Summary for the GSOP 2019 TWSTFT calibration report

F. Meynadier

This document summarizes the report of the 2019 campaign intended for calibration of the TWSTFT links 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.

Author of the report :	H. Esteban (ROA)
Authorized by :	I. Sesia (INRIM)
Reference :	GAL-TN-ROA-GSOP-2019001
Version :	3
Date :	01/10/2019

Date of implementation : 28 Nov. 2019 / MJD 58815

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.

SP01

```
* CAL 489 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.900 ns
* CAL 496 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 497 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 498 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 499 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 500 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 501 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

             CI  S CALR
SP01 PTF101  489 1 20.000
SP01 PTB05   496 1 0.100
SP01 IT02    497 1 273.700
SP01 OP01    498 1 7113.400
SP01 ROA01   499 1 -22.000
SP01 IT01    500 1 0.600
SP01 ROA02   501 1 -24.000
```

PTB05

```
* CAL 490 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 496 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 502 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 503 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 504 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 505 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 506 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

              CI  S CALR
PTB05 PTF101 490 1 20.200
PTB05 SP01   496 1 -0.100
PTB05 IT02   502 1 275.400
PTB05 OP01   503 1 7112.700
PTB05 ROA01  504 1 -21.800
PTB05 IT01   505 1 -0.500
PTB05 ROA02  506 1 -25.400
```

IT02

```
* CAL 491 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.900 ns
* CAL 497 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 502 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 507 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 508 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 509 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 510 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

            CI  S CALR
IT02 PTF101 491 1 -253.700
IT02 SP01   497 1 -273.700
IT02 PTB05  502 1 -275.400
IT02 OP01   507 1 6838.600
IT02 ROA01  508 1 -296.600
IT02 IT01   509 1 -274.300
IT02 ROA02  510 1 -298.700
```

OP01

```
* CAL 492 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 498 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 503 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 507 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 511 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 512 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 513 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

             CI S CALR
OP01 PTF101 492 1 -7093.600
OP01 SP01   498 1 -7113.400
OP01 PTB05  503 1 -7112.700
OP01 IT02   507 1 -6838.600
OP01 ROA01  511 1 -7135.500
OP01 IT01   512 1 -7113.600
OP01 ROA02  513 1 -7138.100
```

ROA01

```
* CAL 493 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.900 ns
* CAL 499 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 504 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 508 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 511 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 514 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 515 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

              CI S CALR
ROA01 PTF101 493 1 41.900
ROA01 SP01   499 1 22.000
ROA01 PTB05  504 1 21.800
ROA01 IT02   508 1 296.600
ROA01 OP01   511 1 7135.500
ROA01 IT01   514 1 22.500
ROA01 ROA02  515 1 -2.200
```

IT01

```
* CAL 494 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.900 ns
* CAL 500 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 505 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 509 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 512 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 514 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 516 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

            CI S CALR
IT01 PTF101 494 1 19.600
IT01 SP01   500 1 -0.600
IT01 PTB05  505 1 0.500
IT01 IT02   509 1 274.300
IT01 OP01   512 1 7113.600
IT01 ROA01  514 1 -22.500
IT01 ROA02  516 1 -25.100
```

ROA02

```
* CAL 495 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.900 ns
* CAL 501 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 506 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 510 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 513 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 515 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns
* CAL 516 TYPE: PORT ES REL MJD: 58629 EST. UNCERT.: 0.800 ns

             CI S CALR
ROA02 PTF101 495 1 44.800
ROA02 SP01   501 1 24.000
ROA02 PTB05  506 1 25.400
ROA02 IT02   510 1 298.700
ROA02 OP01   513 1 7138.100
ROA02 ROA01  515 1 2.200
ROA02 IT01   516 1 25.100
```

TWSTFT CALIBRATION REPORT

GSOP

UNCLASSIFIED

Prepared by:	H. Esteban (ROA)
Approved by:	H. Esteban (ROA)
Authorized by:	I. Sesia (INRIM)
Customer Approval	Approval level: R

Code:	GAL-TN-ROA-GSOP-2019001
Version:	3
Date:	01/10/2019

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. SCOPE OF THE DOCUMENT

This document presents the results of the 2019 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. It was produced in the frame of WP 10.1.4.3 of the GSOP contract between INRiM and ROA.

For both PTF, this is the third calibration campaign involving a mobile TWSTFT station since the full Deployment and Operations phase of the Galileo Program (the first calibration took place in summer 2014, and the second in spring 2016). For the PTF1, this is the fourth one. The first one was carried out in autumn 2013, in the frame of the IOV Galileo Time Validation Facility contract between TAS-F, INRIM, and PTB.

1.2. CHANGE FORECAST

This document reports on work done during the third TWSTFT calibration campaign in the frame of the Galileo GSOp contract. No further issues are planned.

1.3. 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 acronyms used).

Section 2 presents an overview of the contractual baseline regarding time transfer between the partners associated with the GSOp. It 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 March / May 2019 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.

This Report concludes with a summary of the lessons learnt throughout this calibration campaign (Section 8).

1.4. DOCUMENTS

1.4.1. APPLICABLE DOCUMENTS

The following documents are applicable and have been used as the basis for this work.

Table 1-1: Applicable documents.

Ref.	Title	Code	Version	Date
AD01	Time and geodetic Validation Facility Requirements Document	ESA-DTEN-NG-REQ-03766	1.1	

1.4.2. REFERENCE DOCUMENTS

The following documents are used as reference in this document.

Table 1-2: Reference documents.

Ref.	Title	Code	Version	Date
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		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.		08/2015
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	Galileo TVF TWSTFT Relative Calibration Report	TGVF-PTB-1F000-RP0001	4.1	June 2012
RD06	Galileo TVF TWSTFT Relative Calibration Report	TGVF-PTB-1F000-RP0002	1.0	March 2013
RD07	Galileo IOV TVF TWSTFT PTF1 Calibration Report	TGVF-PTB-1F000-RP0003	3.0	March 2014
RD08	Galileo TGVF-FOC TWSTFT Calibration Report	GAL-TN-ROA-TGVFFOC-20036	2.0	2015-02-16
RD09	Galileo GAL-TN-ROA-TGVFFOC Calibration Report	GAL-TN-ROA-TGVFFOC-20056	1.0	06/09/2016
RD10	TVFFOC TWSTFT Calibration: Site Preparation document checklist	GAL-TN-ROA-GSOP-001	2.4	2016-05-24
RD11	MODEL SR620 Universal Time Interval Counter, Stanford Research Systems, Revision 2.7 (2006).		2.7	2006
RD12	J. Achkar; D. Rovera; I. Sesia; P. Tavella, "Determination of differential delays of earth stations in Paris and Torino from the calibrated OP-IT TWSTFT link", in Proceedings of 2016 European Frequency and Time Forum (EFTF).	DOI:10.1109/EFTF.2016.7477800	2.7	2016

1.5. ACRONYMS AND ABBREVIATIONS

Table 1-3: List of Acronyms and Abbreviations

Acronym	Definition
AGS	Americom Government Services
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)
ESA	European Space Agency
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
GCC	Galileo Control Centre
GEO	Geo-stationary satellite
GMS	(Galileo) Ground Mission Segment
GPS	Global Positioning System
GST	Galileo System Time
GST(MC)	GST physical realization point within PTF
IERS	International Earth Rotation and Reference Systems Service
IIOTIC	Intelligent In/Out and Time Interval Counter
IOV	In-Orbit Validation
INRIM	Istituto Nazionale di Ricerca Metrologica
ITU	International Telecommunication Union
MJD	Modified Julian Date
NMI	National Metrology Institute

Acronym	Definition
OP	LNE-SYRTE, Observatoire de Paris
PDIS	Pulse distribution amplifier
PTB	Physikalisch-Technische Bundesanstalt
PTF	Precise Timing Facility
PTF1, PTF2	Galileo Precise Timing Facilities
RISE	Research Institutes of Sweden
ROA	Real Instituto y Observatorio de la Armada
SOW	Statement of Work
TAI	International Atomic Time
TAS (- F)	Thales Alenia Space (- France)
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
WP	Work Package
	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.
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. TIME TRANSFER IN THE TVF CONTEXT

2.1. OVERVIEW

The operation of a Global Navigation Satellite System requires accurate synchronization among the various elements in the ground and space segment. The core navigation function of Galileo is based on Galileo System Time (GST) as realized in the Precise Timing Facilities (PTF). They are located in the Galileo Control Centres (GCC) which are part of the Ground Mission Segment (GMS). The additional use of Galileo as a time dissemination system requires that the relation between GST and international time references such as Coordinated Universal Time (UTC) and International Atomic Time (TAI), maintained by the Bureau International des Poids et Mesures (BIPM) with input from the International Earth Rotation and Reference Systems Service (IERS), is well defined and broadcast in the Galileo Signal in Space. The required support for such "metrological time-keeping" is provided by the Time Validation Facility which is a part of the Time and Geodetic Validation Facility.

During the GalileoSat Development and Validation ("IOV") phase, only PTF1, located in the GCC-2 at Fucino Space Centre, Ortucchio (L'Aquila), Italy, was operational. PTF2 (Oberpfaffenhofen, DE) accomplished the readiness in 2014, during the Deployment and Operations ("FOC") phase of the Galileo Program. This Report deals with the calibration of the time links between PTF1 and PTF2, and associated UTC(k) laboratories, INRIM, OP, PTB, ROA, and SP based on TWSTFT [RD01, RD02]. In the case of INRIM and ROA, the time links were calibrated involving two TW stations: the main station (ROA01, IT02) and spare one (ROA02, IT01). This exercise is the sixth of its kind. The first and second ones (March 2012 [RD05], and March 2013 [RD06]) were done with reference to preceding GPS-based calibrations. The third, fourth and fifth ones (October-November 2013 [RD07], June-August 2014 [RD08], and April-June 2016 [RD09]), involved the same traveling TWSTFT station and followed the method described in [RD03], similarly to the current one.

In this context the present campaign followed the TWSTFT calibration guidelines [RD04], approved by the CCTF WG on TWSTFT in September 2015 and currently in force.

2.2. 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 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 was renewed to cover until May 2020.

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

Beacon frequency: 11699.5 MHz

<u>For the Europe to Europe link:</u>

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

2.3. CONTRACTUAL ARRANGEMENTS FOR THE FOC TVF TWSTFT CALIBRATIONS

According to the GSOp Statement of Work, a calibration exercise involving a traveling TWSTFT station and comprising PTF1, PTF2, INRIM, OP, PTB, ROA, and SP, should be organized and evaluated by ROA in 2019 and took place in spring of 2019 (February 26th to May 26th).

The provision of the mobile TWSTFT station (designated as MOB in this Report) and its operation was directly subcontracted to TimeTech by INRiM.

3. ORGANIZATION OF THE CAMPAIGN

3.1. DIRECTLY INVOLVED INSTITUTES AND ORGANISATIONS

INRIM:

Dr Ilaria Sesia

Istituto Nazionale di Ricerca Metrologica, Optics Division
Strada delle Cacce, 91
10135 TORINO, Italy

LNE-SYRTE:

Dr Joseph Achkar

LNE-SYRTE,Observatoire de Paris, Université PSL, CNRS, Sorbonne Université

61 avenue de l'Observatoire

75014 PARIS, France

PTB:

Dr Dirk Piester

Physikalisch-Technische Bundesanstalt, WG 4.42 Time Dissemination

Bundesallee 100

D-38116 Braunschweig, Germany

RISE:

Dr Kenneth Jaldehag

Research Institutes of Sweden

Measurement Technology - Time and Frequency

Brinellgatan 4, 504 62 Borås, Sweden

ROA:

Dr Héctor Esteban

Real Instituto y Observatorio de la Armada

Sección de Hora

Plaza de las Tres Marinas s/n

11100 San Fernando (Cádiz), Spain

PTF1:

Fucino Space Center c/o Telespazio

Via Cintarella

67050 Ortucchio (AQ), Italy

PTF2:

DLR German Aerospace Center
Oberpfaffenhofen
Münchener Straße 20
82234 Weßling, Germany

TIM:

Dr Thorsten Feldmann
TimeTech GmbH
Curiestrasse 2
D-70563 Stuttgart, Germany

3.2. TRAVEL SCHEDULE AND MEASUREMENT PERIODS

3.2.1. TRAVEL SCHEDULE

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

From	To	Distance	Time to travel
Stuttgart	Boras	1350 km	17 hrs
Boras	Braunschweig	844 km	11 hrs
Braunschweig	Oberpfaffenhofen	725 km	10 hrs
Oberpfaffenhofen	Torino	660km	9 hrs
Torino	Ortucchio	800 km	10 hrs
Ortucchio	San Fernando	2576 km	30 hrs
San Fernando	Stuttgart	2307 km	27 hrs
Stuttgart	Paris	640 km	8 hrs
Paris	Stuttgart	640 km	8 hrs

3.2.2. 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	9	Tue, 26 Feb 2019 00:00	Sun, 03 Mar 2019 05:00	58540 – 58545
RISE	10	Tue, 05 Mar 2019 09:00	Fri, 08 Mar 2019 09:00	58547 – 58550
PTB	11	Mon, 11 Mar 2019 14:00	Fri, 15 Mar 2019 07:00	58553 – 58557
PTF2	12	Mon, 18 Mar 2019 14:00	Thu, 21 Mar 2019 09:00	58560 – 58563
INRIM	13	Mon, 25 Mar 2019 15:30	Fri, 29 Mar 2019 10:00	58567 – 58571
PTF1	14	Mon, 01 Apr 2019 13:00	Fri, 05 Apr 2019 06:00	58574 – 58578
ROA	15	Mon, 08 Apr 2019 10:00	Fri, 12 Apr 2019 07:00	58581 – 58585
OP	17	Tue, 23 Apr 2019 13:30	Fri, 26 Apr 2019 10:00	58596 – 58599
TIM	21	Tue, 21 May 2019 00:00	Sun, 26 May 2019 00:00	58624 – 58629

3.3. 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
INRIM	Torino IT	IT01	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 36:27:47.784 LO: W 006:12:22.682 HT: 80.8 m

T&F Lab. Code	Location	TWSTFT St code even hours	TWSTFT St code odd hours	Position deg: min: sec
ROA	San Fernando ES	ROA02	ROA12	LA: N 36:27:47.784 LO: W 006:12:22.847 HT: 80.8 m
LNE-SYRTE (OP)	Paris FR	OP01	OP11	LA: N 48:50:09.236 LO: E 002:20:05.873 HT: 78.0 m
RISE	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
PTF2	Oberpfaffenhofen DE	PTF201		LA: N 48:05:24.000 LO: E 011:16:48.000 HT: 578.0 m
PTF1	Fucino IT	PTF101		LA: N 41:57:31.000 LO: E 13:38:42.000 HT: 662.6 m
TIM	Stuttgart DE	TIM01	TIM11	LA: N 48:44.16.272 LO: E 09:06:45.106 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, PTB, PTF2, and PTF1. 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, and extra sessions during odd hours.

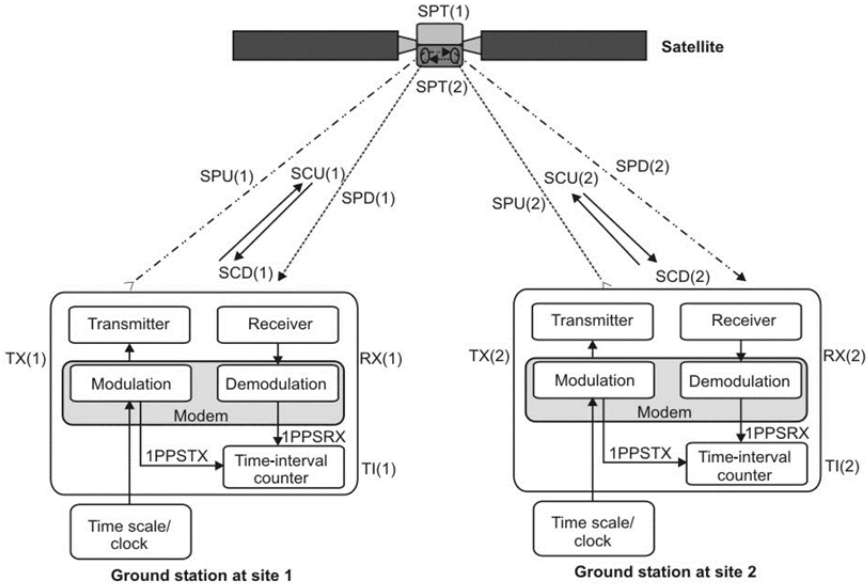
4. BACKGROUND INFORMATION ON TWSTFT

4.1. BACKGROUND INFORMATION ON TWSTFT

In this section, we recall the theoretical background and derive the equations necessary for the determination of calibration constants. We follow, if 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 the equations, which are listed in Table 1-3.

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

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

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

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

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

For its determination, two different approaches are in principle possible, the so-called <u>site-mode</u> which requires common clock measurements taken at each site and the <u>baseline-based</u> which avoids that. Both methods include the use of a mobile TWSTFT station (MOB), in addition to the permanent ground stations. According to (3) and (4), a calibration constant can then be calculated from:

(5) $$\mathrm{CALR(1,2) = [TS(1) - TS(2)]_{LINK} - 0.5 * [TW(1) - TW(2)].}$$

The baseline-based mode is subsequently described in more detail. First, the MOB is operated in parallel to station 1, both connected to a single clock. Eq. 3 is, thus, simplified to:

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

We define the common-clock difference, CCD(MOB@1,1), as the last addend in (6), and determine it consequently from a TWSTFT measurement between 1 and MOB as

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

Note that $\mathrm{DLD(MOB)}$ 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). The time-scale difference $\mathrm{TS(1) - TS(2)}$ can be measured by performing a TWSTFT measurement between the MOB located at site 2 and site 1; combining (3) with (7), this last particularized for site 2, and considering (6), we get:

(8) $$\mathrm{[TS(1) - TS(2)]_{LINK} = 0.5 * [TW(1) - TW(MOB@2)] - CCD(1, MOB@1) + \\ - [SCD(1) - SCD(2)]}$$

and therefore, according to (5):

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

Where, the second term is known as Bridged $\mathrm{CCD}(\mathrm{MOB@2},2)$.

The site mode was the approach used between pairs of UTC(k) laboratories. This approach of performing a calibration includes the repetition of the CCD measurement described by (7) at a second site. This gives a second common-clock difference value at site 2:

(10) $$\mathrm{CCD}(\mathrm{MOB@2,2}) = 0.5 * [\mathrm{TW}(\mathrm{MOB@2}) - \mathrm{TW}(2)]$$

Forming (7) – (10) gives:

(11) $$\mathrm{CCD}(\mathrm{MOB@1,1}) - \mathrm{CCD}(\mathrm{MOB@2,2}) = 0.5 * [\mathrm{DLD}(1) - \mathrm{DLD}(\mathrm{MOB})] - 0.5 * [\mathrm{DLD}(2) - \mathrm{DLD}(\mathrm{MOB})] = \\ = 0.5 * [\mathrm{DLD}(1) - \mathrm{DLD}(2)].$$

And thus from (4):

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

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 5-2 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 (7), one has to consider

(13) $$\mathrm{CCD}(\mathrm{MOB@k},\mathrm{k})_{\mathrm{true}} = 0.5 * (\mathrm{TW}(\mathrm{MOB@k}) - \mathrm{TW}(\mathrm{k})) + \\ + \mathrm{REFDELAY}(\mathrm{MOB@k}) - \mathrm{REFDELAY}(\mathrm{k}) = \\ = 0.5 * (\mathrm{TW}(\mathrm{MOB@k}) - \mathrm{TW}(\mathrm{k})) + \mathrm{REFDLYdiff}(\mathrm{MOB@k},\mathrm{k}).$$

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 (13) is appropriate for all links involved. The delay between the fast-rising pulses that define 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 [RD13]. 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	REFDLY(MOB@k) [ns]	REFDLY(UTC(k)) [ns]	REFDLYdiff(MOB@k,k) [ns]	SCD(Loc) [ns]
TIM1	39.540	705.160	-665.620	104.78
INRIM (IT02)	128.960	789.400	-660.440	109.52
INRIM (IT01)	128.960	835.470	-706.510	109.52
ROA (ROA01)	305.170	964.343	-661.471	91.26
ROA (ROA02)	305.170	1055.771	-750.601	91.26
OP	89.480	826.040	-736.560	92.18
SP	49.160	784.548	-735.388	90.01
PTB	63.220	736.134	-672.914	99.32
TIM2 (*)	42.170	705.147	-662.977	104.78

(*) A different Pulse Distribution Unit was used to provide the 1 PPS AUX signal for the mobile station.

Combining equations 9 and 13, we get:

$$(14)\quad \mathrm{CALR}(1,2) = \mathrm{CCD}(\mathrm{MOB@1},1) + \mathrm{REFDLYdiff}(\mathrm{MOB@1},1) + \\ -0.5 * \left[\left(\mathrm{TW}(\mathrm{MOB@2}) - \mathrm{TW}(1)\right) - \left(\mathrm{TW}(2) - \mathrm{TW}(1)\right)\right] + \\ -\mathrm{REFDLYdiff}(\mathrm{MOB@2},2) - \mathrm{SCD}(1) + \mathrm{SCD}(2).$$

Likewise, combining equations 12 and 13 for the site-mode, we get:

$$(15)\quad \mathrm{CALR}(1,2) = \mathrm{CCD}(\mathrm{MOB@1},1) + \mathrm{REFDLYdiff}(\mathrm{MOB@1},1) + \\ -\mathrm{CCD}(\mathrm{MOB@2},2) - \mathrm{REFDLYdiff}(\mathrm{MOB@2},2) + \\ -\mathrm{SCD}(1) + \mathrm{SCD}(2).$$

Finally, eq. 18 shows how the calibration value enters in the calculation of time scale differences (simplified from [RD01]):

$$(16)\quad \mathrm{TS}(1) - \mathrm{TS}(2) = \\ +0.5 * [\mathrm{TW}(1) - \mathrm{TW}(2)] + \mathrm{REFDELAY}(1) - \mathrm{REFDELAY}(2) + \mathrm{CALR}(1,2).$$

4.3. CALIBRATION METHOD

In order to follow the same procedure than in previous calibration, the baseline-based mode (eq. 14) was used during the current campaign for the calibration of all the links.

In the baseline-based mode, the net result of previous equation entails cancellation or at least mitigation of MOB code effect, so avoiding REFDLYdiff and Sagnac effect, eq. 14 for A and B stations, it becomes:

$$\mathrm{CCD}(\mathrm{MOB@A},\mathrm{A}) - 0.5 * \left[\left(\mathrm{TW}(\mathrm{MOB@B}) - \mathrm{TW}(\mathrm{A})\right) - \left(\mathrm{TW}(\mathrm{B}) - \mathrm{TW}(\mathrm{A})\right)\right] = \\ = 0.5 * (\mathrm{MOB}_\mathrm{M}^\mathrm{A} - \mathrm{A}_\mathrm{A}^\mathrm{M}) - 0.5 * \left[(\mathrm{MOB}_\mathrm{M}^\mathrm{A} - \mathrm{A}_\mathrm{A}^\mathrm{M}) - (\mathrm{B}_\mathrm{B}^\mathrm{A} - \mathrm{A}_\mathrm{A}^\mathrm{B})\right] \\ = 0.5 * (\mathrm{B}_\mathrm{B}^\mathrm{A} - \mathrm{A}_\mathrm{A}^\mathrm{B})$$

where the subscripts and superscripts indicate the code transmitted and received respectively, finally resulting in the expected combination for the TW link between A and B stations.

5. OPERATION OF MOB

For completeness of this document we repeat part of the documentation provided as [RD10].

5.1. SIGNAL SCHEME

Figure 5-1 shows a simplified block diagram of the mobile TSTFT calibration station and the interfaces between the institute or laboratory and the mobile station. UTC(k) designates the reference time scale of the institute. If the UTC(k) interface is not directly accessible, the laboratory provides a signal UTC CAL along with the offset and the uncertainty with respect to UTC(k).

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

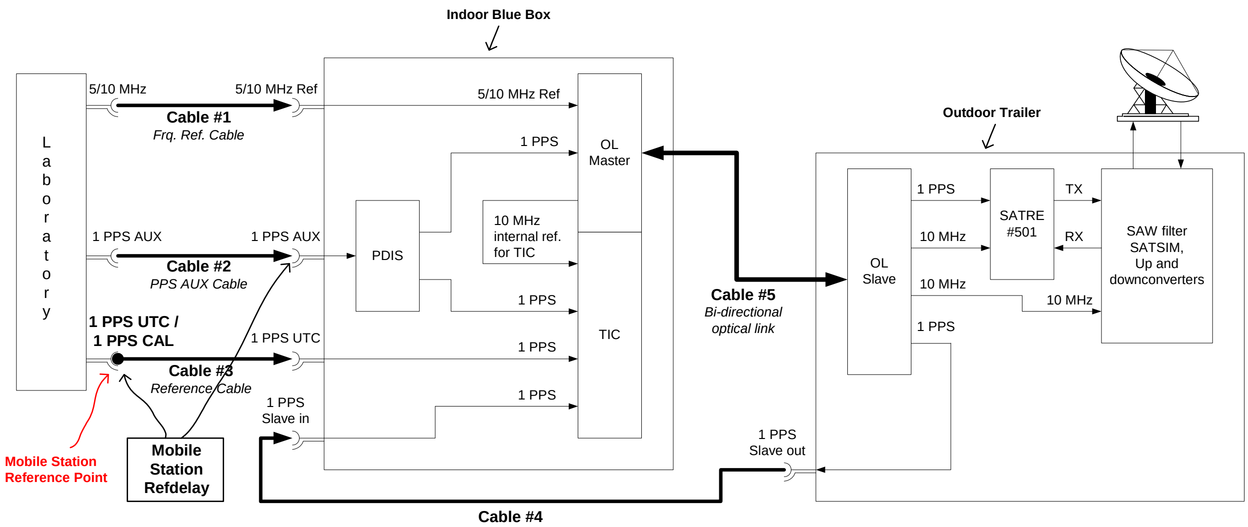


Table 5-1: Description of cables used

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 18	4.60 mm	N(M) - N(M)	19 mm
Cable #4	Test cable	200 m	Ecoflex 10	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. The cable #4 is a test cable used to verify the 1 PPS of the optical link slave with the TIC inside the Blue Box: It is used to check that there is no error of outdoor synchronization with respect to 1 PPS AUX. The use of the Reference cable #3 is mandatory, since the Reference Point of the mobile station is defined at the endpoint of this cable.

5.2. OPLINK PRINCIPLE OF OPERATION

The optical link (OPLINK) connecting the indoor "Master" with the outdoor "Slave" in the mobile station refers to all time interval measurements to the 1 PPS AUX input, independent of the phase of the reference frequency. The TIC that is an integral part of the Master replaces the external counter that was used to be shipped around in previous years. 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 the end of February to the end of May, 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		PTB05		IT02		ROA01		MOB02		PTF101		PTF201		TIM01		Lab
				TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	
				a		d		e		i		k		v		r		s		t		file Char
hhmmss	hhmmss		s	-20		-40		40		-60		-100		-70		-50		50		-30		offset kHz
UTC	UTC			0		3		4		6		7		31		12		13		14		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	CAL	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	31	31	12	12	13	13	14	14	
0:07:00	0:08:59	Ranging	120	0	0	3	3	4	4	6	6	7	7	31	31	12	12	13	13	14	14	
0:09:00	0:09:59	Prep.time	60	0						6	7	7	6			12	13	13	12			
0:10:00	0:11:59	Measure	120	0						6	7	7	6			12	13	13	12			
0:12:00	0:12:59	Prep.time	60	0				4	6	6	4											
0:13:00	0:14:59	Measure	120	0				4	6	6	4											
0:15:00	0:15:59	Prep.time	60	0	3	3	0	4	7	6		7	4									
0:16:00	0:17:59	Measure	120	0	3	3	0	4	7	6		7	4									
0:18:00	0:18:59	Prep.time	60	0	4	3	7	4	0	6		7	3	31	14					14	31	
0:19:00	0:20:59	Measure	120	0	4	3	7	4	0	6		7	3	31	14					14	31	
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	6	10			31	4							
0:34:00	0:35:59	Measure	120					4	31	6	10			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			31	6	12	0	13	3			
0:40:00	0:41:59	Measure	120	0	12	3	13			6	31			31	6	12	0	13	3			
0:42:00	0:42:59	Prep.time	60							6	9	7	31	31	7			13	0			
0:43:00	0:44:59	Measure	120							6	9	7	31	31	7			13	0			
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					31	0	12	4					
0:52:00	0:53:59	Measure	120	0	31			4	12					31	0	12	4					
0:54:00	0:54:59	Prep.time	60			3	31	4	13					31	3			13	4			
0:55:00	0:56:59	Measure	120			3	31	4	13					31	3			13	4			
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	CAL	120	0	0	3	3	4	4	6	6	7	14							14	7	

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

First	Last	Action	Length	OP11		SP11		PTB15		IT12		ROA11		TIM11		ROA12		MOB12		IT11		Lab
				TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	TX	RX	
				a		d		e		i		k		t		w		v		j		file Char
hhmmss	hhmmss		s	-20		-40		40		-60		-100		-30		100		-70		90		offset kHz
UTC	UTC			0		3		4		6		7		14		18		31		17		TX code
		U/D link		EUR	EUR	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	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3	
1:04:00	1:05:59	Ranging	120	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3	
1:06:00	1:06:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4	
1:07:00	1:08:59	Measure	120	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4	
1:09:00	1:09:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	14	17	18	14	31	7	17	6	
1:10:00	1:11:59	Measure	120	0	4	3	3	4	0	6	17	7	31	14	17	18	14	31	7	17	6	
1:12:00	1:12:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7	
1:13:00	1:14:59	Measure	120	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7	
1:15:00	1:15:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14	
1:16:00	1:17:59	Measure	120	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14	
1:18:00	1:18:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18	
1:19:00	1:20:59	Measure	120	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18	
1:21:00	1:21:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31	
1:22:00	1:23:59	Measure	120	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31	
1:24:00	1:24:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17	
1:25:00	1:26:59	Measure	120	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17	
1:27:00	1:27:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0	
1:28:00	1:29:59	Measure	120	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0	
		U/D link		EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	EUR	
1:33:00	1:33:59	Prep.time	60	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3	
1:34:00	1:35:59	Measure	120	0	0	3	17	4	31	6	18	7	14	14	7	18	6	31	4	17	3	
1:36:00	1:36:59	Prep.time	60	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4	
1:37:00	1:38:59	Measure	120	0	3	3	0	4	17	6	31	7	18	14	14	18	7	31	6	17	4	
1:39:00	1:39:59	Prep.time	60	0	4	3	3	4	0	6	17	7	31	14	18	18	14	31	7	17	6	
1:40:00	1:41:59	Measure	120	0	4	3	3	4	0	6	17	7	31	14	18	18	14	31	7	17	6	
1:42:00	1:42:59	Prep.time	60	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7	
1:43:00	1:44:59	Measure	120	0	6	3	4	4	3	6	0	7	17	14	31	18	18	31	14	17	7	
1:45:00	1:45:59	Prep.time	60	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14	
1:46:00	1:47:59	Measure	120	0	7	3	6	4	4	6	3	7	0	14	17	18	31	31	18	17	14	
1:48:00	1:48:59	Prep.time	60	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18	
1:49:00	1:50:59	Measure	120	0	14	3	7	4	6	6	4	7	3	14	0	18	17	31	31	17	18	
1:51:00	1:51:59	Prep.time	60	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31	
1:52:00	1:53:59	Measure	120	0	18	3	14	4	7	6	6	7	4	14	3	18	0	31	17	17	31	
1:54:00	1:54:59	Prep.time	60	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17	
1:55:00	1:56:59	Measure	120	0	31	3	18	4	14	6	7	7	6	14	4	18	3	31	0	17	17	
1:57:00	1:57:59	Prep.time	60	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0	
1:58:00	1:59:59	CAL	120	0	17	3	31	4	18	6	14	7	7	14	6	18	4	31	3	17	0	

As it appears in the Table 5-3, the schedule for odd hours included the second TWSTFT station at INRIM (IT11) and at ROA (ROA12). These stations were currently not taking part in the regular TWSTFT operations scheduled by CCTF WG on TWSTFT, therefore even hour sessions involving IT01 and ROA02 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. The average was calculated separately for each data set. The uncertainty values were found in some cases significantly smaller than the ordinate difference between even and odd hour data. This actually suggests some systematic effects in the modems involved, namely that the measurement obtained for one 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 12 to 24 hours), and was included a contribution to the uncertainty budget based on the findings.

In total, at least 100 pairs of link data for each time link in even and odd hours were taken. The only exception to this was the smaller number of data involving SP01, IT01 and ROA02, about 60, as a result of a problem related to MOB's schedule with SP01, and the operation in the last two stations, which was restricted to odd hours.

Usually, diurnal variations in the TWSTFT data were observed. The cause of the diurnals is not well understood, and they might prevent from reaching a 1 ns-uncertainty for the CALR values in some cases.

6.1. DATA COLLECTION AND INDIVIDUAL RESULTS RELATIVES 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:

$[\mathrm{CCD}+\mathrm{REFDLYdiff}](\mathrm{MOB@TIM},\mathrm{TIM})\_1$: mean_even = -761.06 ns, TDEV = 0.26 ns, N: 37 values
mean_odd = -761.73 ns, TDEV = 0.17 ns, N: 80 values

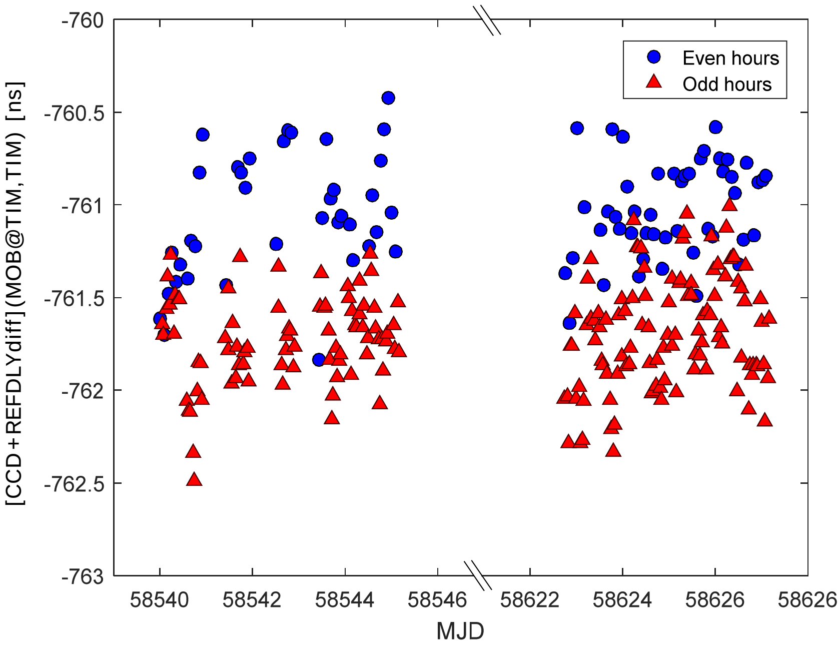
$[\mathrm{CCD}+\mathrm{REFDLYdiff}](\mathrm{MOB@TIM},\mathrm{TIM})\_2$: mean_even = -761.01 ns, TDEV = 0.23 ns, N: 48 values
mean_odd = -761.69 ns, TDEV = 0.20 ns, N: 107 values

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 each REFDLYdiff value, providing the uncertainty $\mathrm{u}_{\mathrm{CCDi}}$; i = 1, 2.

Since the combined standard deviation $\mathrm{CSD}=\sqrt{(\mathrm{u}_{\mathrm{CCD1}})^2+(\mathrm{u}_{\mathrm{CCD2}})^2}$ = 0.35 ns (0.26 ns odd hours) was higher than the change in the CCD value along the trip, $\mathrm{CCD}_1-\mathrm{CCD}_2$ = 0.05 ns (0.04 ns odd hours), 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



6.1.2. MOB AT RISE

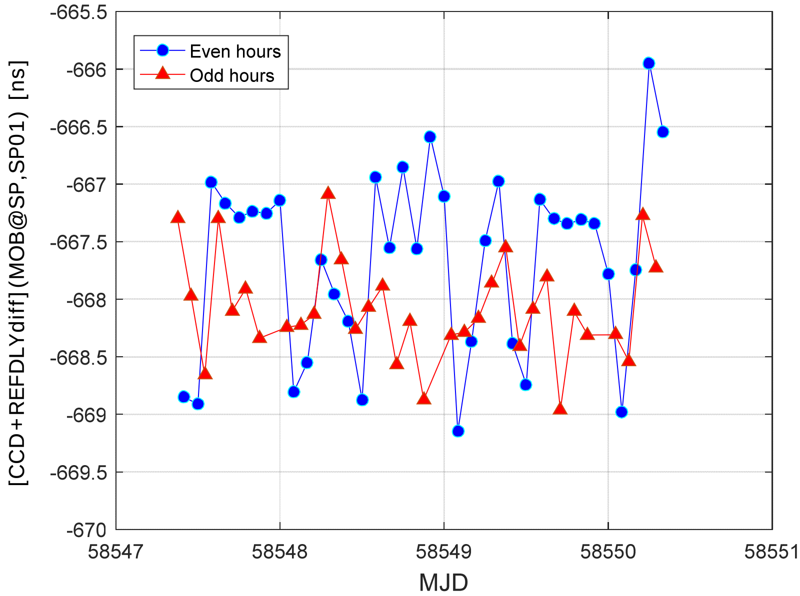
The picture of the Figure 6-2 shows the trailer during pre-operation preparations at RISE.

Figure 6-2: View of the mobile station at RISE

The following result, illustrated in Figure 6-3, was obtained:

[CCD + REFDLYdiff](MOB@SP, SP): mean_even = -667.67 ns, TDEV=0.65 ns, N: 36 values
mean_odd = -668.11 ns, TDEV=0.40 ns, N: 33 values

Figure 6-3: Result of common-clock measurements MOB at SP



6.1.3. MOB AT PTB

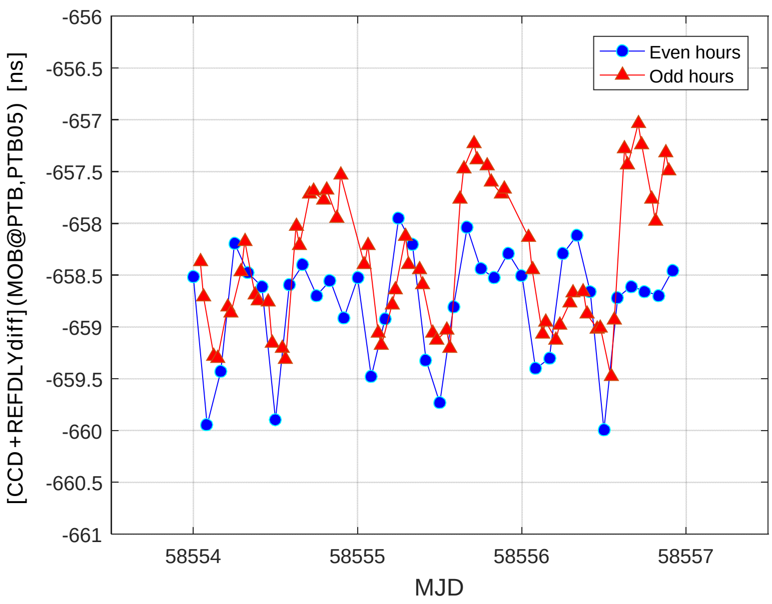
The picture of the Figure 6-4 shows the trailer while was installed at PTB.

Figure 6-4: View of the mobile station at PTB

The following result, illustrated in Figure 6-5, was obtained:

[CCD + REFDLYdiff](MOB@PTB, PTB): mean_even = -658.77 ns, TDEV=0.55 ns, N: 36 values
mean_odd = -658.37 ns, TDEV=0.49 ns, N: 66 values

Figure 6-5: Result of common-clock measurements MOB at PTB



6.1.4. 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 setting up. CCD involving IT01 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 6-6 shows the trailer while was installed at INRIM.

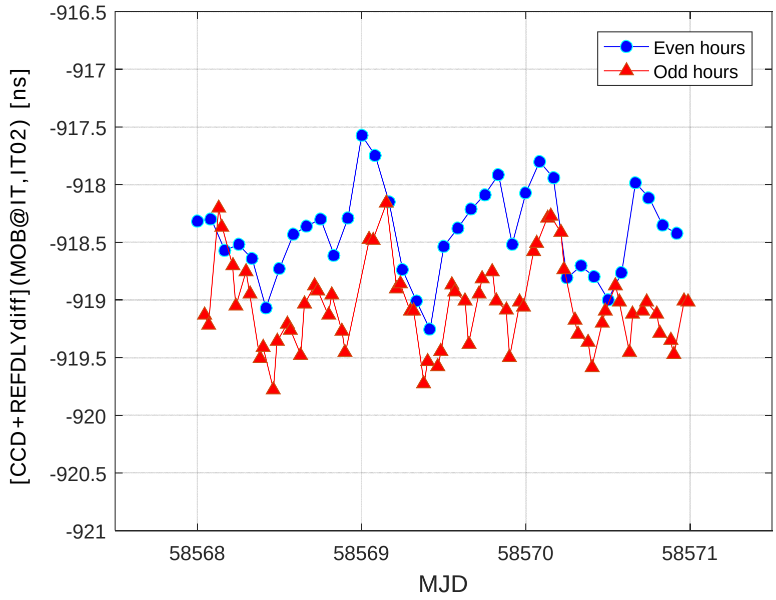
Figure 6-6: View of the mobile station at INRIM

6.1.4.1. CCD measurement involving IT02

After considering the REFDLYdiff(MOB@IT, IT02) on the combination of TWSTFT measurement data, the following result, illustrated in Figure 6-7, was obtained for the CCD measurement involving IT02 station at INRIM:

$[\mathrm{CCD} + \mathrm{REFDLYdiff}](\mathrm{MOB@IT}, \mathrm{IT02})$: mean_even = -918.42 ns, TDEV=0.39 ns, N: 36 values
mean_odd = -919.04 ns, TDEV=0.33 ns, N: 69 values

Figure 6-7: Result of common-clock measurements MOB at INRIM, IT02

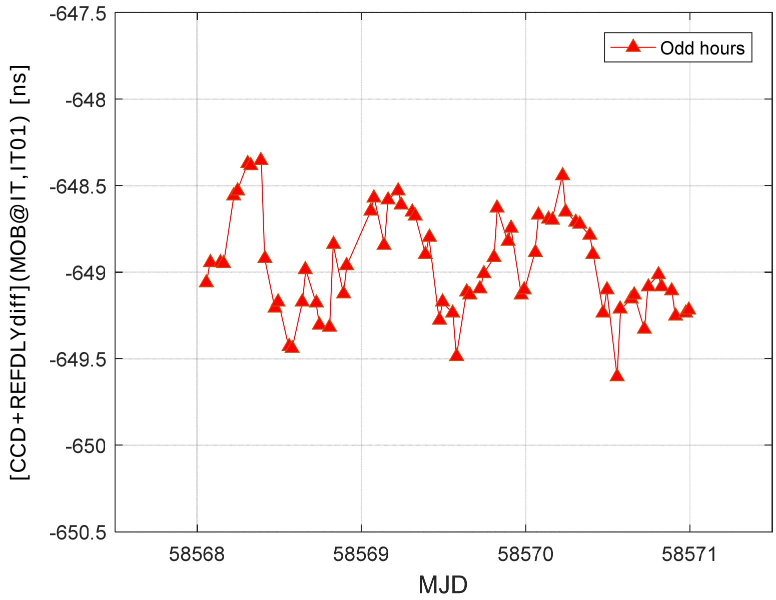


6.1.4.2. CCD measurement involving IT01

Similarly, the following result, illustrated in Figure 6-8, was obtained for the CCD measurement involving IT01 station at INRIM:

$[\mathrm{CCD} + \mathrm{REFDLYdiff}](\mathrm{MOB@IT}, \mathrm{IT01})$: mean_odd = -648.95 ns, TDEV=0.28 ns, N: 70 values

Figure 6-8: Result of common-clock measurements MOB at INRIM, IT01



6.1.5. MOB AT ROA

The photography of the Figure 6-9 shows the MOB and ROA fixed stations antennas during the visit to the Spanish Navy Observatory.

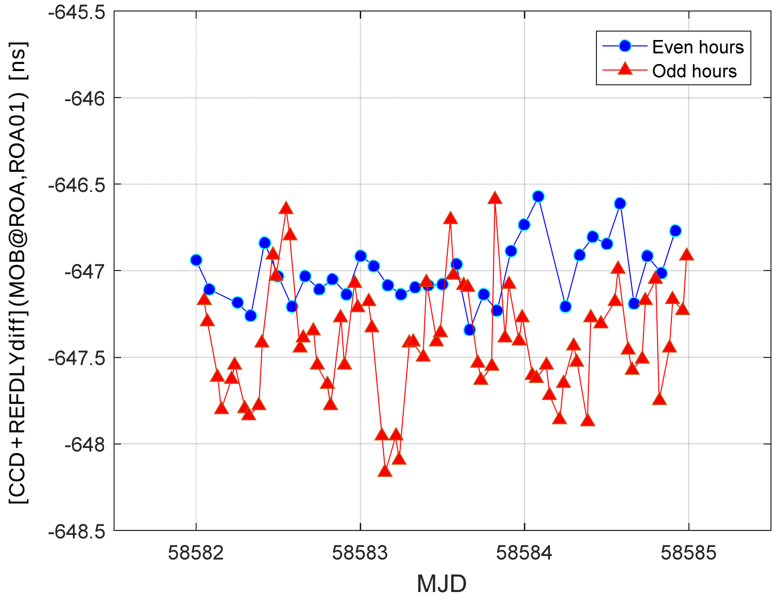
Figure 6-9: Foreground view of the mobile station antenna at ROA and ROA fixed station antennas in the background

6.1.5.1. CCD measurement involving ROA01

Following a procedure similar to the one used for ROA, the result obtained, illustrated in Figure 6-10, was:

$[\text{CCD} + \text{REFDLYdiff}](\text{MOB@ROA}, \text{ROA1})$: mean_even = -647.01 ns, TDEV=0.12 ns, N: 34 values
mean_odd = -647.40 ns, TDEV=0.31 ns, N: 71 values

Figure 6-10: Result of common-clock measurements MOB at ROA, ROA01

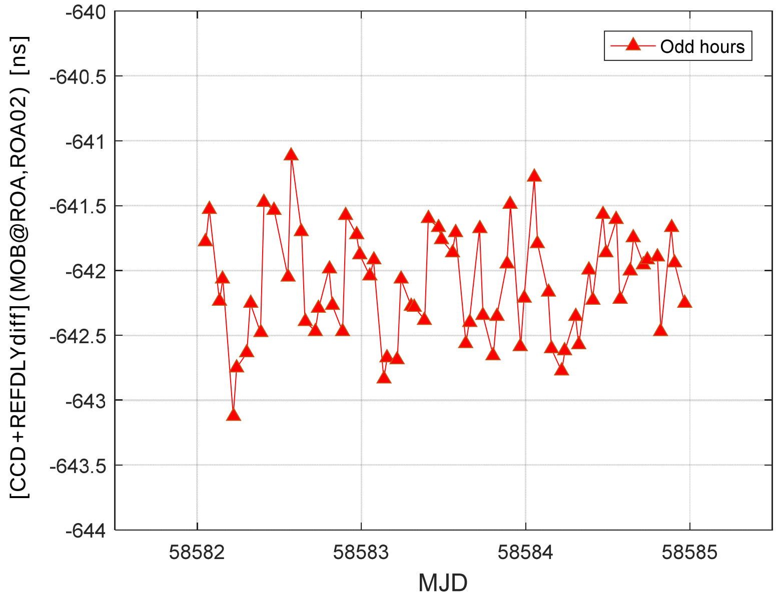


6.1.5.2. CCD measurement involving ROA02

Similarly, the following result, illustrated in Figure 6-11, was obtained for the CCD measurement involving ROA02 station at ROA:

$$[\mathrm{CCD} + \mathrm{REFDLYdiff}](\mathrm{MOB@ROA}, \mathrm{ROA02})\text{: mean\_odd = -642.10 ns, TDEV 0.32 ns, N: 70 values}$$

Figure 6-11: Result of common-clock measurements MOB at ROA, ROA02



6.1.6. MOB AT OP

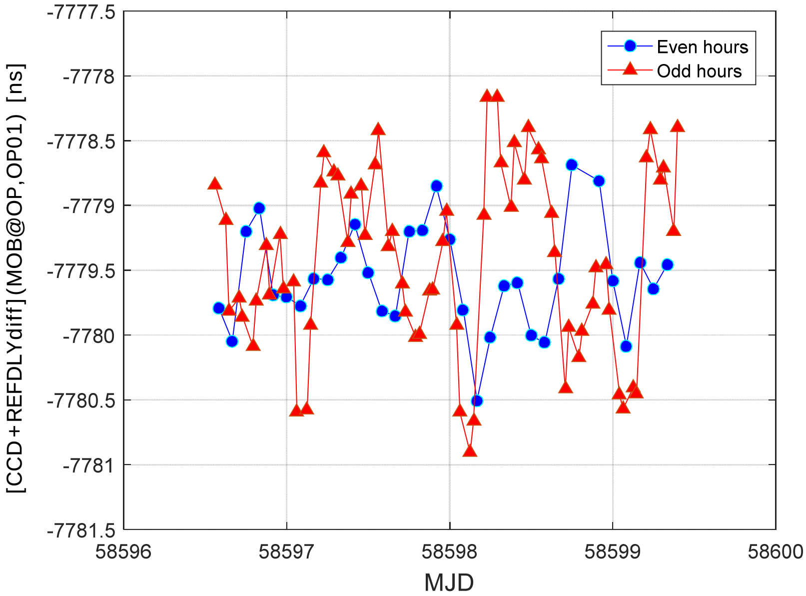
Figure 6-12 shows a photograph of the trailer while was installed at OP:

Figure 6-12: View of the mobile station at OP

The following result, depicted in Figure 6-13, was obtained:

$[\mathrm{CCD} + \mathrm{REFDLYdiff}](\mathrm{MOB@OP}, \mathrm{OP})$: mean_even = -7779.56 ns, TDEV=0.35 ns, N: 33 values
mean_odd = -7779.41 ns, TDEV=0.52 ns, N: 69 values

Figure 6-13: Result of common-clock measurements MOB at OP, circles: data taken at even hours, triangles: data taken at odd hours



6.2. TWSTFT LINK CALIBRATION VALUES

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

6.2.1. TWSTFT LINK CALIBRATION VALUES

Table 6-1 explains the results obtained for INRIM, OP, ROA, PTB and SP for all possible pair combinations, when eq. 14 is applied.

Table 6-1: CALR values (in ns) for all possible combinations, ESDVAR reset to zero.

New CALR for station "j" against "k", ESDVAR set to zero					
	CCD(MOB@j,j) + REFDLYdiff(MOB@j, j)	Bridged CCD(MOB@k,k) + REFDLYdiff(MOB@k, k)	SCD(j)	SCD(k)	CALR
CALR*(SP01,PTB05)	-667.89	-658.76	90.01	99.32	**0.17**
CALR*(SP01,IT02)	-667.89	-918.50	90.01	109.52	**273.82**
CALR*(SP01,OP01)	-667.89	-7779.24	90.01	92.18	**7113.52**
CALR*(SP01,ROA01)	-667.89	-647.24	90.01	91.26	**-19.40**
CALR*(PTB05,SP01)	-658.57	-667.90	99.32	90.01	**0.02**
CALR*(PTB05,IT02)	-658.57	-920.18	99.32	109.52	**275.51**
CALR*(PTB05,OP01)	-658.57	-7778.30	99.32	92.18	**7112.59**
CALR*(PTB05,ROA01)	-658.57	-647.16	99.32	91.26	**-19.46**
CALR*(IT02,SP01)	-918.73	-668.37	109.52	90.01	**-273.57**
CALR*(IT02,PTB05)	-918.73	-657.61	109.52	99.32	**-275.02**
CALR*(IT02,OP01)	-918.73	-7778.19	109.52	92.18	**6838.42**
CALR*(IT02,ROA01)	-918.73	-646.68	109.52	91.26	**-294.01**
CALR*(OP01,SP01)	-7779.49	-668.31	92.18	90.01	**-7113.35**
CALR*(OP01,PTB05)	-7779.49	-659.54	92.18	99.32	**-7112.81**
CALR*(OP01,IT02)	-7779.49	-919.69	92.18	109.52	**-6838.75**
CALR*(OP01,ROA01)	-7779.49	-647.25	92.18	91.26	**-7133.16**
CALR*(ROA01,SP01)	-647.20	-668.26	91.26	90.01	**19.80**
CALR*(ROA01,PTB05)	-647.20	-658.78	91.26	99.32	**19.64**
CALR*(ROA01,IT02)	-647.20	-919.91	91.26	109.52	**294.67**
CALR*(ROA01,OP01)	-647.20	-7779.72	91.26	92.18	**7133.43**
CALR*(SP01,IT01)	-667.67	-648.77	90.01	109.52	**0.61**
CALR*(PTB05,IT01)	-658.77	-648.11	99.32	109.52	**-0.46**
CALR*(IT02,IT01)	-918.42	-647.81	109.52	109.52	**-274.31**
CALR*(OP01,IT01)	-7779.56	-648.64	92.18	109.52	**-7113.58**
CALR*(ROA01,IT01)	-647.01	-648.93	91.26	109.52	**20.18**
CALR*(SP01,ROA02)	-667.67	-642.46	90.01	91.26	**-23.96**

CALR*(PTB05,ROA02)	-658.77	-641.44	99.32	91.26	**-25.39**
CALR*(IT02,ROA02)	-918.42	-641.67	109.52	91.26	**-298.71**
CALR*(OP01,ROA02)	-7779.56	-642.43	92.18	91.26	**-7138.05**
CALR*(ROA01,ROA02)	-647.01	-642.5	91.26	91.26	**-4.51**
CALR*(IT01,ROA02)	-648.95	-642.10	109.52	91.26	**-25.11**

The calibration values in Table 6-1 (CALR*) have been obtained from the one half of the sum of the average values collected separately in even and odd hours, and take into account that the earth stations delay variations (ESDVAR) will be re-set 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, convenient to compare the new values against old ones corrected by the ESDVAR, 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 for old CALR modified by ESDVAR, as shown in the Table 6-2.

Table 6-2: $CALR_{interim}$ for all possible combinations, except for IT01 and ROA02 stations.

CALRinterim for station "j" against "k", ESDVAR unchanged			
	ESDVAR(j)	ESDVAR(k)	$CALR_{OLD}$(j, k) + 0.5*[ESDVAR(j) - ESDVAR(k)]
CALR(SP01,PTB05)	-0.53	-5.92	**1.10**
CALR(SP01,IT02)	-0.53	-7.4	**275.33**
CALR(SP01,OP01)	-0.53	-3.53	**7113.70**
CALR(SP01,ROA01)	-0.53	-27.93	**-19.90**
CALR(PTB05,IT02)	-5.92	-7.4	**275.64**
CALR(PTB05,OP01)	-5.92	-3.53	**7112.60**
CALR(PTB05,ROA01)	-5.92	-27.93	**-20.60**
CALR(IT02,OP01)	-7.4	-3.53	**6837.16**
CALR(IT02,ROA01)	-7.4	-27.93	**-296.14**
CALR(OP01,ROA01)	-3.53	-27.93	**-7133.40**

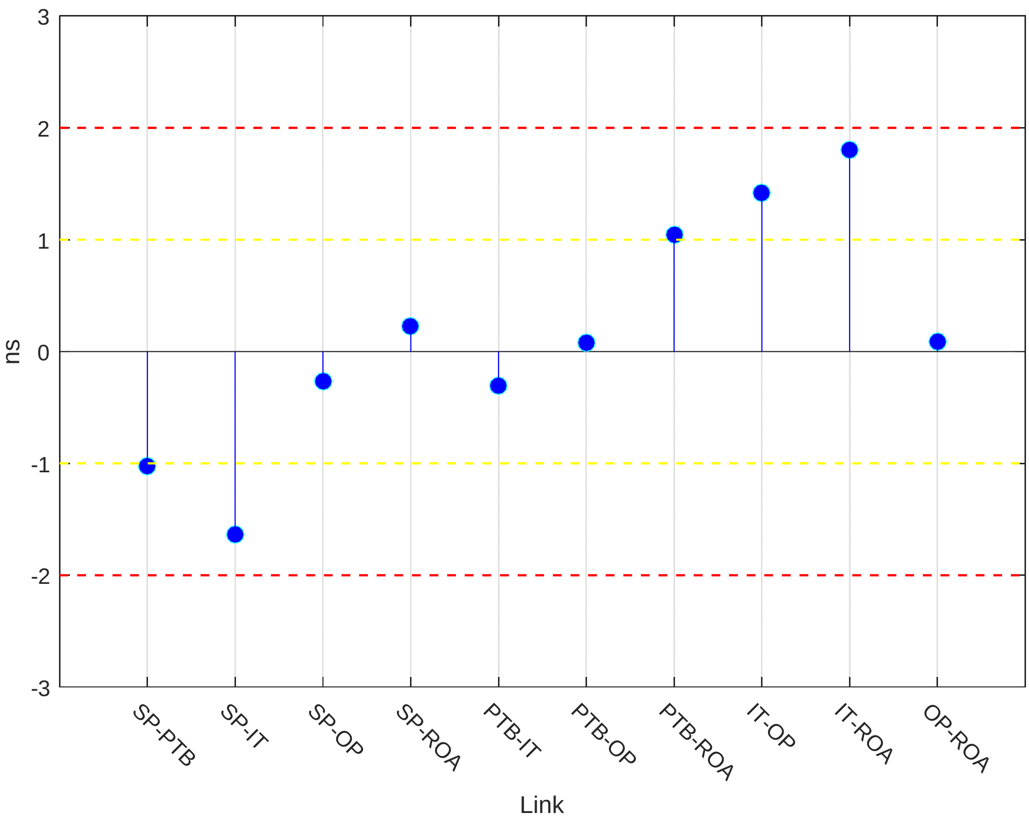
The "*" in $\mathrm{CALR}^*(\mathrm{j,k})$ means that $\mathrm{CALR}^*(\mathrm{j,k})$ is not generally equal to $-\mathrm{CALR}^*(\mathrm{k,j})$. $\mathrm{CALR}(1,2)$ new calibration values of Table 6-3, with calibration switch S = 1, are computed by the weighted average of the corresponding values of the last column of Table 6-1: $\mathrm{CALR}(1,2) = (\mathrm{W1} * \mathrm{CALR}^*(1,2) - \mathrm{W2} * \mathrm{CALR}^*(2,1))/(\mathrm{W1} + \mathrm{W2})$, where W1 and W2 weights are based on the TDEV results.

In Table 6-3 the results obtained hitherto are contrasted with the previously assumed CALR values [RD08], conveniently updated with the ESDVAR values.

Table 6-3: $CALR_{interim}$ and new CALR values (in ns) obtained during the campaign

Link	CALRinterim	CALR	CALR variation
SP01-PTB05	1.10	0.08	**-1.02**
SP01-IT02	275.33	273.66	**-1.67**
SP01-OP01	7113.70	7113.41	**-0.29**
SP01-ROA01	-19.90	-19.73	**0.17**
PTB05-IT02	275.64	275.41	**-0.23**
PTB05-OP01	7112.60	7112.67	**0.07**
PTB05-ROA01	-20.60	-19.52	**1.08**
IT02-OP01	6837.16	6838.58	**1.42**
IT02-ROA01	-296.14	-294.28	**1.86**
OP01-ROA01	-7133.40	-7133.24	**0.16**

Figure 6-14: Differences between new CALR and $CALR_{interim}$ values.



It should be noted that the observed differences illustrated in Figure 6-14 are not significant. The discrepancy can be considered not significant when a difference lies below the expanded uncertainty (red line), obtained for a coverage factor of 2 (which gives a level of confidence of approximately 95 %), taking as reference the traditionally stated uncertainty of 1 ns for this kind of links.

6.2.2. SUMMARY AND DISCUSSION OF UNCERTAINTY CONTRIBUTIONS

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

The total calibration uncertainty U is given by the geometric sum of components coming from statistical analysis, or type "a" (ua), and components type "b" or evaluated by means other than the statistical analysis of series of observations (ub):

Two statistical uncertainty components were identified:

ua(i) reflects the instability of CCD or indirect CCD (baseline-based mode) measurements at site i. These include the contributions of the fixed TWSTFT installation (remote installation in baseline-based mode), the traveling two-way equipment, and the uncertainty associated with the difference of REFDELAY values.

As explained in section 6.1.1, the statistical measurement uncertainty was stated by the worst TDEV value estimated for the range from 12 to 24 hours, rather than by $\mathrm{sigma}/\sqrt{\mathrm{N}}$ (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 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 between 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.

ub,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 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 6-4: Uncertainty due to the impact of temperature variations

location	device	Temp coef.	unit	variation	unit	Contribution to ub,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
				ub,1 (ps) =		**$136\times\sqrt{2}=192$**

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

Other uncertainty contributions in these equipments are:

Table 6-5: Uncertainty due to other contributions related to mobile TWSTFT station

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

ub,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).

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

ub,I = 0.27 ns

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

II) Laboratory station and related equipment

ub,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 6-6.

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

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

ub,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 link-mode approach, this contribution was estimated as:

ub,5 = 0.020 ns

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

ub,II = 0.09 ns

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

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

ub,7 – uncertainty due to contributions in equipments related to laboratory stations.

This uncertainty contribution resulting from the instabilities signal distribution systems has been estimated considering the instability of PDIS/FDIS and rise time of 1PPS signals [RD11-12].

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

ub,7 = 0.200 ns

ub,8 – uncertainty due to TIC resolution.

According to the description in the manual of the widely used TIC SR620 [RD11], ub,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.

ub,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 [RD11], 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, ub,9 was estimated in 130 ps for each link.

Table 6-7 summarizes the group III uncertainty contribution values. All values are in ns.

Table 6-7: Uncertainty contributions and combined uncertainty - Group III

Case	ub,6(1)	ub,6(2)	ub,7	ub,8	ub,9	ub,III
CALR(UTC(j), UTC(k))	0.05	0.05	0.20	-	0.13	**0.25**

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 are quite different in magnitude and they seem to "come and go" in the course of time without a root cause would be known. In this case 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 stated in three days, 3) CCD in this exercise showed a maximum amplitude (peak value) of about 2.5 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. On these assumptions, this potential deviation can reach 0.4 ns. Consequently, 0.23 ns ($0.4/\sqrt{3}$, considering a uniform distribution) has been considered as the ADUO uncertainty contribution.

Here, as in all cases mentioned before, we distinguish first between data collected in even and odd hours, and the average is calculated separately for each data set. The uncertainty values were found in some cases significantly smaller than the ordinate difference between even and odd hour data, as it is shown in Figure 6-15. That is the reason why an uncertainty of 0.5 ns, estimated from standard deviation of residuals of these differences (0.45 ns for baseline-based mode), has been included. As expected, site mode shows a larger difference, around 0.65 ns.

The table below gives the uncertainties budget that matches findings in this campaign quite well.

Figure 6-15: Differences between results in even and odd hours.

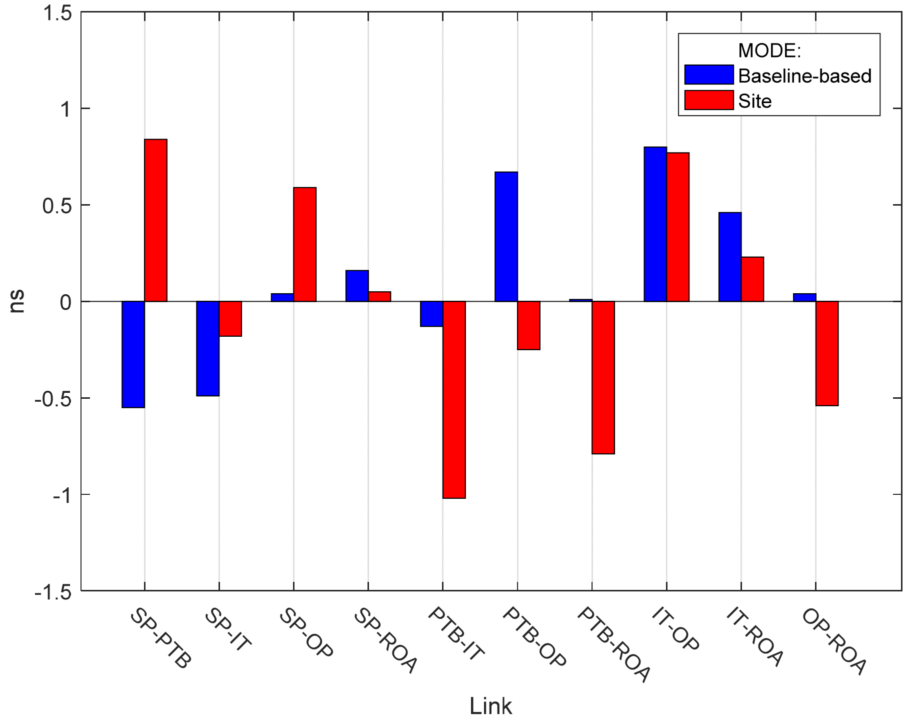


Table 6-8: Uncertainty contributions and combined uncertainty - Group IV

Sub group	Source	Contribution to ub,IV (ns)
Sat com	Tx power, C/N0	0.150
Atmosphere	Ionosphere	0.030
	Troposphere	0.001
	Temperature variations on ground station	0.100
	Humidity changes	0.010
Satellite motion	ADUO	0.230
	Residual Sagnac (A)	0.250
	Path delay difference (B)	0.002
Even and odd hours measures	Possible interferences between PRN codes	0.500
	ub,IV =	0.63

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

Table 6-9 summarizes the uncertainty contribution case by case. All values are in ns, U represents the 1-σ uncertainty, rounded to 0.1 ns.

Table 6-9: Uncertainty contributions and combined uncertainty U

Case	ua(1)	ua,f(2)	ub,I	ub,II	ub,III	ub,IV	U
CALR(SP01,PTB05)	0.33	0.16	0.27	0.09	0.25	0.63	**0.8**
CALR(SP01,IT02)	0.27	0.27	0.27	0.09	0.25	0.63	**0.8**
CALR(SP01,OP01)	0.28	0.17	0.27	0.09	0.25	0.63	**0.8**
CALR(SP01,ROA01)	0.25	0.10	0.27	0.09	0.25	0.63	**0.8**
CALR(SP01,IT01)	0.28	0.28	0.27	0.09	0.25	0.63	**0.8**
CALR(SP01,ROA02)	0.18	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(PTB05,IT02)	0.36	0.20	0.27	0.09	0.25	0.63	**0.8**
CALR(PTB05,OP01)	0.11	0.14	0.27	0.09	0.25	0.63	**0.8**
CALR(PTB05,ROA01)	0.20	0.10	0.27	0.09	0.25	0.63	**0.8**
CALR(PTB05,IT01)	0.27	0.28	0.27	0.09	0.25	0.63	**0.8**
CALR(PTB05,ROA02)	0.21	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(IT02,OP01)	0.27	0.15	0.27	0.09	0.25	0.63	**0.8**
CALR(IT02,ROA01)	0.26	0.10	0.27	0.09	0.25	0.63	**0.8**
CALR(IT02,IT01)	0.19	0.28	0.27	0.09	0.25	0.63	**0.8**
CALR(IT02,ROA02)	0.10	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(OP01,ROA01)	0.31	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(OP01,IT01)	0.23	0.28	0.27	0.09	0.25	0.63	**0.8**
CALR(OP01,ROA02)	0.27	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(ROA01,IT01)	0.25	0.28	0.27	0.09	0.25	0.63	**0.8**
CALR(ROA01,ROA02)	0.25	0.13	0.27	0.09	0.25	0.63	**0.8**
CALR(IT01,ROA02)	0.10	0.13	0.27	0.09	0.25	0.63	**0.8**

6.3. DISCUSSION OF RESULTS

During the campaign, new CALR values were determined with uncertainties of around 0.8 ns. These uncertainties are of similar order than those got in previous campaigns [RD03, RD07, RD08 and RD09]. 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.

The apparent changes in the CALR values for all of the links show a non-significant discrepancy with respect to the old ones, with discrepancy values clearly below 2 ns for all links, being most of them between the range of 0 and 1 ns.

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 proposed that the ESDVAR be set to zero. The calibration identifiers 489 - 516 were provided by BIPM.

ROA1 REFDELAY value will be updated jointly with the CALR implementation, passing from 966.641 ns to 964.343 ns, so the CALR values indicated in Table 6-1 have been increased in 2.3 ns.

SP01

```
* CAL   489 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.900 ns
* CAL   496 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   497 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   498 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   499 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   500 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   501 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

                CI S    CALR
  SP01 PTF101  489 1    20.000
  SP01  PTB05  496 1     0.100
  SP01   IT02  497 1   273.700
  SP01   OP01  498 1  7113.400
  SP01  ROA01  499 1   -22.000
  SP01   IT01  500 1     0.600
  SP01  ROA02  501 1   -24.000
```

PTB05

```
* CAL   490 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   496 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   502 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   503 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   504 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   505 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   506 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

                CI S    CALR
 PTB05 PTF101  490 1    20.200
 PTB05   SP01  496 1    -0.100
 PTB05   IT02  502 1   275.400
 PTB05   OP01  503 1  7112.700
 PTB05  ROA01  504 1   -21.800
 PTB05   IT01  505 1    -0.500
 PTB05  ROA02  506 1   -25.400
```

IT02

```
* CAL   491 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.900 ns
* CAL   497 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   502 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   507 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   508 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   509 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   510 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

              CI S    CALR
  IT02 PTF101 491 1  -253.700
  IT02   SP01 497 1  -273.700
  IT02  PTB05 502 1  -275.400
  IT02   OP01 507 1  6838.600
  IT02  ROA01 508 1  -296.600
  IT02   IT01 509 1  -274.300
  IT02  ROA02 510 1  -298.700
```

OP01

```
* CAL   492 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   498 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   503 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   507 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   511 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   512 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   513 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

              CI S    CALR
  OP01 PTF101 492 1 -7093.600
  OP01   SP01 498 1 -7113.400
  OP01  PTB05 503 1 -7112.700
  OP01   IT02 507 1 -6838.600
  OP01  ROA01 511 1 -7135.500
  OP01   IT01 512 1 -7113.600
  OP01  ROA02 513 1 -7138.100
```

ROA01

```
* CAL   493 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.900 ns
* CAL   499 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   504 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   508 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   511 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   514 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   515 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

                CI S     CALR
 ROA01 PTF101  493 1     41.900
 ROA01   SP01  499 1     22.000
 ROA01  PTB05  504 1     21.800
 ROA01   IT02  508 1    296.600
 ROA01   OP01  511 1   7135.500
 ROA01   IT01  514 1     22.500
 ROA01  ROA02  515 1     -2.200
```

IT01

```
* CAL   494 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.900 ns
* CAL   500 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   505 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   509 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   512 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   514 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   516 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

                CI S     CALR
  IT01 PTF101  494 1     19.600
  IT01   SP01  500 1     -0.600
  IT01  PTB05  505 1      0.500
  IT01   IT02  509 1    274.300
  IT01   OP01  512 1   7113.600
  IT01  ROA01  514 1    -22.500
  IT01  ROA02  516 1    -25.100
```

ROA02

```
* CAL   495 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.900 ns
* CAL   501 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   506 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   510 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   513 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   515 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns
* CAL   516 TYPE: PORT ES REL        MJD: 58629  EST. UNCERT.:    0.800 ns

                CI S     CALR
 ROA02 PTF101  495 1    44.800
 ROA02   SP01  501 1    24.000
 ROA02  PTB05  506 1    25.400
 ROA02   IT02  510 1   298.700
 ROA02   OP01  513 1  7138.100
 ROA02  ROA01  515 1     2.200
 ROA02   IT01  516 1    25.100
```

8. LESSONS LEARNT

The current campaign was the seventh one involving the mobile station provided by TimeTech, and the fourth one to involve Galileo GMS. It is still possible to learn and improve some aspects looking towards future campaigns.

1) Proposals to the GST(MC)/UTC(k) sites visited in future

Adherence to the Site Preparation Document is mandatory as it is helpful for all. ITU-files should be built according to [RD01], including the designation of stations etc. This is a recurrent aspect, proposed during the previous campaign.

2) Adverse weather conditions

Due to several changes over the original schedule, the visit to RISE laboratory was moved at the beginning of campaign, where cold weather conditions were not suitable for the realization of this kind of activity, with slippery roads due to presence of snow and ice. So for future calibrations, it would be recommended to delay the start of calibration in order to avoid cold weather, at least in the northernmost laboratories, or to schedule them to the end of the campaign.

Acknowledgement

The support received at GCC-1 and GCC-2 by the local teams was instrumental for getting anything done at both GCC sites.

Support in the installation and operation of the traveling station at GCC-2 by Juan Manuel González, from ROA, as well as the helpful discussion during the writing of this report, were essential for the successful closure of that activity.

It is gratefully acknowledged the Thorsten's devotion to work and dedication all the time. Working with Thorsten Feldmann from TimeTech during the campaign, and particularly with the driver Ioannis Charakopidis, was a pleasure.

END OF DOCUMENT