

# ABSOLUTE CALIBRATION OF TIME RECEIVERS WITH DLR'S GPS/GALILEO HW SIMULATOR

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## Abstract

*A usual way for time transfer between atomic clocks operated at different locations is the use of the well known GNSS Common View technique. This technique is based on time receivers measuring the time differences between the connected atomic clock and the GNSS satellite clocks. The results obtained can be used for time scale generation, such as UTC or TAI. In order to produce a very accurate time scale from all time differences measured with different GNSS time receivers, the accurate calibration of them is essential.*

*In recent years, two main methods for time receiver calibration have been proposed. One is to compare the obtained time differences relative to a calibrated receiver. In the second method, one performs an absolute calibration of time receivers using a GPS HW simulator. In this paper, the absolute calibration of time receivers with DLR's GPS/Galileo HW simulator is analyzed and described in detail.*

*The primary step is to calibrate the simulator itself. In this context, the most important facts and values that have to be measured are explained. After the calibration of the simulator, the receiver is fed with satellite signals generated by the simulator belonging to a standard GPS satellite constellation in order to determine the absolute offset of the receiver (internal delay) compared to the simulator output.*

*Additionally, the precision of a combined GPS/Galileo receiver for frequency transfer is investigated and determined.*

## INTRODUCTION

In recent years, more and more GPS time receivers have been used for time transfer between remote atomic clocks. As the precision of the time transfer – using dual frequency, multi channel time receivers – is getting better and better, the accurate calibration of all time transfer equipment is becoming more important. The equipment that has to be calibrated is composed of a GNSS antenna, antenna cables, a GNSS time receiver, and clock cables. This paper focuses on the calibration of the time receiver.

One method for time receiver calibration is to compare the time differences obtained for the “test receiver” relative to a calibrated receiver, the “golden receiver”. This method is actually used by the International Bureau of Weights and Measures (BIPM) for the periodic calibration of the time receivers at

the different UTC laboratories.

In this paper, an absolute calibration of dual frequency time receivers using a GNSS hardware simulator is presented. The calibration of the GNSS hardware simulator itself can be verified using certified standard laboratory equipment, such as a fast digital storage oscilloscope.

The absolute calibration using a GNSS hardware simulator provides a couple of advantages in comparison to the relative calibration using real GNSS satellite signals. First of all, the calibration process is repeatable in detail, i.e. the receiver can be calibrated using always the same GNSS scenario. Another advantage is that errors such as satellite orbit and clock instabilities, ionosphere, troposphere, and multipath errors can be only excluded by using a simulator. Assuming also that the error corrections concerning ionosphere and troposphere at the receiver can be disabled, this method allows a more accurate calibration of the time receiver itself. Therefore, the use of a GNSS hardware simulator for the absolute calibration of GNSS time receivers seems to be a promising method.

The GNSS hardware simulator, which is available at the DLR Institute of Communications and Navigation, is able to simulate GPS and Galileo signals in parallel. As there is no Galileo stand-alone or combined GPS/Galileo time receiver available yet, the precision of the GPS and Galileo pseudoranges determined by a combined GPS/Galileo receiver have been analyzed.

## TIME RECEIVER CALIBRATION WITH GNSS HW SIGNAL GENERATOR

DLR's hardware GNSS signal generator "Multi-output Advanced Signal Test Environment for Receivers" (MASTER) is used for calibration of time receivers. Three dual-frequency, multichannel time receivers are calibrated: two Septentrio PolaRx2 time receivers and one Ashtech Z12T time receiver. For synchronization purposes the 10 MHz signal provided by an active H-Maser is connected to the following equipment: MASTER, the receiver, the time-interval counter, and the scope (see Fig. 1). For the Ashtech Z12T receiver, a 20 MHz signal derived from the same active H-maser was used as reference signal. The MASTER generates its GNSS signals and a 1PPS signal based on this H-maser reference frequency. Both signals are fed into the time receiver, which collects the pseudorange data in RINEX format every 30 seconds, as it is usual for dual-frequency, multichannel time receivers.

A standard GPS satellite constellation with additional geostationary satellites is simulated for a stationary receiver. Geostationary satellites are used, because in this case no Doppler corrections caused by the satellite movements have to be considered. Errors concerning satellite clock, satellite delay, ionosphere, troposphere, and multipath are not introduced in the simulation.

The pseudorange  $PR$  is calculated as

$$PR = R + c \cdot (\Delta t_{rx} - \Delta t_{sat} + bias_{rx} + bias_{sat} + bias_{Simulator} + n) + r_{iono} + r_{tropo} + r_m \quad (1)$$

with  $R$  : True range,  
 $\Delta t_{rx}$  : Receiver clock delay,  
 $\Delta t_{sat}$  : Satellite clock delay,  
 $bias_{rx}$  : Receiver delay,  
 $bias_{sat}$  : Satellite delay,

- $bias_{Simulator}$  : Simulator 1PPS to code offset,
- $n$  : Noise,
- $r_{iono}$  : Ionospheric error,
- $r_{tropo}$  : Tropospheric error,
- $r_m$  : Multipath error.

One advantage of the absolute calibration using a hardware signal generator is that most of the errors mentioned above can be excluded in the simulation. Therefore, the receiver delay plus noise of the connected time receiver can be derived from the formula above as

$$bias_{rx} + n = \frac{PR - R}{c} - bias_{Simulator} . \quad (2)$$

The “MASTER 1PPS to code offset” –  $bias_{Simulator}$  – has to be determined during the simulator calibration, which is explained in the next chapter.

The receiver delay –  $bias_{rx}$  – can be separated in different receiver specific delays. The description of the receiver delays for the Z12T can be found in [2]. The receiver delays of the Septentrio PolaRx2 receiver are divided into three parts. The first one is the fixed measurement latching bias of 8.7 ns for firmware version 2.3 and higher as described in its manual [3]. The second delay is a measurement latching bias between the 1PPS input signal defined at the receiver 1PPS input connector and the latching of the measurements in the receiver. The exact delay depends on the phase relationship between the 10 MHz reference frequency and the 1PPS input signal. 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. Therefore, the time difference between the 1PPS-in and the 1PPS-out signal of the receiver is measured with a time-interval counter (TIC). This delay is constant and insensitive to powering off and on the receiver if the cables are not changed. The third part of the delay of the PolaRx is the receiver internal delay, which we determine as receiver internal calibration value in this paper.

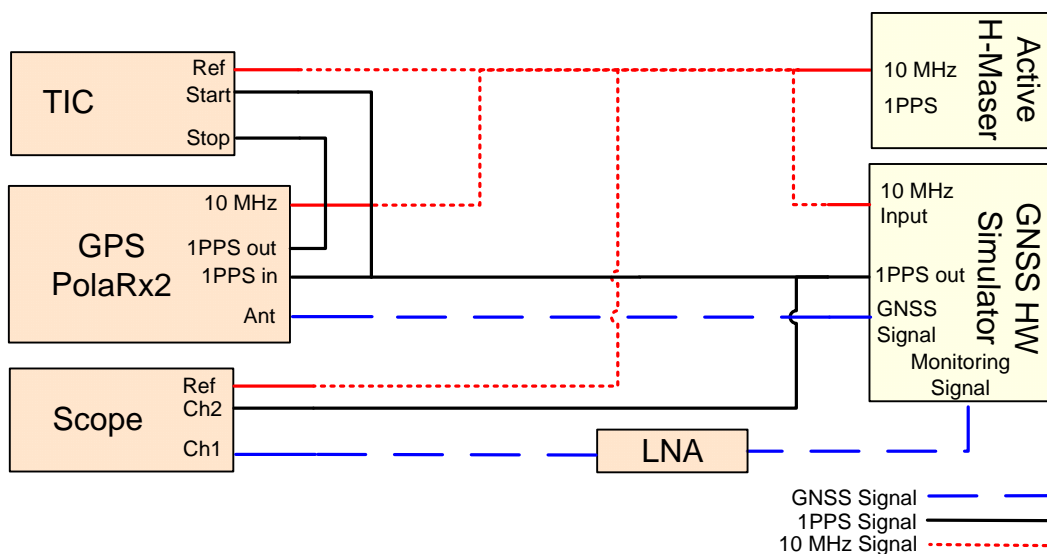


Figure 1. Time receiver calibration setup.

## SIMULATOR CALIBRATION

In order to provide a 1PPS signal accurate synchronized to the GNSS signal, the simulator itself has to be calibrated first.

MASTER uses the 10 MHz reference frequency of the active H-maser to synchronize the generated GNSS signal and the 1PPS output signal. Both signals are fixed in the phase to the 10 MHz reference frequency, but a random offset during powering off and on the simulator can occur. Therefore, the calibration has to be repeated every time after powering on the simulator. The offset between the code phase of the GNSS signal, the internal reference frequency and, accordingly, the 1PPS signal, can be shifted by a so-called “Zoffus” value within the simulator. This is necessary, as MASTER is not an off-the-shelf simulator, but a modified and expanded version of Spirent’s GSS7790 GPS simulator. The expansion is required for a so called “wave front matrix” and causes an additional delay in the signals. The “wave front matrix” can be used for simulations of multipath effects, as well as for simulations of multi-antenna-receivers [4].

The difference between the GPS spreading code and the 1PPS signal is measured by a fast multichannel digital storage oscilloscope (Tektronix, DPO 71254, 12.5 GHz, 50 GS/s). The GPS signal provided by the monitor output of MASTER, which gives approximately 50 dB more power than the typically used combined output, is amplified with a high quality LNA and is connected to the scope. The fixed delay between the monitoring signal output and the GNSS signal output is well known and has no influence due to the possibility of correction. Additionally, all cables, connectors, and the LNA have to be measured concerning signal propagation delays, as described in [5].

In former papers [1], it was assumed that the next dip in the amplitude of the envelope of the GPS signal is the start of the code that relates to the GPS time. Due to the fact that the 1PPS and GPS signal offset of MASTER can reach an order of several 10ths of a  $\mu\text{s}$  – depending on the “Zoffus” value – we decide not only to determine the offset between the 1PPS signal and the dip in the amplitude of the next envelope [1] of the signal, which could be any chip of the code, but we determine the offset of the 1PPS signal to the start of the code that means the first chip of the code. Therefore, the GNSS code and the 1PPS signal amplitudes are recorded with the scope over a period of several code lengths. A correlation between the recorded code and a synthetical code generated in software by MATLAB is performed offline. The obtained correlation peak denotes the start of the code. The offset between that correlation peak and the recorded 1PPS signal represents the simulator 1PPS to code offset taking into account the propagation delays. These delays are caused by cables, connectors, LNA, and the fixed delay between the monitoring signal output and the GNSS signal output. Be aware that to get the right 1PPS-to-code offset, the true range provided by MASTER has to be considered.

## RECEIVER CALIBRATION RESULTS

As described in the second Section of this paper (“*Time Receiver Calibration with GNSS HW Signal Generator*”), a standard GPS constellation including four geostationary satellites is used to calibrate each receiver. The scenario contains no satellite orbit and clock, ionosphere, troposphere, and multipath errors. The receiver has a fixed position on the Northern Hemisphere on earth. The measurement setup for the calibration is shown in Fig. 1, where the scope, the LNA, and their connecting cables were excluded.

To calculate the internal receiver delay regarding equation (2), the true ranges delivered by the simulator, the receiver’s pseudoranges from the RINEX file, and the simulator bias are used. All signal propagation delays included by cables and connectors are considered. Additionally the fixed measurement latching bias of 8.7 ns and the measurement latching bias described by the 1PPS-in to 1PPS-out measurement are

fitted into the equation as a part of the  $bias_{rx}$  as described. The resulting internal receiver delay is shown in Table 1.

Table 1. Receiver internal delay calibration results.

Internal Receiver Delay	Absolute Calibration Results		Relative Calibration Results (provided by BIPM, Calibration Campaign 2007)	
	P1/ $\sigma$ [ns]	P2/ $\sigma$ [ns]	P1 [ns]	P2 [ns]
PolaRx2-I	190.7/0.2	192.1/0.2	188.3	189.3
PolaRx2-II	185.5/0.2	188.0/0.2	183.5	185.8
Ashtech Z12T	278.1/0.3	286.7/0.3	x	x

Fig. 2 below shows the internal receiver delays of the PolaRx2-II receiver on the left side for typical GPS satellites (PRN 2-4) and on the right side for a satellite (PRN 28) forced artificially for the simulation with MASTER to be geostationary. Comparing the subfigures, it seems that the standard deviation using the results of the geostationary satellite is less than using the nominal satellites. For instance, the calculated standard deviation for satellite with PRN-2 is  $\sigma = 0.29$  ns for P1 and  $\sigma = 0.23$  ns for P2. The calculated standard deviation for the geostationary satellite with PRN-28 in our experimental setup is  $\sigma = 0.19$  ns for P1 and  $\sigma = 0.17$  ns for P2. One could deduce that using geostationary satellites for absolute calibrations with a GNSS hardware simulator could provide better result. The process is simplified by getting rid of any Doppler shifts. This has to be further investigated.

## CALIBRATION UNCERTAINTY BUDGET

To calculate the delay of the GPS receiver, several different measurements must be performed as described in the sections before. Whenever possible, uncertainty estimations are determined by taking several measurements and computing a standard deviation.

The following equipment and measurements contribute to the uncertainty of the calibration of the Septentrio PolaRx2 receivers, in case of the Ashtech Z12T receiver (see references [1,2]). The first source of uncertainty is the simulator itself. For the simulator, we assume 1 ns as the accuracy uncertainty [1,2], which is a very conservative assumption. Further, the variation of the 1PPS rising edge to the GPS code measurement has to be taken into account. This is done in using a fast digital oscilloscope (Tektronix, DPO 71254), with an accuracy uncertainty of 0.5 ns. The 1PPS-in to 1PPS-out measurement, which was performed with a time-interval counter SR620 from Stanford Research, includes an error of about 0.5 ns. The measurements of the delay of the cables and connectors [5] also contribute to the uncertainty budget of 0.3 ns.

Table 2 shows an overview of the different error sources and their expected values. Finally, an over all error of 1.3 ns is determined.

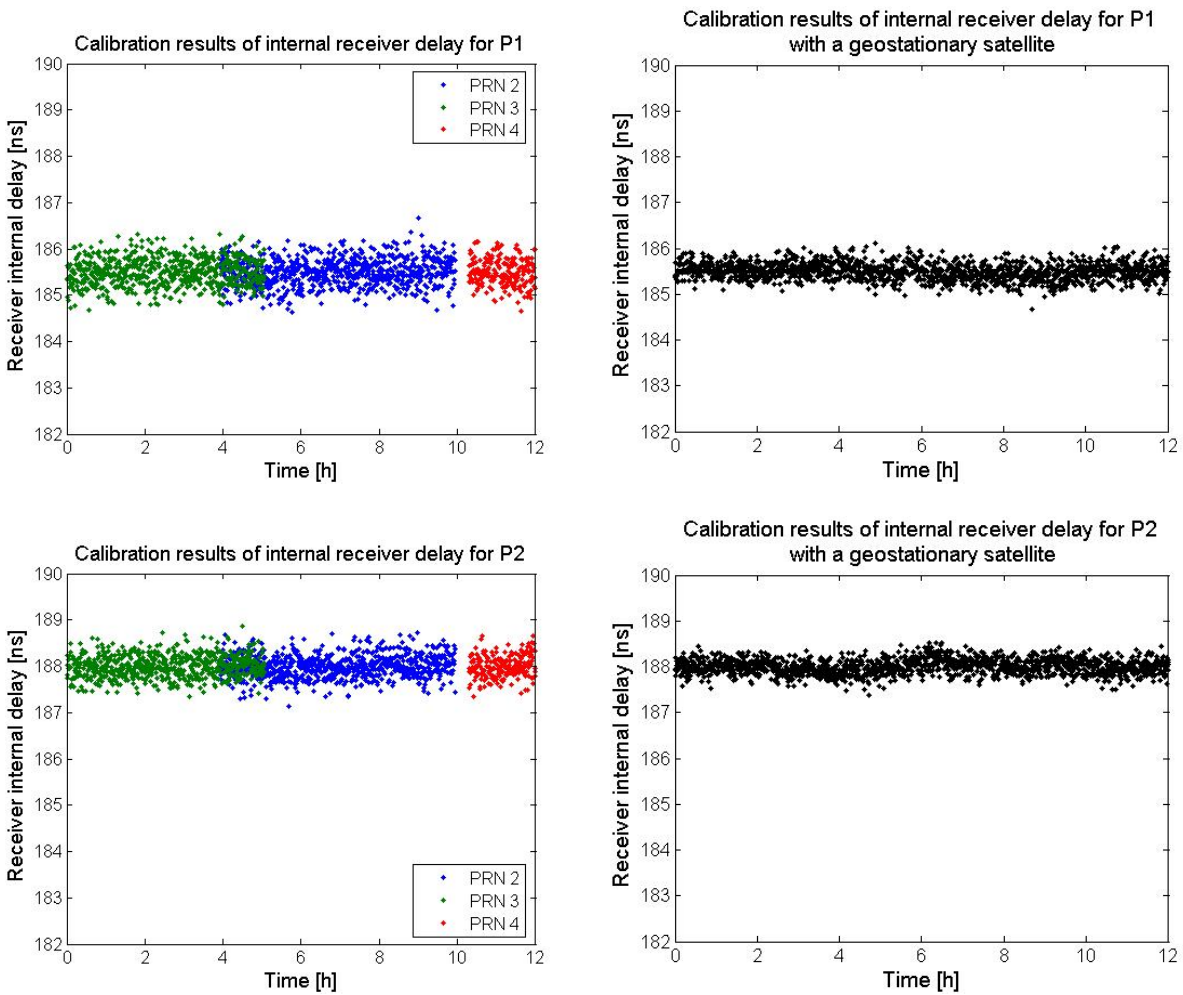


Figure 2. Internal Receiver Delay of the PolaRx2-II: left nominal, right geostationary satellites.

Table 2. Measurement uncertainty for receiver calibration [1,2].

Error Source	Estimate [ns]
1PPS-in to 1PPS-out	0.5
1PPS to Code	0.5
Cables/Connectors	0.3
Simulator Accuracy	1.0
$\sqrt{\sum E_i^2}$	1.3

## GPS/GALILEO RECEIVER

MASTER is able to provide both GPS and Galileo signals. In this experiment, a combined GPS/Galileo receiver is used to compare GPS and Galileo concerning precision in calculating pseudoranges, with focus on the precision of time transfer applications. The receiver used here is the NovAtel EuroPak-L1-

L5-E5, a combined GPS/Galileo model with 16 configurable channels. Since the NovAtel receiver is not a time receiver such as the used Ashtech or Septentrio receivers, an absolute calibration of this receiver is not possible.

For the experiment, a nominal GPS plus a nominal Galileo constellation was generated by the Simulator. Additionally, two geostationary satellites for each GNSS system (GPS, Galileo) were included in the simulation scenario. The ionosphere and troposphere correction of the receiver can't be turned off. Therefore, the simulation scenario contains ionosphere and troposphere modeling, too.

Fig. 3 shows the variation of the difference of the true range provided by the simulator and the pseudorange calculated by the receiver. The NovAtel receiver uses GPS time derived from the L1 CA-Code to calculate the ranges for GPS and Galileo E1 Open-Service.

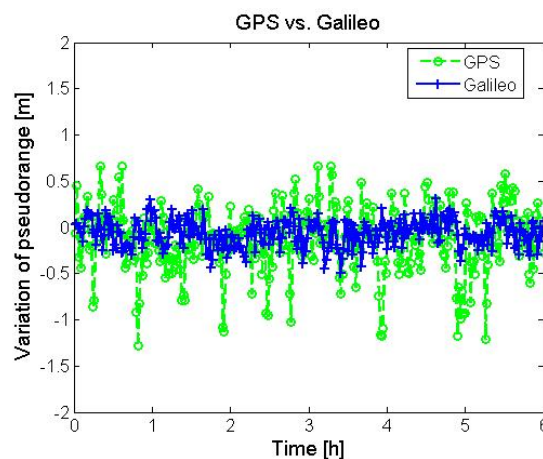


Figure 3. Variation of pseudoranges for GPS vs. Galileo measured with the NovAtel EuroPak-L1-L5-E5a combined GPS/Galileo receiver.

The comparison results a standard deviation of  $\sigma = 0.36$  m for GPS and  $\sigma = 0.15$  m for Galileo measured with the NovAtel GPS/Galileo receiver. Note that this result doesn't include the planned modernizations of GPS in the next few years.

## SUMMARY

The absolute calibration of time receivers using a GNSS hardware simulator is a promising method and features a lot of advantages compared to the relative calibration. First of all, the calibration process is repeatable in each detail, i.e. the receiver can be calibrated using always the same GNSS scenario. Furthermore, errors such as satellite orbit and clock instabilities and ionosphere, troposphere, and multipath can be excluded by using a simulator. Assuming that the error corrections concerning ionosphere and troposphere at the receiver can also be disabled, this fact allows a more accurate calibration of the time receiver itself.

In this paper, the absolute calibration of two Septentrio PolaRx2 time receivers and one Ashtech Z12T time receiver using DLR's GNSS hardware simulator MASTER has been explained. At first, the

simulator itself has to be calibrated. Therefore, the offset between the 1PPS signal and the GNSS signals is determined. In the next step, the calibration of the time receivers is done and the results are compared to relative calibration results. The variance of the internal receiver delays obtained by geostationary satellites seems to be less than that obtained by nominal satellites. This has to be further investigated.

In order to calibrate not only the time receiver, but the whole time transfer equipment, the absolute calibration of GNSS antennas would be the next step.

A combined GPS/Galileo receiver was used to compare GPS and Galileo concerning the precision in calculating pseudoranges, with focus on the precision of time transfer applications. As soon as combined GPS/Galileo time receivers are available, further investigations should be made.

## ACKNOWLEDGMENTS

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