CNES – CENTRE NATIONAL D'ÉTUDES SPATIALES	Orbital Systems Directorate Radiofrequency Department Signal, Time/Frequency and Radiodetermination Department **Non sensitive**	Réf : **DSO/RF/STR-2020.0032712** Date : **27/08/2020** Edition : **1**, Révision : **0**

TECHNICAL NOTE « CNES REPORT ON THE ABSOLUTE CALIBRATION OF THE BIPM BP27 RECEIVER CHAIN »

	Name, CNES entity	Date and Signature
Prepared by	**Jérôme DELPORTE** **DSO/RF/STR**	Signature numérique de Jérôme Delporte DN : cn=Jérôme Delporte, o=CNES, ou=DCT/RF/HT, email=jerome.delporte@cnes.fr, c=FR Date : 2020.08.27 17:32:51 +02'00'
Verified by	**David VALAT** **DSO/RF/STR**	Signature numérique de Valat David DN : c=FR, o=CNES, ou=0002 775665912, ou=Agents CNES, 2.5.4.45=valatd@cnes.fr, cn=Valat David Date : 2020.08.27 17:51:49 +02'00'
Authorized by	**Thierry ROBERT** **Head of DSO/RF/STR Department**	Robert Thierry 2020.09.01 10:26:41 +02'00'

INTERNAL/EXTERNAL DISTRIBUTION LIST			
CNES entity/ Company Organization	**Name (+email address if external)**	**Observation for**	
		Action	**Information**
DSO/RF/D	D. PRADINES		x
DSO/RF/DA	C. LAPORTE		x
DSO/RF/STR	FX ESNAULT, D. VALAT, J. DELPORTE		x
BIPM	G. PETIT (gpetit@bipm.org)		x
ORB	P. DEFRAIGNE (pascale.defraigne@oma.be)		x

INDEXATION

Authors in case of several authors: **Jérôme Delporte, David Valat**		
Title/Scope : CNES report on the absolute calibration of the BIPM BP27 receiver chain		
Configuration management: **Yes/No**	Date:	By :
Contract :		

MODIFICATION DIRECTORY

Issue	Date	Evolutions
1.0	**27/08/2020**	Document creation

TERMS, DEFINITIONS AND ABBREVIATIONS

Acronym : Abbreviation	Definition

TABLE OF CONTENTS

1 INTRODUCTION

This document describes the results obtained by CNES on the absolute calibration of the BIPM BP27 GNSS receiver chain together with the estimated uncertainties. This chain includes a GNSS antenna, an RF antenna cable (composed of a long cable, a splitter and a short 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 chain which absolute calibration is reported in this document.

	BP27
GNSS antenna	SEPCHOKE_B3E6 s/n 5296 (without radome)
RF cables	Long cable labelled ‘C207’ and ‘Station’ Splitter (Mini-Circuits) labelled ‘SP-BP27’ Short cable labelled ‘C209’
GNSS receiver	Septentrio PolaRx5TR-3046906 5.2.0 s/n 4701324 BIPM reference name = “BP27” BIPM id number = “2706091”

Table 1: Devices undergoing the absolute calibration

The GNSS simulator used for these calibration is a Spectracom GSG-64 s/n 200823 (firmware 7.5.1a), with scenario Cal_all_GNSS_2020.scen.

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* 57 (2020) 025019, https://doi.org/10.1088/1681-7575/ab57f5
RD2 :	Septentrio PolaRx5TR User Manual v1.1
RD3 :	Proia A, “Contribution à l’étalonnage en absolu d’une chaine de réception GNSS”, PhD dissertation, 2011.

2 RESULTS

2.1 GNSS ANTENNA

Table 2 below summarizes the results of the absolute calibration of the GNSS antenna. All results are given in ns.

[ns]	**BIPM B3E6 antenna**	
GNSS code	AD	u_{AD}
C1	19.9	0.4
P1	20.0	0.4
E1	19.8	0.3
P2	18.5	0.3
C5	21.2	0.3
E5a	21.2	0.3
B1	19.7	0.5
B2	18.0	0.4

Table 2: Absolute calibration results for the GNSS antennas

2.2 RF CABLES

2.2.1 GNSS SIMULATOR MEASUREMENT

Table 3 below summarizes the results of the absolute calibration of the RF cables. The result below is the overall delay of the long cable, the splitter and the short cable calibrated together in a single set (see Figure 5). All results are given in ns.

[ns]	**BIPM BP27 cables**
GNSS code	CD
C1	200.5
P1	200.7
E1	200.6
P2	200.9
C5	201.0
E5a	201.0
B1	200.8
B2	200.8

Table 3: Absolute calibration results for the RF cables

The single RF cable delay applicable for all GNSS codes is the mean value: **200.8** ns (σ = 0.2 ns).

2.2.2 VNA MEASUREMENT

A second measurement of the cables delay has been performed with a VNA (Rhode & Schwarz ZNB 4, n° chrono 2139075, with calibration unit R&S ZV-Z53, n° chrono 2200285). The raw transmission delay over the 1-2 GHz frequency band is measured to be 200.88 ns. This measurement is performed with a TNC/N adaptor and an N/N adaptor (compared to the VNA calibration).

The delay of these adaptors is also measured with the VNA. Each adaptor has a delay of 0.06 ns. The final VNA result is obtained by correcting the raw result with the delays of both adaptors.

The RF cables delay measured by the VNA method is **200.8** ns (σ = 0.2 ns [RD3]).

2.3 GNSS RECEIVER

Concerning the BIPM BP27 PolaRx5TR receiver, the PPS_IN internal delay compensation has been set to “Auto” and the measurements have been collected only after this internal compensation was announced to be done [RD2].

Moreover, in the receiver configuration, the notch filters have been set to OFF, otherwise the noise of the pseudo-ranges produced by the receiver made the calibration impossible.

Table 4 below summarizes the results of the absolute calibration of the GNSS receiver. All results are given in ns.

[ns]	**BIPM BP27 receiver**	
GNSS code	RxD	u_{RxD}
C1	9.8	0.3
P1	9.8	0.3
E1	10.3	0.3
P2	7.6	0.3
C5	9.5	0.3
E5a	9.8	0.3
B1	2.6	0.3
B2	5.1	0.3

Table 4: Absolute calibration results for the GNSS receiver

2.4 COMPLETE GNSS RECEIVER CHAIN

Table 5 below summarizes the results of the absolute calibration of the complete GNSS receiver chain. All results are given in ns.

[ns]	**BIPM BP27 complete chain**	
GNSS code	delay	uncertainty
C1	230.5	0.5
P1	230.6	0.5
E1	230.9	0.5
P2	226.9	0.5
C5	231.5	0.5
E5a	231.8	0.5
B1	223.1	0.6
B2	223.9	0.5

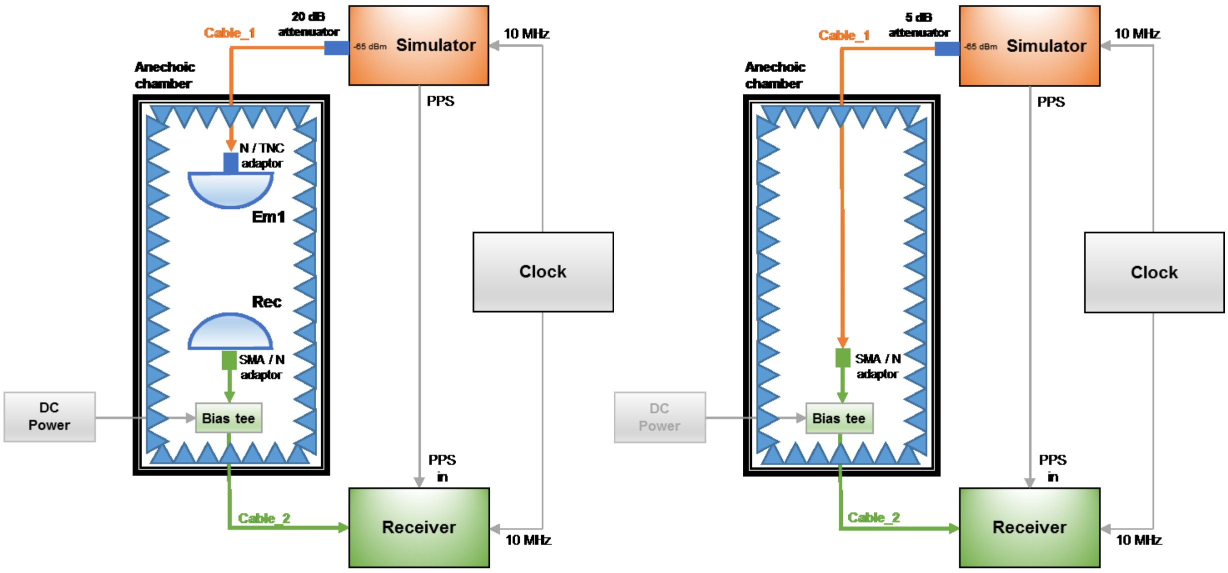
Table 5: Absolute calibration results for the complete GNSS receiver chain

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 (referred to as Em1) used as a transmitting antenna is placed at the top of the chamber, while the BIPM B3E6 antenna (referred to as Rec) 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 delays of the antennas, we use a triangulation method as described in [RD1]. For that purpose, two additional setups are necessary. In the first one, the pair of antennas used is Em2 (a passive antenna similar to Em1) and Rec. In the second one, the pair of antennas used is Em1 and Em2. With the measurements in these three configurations, the delays of the three antennas (Em1, Em2 and Rec) are determined by a triangulation method [RD1].

The determination of the delay mostly relies on the difference between the pseudoranges measured by the receiver and the pseudoranges 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), which avoids measuring the delay of the cables used. The difference of configuration (adaptors) is taken into account. The distance between the phase centers is determined using a laser range finder and the IGS file igs14.atx.

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

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

where $Tare_{mean}$ is the average of $Tare_{before}$ and $Tare_{after}$, and 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.

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

The uncertainty on SAD is:

$$\mathrm{u_{SAD_{XY}}} = \sqrt{(\mathrm{u_{CV_{XY}}}/c)^2 + (u_{dist_{XY}}/c)^2 + {u_{C_{XY}}}^2 + \mathrm{u_{PWR}}^2}$$

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

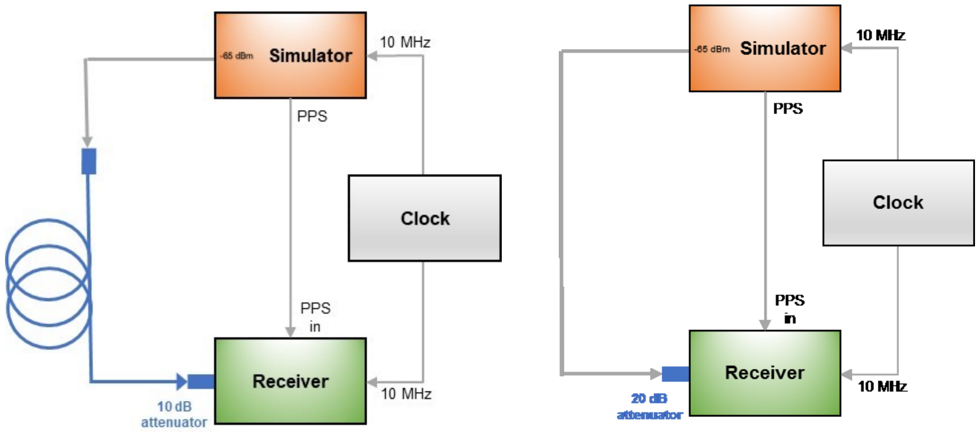
$$\mathrm{u_{AD_{Rec}}} = \sqrt{{u_{CV_{\mathrm{Em1Rec}}}}^2 + {u_{dist_{\mathrm{Em1Rec}}}}^2 + {u_{AD_{\mathrm{Em1}}}}^2 + {u_{C_{\mathrm{Em1Rec}}}}^2 + {u_{Tare_{mean}}}^2 + {u_{Tare_{closure}}}^2 + \mathrm{u_{PWR}}^2 + \mathrm{u_{AZEL}}^2}$$

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 on the delay of the passive antenna Em1	0.15 to 0.3 ns
the uncertainty resulting from the differences between the tare setup and the antennas measurement setups (u_C)	0.1 ns
the uncertainty of the tare measurement (u_{Tare_mean})	0.02 to 0.15 ns
the uncertainty resulting from the tare closure ($u_{Tare\_closure}$)	0.01 to 0.06 ns
the uncertainty due to the RF input power level sensitivity of the receiver (u_{PWR})	0.1 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
Typical overall uncertainty of the antenna delay	**0.26 to 0.49 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. In order to obtain similar receiver AGC values between the tare setup and the calibration setup, the 20 dB attenuator used in the tare setup is replaced by a 10 dB attenuator of the same physical length in the calibration setup.



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

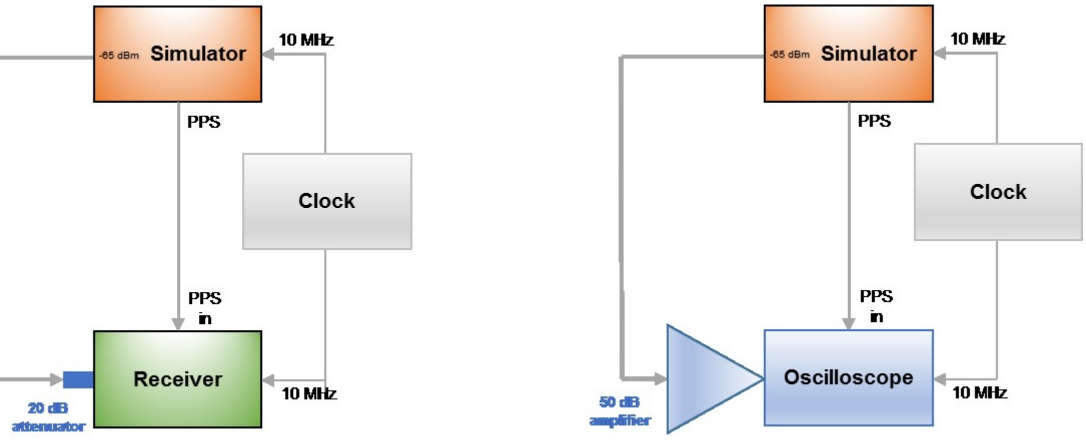
Source of uncertainty	Typical value
the standard deviation of the common-views (u_{CV})	0.02 to 0.1 ns
the uncertainty resulting from the differences between the tare setup and the antennas measurement setups (u_C)	0.1 ns
the uncertainty due to the RF input power level sensitivity of the receiver (u_{PWR})	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
Typical overall uncertainty of the RF cable delay	**0.15 to 0.23 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 Spectracom 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
Typical uncertainty of the simulator delay	**0.11 to 0.19 ns**

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

BIPM BP27 receiver has been set up in the so-called “Auto” mode for the PPS_IN internal delay compensation, so that no measurements of PPS_IN – PPS_OUT are needed. The associated uncertainty claimed by the manufacturer is 0.1 ns (1 σ) [RD2].

The overall RxD uncertainty is given by:

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

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})	0.18 to 0.25 ns
the uncertainty of the Rx1pps (u_{Rx1pps})	0.1 ns
Typical overall uncertainty of the receiver delay	**0.27 to 0.35 ns**

Table 9: Typical 1-σ uncertainty of the receiver delay

3.4 PICTURES OF THE CALIBRATIONS

The picture below shows the calibration of the BIPM B3E6 antenna installed at the bottom of our anechoic chamber.

Figure 4: Picture of the antenna calibration

The picture below shows the calibration of the BP37 cables (long cable + splitter + short cable). The GNSS receiver used for this calibration was a CNES Septentrio PolaRx4TR.

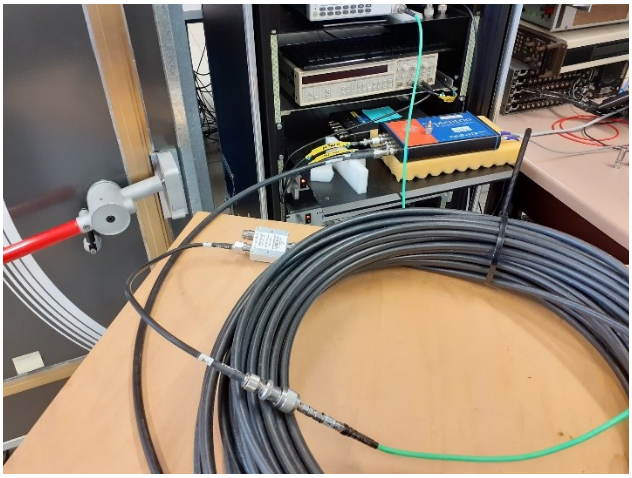


Figure 5: Picture of the cables calibration

The picture below shows the setup of the calibration of the GNSS receiver. Starting from the top, we can see the Tektronix oscilloscope, the Spectracom GNSS simulator and the BIPM BP27 Septentrio PolaRx5TR.

Figure 6: Picture of the GNSS receiver calibration

END OF DOCUMENT