Absolute Calibration of Time Receivers with GPS/Galileo HW Simulator

U. Grunert, S. Thoelert, H. Denks, J. Furthner,
German Aerospace Center (DLR), Institute of Communications and Navigation, Oberpfaffenhofen, Germany

BIOGRAPHY

U. Grunert received his diploma degree of Geodesy at the Technical University of Munich (TUM), Germany, in 1999. Thenceforward he has been working in the field of satellite navigation as a scientific assistant at German Aerospace Center (DLR), Institute of Communications and Navigation. He is specialized in the topic of time transfer, time synchronization, atomic clock measurement systems and calibration.

S. Thoelert received his diploma degree in Electrical Engineering with fields of expertise in high-frequency engineering and communications at the University of Magdeburg in 2002. The next four years he worked on the development of passive radar systems at the Microwaves and Radar Institute at the German Aerospace Centre (DLR). In 2006 he changed to the department of navigation at German Aerospace Centre (DLR), Institute of Communications and Navigation. Now he is working within the topics of calibration, civil security and automation of technical processes.

H. Denks received his diploma in Electrical Engineering and Communications from the University of Kiel, Germany, in 2002. He was involved in investigation and simulation of communications systems. In 2002 he joined the Institute of Communications and Navigation of the German Aerospace Center (DLR). Currently he works on simulations of Galileo signals.

J. Furthner received his diploma in Physics from the University of Regensburg, Germany, in 1990. In 1994 he received his Ph.D. in Physics with the main topic of ultra stable pulsed laser. In 1995 he joined the Institute of High Frequency of the German Aerospace Center (DLR). He was involved in investigation and simulation of navigation satellite systems. In 2000 he changed to the Institute of Communications and Navigation of DLR. Since this time he was involved in the development of the German Galileo Test Range in Berchtesgaden (near Munich) and worked as consultant in the Galileo Ground Mission Segment for the Galileo Precise Time Facility Currently he works on the validation of the Galileo In-Orbit Validation Satellites GIOVE-A and GIOVE-B.

1. INTRODUCTION

Time transfer usually is realized by the All in View (Common View) method using measurements of GNSS time receivers connected to the remote atomic clocks. As the precision of this time transfer method – using dual frequency, multi channel time receivers - is getting better and better the accurate calibration of the whole time transfer equipment is getting more significant influence. The equipment which has to be calibrated is composed of a GNSS antenna, antenna cables, the GNSS time receiver and clock cables. This paper is focused on the calibration of the time receiver.

One method for time receiver calibration is to compare the obtained time differences of the “test receiver” relative to a calibrated receiver, the “golden receiver”.

In this paper an absolute calibration of dual frequency time receivers using a GNSS hardware simulator is presented. Therefore the accurate calibration of the GNSS hardware simulator itself is essential.

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 each detail, i.e. the receiver can be calibrated using always the same GNSS scenario. Another advantage using a GNSS simulator is that errors such as satellite orbit and clock instabilities, ionosphere, troposphere and multipath errors can be excluded. All these facts allow a more accurate calibration of the time receivers in comparison to real GNSS conditions. Therefore, the use of a GNSS hardware simulator for the absolute calibration of GNSS time receivers seems to be a promising method.

The used GNSS hardware simulator provides GPS and Galileo signals in parallel and therefore additionally can be used for absolute calibration of combined GPS/Galileo or stand alone Galileo time receivers. As there are no such receivers available yet, the precision of the GPS and Galileo pseudoranges determined by a combined GPS/Galileo receiver is analyzed.

2. ABSOLUTE CALIBRATON OF TIME RECEIVERS WITH GPS/GALILEO HW SIMULATOR

The hardware GNSS signal generator “Multi-output Advanced Signal Test Environment for Receivers” (MASTER) of DLR is used for the calibration of time receivers. Three dual frequency, multi channel 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, time receiver, time interval counter and scope (s. Fig. 1). For the Ashtech Z12T receiver a 20 MHz signal derived from the same active

H-Maser was used as reference signal. The simulator MASTER generates its GNSS signals and a 1PPS signal based on the 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, multi channel time receivers.
A standard GPS satellite constellation and additional geostationary satellites are 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

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

with
- R : True range,
- c : Speed of light
- Δt_{rx} : Receiver clock delay,
- Δt_{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

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

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 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 second delay is the fixed bias between the measurement latching and the 1PPS output signal of 8.7 ns for firmware version 2.3 and higher as described in its manual [3]. 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.

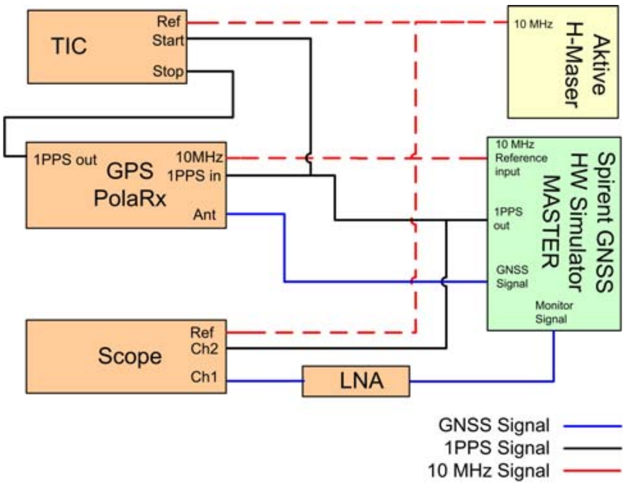

Fig 1: Setup of Absolute Time Receiver Calibration

3. SIMULATOR CALIBRATION

In order to guarantee that the 1PPS and the GNSS signal provided by the simulator are accurately synchronized the simulator itself has to be calibrated first.

MASTER uses the 10 MHz reference frequency of the active H-Maser to synchronize the 1PPS output signal and the generated GNSS signal. Both signals are fixed in phase to the 10 MHz reference frequency [4].

For the calibration purposes the receiver position is simulated onboard the satellite. The range between satellite and receiver antenna is than zero and the delay between the 1PPS signal and the GPS spreading code is assumed to be the simulator 1PPS to code offset $bias_{Simulator}$. This delay can be measured using a fast multi channel digital storage oscilloscope (Tektronix, DPO 71254) connected to the 1PPS signal of the simulator and the GPS signal. As the normal GPS signal power is too weak the monitor output of MASTER providing approximately 50 dB more power than the typically used combined output is used which is additionally amplified by a high quality LNA. 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. All cables, connectors and the LNA have to be measured concerning signal propagation delays as described in [5].

This 1PPS to code offset $bias_{Simulator}$ between the 1PPS signal and the dip in the amplitude of the envelope of the GNSS signal can be determined for a single PRN signal by reading off the delay on the scope [1]. In order to evaluate the offset between the 1PPS signal and several PRN signals provided on several simulator channels in parallel it is necessary to record the signals with the scope. Hence, a statistical variation of the different simulator channels can be calculated which can be used in the uncertainty estimation for the simulator calibration error. A correlation between each recorded code and the corresponding PRN code generated by MATLAB can be computed 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 delays caused by cables, connectors, LNA and the fixed delay between the monitoring signal output and the GNSS signal output.

4. RECEIVER CALIBRATION RESULTS

As described in chapter 2 a standard GPS constellation and additionally 4 geostationary satellites are 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 (P1 and P2) from the RINEX file and the simulator bias are used. All signal propagation delays included by cables and connectors are considered. The resulting internal receiver delays are shown in Table 1. The internal receiver delays obtained by a relative calibration campaign organized by BIPM in 2007 are shown in Table 2.

Internal Receiver Delay	Calibration Results	
	P1/σ [ns]	P2/σ [ns]
PolaRx2-I	189.3/0.4	190.1/0.4
PolaRx2-II	193.1/0.4	192.7/0.4
Ashtech Z12T	286.1/0.4	288.7/0.4

Table 1: Receiver internal delay obtained by absolute calibration

Internal Receiver Delay	Calibration Results (provided by BIPM, Calibration Campaign 2007)	
	P1 [ns]	P2 [ns]
PolaRx2-I	188.3	189.3
PolaRx2-II	183.5	185.8
Ashtech Z12T	284.1	290.2

Table 2: Receiver internal delay obtained by relative calibration

Figure 2 shows the internal receiver delays of the PolaRx2-II receiver for typical GPS satellites (PRN 1 to 9) using P1 data from RINEX. Figure 3 shows four satellites (PRN 25 to 28) forced artificially for the simulation with MASTER to be geostationary.

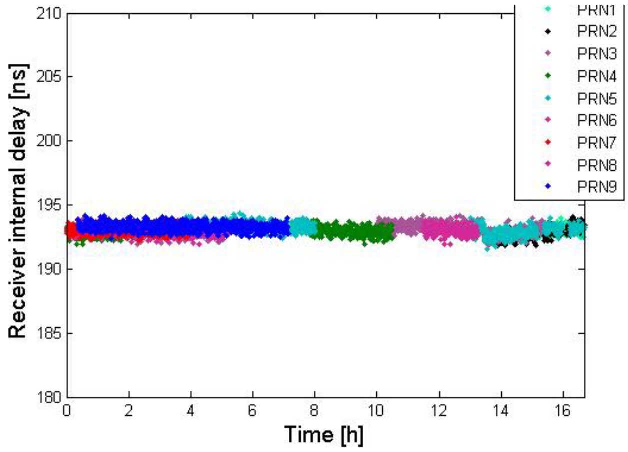

Figure 2: Receiver internal delays (P1) for standard GPS satellites

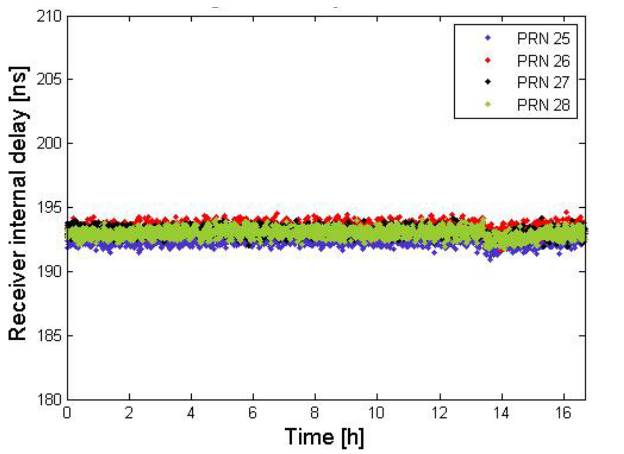

Figure 3: Receiver internal delay (P1) for geostationary satellites

The internal receiver delays of the PolaRx2-II receiver using P2 for GPS standard satellites and for geostationary satellites are presented in figure 4 and 5.

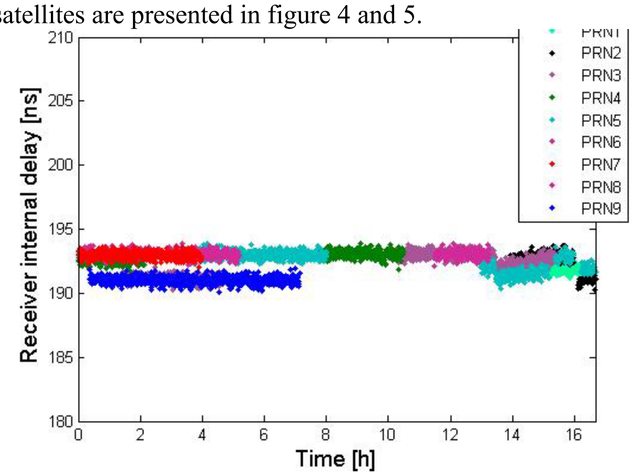

Figure 4: Receiver internal delay (P2) for standard GPS satellites

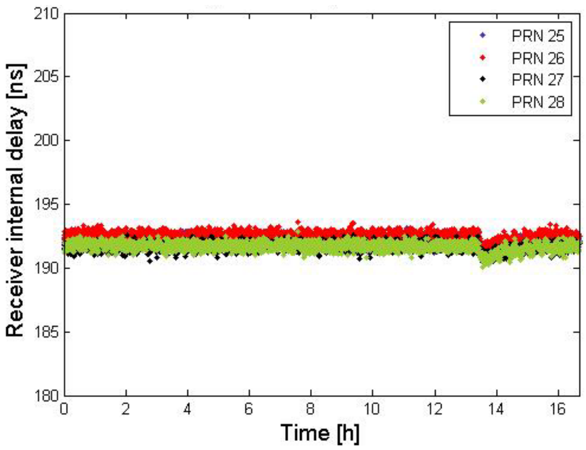

Figure 5: Receiver internal delay (P2) for geostationary satellites

5. CALIBRATION UNCERTAINTY BUDGET

To calculate the internal 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 MASTER itself. For the simulator we assume 1 ns (1σ) as accuracy uncertainty. This uncertainty includes the misalignments between the simulator channels as well as the instability of the provided 1PPS and GNSS signals. Further the variation of the 1PPS rising edge to the GPS code measurement has to be taken into account. The measurement is done in using a fast digital oscilloscope (Tektronix, DPO 71254) with an uncertainty in accuracy of 0.3 ns (1σ). The uncertainty of the calibration of all cables and connectors performed by using a network analyzer or TIC [5] is assessed to 0.3 ns (1σ). The 1PPS-in to 1PPS-out measurement is performed with a time interval counter SR620. The absolute error of the TIC is calibrated. After that an uncertainty of 0.1ns is established for the TIC.

Uncertainty Sources	**Uncertainty [ns]**
Simulator accuracy (include interchannel error, stability)	1.0
Oscilloscope	0.3
Cables/Connectors (include error of NWA)	0.3
TIC	0.1
1PPS-in to 1PPS-out (variable Measurement latching)	0.2
Correlation uncertainty	0.2
Receiver	0.4
$\sqrt{\sum E_i^2}$	**1.2**

Table 3: Measurement uncertainty for receiver calibration

The uncertainty of the 1PPS-out signal of the PolaRx2 denoting the receiver internal measurement latching is appraised to 0.2 ns (1σ). The uncertainty in the correlation of the recorded GPS code with the corresponding PRN code generated by MATLAB is estimated to 0.2 ns (1σ). At last the uncertainty in the measurements of the GPS receiver itself is assumed to be 0.4 ns (1σ).

Table 3 shows an overview of the described uncertainty sources including their expected values. Finally, an over all measurement uncertainty of 1.2 ns is determined.

6. 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 (L1) and Galileo (E5a) 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, 2 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 modelling, too.

Fig. 6 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 calculating the ranges for GPS (L1) and Galileo (E5a).

The comparison results a standard deviation of $\sigma = 0.36$ m for GPS (L1) and $\sigma = 0.15$ m for Galileo (E5a) measured with the Novatel GPS/Galileo receiver. It can be seen that using new signals as E5a of Galileo promises higher precision in pseudorange determination. This will also have a positive effect for the precision of time transfer using GNSS time receivers.

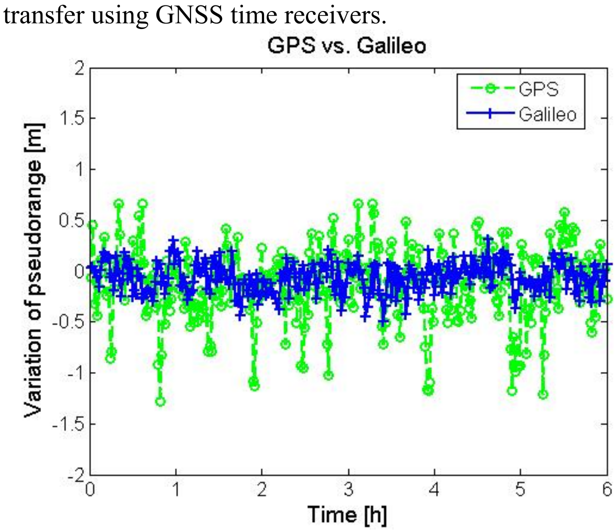

Figure 6: Variation of pseudoranges for GPS (L1) vs. Galileo (E5a) measured with the Novatel EuroPak-L1-L5-E5a combined GPS/Galileo receiver

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, ionosphere, troposphere and multipath errors can be excluded by using a simulator which allows a more accurate calibration of the time receivers 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 is 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.

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 is used to compare GPS (L1) and Galileo (E5a) 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 on the market, further investigations should be made.

ACKNOWLEDGEMENTS

We thank to BIPM for calculating and providing the relative calibration results for our time receivers.

REFERENCES

[1] J. White, 2001, "Dual frequency absolute calibration for a geodetic GPS receiver for time transfer", 15th European Frequency and Time Forum (EFTF).

[2] J. Plumb, 2005, "Absolute Calibration of a Geodetic Time Transfer System", Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on Volume 52

[3] User Manual, Septentrio PolaRx2, Version 2.6, Chapter 2.17, 2005.

[4] A. Hornbostel, H. Denks, and H. Venus, "First Results of Baseband Wavefront Generation with a Digital Channel Matrix for Testing of CRPA", in Proc. ION GNSS 2006, Fort Worth, TX, September 2006.

[5] K. Kalliomaki, 2006, "Applicability of Coaxial Cables at Picosecond Range Timing", 20th European Frequency and Time Forum (EFTF).