ABSOLUTE CALIBRATION AND EVALUATION OF GEODETIC RECEIVERS

A.Proia[1,2], G.Cibiel[1], L.Yaigre[3]

[1]Centre National d'Etudes Spatiales
18 Avenue Edouard Belin - 31401 Toulouse - France
E-mail : amandine.proia@cnes.fr
E-mail : gilles.cibiel@cnes.fr

[2] Bureau International des Poids et Mesures
Pavillon de Breteuil-92312 - Sèvres – France

[3]Sogeti High-Tech
Park Avenue 2 - 57 Avenue du Général DeCroute – 31100 Toulouse
E-mail : leslie.yaigre@sogeti.com

INTRODUCTION

Global Navigation Satellite System (GNSS) time and frequency transfer is among the most useful tools for comparison of remote clocks. It represents the basis of the time laboratories contributions for the realization of the Temps Atomique International (TAI). These comparisons are carried out with dual frequency P-code GPS receivers which must be calibrated and evaluated periodically to ensure the accuracy and long term stability of time links. Presently, several receivers models are available and used in time laboratories as Ashtech Z12-T, Septentrio PolaRx2, Dicom GTR50 or TTS03. The usual approach to evaluate and calibrate a receiver consists in working on natural reception, i.e. in using a GNSS reception chain (antenna, cable antenna, receiver). The common approach to perform this experiment is the differential calibration developed by BIPM [1]: One GNSS equipment is designated as the reference equipment and is in constant circulation among time laboratories. A relative calibration is performed between this equipment and the laboratory equipment. This paper proposes an alternative method in replacing the natural GPS signal by an artificial signal provided by a GNSS signal simulator (GSS). Up to now, this approach was only used to calibrate the receiver. This calibration method was first defined and used by the Colorado University and puts into operation by Naval Research Laboratory. Since 2005, CNES is developing this method with a similar approach and studying also the parameters having an influence on the receiver delay determination. This paper is focused on the evaluation and the calibration of some different receivers in using the artificial reception approach. It will also describe the temperature effect on the pseudo-ranges produced by the simulator.
Section II presents geodetic receivers and describes their characteristics. Three kind of time receivers, two Ashtech Z12-T receivers, two Septentrio PolaRx2 receivers and two Dicom GTR50 receivers were investigated. The method to calibrate and evaluate the receivers in using the artificial signal is described in Section III. The time stability measurement of the receivers is presented in section IV. The section V is dedicated to the results of receivers calibration and their uncertainties. Finally, the study of the temperature sensibility of the simulator is presented in the section VI.

RECEIVERS

Geodetic GPS receivers (Rx) used for time transfer are characterized by two features:

a. The receiver internal clock is driven by an external frequency provided by the laboratory
b. The receiver has a 1 Pulse Per Second (1PPS) input that allows to define an "internal reference" from the internal clock

The precise definition of the internal reference depends on the receiver model.

Ashtech Z12-T, Septentrio PolaRx2 or Dicom GTR50 receivers fulfill both criteria.

The delay between the 1PPS input and the internal reference will be referred as Rx_{1PPS}. This value is specific to every kind of receiver and depends on the electronic architecture of the equipment. The Rx_{1PPS} definition is generally provided by the supplier. The output data must be corrected of this bias to be reference to the internal system clock.

1. Ashtech Z12-T

The Ashtech Z12-T receiver performs pseudo-range and carrier phase measurements which are referred to an "internal reference" derived from a 20 MHz external signal [5]. The 1PPS external signal allows the receiver to choose one particular cycle of the 20 MHz to form the internal reference. This operation allows to guarantee repeatability of this reference in case of interruption of the tracking or operation of the receiver. The internal reference is then defined as the first positive zero crossing of the 20-MHz-in following the rising tick of the 1PPS-in signal [6]. The delay between the 1PPS signal and 20 MHz signal (Rx_{1PPS} : TtP) is measured with a digital oscilloscope. By direct measurement on the oscilloscope display, it is possible to determine the relative phase of the two signals.
The Ashtech Z12-T is no more commercially available since 2005.

2. Septentrio PolaRx2

The Septentrio PolaRx2 receiver provides dual-frequency tracking of the GPS signal and simultaneous tracking of up to 6 Space-Based Augmentation System (SBAS) satellites [5]. The receiver accepts a 10 MHz external frequency and an associated 1PPS input. As for the Ashtech receiver, the Septentrio internal time scale is synchronized on the 1PPS signal, providing repeatability of this reference. The receiver synchronizes its measurement latching with the first low-to-high transition it detects on the 1PPS input connector. The delay between a low-to-high transition on the 1PPS input connector and the latching of the measurements in the receiver is between 221.7 and 255ns (±2ns). The exact delay depends on the phase relationship between the 10 MHz frequency reference and the 1PPS input signal (Rx_{1PPS} : X_0). This delay is constant and is insensitive to powering off and on the receiver. In order to measure the delay between the 1PPS input pulse and the measurement latching, it is possible to synchronize the 1PPS output signal from the receiver with the measurement latching epoch. The constant offset between the 1PPS output and the measurement latching is indicated in Septentrio PolaRx2's documentation: *"measurement latching" = "Output 1PPS" plus 8.7 ns (for firmware version 2.3 and higher)*. Thus, by measuring the delay from the 1PPS input to the 1PPS output, we have access to the internal reference that we have defined.

3. Dicom GTR50

The GTR50 receiver is a Linux PC with a GPS board and a time interval counter all together in a 19" chassis. The time interval counter and the GPS board are located in a thermostated box (a fan maintains air circulation in the box) to minimize their temperature drift. The temperature is 45°C with a maximum deviation of 1°C.The Javad GPS board supports both code and phase measurements. The internal quartz oscillator is the source of the 1PPS output synchronized to GPS Time. The time difference between the 1PPS external signal and this internal time base (Rx_{1PPS}) is collected like the receiver measurements data (pseudo-ranges and phase measurements to individual satellites) in hourly files. Contrary to the previous receivers, no 1 PPS internal delay is considered and all the output data (RINEX, CGGTTS, L3P, RAW) are referenced to the external 1PPS. Five calibration delays (antenna cable delay, 1PPS delay, C1 receiver delay, P1-C1 receiver differential delay and P1-P2 receiver differential delay) are applied on all output data to keep data in all these formats fully consistent. The antenna cable delay and the 1PPS delay can be changed from the web user interface. The receiver internal delay and the P1-C1 and P1-P2 differential delays can be cancel contrary to the Rx_{1PPS} of which the correction is automatically applied at each acquisition.
The current version of the GTR50 does not require an external 10 MHz reference. Indeed, the time interval counter uses an internal frequency reference which is continuously calibrated with respect to the GPS time.
In this present work, all bias corrections are equal to zero except the Rx_{1PPS} value.

EVALUATION AND CALIBRATION METHOD

The CNES approach of the receivers calibration consists in an artificial reception free of delays, effects and noises upstream at the output of antenna : atmospheric delays (troposphere and ionosphere), multipath effects or antenna delay. These conditions can be conducted with a GNSS Signal Simulator (GSS) (Fig. 1). The simulator used is a Spirent STR4760 8 channels. It allows to simulate the signals emitted by the GPS satellites in real conditions. It is able to produce the GPS signal but also all the noises present in natural reception (propagation, clock error…).
For the artificial reception method, the emitted signal does not included noises. The simulator generates only the navigation message and two carrier frequencies : L1 modulated by the C/A and P codes and L2 modulated by P code.

The power of the radiofrequency signal is -70 dBm and must be adjusted to correspond to the reception level acceptable by the receiver (-110 dBm generally). It provides also a 1PPS signal which lets the receivers to be synchronized with the simulator.

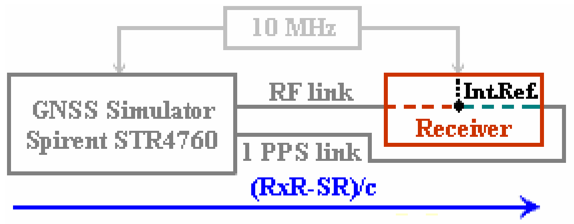

Fig. 1. Schematic of artificial reception method

The time deviation of the pseudo-distances between the simulator and the receiver allows to determine the time stability of the receiver, i.e. the specific performance of the receiver.

Figure 2 describes a schematic of receiver absolute calibration. This calibration method was first defined by the Colorado University and put into operations by Naval Research Laboratory [2]. Since 2005, CNES is developing this method with a similar approach [3,4].

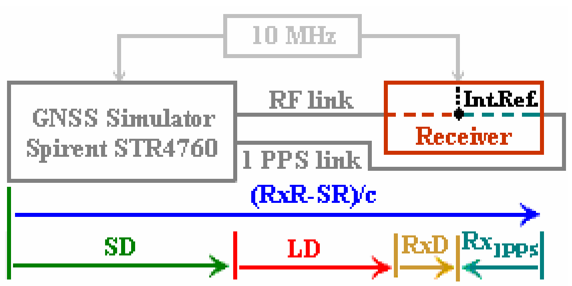

Fig. 2. Schematic of receiver absolute calibration

This fixed relationship lets the receiver delay calculation. The internal electrical time delay of the receiver is calculated thanks to the Equation (1):

$$RxD = \frac{RxR - SR}{c} - LD - SD + Rx_{1PPS} \qquad (1)$$

where :

- RxD: Receiver delay
- RxR-SR: Difference of receiver and simulator pseudo-ranges
- c : Light celerity
- LD: 1PPS and RF links delays difference (LD_{RF}-LD_{1PPS})
- SD: Simulator delay
- Rx_{1PPS} : Time delay between the receiver internal reference and the external 1 PPS

Six receivers were evaluated and absolute calibrated: two Dicom GTR50 receivers (BIPM, PTB Rx), two Ashtech Z12-T receivers (CNES, OP Rx) and two Septentrio PolaRx2 receivers (CNES Rx).

During the calibration measurement, due to their temperature sensitivity [3], the simulator and the receivers were located in a temperature regulated room at 20°C with a maximum deviation of ±1°C.

RECEIVER TIME STABILITY

The receiver time stability is defined by the time deviation of the pseudo-ranges acquisition in second. The figure 3 shows the results obtained for the P1-code and P2-code of a Septentrio receiver.

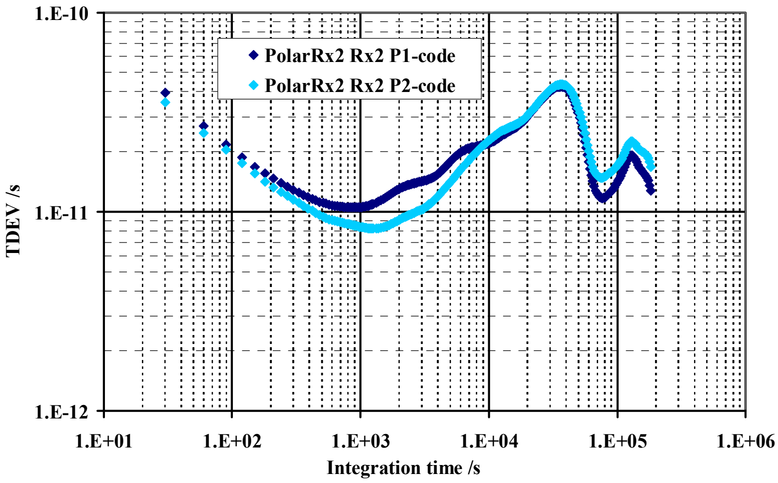

Fig. 3. Tdev of P1-code and P2-code of
the PolaRx2 Rx2

A daily term due to the temperature degrades the time deviation. Indeed, the equipment is very sensitive to the temperature fluctuations and this phenomenon makes difficult the evaluation of the daily term stability of receivers. A pseudo-ranges scattering estimated up to 0.4 ns/°C was already noted [3].

In order to take into account this problem, two similar receivers get simultaneously the simulator signal (Fig. 4) so that the output data difference allows to cancel the pseudo-range fluctuations.

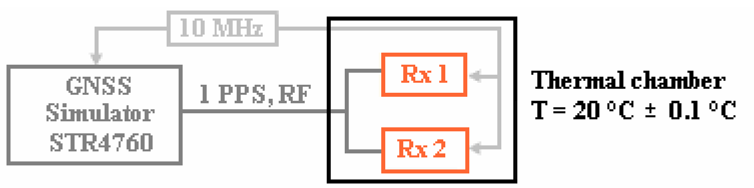

Fig. 4. Schematic of time stability measurement
with GSS thermal sensitivity cancellation

The simulator is located in a temperature regulated room at 20 °C with a maximum deviation of 1 °C and the receivers are placed in a thermal chamber where the temperature is regulated to 20 °C ± 0.1 °C. A peer of Ashtech and Septentrio receivers are placed in this configuration to be evaluated. The Dicom GTR50 receivers are too voluminous to be completely placed in the thermal chamber. The box is then not closed hermetically and the thermal regulation is less efficient.

At each acquisition, the pseudo-ranges average is calculated with all the satellites in view. This operation is performed for every receivers peer. The P1-code pseudo-ranges for the PolarRx2 Rx1 and the PolarRx2 Rx2 are presented in figure 5.

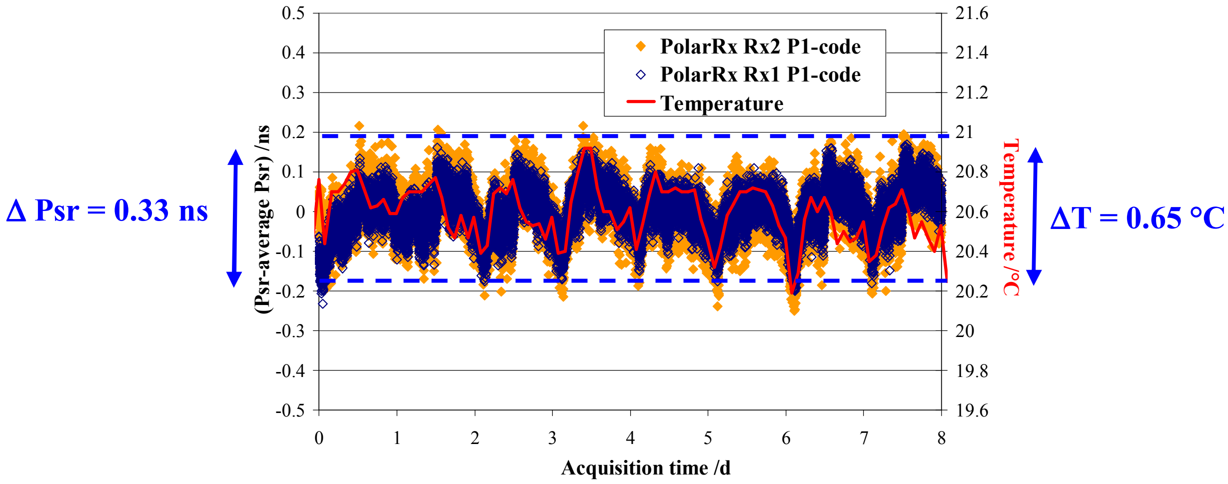

Fig. 5. Pseudo-ranges of P1-code for the PolarRx2 Rx1 and the PolarRx R2

It can be noted that the thermal sensitivity of the simulator is visible on the pseudo-ranges and is about 0.5 ns/°C at a temperature of 21°C in agreement with [3].

The pseudo-ranges difference of receivers peer is performed to evaluate the time stability of different equipment. The total time stabilities of the P-code difference are the quadratic sum of time stability of each receiver (Rx1 & Rx2). The figure 6 illustrates the time deviation of the P1 and P2 code difference of each kind of receivers for a six days acquisition duration.

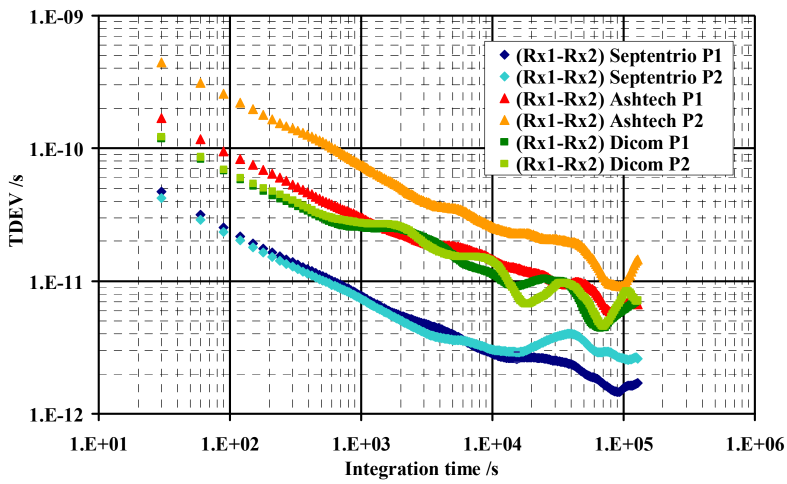

Fig. 6. Time deviation of the P-code difference

In the case of Ashtech receivers, the time stability of both receivers is equivalent and corresponds to the total stability divides by √2. In the case of Septentrio and Dicom receivers, the time stabilities of both receivers are not equivalent and the total time stability is imposed by the worst receiver time stability.

The acquisitions difference of Dicom receivers shows a periodic phenomenon. These devices are Linux PC which eject hot air. In this conditions, the thermal chamber can not regulate the temperature with precision and the pseudo-ranges acquisition fluctuates with the temperature.

The table 1 resumes the short term (at 30 s) and middle term (at one day) stability of the receivers:

Table 1. Receivers time stability

	Short term stability 30s (ps)				Middle term stability 1 day (ps)			
Receiver	L1	u (L1) σ=1	L2	u (L2) σ=1	L1	u (L1) σ=1	L2	u (L2) σ=1
Ashtech Z12-T	168.30	2.50	445.70	6.70	6.09	11.74	9.30	22.52
Septentrio PolaRx2	47.16	0.59	42.26	0.59	1.48	1.29	2.79	3.45
Dicom GTR50	118.30	1.80	121.80	1.80	5.42	32.39	6.08	30.83

The Septentrio receiver has the best stability: between 40 ps et 50 ps in short term and below 3 ps in middle term. His time stability uncertainty at one day is about 10 time weaker than the Ashtech and Dicom time stability uncertainty. The short term stability of P1 and P2 code are close for the Septentrio and Dicom receivers contrary to the Ashtech which shows an important difference of about 300 ps.

RECEIVERS TIME DELAY

The time delay of each receiver is defined by the absolute calibration method. The GTR50 receivers measurements were performed in cancelling all the bias corrections except the $Rx_{1PPS.}$ The Table 2 presents L1 and L2 electrical delay of each receiver and their uncertainties for one sigma.

Table 2. L1 and L2 time delay of each receiver and uncertainties for σ=1

Time delay		P1 (ns)	P1 uncertainty (ns) σ=1	P2 (ns)	P2 uncertainty (ns) σ=1	[P2-P1] (ns)
Ashtech Z-12 T	***CNES Rx***	284.49	0.39	290.71	0.40	6.22
	OP Rx	286.11	0.41	302.58	0.40	16.47
Septentrio PolaRx2	***CNES Rx1***	192.12	0.416	190.92	0.415	-1.20
	CNES Rx2	191.72	0.43	193.26	0.43	1.54
Dicom GTR50	***BIPM Rx***	93.42	0.37	106.87	0.37	13.45
	PTB Rx	24.54	0.37	30.91	0.37	6.37

The only changing parameters according to the used receiver are the Rx_{1PPS} and the pseudo-ranges measurements. The calibration uncertainties are to the same order of magnitude for all the receivers (about 0.4 ns/°C) because the error budget is dominated by the pseudo-ranges error and the interchannel bias of the simulator (0.33 ns) [3]. Indeed, in the simulator electronic architecture, each channel is produced by a different card which inserts also a bias between the channels. The error taken into account in the error budget is the value given by the supplier.
The [P2-P1] differential delays are not constant for the same kind of receivers. This difference is due the to various manufactured versions of receivers.

EQUIPMENT TEMPERATURE SENSITIVITY

Previous works using the artificial reception method show that the receivers but also the simulator are sensitive to the room temperature fluctuations. Pseudo-ranges fluctuations of about 0.4 ns/°C are already observed [3,4]. The temperature sensitivities of the Spirent 4760 simulator will be evaluated in details in this section. The temperature behaviour of the Ashtech and Septentrio receivers were already studied [3]:

- Z12-T receivers : 0.15 ns/°C in temperature range [0 – 40 °C]
- PolaRx2 Rx1 : 0.20 ns/°C in temperature range [5-15°C]
  0.02 ns/°C in temperature ranges [0-5°C] and [20-40°C]
- PolaRx2 Rx2 : 0.20 ns/°C in temperature range [10-20°C]
  0.02 ns/°C in temperature ranges [0-10°C] and [25 - 40°C]

The environmental specifications given by Spirent indicate that the operating temperature of the simulator STR4760 is included between 10 and 40°C. We have therefore decided to evaluate the simulator temperature sensitivity in a range of 13°C to 35°C. For this experiment, the simulator is placed in a thermal chamber where the temperature increases regularly in all the temperature range. The receiver, a Septentrio PolaRx2 (CNES Rx1) is also located in a thermal

chamber at constant temperature of 20 °C with a maximum deviation of 0.1 °C. This operation is necessary because the room where takes place this experiment is not regulated in temperature.
The figure 7 represents the receiver delay of the C/A, P1 and P2 code, the thermal chamber temperature and the simulator surface temperature versus the acquisition time. During this experiment, the temperature increases of 0.25°C/h.

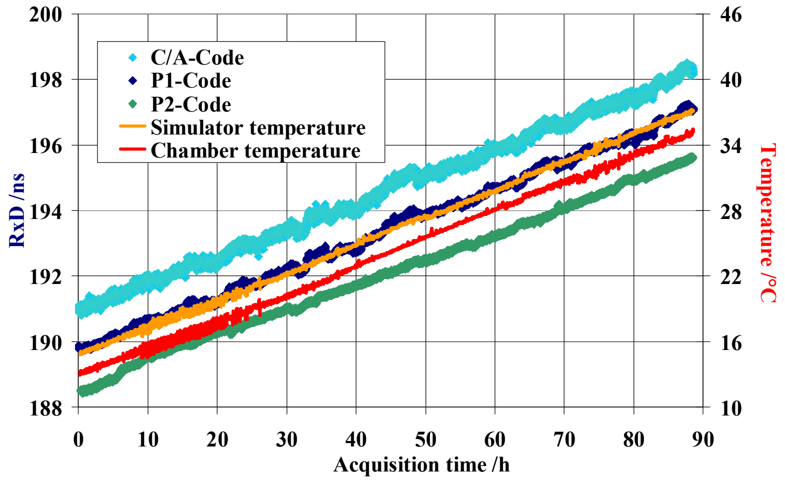

Fig 7. Delay receiver, room temperature and receiver surface temperature versus acquisition time

The temperature difference between the thermal chamber and the simulator surface stays constant on all the temperature range and is on average of 1.91 °C.
The variations of the pseudo-ranges acquired with the receiver are strongly correlated with the room temperature where is located the simulator. With a complete control environment, the pseudo-ranges show again few fluctuations. This phenomenon is due to the simulator noise and to the own noise of the receiver.
The powerful temperature influence on the simulator is probably due to its discreet electronic architecture. Indeed, this type of electronic is constituted by many electronic components notably by resistances which are particularly sensitive to the temperature effects.

With this experiment, we can define the relation between the pseudo-ranges variations for each code and the temperature:

- For the C/A code: $(RxR-SR)/c\ C/A = 0.32\ T° + RxD(C/A)_0$ (2)
- For the P1 code: $(RxR-SR)/c\ P1 = 0.32\ T° + RxD(P1)_0$ (3)
- For the P2 code: $(RxR-SR)/c\ P2 = 0.31\ T° + RxD(P2)_0$ (4)

where :
- RxD: Receiver delay [ns]
- (RxR-SR)/c: Difference of receiver and simulator pseudo-ranges divided by the light celerity [ns]
- T°: Temperature [°C]

The standard deviation for all the acquisition time is:
- For the C/A code: σ (C/A) = 0.17 ns
- For the P1 code: σ (P1) = 0.11 ns
- For the P2 code: σ (P2) = 0.09 ns

The simulator presents therefore on average a linear temperature dependence of 0.32 ns/°C for a room temperature range of 13 to 35 °C with a standard deviation of the pseudo-ranges equals to 0.10 ns.

The observed fluctuations at room temperature during the experiment in using the artificial reception method are about 0.4 ns/°C. The equipment temperature study proves that this phenomenon is due to the temperature sensitivity of the receivers and the simulator. The pseudo-ranges fluctuations due to the temperature are taken into account in the uncertainty budget in calculating the data standard deviation. The temperature effect on the simulator could be considerably reduce with an electronic which is less temperature sensitive.

CONCLUSION

The artificial reception method which uses a GNSS signal simulator is now a proofed method. It lets to determine the electrical delay of the most of geodetic receivers used in time laboratories: Ashtech Z12-T, Septentrio PolaRx2 and Dicom GTR50 with an uncertainty of about 0.4 ns.
A performance comparison of three receivers was also performed. The equipment is very sensitive to the temperature. With a deviation of 1°C, the pseudo-ranges fluctuations are about 0.4 ns/°C. In order to limit this problem, two similar receivers get simultaneously the simulator signal. The output data difference allows to cancel the pseudo-ranges fluctuations. At each acquisition, the output data average is calculated with all the satellites in view.
It lets also to define more easily the time stability of the receiver in calculating the time deviation of the pseudo-ranges difference. The daily stabilities of receivers for L1 and L2 are:

- Ashtech Z12-T : L1 = 6.09 ps, L2 = 9.30 ps
- Septentrio PolaRx2 : L1 = 1.48 ps, L2 = 2.79 ps
- Dicom GRT50 : L1 = 5.42 ps, L2 = 6.08 ps

The Septentrio receiver has the best short and middle term stability. The short term stability of P1 and P2 code is to the same order of magnitude for the Septentrio and Dicom receivers when the Ashtech shows an important difference of about 300 ps.
The study of the simulator temperature sensitivity points out a strong correlation between variations of the pseudo-ranges emitted by the simulator with the temperature variations. The Spirent 4760 simulator presents a linear temperature dependence of 0.32 ns/°C for a room temperature range of 13 to 35 °C. On average, the Ashtech and Septentrio receivers have a thermal dependence of 0.18 ns/°C for a room temperature. The observed fluctuations during the receiver calibration or evaluation are therefore the sum of the temperature effects on the simulator and the receivers.
A simulator with a more recent electronic where the pseudo-ranges are produced by a single chip will allow to reduce the uncertainties due to the thermal sensitivity and the interchannel bias. The error budget of the absolute calibration method will be thus reduce.

In the future, the aim will consist in extending this investigation as whole the GNSS reception chain, the receiver but also the antenna cable and the antenna.

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