GNSS CALIBRATION REPORT

G1G2_1017-2021

Prepared by: Héctor Esteban (ROA)

Authorized by: BIPM

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1. INTRODUCTION

1.1. SCOPE OF THE DOCUMENT

In 2014, as a result of a CCTF recommendation for a collaboration between the BIPM and the RMOs for GNSS equipment calibration, some National Metrology Institutes (NMIs) and Designated Institutes (DIs), were selected to be G1 laboratories, to function as regional nodes for the GPS calibrations. The mission of these Labs, once calibrated by BIPM, was to perform new calibration trips between G2 laboratories, under the responsibility of RMOs.

ROA, as EURAMET G1 laboratory, organized this year, a GNSS receiver relative calibration campaign, which took place at IPQ (Portugal).

In this campaign was carried out a differential calibration with closure, where the travelling system served as a transfer between all systems visited during the trip and the reference receiver RO10. This last was calibrated and reported this year (Cal_Id=1001-2020 [RD01]), being continuously monitored since then.

1.2. DOCUMENT STRUCTURE

The current campaign has been carried out in accordance with ROA calibration procedure and following as much as possible the BIPM guidelines for GNSS calibrations [RD02]. The results will be reported using Cal_Id 1017-2021, and they will provide the visited receivers' internal delays for GPS (C1, P1, P2) and Galileo (E1, E5a) code signals.

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

Section 2 reports, the participating laboratories, dates of visits, and GNSS receivers involved in this calibration campaign.

Section 3 presents an overview of the travelling equipment specifically prepared for this activity.

Section 4 basically describes the calibration procedure.

Section 5 explains the data processing carried out by our own software and all the necessary tables to get the results.

Section 6 is focused in the uncertainty estimation, in all the terms taken into account for the uncertainty budget.

Section 7 shows the final results, with the new internal delays, as well as all the necessary information to get them.

The report concludes with the Annex-A for each visited receiver, and the Annex-B, which contains all the figures with the common clock differences (CCD).

1.3. DOCUMENTS

REFERENCES	
RD01	BIPM report 1001-2020 V1.2 / 20210712, subject: 2021 Group 1 GNSS calibration trip (Phase 2).
RD02	BIPM guidelines for GNSS calibration, V3.2, 15/02/2016.
RD03	G. Petit, Z. Jiang, P. Moussay, J. White, E. Powers, G. Dudle, P. Uhrich, 2001, Progresses in the calibration of geodetic like GPS receivers for accurate time comparisons, Proc. 15th EFTF, pp. 164-166.
RD04	p. Defraigne, C. Bruyninx, 2001, Time Transfer for TAI using a geodetic receiver, An Example with the Ashtech ZXII-T, GPS Solutions, 5(2), pp. 43-50.
RD05	J. Kouba, P. Heroux, 2002, Precise Point Positioning Using IGS Orbit and Clock Products, GPS Solutions, Vol. 5, No. 2, pp. 12-28.

1.4. ACRONYMS AND ABBREVIATIONS

Table 1-1: List of Acronyms and Abbreviations

Acronym	Definition
BIPM	Bureau International des Poids et Mesures.
CCD	Common Clock Difference.
CCTF	Consultative Committee for Time and Frequency.
CGGTTS	CCTF Generic GNSS Time Transfer Standard.
CCTF	Consultative Committee for Time and Frequency.
DI	Designated Institute.
EURAMET	European Association of National Metrology Institutes.
Galileo	European GNSS
GNSS	Global Navigation Satellite System
GPS	Global Positioning System.
IGS	International GNSS Service.
IPQ	Instituto Português da Qualidade, Lisbon, Portugal.
ITRF	International Terrestrial Reference Frame.
MJD	Modified Julian Date.
NMI	National Metrology Institute.
NRCan	Natural Resources Canada.
PPP	Precise Point Positioning.
RINEX	Receiver Independent Exchange Format.
RMO	Regional Metrology Organization.
ROA	Real Instituto y Observatorio de la Armada, San Fernando, Spain.
TDEV	Time Deviation. Is a measure of time stability based on the modified Allan variance.
TIC	Time Interval Counter.
UTC	Coordinated Universal Time.
UTC(k)	Version of UTC realized at each of the contributing NMIs.

Acronym	Definition
	CGGTTS specific acronyms
CAB DLY	Field present in the CGGTTS header. It is the group delay inside the antenna cable, including both end connectors.
INT DLY	Field present in the CGGTTS header. It is the code- and frequency-dependent combined electric delay of the GNSS signal inside the antenna and the receiver**.** See also [RD03].
REF DLY	Field present in the CGGTTS header. It is the time offset between the receiver internal clock (or its conventional realization by an external signal) and the local clock at the station. See also [RD03].
REFGPS	Time difference between the reference clock and GPS time, for each satellite at the mid-point of the 13 min track. Receiver delay, cable delay, tropospheric delay and (for one single code) modelled ionospheric delay corrections have been applied.

2. PARTICIPANTS AND SCHEDULE

Participating laboratories, dates and GPS receivers involved in the calibration campaign are summarized in Table 2-1 and Table 2-2. Nevertheless, a complete information related with the receiver set-up and the signal distribution system have been provided by all Labs (see relevant Annex-A).

Table 2-1: List of participants.

Institute	Point of contact	Postal address
ROA	Dr Héctor Esteban Tel +34 956599286 hesteban@roa.es	Real Instituto y Observatorio de la Armada Plaza de las Tres Marinas s/n 11100, San Fernando Spain
IPQ	Mr Carlos Pires Tel. +351 212948158 CarlosP@ipq.pt	Instituto Português da Qualidade Rua António Gião, 2 2829-513 Caparica Portugal

Table 2-2: Schedule of the campaign and involved receivers.

Institute	Status of equipment	Dates of measurements	Receiver type	BIPM code
ROA	Traveling		Septentrio PolaRx5TR	TR
ROA	Group 1 reference	MJD: 59366-59370 01/06/21-05/06/21	Septentrio PolaRx5TR	RO10
IPQ	Group 2	MJD: 59384-59388 19/06/21-23/06/21	Piktime TTS-4	IP05
ROA	Group 1 reference	MJD: 59414-59418 19/07/21-23/07/21	Septentrio PolaRx5TR	RO10

3. THE ROA TRAVELING EQUIPMENT

Traveling equipment consists of one shipping box containing the following items:

- 1 PolaRx5TR receiver SN: 4701310.
- 1 Portable PC Toshiba Tecra M9 laptop SN: X7052920H.
- 1 Novatel antenna GPS-703-GGG SN: NEG15300017.
- 60 m H155 antenna cable.

As it is shown in the equipment list, only one receiver was used as traveling equipment. We used a direct antenna cable to connect the PolaRx5TR and the Novatel antenna.

The PolaRx5TR receiver has been configured with the internal auto-compensation delay mode PPS IN enabled.

4. CALIBRATION PROCEDURE

The calibration has been performed based on C1, P3 GPS and E1, E3 Galileo CGGTTS files. Instead using the files automatically generated by each particular receiver, we have generated them from RINEX V.3 observation files, by means of R2CGGTTS software tool V8.3 developed at the Royal Observatory of Belgium [RD04]. This was done to avoid any systematic error induced by the use of a different tropospheric model, and mainly by imprecise antenna positions.

On this latter point, the coordinates of the antenna phase centre at each location have been especially computed for the calibration period from RINEX files by using the NRCan PPP software [RD05], so the time transfer error caused by this factor is nearly negligible.

Basically the calibration consists on the following. From the known delays of the reference receiver (RO10) and an average of the traveling receiver delays between the start and the end of the campaign, we can obtain INTDLY(C1), INTDLY(P1) and INTDLY(P2) for the receivers in the visited Labs. As the calibration is consisting in building differential pseudo-ranges for each code C1, P1 and P2 between pairs of receivers in common-clock set-up, they can be easily obtained by using the data collected in C1 and also in P3 (GZ) CGGTTS files:

$$\gamma = (f_1/f_2)^2 = (77/60)^2$$

$$REFGPS(P1) = REFSYS(P3) + MSIO$$

$$REFGPS(P2) = REFGPS(P3) + \gamma \times MSIO$$

where *MSIO* are the measured ionospheric delays.

In a similar way, with $\gamma = (E1/E5a)^2 = (1575.42/1176.45)^2$, INTDLY(E1) and INTDLY(E5a) can be obtained from EZ CGGTTS files.

5. DATA PROCESSING

For the calculation process we have used a ROA-authored program, in which the common clock differences (CCD) are obtained from the common-view of CGGTTS files. For each location, the coordinates of the antenna have been carefully calculated for the calibration period.

As was stated before, from the known delays of the reference receiver RO10, it has been obtained the internal delays for the receiver at the visited site. Normally the antenna cable delay (CABDLY) is maintained without any change, and the reference delay (REFDLY) is normally updated, anyway, any variation with respect to the true values, will be assumed by the INTDLY results.

Table 5-1 summarizes the initial delays of the IPQ receiver at the start of calibration. With REF DLY and CAB DLY values, and with INT DLY values set to zero, new CGGTTS files have been generated for this receiver. Tables 5-2 and 5-3 show the raw CCD differences at the visited Lab.

Table 5-1: Initial delays (in ns) of receiver at start of calibration.

BIPM code	INT DLY C1	INT DLY P1	INT DLY P2	INT DLY E1	INT DLY E5a	REF DLY	CAB DLY
IP05	-14.81	-14.41	-7.96	0.0	0.0	-40.0	141.8

Table 5-2: GPS raw common clock differences, all values in ns.

Pair	RAW ΔC1	Sigma	RAW ΔP1	Sigma	RAW ΔP2	Sigma
TR-IP05	-15.10	0.57	-13.74	0.51	-11.78	0.78

Table 5-3: Galileo raw common clock differences, all values in ns.

Pair	RAW ΔE1	Sigma	RAW ΔE5a	Sigma
TR-IP05	-15.67	0.50	-27.30	0.64

Taking a close loop to the closure measurements of Tables 5-4 and 5-5, we can observe a normal behavior of TR receiver, where the C1, P1, P2, E1 and E5a variations have remained relatively constant (below 0.3 ns).

Table 5-4: GPS closure measurements at ROA, all values in ns.

Pair	RAW ΔC1	Sigma	RAW ΔP1	Sigma	RAW ΔP2	Sigma
TR-RO10 (before the trip)	-0.03	0.37	-0.01	0.41	-0.02	0.52
TR-RO10 (after the trip)	-0.07	0.39	-0.03	0.43	-0.05	0.54
Misclosure	0.04		0.02		0.03	
Mean	-0.05		-0.02		-0.04	

Table 5-5: Galileo closure measurements at ROA, all values in ns.

Pair	RAW ΔE1	Sigma	RAW Δ5a	Sigma
TR-RO10 (before the trip)	-0.01	0.36	-0.01	0.38
TR-RO10 (after the trip)	-0.07	0.36	-0.25	0.38
Misclosure	0.06		0.24	
Mean	-0.04		-0.13	

6. UNCERTAINTY ESTIMATION

The overall uncertainty of the INT DLY values obtained as a result of the calibration is given by:

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}\ , \qquad (1)$$

with the statistical uncertainty u_a and the systematic uncertainty u_b. The statistical uncertainty is related to the instability of the common clock data collected at each site and collected at ROA when the INT DLY of travelling equipment was determined. The systematic uncertainty is given by:

$$u_b = \sqrt{\sum_n u_{b,n}^2} \qquad (2)$$

The contributions to the sum (2) are listed and explained subsequently. In the Table 6-1, we have considered the larger type A uncertainty found at remotes sites, which is quite small, so there is no need to develop it in detail for each Lab. Note that the uncertainty of the INT DLY values of ROA's fixed receiver RO10, which served as the reference, is not included.

Table 6-1: Uncertainty contributions for the calibration of receiver delays

	Uncertainty	Value C1 ns	Value P1 ns	Value P2 ns	Value E1 ns	Value E5a ns	Description
1	$u_{a(ROA)}$	0.10	0.10	0.10	0.10	0.10	CCD uncertainty at ROA, TDEV at τ = 1 day
1	$u_{a(IPQ)}$	0.10	0.10	0.10	0.10	0.10	CCD uncertainty at remote Lab, TDEV at τ = 1 day
	Systematic components due to antenna installation						
2	$u_{b,11}$	0.04	0.02	0.03	0.06	0.24	TR misclosure, see Tables 5-3 and 5-4
	Systematic components due to antenna installation						
2	$u_{b,12}$	0.05	0.05	0.05	0.05	0.05	Position error of RO10 receiver
3	$u_{b,13}$	0.05	0.05	0.05	0.05	0.05	Position error at remote Lab.
4	$u_{b,14}$	0.10	0.10	0.10	0.10	0.10	Multipath at ROA.
5	$u_{b,15}$	0.10	0.10	0.10	0.10	0.10	Multipath at remote Lab.
	Installation of RO10 and IPQ receivers						
6	$u_{b,21}$	0.30	0.30	0.30	0.30	0.30	Connection of TR to UTC(ROA) (REF DLY).
7	$u_{b,22}$	0.50	0.50	0.50	0.50	0.50	Connection of TR to UTC(k) (REF DLY).
7	$u_{b,23}$	0.30	0.30	0.30	0.30	0.30	Connection of reference receiver to UTC(ROA) (REF DLY).
7	$u_{b,24}$	0.50	0.50	0.50	0.50	0.50	Connection of receivers at site k to UTC(k) (REF DLY).
7	$u_{b,25}$	0.10	0.10	0.10	0.10	0.10	TIC nonlinearities at ROA.
10	$u_{b,26}$	0.10	0.10	0.10	0.10	0.10	TIC nonlinearities at remote sites.

7. FINAL RESULTS

The results of the internal calibration are summarized in Table 7.1-2. INTDLY and associated uncertainty C1 values have been calculated from Tables 5-1,3 and 6-1, respectively, rounded to the tenth of a nanosecond (the same for GPS P1, P2 and Galileo E1, E5a codes):

$$\text{INTDLY C1} = -\Delta\text{C1(Table 5.2)} + \Delta\text{C1}_{mean}\text{(Table 5.4)}$$

Table 7-1: GPS calibration results, all values in ns.

Receiver	REF DLY	CAB DLY	INTDLY C1	u_{cal} C1	INT DLY P1	u_{cal} P1	INT DLY P2	u_{cal} P2
IP05	-40.0	141.8	15.1	0.9	13.7	0.9	11.7	0.9

Table 7-2: Galileo calibration results, all values in ns.

Receiver	REF DLY	CAB DLY	INTDLY E1	u_{cal} E1	INT DLY E5a	u_{cal} E5a
IP05	-40.0	141.8	15.6	0.9	27.2	0.9

8. ANNEX-A

8.1. CALIBRATION INFORMATION SHEET AT ROA

Laboratory:	ROA
Date and hour of the beginning of measurements:	01.06.2021
Date and hour of the end of measurements:	05.06.2021

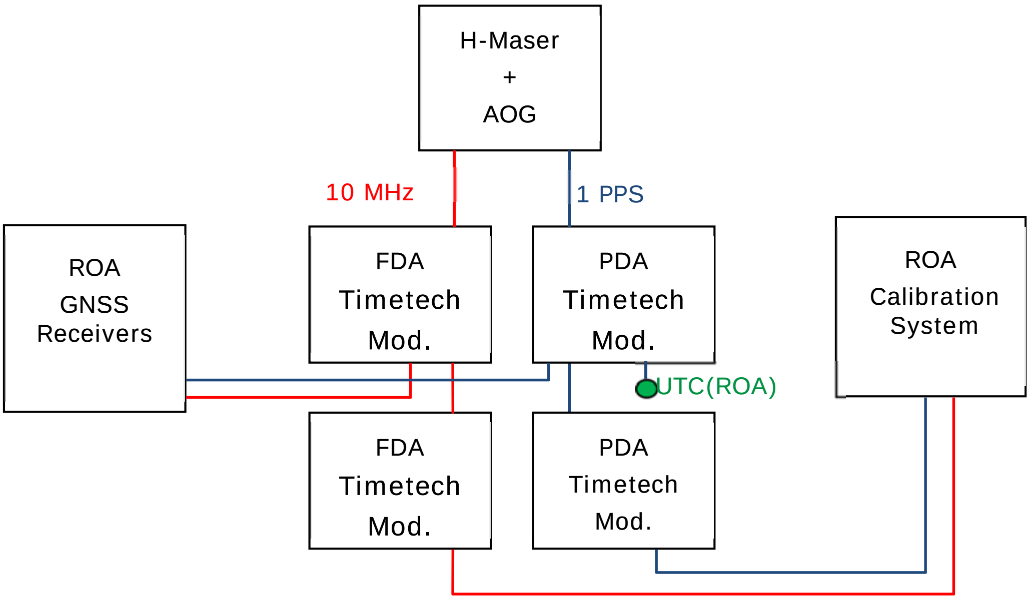
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	RO10	TR
• Receiver maker and type: Receiver serial number:	Septentrio PolaRx5TR v5.3.2 4701187	Septentrio PolaRx5TR v5.3.2 4701310
1 PPS trigger level /V:	1 V	1 V
• Antenna cable maker and type: Phase stabilised cable (Y/N):	LDF1RK-50	H155
Length outside the building /m:	Approximately 37 m	Approximately 30 m
• Antenna maker and type: Antenna serial number:	LEICA AR25 726362	Novatel antenna GPS-703-GGG NEG15300017

Measured delays /ns		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	5.1 ns Auto-compensation PPS IN: ON	295.5 ns Auto-compensation PPS IN: ON
Delay from 1 PPS-in to internal Reference (if different): (see section 2 for details)		
• Delay from local UTC to receiver 1 PPS-out:		
• Antenna cable delay: Antenna cable type:	199.0 ns	133.2 ns

Data used for the generation of CGGTTS files		
	Local:	**Travelling:**
• INT DLY (GPS) /ns:	29.9 ns C1, 28.2 ns P1, 25.7 ns P2	27.4 ns C1, 25.0 ns P1, 25.0 ns P2
• INT DLY (GALILEO) /ns:	30.1 ns E1, 29.7 ns E5a	27.6 ns E1, 26.6 ns E5a
• CAB DLY /ns:	199.0 ns	133.2 ns
• REF DLY /ns:	5.1 ns	295.5 ns
• Coordinates reference frame:	ITRF	ITRF
Latitude or X /m:	5105577.48 m	5105580.26 m
Longitude or Y /m:	-555208.94 m	-555189.34 m
Height or Z /m:	3769714.20 m	3769707.26 m

General information	
• Rise time of the local UTC pulse:	0.5 ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	(22 ± 2) °C
Set humidity value and uncertainty:	< 70 %

Diagram of the experiment set-up:



8.2. CALIBRATION INFORMATION SHEET AT IPQ

Laboratory:	IPQ
Date and hour of the beginning of measurements:	19.06.2021
Date and hour of the end of measurements:	23.06.2021

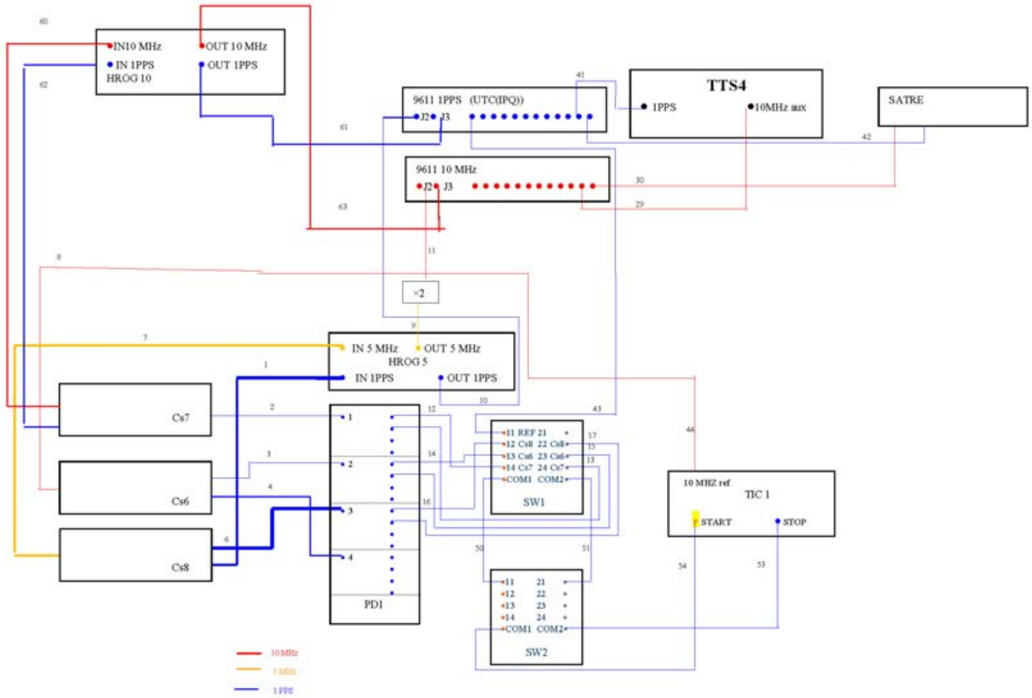
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	TTS-4	TR
• Receiver maker and type: Receiver serial number:	PIKTIME TTS-4 v5.3.2 HW:123.55, SW:3.3 103	Septentrio PolaRx5TR v5.3.2 4701310
1 PPS trigger level /V:	1 V	1 V
• Antenna cable maker and type: Phase stabilised cable (Y/N):		H155
Length outside the building /m:	Approximately 30 m	Approximately 30 m
• Antenna maker and type: Antenna serial number:	Javad antenna JAV_GRANT-G3T 457	Novatel antenna GPS-703-GGG NEG15300017

Measured delays /ns		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	20.0 ns	8.4 ns Auto-compensation PPS IN: ON
Delay from 1 PPS-in to internal Reference (if different): (see section 2 for details)	phase corr: 2.48 ns fw corr: -62.50 ns	
• Total delay:	-40.02 ns	
• Antenna cable delay: Antenna cable type:	141.82 ns	133.2 ns

Data used for the generation of CGGTTS files		
	Local:	**Travelling:**
• INT DLY (GPS) /ns:	-14.81 ns C1, -14.41 ns P1, -7.96 ns P2	27.4 ns C1, 25.0 ns P1, 25.0 ns P2
• INT DLY (GALILEO) /ns:	0 ns E1, 0 ns E5a	27.6 ns E1, 26.6 ns E5a
• CAB DLY /ns:	141.82 ns	133.2 ns
• REF DLY /ns:	-40.02 ns	8.4 ns
• Coordinates reference frame:	ITRF	ITRF
Latitude or X /m:	4922390.09 m	4922394.45 m
Longitude or Y /m:	-796031.37 m	-796017.40 m
Height or Z /m:	3963975.32 m	3963972.63 m

General information	
• Rise time of the local UTC pulse:	0.5 ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	(22 ± 2) °C
Set humidity value and uncertainty:	< 70 %

Diagram of the experiment set-up:



9. ANNEX-B: CCD at each Lab

Figure 9-1: Before the calibration trip (GPS)

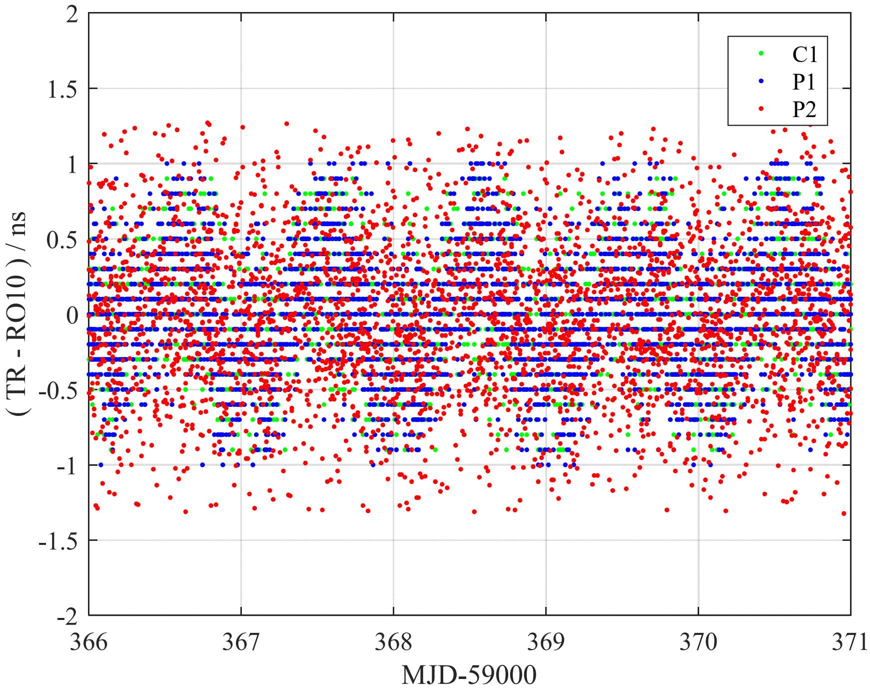


Figure 9-2: Before the calibration trip (Galileo)

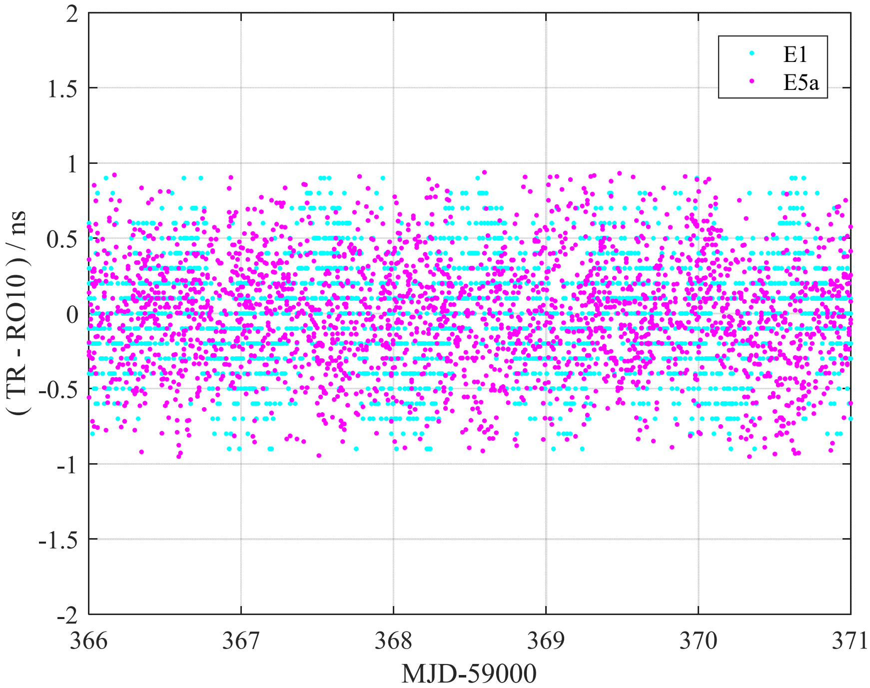


Figure 9-3: After the calibration trip (GPS)

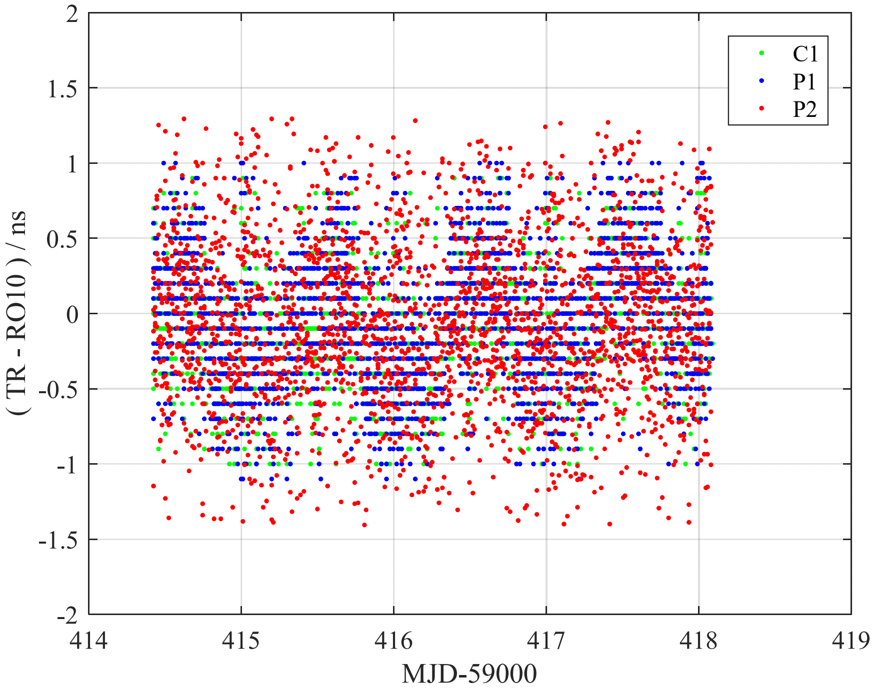


Figure 9-4: After the calibration trip (Galileo)

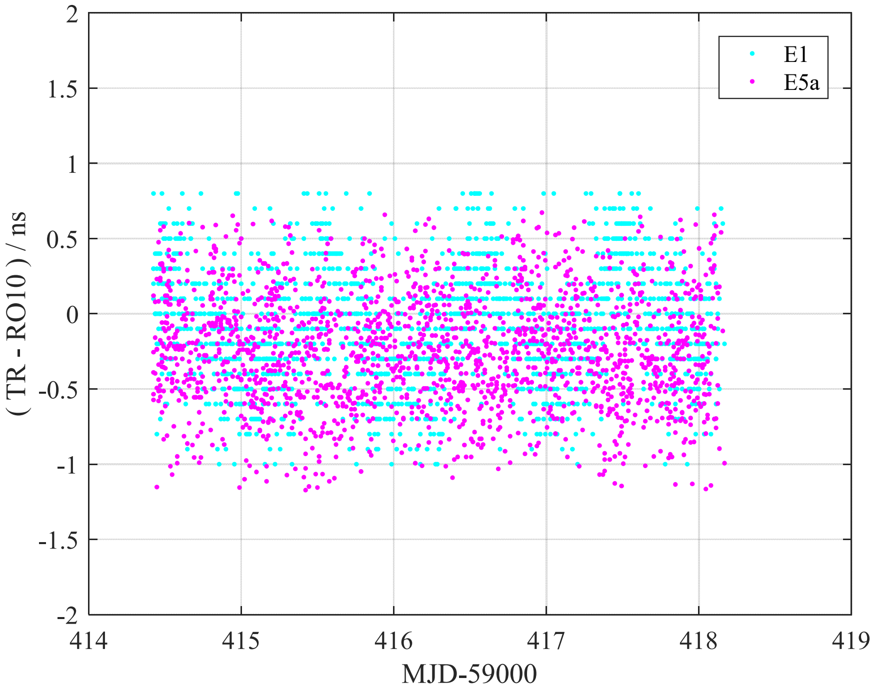


Figure 9-5: GPS CCD at IPQ

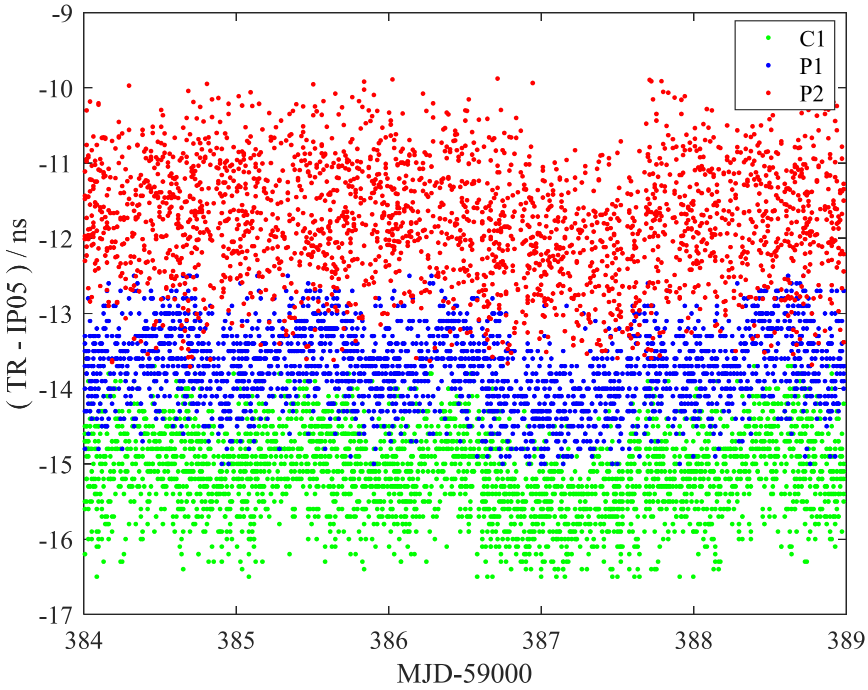
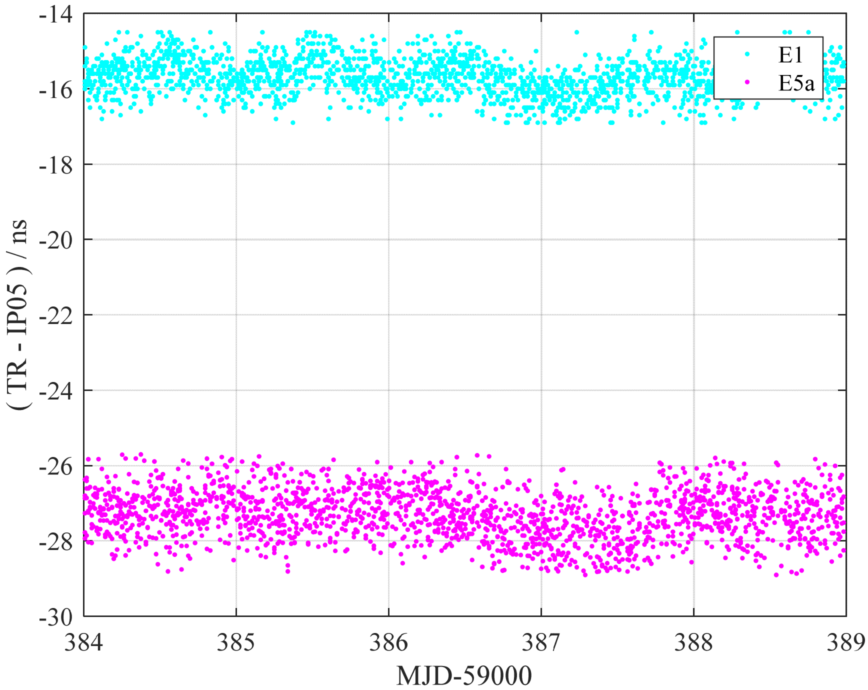


Figure 9-6: GPS CCD at IPQ



Acknowledgement

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END OF DOCUMENT