CNES Accurate Monitoring of GNSS Time Scales Based on Absolute Calibration

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***Summary*—This paper describes the recent improvements in the absolute calibration of GNSS receiver chains at CNES. This calibration activity is mainly used for an independent monitoring of GNSS time scales (GPS, Galileo and BDS). The results are presented with a consolidated uncertainty that is essential to a proper performance evaluation, leading to a metrological comparison to specifications.**

Keywords—GNSS; time transfer; time scales; absolute calibration

I. INTRODUCTION

The absolute calibration of GNSS receiver chains is a mandatory task for an accurate assessment of GNSS time scales. For several years, CNES has worked on this topic and developed a method based on pioneering activities at University of Colorado, NRL and USNO [1-2]. This absolute calibration consists in determining the propagation delay within the GNSS receiver chain (from the GNSS antenna phase center to the GNSS receiver internal reference point) irrespective of any reference or golden chain. A consolidated determination of the associated uncertainty is of utmost importance.

At CNES, we calibrate the antenna, the antenna cable and the receiver separately, using a GNSS simulator for the 3 pieces of equipment. The details of our method are given in [3]. The overall uncertainty for a complete receiver chain reaches 0.5 to 1 ns (1-σ) [3]. CNES and ESA have performed a cross-validation campaign in [4] for GPS and Galileo, including in actual live GNSS reception in common-clock configuration. We also recently extended the method to BDS-III signals (B1C and B2a).

In this paper, we will first briefly describe the recent improvements we carried out on the GNSS simulator calibration. Then, we will show the results of the common views between our GNSS receiver chains that all have an absolute calibration. Finally, we present the GNSS time scale monitoring performed with our stations, together with a consolidated evaluation of the related uncertainties.

II. RECENT IMPROVEMENTS ON GNSS SIMULATOR CALIBRATION

A crucial step in the absolute calibration of a GNSS receiver chain is the calibration of the GNSS simulator.

A. GNSS data file length

For a given GNSS code, the calibration of the GNSS simulator consists in determining the time delay between the beginning of this GNSS code and the 1 PPS, both being generated by the simulator. We use a fast oscilloscope with which we digitize both the 1 PPS and the GNSS signal provided by the simulator. For this step, the simulator has to be configured to generate only one satellite and one GNSS signal in a zero-range, zero-Doppler mode [3]. This mode is called “Single Channel Utility” for the Spirent simulators and “Signal Generator” for the Spectracom simulators. Then we use a dedicated correlation software that processes the oscilloscope measurements to estimate the GNSS simulator delay for the GNSS signal we used.

For a more accurate determination of the simulator delay, we typically perform 10 acquisitions for each GNSS signal and compute the average of the results. This evaluation is done twice: before and after the calibration of the receiver. An important feature is the duration of the GNSS data files. Considering the important number of GNSS signal data files (10 files for each GNSS signal) and the size of these files, there is a trade-off to carry out between accuracy and processing duration.

In our correlation software, the simulator delay is first coarsely estimated using a so-called rough correlation (in fact, a correlation performed in the usual GNSS signal processing sense) performed on down-sampled data. This rough estimation allows locating each chip transition of the known spreading code on which a so-called fine correlation is then performed. The overall simulator delay is then the average of the fine delays estimated on each chip transition.

Fig. 1 shows an example of simulator delay (SD) as a function of the number of chip transitions for a L1C/A data file of 2 ms length with a sampling time of 50 ps (corresponding to 20 GS/s). This figure shows that there is a convergence phase for both simulators, this convergence being much faster for the Spirent simulator. This figure also shows that, when using the Spectracom, the duration of the GNSS signal data file should not go below 800 µs for GPS L1C/A in order to reach a good level of convergence. We chose to use GNSS data files of 1 ms for all GNSS signals, it is deemed to be a good trade-off between convergence of the SD and processing duration.

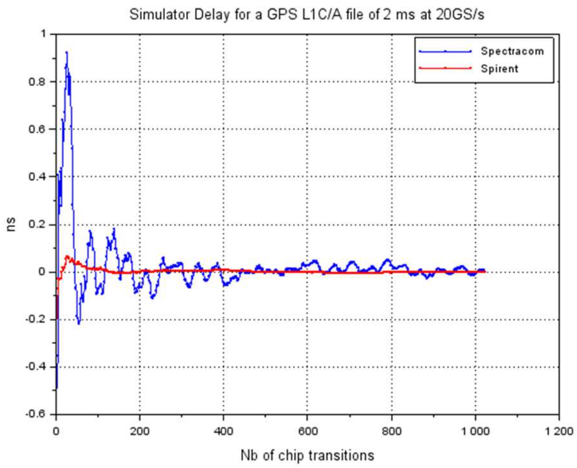

Fig. 1. Convergence of the Simulator Delay (SD) for L1C/A for 2 different simulators (final value subtracted)

B. *Validation with theoretical data*

With a view to validating our correlation software, we used so-called theoretical GNSS data i.e. GNSS data created by software using the public definition of these signals. The key advantage of using such software-defined GNSS data is that the delay can be configured, so that the output of the correlation software is known in advance. Another advantage is that the C/N0 can be adjusted to be in similar conditions to the experimental setup.

We compared the expected simulator delay to the average output of the correlation software for 10 realizations of theoretical data files. The mean minus the expected value and the standard deviation for some GNSS signals are summarized in Table I. This validates our correlation software at the level of 0.1 ns.

III. Consistency of absolute calibrations in common-clock configuration

A. *CNES setup*

In the CNES Time-Frequency Laboratory, there are four GNSS receiver chains with absolute calibrations, operated in parallel, in common-clock configuration. Two of these chains (CS11 and CS12) are based on Septentrio PolaRx4TR, and the two others (CS13 and CS14) on Septentrio PolaRx5TR.

The CS11 and CS12 data are provided to BIPM under the respective names CS21 and CS22. While CS11 and CS12 use the CNES absolute calibration, CS21 and CS22 use the BIPM relative calibration. Note that only the CNES absolute calibrations are considered in this paper.

TABLE I. Validation of our correlation software on theoretical data

[ns]	**GPS L1C/A**	**GPS L2C**	**GPS L5**	**Galileo E1BC**	**Galileo E5a**	**BDS-2 B1**
Mean – expected value	0.05	0.06	0.03	0.01	0.03	0.08
Stdev	0.01	0.01	0.01	0.01	0.01	0.01

TABLE II. CNES GNSS setup

	CS11	**CS12**	**CS13**	**CS14**
Receiver	PolaRx4TR	PolaRx4TR	PolaRx5TR	PolaRx5TR
Antenna	B3E6	B3E6	B3E6	AR25
GPS	*	*	*	*
GAL	*	*	*	*
BDS-2			*	*

TABLE III. Absolute calibration uncertainties of the 4 GNSS receiver chains

[ns]		**CS11**	**CS12**	**CS13**	**CS14**
GPS	P1	0.81	0.57	0.57	0.59
	P2	1.04	0.51	0.48	0.51
Galileo	E1	0.69	0.52	0.50	0.54
	E5a	0.65	0.51	0.48	0.52
BDS-2	B1			0.57	0.63
	B2			0.53	0.57

Each receiver is connected to its own GNSS antenna. The setup is detailed in Table II. A star in Table II indicates the absolute calibrations we carried out for GPS, Galileo and BDS-2. We can therefore evaluate the consistency of the absolute calibration by single-differences for a given code (e.g. GPS P1 and P2, Galileo E1 and E5a) for each pair of receivers.

B. *Absolute calibration uncertainties of the complete receiver chains*

We carried out the absolute calibration of the four GNSS receivers, antennas and cables and we estimated the associated uncertainties using the methodology described in [3]. The Table III summarizes these 1-σ uncertainties for each chain.

C. *Common views in common-clock configuration between the 4 GNSS receiver chains*

We computed the common views between all possible pairs of GNSS receivers. This comparison is essential to check the consistency of the absolute calibrations and for redundancy, in particular when a GNSS receiver chain fails.

The means and standard deviations for GPS P1 and P2 are given in Table IV, for Galileo E1 and E5a in Table V and for BDS-2 in Table VI. As all the receiver chains are calibrated, we expect to get zero within the combined uncertainties. We observe indeed that the common-views are consistent with the quadratic sum of the 1-σ uncertainties of the GNSS receiver chains, except in some mixed PolaRx4/PolaRx5 configurations. Nevertheless, the average values are below 2 ns for all cases.

We also observe that the noise related to the CGGTTS is somewhat similar for GPS and Galileo, but is higher for BDS-2 (this is particularly true for BDS-2 GEO and IGSO satellites, as they are observed from Toulouse).

TABLE IV. COMMON VIEWS FOR GPS P1 AND P2

[ns]		CS11	CS12	CS13
CS12	P1	0.05 (σ = 0.26)		
	P2	-0.79 (σ = 0.25)		
CS13	P1	0.35 (σ = 0.33)	0.35 (σ = 0.21)	
	P2	0.59 (σ = 0.30)	1.37 (σ = 0.30)	
CS14	P1	0.51 (σ = 0.37)	0.51 (σ = 0.22)	0.16 (σ = 0.20)
	P2	1.11 (σ = 0.33)	1.88 (σ = 0.36)	0.52 (σ = 0.32)

TABLE V. COMMON VIEWS FOR GALILEO E1 AND E5A

[ns]		CS11	CS12	CS13
CS12	E1	0.10 (σ = 0.30)		
	E5a	-0.22 (σ = 0.27)		
CS13	E1	-0.92 (σ = 0.29)	-0.97 (σ = 0.23)	
	E5a	-0.09 (σ = 0.29)	0.16 (σ = 0.28)	
CS14	E1	-0.48 (σ = 0.28)	-0.53 (σ = 0.22)	0.43 (σ = 0.21)
	E5a	-0.19 (σ = 0.30)	0.06 (σ = 0.29)	-0.09 (σ = 0.26)

TABLE VI. COMMON VIEWS FOR BDS-2 B1 AND B2

[ns]		CS14
CS13	B1	0.82 (σ = 1.18)
	B2	0.10 (σ = 1.23)

The results given here are obtained on a long period: between January 2021 and March 2022 for CS11 and CS12. The common views between these chains are plotted in Fig. 2 for GPS and Fig. 3 for Galileo. Note that an offset of 3 ns has been subtracted on P2 and on E5a on these figures for clarity purposes. The light blue zone correspond to the 1-σ combined uncertainties.

We observe that the common views with P1 and E1 show some small variations of a few hundreds of ps, while the common views with P2 and E5a seem more stable. As this effect is visible on all baselines that involve CS11, this is likely due to a local effect affecting only this GNSS receiver chain on the L1 band.

The absolute calibration of CS13 and CS4 is more recent, so the common views between CS13 and CS14 presented in Fig. 4Fig. 2 and Fig. 5 start in July 2021.

There are no results on BDS-3 yet, as the ORB RINEX to CGGTTS tool does not process the BDS-3 observables at the time of writing.

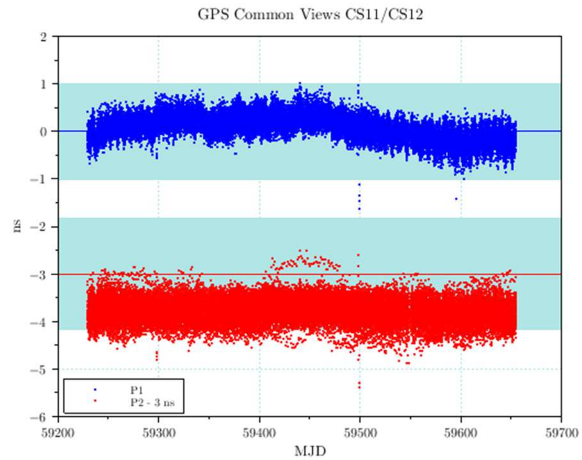

Fig. 2. GPS CV between CS11 and CS12 for P1 and P2

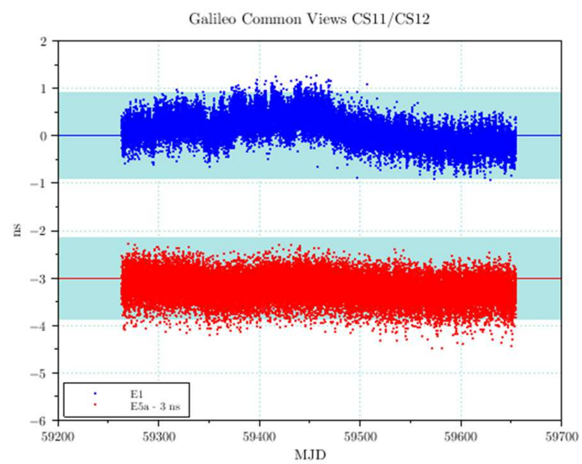

Fig. 3. Galileo CV between CS11 and CS12 for E1 and E5a

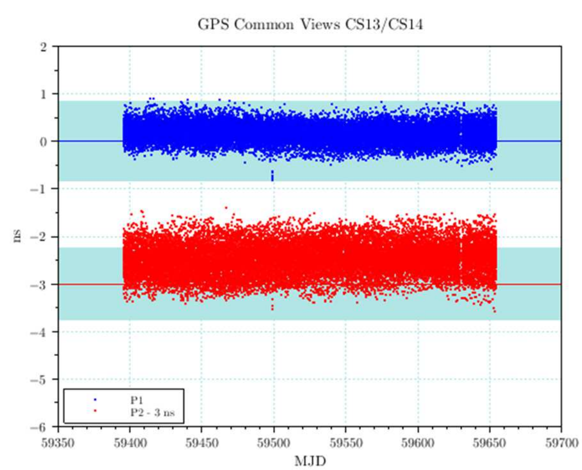

Fig. 4. GPS CV between CS13 and CS14 for P1 and P2

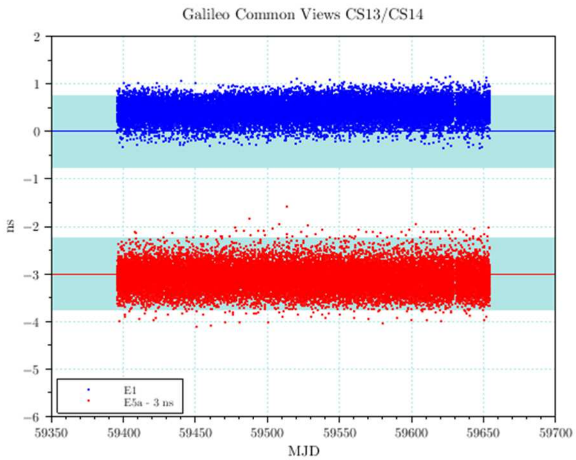

Fig. 5. Galileo CV between CS13 and CS14 for E1 and E5a

IV. GNSS TIME SCALES MONITORING

A. Evaluation of GNSS_time - UTC

Our receivers are used to monitor GPS, Galileo and BDS time scales. It is important to underline that we consider the uncertainty associated with the determination of GNSS_time – UTC(CNES) and GNSS_time – UTC. A detailed evaluation of these uncertainties is given in [3].

The determination of GNSS_time – UTC(CNES) is done with a one-hour latency, using hourly processing to get the raw sbf files into RINEX observation files and CGGTTS files. Combining these time differences to UTC – UTC(CNES) obtained in the BIPM Circular T, we have access to GNSS_time – UTC.

The time differences GPST – UTC, GST – UTC and BDT – UTC between June 2020 and February 2022 are presented in Fig. 6. The associated uncertainty is the quadratic sum of the uncertainty of the GNSS receiver chain absolute calibration for the iono-free combination, the standard deviation of UTC(CNES) – GNSS_time in the CCGGTTS, the uncertainty related to the position and to multipath (as presented in [3]) and the uncertainty on UTC – UTC(CNES) in the BIPM Circular T. This 1-σ uncertainty is represented by a light color zone on either side of each curve of Fig. 6.

GPST and GST remain close to UTC at the level of a few ns, except in August 2021 (around Modified Julian Day 59450) where GST – UTC reaches nearly -20 ns. Conversely, we observe that BDT presents large variations until December 2020 and then seems to stabilize around 20 to 30 ns.

B. Comparison to GPUT and GAUT broadcast values

GPS and Galileo broadcast an estimation of their time offset to UTC, referred to as GPUT and GAUT respectively. In order to validate these broadcast messages, we can compare them to our estimations presented in the previous paragraph. For the broadcast values, we used the GPUT and GAUT information present in the header of our daily RINEX navigation files. This comparison for GPS is given in Fig. 7 and for Galileo in Fig. 8.

We observe that the drift of GST of about 20 ns is well reflected in the UTC time offset broadcast by Galileo. It means that the Galileo user who applies this broadcast message will continue to have an accurate access to UTC.

C. Comparison to GPGA broadcast value

For interoperability purposes, the Galileo navigation message includes the time offset with GPS. With our calibrated GNSS receiver chains, we can estimate the time offset between Galileo and GPS and compare to the information broadcast by Galileo, as shown in Fig. 9. There is a good level of consistency between the GPGA broadcast by Galileo and our estimation.

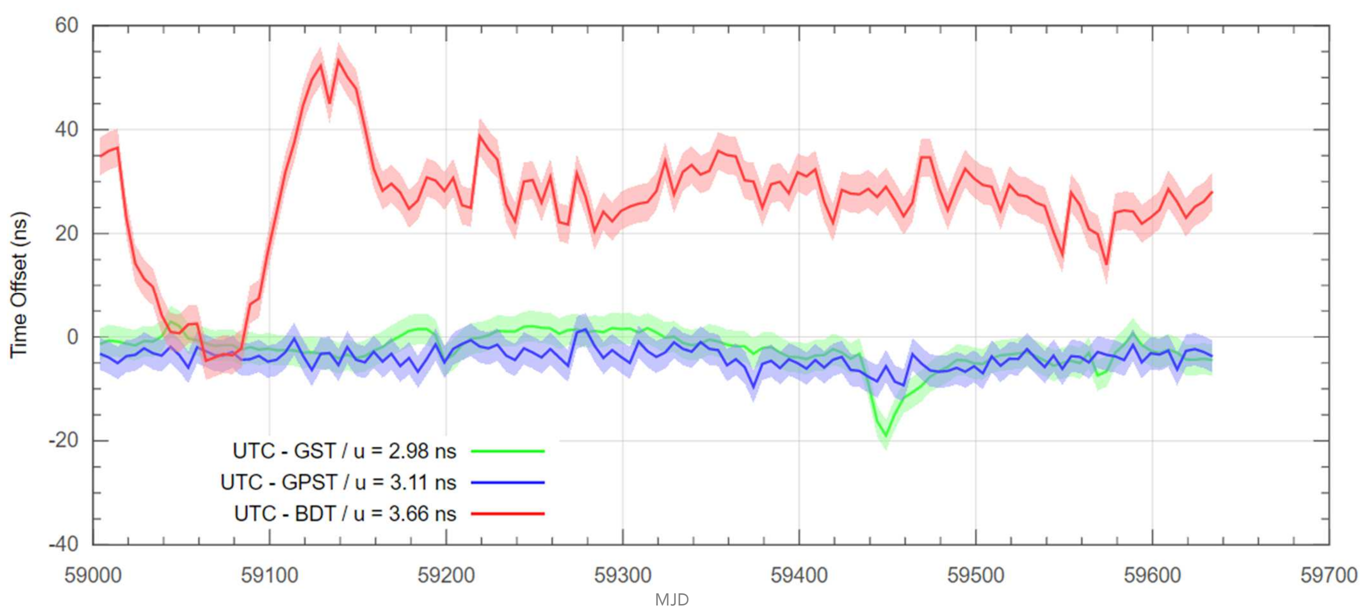

Fig. 6. UTC – GST, UTC – BDT and UTC – GPST

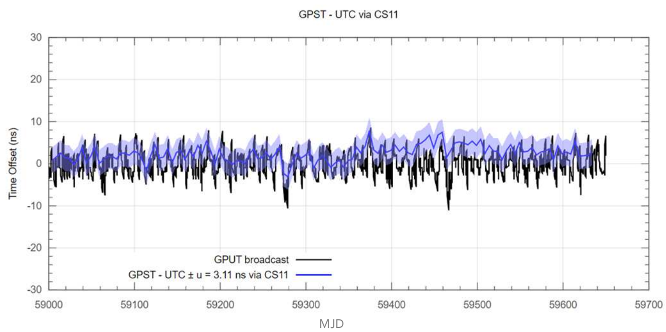

Fig. 7. GPST – UTC

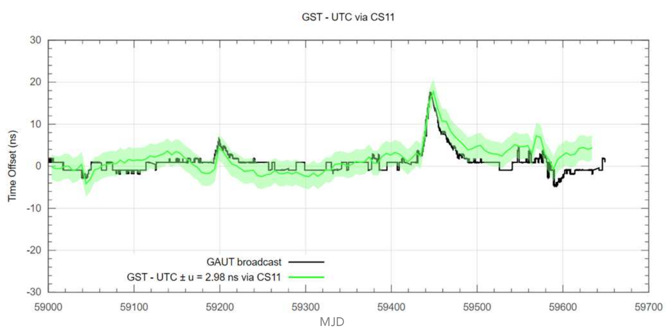

Fig. 8. GST – UTC

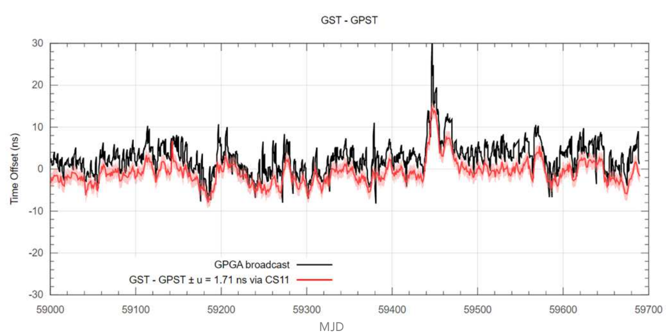

Fig. 9. GST – GPST

V. CONCLUSIONS

We presented in this paper our recent improvements in the absolute calibration of GNSS receiver chains, our GNSS setup and the independent monitoring of GNSS time scales that we carry out.

The long-term monitoring of GNSS time scales is crucial for benchmarking the various GNSS and the absolute calibration of GNSS receiver chains plays a key role in this monitoring. The associated uncertainties have been determined and taken into account to ensure a consolidated evaluation of these time offsets. This paves the way to a metrological comparison to the GNSS specifications.

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