A Comparative Performance Assessment of Galileo and GPS Satellite Clocks

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1. Abstract

Galileo’s system design is promising enhanced performance compared to other Global Navigation Satellite Systems (GNSS). Several studies have already demonstrated the good performance of Galileo. One key component of Galileo's superiority is the performance of the atomic frequency standards (AFS) used onboard the satellites. In this study we analyzed the performance of the Galileo AFSs in comparison to GPS. We performed a quantitative analysis based on the offset and the drift of the satellite clocks as well as their stability, which is assessed by means of the Allan deviation. Moreover, in our analysis we distinguished among the different types of AFSs (Rubidium, Cesium, H-maser) and the different satellite blocks. Our analysis showed that there is a significant difference in the AFS performance between Galileo and GPS, as well as among GPS satellites of different blocks. Generally speaking, the GPS clocks exhibit smaller drifts and offsets, whereas Galileo clocks are characterized by a better short-term stability, which is vital for advanced applications like high-rate Precise Point Positioning (PPP).

Keywords: GPS, Galileo, Clock stability, Rubidium, Cesium, H-maser, Allan deviation.

2. Introduction

It is well known that precise time keeping is crucial for every global navigation satellite system. Any unmodelled satellite clock errors seriously degrade the positioning accuracy. For applications requiring cm-level precision, the requirements on precise timekeeping are even higher (Hesselbarth and Wanninger, 2008). Galileo is the first GNSS designed to use high performance hydrogen atomic clocks onboard the satellites. Such a clock was already used in the second Galileo satellite (GIOVE-B) launched in 2008. Thus, the Galileo clocks have drawn the scientific attention. Several researchers analysed their performance in comparison to other global navigation satellite systems. Examples of such studies are Huang et al., 2019; Ai et al., 2021; Cao et al., 2021. Different than these studies, our comparison between Galileo and GPS also takes into account the latest generation of GPS III satellites, which were put into orbit in the very latest years.

2.1 Atomic Frequency standards

The high requirements of GNSS satellites for precise timekeeping can only be fulfilled by space qualified atomic clocks. Other timekeeping standards, even very good space-qualified ovenized crystal oscillators (OCXO) are not suitable (Jaduszliwer and Camparo, 2021). Three types of atomic frequency standards are used onboard GNSS satellites: Cesium (Cs) AFS, Rubidium (Rb) AFS (RAFS) and Passive Hydrogen Masers (PHM). Generally speaking, the Cesium clocks have worse short-term stability than RAFSs, but they offer excellent long-term stability. The PHMs have good short-term as well as long-term performances (Bandi, 2022).

GPS satellites are equipped with different types of AFSs depending on the satellite block (Hauschild et al, 2013). The Block II/IIA GPS satellites contain two Cs and two Rb clocks. Block IIR and Block IIR-M satellites carry three Rb clocks. Block IIF satellites contain one Cs and two Rb clocks. The latest generation of GPS satellites, i.e Block III, were designed to contain 3 Rb clocks (Beard and Senior, 2017). This information is summarized in Table 1.

Table 1. Types and amount of AFS used in each GPS satellite block

Block	Cs	Rb
IIA	2	2
IIR, IIR-M	×	3
IIF	1	2
III	×	3

In the case of Galileo system, each satellite is equipped with four AFSs (two RAFSs and two PHMs), in order to ensure the high redundancy of the timing system (Huang, 2019).

Regarding the GLONASS and BeiDou systems, GLONASS-M satellites carry 3 Cs clocks and GLONASS K-1 contain two Cs and two Rb clocks; BDS-2 satellites contain four RAFS and BDS-3 carry 2 RAFS plus 2 H-masers (Batori et al., 2021).

2.2 Clock offset modelling

Generally speaking, an atomic frequency standard suffers from drift and aging. The clock offset $\delta(t)$ of a timekeeping AFS at a given time t is expressed as:

$$\delta(t) = \alpha_0 + \alpha_1(t - t_0) + \alpha_2(t - t_0)^2 \quad (1)$$

where α_0 is the bias at the reference time t_0, α_1 is the drift and α_2 is the aging (or drift rate). The units are sec, sec/sec and sec/sec^2, respectively. The Equation (1) is used for the description of the clock offset in the broadcast ephemerides of GPS, Galileo, BeiDou, QZSS and IRNSS (IGS, 2018). The term a_2 is usually set to zero in the broadcast ephemerides as they are updated regularly (e.g. every 2-3 hours) and the aging of the AFSs is very small (e.g. 10^{-20}).

2.3 Allan variance

For real time applications the clock behaviour should be predicted and made available to the users a-priori, for instance by means of the broadcast ephemeris or the ultra-rapid clock information. The predictability of the clock offset (and consequently the reliability of the predicted clock parameters) depend mainly on the short-term stability of the clock. As the standard variance does not converge for some types of noises commonly observed in AFSs, the short-term frequency stability of an AFS is usually described by other measures, mostly using the Allan variance (Misra and Enge, 2011):

$$\sigma_y^2(\tau) = \frac{1}{2N} \sum_{i=1}^{N-1} (y_{i+1} - y_i)^2 \quad (2)$$

where y_i is the ith value of the relative frequency deviation of the oscillator. Other types of variances used to describe the stability of AFSs include the modified Allan variance and the Hadamard variance. For more details the reader is referred to Riley (2008) and Beard and Senior (2017).

3. Data analysis

In this section the GPS and Galileo satellites are compared in terms of the amount of offset and drift of their clocks, as well as their short-term stability.

3.1 Data used

For our analysis we used clock information (30 sec final clk files) issued by CODE (Centre for Orbit Determination in Europe), ESA (European Space Agency), CNES (Centre national d'études spatiales) and IGS (International GNSS Service). When examining the GPS satellite clocks, one should take into consideration that the assignment of a SVN (Space Vehicle Number) to a PRN number can change from time to time. So, in order to ensure that the space vehicle beyond a particular PRN does not change throughout the examined time-period, we considered the information given in the IGS ANTEX files. In addition, we used:

- the GPS Operational Advisory files issued by the USCG (US Coast Guard) Navigation Centre
- the Notice Advisory to Galileo Users issued by the European GNSS Service Centre

for obtaining the information about the type of AFS used onboard each GPS and Galileo satellite, respectively.

The used data are summarized in Table 2. Regarding the time-period of the examined data, we considered three different time-periods as seen in Table 3. The first time-period was from 2010 to 2014, which includes four different blocks of GPS satellites (Block IIA, IIR-A, IIR-B and IIR-M). The second time-period was from 2018 to 2022, which includes GPS Block IIF and Block III satellites. Lastly, for the Galileo satellites we used a data span from 2013-2023.

Table 2. Data used in this study

Agency/Source	Data	Information used
CODE, ESA, CNES, IGS	Final clk files (30 sec)	Satellite clock offset
IGS	ANTEX files	GPS: PRN & SVN
USCG Navigation Centre	GPS Operational Advisory files	AFS type used on each satellite
European GNSS Service Centre	Notice Advisory to Galileo Users	AFS type used on each satellite

Table 3. Time-periods of examined data

<table>
<tr><th colspan="7">GPS</th></tr>
<tr><td>Block</td><td>IIA</td><td>IIR-A</td><td>IIR-B</td><td>IIR-M</td><td>IIF</td><td>III</td></tr>
<tr><td>Examined data</td><td colspan="4">2010-2014</td><td colspan="2">2018-2022</td></tr>
<tr><th colspan="7">Galileo</th></tr>
<tr><td>Examined data</td><td colspan="6">2013-2023</td></tr>
</table>

3.2 Satellite clock offset

In this section the behaviour of the clock offset of each satellite is examined, in dependence of the type of used AFS and its block (for GPS satellites). In each one of the Figures 1-7, the range of values on the y-axes is the same for all plots, in order to facilitate a direct comparison between the satellites of the same block.

Figure 1 depicts the clock offset for a representative set of GPS Block IIA satellites. Some noteworthy remarks are:

- the clock offset of satellites G04 and G26 becomes zero several times (roughly, once per year)
- the drift of G04 after October 2013 remains at a low level remarkable for RAFS as it is comparable to that of the Cesium clocks of satellites G08 and G10 (bottom of Fig. 1).
- the clock drift of satellite G26 was positive from May 2012 to November 2013, whereas for the rest of the examined time period it was negative.
- the clock offset of satellite G32 progresses smoothly throughout the five years without any reset, but after 2013 shows an aging pattern.
- the clock offsets of satellites G08 and G10 show a behaviour which is typical for Cs clocks (good long-term stability with a very small drift).

Figures 2 and 3 show the clock offset for a representative set of GPS Block IIR-A & IIR-B satellites, respectively. The RAFSs of these satellites exhibit considerably smaller drift than the RAFSs of the Block II-A satellites. Thus, their offsets remain within limits and no discontinuities are observed, as it was the case with the Block IIA satellites (see first remark on Fig. 1). A behaviour similar to that of Block IIR-A & IIR-B satellites is observed also for the GPS Block IIR-M satellites, as can be seen in Fig. 4. On the contrary, the RAFSs of the next block of GPS satellites, namely the Block IIF, show a different behaviour. As seen in Fig. 5:

- the clock offset reaches big values and from time to time it is set to zero, as it was the case with the Block IIA satellites
- unlike the Block IIA RAFSs, the RAFSs of Block IIF present an aging component, obvious also within time periods of just one or two years
- the better long-term stability of the Cs AFSs compared to the RAFSs can clearly be seen in the clock offset of G10, G24 and G08.

As can be seen in Fig. 6, the Rb standards of the latest generation of GPS satellites, i.e. Block III, appear to be free of large offsets and significant drifts. However, it should be underlined that the Block III satellites are available since a limited number of years, thus, more time is needed to draw firm conclusions.

Some characteristic examples of the clock offset of Galileo satellites are presented in Figures 7 and 8. As shown in Fig. 7, the satellites E11 and E19 switched within the investigated time period between RAFS and PHM. Some notable remarks are:

- the long-term stability for satellite E11 during the years 2013 to 2016 is quite different in dependence on the type of AFS used, as it was as expected
- extremely high drift values are observed not only for RAFS (E11 in 2018 and 2020), but also for PHM (E19 in 2020)
- in certain cases, the clock offset reaches values of several milliseconds, being one to two orders of magnitude bigger than those of the GPS satellites.

Inspecting the Figures 7 and 8 one can observe that the above-mentioned big clock offsets occurred up to 2020. In the following years, when the offset approaches ~1 msec it will be set to zero (see e.g. E01 at epoch ~2021.7, E04 & E07 at epoch ~2022.8). So, one could expect that these high clock offsets will no longer appear.

A summary comparison of the clock offsets is given in Figures 9 and 10. Fig. 9 depicts the maximum clock offset (absolute values) observed for each satellite within the examined time-period (left for GPS and right for Galileo). Fig. 10 shows the same values in a common plot, facilitating the direct comparison between GPS and Galileo.

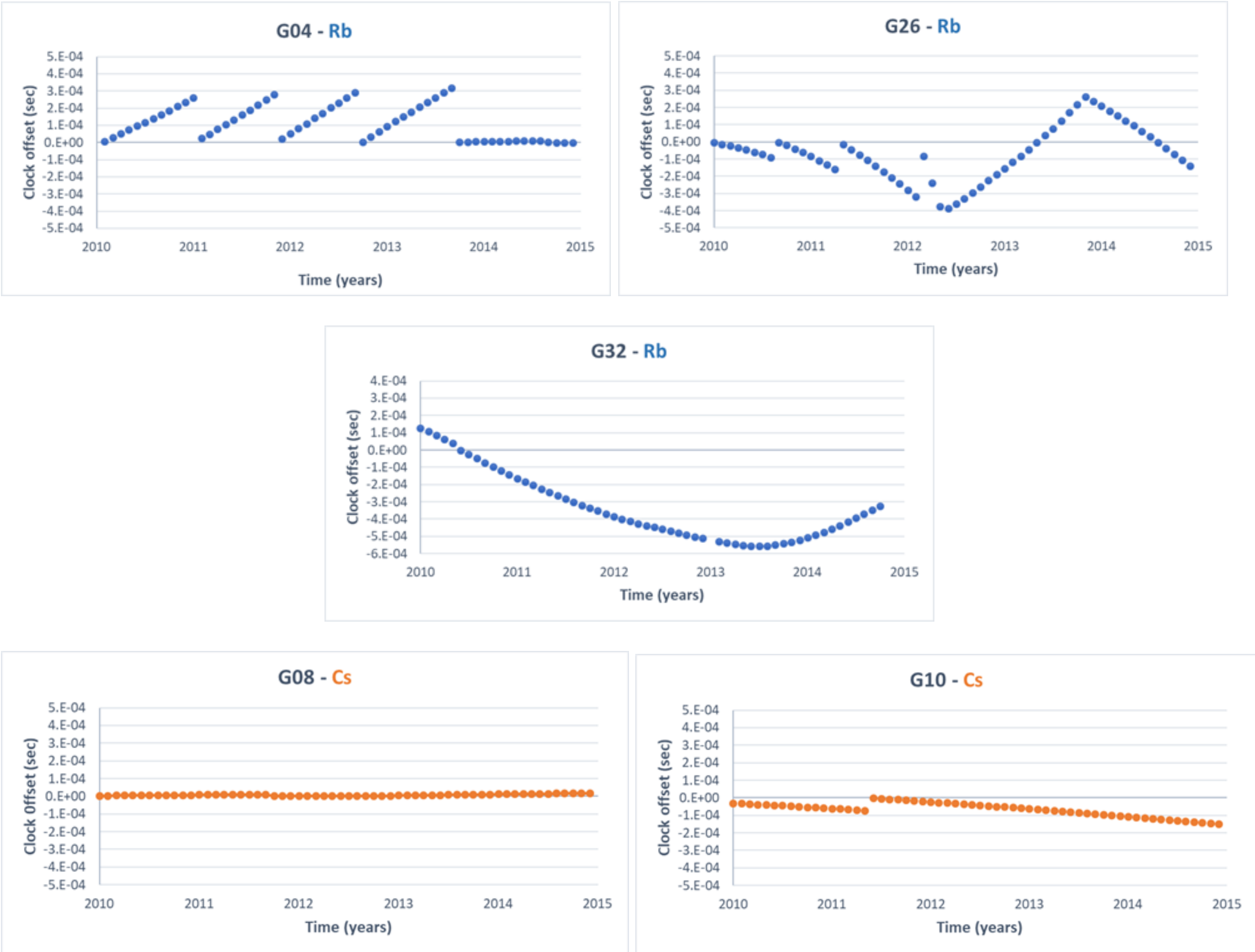

Fig. 1 Clock offset of GPS Block IIA satellites (blue is for Rb; orange for Cs AFS).

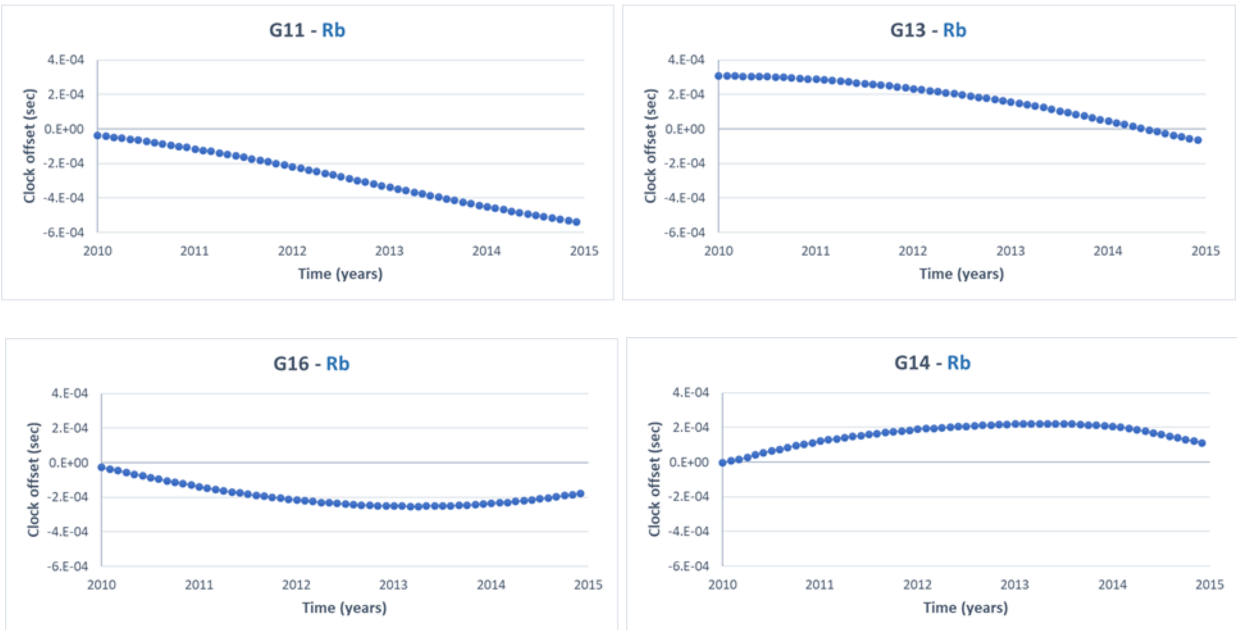

Fig. 2 Clock offset of GPS Block IIR-A satellites.

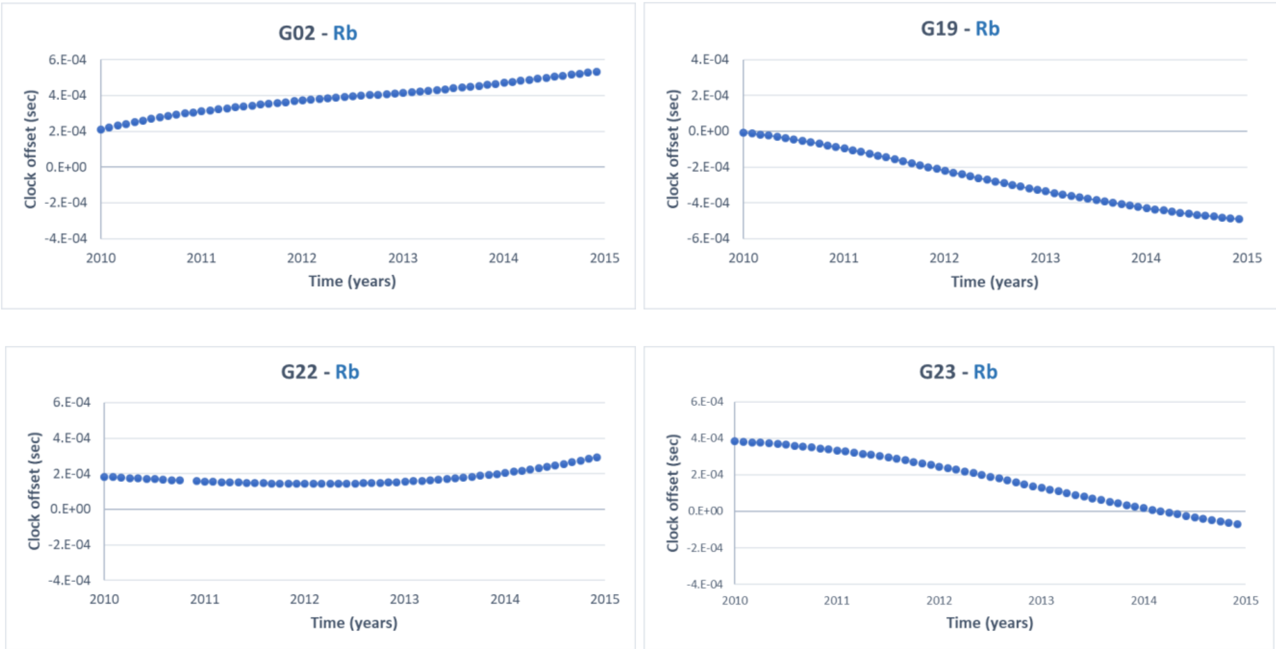

Fig. 3 Clock offset of GPS Block IIR-B satellites.

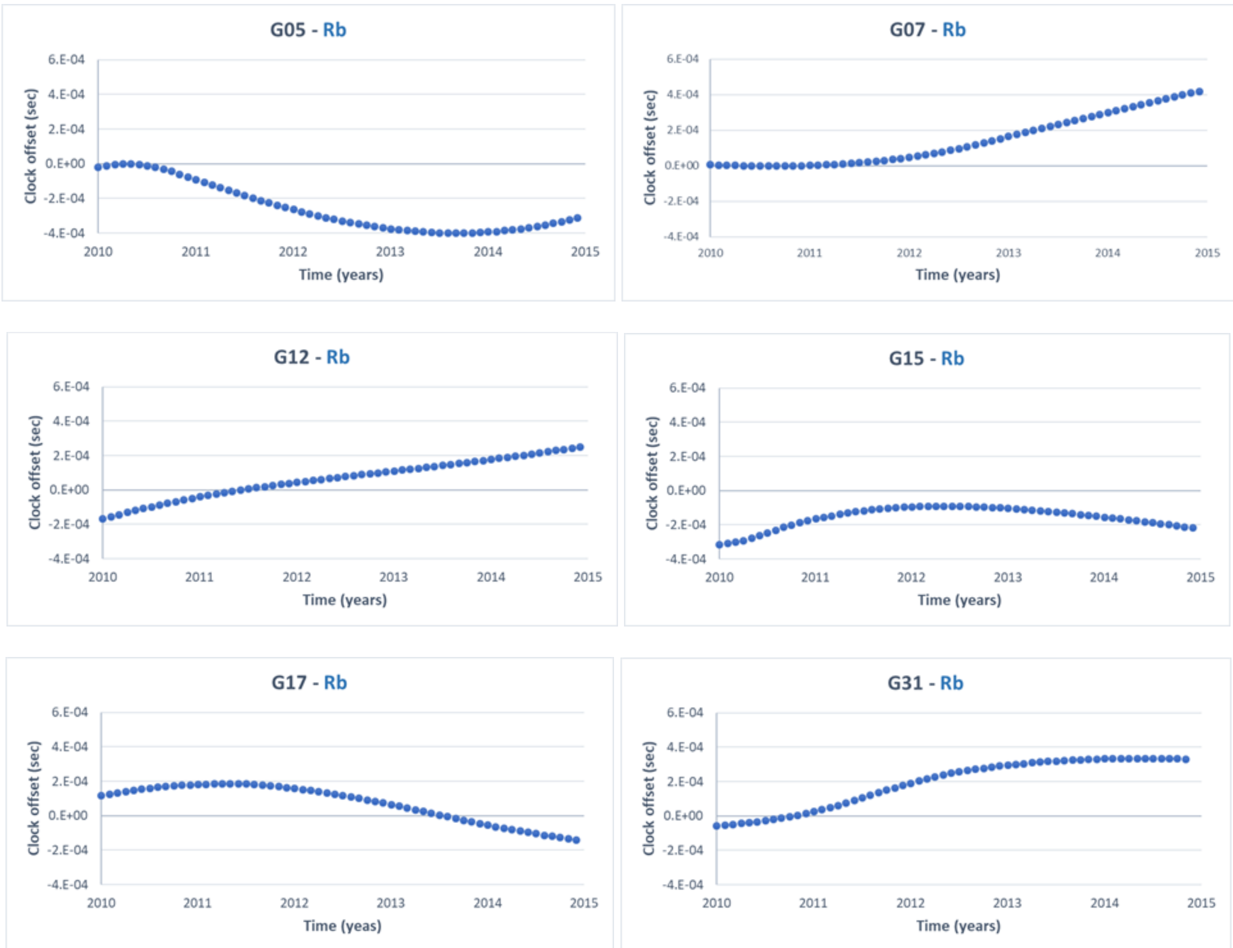

Fig. 4 Clock offset of GPS Block IIR-M satellites.

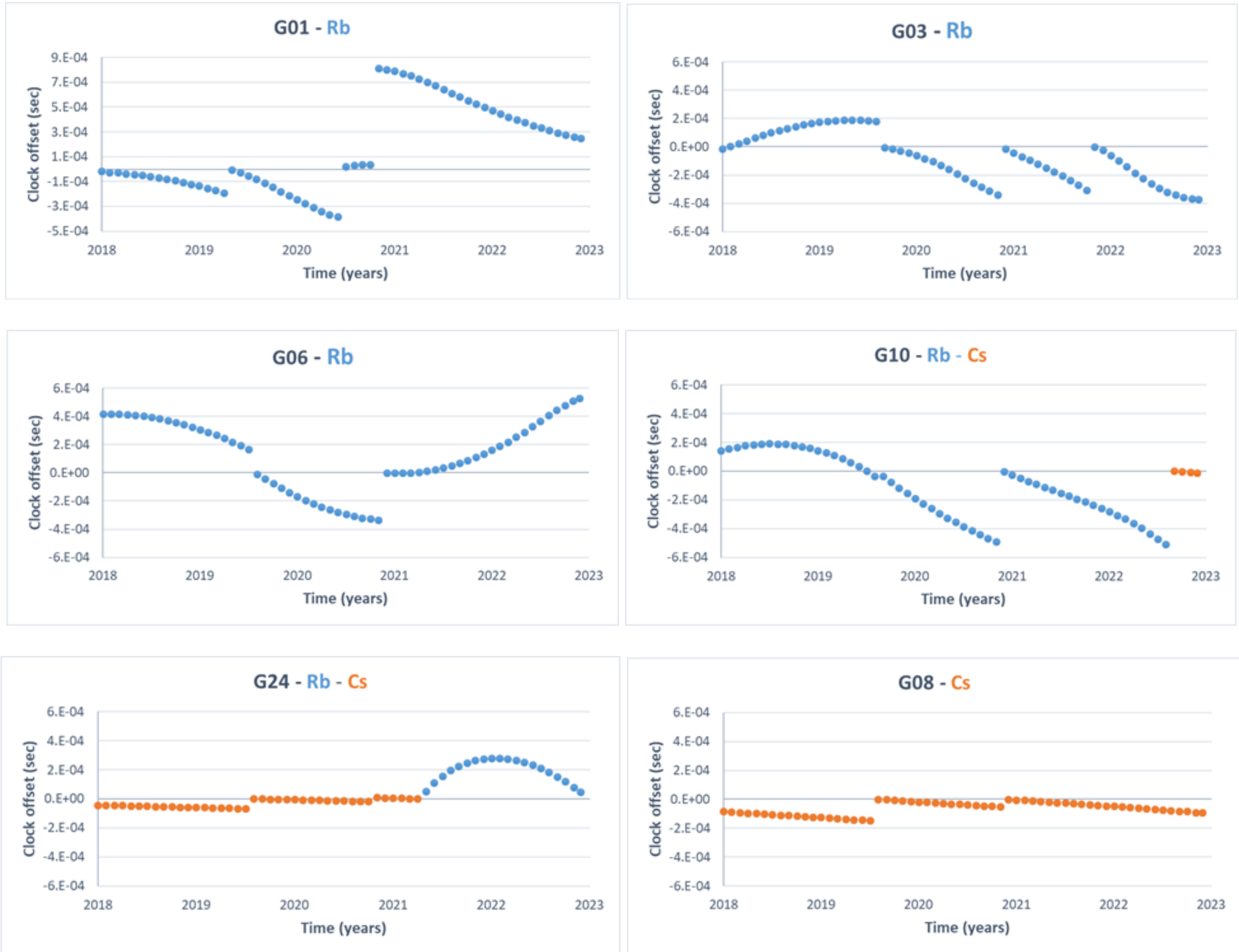

Fig. 5 Clock offset of GPS Block IIF satellites (blue is for Rb; orange for Cs AFS).

Fig. 6 Clock offset of GPS Block III satellites.

Fig. 7 Clock offset of Galileo satellites switching between Rb and PHM (blue is for Rb; red for PHM AFS). (For E19 two plots are given: one with all values (left) and one after excluding excessive values (right)).

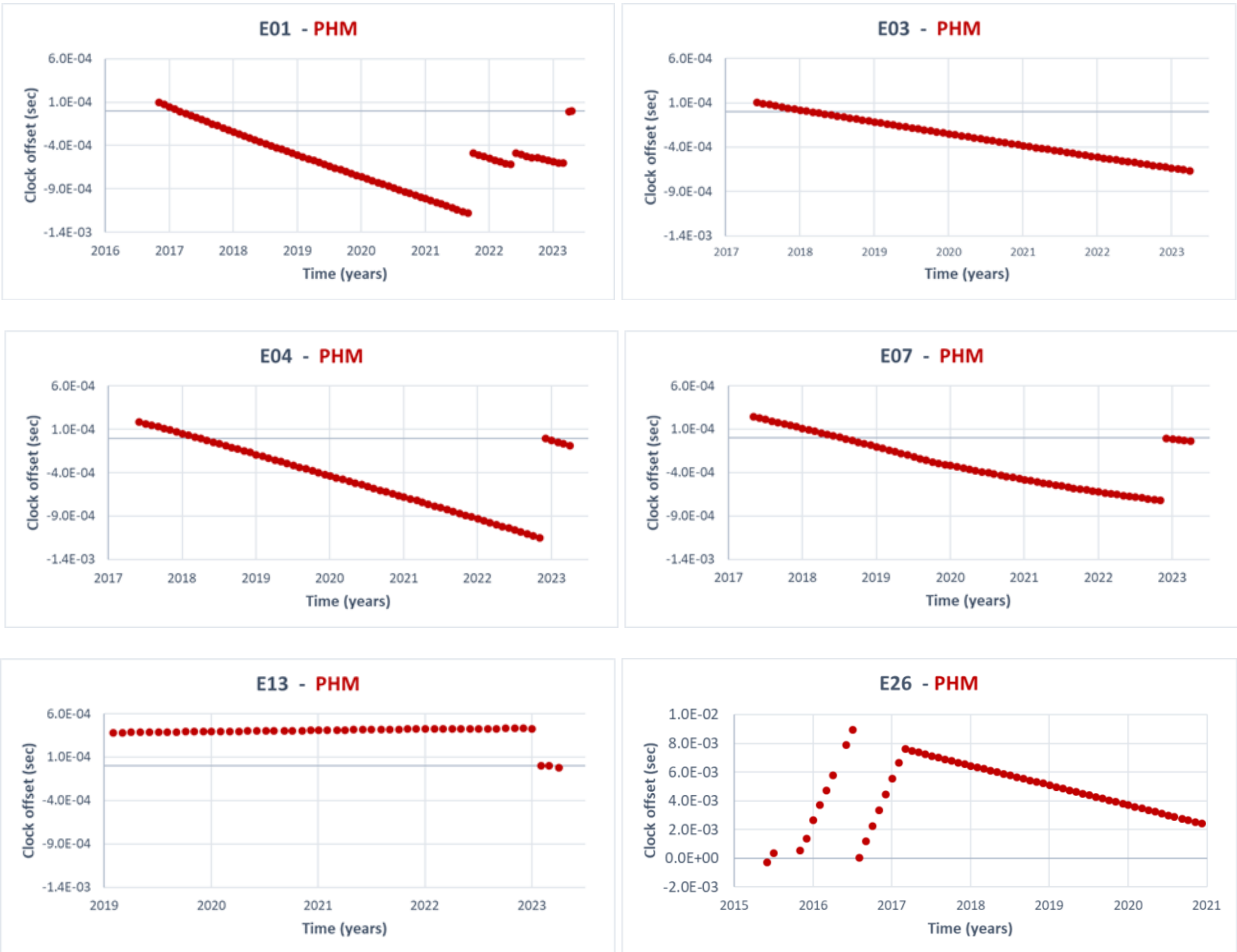

Fig. 8 Clock offset of Galileo satellites running on PHM.

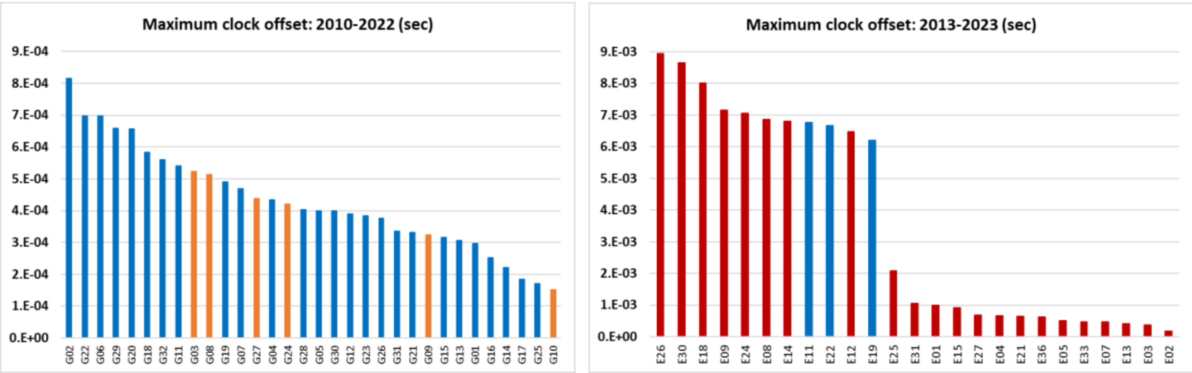

Fig. 9 Maximum clock offset (absolute value) observed within the examined time-period of GPS (left) and Galileo. satellites (right).

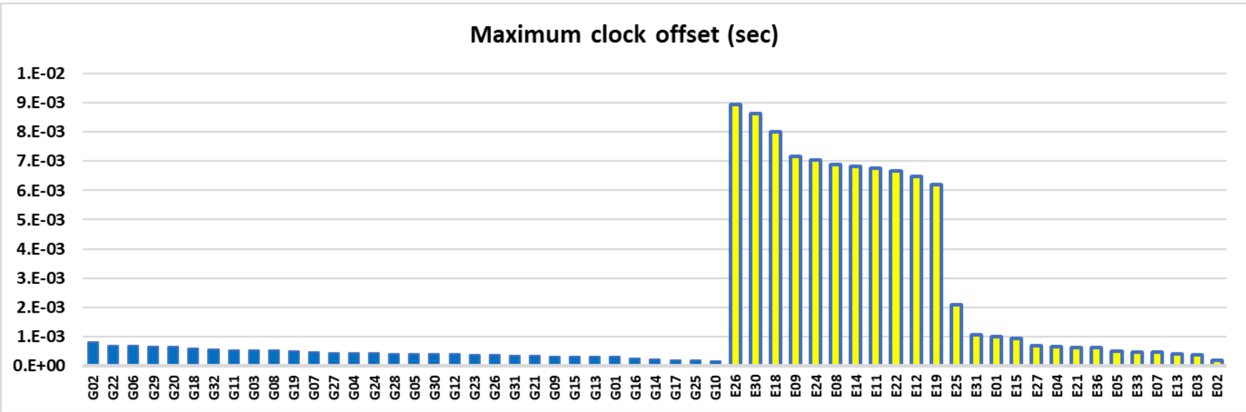

Fig. 10 Maximum clock offset (absolute value) observed within the examined time-period (common plot for GPS and Galileo satellites).

3.3 Satellite clock drift

The plots of the clock offsets given in section 3.2 revealed significant differences between the drift values of the AFSs of different satellites. In order to make a more detailed comparison of the drift values, we estimated the maximum drift exhibited by each satellite within the time-period under investigation. The results (absolute values) are summarized in Fig. 11.

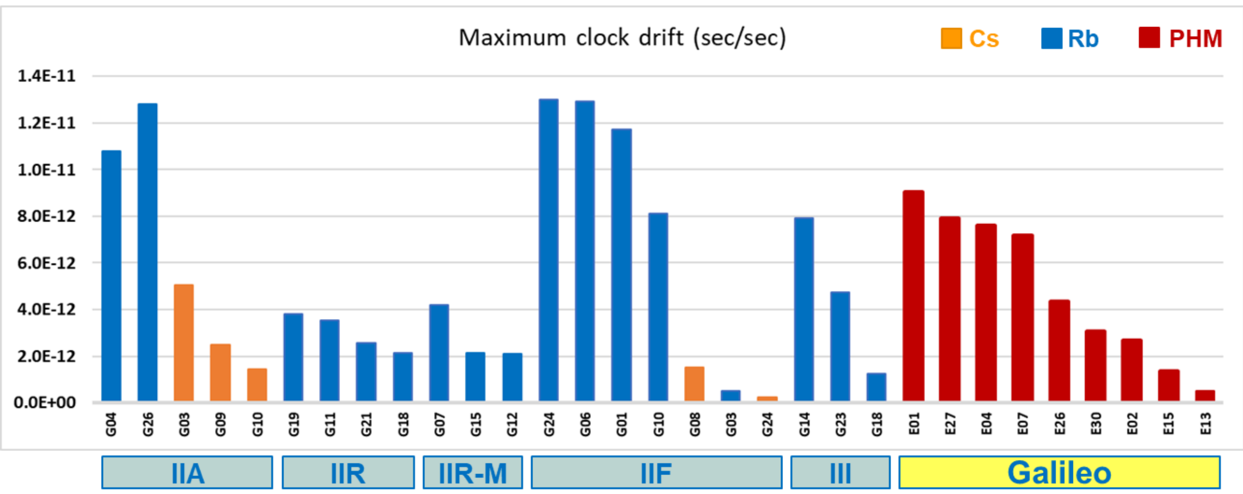

Fig. 11 Maximum drift (absolute value) observed within the examined time-period for the GPS (left) and Galileo satellites (right).

Some notable remarks on Fig. 11 are:

- the Cs AFSs show smaller drifts compared to the RAFSs, as expected
- among the RAFSs of the GPS satellites, those of Block IIR & IIR-M satellites exhibit the smallest drifts, having drifts close to that of Cs clocks
- the drift of the Galileo PHMs is comparable to that of the RAFSs of the GPS III satellites.

3.4 Short-term stability

The atomic clocks onboard GNSS satellites should exhibit good short-term stability and, thus, high predictability. In order to assess their short-term stability, we estimated the Allan deviation for different averaging times (τ) for each satellite under investigation. More precisely, we calculated the Allan deviation for the following averaging times: 30, 60, 120, 240, 480, 960, 1920, 3840 and 7680 sec. The results are depicted in Fig. 12. It can clearly be distinguished between two groups of AFSs: the upper one with bigger values (plotted in purple) and the lower one with smaller values (plotted in green). The upper group consists of the GPS Block IIA, IIR, IIR-M satellites, as well as the Block IIF satellites using Cs clocks. To the lower group belong the Galileo satellites and the GPS satellites of Block III and those of Block IIF that are running on RAFS. These results verify the good short-term stability of the Galileo's PHMs. It is also noteworthy that the RAFSs of the latest GPS blocks (IIF&III) have a short-term stability which is considerably improved comparing to the previous blocks and comparable to that of the Galileo's PHM.

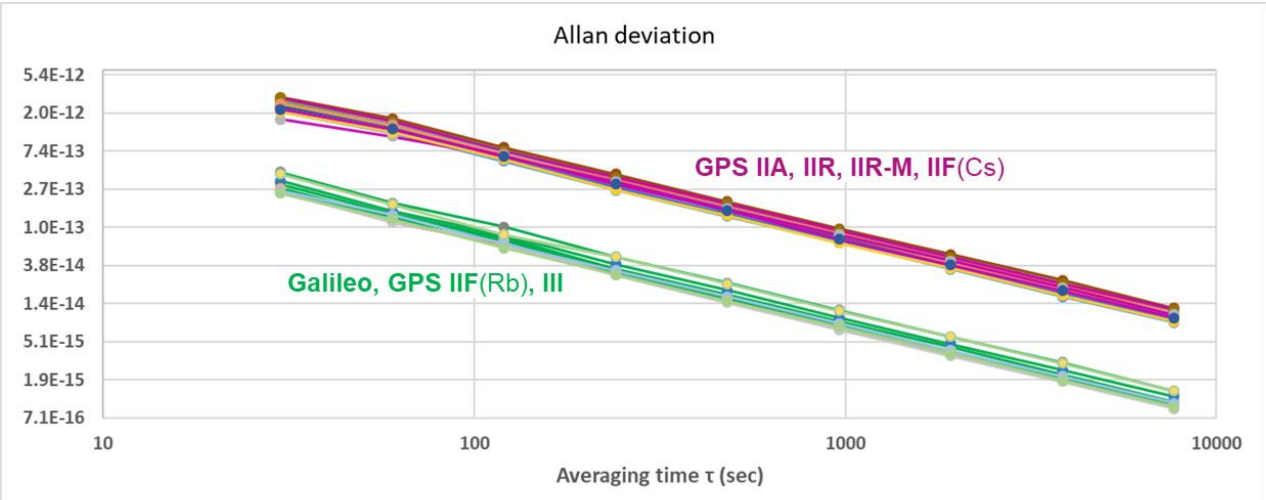

Fig. 12 Allan deviation for GPS and Galileo AFSs for different averaging times.

4. Discussion-Conclusions

Based on the data analysis of section 3.2 and the information summarized in Fig. 9-10, the clock offset (absolute value) of all investigated GPS satellites throughout the examined time period did not exceed $9 \cdot 10^{-4}$ sec. On the contrary, Galileo satellites reached values one order of magnitude higher. More specifically, values between $6 \cdot 10^{-3}$ sec and $9 \cdot 10^{-3}$ sec were observed for eleven Galileo satellites, regardless of the type of AFS being used to drive their navigation payload (RAFS or PHM). However, after 2020 such high clock offsets were not observed, as when the offset approaches ~1 msec it is set to zero.

The drift analysis (summarized in Fig. 11) revealed that the Cs clocks have the best long-term stability, not only compared to RAFS (which was expected) but also in comparison to the Galileo's

PHMs. Regarding the evolution in the drift of the GPS Rb clocks, it was shown that the RAFSs of the Blocks IIF/III satellites exhibit bigger drift than their predecessors of the Blocks IIR/IIR-M. This seemingly strange result is addressed in the next paragraph.

Regarding the short-term stability, the best performance was demonstrated by the PHMs of Galileo and the RAFS of GPS Blocks IIF/III satellites. These clocks showed Allan deviation one order of magnitude better than all other AFSs examined within this study. Thus, although the RAFSs of Blocks IIF/III satellites have worse drift than their predecessors of Block IIR/IIR-M, they are superior with respect to the short-term stability. This may be explained by the fact that the most important characteristic of an AFS used in a GNSS is not its long-term, but rather its short-term stability. So, one might assume that the main goal during the development of the new RAFSs was the improvement of the short-term rather than the long-term stability.

Future work on the performance of AFSs used in GNSS should include the RAFS and PHM of BDS-3 as well as more years of GPS III data. Finally, the impact of the clock performance on different positioning methods should be studied.

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