# Update on the In-orbit Performances of GIOVE Clocks

*Pierre Waller, Francisco Gonzalez, Stefano Binda, ESA/ESTEC*
*Ilaria Sesia, Patrizia Tavella, INRiM*
*Irene Hidalgo, Guillermo Tobias, GMV*

*Abstract*— **The Galileo In-Orbit Validation Element (GIOVE) is an experiment led by the European Space Agency (ESA) aimed at supporting the on-going implementation of Galileo, the European Global Navigation Satellite System (GNSS). Among others, the objectives of the GIOVE Mission are the validation and characterization of the on-board clock technologies. The today baseline technologies for on-board clocks are the Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHM). Both technologies have been validated and qualified on ground and are now being further validated in a representative in-orbit environment on-board two spacecrafts, GIOVE-A and GIOVE-B. This paper presents the results obtained on both spacecrafts, after more than three years (GIOVE-A) and almost one year (GIOVE-B) of operation.**

## I. INTRODUCTION

In the preparation of Galileo, the European Global Navigation Satellite System (GNSS), the European Space Agency (ESA) has set-up the Galileo In-Orbit Validation Element (GIOVE) Mission, whose objectives are the filing of the L-band frequencies, the characterization of the Medium-Earth Orbit (MEO) environment, the early validation of navigation and integrity assumptions and algorithms, as well as the characterization and validation of the on-board clock technologies.

The development of on-board clock technologies was initiated by ESA in the late nineties and has resulted in the validation and qualification on-ground of two technologies.

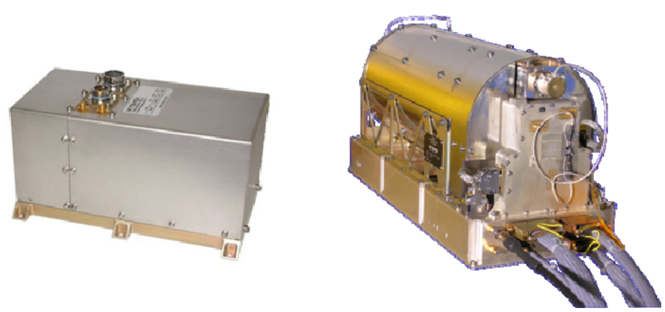

Figure 1. The two on-board clock technologies developped for Galileo (a) the Rubidium Atomic Frequency Standard (RAFS), (b) the Passive Hydrogen Maser (PHM)

First the Rubidium Atomic Frequency Standard (RAFS) technology – a vapour-cell with buffer gas atomic clock based on the double optical-microwave resonance – is an intrinsically compact and low power consumption atomic clock with short-term frequency stability (ADEV) better than $5x10^{-12}\tau^{-1/2}$ over one day of integration time. Second, the Passive Hydrogen Maser (PHM) – a low density vapour-cell atomic clock based on the stimulated amplification of microwave frequency (passive mode) – has demonstrated excellent frequency stability (factor 5 better than RAFS) at the expanses of mass and power consumption. Figure 1 shows a picture of both technologies.

It was one of the objectives of the GIOVE Mission to validate these two technologies in orbit. The GIOVE Mission includes two satellites orbiting at MEO altitude (~26000km) with an inclination of ~56°. GIOVE-A was launched on 28 December 2005 and embarks two RAFS (Flight Models FM4 and FM5) operating in cold redundancy. The GIOVE-B satellite was launched on 25 April 2008 and embarks the first PHM ever placed in MEO orbit as well as two RAFS (Flight Models PFM and FM1). In nominal GIOVE-B operation, the PHM is always on, while RAFS are operating in cold redundancy. Table 1 summarizes the salient features of GIOVE-A and GIOVE-B spacecrafts.

TABLE I. GIOVE SPACECRAFTS AND CLOCKS

| | GIOVE-A | GIOVE-B |
|---|---|---|
| mass/power | 600kg / 700W | 500kg / 760W |
| signals transmitted | E1 – E6 – E5 | E1 – E6 – E5 |
| on-board clocks | 2 RAFS | 1 PHM + 2 RAFS |
| launch date | 28 December 2005 | 25 April 2008 |
| status | original mission duration extended | nominal mission on-going |

## II. IN-ORBIT CLOCK PERFORMANCE ASSESSMENT METHODS AND VALIDATION

For the performance assessment of the GIOVE on-board clocks, a ground infrastructure – the GIOVE Ground Segment – was deployed. It consists first in the two Ground Stations controlling the two spacecrafts. GSC-A is located at Guildford (GB) and is controlling the GIOVE-A spacecraft while GSC-B is located at Fucino (I) and is in charge of controlling the GIOVE-B spacecraft. Both stations are responsible for the download of on-board telemetries during satellite visibility.

Further, a network of 13 Galileo Experimental Sensor Stations (GESSs) has been evenly deployed around the world. These stations are equipped with dual GPS/GIOVE receivers and are tracking both GIOVE and GPS observables (dual frequency pseudoranges and phases). Initially, two of these ground stations were connected to an Active Hydrogen Maser: GIEN located at INRiM (Torino, I) and GUSN located at USNO (Washington, USA). Since January 2009, the station GNOR located at ESTEC (Noordwijk, NL) is also connected to an Active Hydrogen Maser. The station located at INRiM provides the nominal reference timescale of the GIOVE Mission. Finally, the GIOVE Ground Segment is completed by a centralised processing centre located at ESTEC (Noordwijk, NL) in charge of collecting and archiving both the on-board telemetry data and the GESS observables data. In addition, the GIOVE Processing Centre is responsible for the execution of the Orbit Determination and Time Synchronisation (ODTS) processes. Figure 2 depicts an overview of the whole GIOVE Mission architecture.

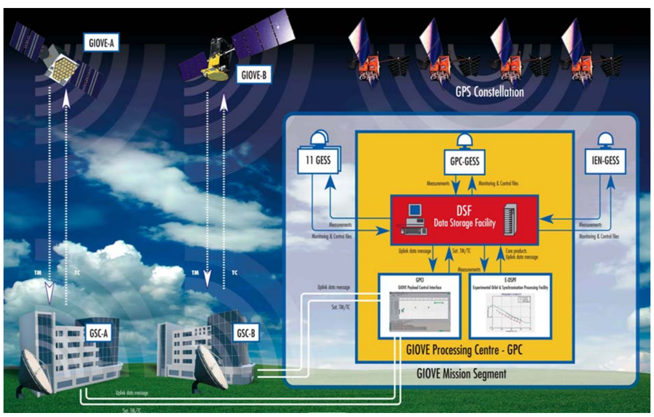


Figure 2. The GIOVE Mission Architecture

The performance assessment of the GIOVE on-board clocks is ultimately provided by the ODTS process. Using the iono-free combination of GIOVE and GPS observables, this least-square batch process solves the satellite orbit parameters, the Solar Radiation Pressure parameters, and provides, at each epoch, an independent estimate of the difference in phase between the on-board clock and the ground reference timescale provided by the GESS located at INRiM. This is this last estimation and its evolution over time that is called the in-orbit performance of the GIOVE clocks and that will be reported in this paper.

It is important to underline that a direct comparison between this estimation (sometimes called "apparent clock") and measurement of the same clock on ground is delicate as the ODTS method is affected by a number of limitations whose contribution to the end results is difficult to estimate. These limitations include on-board phase stability, receiver noise, possible orbital residuals… The combined effects of these limitations in the GIOVE infrastructure (called the "GIOVE System Noise"), has been estimated and shall be considered as the lower limit under which no on-board clock estimation is possible. Taking advantage of the fact that at least two GESS are connected to an Active Hydrogen Maser (nominally GUSN and GIEN), the System Noise is defined as the ODTS estimation of the phase difference between these two stations. Figure 3 provides an example of this estimation (converted into fractional frequency offset).

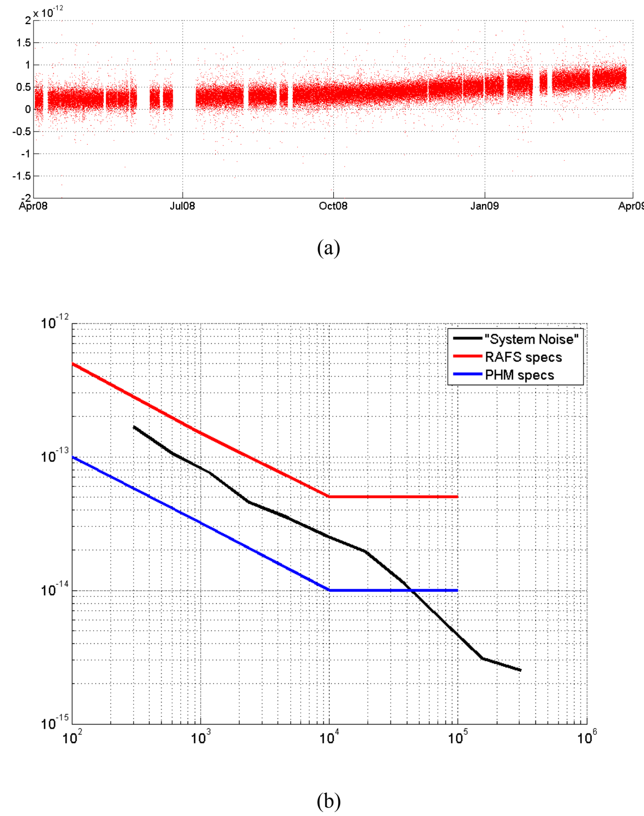


Figure 3. GIOVE System Noise estimation (a): fractional frequency offset over the period Apr 08 – Apr 09, (b): Allan Deviation computed over the last month of data, together with the ground specifications for PHM and RAFS.

Figure 3 shows first that the level of the System Noise is very consistent over time and does not vary significantly. Furthermore, it shows that the level of System Noise is at least a factor two below the ground specifications for the RAFS over the whole integration period of interest. Yet it also shows that the System Noise is well above the PHM ground specifications until at least 45000sec. This indicates that in order to validate the in-orbit performance of the PHM, one will have to integrate until at least 45000sec to be above the system noise. While this is clearly identified as a limitation of the GIOVE infrastructure, it shall be underlined that this level of System Noise is very close to what IGS provides, which is considered as the state-of-the-art.

## III. RAFS ON-BOARD GIOVE-A

Over the first year of GIOVE-A in-orbit, both on-board RAFS have been operated and subject to a number of on-off sequences due to platform and payload commissioning, test and validation. Over the same period, the GIOVE Ground Segment was not yet operational and no on-board clock performance assessment was therefore possible. Over the remaining ~2.5 years of operation, both on-board RAFS have been sequentially used and characterized over continuous periods of up to 428 days. During all these operations, all

RAFS telemetries have been fully nominal. Table 2 provides a summary of GIOVE-A on-board clock operation as of 31st of March 2009.

TABLE II. GIOVE-A ON-BOARD CLOCK OPERATIONS

| | RAFS-A | RAFS-B |
|---|---|---|
| # on-off sequences | 14 | 3 |
| accumulated operation | 747 days | 285 days |
| longest operation period | 428 days | 179 days |

Figure 4 shows an overview of the operation and estimated fractional frequency offset of both RAFS on-board GIOVE-A over the whole mission until 31st of March 2009. It shows that RAFS-A has been operated continuously for most of the time, and in particular its performance has been estimated continuously over more than one year. RAFS-B has first been operated and estimated over about three months in 2007, and then over six months end 2008 – beginning 2009.

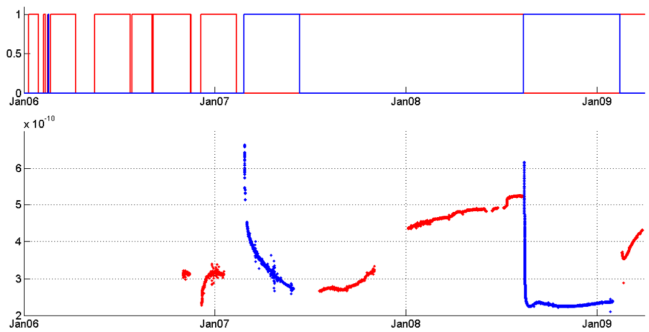


Figure 4. Operation and Performance (Estimated Fractional Frequency Offset) of both RAFS on-board GIOVE-A (red: RAFS-A, blue; RAFS-B).

Figure 5 shows the estimated fractional frequency offset of RAFS-A on-board GIOVE-A over its longest operation period. It shows a clear trend towards the stabilization of the long-term drift (below $2x10^{-13}$ per day). Yet, it also shows that over shorter time frame, the variation of the drift does not always follow a smooth and monotonous trend and is affected by sudden abrupt frequency changes. In addition, as indicated in the zoom depicted in Figure 6, the estimated fractional frequency offset is affected by a periodic oscillation with a period equal to the orbital period. This second behavior is clearly explained by the fact that the clock is operating outside its nominal temperature range and that the temperature variation over one orbit is also larger than what was expected. This was a known and identified limitation of the GIOVE-A platform. The first behavior is a little bit more surprising. It is currently explained by a combination of various factors including some design limitations, the high temperature operation, the large number of on-off sequences both on-board and on-ground during satellite integration tests. Finally Figure 7 shows a typical Allan Deviation on drift-removed data. It shows that the short-term frequency stability is at the expected level while at longer integration intervals, the oscillation in the ADEV reflects the oscillation at the orbital period due to temperature sensitivity. Also reported on this plot is the level of System Noise estimated over this particular period, which is well below the data of interest.

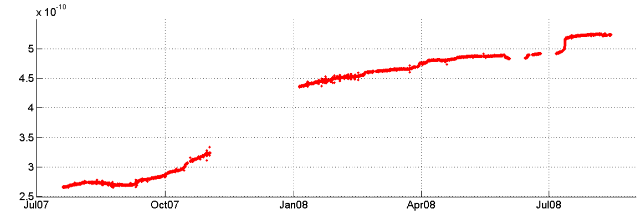


Figure 5. Estimated Fractional Frequency Offset of RAFS-A on-board GIOVE-A over its longest continuous operation period.

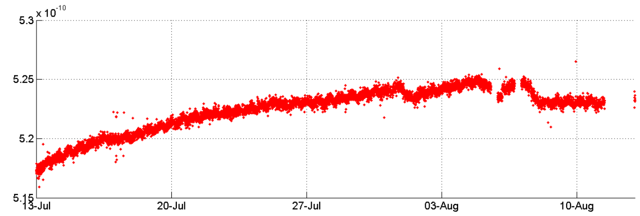


Figure 6. Estimated Fractional Frequency Offset of RAFS-A on-board GIOVE-A (zoom)

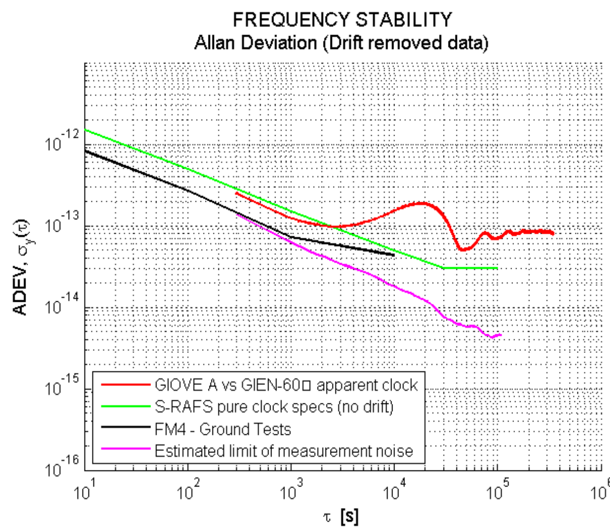


Figure 7. Typical Allan Deviation of estimated RAFS-A on-board GIOVE-A

Figure 8 presents the estimated fractional frequency offset of RAFS-B on-board GIOVE-A over its longest operation period. It follows a typical long-term trend with a frequency drift stabilizing below $2x10^{-13}$ per day shortly after switch-on. On the zoom provided in Figure 9, it is noticeable that here again, the estimated fractional frequency offset is affected by an oscillation at the orbital period, with amplitude similar to what was obtained with RAFS-A. This behavior is also explained by high frequency sensitivity to temperature due to operation outside the nominal temperature range. The long term behavior of RAFS-B is clearly smoother and more monotonous than the one of RAFS-A. This can be explained by various reasons, in particular by the fact that this unit has undergone less stress during operation in-orbit (less number of on-off sequences) but also during tests on ground. Finally Figure 10 presents a typical Allan Deviation for RAFS-B on drift-removed data. Here, comments to RAFS-A results are also applicable to RAFS-B.

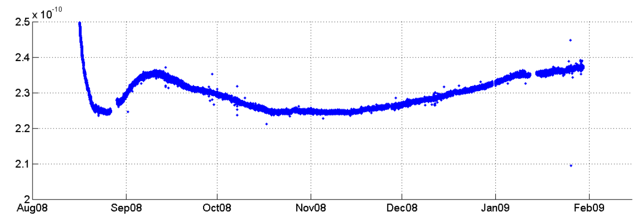


Figure 8. Estimated Fractional Frequency Offset of RAFS-B on-board GIOVE-A over its longest operation period.

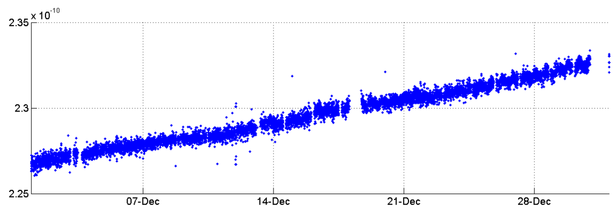


Figure 9. Estimated Fractional Frequency Offset of RAFS-B on-board GIOVE-A (zoom).

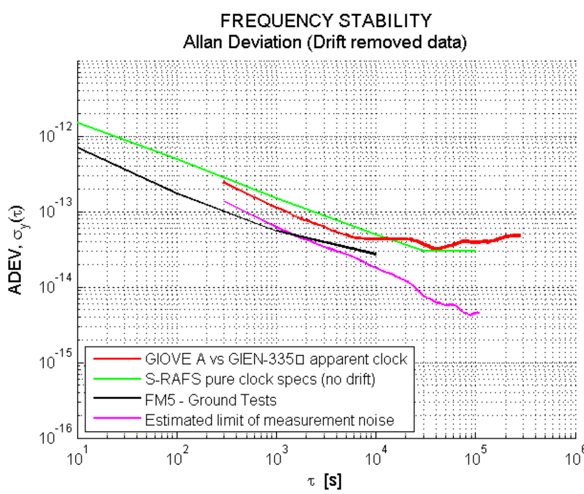


Figure 10. Typical Allan Deviation of estimated RAFS-B on-board GIOVE-A

In a GNSS context, it is also instructive to assess the estimated performance of the on-board clocks in terms of prediction error. In such systems, on-board clocks are estimated over a given period and the parameters of a given clock model are derived (usually quadratic model in phase). This model is then extrapolated over a given prediction interval. One can assess the prediction error my evaluating, over a given prediction interval, the difference between the extrapolated model and the estimated clock. This exercise has been performed with all GIOVE-A data (combined RAFS-A and RAFS-B) and is summarized in Table III for various prediction intervals.

TABLE III. GIOVE-A (RAFS) PREDICTION ERROR

| **prediction interval** | **prediction error (1σ)** |
|---|---|
| 10 min | 0.3 nsec |
| 100 min | 1.3 nsec |
| 1 day | 33 nsec |

Table III shows that for the today nominal prediction interval of the Galileo System (100min), the clock prediction error is 1.3nsec (1σ). This is below the Galileo specifications assuming equal contribution of orbit and clock errors into the user range error. At one day, the clock prediction error is clearly affected by the inability of the current clock model to "follow" the periodic oscillations due to frequency sensitivity to temperature.

## IV. PHM ON-BOARD GIOVE-B

Shortly after the launch of GIOVE-B, the PHM was switched on and subsequently underwent several on-off sequences that all appear to be perfectly nominal. As of 31st of March 2009, the PHM has accumulated almost 300 days of operation and a longest operating period of 189 days. Table IV summarizes the operation of PHM on-board GIOVE-B.

TABLE IV. PHM OPERATION ON-BOARD GIOVE-B

| | **PHM** |
|---|---|
| # on-off sequences | 4 |
| accumulated operation | 298 days |
| longest operation period | 189 days |

As soon as the first GIOVE-B signals were transmitted, the GIOVE Ground Segment described in section II was able to track and record relevant observables and to run the ODTS process with GIOVE-B data. This is illustrated in Figure 11 which depicts the operation and estimated fractional frequency offset of PHM on-board GIOVE-B over the full mission until end of March 2009.

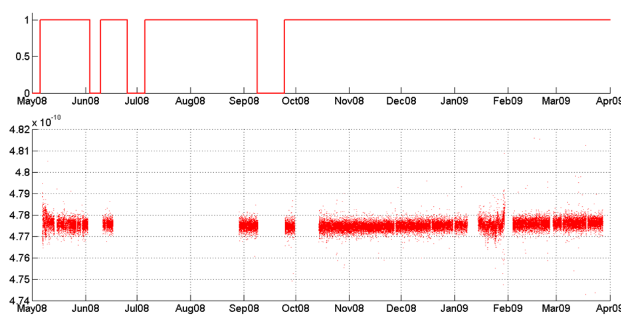


Figure 11. Operation and Performance (Estimated Fractional Frequency Offset) of PHM on-board GIOVE-B.

Figure 11 shows that for most of the time the estimated PHM fractional frequency offset has an extremely flat behavior, with a frequency drift that is well below $5 \times 10^{-15}$ per day almost immediately after switch-on. During the very first week of operation (May 2008), one can notice a slightly higher level of noise which corresponds to the GIOVE-B In-Orbit Test campaign during which the signal configuration was changed intermittently. A similar increase in noise is evident during the second half of January 2009 which corresponds to a change in the signal configuration from E1-E5 to E1-E6. Apart from that, and as depicted in Figure 12, the estimated PHM fractional frequency offset is affected by a periodic oscillation at orbital period, with an amplitude significantly below the one observed on GIOVE-A. On-board GIOVE-B, the PHM operates well within its nominal temperature range and the temperature at PHM location is extremely stable. Similarly, the magnetic field variation at PHM location cannot explain such behavior. It is therefore assumed that this oscillation does not come from the PHM itself but rather from a combination of on-board phase stability and orbital residuals.

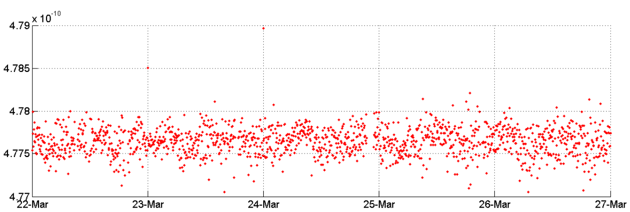


Figure 12. Estimated Fractional Frequency Offset of PHM on-board GIOVE-B (zoom)

Finally Figure 13 reports a typical Allan Deviation computed on the estimated PHM fractional frequency offset after removal of linear frequency drift. Also depicted in this plot is the level of System Noise estimated over the same period. This plot clearly shows that as anticipated, the estimation of PHM on-board GIOVE-B is limited over the short-term by the System Noise. At higher integration time, the oscillation in the Allan Deviation illustrates the oscillation at the orbital period. It is remarkable to notice that the Allan Deviation reaches a few $10^{-15}$ after few days of integration.

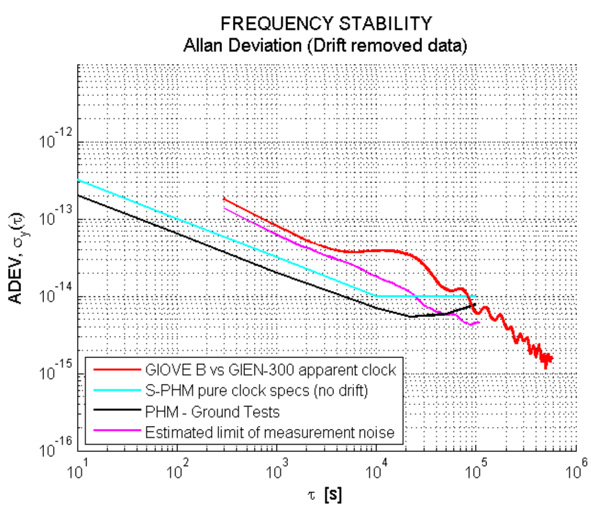


Figure 13. Typical Allan Deviation of estimated PHM on-board GIOVE-B

As for RAFS on-board GIOVE-A, the PHM prediction error has also been computed for GIOVE-B and is sumarized in table V. In this case, the prediction error at 10min and 100min is clearly limited by the System Noise while at 1day, it is limited by the effects of the periodic oscillation.

TABLE V. GIOVE-B (PHM) PREDICTION ERROR

| **prediction interval** | **prediction error (1σ)** |
|---|---|
| 10 min | 0.27 nsec |
| 100 min | 0.27 nsec |
| 1 day | 1.2 nsec |

## V. SUMMARY AND CONCLUSIONS

After almost 3.5 and 1 year respectively, GIOVE-A and GIOVE-B spacecrafts together with their associated Ground Segment have allowed an extensive characterization of their on-board clocks. Both RAFS on-board GIOVE-A and PHM on-board GIOVE-B have demonstrated excellent performances in terms of Allan Deviation (as depicted in Figure 14). Furthermore they have shown that with the nominal prediction interval, they meet the current Galileo specifications, with significant margins for the PHM. Some limitations have been identified for the RAFS and corrective actions have already been injected into the next steps of the programme. The GIOVE Mission has appeared to be an excellent basis for the on-going implementation of the Galileo Programme.

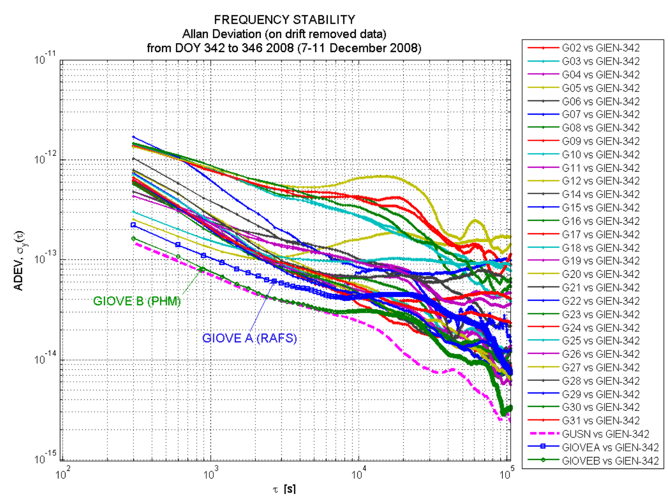


Figure 14. ODTS estimation of Allan Deviation for GIOVE-A (RAFS), GIOVE-B (PHM), and GPS satellites (in pink: System Noise estimation)