Group 2 GNSS Receiver INTDLY Calibration

**Relative calibration of VSL Javad Delta 3 receiver (VSLG)
with respect to VSL Septentrio PolaRx4 receiver (VSLF)**

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Summary

This calibration report describes the internal delay (INTDLY) calibration of the receiver VSLG with respect to the reference receiver VSLF. The INTDLY calibration includes signal delays of GPS P1 & P2 code, and Galileo E1 & E5a code.

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1   Introduction

Starting from 2021-09-05 00:00:00 (MJD59461.000000), the internal electric delays of the receiver VSLG changed after the reboot. In order to recalibrate the internal signal delays of VSLG, a relative calibration was performed that VSLG was aligned to the reference receiver VSLF, where VSLG and VSLF work under the same reference time scale UTC(VSL).

The purpose of this calibration is to calculate the combined electric delay of the GNSS signal inside the antenna and the receiver, which is designated as INTDLY in CGGTTS files for the GNSS receiver VSLG. Since INTDLY is frequency-dependent and code-dependent, it will be calculated for each signal of GNSS constellations including GPS P1 and P2 code and Galileo E1 and E5a code.

In this report, VSLG, which is the receiver to be calibrated, is designated as Receiver DUT (RxDUT), and the reference receiver VSLF is designated as Receiver REF (RxREF).

2   Log of events

UTC 2021-09-05 00:00:00	INTDLY values of the receiver VSLG changed after reboot
UTC 2024-08-01 00:00:00	Start calibration measurements
UTC 2024-08-05 23:59:59	End calibration measurements
UTC 2024-08-20 00:00:00	Apply new INT DLY values to CGGTTS files of the receiver VSLG

3   GNSS receiver general information

The general information of the receiver to be calibrated (RxDUT) and the reference receiver (RxREF) is listed in Annex – Information Sheet, following the template provided by [RD01]. In addition, the software version of the two receivers is listed in Table 1.

Table 1 General information on versions of DUT and REF receivers

GNSS receiver	Receiver DUT (RxDUT)	Receiver REF (RxREF)
4-character BIPM code	VSLG	VSLF
Station and receiver code in cggtts file name	VS07	VS06
GNSS Receiver firmware version	JAVAD TRE 3 DELTA 3.6.4	PolaRx4TR PRO (2.3.3)

GNSS receiver binary file to RINEX file conversion software version	JPS2RIN v.2.1.219	sbf2rin-13.4.5
RINEX file version	3.02	3.04
RINEX to CGGTTS conversion software version	R2CGGTTS v8.3	R2CGGTTS v8.3
CGGTTS version	CGGTTS - version 2E	CGGTTS - version 2E

4 Calibration procedure

4.1 Principle of GNSS receiver relative calibration

For a dual-frequency GNSS receiver, the measured time differences between the local timescale and the timescale of the GNSS at the frequency of $f1$ and $f2$ conform to the relation of

$$\text{REFSYS}_{f1}(\text{RxID}, j_{sat}, t_{epoch}) = \text{REFSYS}(\text{RxID}, j_{sat}, t_{epoch}) + \text{MDIO}(\text{RxID}, j_{sat}, t_{epoch}) \tag{1}$$

$$\text{REFSYS}_{f2}(\text{RxID}, j_{sat}, t_{epoch}) = \text{REFSYS}(\text{RxID}, j_{sat}, t_{epoch}) + \text{MDIO}(\text{RxID}, j_{sat}, t_{epoch}) + \left(\left(\frac{f1}{f2}\right)^2 - 1\right)\text{MSIO}(\text{RxID}, j_{sat}, t_{epoch}) \tag{2}$$

where RxID represents the ID of the GNSS receiver, j_{sat} is the reported satellite number and code, t_{epoch} is the recorded observation time in CGGTTS file, REFSYS_{f1} and REFSYS_{f2} are the measured time difference between the local timescale and the timescale of the GNSS at the frequency $f1$ and $f2$, respectively. The values of $f1$ and $f2$ for each constellation are listed in Table 2. $\text{REFSYS}(\cdot)$ is the dual frequency iono-free time difference measurements, $\text{MDIO}(\cdot)$ is the modelled ionospheric delay, and $\text{MSIO}(\cdot)$ is the measured ionospheric delay.

When the common view condition is fulfilled for the observations with RxDUT and RxREF, the measured REFSYS difference between the two receivers can be expressed as

$$\Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}, j_{sat}, t_{epoch}) \triangleq \text{REFSYS}_{fi}(\text{RxDUT}, j_{sat}, t_{epoch}) - \text{REFSYS}_{fi}(\text{RxREF}, j_{sat}, t_{epoch}) \tag{3}$$

where $\Delta\text{SIGNAL}i$ represents the REFSYS difference recorded between RxDUT and RxREF under frequency fi, and the representation of $\text{SIGNAL}i$ in constellations is listed in Table 2.

Taking the average from all-in-view satellites at each observation time, the averaged REFSYS difference at the specific observation epoch can be obtained as

$$\Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}, t_{epoch}) = \langle\Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}, j_{sat}, t_{epoch})\rangle \tag{4}$$

where $\langle\,\cdot\,\rangle$ denotes the average operator.

The final averaged value of the REFSYS difference between RxDUT and RxREF would be the averaged $\Delta\text{SIGNAL}i$ during the whole observation period, which can be obtained as

$$\Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}) = \langle\Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}, t_{epoch})\rangle \tag{5}$$

Then the new INTDLY values of $\text{SIGNAL}i$ for RxDUT can be calculated as

$$\text{INTDLY}_{new}(\text{RxDUT}, \text{SIGNAL}i) = \Delta\text{SIGNAL}i(\text{RxDUT}, \text{RxREF}) + \text{INTDLY}_{old}(\text{RxDUT}, \text{SIGNAL}i) \tag{6}$$

where $\text{INTDLY}_{old}(\text{RxDUT}, \text{SIGNAL}i)$ is the INTDLY value of $\text{SIGNAL}i$ used for RxDUT to generate its current CGGTTS file.

With the prior knowledge that the correction of frequency-dependent hardware delay is as follows:

$$\text{REFSYS}(j_{sat}, t_{epoch}) = \text{REFSYS}_{\text{RAW}}(j_{sat}, t_{epoch}) - \text{CABDLY} - \text{INTDLY}_{\text{SIGNAL3}} + \text{REFDLY} \tag{7}$$

where REFSYS$_{RAW}$ represents the uncorrected GNSS time scale, CABDLY is the delay from the antenna to the main unit of the receiver, REFDLY is the time delay between the local timescale and the receiver's internal clock, and INTDLY$_{SIGNAL3}$ is the internal delay with dual frequency observation which has the relation:

$$\mathrm{INTDLY(SIGNAL3)} = \mathrm{INTDLY(SIGNAL1)} + \alpha_{12}(\mathrm{INTDLY(SIGNAL1)} - \mathrm{INTDLY(SIGNAL2)})$$

$$\text{where } \alpha_{12} = \frac{f_2^2}{f_1^2 - f_2^2} \tag{8}$$

Accordingly, the 1-σ uncertainty of INTDLY(SIGNAL3) can be obtained as follows:

$$u\mathrm{INTDLY(SIGNAL3)} = \sqrt{u\big(\mathrm{INTDLY(SIGNAL1)}\big)^2 + \alpha_{12}{}^2 u\big(\mathrm{INTDLY(SIGNAL1)} - \mathrm{INTDLY(SIGNAL2)}\big)^2} \tag{9}$$

where SIGNALi (i=1,2,3) and fi(i=1,2) are defined in Table 2.

Table 2 Denotations in INTDLY calculation equations

GNSS system	SIGNAL	$i = 1$		$i = 2$		$i = 3$	α_{12}
		SIGNAL1	$f1$	SIGNAL2	$f2$	SIGNAL3	
GPS	P	P1	1575.42 MHz	P2	1227.60 MHz	L3P	1.545
Galileo	E	E1	1575.42 MHz	E5a	1176.45 MHz	L3E	1.261

4.2   Calibration setup

The calibration setup is described in Figure 2. RxDUT (BIPM code: VSLG) and RxREF (BIPM code: VSLF) have separate antennas and RF coaxial cables which connect the main unit of the receiver to the antenna, respectively. Both antennas are mounted on the roof of the same building, and the distance between the two antennas is approximately 5 meters in horizontal with the same height. Figure 1 demonstrates the photo of the two antennas for VSLF and VSLG.

Figure 1 Photo of the VSLF and VSLG antennas

As shown in Figure 2, the external timing signals of the two receivers, 1PPS and 10MHz, come from the same timing source which is traceable to UTC(VSL). Therefore, RxDUT (BIPM code: VSLG) and RxREF (BIPM code: VSLF) are

satisfied with the criteria of common-clock reference and common-view observations during the whole calibration period.
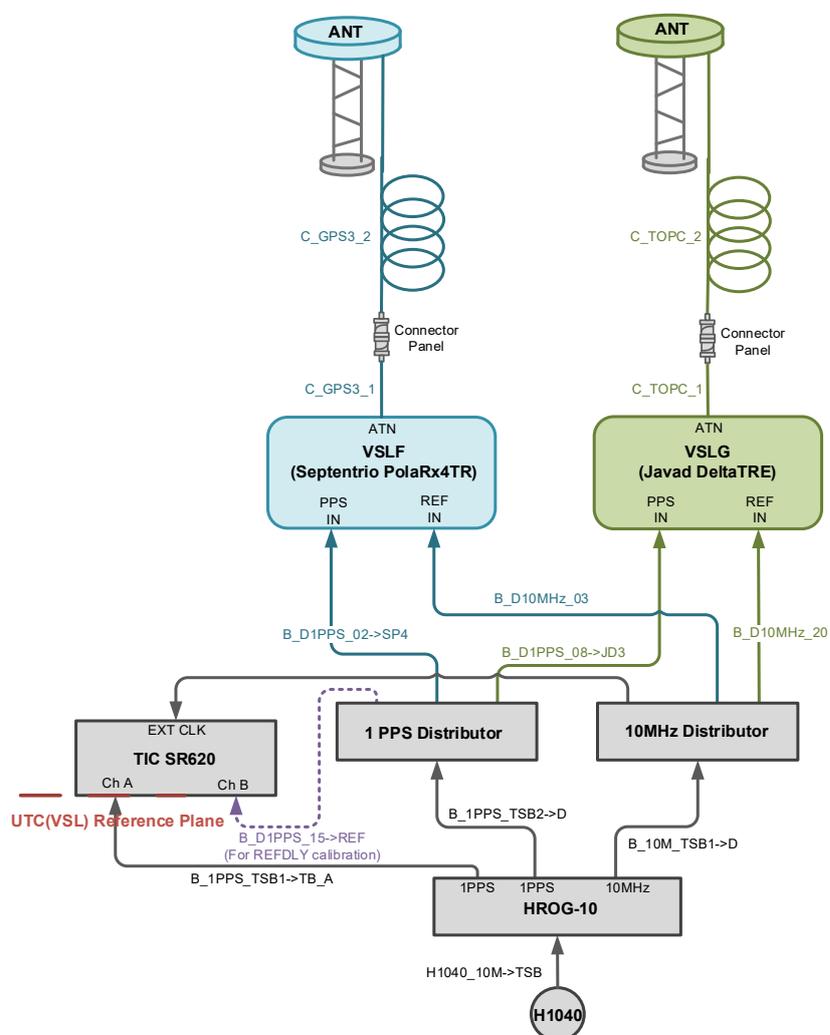

Figure 2 Schematic diagram of the VSLG calibration set-up at VSL

5   Calibration results

The raw data used in the calculation of the following calibration results are taken from the CGGTTS files as follows:

GNSS system	RxDUT (BIPM code: VSLG) raw data files	RxREF (BIPM code: VSLF) raw data files	Time duration of <mj.ddd>
GPS	GZVS07<mj.ddd>	GZVS06<mj.ddd>	MJD 60523 – MJD 60527
Galileo	EZVS07<mj.ddd>	EZVS06<mj.ddd>	MJD 60523 – MJD 60527

5.1   GPS L3P signal INTDLY calibration results

Table 3 and Figure 3 demonstrate the statistics of the ΔPi (i=1,2) between the two receivers RxDUT and RxREF, where the two receivers are running under the same local timescale, see Figure 1. In Table 3 and Figure 2, ΔP1 and ΔP2 are calculated from Equation (4).

Table 3 GPS L3P signals CCD calibration statistics between RxDUT (BIPM code: VSLG) and RxREF(BIPM code: VSLF)

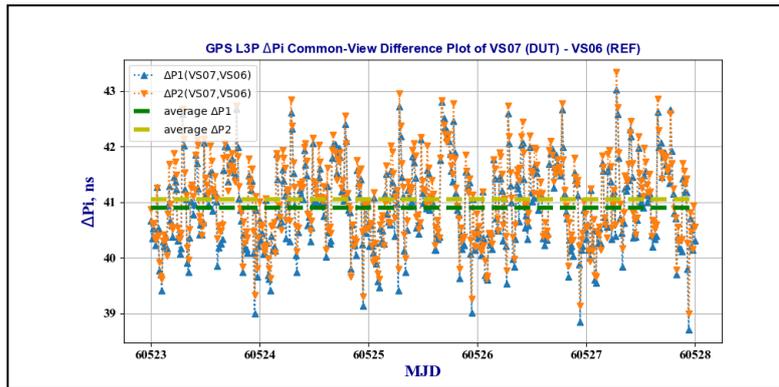| ΔSIGNAL*i* (RxDUT,RxREF)	Mean Unit: ns	Median Unit: ns	stdev Unit: ns	TDEV @τ Unit: ns	No. of epoches
ΔP1 (VS07,VS06)	40.90	40.94	0.75	0.33 @30720s	447
ΔP2 (VS07,VS06)	41.05	41.07	0.75	0.34 @30720s	447

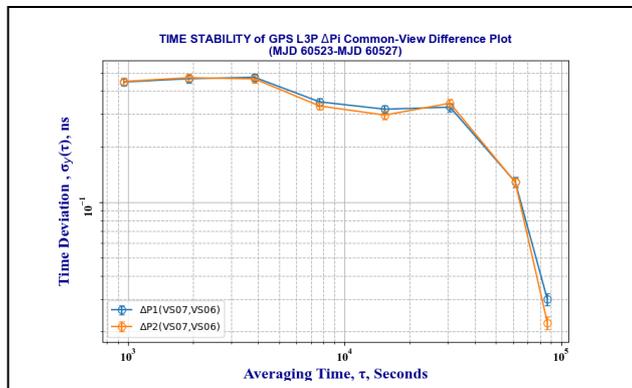Figure 3 GPS L3P CCD plot of INTDLY difference between RxDUT and RxREF

Figure 4 TDEV of GPS L3P CCD plot of INTDLY difference between RxDUT and RxREF

Table 4 gives the INTDLY L3P calculation result of RxDUT, where the new P1 and P2 are calculated according to Equation (6).

Table 4 GPS L3P signal INTDLY calibration results of the RxDUT (BIPM code: VSLG)

RxDUT ID	INTDLY before calibration		Calibration statistics		INTDLY after calibration	
	P1 (old) Unit: ns	P2 (old) Unit: ns	ΔP1 Unit: ns	ΔP2 Unit: ns	P1 (new) Unit: ns	P2 (new) Unit: ns
VSLF (VS07)	-19.8	-18.6	40.9	41.1	21.1	22.5

5.2   Galileo L3E signal INTDLY calibration results

Table 5 and Figure 4 demonstrate the statistics of the $\Delta Ei(i=1,5a)$ between the two receivers RxDUT and RxREF, where the two receivers are running under the same local timescale, see Figure 1. In Table 5 and Figure 4, $\Delta E1$ and $\Delta E5a$ are calculated from Equation (4).

Table 5 Galileo L3E signals CCD calibration statistics between RxDUT (BIPM code: VSLG) and RxREF (BIPM code: VSLF)

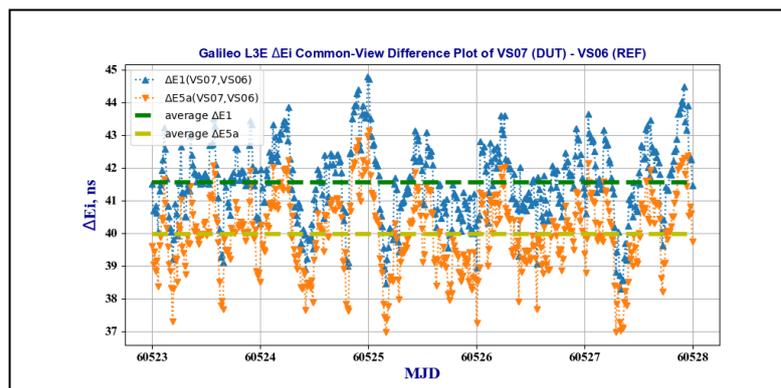| ΔSIGNALi (RxDUT,RxREF)	Mean Unit: ns	Median Unit: ns	stdev Unit: ns	TDEV@τ Unit: ns	No. of epochs
ΔE1 (VS07,VS06)	41.55	41.57	1.20	0.72 @30720s	447
ΔE5a (VS07,VS06)	39.97	39.99	1.18	0.71 @30720s	447

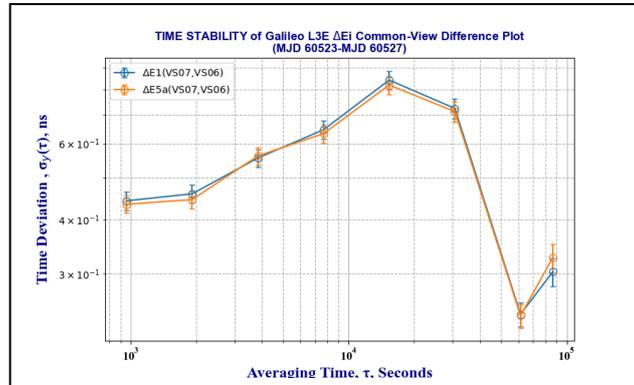Figure 5 Galileo L3E CCD plot of INT DLY difference between RxDUT and RxREF

Figure 6 TDEV of Galileo L3E CCD plot of INT DLY difference between RxDUT and RxREF

Table 6 gives the INTDLY L3E calculation result of RxDUT, where the new E1 and E5a are calculated according to Equation (6).

Table 6 Galileo L3E signal INT DLY calibration results of RxDUT (BIPM code: VSLG)

Rx DUT ID	INT DLY before calibration		Calibration statistics		INT DLY after calibration	
	E1 (old) Unit: ns	E5a (old) Unit: ns	ΔE1 Unit: ns	ΔE5a Unit: ns	E1 (new) Unit: ns	E5a (new) Unit: ns
VSLF (VS07)	-19.8	-18.6	41.6	40.0	21.7	21.4

5.3 INTDLY calibration uncertainty evaluation

Table 7 lists the uncertainty budget of the RxDUT-RxREF (BIPM code: VSLG - VSLF) relative calibration, where the classification of the uncertainty group and sub-group take the reference of [RD01][RD02]. uINTDLY(SIGNAL3) is calculated according to Equation (9).

Table 7 List of uncertainty budget of RxDUT (BIPM code: VSLG) with respect to RxREF (BIPM code: VSLF)

Uncertainty group	Uncertainty sub-group	Description	uINTDLY (SIGNAL1) Unit: ns	uINTDLY (SIGNAL2) Unit: ns	uINTDLY (SIGNAL1-SIGNAL2) Unit: ns	uINTDLY (SIGNAL3) Unit: ns
ua Measurement uncertainty	ua,1 (GPS)	CCD measurement uncertainty (TDEV of ΔPi)	0.3	0.3	0.43	0.61
	ua,1 (GAL)	CCD measurement uncertainty (TDEV of ΔEi)	0.7	0.7	0.99	1.68
ub,I	ub,I1	Position error of RxREF①	0.0	0.0	0.0	0.0

Systematic components due to antenna installation	ub,I2	Position error of RxDUT	0.1	0.1	0.14	0.28
	ub,I3	Multipath of RxREF①	0.0	0.0	0.0	0.0
	ub,I4	Multipath of RxDUT	0.2	0.2	0.0	0.2
ub,II Reference timescale delay (REFDLY) at VSL	ub,II1	Connection of RxREF to UTC(VSL)①	0.0	0.0	0.0	0.0
	ub,II2	Connection of RxDUT to UTC(VSL)	0.2	0.2	0.0	0.2
ub,III Reference timescale delay (REFDLY) at PTB	ub,III1	Connection of RxREF to UTC(PTB)①	0.0	0.0	0.0	0.0
	ub,III2	Connection of RxDUT to UTC(PTB)	--	--	--	--
ub,IV Antenna cable delay (CABDLY)	ub,IV1	Uncertainty estimate for RxREF CABDLY①	0.0	0.0	0.0	0.0
	ub,IV2	Uncertainty estimate for RxDUT CABDLY	0.5	0.5	0.0	0.5

①: This item of uncertainty has been included in CAL_ID 1013-2021.

Table 8 lists the uncertainty budget of RxREF (BIPM code: VSLF), including the uncertainty calculated by CAL_ID 1013-2021 and the ageing contribution afterwards.

Table 8 Uncertainty budget of RxREF (BIPM code: VSLF)

Uncertainty group	Uncertainty sub-group	Description	uINTDLY (SIGNAL1) Unit: ns	uINTDLY (SIGNAL2) Unit: ns	uINTDLY (SIGNAL3) Unit: ns
uRxREF Uncertainty of RxREF	uRxREF$_{CAL0}$ (GPS)	Uncertainty of RxREF in the latest calibration②	0.88	0.89	1.00
	uRxREF$_{CAL0}$ (GAL)	Uncertainty of RxREF in the latest calibration②	0.87	0.88	1.00
	uRxREF$_{AG}$	Ageing contribution of uRxREF$_{CAL0}$③	1.40	1.40	1.40

②: The uncertainty of RxREF(VSLF) is obtained from [RD02].

③: According to [RD01], $u_{AG} = \max\left(c_{AG}\sqrt{\Delta t_{month}} - 1.0, 0.0\right)$, where $c_{AG} = 0.4$ ns and Δt_{month} is the age in months since the latest calibration.

Therefore, the total uncertainty budget of RxDUT (BIPM code: VSLG) would be the sum of the relative Type A & Type B uncertainty between RxDUT and RxREF and the uncertainty of RxREF, which can be expressed as

$$uRxDUT = \sqrt{ua^2 + ub^2 + uRxREF^2}$$ (10)

Table 9 lists the total uncertainty budget of RxDUT (BIPM code: VSLG), where ua and ub are taken from Table 7, $uRxREF$ are taken from Table 8 and the final $uRxDUTs$ are calculated according to Equation (10). $uRxDUT$ shown in Table 9 indicate the 1-σ uncertainty result, and the κ=2 expanded uncertainty results are shown in the last column of Table 9.

Table 9 Summary of total uncertainty budget of RxDUT (BIPM code: VSLG)

GNSS system & signal	u(RxDUT-RxREF) u(VSLG-VSLF)						uRxREF u(VSLF) Unit: ns	uRxDUT u(VSLG) Unit: ns	2-σ uRxDUT Unit: ns
	$\sqrt{ua^2+ub^2}$ Unit: ns	ua Unit: ns	ub						
			ub,I Unit: ns	ub,II Unit: ns	ub,III Unit: ns	ub,IV Unit: ns			
GPS P1	0.66	0.3	0.22	0.2	0.0	0.5	1.65	1.78	3.56
GPS P2	0.66	0.3	0.22	0.2	0.0	0.5	1.66	1.78	3.57
GPS L3P	0.89	0.61	0.34	0.2	0.0	0.5	1.72	1.94	3.87
Galileo E1	0.91	0.7	0.22	0.2	0.0	0.5	1.65	1.88	3.77
Galileo E5a	0.91	0.7	0.22	0.2	0.0	0.5	1.65	1.89	3.78
Galileo L3E	1.80	1.68	0.34	0.2	0.0	0.5	1.72	2.49	4.98

6   Annex – Information Sheet

Laboratory:	VSL
Date and hour of the beginning of measurements:	UTC 2024-08-01T00:00:00
Date and hour of the end of measurements:	UTC 2024-08-05T23:59:59

Information on the system		
	Receiver DUT	**Receiver REF**
4-character BIPM code	VSLG	VSLF
• Receiver maker and type: Receiver serial number:	JAVAD Delta TRE 3.4 02336	Septentrio PolaRx4TR 3001395
1 PPS trigger level /V:	0.5V	0.5V
• Antenna cable maker and type: Phase stabilised cable (Y/N):	SSB Electronic GmbH, Aircom Plus N	SSB Electronic GmbH, Aircom Plus N

Total length /m: Length outside the building /m:	30 10	30 10
• Antenna maker and type: Antenna serial number:	Topcon TPSCR3_GGD 2170239	Topcon TPSCR.G3 (TPSH) 383-1235
Temperature (if stabilised) /°C	not stabilized	not stabilized

Measured delays /ns		
	Receiver DUT	**Receiver REF**
• Delay from local UTC to receiver 1 PPS-in:	32.3	180.7
Delay from 1 PPS-in to internal Reference (if different):	--	PPS Sync enabled, determined automatically by receiver software
• Antenna cable delay /ns:	124.8	124.7
Splitter delay (if any):	N/A	N/A
Additional cable delay (if any):	N/A	N/A

Data used for the generation of CGGTTS files		
	Receiver DUT	**Receiver REF**
• INT DLY (GPS) /ns:	-19.8 ns (GPS P1), -18.6 ns (GPS P2) CAL_ID = 1012- 2016+VSL2020070	53.2 ns (GPS P1), 61.7 ns (GPS P2) CAL_ID = 1013-2021
• INT DLY (Galileo) /ns:	-19.8 ns (GAL E1), -18.6 ns (GAL E5a) CAL_ID = 1012- 2016+VSL2020070	54.5 ns (GAL E1), 73.1 ns (GAL E5a) CAL_ID = 1013-2021
• INT DLY (GLONASS) /ns:	N/A	N/A
• CAB DLY /ns:	124.8	124.7
• REF DLY /ns:	32.3	180.7
• Coordinates reference frame:	ITRF	ITRF
Latitude or X /m:	+3924692.88	+3924692.57
Longitude or Y /m:	+301141.95	+301141.19
Height or Z /m:	+5001908.16	+5001908.32

General information	
• Rise time of the local UTC pulse:	0.7 ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	(23.0±0.5) °C
Set humidity value and uncertainty:	(45±5) %

References

[RD01]	BIPM guidelines for GNSS calibration V4.0, 05/08/2021.
[RD02]	PTB Report: GNSS CALIBRATION REPORT G1G2_1013_2021, 09/09/2021.
[RD03]	P. Defraigne, G. Petit, CGGTTS-Version 2E: an extended standard for GNSS time transfer. Metrologia 2015 52 G1.