Absolute Calibration of Dual Frequency Timing Receivers for Galileo

B. P. B. Elwischger, S. Thoelert, M. Suess, J. Furthner
Institute for Communications and Navigation, German Aerospace Center (DLR)
Muenchner Strasse 20, 82234 Oberpfaffenhofen, Germany
mail: bernhard.elwischger@dlr.de

***Abstract*—The timing service of Global Navigation Satellite Systems (GNSS) is being steadily improved. Generally, this fact traces back to increasing accuracy of the provided ephemeris data, improvements in Precise Point Positioning, continuous refinement of time transfer techniques, the utilization of modern signals, the use of wider bandwidth, and a growing number of available satellites—the latter particularly due to the coexistence of an increasing number of independent GNSSs available. The accuracy achievable by the GNSS common view time transfer method is within range of nanoseconds. In particular the upcoming Galileo in combination with the Global Positioning System is expected to improve that accuracy even further.**
In this paper, we present results for an approach for absolute calibration of Galileo timing receivers operating in the L1BC and E5 signal bands. The internal receiver delays for Galileo E1 and GPS L1 signals of the institute's Septentrio PolaRx4 TR PRO are assessed. The approach utilizes a hardware simulator, which is an expanded version of a GSS7790 GNSS simulator from Spirent Communications. The simulator, the receiver under test, as well as the utilized measurement equipment use the 10 MHz signal from the same cesium clock as reference.

***Keywords*—Receiver calibration, multi frequency, GNSS, synchronization, time transfer**

I. Introduction

With *two-way satellite time and frequency transfer* (TW-STFT) [7] "potentially even sub-nanosecond uncertainty can be achieved" [5]. Multi-GNSS time and frequency transfer will further push the limits. In this context, the need for accurate calibration of the utilized equipment at nanosecond level draws more and more attention.
GNSS time transfer requires calibration of the entire synchronization chain of the station setup including antenna (i.e., its group delay, the coordinates of its phase center, aperture, etc.), cables, passive splitters, active signal distributors, and the internal receiver delays of the GNSS timing receiver. Here, the calibration of the internal receiver delays, which may differ by hundreds of nanoseconds for different receiver models [12], is one of the most crucial issues.

We focus this paper on accurate calibration of multi frequency GNSS timing receivers for Galileo signals on nanosecond level. Results are given in comparison to calibration results for GPS signals in the same setup.

A. Applications for satellite time and frequency transfer

It is a well-established approach to use the common view technique for comparison of clocks located at different sites. It enables time scale generation in distributed systems or networks, such as the *International Atomic Time* (TAI) [4]. TAI is generated by the *International Bureau of Weights and Measure* (BIPM) based on the comparison of atomic frequency standards in various laboratories. A similar laboratory supporting TAI is located at our institute.
Apart from that, *satellite time and frequency transfer* (STFT) can be utilized to provide syntonization or synchronization within any distributed system. If reception of GNSS signals is available, such a system can span thousands of kilometers. This enables e.g. maintenance of consistency in globally distributed databases [3], or time-based positioning using non-GPS signals [13].
On the one hand, STFT can serve as a tool to monitor the station clocks, in order to assess their stability. On the other hand, the time offsets determined by STFT can be used to correct the measured offsets between the station clocks. Thus, synchronization errors are minimized, and prevented from masking other errors.

B. The need for absolute calibration

Absolute calibration is required for time transfer (i.e., for synchronization of the stations' clocks), but not for frequency transfer (i.e., syntonization of the stations' clocks), which is illustrated in the following.

Assume a system of stations at different locations, including a clock each, and a single external clock. For STFT, that external clock would be a satellite clock. Each station can conduct time or frequency transfer of that external clock through an individual time transfer chain. If the system's clocks are just to be synchronized to each other but not to the external clock, then relative calibration of the individual time transfer chains is sufficient. That case merely enables frequency transfer of the individual clock to the network's clocks (i.e., no time transfer).
Synchronization of the system's stations to the external clock, however, requires absolute calibration. It is a prerequisite for achieving time transfer from the external clock to the individual stations' clocks.

II. Existing Methods for absolute calibration

To calibrate a GNSS timing receiver there exist two common methods. One of those uses a fully calibrated receiver often referred to as *golden receiver* (GR) to determine the internal delays of the *device under test* (DUT) based on the comparison between the GR and DUT. The second method is based on hardware (HW) simulation of the GNSS signals, and came up with the development of GNSS HW signal simulators. The following two sections give a short description of these two established methods.

A. Calibration using a golden receiver

This calibration method is based on the comparison between the accurately determined internal delays of the GR and the unknown delays of the DUT. To perform the calibration, the GR and the DUT are placed in parallel into a nominal setup to measure GNSS signals. Figure 1 illustrates the setup briefly.

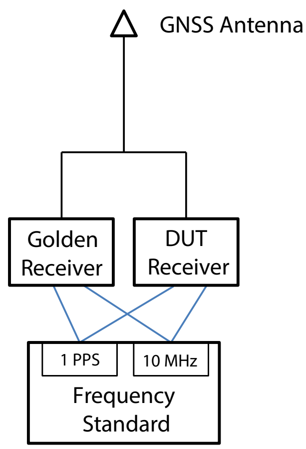

Figure 1: Calibration setup for the GR method

In the shown setup, GNSS pseudorange measurements are conducted. Assuming the cables from the GNSS antenna and from the connection to the frequency standard are equal for both signal chains, the internal delays of the DUT can be calculated based on the resulting differences within the range measurements and the accurately known internal delays of the GR. For more details concerning the delay calculation see [9].
Note that using the above described method the calibration accuracy achieved for the DUT is lower than the calibration accuracy of the GR itself. The pseudorange measurements in the setup for the GR method introduce additional uncertainties. The advantage of this method is that it only temporarily requires the GR as well as a set of cables and connectors.

B. Calibration using a GNSS hardware simulator

A GNSS hardware signal simulator provides defined GNSS and timing signals which are the basis to perform an absolute calibration of a GNSS timing receiver. If the simulator itself and the employed cable links to the receiver are well calibrated, the internal delays of the DUT can be derived based on pseudorange measurements acquired by the DUT and the simulated ranges.
The absolute calibration using a GNSS hardware simulator provides a couple of advantages over the GR calibration using real GNSS signals. The calibration process is repeatable in each detail and environmental errors such as satellite orbit and clock instabilities, ionosphere, troposphere and multipath errors, which may effect the pseudorange measurements of the GR and DUT in a different way, can be excluded. All these facts allow a more accurate calibration of the GNSS timing receiver in comparison to calibration methods applied under real GNSS conditions.

III. Calibration

The absolute calibration of a GNSS timing receiver is based on the assumption that at its input ports a more or less ideal and accurate calibrated *radio frequency* (RF) GNSS signal and a timing signal (1 PPS) are available. To fullfil this requirement, it is necessary to calibrate the GNSS HW simulator in a first step. Calibration in this context means a very accurate determination of the delay between the RF GNSS signal and the 1 PPS timing signal. This includes additionally utilized equipment such as cables and adaptors, up to the DUT's inputs. In a second step the DUT can be calibrated based on pseudorange measurements and the determination of receiver specific measurement latchings. The following section will describe all necessary steps in detail.

A. Measurement setup

The measurement setup applied to both above-mentioned steps is illustrated in Figure 2. The utilized simulator is an expanded version of a GSS7790 GNSS simulator from Spirent Communications, which consists of two simulator units with 24 hardware channels each (i.e., with a total of 48 channels). In the chosen hardware configuration, each of the two simulator units provides its 24 channels at one single combined RF output. By the aid of a passive combiner, the signals of those two RF outputs are then combined to one single RF signal.
The simulator and the receiver under test use the 10 MHz signal from the same 5071A type cesium clock as reference. In order to keep the correct timing between those two signals, a fast *digital storage oscilloscope* (DSO) type DPO71254 from Tektronix, and a Stanford SR620 *time interval counter* (TIC) are part of the setup. The setup will be explained more in detail within the following sections.

The main feature of the chosen measurement setup is that, apart from the attenuator and two RF adapters to connect the timing receiver in the second step, the setup remains unchanged for the calibration of the hardware simulator and the calibration of the GNSS timing receiver.

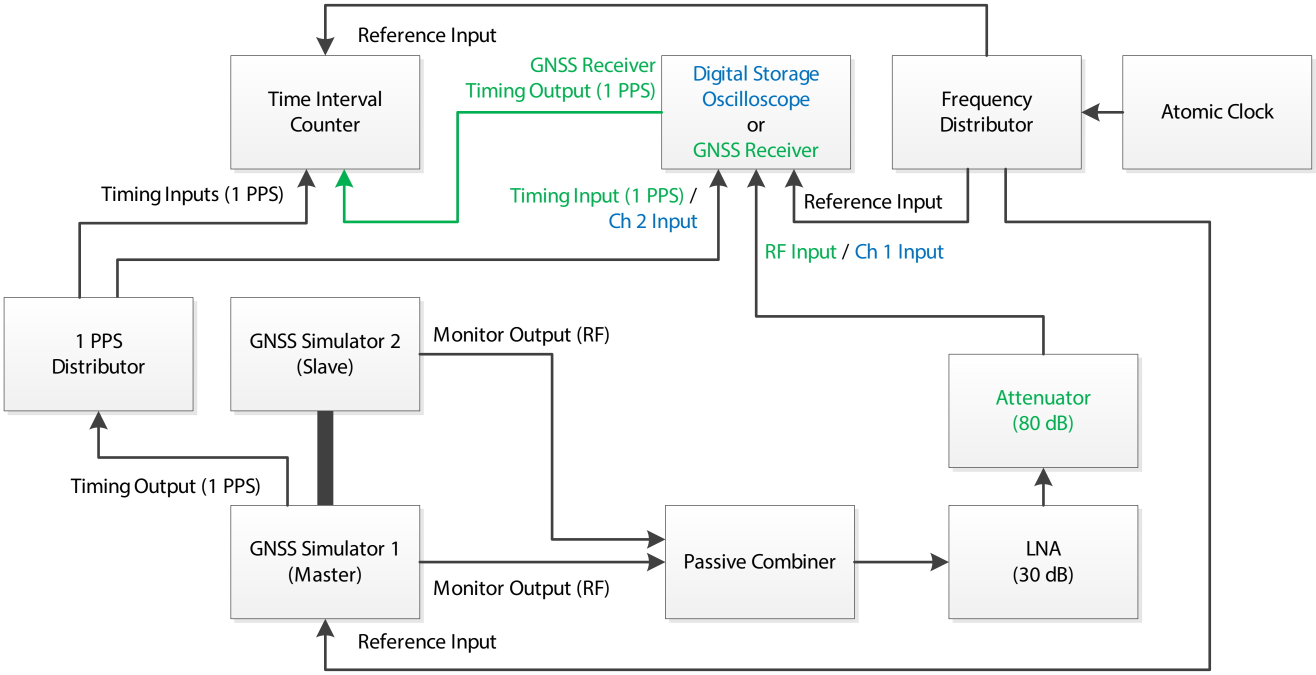

Figure 2: The hardware setup for simulator calibration is composed of all components marked in black and blue, for receiver calibration of all components and connections marked in black and green.

B. Utilized satellite constellations & signals

Concerning the satellite constellations for calibration, focus is given to *geostationary* (GEO) satellites. This avoids introduction of additional errors caused by nonperfect Doppler correction and consequent distortions of the correlation function within the signal processing.

1) Constellations for simulator calibration

For simulator calibration, the constellation can be designed as simple as possible. Since the channels of the hardware simulator have to be calibrated individually, they can be calibrated for satellites placed on the same position. This can be achieved either by using a constellation merely consisting of one single satellite, which is then switched between the channels for individual simulator channel measurements. Or a constellation of 12 GEO satellites at one position is used, so that only a single channel is set active for each individual simulator channel measurement. For this study, the latter approach is used. Separate recording of each satellite allows direct identification of the complex baseband signal, and simple carrier phase correction prior to individual correlation of its in-phase or quadrature component with the corresponding code. Furthermore, this approach prevents the ocurrence of eventual channel cross-correlations [8].

In the utilized configuration of the HW simulator for L1, L2, E1, and E5, the signals of 12 GPS and 12 Galileo satellites could be simulated simultaneously. The 12 GEO satellites of one constellation can be equally distributed along a circle segment in the plane $x := 0$ in Earth-centered, Earth-fixed (ECEF) Cartesian coordinates.

2) Constellations for receiver calibration

The results presented in this paper are based on a Galileo constellation with 12 GEO satellites, a mixed Galileo constellation, and a mixed GPS constellation. Each of those two mixed constellations consists of 28 *medium earth orbit* (MEO) satellites of the nominal constellation in addition to 4 GEO satellites. The GPS constellation is simulated simultaneously with either one of the two Galileo constellations. As the utilized hardware configuration of the hardware simulator is limited to a number of 12 instantaneous satellites per constellation, simulation is limited to an instantaneous number of 8 MEO and 4 GEO satellites for the mixed constellations. Additional satellites in view are automatically dropped by the simulation software through *geometric dilusion of precision* (GDOP) selection.

On the one hand, GEO satellites may result in a lower variance in the pseudorange measurements [14]. Furthermore, simulation of satellites along curved paths by the HW simulator is non-ideal, as the simulator determines the ranges between the satellites and the user only for discrete points in time, and interpolates for the time periods in between.

On the other hand, the timing receiver requires a number of at least 4 satellites in a geometry with sufficient GDOP for proper operation. For a pure GEO constellation, fulfillment of that requirement would be problematic.

3) Used signals

Table 1 shows the GNSS signals emitted by the HW simulator in the utilized hardware configuration[1]. The last column lists the actual signal levels at the two combined GNSS monitor outputs of the HW simulator. Initially, the measurements and analysis are performed using the Galileo E1 signal, and for comparison the GPS L1 signal was measured as well.

C. GNSS HW simulator calibration

The calibration of the hardware simulator itself is achieved by analysis of the simulated RF GNSS signal from a GPS or Galileo satellite constellation in relation to the 1 PPS signal the simulator generates from its reference. Additionally all equipment up to the DUT's physical inputs is included within this analysis. That means that finally we determine the relation between RF and 1 PPS signal up to the DUT input connectors as accurately as possible. For that purpose both signals are captured in parallel with the DSO. Here, the 1 PPS signal serves both as input and trigger signal.

1) Bias determination

Performing the analysis of the delay between GNSS signal and 1 PPS signal two approaches are suitable:

— *bias analysis by code correlation*: After RF and 1 PPS signal have been captured using the oscilloscope, the RF signal is mixed down to baseband, and demodulated. This demodulated baseband signal is then correlated with the expected GNSS code sequence to determine the begin of a code epoch. The resulting difference between the 1 PPS signal and the correlation peak and consequently the begin of the code epoch represents the simulator bias. During the calibration campaign it was found out that the simulator bias depends on the used hardware channel, and on the used signal (frequency and GNSS type). Figure 3 shows the results of the HW simulator calibration. The resulting hardware channel dependency is caused by the imperfect inter-channel calibration of the simulator. It is noted that the simulator is within the specifications concerning the inter-channel bias, but to achieve an accuracy below 1 ns concerning the receiver calibration we have to improve the inter-channel bias calibration of the HW simulator using the explained calibration method.

— *bias analysis by the dip in the amplitude*: A simple and practical approach that avoids the necessity of correlation processing, is the assessment of the simulator bias by the dip in the amplitude. For absolute calibration of GNSS timing receivers, it was first proposed in [15]. GNSS RF signals may have the characteristic that during the code transition the amplitude becomes zero. The difference between this so-called *dip* and the 1 PPS signal represents also the simulator bias. Dependent on the signal structure, this method may not be suitable for all signals of all existing GNSS systems. Besides, the approach is not as accurate as code correlation.

[1] It is denoted as "12L1+12L2+12E1+12E5 Combined Output".

2) Measurement requirements

To achieve accurate results for the simulator bias, the measurement setup requires reasonable settings.
The record length for the DSO measurements depends on the used bias analysis method. Concerning the method based on correlation, which is used in this work, two major aspects dictate the record length. One of these constraints is the underlying GNSS signal, in particular its code length. Data acquisition of at least one code length is required, and averaging over several code lengths was applied to reduce measurement uncertainties.
Furthermore, the record length seems to be a matter of clock stability. Within the data record interval, the clock stability must remain within a certain bound to guarantee that the error budget is met. For the cesium clock, the time domain stability is provided as root Allan variance $\sigma_y(2, \tau)$, i.e., as function of the averaging time τ. For an averaging time of 10 ms, it stays below 75 ps, and for 100 ms below 12 ps [1]. Hence, the maximum error due to clock instability can be estimated as below 0.1 ns for a correlation data length greater or equal than 10 ms.

Recording the RF signals in the time domain with the oscilloscope, the analogue bandwidth of the used oscilloscope should be at least 1.6 GHz to maintain the full bandwidth of the Galileo E1 and E5 RF signals in the time domain, compare Table 1. The DSO used for this study provides an analogue bandwidth of 12.5 GHz. The sampling rate is set to 25 GS/s to maintain the full analog bandwidth of the sampled signals according to the Nyquist-Shannon theorem. That prevents aliasing in case residual noise from the hardware simulator at higher frequencies is present. We additionally amplify with a *low-noise amplifier* (LNA) providing 30 dB amplification, in order to reach voltage levels which the DSO can track.

As there is only one timing output of GNSS Simulator 1 available, an active 1 PPS distribution amplifier is used for distribution either to DSO or GNSS receiver, in parallel to the TIC. An active distribution amplifier is preferred to a passive splitter in order to ensure defined and sufficient signal levels. Furthermore, it eases connection of devices with different input impedances parallel to each other to the timing output of the HW simulator.

D. Receiver calibration

Within the timing receiver we have to consider two aspects. These are the delay of the GNSS signal within the receiver hardware which is referred as "internal delay", and the timing delay which is also referred as "measurement latching". For the used Septentrio receiver the measurement latching can be determined using a TIC. The timing delay depends on the receiver model as well as on the relation between the 10 MHz reference signal and the 1 PPS signal. In a fixed setup the timing

Carrier [MHz]	Signal	Type	Modulation	Chipping rate	Code length	Full length [ms]	power level
L1: 1575.42	C/A	Data	BPSK	1.023 Mcps	1023	1	-60 dBm
	P	Precise	BPSK	10.023 Mcps	7 days	7 days	-63 dBm
L2: 1227.60	P	Precise	BPSK	10.023 Mcps	7 days	7 days	-66 dBm
E1: 1575.42	B	Data	BOC(1,1)	1.023 Mcps	$4092 * 1$	4	-58 dBm
	C	Pilot	BOC(1,1)	1.023 Mcps	$4092 * 25$	100	-58 dBm
E5a: 1176.450	a-I	Data	AltBOC(15, 10)	10.23 Mcps	$10230 * 20$	20	-58 dBm
	a-Q	Pilot	AltBOC(15, 10)	10.23 Mcps	$10230 * 100$	100	-58 dBm
E5b: 1207.140	b-I	Data	AltBOC(15, 10)	10.23 Mcps	$10230 * 4$	4	-58 dBm
	b-Q	Pilot	AltBOC(15, 10)	10.23 Mcps	$10230 * 100$	100	-58 dBm

Table 1: Galileo signals provided by the GNSS HW simulator, following [2].

delay is constant and unaffected by power cycles of the receiver. Given that timing delay, the internal delay of the receiver can be determined by comparison of the code range measurements of the simulated satellite constellation to the actual range between the individual satellites and the simulated user position.

In order to extract the internal receiver delay from a receiver's pseudorange measurements, the corresponding equation for the internal receiver delay Δt_{Rx} for a specific code signal on a particular carrier has to be solved:

$$\begin{aligned}\Delta t_{Rx} = \frac{P-R}{c_0} + \Delta t_{rel} - \Delta t_{trop} - \Delta t_{iono} - \Delta t_{RF} \\ + \Delta t_{ref} + \Delta t_{Rxref} - REF_{SV} - bias_{sim},\end{aligned} \quad (1)$$

where REF_{SV} denotes the clock offset between the reference clock of the HW simulator and the satellite time, P the pseudorange measurement, R the true range, c_0 the speed of light in vacuum, Δt_{rel} the relativistic correction [6], Δt_{trop} the tropospheric correction, Δt_{iono} the ionospheric correction, Δt_{RF} the antenna cable delay from the antenna/simulator to the receiver, Δt_{ref} the timing reference cable delay, Δt_{Rxref} the receiver internal clock delay (denoted by Septentrio as "latching delay"), and $bias_{sim}$ the time span that the generated GNSS signal lags behind the generated 1 PPS signal of the HW simulator. The latter is sometimes referenced as "tick-to-code delay" [10]. Utilization of a HW simulator offers the possibility for simple cancellation of unnecessary terms by disabling them within the simulator control software, e.g. neglect atmospheric effects and simulate satellite clocks that strictly follow their time system (i.e., the satellites' clocks yield neither bias nor drift). Equation (1) becomes

$$\Delta t_{Rx} = \frac{P-R}{v_0} - \Delta t_{RF} + \Delta t_{ref} + \Delta t_{Rxref} - bias_{sim}. \quad (2)$$

If we define

$$\Delta t_{DSO} = \Delta t_{RF} - \Delta t_{ref} + bias_{sim}, \quad (3)$$

we obtain

$$\Delta t_{Rx} = \frac{P-R}{v_0} - \Delta t_{DSO} + \Delta t_{Rxref}. \quad (4)$$

The aggregated time delay Δt_{DSO} is only valid for a specific signal on a particular carrier, and to be determined by the use of a DSO, see Figure 2. In addition to signal type and carrier, this delay also varies between channels of the HW simulator. Hence Δt_{DSO} should be determined individually for each channel if more than one channel of the HW simulator is required for calibration.

Note that concerning the receiver calibration, an attenuator is interconnected in order to reduce the signal level (C/N_0) so that it can be tracked by the receiver.

IV. Results

In the first step, the simulator including all connections is calibrated. The calibration is referenced to the input ports of the receiver, and conducted for GPS L1 and Galileo E1 signals. After that, the internal delays of a PolaRx4 TR PRO for those signals are determined.
The signal power levels of the satellites belonging to the same constellation are set to the same constant value provided in Table 1 (i.e., rather than making them depend on the range between satellite and user).

A. Simulator calibration results

As mentioned before, the simulator has 48 channels. The utilized hardware configuration provides Galileo E1 and E5 signals, and GPS L1 and L2 signals, with 12 channels for each signal. For this study, 24 channels are examined, as we focus on comparisons between GPS L1 and Galileo E1. The HW simulator calibration is based on GEO satellites according to Section III-B1, with the signals of only one single satellite active at a time. Thus, the HW simulator is calibrated channel per channel by the correlation method described in Section III-C1.
Figure 3 shows the resulting HW simulator inter-channel bias for GPS L1 C/A code and Galileo E1 data code, individually for each of the HW simulator's channels. The data in Figure 3 are obtained from correlation with about 30 code lengths for GPS L1 C/A code, and 10 code lengths for Galileo E1 data code. The number for the latter was chosen lower, as it is four times the length of the former, see Table 1. The standard deviation is also provided. The average bias has been subtracted to highlight the inter-channel bias. A polynomial fit is applied

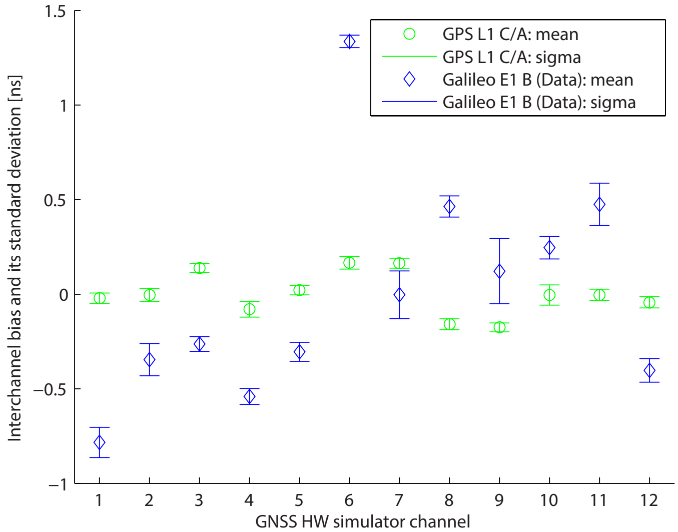

Figure 3: HW simulator inter-channel biases & standard deviation

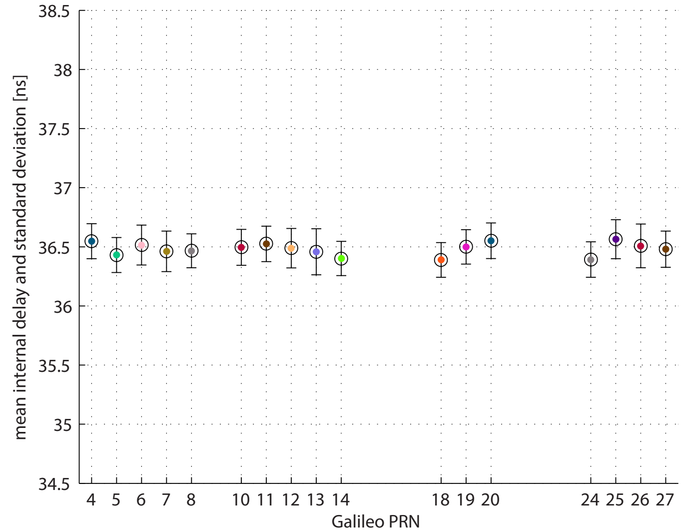

Figure 5: Internal delay and σ for Galileo E1 from MEO satellites.

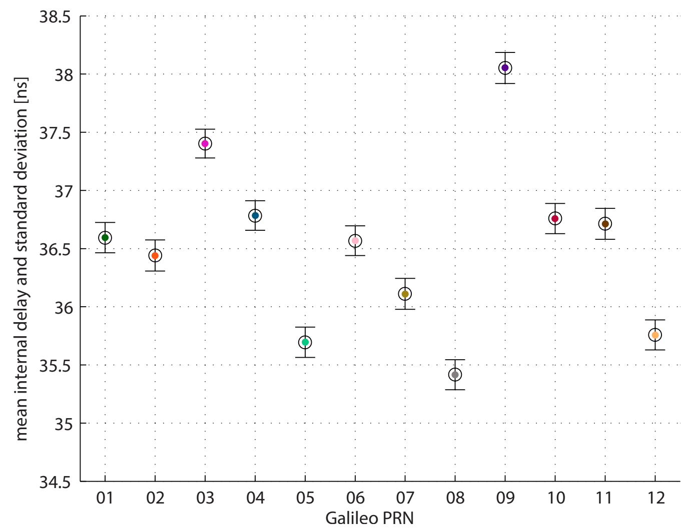

Figure 6: Internal delay and σ for Galileo E1 from GEO satellites.

to the 1 PPS signal, reducing measurement noise and avoiding limitation of the measurement precision by the sampling interval of 40 ps.

B. Receiver calibration results

The internal receiver delay Δt_{Rx} of the institute's Septentrio PolaRx4 TR PRO for Galileo E1 and GPS L1 signals is assessed by measurement of pseudoranges for a time span of about 8 hours, and application of Equation (4). The applied GPS constellation (see Section III-B2) consists of the nominal constellation with a little modification: the satellites with *pseudorandom noise* (PRN) codes 29 to 32 are GEO. For the mixed Galileo constellation, the MEO satellites with PRNs 1 to 28 belong to the nominal constellation, with additional GEO satellites. The second Galileo constellation consists of 12 GEO satellites. The measurement interval is 1 second.

1) Internal delay for Galileo E1

Figure 4 illustrates the receiver internal delay Δt_{Rx} for Galileo E1 over time, independently for each MEO satellite of the mixed Galileo constellation. Based on averaging the measurements shown in Figure 4, Figure 5 provides the mean internal delay, and the standard deviation σ, both individually for each satellite.

The results for the second Galileo constellation, which consists of 12 GEO satellites, are provided in Figure 6. Here, the assignment of the 12 simulated E1 satellites' signals to the HW simulator channels as well as to the receiver channels is fixed throughout the entire measurement period[2].

[2]The PRNs 1 to 12 were assigned to the 12 HW simulator channels in consecutive order. The assigned GNSS timing receiver channels were: 40, 44, 48, 28, 29, 30, 31, 32, 51, 52, 3, and 4.

2) Internal delay for GPS L1

The internal delay based on GPS C/A and P code measurements in the L1 band is determined in a similar manner as for Galileo. Separately for each satellite, the mean internal delay and the standard deviation from that mean internal delay is illustrated in Figure 7 for C/A code, and in Figure 8 for P code. Both figures are based on the simulator calibration for C/A code.
The utilized GPS constellation is the mixed constellation described in Section III-B2. The satellites with PRNs 1 to 28 are MEO satellites, the ones with PRNs 29 to 32 are GEO satellites. The figures suggest that variance and bias are higher for the GEO satellites, in particular for C/A code measurements.

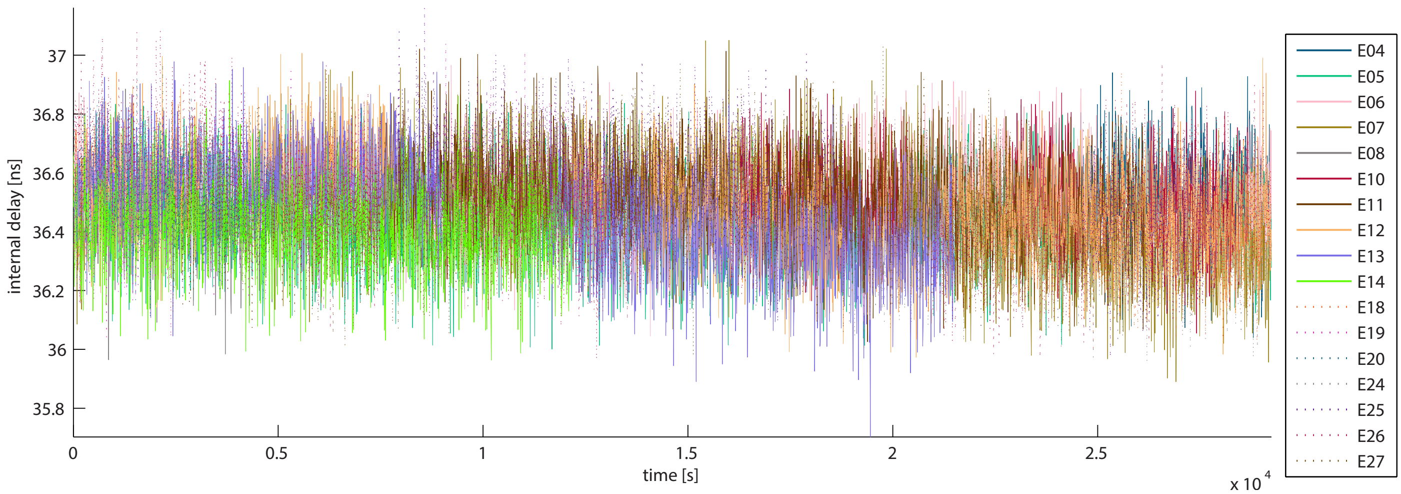

Figure 4: Internal delay of the PolaRx4 TR PRO for the Galileo E1 signal of the MEO satellites over time.

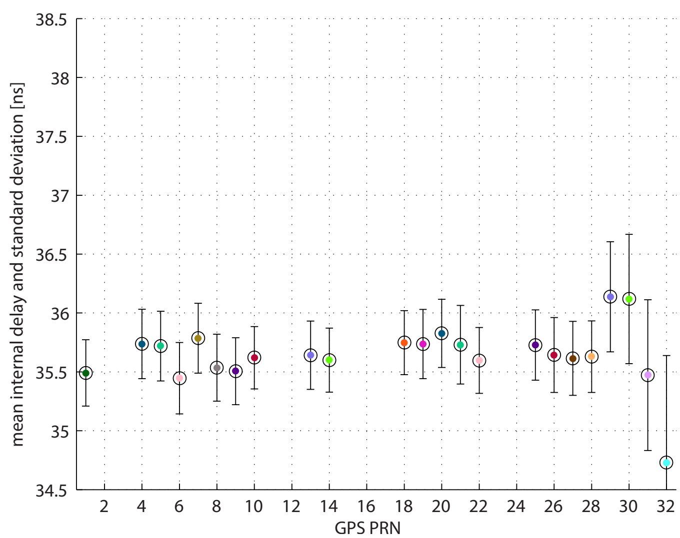

Figure 7: Internal delay and σ for GPS L1 C/A code signals from MEO satellites (G01 to G28), and from GEO satellites (G29 to G32).

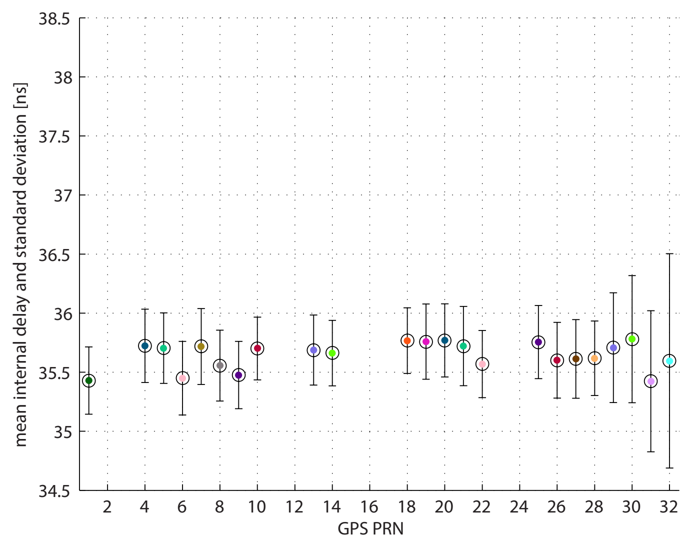

Figure 8: Internal delay and σ for GPS L1 P code signals from MEO satellites (G01 to G28), and from GEO satellites (G29 to G32).

3) Dependency on the utilized receiver channel

A possible source of the differences of the internal receiver delays for signals emitted by GEO satellites was suggested to be differences in the utilized receiver channels. In another calibration measurement for Galileo E1 signals similar to the one presented in Figure 6, the assignment of the receiver channels was dynamically changed through the “RxControl” software that came with the receiver. The plot of the internal receiver delay over time in Figure 9 shows no noticeable change.

It was verified that the receiver indeed switched the assigned channels. This was achieved by interpreting the data stream from the receiver, which includes information about which measured signal is assigned to which channel for every measurement epoch.

C. Final results

The resulting uncertainties including the total *root sum of squares* (RSS) are summarized in Table 2. As the quality of the results differed for GEO and MEO satellites, evaluation is done separately. The first row of Table 2 shows the average standard deviation per channel for the HW simulator calibration, obtained from the data presented in Figure 3. It is 0.08 ns for Galileo E1 data code, and 0.03 ns for GPS L1 C/A code.

The numbers for the standard deviation of the mean internal delays are provided in the second row. For Galileo E1, the standard deviation is gained from 17 single values for MEO satellites (see Figure 5), and from 12 for GEO satellites (see Figure 6). The numbers for GPS L1 are based on 19 single values for MEO satellites, and on 4

Uncertainy	E1 (GEO)	E1 (MEO)	L1 C/A (GEO)	L1 C/A (MEO)	L1 P (GEO)	L1 P (MEO)	IS bias affected
HW simulator	0.08 ns	0.08 ns	0.03 ns	0.03 ns	≈0.03 ns	≈0.03 ns	yes
pseudoranges	0.7 ns	0.05 ns	0.58 ns	0.10 ns	0.13 ns	0.11 ns	yes
adapter	0.05 ns	0.05 ns	0.05 ns	0.05 ns	0.05 ns	0.05 ns	no
1 PPS edge	0.5 ns	0.5 ns	0.5 ns	0.5 ns	0.5 ns	0.5 ns	in parts
atomic clock	0.1 ns	0.1 ns	0.1 ns	0.1 ns	0.1 ns	0.1 ns	no
RSS	0.87 ns	0.52 ns	0.77 ns	0.52 ns	0.53 ns	0.52 ns	

Table 2: Uncertainties for the measurement setup for the Septentrio PolaRx4 TR PRO GNSS timing receiver.

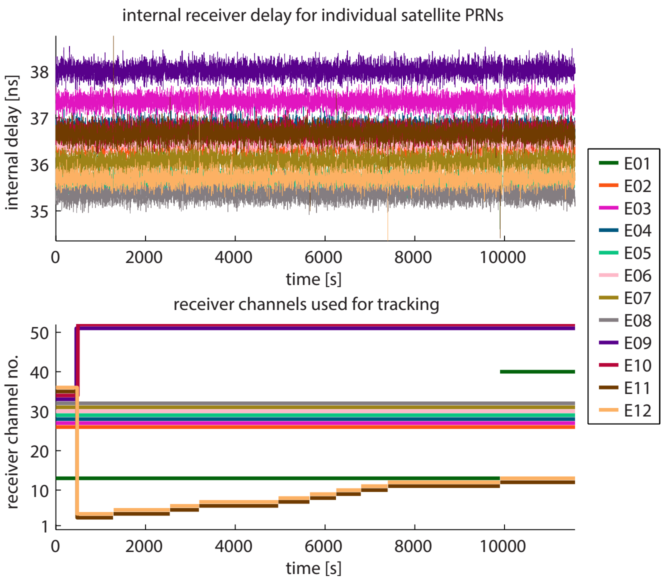

Figure 9: Internal delay over time for the signals of Galileo E11 and E12 switched between different receiver channels.

values for GEO satellites (see Figure 7 and Figure 8). This standard deviation is significantly larger for GEO than for MEO satellites, in particular for the L1 C/A signal; it equals 0.58 ns versus 0.1 ns. The best value of 0.05 ns is achieved for Galileo E1 using MEO satellites.
The 1 PPS signals from the timing outputs of the HW simulator had a typical 10% to 90% step height rise time between 0.94 ns and 1.11 ns, when they were recorded with the DSO. Without further analysis of the edge of the 1 PPS signal and input impedances, the uncertainty from the TIC measurements is conservatively estimated as 0.5 ns [14]. Please note that this uncertainty does affect the delay for E1 and L1 in equal measure, when the internal delays for L1 and E1 are assessed simultaneously. Thus, it does not influence the *inter-system* (IS) bias for simultaneous measurements of L1 and E1 signals. The IS bias denotes the bias between GPS and Galileo system time introduced by the GNSS timing receiver.
There are no uncertainties from the cables and the LNA, as all those were included in the calibration of the HW simulator. The clock instability was estimated as below 0.1 ns (refer to Section III-C). On the long term, we assume that clock variations cancel out for sufficiently long averaging intervals. The measurements were done in a climatic room with constant temperature. Therefore dependencies of temperature and humidity are not in the scope of this paper. Results for these parameters are available for the PolaRx2 receiver model [11].
The final internal receiver delays for Galileo E1, GPS L1 C/A and GPS L1 P signals are provided in Table 3. They are gained as the mean of the mean internal delays per satellite from Figure 5, Figure 6, Figure 7, and Figure 8.

Signal	Delay	RSS error
Galileo E1 (GEO)	36.52 ns	0.87 ns
Galileo E1 (MEO)	36.48 ns	0.52 ns
GPS L1 C/A (GEO)	35.61 ns	0.77 ns
GPS L1 C/A (MEO)	35.65 ns	0.52 ns
GPS L1 P (GEO)	35.63 ns	0.53 ns
GPS L1 P (MEO)	35.65 ns	0.52 ns

Table 3: Internal delays of the analyzed PolaRx4 TR PRO (s/n 41).

V. Conclusion

The internal receiver delays of the Septentrio PolaRx4 TR PRO model for GPS L1 and Galileo E1 signals could be assessed in the proposed calibrated setup. The determination of the internal delay included calibration of the utilized HW simulator. It can be seen that the results for GEO satellites have a larger variance than for MEO satellites (see Figure 5 and Figure 6). Testing several channels of the GNSS timing receiver systematically, the variance in the results of the GEO satellites was not found to be the effect of eventual inter-channel biases of the GNSS timing receiver. Thus, an influence from channel cross-correlations [8] seems probable.
Due to the inter-channel calibration of the HW simulator, the accuracy of the absolute calibration could be improved concerning earlier studies [10], [14].

Acknowledgments

The authors want to express their gratitude to Michael Meurer, Andriy Konovaltsev and Matteo Sgammini from DLR for fruitful discussions about the Galileo signal structure and the processing in GNSS receivers. Furthermore the authors thank for the worthy commitment of the Septentrio support team in response to any questions they had.

References

[1] *Agilent 5071A Primary Frequency Standard Operating and Programming Manual (Manual part number 05071-90041)*, Agilent Technologies, December 2000.

[2] K. Borre. (2009, May) The E1 Galileo signal. [Online] http://waas.stanford.edu/~wwu/papers/gps/PDF/Borre/galileo_sig.pdf.

[3] J. C. Corbett *et al.*, "Spanner: Google's globally distributed database," *Proceedings of OSDI '12: Tenth Symposium on Operating System Design and Implementation*, October 2012.

[4] P. Defraigne and G. Petit, "Time transfer to TAI using geodetic receivers," *Metrologia*, vol. 40, pp. 184–188, 2003.

[5] H. Esteban, J. Palacio, F. Galindo, T. Feldmann, A. Bauch, and D. Piester, "Improved GPS-based time link calibration involving ROA and PTB," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 57, no. 3, pp. 714–720, March 2010.

[6] *Interface Specification IS-GPS-200E*, Global Positioning System Wing (GPSW) System Engineering & Integration Std., Rev. E, June 2010.

[7] D. Kirchner, "Two-way time transfer via communication satellites," *Proceedings of the IEEE*, vol. 79, no. 7, pp. 983–990, July 1991.

[8] D. Margaria, B. Motella, and F. Dovis, "On the impact of channel cross-correlations in high-sensitivity receivers for Galileo E1 OS and GPS L1C signals," *International Journal of Navigation and Observation*, vol. 2012, 2012.

[9] G. Petit and Z. Jiang, "Differential calibration of Ashtech Z12-T receivers for accurate time comparisons," *14th European Frequency and Time Forum (EFTF)*, 2000.

[10] J. Plumb, K. Larson, J. White, and E. Powers, "Absolute calibration of a geodetic time transfer system," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 52, no. 11, pp. 1904–1911, 2005.

[11] A. Proia and G. Cibiel, "Progress report of CNES activities regarding the absolute calibration method," *42nd Annual Precise Time and Time Interval (PTTI) Meeting*, pp. 541–556, 2010.

[12] A. Proia, G. Cibiel, and L. Yaigre, "Time stability and electrical delay comparison of dual-frequency GPS receivers," *41st Annual Precise Time and Time Interval (PTTI) Meeting*, 2009.

[13] N. Schneckenburger, B. P. B. Elwischger, B. Belabbas, D. Shutin, M.-S. Circiu, M. Suess, M. Schnell, J. Furthner, and M. Meurer, "LDACS1 navigation performance assessment by flight trials," *European Navigation Conference 2013, Vienna*, 2013.

[14] S. Thoelert, U. Grunert, H. Denks, and J. Furthner, "Absolute calibration of time receivers with DLR's GPS/Galileo HW simulator," *39th Annual Precise Time and Time Internal (PTTI) Meeting*, 2007.

[15] J. White, R. Beard, G. Landis, G. Petit, and E. Powers, "Dual frequency absolute calibration of a geodetic GPS receiver for time transfer," *Proceedings of the 15th European Frequency and Time Forum (EFTF)*, pp. 167–170, March 2001.

Biographies

Bernard Philipp Bernhard Elwischger received his BSc degree in Electrical Engineering & Information Technology, and his Dipl.-Ing. (MSc) degree in Computer Engineering, both from the Vienna University of Technology. He worked in the time synchronization group at the Institute of Integrated Sensor Systems of the Austrian Academy of Sciences, where he also wrote his master thesis about the efficiency of hyperbolic positioning algorithms and geometric aspects of navigation. Since 2012 he is at the German Aerospace Center (DLR), working in the fields of synchronization and navigation in positioning and timing systems, in particular GNSS.

Steffen 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 Center (DLR). In 2006 he changed to the Department of Navigation at DLR, Institute of Communications and Navigation. Now he is working on the topics of signal quality assessment, calibration and automation of technical processes.

Matthias Suess is member of the GNSS group of the Institute of Communications and Navigation at DLR. His research focuses on atomic clock modelling, robust steering and composite clock algorithms. He graduated as computer scientist with field of specialization in mathematical modelling at the University of Passau, Germany.

Johann Furthner received a Ph.D. in Physics in the field of laser physics at the University of Regensburg in 1994. Since 1995 he is scientific staff at DLR. In 2008 he stayed half year at ESA in the Galileo Project Team. He is working on the development of navigation systems in a number of areas. Since 2011 he is leader of the GNSS group at the Department of Navigation.