70142756 119 14 999 9 999999999 999999999 99999
A MOB52 PTB55 4 4 1000 70169589 119 14 999 9 999999999 999999999 99999
A MOB52 OP51 7 0 1000 70142756 119 14 999 9 999999999 999999999 99999
A MOB52 PTB55 7 4 1000 70169589 119 14 999 9 999999999 999999999 99999
...
A MOB52 OP51 XX 0 1000 70142756 119 14 999 9 999999999 999999999 99999
A MOB52 PTB55 XX 4 1000 70169589 119 14 999 9 999999999 999999999 99999
...
A MOB52 OP51 58 0 1000 70142756 119 14 999 9 999999999 999999999 99999
A MOB52 PTB55 58 4 1000 70169589 119 14 999 9 999999999 999999999 99999
[END]

[REFDELAY_ns]
123.456

[UTC-PC_s]
+5
```

XX is filled with 04, 07, 10, 13, 16, 19, 22, 25, 28, 34, 37, 40, 43, 46, 49, 52, 55, and 58 (total 18 sessions).

V. Operation

Table 7 summarizes the operation procedure which is described in detail below.

Table 7 Steps to operate the SDR travelling equipment

Step	Action	Response
1	Open the travelling equipment	
2	Check the appearance	
3	Check the dedicated cables	
4	Cabling	
4.1	Connect “RF # IN Monitor” to IF(A) IN	
4.2	Connect “RF OUT Monitor” to IF(B) IN	
4.3	Connect 10 MHz to REF IN	
4.4	Connect 1 PPS to 1 PPS IN	
4.5	Connect monitor	
4.6	Connect a mouse and a keyboard	
5	Apply AC power	
5.1	Apply the travelling equipment to 220 – 240 V AC	
5.2	Switch on the power line extender	
6	Power on the computer	
7	Check if the travelling equipment is receiving the signals	
8	Report [UTC – PC]	_____ s
9	Report REFDELAY	_____ ns
10	Copy data and send them to the coordinator	
11	Power off the computer	
12	Close the travelling equipment	

Description of the steps:

1. Open the front and rear covers of the SDR travelling equipment

2. Check the appearance



Figure 3 Front (left) and rear (right) appearances

3. Check the four cables as listed in **Table 1**

4. Make cabling as shown in **Figure 4**

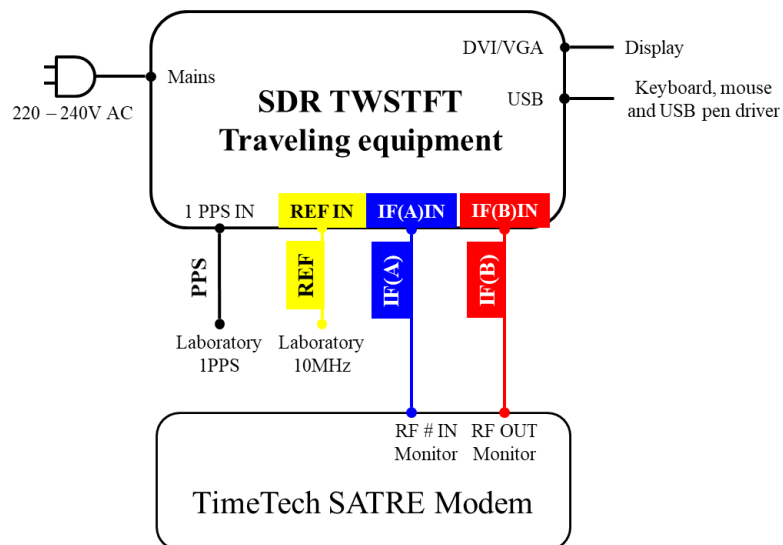


Figure 4 Connections between the SDR travelling equipment and the SATRE modem of mobile station

4.1. Use the cable **IF(A)** to connect “RF # IN Monitor” on the rear panel of the SATRE modem to **IF(A) IN**

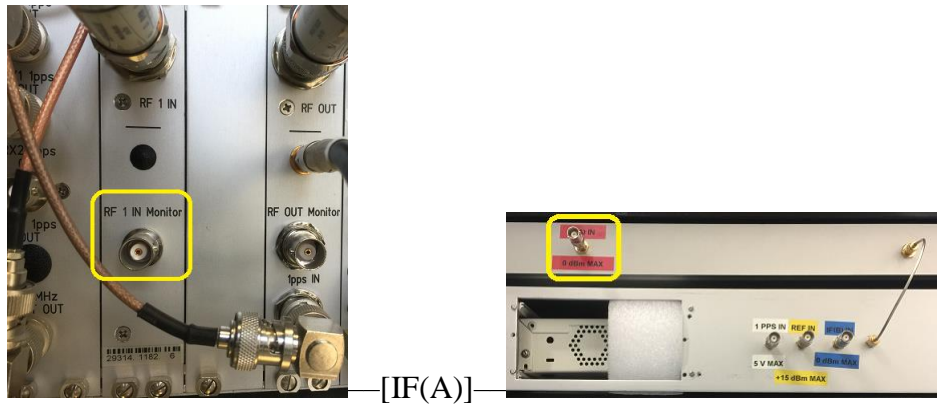


Figure 5 RF IN Monitor connection

4.2. Use the cable **IF(B)** to connect “RF OUT Monitor” on the rear panel of the SATRE modem to **IF(B) IN**

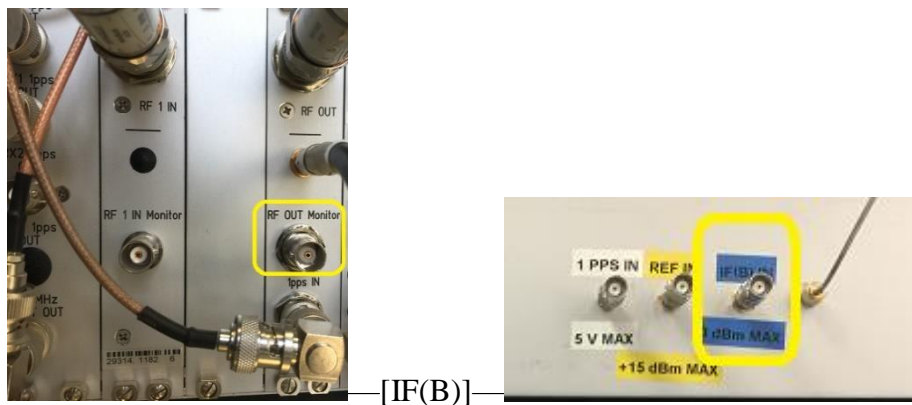


Figure 6 RF OUT Monitor connection

4.3. Use the cable **REF** to connect laboratory 10 MHz to **REF IN**

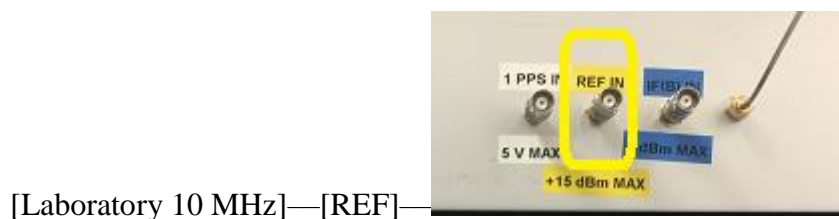


Figure 7 REF IN connection

4.4. Use the cable PPS to connect laboratory 1 PPS to 1 PPS IN

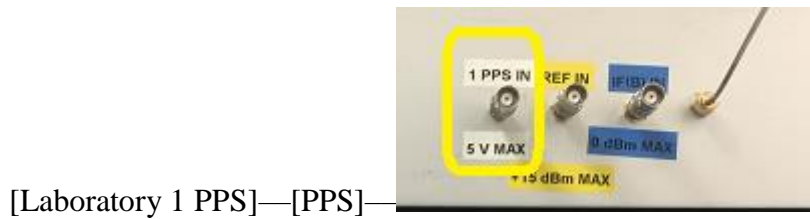


Figure 8 PPS IN connection

4.5. Connect a DVI or VGA monitor to the computer

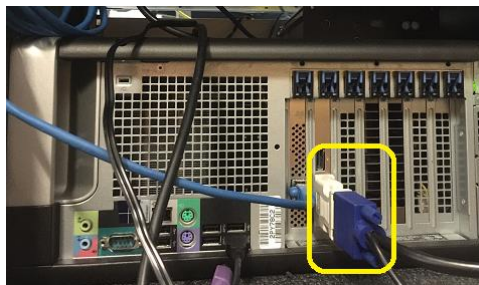


Figure 9 Monitor connector supporting DVI and VGA

4.6. Connect a mouse and a keyboard to the computer through USB or PS/2 connector

5. Apply AC power

5.1. Take out the plug from the box and apply it to 220 – 240 V AC mains

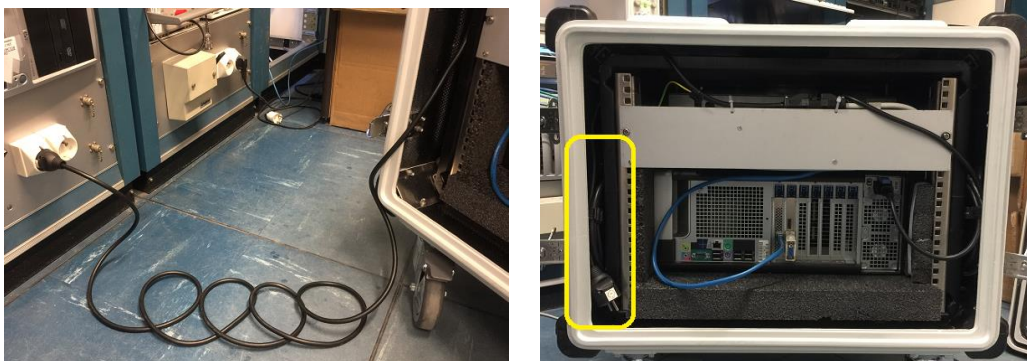


Figure 10 The Type E socket and the power line extender

5.2. Turn on the switch of the power line extender and check if the LEDs of DC module and computer socket are on (the computer LED will be off in a few seconds)

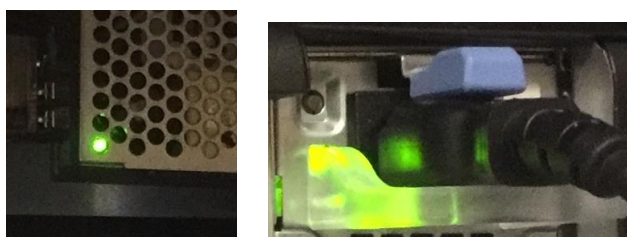


Figure 11 LEDs of DC module (left) and computer socket (right)

6. Power on the computer and wait around one minute to enter Linux Ubuntu desktop



Figure 12 The button for computer power-on

7. The software will start automatically. Check if channel A and B are receiving the signals listed in **Table 5** and **Table 6**, respectively

```
time@sdr: ~
PWR A: -6.87 dBm , PWR B: -13.17 dBm
A: #00 1.0 Mcps 70017798.665 Hz 262292296.527 ( 1.128) ns S/N -14.95 dB
A: #04 1.0 Mcps 70044998.575 Hz 264466954.815 ( 1.214) ns S/N -14.79 dB
B: #31 1.0 Mcps 70016056.000 Hz 2202.253 ( 0.013) ns S/N 2.14 dB
2019/02/26 10:23:50 PC
```

Figure 13 On-the-screen information. According to **Table 5** and **Table 6**, the PRN #00, #04 should be received in channel A, and #31 in channel B

Manually launch the software in case of troubles.

7.1. Press **Ctrl + Alt + t** to open a terminal

7.2. Issue the command below

```
$ ~/twsdr/bin/rx50 ~/twsdr/result ~/twsdr/bin/satre.param pctime
```

8. Observe the offset of computer time from UTC, namely $[UTC-PC]$, and report the value in **Table 7**. The value should be always the same if the software is running without restart.

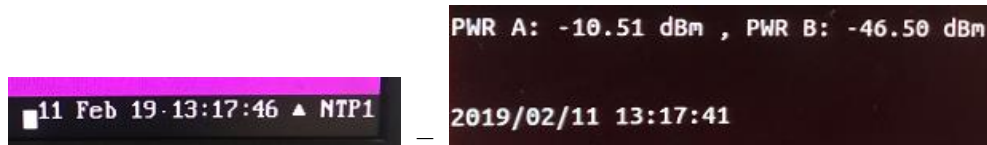


Figure 14 UTC time displayed in the SATRE modem (left) and computer time on the screen (right). In this case, the $[UTC-PC]$ value is reported +5 s.

Open the file “ITU_CALR2019.param” in the folder “~/twcdr/conf”, and then put the value in the $[UTC-PC_s]$

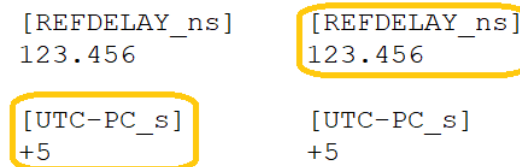


Figure 15 the entries to put $[UTC-PC]$ (left) and reference delay (right)

9. The reference delay of the mobile station is defined by $[UTC(k)-1PPSTX]$. Measure the value and report it in **Table 7**, and also put it in the “ITU_CALR2019.param”.

10. Copy the raw data stored in the folder “~/twcdr/result” and the ITU files in “~/twcdr/ITU/CALR2019” into a USB flash drive, and then send them to the coordinator. The ITU and raw data filenames look like as follows.

raw data file: **#####.ch#.pn##.1000kcps.dat**
 ITU file: **twmob##.###**

11. In the end of measurement, power off the computer by left-clicking the top-right button in Linux Ubuntu desktop

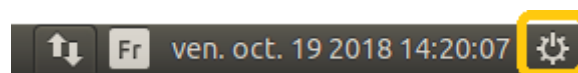


Figure 16 The button for computer power-off

12. Disconnect the cables and close the SDR travelling equipment



Figure 17 Top view of the box. Be aware of the arrows when closing the doors.

VI. Data processing

The time-scale difference can be measured by TWSTFT when their earth stations have been calibrated. Using a TWSTFT mobile station on baseline mode, the calibration will be carried out by seven steps below:

1. Install MOB at Station 1, and then select a proper 1 PPS as the calibration reference point (CRP). Usually the UTC(k) is selected.
2. Perform TWSTFT between Station 1 and MOB on the MJD date $mjddd$. Two ITU files $TWLAB1mj.ddd$ and $TWMOBmj.ddd$ are generated by Station 1 and MOB, respectively.
3. Calculate CCD by equation (1):

$$CCD = 0.5[TW(m; 1) - TW(1; m)] + [REFcal(m; 1) - REFcal(1)] \quad (1)$$

where in equation (1),

- 3.1. $TW(m; 1)$ is the TW value in $TWMOBmj.ddd$ where LOC is MOB and REM is Station 1.
 - 3.2. $TW(1; m)$ is the TW value in $TWLAB1mj.ddd$ when LOC is Station 1 and REM is MOB.
 - 3.3. $REFcal(m; 1)$ is the time delay from Station 1 CRP to the mobile station $1PPSTX$.
 - 3.4. $REFcal(1)$ is the time delay from Station 1 CRP to Station 1 $1PPSTX$.
4. Install MOB at Station 2, and then select a proper 1 PPS as CRP.
 5. Perform TWSTFT between Station 1 and MOB on the MJD date $mjjjd$. Three ITU files $TWLAB1mj.jjd$, $TWLAB2mj.jjd$ and $TWMOBmj.jjd$ are generated by Station 1, Station 2 and MOB, respectively.
 6. Calculate DLK by equation (2):

$$DLK = +0.5[TW(1; 2) - TW(2; 1)] - 0.5[TW(1; m) - TW(m; 1)] + [REFcal(m; 2) - REFcal(2)] \quad (2)$$

where in equation (2),

6.1. $TW(1;2)$ is the TW value in $TWLAB1mj.jjd$ where LOC is Station 1 and REM is Station 2;

6.2. $TW(2;1)$ is the TW value in $TWLAB2mj.jjd$ where LOC is Station 2 and REM is Station 1;

6.3. $REFcal(m;2)$ is the time delay from Station 2 CRP to the mobile station 1PPSTX;

6.4. $REFcal(2)$ is the time delay from Station 2 CRP to Station 2 1PPSTX.

7. Calculate $CALR(1,2)$ by equation (3):

$$CALR(1,2) = CCD - DLK - SCD(1) + SCD(2) \quad (3)$$

where $SCD(1)$ and $SCD(2)$ are the delay values due to Sagnac effect.

References

- [1] The operational use of two-way satellite time and frequency transfer employing pseudorandom noise codes. *Recommendation ITU-R TF.1153-4*, Geneva 2015.
- [2] F J Galindo, A Bauch, D Piester, H Esteban, I Sesia, J Achkar and K Jaldehag. European TWSTFT Calibration Campaign 2016. *Calibration Report* issued on 2017-01-31, 2017.

Annex I

Transmission plan (version 2019-02-25)

First	Last	Action	Length	OP11		SP11		PTB15		IT12		ROA11		TIM11		ROA12		MOB12		IT11	
				TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX
hhmmss	hhmmss		s	a	d	e	i	k	t	w	v	j									
UTC	UTC			-20	-40	40	-60	-100	-30	90	-70	100									
				0	3	4	6	7	14	18	31	17									
				EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR									
01:00:00	01:00:59	Prep.time	60																		
01:01:00	01:02:59	CC	120																		
01:03:00	01:03:59	Prep.time	60	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3
01:04:00	01:05:59	Ranging	120	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3
01:06:00	01:06:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4
01:07:00	01:08:59	Measure	120	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4
01:09:00	01:09:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	14	17	18	14	31	7	17	6
01:10:00	01:11:59	Measure	120	0	4	3	3	4	0	6	17	7	31	14	17	18	14	31	7	17	6
01:12:00	01:12:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7
01:13:00	01:14:59	Measure	120	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7
01:15:00	01:15:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14
01:16:00	01:17:59	Measure	120	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14
01:18:00	01:18:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18
01:19:00	01:20:59	Measure	120	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18
01:21:00	01:21:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31
01:22:00	01:23:59	Measure	120	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31
01:24:00	01:24:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17
01:25:00	01:26:59	Measure	120	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17
01:27:00	01:27:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0
01:28:00	01:29:59	Measure	120	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0
		UD link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR
01:30:00	01:30:59	Prep.time	60																		
01:31:00	01:32:59	CC	120																		
01:33:00	01:33:59	Prep.time	60	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3
01:34:00	01:35:59	Measure	120	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3
01:36:00	01:36:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4
01:37:00	01:38:59	Measure	120	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4
01:39:00	01:39:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	14	18	18	14	31	7	17	6
01:40:00	01:41:59	Measure	120	0	4	3	3	4	0	6	17	7	31	14	18	18	14	31	7	17	6
01:42:00	01:42:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7
01:43:00	01:44:59	Measure	120	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7
01:45:00	01:45:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14
01:46:00	01:47:59	Measure	120	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14
01:48:00	01:48:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18
01:49:00	01:50:59	Measure	120	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18
01:51:00	01:51:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31
01:52:00	01:53:59	Measure	120	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31
01:54:00	01:54:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17
01:55:00	01:56:59	Measure	120	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17
01:57:00	01:57:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0
01:58:00	01:59:59	CAL	120	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0