Group 2 GNSS Receiver INTDLY Calibration

Relative calibration of VSL Septentrio PolaRx5TR receiver (VS08) with respect to VSL Javad Delta 3 receiver (VS07)

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Summary

This calibration report describes the internal delay (INTDLY) calibration of the receiver VS08 (Rinex ID: VS08) with respect to the reference receiver VS07 (Rinex ID: VSLG). The INTDLY calibration includes signal delays of GPS P1 & P2 code, and Galileo E1 & E5a code.

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1 Introduction

Starting from UTC 2026-02-06T05:50:00, the GNSS receiver with BIPM ID VS06 stopped working. As a replacement, a new GNSS receiver was designated with ID of VS08 and installed since UTC 2026-02-06T13:00:00. VS08 inherited the antenna and antenna cable of VS06, while the reference delay from UTC(VSL) to the PPS input of the receiver was changed.

In order to calibrate the internal signal delays of VS08, a relative calibration was performed that VS08 was aligned to the reference receiver VS07, where VS08 and VS07 operate 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 noted as INTDLY in CGGTTS files of the GNSS receiver VS08. 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.

The calibration traceability of VS08 is as follows: VS07 was calibrated with alignment to VS06 with a calibration ID of 1013-2021+VSL2024214 in February 2024. VS06 participated in BIPM Group 2 calibration campaign in 2021, where it was calibrated with respect to the reference receiver PTBM. And a calibration ID of 1013-2021 was subsequently assigned to this calibration. Table 1 lists the receiver information and calibration information of the relevant receivers in the traceability.

In this report, VS08, which is the receiver to be calibrated, is designated as Receiver DUC (RxDUC), and the reference receiver VS07 is designated as Receiver REF (RxREF).

Table 1 Receiver IDs and Calibration IDs of the receivers

Receiver BIPM ID	Rinex file identifier	Receiver model & SN	Latest calibration		
			Calibration ID	Calibration year	Reference receiver
VS06	VSLF	Septentrio PolaRx4TR, SN: 3001395	1013-2021	2021	PTBM
VS07	VSLG	JAVAD Delta TRE 3.4, SN: 02336	1013-2021+VSL2024214	2024	VS06
VS08	VS08	Septentrio PolaRx5TR, SN: 3096037	1013-2021+VSL2026213	2026	VS07

2 Log of events

UTC 2026-02-06T05:50:00 (MJD 61077. 243056)	VS06 (Rinex ID: VSLF) stops working
UTC 2026-02-06T13:00:00 (MJD 61077. 541667)	VS08 (Rinex ID: VS08) is installed to replace VS06
UTC 2026-02-07T00:00:00 (MJD 61078. 000000)	Start VS08 calibration measurements with respect to VS07

UTC 2026-02-11T23:59:59 (MJD 61082. 999988)	End VS08 calibration measurements with respect to VS07
UTC 2026-02-13T16:00:00 (MJD 61084.666667)	Apply new INT DLY values to CGGTTS files of VS08 since the date UTC 2026-02-06 (MJD 61077)

3 GNSS receiver general information

The general information of the receiver to be calibrated (RxDUC) and the reference receiver (RxREF) is listed in Annex – Information Sheet, following the template provided by [RD01]. In addition, the software versions of the two receivers are listed in Table 2.

Table 2 General information on versions of DUC and REF receivers

GNSS receiver	Receiver DUC (RxDUC)	Receiver REF (RxREF)
4-character BIPM code	VS08	VS07
Rinex file identifier	VS08	VSLG
GNSS Receiver firmware version	PolaRx5TR PRO (5.5.0)	JAVAD TRE 3 DELTA 3.6.4
GNSS receiver binary file to RINEX file conversion software version	sbf2rin-13.4.5	JPS2RIN v.2.1.219
RINEX file version	3.04	3.02
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

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

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

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 3. $\mathrm{REFSYS}(\cdot)$ is the dual frequency iono-free time difference measurements, $\mathrm{MDIO}(\cdot)$ is the modelled ionospheric delay, and $\mathrm{MSIO}(\cdot)$ is the measured ionospheric delay.

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

$$\Delta\mathrm{SIGNAL}i\left(\mathrm{RxDUC},\mathrm{RxREF},j_{sat},t_{epoch}\right) \triangleq \mathrm{REFSYS}_{fi}\left(\mathrm{RxDUC},j_{sat},t_{epoch}\right) - \mathrm{REFSYS}_{fi}\left(\mathrm{RxREF},j_{sat},t_{epoch}\right) \quad (3)$$

where $\Delta\mathrm{SIGNAL}i$ represents the REFSYS difference recorded between RxDUC and RxREF under frequency fi, and the representation of $\mathrm{SIGNAL}i$ in constellations is listed in Table 3.

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

$$\Delta\mathrm{SIGNAL}i\left(\mathrm{RxDUC},\mathrm{RxREF},t_{epoch}\right) = \langle\Delta\mathrm{SIGNAL}i\left(\mathrm{RxDUC},\mathrm{RxREF},j_{sat},t_{epoch}\right)\rangle \quad (4)$$

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

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

$$\Delta\mathrm{SIGNAL}i(\mathrm{RxDUC},\mathrm{RxREF}) = \langle\Delta\mathrm{SIGNAL}i\left(\mathrm{RxDUC},\mathrm{RxREF},t_{epoch}\right)\rangle \quad (5)$$

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

$$\mathrm{INTDLY}_{new}(\mathrm{RxDUC},\mathrm{SIGNAL}i) = \Delta\mathrm{SIGNAL}i(\mathrm{RxDUC},\mathrm{RxREF}) + \mathrm{INTDLY}_{old}(\mathrm{RxDUC},\mathrm{SIGNAL}i) \quad (6)$$

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

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

$$\mathrm{REFSYS}\left(j_{sat},t_{epoch}\right) = \mathrm{REFSYS_{RAW}}\left(j_{sat},t_{epoch}\right) - \mathrm{CABDLY} - \mathrm{INTDLY_{SIGNAL3}} + \mathrm{REFDLY} \quad (7)$$

where $\mathrm{REFSYS_{RAW}}$ 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 $\mathrm{INTDLY_{SIGNAL3}}$ is the internal delay with dual frequency observation which has the relation:

$$\mathrm{INTDLY(SIGNAL3)} = \mathrm{INTDLY(SIGNAL1)} + \alpha_{12}(\mathrm{INTDLY(SIGNAL1)} - \mathrm{INTDLY(SIGNAL2)})$$
$$\text{where } \alpha_{12} = \frac{f_2^2}{f_1^2 - f_2^2} \quad (8)$$

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

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

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

Table 3 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

RxDUC (BIPM ID: VS08) and RxREF (BIPM ID: VS07) 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 VS08 and VS07.

Figure 1 Photo of the VS07 and VS08 antennas

The calibration setup is described in Figure 2. 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, RxDUC (BIPM ID: VS08) and RxREF (BIPM ID: VS07) are satisfied with the criteria of common-clock reference and common-view observations during the whole calibration period.

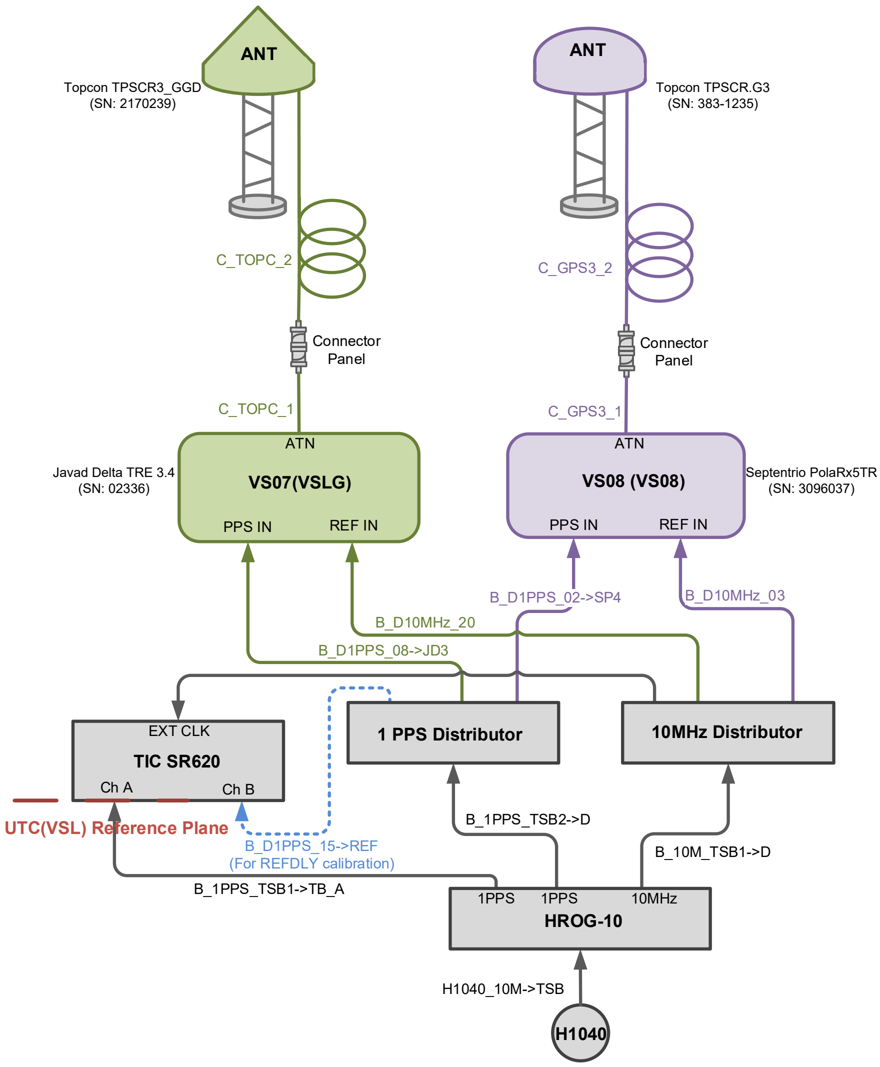

Figure 2 Schematic diagram of the VS08 relative calibration set-up at VSL

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	RxDUC VS08 (Rinex ID: VS08) raw data files	RxREF VS07 (Rinex ID: VSLG) raw data files	Time duration of <mj.ddd>
GPS	GZVS08<mj.ddd>	GZVS07<mj.ddd>	MJD 61078 – MJD 61082

Galileo	EZVS08<mj.ddd>	EZVS07<mj.ddd>	MJD 61078 – MJD 61082

5.1 GPS L3P signal INTDLY calibration results

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

Table 4 GPS L3P signals CCD calibration statistics between RxDUC (VS08) and RxREF(VS07)

ΔSIGNAL*i* (RxDUC,RxREF)	Mean Unit: ns	Median Unit: ns	stdev Unit: ns	TDEV @τ Unit: ns	No. of epoches
ΔP1 (VS08,VS07)	22.67	22.69	0.72	0.24 @30720s	443
ΔP2 (VS08,VS07)	29.95	29.97	0.74	0.27 @30720s	443

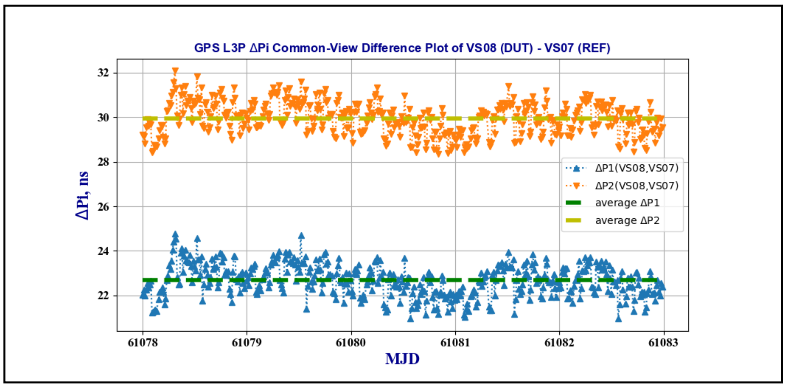

Figure 3 GPS L3P CCD plot of INTDLY difference between RxDUC(VS08) and RxREF(VS07)

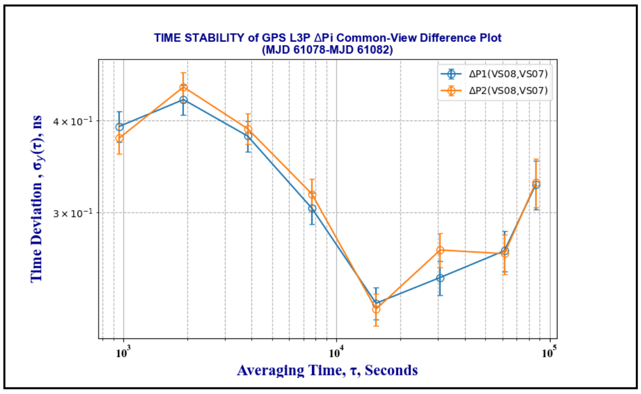

Figure 4 TDEV of GPS L3P CCD plot of INTDLY difference between RxDUC(VS08) and RxREF(VS07)

Table 5 gives the INTDLY L3P calculation result of RxDUC (VS08), where the new P1 and P2 are calculated according to Equation (6).

Table 5 GPS L3P signal INTDLY calibration results of the RxDUC (VS08)

RxDUC 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
VS08	0.0	0.0	22.7	29.9	22.7	29.9

5.2 Galileo L3E signal INTDLY calibration results

Table 6 and Figure 5 demonstrate the statistics of the ΔEi(i=1,5a) between the two receivers RxDUC and RxREF, where the two receivers are running under the same local timescale. In Table 6 and Figure 5, ΔE1 and ΔE5a are calculated from Equation (4). Figure 6 shows the time deviation of the CCD plot of Figure 5.

Table 6 Galileo L3E signals CCD calibration statistics between RxDUC (VS08) and RxREF (VS07)

ΔSIGNAL*i* (RxDUC,RxREF)	Mean Unit: ns	Median Unit: ns	stdev Unit: ns	TDEV@τ Unit: ns	No. of epochs
ΔE1 (VS08,VS07)	24.96	25.05	0.79	0.27 @30720s	443
ΔE5a (VS08,VS07)	35.13	35.20	0.79	0.26 @30720s	443

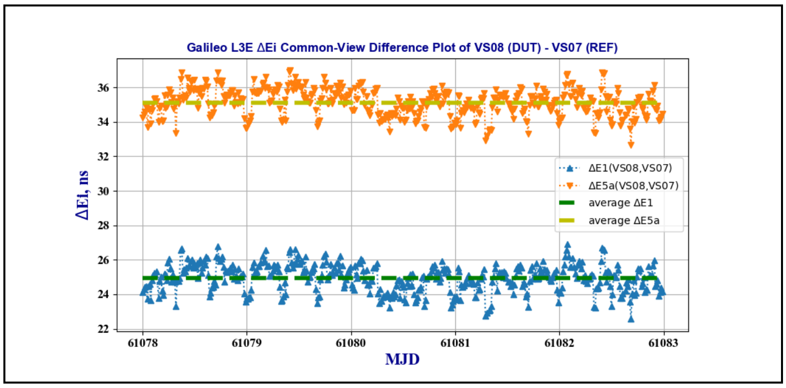

Figure 5 Galileo L3E CCD plot of INT DLY difference between RxDUC and RxREF

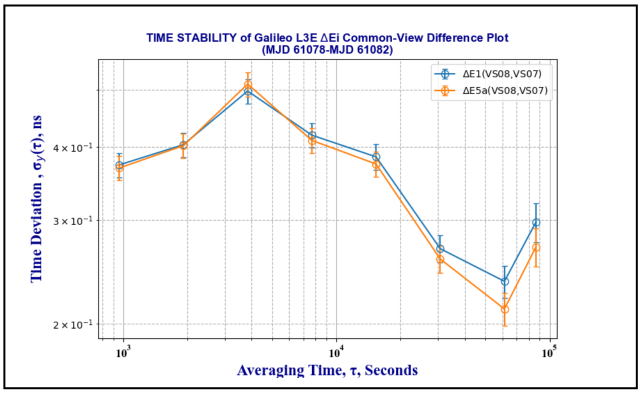

Figure 6 TDEV of Galileo L3E CCD plot of INT DLY difference between RxDUC and RxREF

Table 7 gives the INTDLY L3E calculation result of RxDUC, where the new E1 and E5a are calculated according to Equation (6).

Table 7 Galileo L3E signal INT DLY calibration results of RxDUC (VS08)

Rx DUC 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
VS08	0.0	0.0	25.0	35.1	25.0	35.1

5.3 INTDLY calibration uncertainty evaluation

Table 8 lists the uncertainty budget of the RxDUC-RxREF (VS08 – VS07) relative calibration, where the classification of the uncertainty group and sub-group take the reference of [RD01][RD02]. *u*INTDLY(SIGNAL3) is calculated according to Equation (9).

Table 8 List of uncertainty budget of RxDUC (VS08) with respect to RxREF (VS07)

Uncertainty group	Uncertainty sub-group	Description	*u*INTDLY (SIGNAL1) Unit: ns	*u*INTDLY (SIGNAL2) Unit: ns	*u*INTDLY (SIGNAL1-SIGNAL2) Unit: ns	*u*INTDLY (SIGNAL3) Unit: ns
*u*a Measurement uncertainty	*u*a,1 (GPS)	CCD measurement uncertainty (TDEV of ΔPi)	0.2	0.3	0.36	0.51
	*u*a,1 (GAL)	CCD measurement uncertainty (TDEV of ΔEi)	0.3	0.3	0.37	0.64
*u*b,I	*u*b,I1	Position error of RxREF①	0.0	0.0	0.0	0.0

Systematic components due to antenna installation	ub,I2	Position error of RxDUC	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 RxDUC	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 RxDUC 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)②	--	--	--	--
	ub,III2	Connection of RxDUC to UTC(PTB)②	--	--	--	--
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 RxDUC CABDLY	0.5	0.5	0.0	0.5

①: This item of uncertainty has been included in CAL_ID 1013-2021+VSL2024214.

②: This item of uncertainty is not applicable in this calibration. The reference timescale delay of VS06 at PTB has been included in CAL_ID 1013-2021+VSL2024214.

Table 9 lists the uncertainty budget of RxREF (VS07), including the uncertainty calculated by CAL_ID 1013-2021+VSL2024214 and the ageing contribution afterwards.

Table 9 Uncertainty budget of RxREF (VS07)

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 calibration③	1.78	1.78	1.94
	uRxREF$_{CAL0}$ (GAL)	Uncertainty of RxREF in the latest calibration③	1.88	1.89	2.49
	uRxREF$_{AG}$	Ageing contribution of uRxREF$_{CAL0}$④	0.96	0.96	0.96

③: The uncertainty of RxREF(VS07) is obtained from CAL_ID 1013-2021+VSL2024214.

④: 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 RxDUC (VS08) would be the sum of the relative Type A & Type B uncertainty between RxDUC and RxREF in addition to the uncertainty of RxREF, which can be expressed as

$$u\text{RxDUC} = \sqrt{u\text{a}^2 + u\text{b}^2 + u\text{RxREF}^2} \quad (10)$$

Table 10 lists the total uncertainty budget of RxDUC (VS08), where ua and ub are taken from Table 8, uRxREF are taken from Table 9 and the final uRxDUCs are calculated according to Equation (10). uRxDUC shown in Table 10 indicate the 1-σ uncertainty result, and the κ=2 expanded uncertainty results are shown in the last column of Table 10.

Table 10 Summary of total uncertainty budget of RxDUC (VS08)

GNSS system & signal	u(RxDUC-RxREF) u(VS08-VS07)						uRxREF u(VS07) Unit: ns	uRxDUC u(VS08) Unit: ns	2-σ uRxDUC 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	0.63	0.2	0.22	0.2	--	0.5	2.02	2.12	4.24
GPS P2	0.64	0.3	0.22	0.2	--	0.5	2.02	2.12	4.24
GPS L3P	0.82	0.51	0.34	0.2	--	0.5	2.16	2.31	4.63
Galileo E1	0.64	0.3	0.22	0.2	--	0.5	2.11	2.21	4.41
Galileo E5a	0.64	0.3	0.22	0.2	--	0.5	2.12	2.21	4.43
Galileo L3E	0.90	0.64	0.34	0.2	--	0.5	2.67	2.82	5.63

6 Annex – Information Sheet

Laboratory:	VSL	
Date and hour of the beginning of measurements:	UTC 2026-02-07 00:00:00 (MJD 61078. 000000)	
Date and hour of the end of measurements:	UTC 2026-02-11 23:59:59 (MJD 61082. 999988)	
Information on the system		
	Receiver DUC	**Receiver REF**
4-character BIPM code	VS08 (Rinex ID: VS08)	VS07 (Rinex ID: VSLG)
• Receiver maker and type: Receiver serial number:	Septentrio PolaRx5TR 5.5.0 3096037	JAVAD Delta TRE 3.4 02336
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 TPSCR.G3 (TPSH) 383-1235	Topcon TPSCR3_GGD 2170239
Temperature (if stabilised) /°C	not stabilized	not stabilized
Measured delays /ns		
	Receiver DUC	**Receiver REF**
• Delay from local UTC to receiver 1 PPS-in:	21.2	21.4
Delay from 1 PPS-in to internal Reference (if different):	PPS Sync enabled, determined automatically by receiver software	--
• Antenna cable delay /ns:	124.7	124.8
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 DUC	**Receiver REF**
• INT DLY (GPS) /ns:	22.7 ns (GPS P1), 29.9 ns (GPS P2) CAL_ID= 1013-2021+VSL2026213	21.1 ns (GPS P1), 22.5 ns (GPS P2) CAL_ID = 1013-2021+VSL2024214
• INT DLY (Galileo) /ns:	25.0 ns (GAL E1), 35.1 ns (GAL E5a) CAL_ID = 1013-2021+VSL2026213	21.7 ns (GAL E1), 21.4 ns (GAL E5a) CAL_ID = 1013-2021+VSL2024214
• INT DLY (GLONASS) /ns:	N/A	N/A
• CAB DLY /ns:	124.7	124.8
• REF DLY /ns:	21.2	21.4
• Coordinates reference frame:	ITRF	ITRF
Latitude or X /m:	+3924692.57	+3924692.88
Longitude or Y /m:	+301141.19	+301141.95
Height or Z /m:	+5001908.32	+5001908.16
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.