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TECHNICAL NOTE « CNES REPORT ON THE ABSOLUTE CALIBRATION OF CS13 AND CS14 RECEIVER CHAINS »

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INDEXATION

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MODIFICATION DIRECTORY

Issue	Date	Evolutions
1.0	**16/12/2022**	
1.1	**11/10/2023**	The uncertainty of the OP reference station delay (as determined in [RD3]) is taken into account in the comparison of Table 7.

TABLE OF CONTENTS

1 INTRODUCTION

This document describes the results obtained by CNES on the absolute calibration of two CNES GNSS receiver chains (referred to as CS13 and CS14) together with the estimated uncertainties. Both calibrations are performed for GPS C1, P1, P2 and C5, Galileo E1 and E5a, and BDS-2 B1 and B2.

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 section 4 of this document with typical uncertainty budget for each element.

A comparison of these results with the BIPM relative calibration campaign #1012-2021 [RD2] performed by OP is presented in section 3.

1.1 HARDWARE & SOFTWARE IDENTIFICATION

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

	CS13	CS14
GNSS antenna	SEPCHOKE_B3E6 s/n 5077 CNES reference name = "B3E6_3"	LEICA AR20 s/n 22282006 CNES reference name = "AR20_1"
RF cable	KX13 type labelled "CNES"	KX13 type labelled "CNES_2"
GNSS receiver	Septentrio PolaRx5TR PRO Firmware 5.4.0 s/n 3015994 n° chrono = 2220004	Septentrio PolaRx5TR PRO Firmware 5.4.0 s/n 3052427 n° chrono = 2228591

Table 1: Devices undergoing the absolute calibration

The GNSS simulator used for these calibrations is a Spectracom GSG-64 s/n 200823. The oscilloscope is a Tektronix Digital Phosphor Oscilloscope s/n B022204 (n° chrono 2119228). The correlation software used for the calibration of the GNSS simulator is LOGICORR SW1000 v2.0.

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 :	"Calibration of CNES and ILNAS GNSS Station by LNE-SYRTE" - Calibration Report #1012-2021, 23 April 2021, issue 1.0
RD3 :	« 2018 Group 1 GPS calibration trip » - 1001-2018, v1.1 / 20200106.

2 RESULTS

2.1 GNSS ANTENNAS

The CS13 antenna delays have been estimated with a triangulation measurement involving the NovAtel 701_1 and 704_2 antenna. The CS14 antenna delays have been estimated with a direct measurement versus the NovAtel 704_2 passive antenna.

Table 2 below summarizes the results of the absolute calibration of these antennas. All results are given in ns.

[ns]	**CS13 antenna (B3E6_3)**		**CS14 antenna (AR20)**	
GNSS code	AD	u_{AD}	AD	u_{AD}
C1	22.32	0.24	26.04	0.33
P1	22.51	0.28	25.96	0.35
E1	22.29	0.21	26.03	0.29
P2	19.45	0.17	22.20	0.25
C5	20.14	0.17	26.06	0.25
E5a	20.13	0.17	26.06	0.25
B1	20.90	0.30	25.45	0.40
B2	18.82	0.24	21.06	0.33

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.

[ns]	**CS13 cable**		**CS14 cable**	
GNSS code	CD	u_{CD}	CD	u_{CD}
C1	118.26	0.19	118.46	0.22
P1	118.32	0.19	118.53	0.22
E1	118.26	0.17	118.48	0.21
P2	118.28	0.15	118.49	0.18
C5	118.33	0.15	118.54	0.18
E5a	118.36	0.15	118.49	0.18
B1	118.19	0.21	118.43	0.23
B2	118.19	0.19	118.41	0.22
Mean value	**118.27**	**0.18**	**118.48**	**0.21**

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 with the pps auto-compensation mode ON. All results are given in ns.

[ns]	CS13 receiver		CS14 receiver	
GNSS code	RxD	u_{RxD}	RxD	u_{RxD}
C1	9.36	0.29	9.44	0.28
P1	9.59	0.32	9.74	0.32
E1	9.81	0.26	9.82	0.29
P2	7.41	0.25	9.15	0.25
C5	9.01	0.26	9.45	0.26
E5a	9.41	0.26	9.76	0.26
B1	2.17	0.34	1.80	0.34
B2	5.00	0.29	4.85	0.30

Table 4: Absolute calibration results for the GNSS receivers with pps auto-compensation ON

Another calibration has been performed with the pps auto-compensation OFF. The results are provided in Table 5:

[ns]	CS13 receiver		CS14 receiver	
GNSS code	RxD	u_{RxD}	RxD	u_{RxD}
C1	9.15	0.30	9.34	0.30
P1	9.47	0.31	9.73	0.31
E1	9.57	0.28	9.76	0.28
P2	7.44	0.27	9.15	0.27
C5	9.14	0.28	9.53	0.28
E5a	9.46	0.28	9.85	0.28
B1	1.89	0.33	1.73	0.33
B2	4.73	0.31	4.87	0.31

Table 5: Absolute calibration results for the GNSS receivers with pps auto-compensation OFF

It can be noticed that the results with pps auto-compensation ON and OFF are compatible within the 1-sigma uncertainty.

The results that we finally consider are the ones with auto-compensation OFF, as recommended by OP.

2.4 COMPLETE GNSS RECEIVER CHAIN

Table 6 below summarizes the results of the absolute calibration of the GNSS stations. All results are given in ns.

[ns]	**CS13 complete chain**		**CS14 complete chain**	
GNSS code	delay	uncertainty	delay	uncertainty
C1	149.73	0.43	153.84	0.49
P1	150.3	0.46	154.22	0.52
E1	150.12	0.39	154.27	0.45
P2	145.17	0.35	149.84	0.41
C5	147.61	0.36	154.13	0.42
E5a	147.95	0.36	154.4	0.42
B1	140.98	0.49	145.61	0.57
B2	141.74	0.44	144.34	0.50

Table 6: Absolute calibration results for the GNSS receiver chains

3 COMPARISON WITH BIPM RELATIVE CALIBRATION

A relative calibration campaign of CNES GNSS receiver chains has been performed in January-March 2021 (#1012-2021). This campaign has been organized and managed by LNE-SYRTE (Observatoire de Paris). The results are given in [RD2].

Please note that the CNES GNSS receiver chains CS13 and CS14 are referred to as respectively CS23 and CS24 in [RD2].

Table 7 compares the INT DLY (sum of the delay of the antenna and the receiver) for the absolute and relative calibrations. On top of the uncertainties indicated in [RD2], a thorough comparison between CNES absolute calibration and OP relative calibration must also consider the uncertainty of the calibration of the OP G1 reference station performed by BIPM. The latter uncertainty has been estimated to be 1.1 ns (1-sigma) for GPS P1 and P2, and Galileo E1 and E5a [RD3].

[ns]	**CS13 INT DLY**			**CS14 INT DLY**		
GNSS code	OP	CNES	CNES-OP	OP	CNES	CNES-OP
P1	31.6 (1.3)	32.0 (0.4)	0.4 (1.4)	35.4 (1.3)	35.7 (0.5)	0.3 (1.4)
P2	28.1 (1.2)	26.9 (0.3)	-1.2 (1.2)	32.1 (1.2)	31.4 (0.4)	-0.7 (1.3)
E1	33.3 (1.2)	31.9 (0.4)	-1.4 (1.3)	36.9 (1.2)	35.8 (0.4)	-1.1 (1.3)
E5a	30.7 (1.3)	29.6 (0.3)	-1.1 (1.3)	37.2 (1.3)	35.9 (0.4)	-1.3 (1.4)

Table 7: Comparison of absolute and relative calibration results for CS13 and CS14 receiver chains

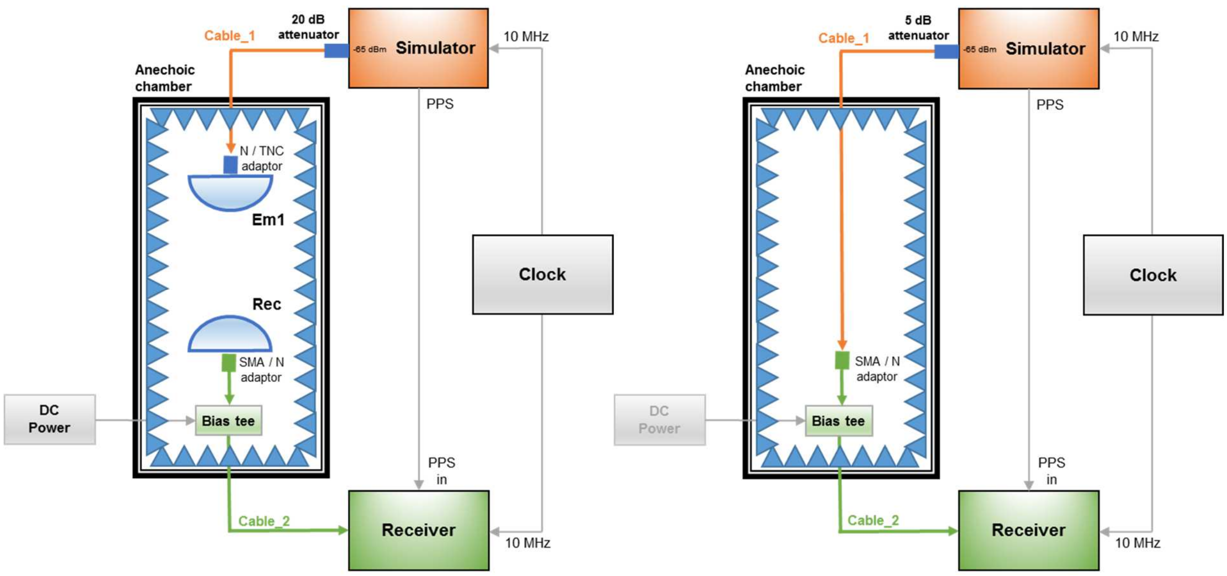
When taking into account the uncertainty of the OP G1 reference station, the relative and absolute calibrations have a very good consistency: they agree within 1-sigma for all the GNSS signals considered here, except E1 for CS13 for which an agreement at 2-sigma is nevertheless reached.

4 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

4.1 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 $Tare_{mean}$ 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.

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:

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

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

$$\mathrm{u_{AD_{Em1}}} = \mathrm{u_{AD_{Em2}}} = \sqrt{{u_{SAD_{\mathrm{Em1Rec}}}}^2 + {u_{SAD_{\mathrm{Em1Em2}}}}^2 + \frac{{u_{SAD_{\mathrm{Em2Rec}}}}^2 + \mathrm{u_{Tare_{mean}}}^2 + \mathrm{u_{Tare_{closure}}}^2}{4}}$$

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

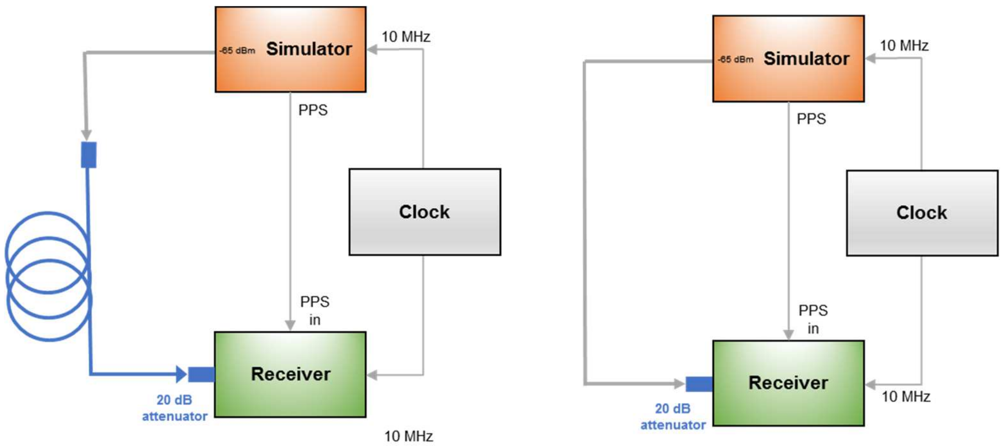
$$\mathrm{u_{AD_{Rec}}} = \sqrt{\mathrm{u_{AD_{Em1}}}^2 + \mathrm{u_{AZEL}}^2}$$

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 8: Typical 1-σ uncertainty of the antenna delay

4.2 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)

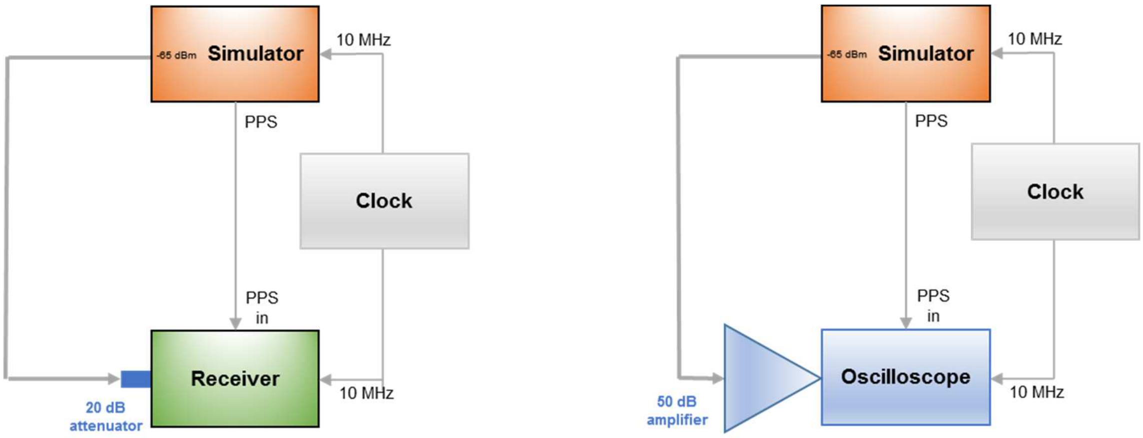
Source of uncertainty	Typical value
the standard deviation of the common-views (u_{CV})	0.02 to 0.1 ns
the uncertainty resulting from the differences between the tare setup and the antennas measurement setups (u_C)	0.1 ns
the uncertainty due to the RF input power level sensitivity of the receiver (u_{PWR})	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 9: Typical 1-σ uncertainty of the RF cable delay

4.3 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)

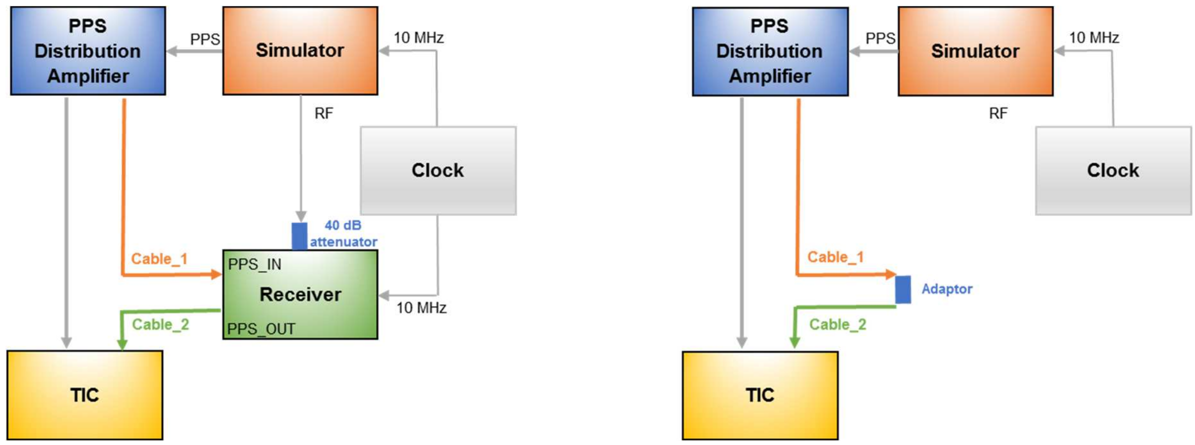
The simulator delay is determined using a fast oscilloscope. It corresponds to the time offset between the beginning of the GNSS PRN code and the internally generated 1 PPS synchronized with the GNSS time. The oscilloscope data are analyzed with a home-made correlation software. Each signal is generated 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 10: 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 PolaRx5TR 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.

In pps auto-compensation ON, these measurements are not necessary (they are estimated and corrected for by the receiver).



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 11: 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 12: Typical 1-σ uncertainty of the receiver delay

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