

# LONG-TERM PERFORMANCE ANALYSIS OF GIOVE CLOCKS

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## Abstract

*Passive Hydrogen Maser (PHM) and Rubidium Atomic Frequency Standard (RAFS) are the two baseline on-board clock technologies for Galileo, the European Global Navigation Satellite System (GNSS), which are currently being validated on-board two experimental spacecrafts, GIOVE-A and GIOVE-B. These two spacecraft are orbiting in a Galileo-representative orbit and transmit Galileo-representative signals that are tracked and collected by a network of evenly distributed sensor stations (the Galileo Experimental Sensor Stations). The collected observables (pseudo-range and carrier phase) are being processed by the GIOVE Processing Centre, providing, as one of its core products, the estimation of the phase offset between the on-board clock and a reference clock, chosen to be an Active Hydrogen Maser connected to one of the sensor stations.*

*RAFS technology has been operated in-orbit for almost 5 years on-board GIOVE-A and PHM technology for more than 2½ years on-board GIOVE-B. The data accumulated over this period have been analyzed together with the long-term performances of these on-board clocks. On GIOVE-B, it will be shown that the GIOVE estimation noise limits the actual characterization of the PHM stability. Over the medium term (12~24 hours), the performance of the on-board clock is affected by oscillations at the orbital period whose possible causes will be discussed. Over the long term (> 1 day), the PHM exhibits excellent frequency drift performances (below  $1 \times 10^{-15}$ /day). On GIOVE-A, it will be shown that the short-term stability of RAFS is not limited by the estimation noise and is below the specified limits ( $5 \times 10^{-12}/\text{SQRT}(\tau)$ ). Over the medium term, the stability is also affected by periodic oscillations at the orbital period that are mostly due to on-board thermal variations. Finally, over the long term, even if not always monotonic, the RAFS frequency drift is below the  $1 \times 10^{-13}$ /day level.*

## INTRODUCTION

The Galileo In-Orbit Validation Element (GIOVE) is one of the development steps in the ongoing implementation of Galileo, the European Global Navigation Satellite System (GNSS). The GIOVE Mission was initiated in 2003 and was aimed at satisfying a number of objectives, including the early validation of critical technologies in orbit and the validation of orbit determination and time

synchronization models and assumptions. The GIOVE Mission architecture consists of a space segment, including two satellites in Medium-Earth Orbit (GIOVE-A and GIOVE-B), and a ground segment that includes a network of evenly distributed sensor stations (the Galileo Experimental Sensor Stations), two ground stations for the control of GIOVE-A and GIOVE-B satellites, and a centralized processing center that collects, processes, and archives all mission data. Figure 1 below depicts the overview of the GIOVE Architecture; more information is available on the GIOVE website [1].

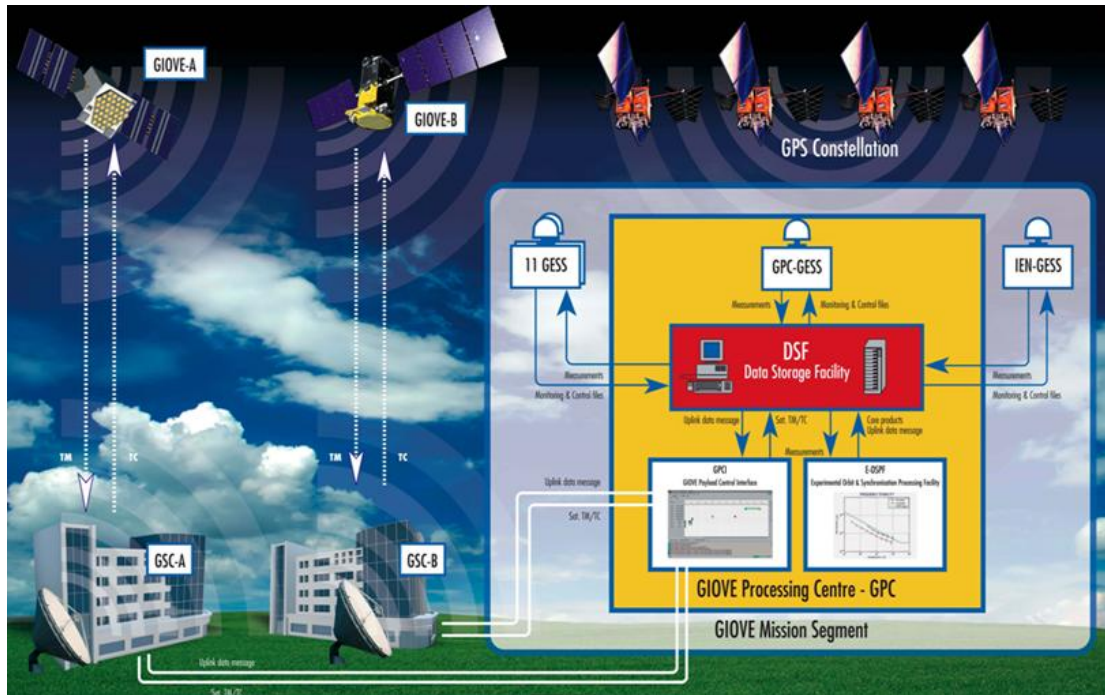


Figure 1. Overview of GIOVE mission architecture.

The GIOVE-A spacecraft was launched on 28 December 2005. Its payload includes most of the critical equipment of the final Galileo payload, in particular the Navigation Signal Generation Unit (NSGU), able to generate Galileo-representative signals (L1-Interplex, E6-Interplex and E5-AltBOC), as well as two Rubidium Atomic Frequency Standards (RAFS) operating in cold redundancy. The GIOVE-B spacecraft was launched on 25 August 2008; its payload is very similar to the one of GIOVE-A, with the capability to transmit also CBOC and TMBOC on the L1 carrier. In addition, it includes the first Passive Hydrogen Maser (PHM) operating in MEO orbit. Pictures of RAFS and PHM are presented in Figure 2 below.



Figure 2. RAFS (left) and PHM (right).

## GIOVE CLOCKS ESTIMATION

The in-orbit performance of the GIOVE clocks is being estimated based on the results of the Orbit Determination and Time Synchronization (ODTS) process, a geodetic network adjustment technique widely used in the community. Both GIOVE and GPS code and phase measurements collected by the network of Galileo Experimental Sensor Stations (GESS) are used. Under this process, the 1-sec undifferenced ionosphere-free code measurements are smoothed with the phase measurements. When available, measurements from Satellite Laser Ranging (SLR) stations are also included in the process. The network adjustment is performed in a batch mode (typically 5-day periods), based on a least-square adjustment method. The estimated parameters include orbit, clocks, troposphere, Solar Radiation Pressure (SRP) coefficients, etc. The estimated parameter of relevance for clock performance assessment is the snapshot estimation of the phase difference between the on-board clocks (as observed through the estimation process) and a specific reference time scale. In the GIOVE Mission, the reference time scale can be selected from any of the three GESS connected to an Active Hydrogen Maser (GIEN, GNOR connected to a free-running Maser, or GUSN connected to a steered maser).

In order to assess and quantify the limits of the on-board clock estimation process, the so-called “system noise” has been analyzed as follows. Over a typical period of observation, the estimation of the phase difference between a GESS connected to an Active Hydrogen Maser and the reference time scale has been analyzed. In Figure 3 below, the black line indicates the Allan deviation of this quantity from data measured during the month of January 2010. For comparison, the blue and red traces indicate the PHM and RAFS specifications respectively.

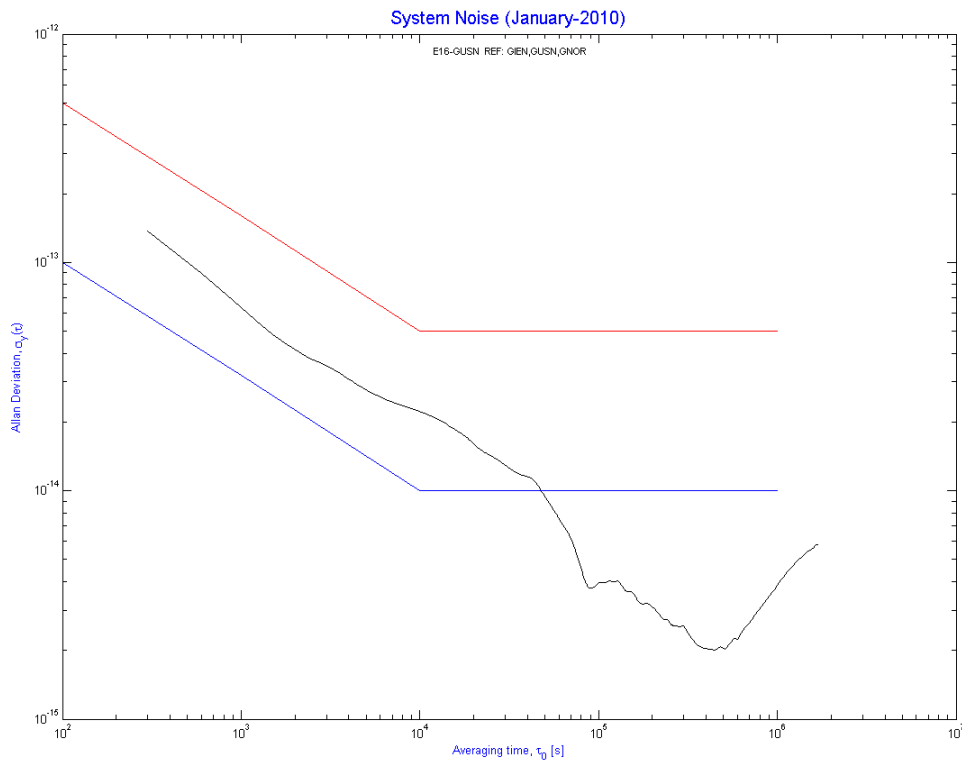


Figure 3. GIOVE system noise estimated over the period of January 2010 (black), PHM performance specifications (blue), and RAFS performance specifications (red).

This figure shows that, with the current GIOVE infrastructure and associated processes, the system noise is at least a factor two below the expected RAFS performances. As a result, the estimation of the latter is not expected to be limited by the system noise. For the PHM however, Figure 3 shows that the system noise is below the expected PHM performance only after integration beyond  $\sim 50000$  sec. The estimation of the PHM in orbit will, therefore, be limited by the system noise up to  $\sim 50000$  sec.

## GIOVE CLOCKS IN-ORBIT OPERATIONS

Shortly after the GIOVE-A and GIOVE-B launches, the on-board clocks have been switched on. In the course of their respective missions, they have been subject to a number of on-off cycles that have all been due to payload operation (e.g., change in signal transmission, change to redundant side, orbit rising, etc.). The characteristics of these switch-on sequences of both the RAFS on-board GIOVE-A and the PHM on-board GIOVE-B, as analyzed through the available telemetries, have all been extremely repetitive and similar to what is typically measured on units tested on the ground.

In addition, the analysis of on-board telemetries of both RAFS and PHM over the long term has shown that the operation of these clocks in-orbit is fully in line with the expectations and do not show any sign of unexpected degradation due to, e.g., the radiation environment. In addition, this analysis has shown that the long-term evolution of these telemetries is very similar to the ones collected from clock lifetests performed on ground [2,3].

The table below summarizes the operation of RAFS and PHM on-board GIOVE-A and GIOVE-B as of 31 October 2010.

Table 1. Overview of RAFS and PHM operation on-board GIOVE-A and GIOVE-B.

	GIOVE-A		GIOVE-B
	RAFS-A	RAFS-B	PHM
Cumulated operating time (days)	1269	286	870
Number of switch ON-OFF sequences	20	3	8

## RAFS PERFORMANCES ON-BOARD GIOVE-A

From the time series of the clock phase differences estimated by the ODTS process, the time series of the fractional frequency differences can be obtained. Figure 4 below plots this latter quantity for both RAFS-A and RAFS-B on-board GIOVE-A from the start of the GIOVE Mission until 31 October 2010. As already reported [4,5], the behavior of both RAFS follows an overall general trend after switch on, in line with the expectation, characterized by a large frequency drift that decreases and stabilizes progressively due to equilibration processes [6]. It must be also noted that the equilibration process appeared to be more stable for RAFS-B than for RAFS-A. This has been attributed to the fact that RAFS-A has been used extensively during tests of the GIOVE-A payload and satellite on ground, and has, therefore, been subject to a large number of switch on-off sequences under ambient pressure, which is expected to affect the equilibration process.

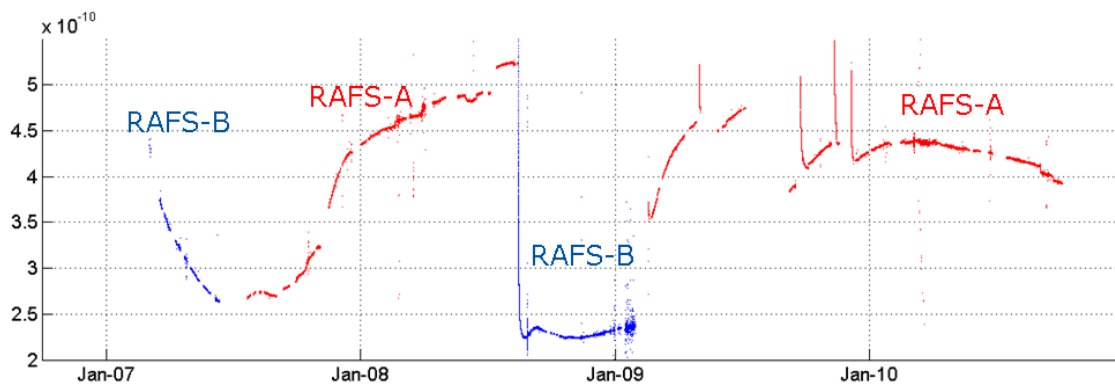


Figure 4. Fractional frequency offset of RAFS on-board GIOVE-A over the full GIOVE Mission (in red: RAFS-A; in blue: RAFS-B).

Figure 5 below presents a zoom of the RAFS-A fractional frequency offset, as measured during the month of August 2010. It shows a good linearity of the frequency drift of  $-7 \times 10^{-12}$  per month that is in line with the expectations for this type of RAFS. Further, and as already reported [5], the fractional frequency is also affected by a periodic oscillation that is directly related to on-board temperature variations. As an experimental spacecraft, GIOVE-A design has not been optimized to guarantee the optimum absolute temperature and its variation, which is clearly visible on this plot.

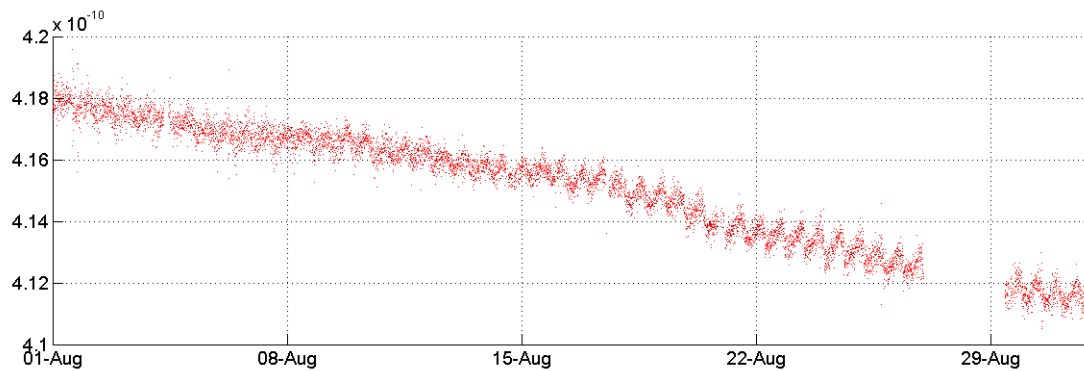


Figure 5. Fractional frequency offset of RAFS-A on-board GIOVE-A over August 2010.

## PHM PERFORMANCES ON-BOARD GIOVE-B

Similar long-term performance analyses have been performed with the PHM on-board GIOVE-B. The PHM in orbit has appeared to have an extremely low frequency drift and its long-term performance has, therefore, been analyzed when being referenced to a steered Active Hydrogen Maser (the one connected to the GUSN station). Figure 6 below shows the fractional frequency offset of the PHM on-board GIOVE-B as estimated by the ODTS (using GUSN as reference) from first switch-on until end October 2010. The various colors correspond to various periods of PHM operations after off-on sequences.

The overall general trend of the PHM is quite different from the one of the RAFS. First, its fractional frequency variation just after switch-on is extremely stable and does not show any sign of nonlinear equilibration processes. This is believed to be due to the intrinsic PHM technology that is less sensitive to long-term physical equilibration processes. Second, the frequency retrace between two subsequent off-on cycles is typically a few parts in  $10^{-12}$ , significantly below the RAFS values. This property had been identified during ground tests already and has allowed the verification of the relativistic frequency shift at the percent level [7]. It must be underlined that the absolute frequency offset as reported in Figure 6 is not fully in line with the expected relativistic frequency shift. On-board, the nominal frequency of the PHM (10 002 857.4060 Hz) is supposed to be translated to the nominal output frequency of 10 230 000.00 Hz using a high-resolution frequency synthesizer based on Direct Digital Synthesizer (DDS) technology. This DDS-based frequency translation has never been adjusted so far and is using the default value, resulting in an actual frequency offset of 4.09 mHz (corresponding to an additional phase drift of 3.45 sec/day). Finally, Figure 6 indicates that the linear drift of the PHM over the full analyzed period is extremely stable and extremely low, especially after the first 6 operating months (typically well below  $1 \times 10^{-15}$  per day).

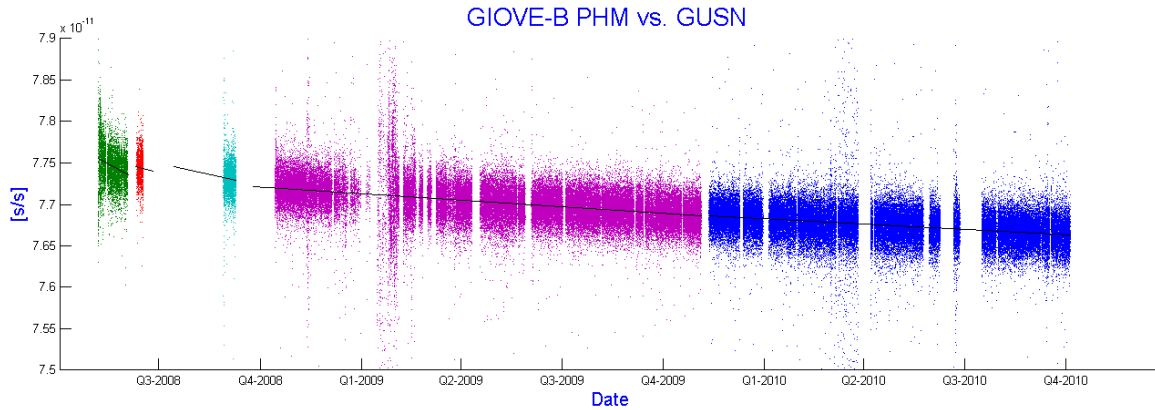


Figure 6. Fractional frequency offset of PHM on-board GIOVE-B from first switch on.

The PHM performances have also been analyzed in terms of Allan deviation, based on two different methods. The first one relies on the direct processing of the ODTS estimated phase offsets. As the ODTS provides a clock estimate every 5 min (300 sec) only, the ADEV cannot be estimated for integration time below this value. The second method is based on the direct processing of the One-Way Carrier Phase measurement (OWCP), and is detailed in [8]. Figure 7 below present the Allan deviation of the PHM on-board GIOVE-B, as estimated by these various methods over the month of January 2010.

This figure shows that as anticipated, the short-term stability of the PHM estimated by the ODTS is limited by the system noise at short term. Beyond ~3000 sec, the estimation is affected by a periodic oscillation at the orbital period. This effect has been reported to be due to a combination of on-board temperature effects and limitation in the orbital models, in particular relativistic models [9,10]. At long term (above 12 hours), the PHM stability as estimated by the ODTS is in line with the specifications. Over the very short term (1-10 sec), the OWCP method is limited by the receiver tracking noise and cannot assess the actual performances of the PHM. In the 10~200 sec interval, the OWCP method shows that the performance of the PHM on-board are almost identical to the one measured on the ground. Beyond this limit, the OWCP method is no longer valid for the estimation of ADEV.

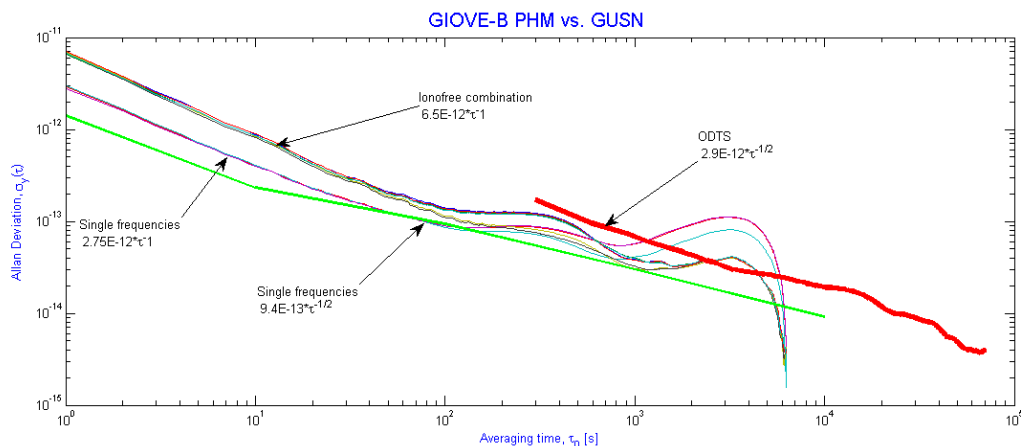


Figure 7. Allan deviation estimation of PHM on-board GIOVE-B.

## SUMMARY AND CONCLUSIONS

After more than 5 years and 2½ years in-orbit respectively, GIOVE-A and GIOVE-B have provided continuous and consistent results in terms of on-board clock operation and performance. Both RAFS and PHM have been operated continuously and do not show any sign of degradation, even after periods exceeding the original lifetime of the spacecraft. The short- and long-term stabilities of RAFS on-board GIOVE-A are fully meeting the requirements, while the medium-term stability is affected by on-board temperature variations, as expected. The long-term performance of the PHM on-board GIOVE-B is extremely stable, with a frequency drift well below  $1 \times 10^{-15}$  per day. Its short-term stability, as estimated by the One-Way Carrier-Phase method is also fully in line with the expectations. As indicated on Figure 8 below, depicting the Allan deviation of GIOVE and GPS clocks as estimated by the ODTs over the month of January 2010, both RAFS and PHM provide excellent performance in orbit.

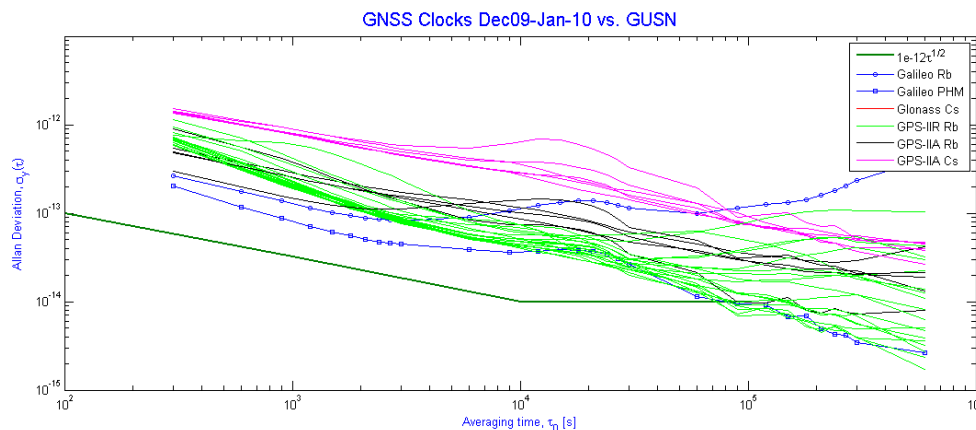


Figure 8. Allan deviation of PHM (GIOVE-B), RAFS (GIOVE-A), and GPS clocks as estimated by the ODTs over the month of January 2010.

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