TECHNICAL NOTE
« CNES REPORT ON THE ABSOLUTE CALIBRATION OF THE CS11 AND CS12 GNSS RECEIVER CHAINS »

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TERMS, DEFINITIONS AND ABBREVIATIONS

Acronym : Abbreviation	Definition

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1 INTRODUCTION

This document describes the results obtained by CNES of the absolute calibration of two CNES GNSS receiver chains (referred to as CS11 and CS12) together with the estimated uncertainties. Both chains include a GNSS antenna, an RF antenna cable and a GNSS receiver. The calibrations have been performed at CNES Time-Frequency laboratory using the methods described in [RD1]. The method used is recalled in the second part of this document with typical uncertainty budget for each element.

1.1 HARDWARE IDENTIFICATION

Table 1 identifies the GNSS receiver chains which absolute calibration is reported in this document.

	CS12	**CS11**
GNSS antenna	SEPCHOKE_B3E6 s/n 5083 CNES reference name = “B3E6_1” n° chrono = 2218115	SEPCHOKE_B3E6 s/n 5067 CNES reference name = “B3E6_2” n° chrono = 2218116
RF cable	KX13_3	KX13_2
GNSS receiver	Septentrio PolaRx4TR PRO s/n 3008022 n° chrono = 2214967	Septentrio PolaRx4TR PRO s/n 3001153 n° chrono = 2139334

Table 1: Devices undergoing the absolute calibration

The GNSS simulator used for these calibration is a Spectracom GSG-64 s/n 200823. The oscilloscope is a Tektronix Digital Phosphor Oscilloscope s/n B022204 (n° chrono 2119228).

1.2 REFERENCE DOCUMENTS

Reference	Title
RD1 :	Valat D and Delporte J, “Absolute calibration of timing receiver chains at the nanosecond uncertainty level for GNSS time scales monitoring”, Metrologia (in press), https://doi.org/10.1088/1681-7575/ab57f5
RD2 :	
RD3 :	

2 RESULTS

2.1 GNSS ANTENNAS

Table 2 below summarizes the results of the absolute calibration of the GNSS antennas. All results are given in ns. Note that the calibration for BeiDou signals has been performed only for CS12.

[ns]	**CS12 antenna**		**CS11 antenna**	
GNSS code	AD	u_{AD}	AD	u_{AD}
C1	21.91	0.27	21.57	0.34
P1	21.99	0.28	21.58	0.34
E1	21.85	0.21	21.58	0.28
P2	19.29	0.17	18.80	0.34
C5	20.48	0.17	20.27	0.35
E5a	20.39	0.18	20.27	0.35
B1	20.58	0.28	-	-
B2	19.07	0.27	-	-

Table 2: Absolute calibration results for the GNSS antennas

2.2 RF CABLES

Table 3 below summarizes the results of the absolute calibration of the RF cables. All results are given in ns.

For the CS12 cable, an offset of 0.3 ns is observed for all L1/E1 signals (both with the simulator and the VNA method). This is believed to be due to a default in this cable. Therefore, for the CGGTTS header, we retain the common value 176.3 ns for the CAB DLY, and we correct of 0.3 ns the L1/E1 values of the INT DLY reported in the next paragraph.

[ns]	**CS12 cable**		**CS11 cable**	
	CD	u_{CD}	CD	u_{CD}
C1	*175.92*	0.20	166.20	0.20
P1	*175.97*	0.20	166.13	0.20
E1	*175.83*	0.20	166.11	0.20
P2	176.37	0.20	166.24	0.20
C5	176.29	0.20	166.25	0.20
E5a	176.29	0.20	166.14	0.20
B1	176.40	0.20	-	
B2	176.29	0.20	-	

Table 3: Absolute calibration results for the RF cables

2.3 GNSS RECEIVERS

Table 4 below summarizes the results of the absolute calibration of the GNSS receivers. All results are given in ns. Note that the calibration for BeiDou signals has been performed only for CS12.

[ns]	CS12 receiver		CS11 receiver	
GNSS code	RxD	u_{RxD}	RxD	u_{RxD}
C1	35.30	0.33	35.98	0.49
P1	35.24	0.34	35.93	0.49
E1	35.65	0.30	36.09	0.42
P2	33.44	0.31	35.27	0.91
C5	42.84	0.28	42.23	0.41
E5a	42.89	0.30	43.00	0.42
B1	35.32	0.36	-	-
B2	32.62	0.34	-	-

Table 4: Absolute calibration results for the GNSS receivers

2.4 COMPLETE GNSS RECEIVER CHAIN

Table 5 below summarizes the results of the absolute calibration of the GNSS receivers. All results are given in ns. Note that the calibration for BeiDou signals has been performed only for CS12.

[ns]	CS12 complete chain		CS11 complete chain	
GNSS code	delay	uncertainty	delay	uncertainty
C1	233.13	0.47	223.75	0.63
P1	233.20	0.48	223.64	0.63
E1	233.33	0.42	223.78	0.54
P2	229.10	0.41	220.31	0.99
C5	239.61	0.38	228.75	0.57
E5a	239.57	0.40	229.41	0.58
B1	232.30	0.50	-	-
B2	227.98	0.48	-	-

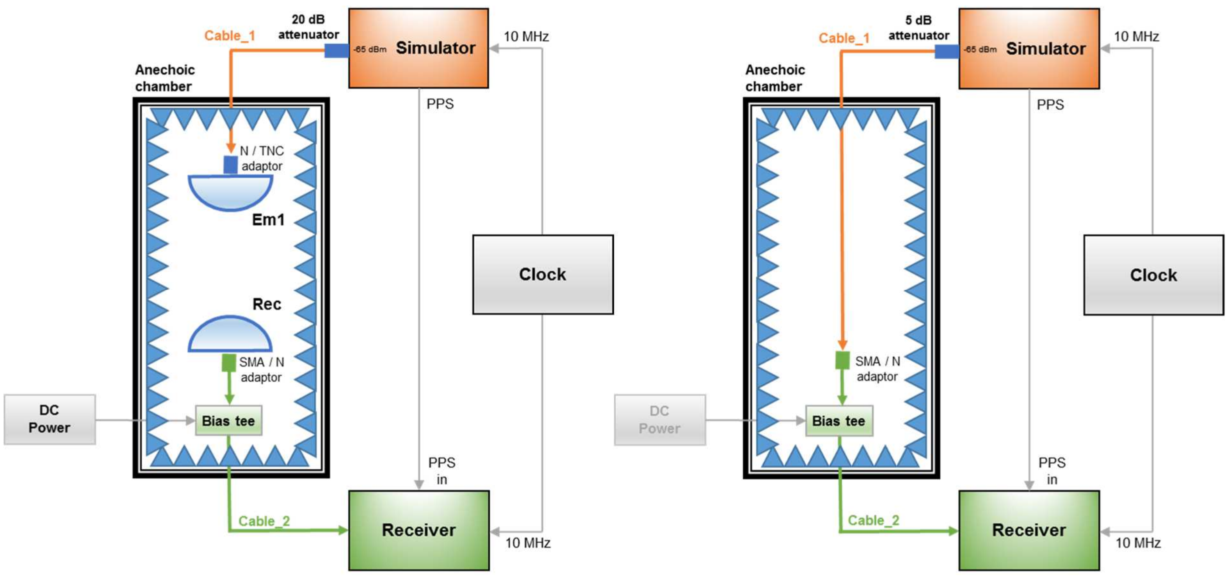
Table 5: Absolute calibration results for the GNSS receiver chains

3 METHODS AND UNCERTAINTIES

The calibration method for the 3 devices (antenna, cable, receiver) relies on the use of a GNSS simulator, namely a Spectracom GSG-6. The simulator output power is determined so that the RF power received by the device under test (DUT) is in the range of -120 to -130 dBm, which corresponds to typical GNSS power levels received in an open-sky environment

3.1 GNSS ANTENNA

The calibration of the antennas is performed using the CNES DSO/RF/STR small anechoic chamber. A passive antenna used as a transmitting antenna is placed at the top of the chamber, while the DUT is placed at the bottom. The distance between the phase centers of the antennas is about 1 m, which fulfills the far-field criterion. Figures 1 below depict the antenna calibration setup.



Figures 1: Antenna calibration setup (left-hand side) – Tare measurement setup (right-hand side)

In order to determine the delay of the passive antenna, a second passive antenna is used, which leads to 3 configurations (passive1/DUT, passive2/DUT, passive1/passive2). The delay of the DUT is determined by a triangulation that provides also the delay of both passive antennas.

The determination of the delay mostly relies on the difference between the pseudoranges measured by the receiver and the ones generated by the simulator (divided by the speed of light), also referred to as the common-views. This difference is corrected by a tare measurement (see Figure 1 – right-hand side). The distance between the phase centers is determined using a laser range finder and the IGS file igs14.atx.

In the following equations, the DUT is referred to as Rec, the first and the second passive antennas are respectively referred to as Em1 and Em2.

The common-views in the Em1/Rec configuration can be expressed as:

$$\mathrm{CV_{Em1Rec}} = \mathrm{AD_{Em1}} + \mathrm{AD_{Rec}} + Tare_{mean} + \frac{dist_{Em1Rec}}{c} + C_{Em1Rec}$$

where $\mathrm{Tare_{mean}}$ is the average of $\mathrm{Tare_{before}}$ and $\mathrm{Tare_{after}}$, and $\mathrm{C_{Em1Rec}}$ is the is the delay resulting from the configuration setup differences (connectors, attenuators, adaptors) between the tare setup and the Em1/Rec measurement setup.

We define SAD as:

$$\mathrm{SAD_{Em1Rec}} = \mathrm{AD_{Em1}} + \mathrm{AD_{Rec}} + Tare_{mean} = \mathrm{CV_{Em1Rec}} - \frac{dist_{Em1Rec}}{c} - C_{Em1Rec}$$

When all the data are collected, the delay of the DUT is given by:

$$\mathrm{AD_{Rec}} = \frac{\mathrm{SAD_{Em1Rec}} + \mathrm{SAD_{Em2Rec}} - \mathrm{SAD_{Em1Em2}} - \mathrm{Tare_{mean}}}{2}$$

The uncertainty on SAD is:

$$\mathrm{u_{SAD}}_{\mathrm{XY}} = \sqrt{(\mathrm{u_{CV}}_{\mathrm{XY}}/c)^2 + (u_{dist_{XY}}/c)^2 + u_{C_{XY}}{}^2 + \mathrm{u_{PWR}}^2}$$

The uncertainty on the delay of the passive antennas is given by:

$$\mathrm{u_{AD}}_{\mathrm{Em1}} = \mathrm{u_{AD}}_{\mathrm{Em2}} = \sqrt{u_{SAD\,\mathrm{Em1Rec}}{}^2 + u_{SAD\,\mathrm{Em1Em2}}{}^2 + \frac{u_{SAD\,\mathrm{Em2Rec}}{}^2 + \mathrm{u_{Tare_{mean}}}^2 + \mathrm{u_{Tare_{closure}}}^2}{4}}$$

Finally, the uncertainty on the delay of the DUT is:

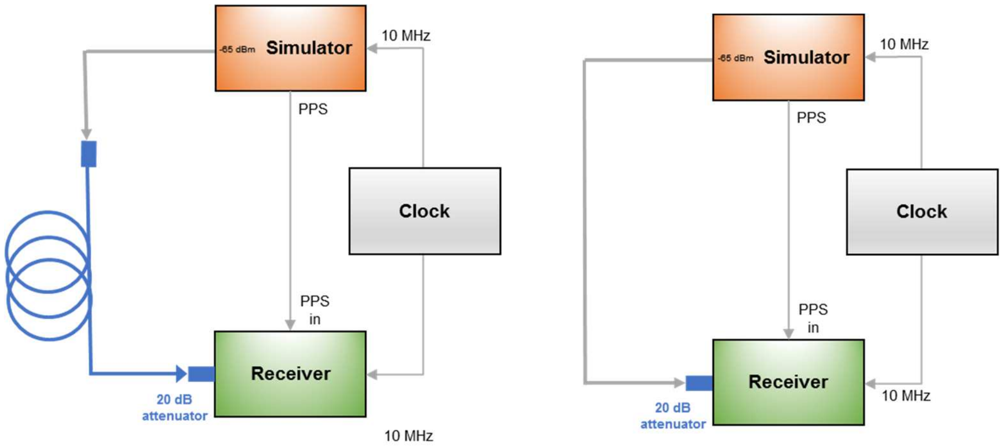
$$\mathrm{u_{AD}}_{\mathrm{Rec}} = \sqrt{\mathrm{u_{AD}}_{\mathrm{Em1}}{}^2 + \mathrm{u_{AZEL}}^2}$$

Source of uncertainty	Typical value
the standard deviation of the common-views (u_{CV})	0.05 to 0.3 ns
the uncertainty of the distance between the phase centers (u_{dist})	0.1 ns
the uncertainty resulting from the differences between the tare setup and the antennas measurement setups (u_C)	0.1 ns
the uncertainty due to the RF input power level sensitivity of the receiver (u_{PWR})	0.1 ns
the uncertainty of the tare measurement (u_{Tare_mean})	0.03 to 0.15 ns
the uncertainty resulting from the tare closure ($u_{Tare\_closure}$)	0.01 ns
the uncertainty on the phase center position with regards to elevation/azimuth of the satellites (the calibration being done only with signals coming from the zenith) (u_{AZEL})	0.02 ns
Overall uncertainty of the antenna delay	**0.15 to 0.40 ns**

Table 6: Typical 1-σ uncertainty of the antenna delay

3.2 RF CABLE

The RF cables are calibrated using a method similar to the above, i.e. by difference with a tare measurement, as depicted on Figures 2.



Figures 2: Cable calibration setup (left-hand side) – Tare measurement setup (right-hand side)

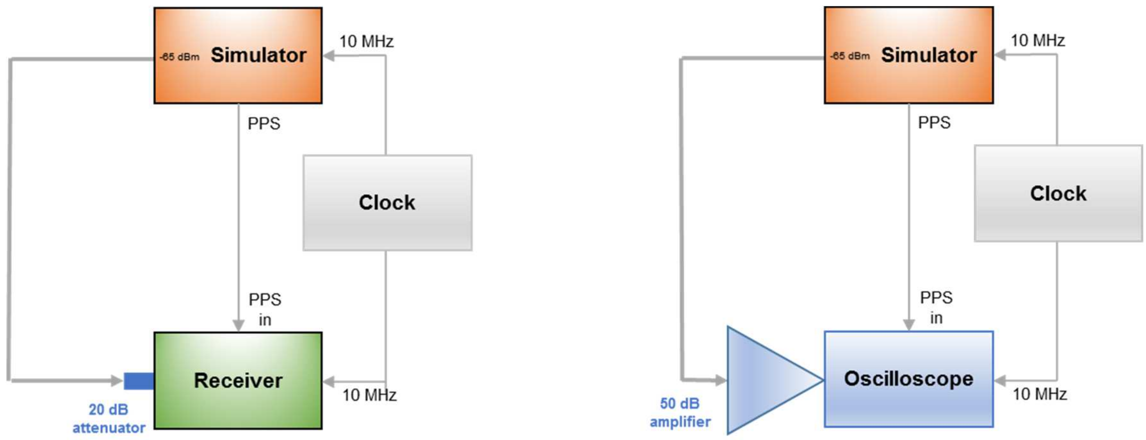
Source of uncertainty	Typical value
the standard deviation of the common-views (u_{CV})	0.02 to 0.1 ns
the uncertainty resulting from the differences between the tare setup and the antennas measurement setups (u_C)	0.1 ns
the uncertainty due to the RF input power level sensitivity of the receiver (u_{PWR})	0.1 ns
the uncertainty of the tare measurement (u_{Tare_mean})	0.03 to 0.15 ns
the uncertainty resulting from the tare closure ($u_{Tare\_closure}$)	0.01 ns
Overall uncertainty of the RF cable delay	**0.15 to 0.22 ns**

Table 7: Typical 1-σ uncertainty of the RF cable delay

3.3 GNSS RECEIVER

The receiver delay RxD is the mean time difference between the pseudoranges measured by the receiver and the pseudoranges generated by the simulator, corrected by different quantities.

Figure 3 (left-hand side) describes the GNSS receiver calibration setup. The first step consists in determining the simulator delay using the setup illustrated in Figure 3 – right-hand side.



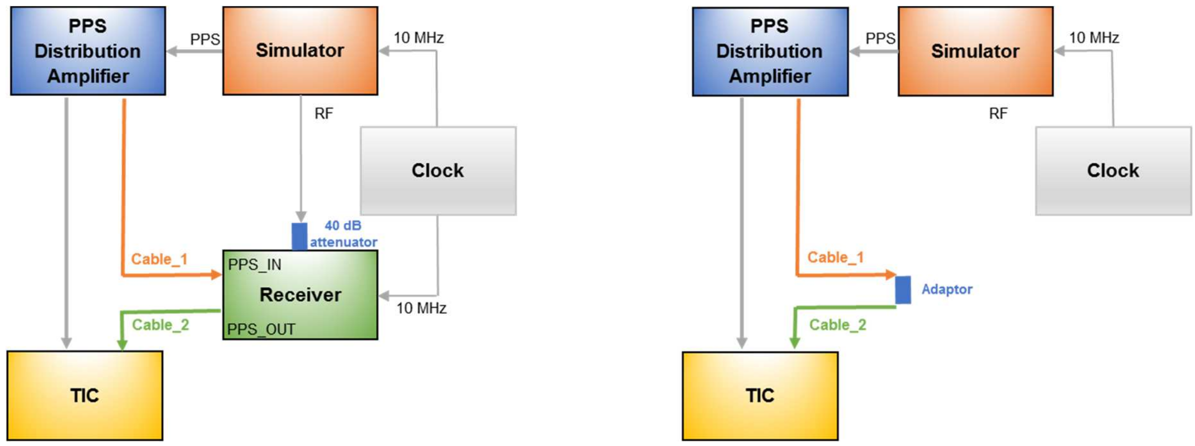
Figures 3: Receiver calibration setup (left-hand side) – Simulator calibration setup (right-hand side)

The simulator delay is determined using a fast oscilloscope. It corresponds to the time offset between the beginning of the GNSS PRN code and the internally generated 1 PPS synchronized with the GNSS time. The oscilloscope data are analyzed with a home-made correlation software. Each signal is generated separately using the Signal Generator mode, and this is repeated 10 times before and after measuring the delay of the receiver.

Source of uncertainty	Typical value
the standard deviation of the SD (u_{SD_mean})	0.02 to 0.1 ns
the uncertainty on the SD closure ($u_{SD\_closure}$)	0.01 to 0.02 ns
the uncertainty due to the use of the Signal generator mode (u_{SD_SG2GEN})	0.05 ns
the uncertainty of the simulator inter-board bias (u_{SD_IBB})	0 to 0.11 ns
the uncertainty of the oscilloscope ($u_{oscillo}$)	0.1 ns
Uncertainty of the simulator delay	**0.11 to 0.17 ns**

Table 8: Typical 1-σ uncertainty of the simulator delay

The Rx1pps is the delay between the 1 PPS at the input of the receiver (PPS_IN) and the receiver internal reference. A PolaRx4TR has to be configured so that the 1 PPS generated by the receiver (PPS_OUT) defines the internal reference, so that the Rx1pps is estimated by a measurement of the delay between PPS_IN and PPS_OUT with a time interval counter. The delay between PPS_IN and PPS_OUT is then estimated by the delay measured in this setup minus the average of the tare delays, as depicted in Figures 4.



Figures 4: Rx1pps measurement setup (left-hand side) – Tare measurement setup (right-hand side)

The mean value and standard deviation of 100 measurements of [PPS_IN – PPS_OUT] is evaluated twice, right before and right after the GNSS data collection providing $\mathrm{Rx1pps_{before}}$, $\mathrm{u_{Rx1pps_{before}}}$, $\mathrm{Rx1pps_{after}}$ and $\mathrm{u_{Rx1pps_{after}}}$. $\mathrm{Rx1pps_{mean}}$ is the mean value with an uncertainty $\mathrm{u_{Rx1pps_{mean}}} = \mathrm{u_{Rx1pps_{before}}} = \mathrm{u_{Rx1pps_{after}}}$.

Source of uncertainty	Typical value
the standard deviation of the TIC measurements (u_{Rx1pps_mean})	0.08 to 0.1 ns
the uncertainty on the SD closure ($u_{Rx1pps\_closure}$)	0.08 to 0.1 ns
the uncertainty due to the TIC resolution ($u_{TIC\_resolution}$)	0.1 ns
the uncertainty of TIC relative error ($u_{TIC\_relative\_error}$)	0.05 ns
Uncertainty of the Rx1pps delay	**0.16 to 0.18 ns**

Table 9: Typical 1-σ uncertainty of the Rx1pps

The overall RxD uncertainty is given by:

$$\mathrm{u_{RxD}} = \sqrt{\mathrm{u}_{CV}{}^2 + \mathrm{u_{SD}}{}^2 + \mathrm{u_{LD}}{}^2 + \mathrm{u_{Rx1pps}}{}^2}$$

Source of uncertainty	Typical value
the standard deviation of the CV measurements (u_{CV})	0.02 to 0.15 ns
the uncertainty on the SD (u_{SD})	0.11 to 0.17 ns
the uncertainty on the delays of the amplifier, attenuator and adaptors (u_{LD})	0.2 to 0.3 ns
the uncertainty of the Rx1pps (u_{Rx1pps})	0.16 to 0.18 ns
Overall uncertainty of the receiver delay	**0.28 to 0.42 ns**

Table 10: Typical 1-σ uncertainty of the receiver delay

For CS11, larger uncertainties are obtained, this is due to the fact that an older version of the procedure was used. The difference does not lead to modifications of the results but to larger uncertainties.

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