Precise estimation of the GPS To Galileo Time Offset: an experimental setup and its associated processing method

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Abstract

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Although the satellite navigation systems are all in their definition based on the international atomic time (TAI), each system has its own realization. There is therefore a difference, variable in time, between different realizations of the same time systems. Thus, the time of the GPS (GPST) and Galileo (Galileo System Time, GST) systems differ in their realization by some nanoseconds. This difference is called GGTO for GPS to Galileo time offset. An independent, accurate and high resolution knowledge of the GGTO can be useful for precise positioning and orbit determination in a multi-constellation context. However, the GGTO, determined by the Galileo ground segment, is not distributed publicly in a precise way.

We present here an experimental setup to estimate the GGTO: the same GNSS antenna is "split" on two receivers, one using the GPST, the other the GST as reference time. Both receivers are connected to the same rubidium oscillator, in order to have the same frequency reference. A preliminary analysis has been carried out using collected pseudo-distance observations. The results obtained show a good agreement with the broadcast GGTO, but a constant bias of few nanoseconds remains, requiring further investigations.

Keywords: GPS to Galileo time offset, time metrology, multi-GNSS time synchronization

1 Introduction

The principle of satellite positioning systems (GNSS) is based on the measurement of distance (trilateration) between satellites and a receiver on the ground. Satellite-receiver pseudo-distances are deduced from a signal propagation time measurement between receiver and satellite. Positioning accuracy therefore depends to a large extent on the accuracy of this propagation time measurement, and therefore on the quality of clock synchronization between the satellites and the receiver, which must all be in the same common time reference.

Satellite positioning geodesy has been undergoing a transformation in recent years: the arrival of new constellations, notably the European Galileo declared operational in 2016 and the Chinese Beidou in 2018, as well as the arrival of GPS Block III in 2018, marks the availability of new signals that offer a host of new perspectives in terms of location accuracy. It is also possible to simultaneously use signals from several positioning systems in so-called multi-GNSS processing. To do this, it is necessary to bring the measurements from the different systems into line with the same time reference. The main GNSS systems are based on TAI time (International Atomic Time). However, each system has a different time realization, and this difference is not constant. The result is a difference between the two time scales that needs to be taken into account in the measurements.

In the following, we focus on the GPS and Galileo systems. As mentioned above, GPS (GPST) and Galileo (*Galileo System Time, GST*) system times are aligned with TAI, but differ in their realization by a few nanoseconds. This difference is called GGTO for *GPS to Galileo time offset*. The GGTO is determined by the Precise Time Facility (PTF) of the Galileo Ground Mission Segment (GMS) [5], but its value (which varies over time) is not precisely distributed publicly. It is only delivered in a simplified and degraded form in the ephemeris broadcasts. The one and only precise and high-resolution representation of the GGTO published during the In-Orbit Validation (IOV) phase is shown in Figure 1.

Relatively little research has been carried out into determining the GGTO itself. During the Galileo constellation design phase, [11] analyzes the various issues related to GPS/Galileo interoperability for positioning and synchronization, including GGTO and synchronization biases, and presents practical experience with GIOVE-A, the

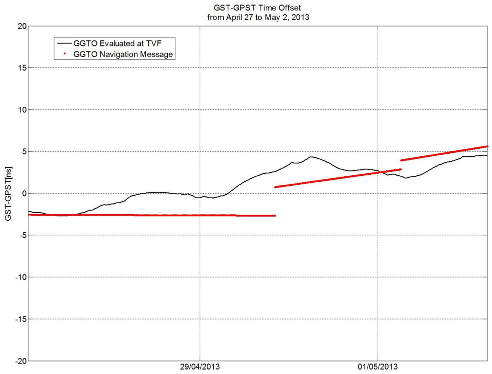

Fig. 1 representation of the GPS to Galileo time offset value, as estimated by the Galileo Time Validation Facility (black line) and the GGTO as transmitted in the navigation message and available to the user (red line). The black curve is the only representation of a precise and high-resolution GGTO available in open source literature. Source: ESA Website https://www.esa.int/Applications/Navigation/Galileo_and_GPS_synchronise_watches_new_time_offset_helps_working_together

first Galileo experimental satellite. [13] proposes several methods for determining the GGTO, but these were probably never subsequently exploited. [7] estimates the GGTO by exploiting Doppler and pseudo-distance measurements from a receiver that records signals from the GPS and Galileo systems. [9] describes the pseudorange equations enabling multi-GNSS calculations, but does not detail precise methods for determining the GGTO itself. After 2016, research has been carried out to determine the GGTO from the user's point of view. [1] describe a method, using least-squares estimation of the GGTO, in addition to user position and time offsets. However, the results show a difference of around 25 nanoseconds between their estimate and the reference GGTO.

There is currently no easy way for the scientific community to access a precise GGTO value, which is a drawback. Similarly, this parameter is not currently considered in geodetic GNSS processing software. GGTO is absorbed more or less homogeneously by satellite clock biases, and in the Inter-System Biases (ISB) specific to each receiver. However, an explicit introduction of the GGTO (and equivalent time offsets for other constellations) into the observation equations of GNSS computations, as a constant for a given epoch or as a parameter to be estimated, would most likely enable the estimation of satellite and receiver clock biases, as well as ISBs, to be refined. In addition to precise positioning, a better understanding of the GGTO could also be useful for GNSS clock combinations [2] and time transfer [10].

Therefore, our present study aims to determine GGTO values independently and accurately, avoiding the official but degraded values broadcast in broadcast orbits. We present an experimental setup which aims to record GNSS observable in an optimal configuration to estimate the GGTO. We propose two approaches to determine GGTO's values over the study period: one using directly the RTKLIB software, and the second using a single difference strategy.

2 Experimental setup and reference GGTO

To attempt an independent determination of the GGTO, we set up the configuration presented in Figure 2 two GNSS receivers (model *Septentrio PolaRx5*) at 1 Hz acquisition rate observing both the GPS and Galileo constellations. Both receivers are connected via a splitter to the same antenna located on the Telgrafenberg, Potsdam, Germany. One receiver (POTG) is set to use GPST as reference time, the other (POTE) is set to GST as reference. An external rubidium standard supplies the same frequency to both receivers. The two receivers must therefore observe exactly the same satellites, but with different time realizations. The measurements are conducted during 160 days between days of year 2021-060 and 2021-220.

Galileo broadcast messages use a polynomial description of the GGTO [6]. We fetch RINEX navigation files, which contain the polynomial coefficients as broadcast by the Galileo system, to compute the GGTO (called GAGP in the RINEX convention) over the experiment's period. These files are generated and supplied by GOP (Geodetic Observatory Pecnỳ, Czechia) [3] for the first 26 days of our experiment, and by NASA's CDDIS [8] for the rest of the period (GOP's GAGP coefficients are missing after this date).

Daily jumps and sharp trend variations from one day to the next are clearly visible. They most likely do not correspond to any physical reality, but are a consequence of the linear approximation of the broadcast messages. The GGTO average value over our study period is around 1.5 nanoseconds, but variations are not negligible, of the order of 20 nanoseconds. This reference from the broadcast messages is represented as a blue curve in the following Figures 3 and 4.

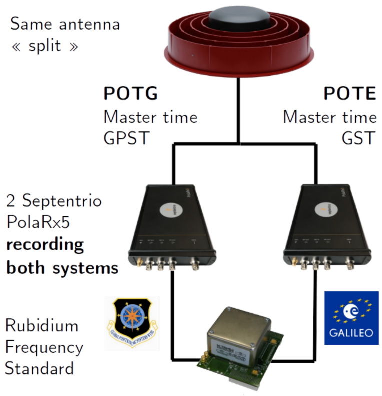

Fig. 2 The experimental setup for GGTO determination used for this study

3 GGTO direct determination using RTKLIB software

We use RTKLIB software [12] with its *explorer demo5 b34g* forked version [4] in single point positioning, named *Single* mode in the software and herefter, i.e. using only one receiver at a time, and only pseudoranges information from GPS and Galileo systems. Data are decimated to 30 seconds. RTKLIB provides an estimate of both the receiver clock bias with respect to GPS time ("*receiver clock bias GPS (ns)*"), and the difference in clock bias between GPS and Galileo time ("*receiver clock bias GAL-GPS (ns)*"). The latter corresponds to GGTO. We compare this estimate with our reference extracted from broadcast messages. The results are presented in Figure 3.

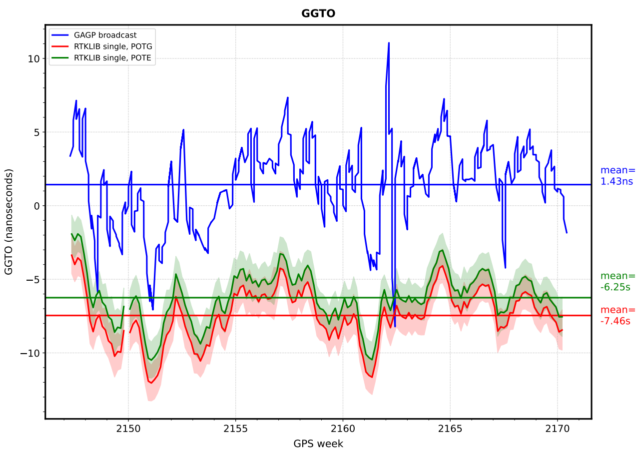

Fig. 3 GGTO estimated using RTKLIB software in single mode. The green and the red curves are the GGTO estimated from the GPS time-synchronized and the Galileo time-synchronized receiver respectively. The blue curve represent the reference GGTO extracted from the broadcast messages.

Blue curve is the broadcast GGTO reference, while red and green curves are the GGTOs estimated by RTKLIB, using data from the GPS time-synchronized receiver and Galileo time-synchronized receiver respectively. For the estimated values, we have taken a daily average of the data calculated every 30 seconds, in order to reduce noise. The $1-\sigma$ daily standard deviation is represented as a faded area. The trends are very similar between the RTKLIB-estimated GGTO and the reference one, but the estimated GGTO is about -8 nanoseconds shifted w.r.t. the reference.

4 GGTO with simple difference estimation

From the specific experimental setup described in section 2, we develop the fundamental observational equations using the principle of simple differences to obtain an analytical definition of the GGTO. Our starting point is the fundamental observation equations for GNSS positioning. We use only the pseudorange data, as the carrier phase data poses the additional problem of resolving ambiguities.

The pseudo distance as recorded by our receivers is defined as follows:

$$p = (t_{rec/rec} - t_{em/sat}) \times c \tag{1}$$

Where:

- p : pseudo-range
- $t_{rec/rec}$: signal reception epoch in the receiver time reference
- $t_{em/sat}$: signal emission epoch in satellite time reference

We therefore need to reduce these times to a common reference, which will be GPS time for our first receiver and Galileo time for the second.

$$\begin{cases} p_{r_1}^S\left(t^G\right) = c\left[t_{r1}\left(t^G\right) + \delta t_{r1}\left(t^G\right) - t^S\left(t^G\right) - \delta t^S\left(t^G\right)\right] \\ p_{r_2}^S\left(t^E\right) = c\left[t_{r2}\left(t^E\right) + \delta t_{r2}\left(t^E\right) - t^S\left(t^E\right) - \delta t^S\left(t^E\right)\right] \end{cases} \tag{2}$$

Where:

- $p_{r_i}^S$: pseudo-range between receiver i and satellite S
- $t_{r_i}\left(t^G\right)$: receiver 1 epoch in GPS time scale
- $t_{r_2}\left(t^E\right)$: receiver 2 epoch in Galileo time scale
- $\delta t_{r_1}\left(t^G\right)$: clock bias of the receiver 1 w.r.t. GPS time scale
- $\delta t_{r_2}\left(t^E\right)$: clock bias of the receiver 2 w.r.t Galileo time scale
- $t^S\left(t^G\right)$: satellite epoch in GPS time scale
- $t^S\left(t^E\right)$: satellite epoch in Galileo time scale
- $\delta t^S\left(t^G\right)$: clock bias of the satellite w.r.t. GPS time scale
- $\delta t^S\left(t^E\right)$: clock bias of the satellite w.r.t. Galileo time scale
- $K_{r_i,j}$: hardware biais of the receiver i at frequency j
- K_j^S : hardware biais of the satellite s at frequency j

By rearranging the equation's terms:

$$\begin{cases} p_{r_1}^S\left(t^G\right) = c\left[t_{r1}\left(t^G\right) - t^S\left(t^G\right)\right] + c\left[\delta t_{r1}\left(t^G\right) - \delta t^S\left(t^G\right)\right] \\ p_{r_2}^S\left(t^E\right) = c\left[t_{r2}\left(t^E\right) - t^S\left(t^E\right)\right] + c\left[\delta t_{r2}\left(t^E\right) - \delta t^S\left(t^E\right)\right] \end{cases} \tag{3}$$

The term $c\left[t_{ri}(t^G) - t^S(t^G)\right]$ corresponds to the exact time the signal took to travel from the satellite to the receiver, since we're now on the same theoretical time scale. The signal is disturbed by various elements along the way. To the geometric distance we must add various delays and biases. The pseudo-distances are therefore rewritten as follows:

$$\begin{cases} p_{r_1,j}^S\left(t^G\right) = d_{r1}^S + \tau_{r1,j,tropo}^S + \tau_{r1,j,iono}^S + \tau_{r1,j,rel}^S + K_{r1,j} + K_j^S + c\left[\delta t_{r1}\left(t^G\right) - \delta t^S\left(t^G\right)\right] \\ p_{r_2,j}^S\left(t^E\right) = d_{r2}^S + \tau_{r2,j,tropo}^S + \tau_{r2,j,iono}^S + \tau_{r2,j,rel}^S + K_{r2,j} + K_j^S + c\left[\delta t_{r2}\left(t^E\right) - \delta t^S\left(t^E\right)\right] \end{cases} \tag{4}$$

Where:

- d_{ri}^S : geometric distance between satellite s and receiver i

- $\tau^S_{ri,j,tropo}$: tropospheric delay between satellite s and receiver i at frequency j
- $\tau^S_{ri,j,iono}$: ionospheric delay between satellite s and receiver i at frequency j
- $\tau^S_{ri,j,rel}$: relativity delay between satellite s and receiver i at frequency j
- $K_{ri,j}$: hardware biais of receiver i at frequency j
- K^S_j : hardware biais of satellite s at frequency j

If we take the difference between two pseudorange measurements, at the same frequency for the same satellite, between the signals received by receiver 1 and receiver 2, we eliminate several terms:

$$p^S_{r_1,j}\left(t^G\right) - p^S_{r_2,j}\left(t^E\right) = K_{r1,j} - K_{r2,j} + c\left[\delta t_{r1}\left(t^G\right) - \delta t_{r2}\left(t^E\right) - \delta t^S\left(t^G\right) + \delta t^S\left(t^E\right)\right] \tag{5}$$

Since our two receivers share the same antenna, the path taken by the signal is the same.

The satellite s clock time can be expressed in either the GPS or Galileo time reference:

$$t^S = t^G + \delta t^S\left(t^G\right) \tag{6}$$

$$t^S = t^E + \delta t^S\left(t^E\right) \tag{7}$$

$$(6) - (7) \rightarrow 0 = t^G - t^E + \delta t^S\left(t^G\right) - \delta t^S\left(t^E\right) \tag{8}$$

This brings us to the definition of GGTO, which is the difference between Galileo system time and GPS system time.

$$t^E - t^G = \delta t^S\left(t^G\right) - \delta t^S\left(t^E\right) = GGTO \tag{9}$$

We can introduce this term into our simple difference equation:

$$p^S_{r_1,j}\left(t^G\right) - p^S_{r_2,j}\left(t^E\right) = K_{r1,j} - K_{r2,j} + c\left[\delta t_{r1}\left(t^G\right) - \delta t_{r2}\left(t^E\right) - GGTO\right] \tag{10}$$

This leaves us with the unknowns of hardware bias and receiver clock bias. But as we saw earlier, the RTKLIB software estimates the latter. In fact, in what it presents as only clock biases, it includes hardware biases. Since it is difficult to separate the two, we therefore have the values of $\left[\delta t_{r1}\left(t^G\right) + K_{r1,j}\right]$ et $\left[\delta t_{r2}\left(t^E\right) + K_{r2,j}\right]$ estimated in section 3.

Thus:

$$\boxed{GGTO = -\left(\frac{p^S_{r_1,j}\left(t^G\right) - p^S_{r_2,j}\left(t^E\right)}{c} - \left[\left(\delta t_{r_1}\left(t^G\right) + K_{r_1,j}\right) - \left(\delta t_{r_2}\left(t^E\right) + K_{r_2,j}\right)\right]\right)} \tag{11}$$

Figure 4 represents the GGTO estimated with this method. A GGTO value is obtained for each pair of pseudo-range observations (note that only C/A pseudoranges are considered here). The GGTOs calculated for each pair are averaged epoch by epoch. In purple, the standard deviation (1σ) of this average is shown. The result is noisy (± 0.5 nanoseconds) but constant over the entire study period, suggesting that the estimated GGTO is stable. Indeed, the mean GGTO value obtained follows the same fluctuations as the broadcast reference, albeit with a -8 nanosecond offset. The result is very similar to RTKLIB estimation's result in *Single* mode.

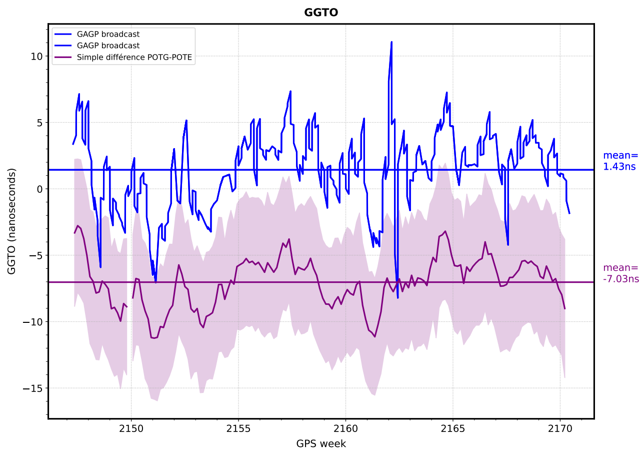

Fig. 4 GGTO estimated using the simple difference method (purple curve). The blue curve represent the reference GGTO extracted from the broadcast messages.

5 Discussion and summary

We have developed an experimental setup based on two receivers, each synchronized on GPS or Galileo time scales, and an associated simple difference processing strategy for determining the GGTO. It provides a continuous value with high temporal resolution. This GGTO is compatible with the daily values estimated by RTKLIB in single point positioning mode for each of the two receivers. Its variations are also consistent with the reference broadcast values.

However, an offset of around 8 nanoseconds between our estimate and the reference GGTO remains visible, both in the simple difference estimate and in the RTKLIB estimate. Several hypotheses are possible: we are likely observing a trade-off effect between the GGTO and clock and/or hardware receiver biases. It should also be noted that the simple difference estimate is not independent of the RTKLIB calculation, since we reuse the hardware and clock receiver biases estimated by the latter as they are. This possible trade-off effect can therefore potentially be propagated into the simple difference estimate. However, insofar as the GGTO values estimated by RTKLIB are of the same order of magnitude for both receivers, and this independently, we must not rule out a possible correction for a constant bias in the reference GGTO broadcast.

Thus, further studies are needed to explain this shift. Furthermore, we have only exploited pseudorange measurements, but taking carrier phase measurements into account would undoubtedly improve the accuracy of the estimated GGTO. In any case, considering the GGTO in geodetic GNSS processing software could potentially lead to improvements in the estimation of satellite and receiver clock biases.

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