IN-ORBIT PERFORMANCE ASSESSMENT OF GIOVE CLOCKS

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Abstract

Two onboard atomic clock technologies have been developed for the Galileo system, one based on vapor cell rubidium technology (RAFS: Rubidium Atomic Frequency Standard) and one based on passive hydrogen maser (PHM) technology. In the years 2004-2005, both technologies have successfully passed a full qualification campaign (including shock, vibration, thermal vacuum, …) aimed at verifying their performance in a Galileo-like environment. In the year 2005, six RAFS and two PHM flight models have been delivered to ESA in order to be installed on two experimental satellites: GIOVE-A (launched on 27 December 2005) embarks two RAFS in a redundant scheme and GIOVE-B (launched on 26 April 2008) embarks two RAFS in a redundant scheme and one PHM.

The clocks onboard both GIOVE-A and GIOVE-B have been monitored on a continuous basis through the GIOVE Mission infrastructure. It includes two Ground Satellite Control Stations (one for each satellite) collecting and archiving onboard telemetries, and a network of 13 Galileo Experimental Sensor Stations (GESS) distributed worldwide that collect both GIOVE and GPS observables (pseudorange and carrier phase). One of these Ground Sensor Stations (located at INRiM, Turin, Italy) is connected to an active hydrogen maser that realizes the reference timescale for the GIOVE Mission. The Galileo Processing Centre located at ESA-ESTEC, Noordwijk centralizes all these data which are then processed through the Orbit Determination and Time Synchronisation (OD&TS) algorithms, allowing the restitution of the phase difference between the transmitted clock signal and the ground reference.

This paper presents the performance assessment of GIOVE-A and GIOVE-B clocks, based on the analysis of the clock behavior as restituted by the ODTS algorithms and GIOVE Mission infrastructure. The very first results of the PHM behavior onboard GIOVE-B are reported and show excellent performances over the analyzed period. It is demonstrated in particular that the PHM frequency stability is the best of all clocks currently in orbit. An update of the behavior of RAFS onboard GIOVE-A is presented as well and also demonstrates excellent performances.

INTRODUCTION

Early in the development of Galileo, the European Global Navigation Satellite System, the decision was made to develop two onboard clock technologies. This solution was dictated by the need to insure a sufficient degree of reliability through technology diversity and to comply with the 12-year lifetime requirements. The first onboard clock is based on vapor-cell rubidium technology (RAFS: Rubidium Atomic Frequency Standard), while the second one is based on passive hydrogen maser (PHM) technology.

Both RAFS and PHM technology developments for Galileo started in the late nineties and were successfully qualified on ground in 2003. This ground qualification consisted in the test of several units in a representative environment and included vibration tests, shock tests, EMC tests, thermal vacuum tests, and radiation tests **[1]**. In addition, a number of units were put on lifetest to identify possible long-term degradation. In 2005, six Flight Models of RAFS and two Flight Models of PHM were delivered to the European Space Agency (ESA). Figures 1 and 2 present a picture of the RAFS and PHM flight models.

Figure 1. RAFS flight model.

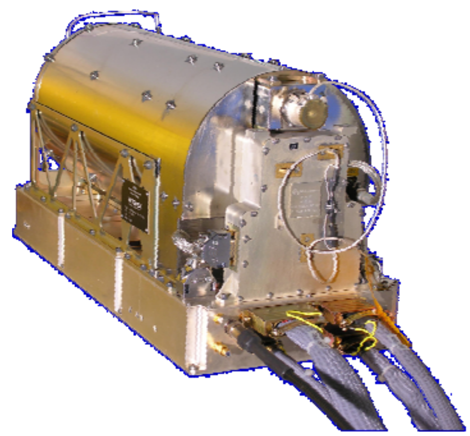

Figure 2. PHM flight model.

In parallel, ESA started in 2002 the development of an experimental Galileo Test-Bed aimed at validating the architecture and algorithms of the Galileo Ground Mission Segment. This system test-bed was based on experimental processing facilities and making use of measurements collected by a network of dedicated GPS stations. It resulted in 2003 in the successful validation of the Galileo Orbit Determination and Time Synchronisation (ODTS) algorithms as well as Integrity algorithms. Furthermore, it allowed the preliminary assessment of Galileo performances **[2]**.

The next step in the development and validation of Galileo was the start in 2003 of GIOVE, the Galileo In-Orbit Validation Element. The main objectives of GIOVE were related to Signal-in-Space occupation and validation, the monitoring of Galileo in-orbit environment, and the validation and characterization of onboard clock technologies.

The overall GIOVE architecture is depicted in Figure 3. The GIOVE space segment consists of two dedicated experimental spacecrafts, GIOVE-A and GIOVE-B, in a Galileo-representative orbit and is complemented by the GPS satellites constellation. GIOVE-A spacecraft was launched on 27 December 2005 and its payload includes two RAFS (FM4 and FM5) in a cold redundant configuration **[3]**. The GIOVE-B spacecraft was launched on 26 April 2008 and its payload includes one PHM (FS) and two RAFS (PFM and FM1) in a hot redundancy scheme **[4]**. Both satellites can transmit two of the three Galileo frequencies at a time (E1 + E5 or E1 + E6). While both satellites are able to transmit E1-Interplex, E6-Interplex, and E5-AltBOC modulations, GIOVE-B is also able to transmit E1-CBOC and E1-TMBOC modulations. Both satellites also include onboard radiation monitors and laser retro-reflectors.

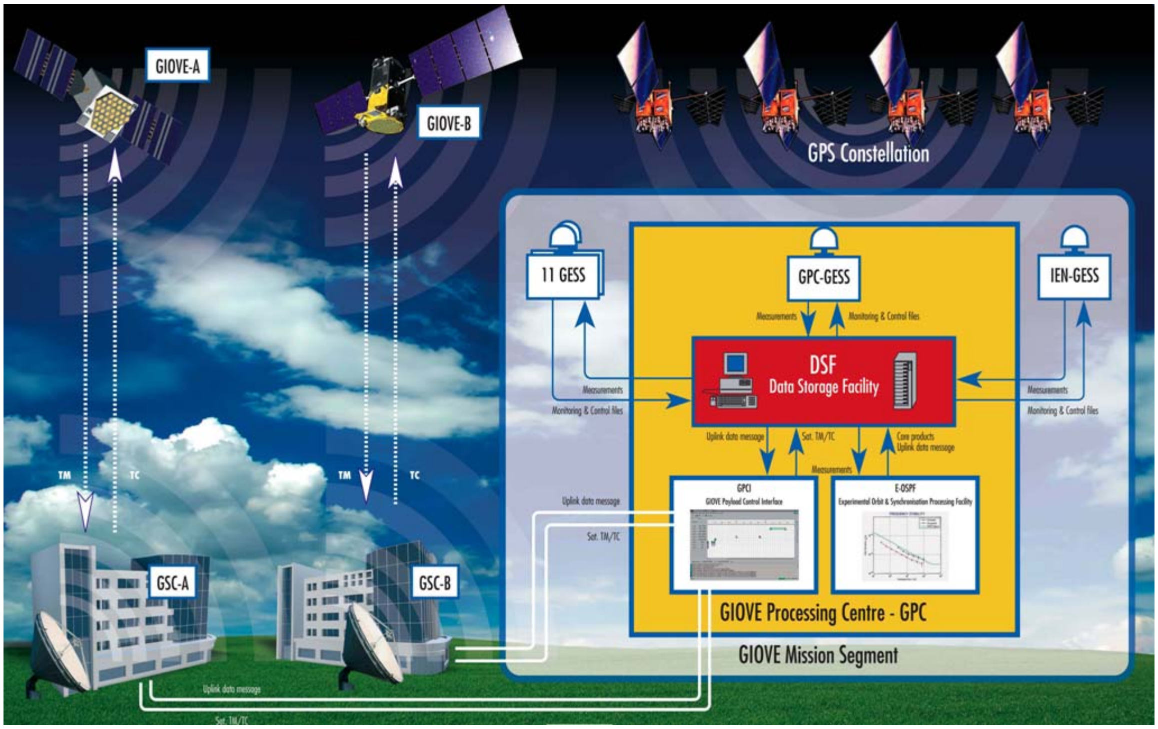

Figure 3. GIOVE overall architecture.

The GIOVE ground segment is divided into a Ground Control Segment and a Ground Mission Segment. The GIOVE Ground Control Segment includes the GIOVE-A Control Centre located at Guildford, UK and the GIOVE-B Control Centre located at Fucino, Italy. Both control centers are responsible for spacecraft control and operation through dedicated S-band telecommand and telemetry links. The GIOVE Mission Segment includes a network of 13 Galileo Experimental Sensor Stations (GESS) distributed worldwide and collecting both GIOVE and GPS pseudoranges and carrier-phase observables at a 1 s interval. One GESS located in Torino, Italy, is connected to an active hydrogen maser and realizes the primary reference timescale for the GIOVE mission. A second GESS located in Washington, USA, is also connected to an active hydrogen maser and provides a backup.

All data recorded at the GESS stations and Control Centres are collected by the Galileo Processing Centre (GPC) located in Noordwijk, The Netherlands **[5]**. The first function of the GPC is to collect, archive, and make available to trusted users GESS data and spacecraft telemetry data. It also interfaces with external service suppliers like the International Laser Ranging System (ILRS). The second function is to operate and run the Orbit Determination and Time Synchronisation processes which estimate the orbit and clock of both GIOVE and GPS satellites **[6]**.

This paper presents the performance assessment of the clocks onboard GIOVE-A and GIOVE-B as estimated by the GIOVE infrastructure.

PERFORMANCE ASSESSMENT METHODS

The principal method used to evaluate the performance of the GIOVE onboard clocks is based on high accuracy geodetic techniques using dual-frequency carrier-phase observables and is schematically described in Figure 4. The so-called Orbit Determination and Time Synchronisation (ODTS) process is a batch least-squares algorithm that processes iono-free GIOVE and GPS code and phase combinations, that can be complemented by SLR measurements, when available. The 1-second code measurements are smoothed with phase using a Hatch filter. The ODTS solves for orbits, clocks, troposphere, and the so-called station inter-system bias **[6]**. The phase offset between the reference and all clocks in the network (onboard and all station clocks) is estimated continuously at 5-minute intervals.

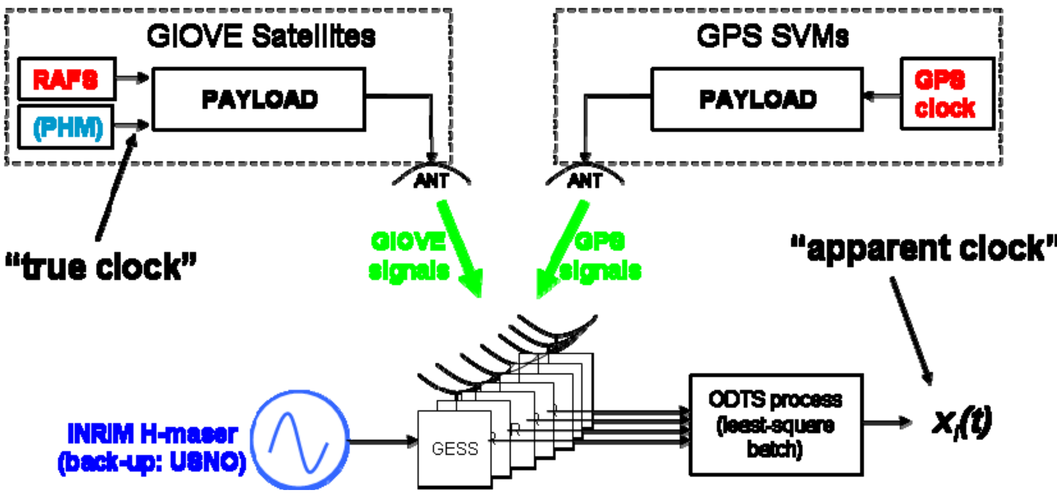

Figure 4. Performance assessment method.

One of the outputs of the ODTS process is, therefore, an estimation of the phase difference between the onboard clock and the ground reference timescale, as seen through the whole measurement system. It is important to note that this estimated clock (called "apparent clock") is different from the actual onboard clock (called "true clock") as it is affected by the noise of the measurement system. There are various possible causes for such system noise (e.g., variation of payload delays, imperfect orbital modelling, receiver noise, …) and in order to properly characterize the onboard clock, its level shall be carefully assessed.

Two techniques have been used to evaluate the level of the GIOVE system noise. Under the valid assumption that the two active hydrogen masers connected to the GIOVE network have very similar noise performances, these techniques are based on the analysis of the phase difference between these two stations. In the first technique, the analysis is based on the phase difference directly estimated by the ODTS process. The second technique makes use of an alternative time transfer method based on the NRCan Precise Point Positioning (PPP), using GPS observables collected by the GIOVE network **[7]**.

Figure 5 presents typical results of the GIOVE System Noise assessment, as estimated over the period 19 June 2008 to 23 June 2008. The plot on the left shows the phase offset between the two stations connected to an active hydrogen maser (GIEN and GUSN) as estimated by both ODTS and PPP techniques (linear trend removed). The plot on the right shows the corresponding overlapping Allan deviation. For reference, the dashed black curve on the right plot represents the specifications of the onboard PHM.

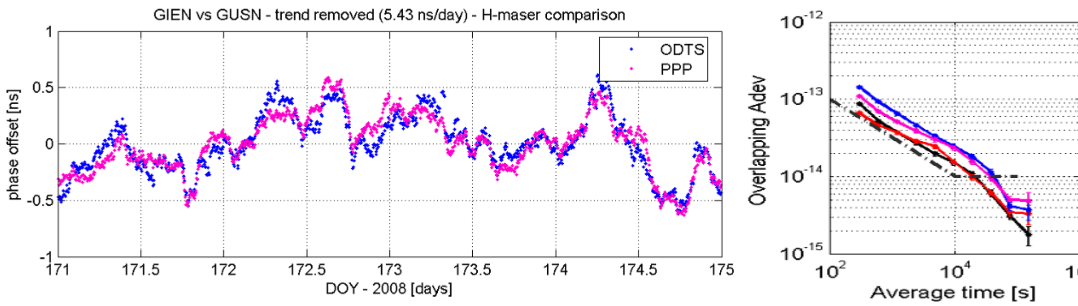

Figure 5. GIOVE system noise assessment.

These plots show that both techniques provide very similar results in the assessment of GIOVE system noise. Furthermore, it is shown that the level of GIOVE system noise is well below the specifications of the onboard RAFS; however, it is slightly above the ones of the PHM. It can, therefore, already be concluded that the noise of the GIOVE measurement system will most probably affect the estimation of the onboard PHM.

The current GIOVE system noise level is expected to be mainly limited by the relatively low number of sensor stations (13). It has to be noted, however, that with a typical value of ~0.5 ns (as indicated on Figure 5), the level of the GIOVE system noise is not significantly higher than the state of the art (IGS) with its 300+ stations.

As a complement to the ODTS process, an alternative technique that is less sensitive to system noise has been developed and used to further assess the performance of the onboard clocks, in particular over the short term. This technique is based on the analysis of phase offset between the onboard generated carrier-phase and an ultra-stable reference on ground **[8]**. This technique is, however, limited to the few periods during which the GIOVE satellites are in visibility of stations equipped with active hydrogen masers (GIEN and GUSN) and when the satellite is at a sufficiently high elevation so that the orbital and other errors are negligible. Practically, this limits the typical observation interval of analysis to 200 ~ 300 s.

RESULTS

This section presents the results of the GIOVE onboard clock performance assessment based on the GIOVE measurement system and techniques described in the previous section. The data available are the estimated phase offsets between the onboard clock and ground reference. The availability of data is obviously subject to ground network availability (in particular the GIEN reference station), as well as spacecraft transmission.

GIOVE-B Results (PHM)

The GIOVE-B Spacecraft was launched on 26 April 2008. After final orbit injection and platform commissioning, the PHM and the payload were switched on 5 May 2008. After a successful and fully nominal PHM switch-on sequence, the rest of the payload was progressively switched on and the first signal were transmitted on 7 May 2008 at 00:04:56 UTC. As soon as the first signals reached nominal power, the GESS network started to track and record GIOVE-B data. As a result, the ODTS was able to generate PHM estimates almost immediately after its switch-on.

Figure 6 presents the fractional frequency offset between the onboard PHM and the ground reference as estimated by ODTS over the first 1.5 month of operation. This corresponds to the in-orbit test period, during which all possible payload and platform configurations were tested. As indicated on the figure, the PHM was switched off during about 9 days during these operations and, therefore, was subjected to a second switch-on sequence that has also been fully nominal.

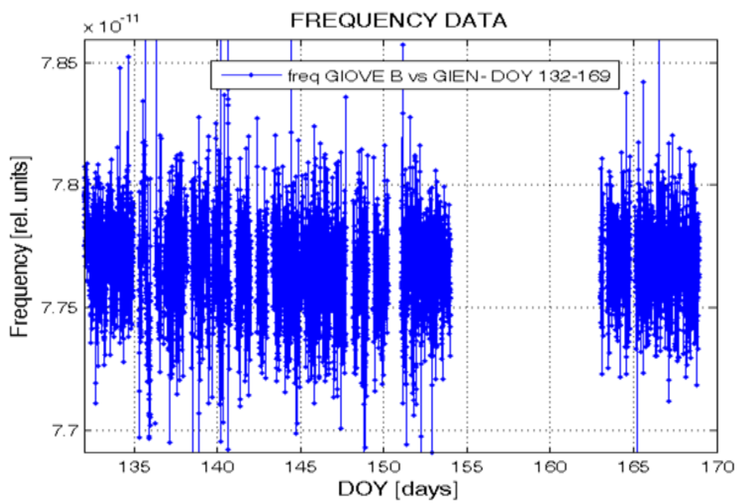

Figure 6. GIOVE-B (PHM) estimated fractional frequency offset.

Figure 6 shows that the estimated absolute fractional frequency offset is $+7.77\times10^{-11}$. This has been demonstrated to be fully in line with the combined effects of ground frequency calibration, initial PHM accuracy, and the expected relativistic frequency shift. It should be noted that the data reported in Figure 6 are the raw data, without any removal of linear trend. Averaged over the first 20 days of operation, the linear fractional frequency drift of the PHM is estimated to be below 10^{-14}/day, which is in line with the specifications. In addition to this very low fractional frequency drift, it shall be noted that the PHM is not affected by the effects of drift stabilization that are usually noticed on vapor-cell (rubidium) standards.

Figure 7 presents an Allan deviation computed with estimated PHM data. Also reported (in pink) is the estimated level of system noise over the same period and (in light blue), the specification of the "pure" PHM. This plot shows that, as anticipated, the estimation of the onboard PHM is dominated by the system noise, which is above the specification of the "pure" PHM. This limitation is particularly true in the short term.

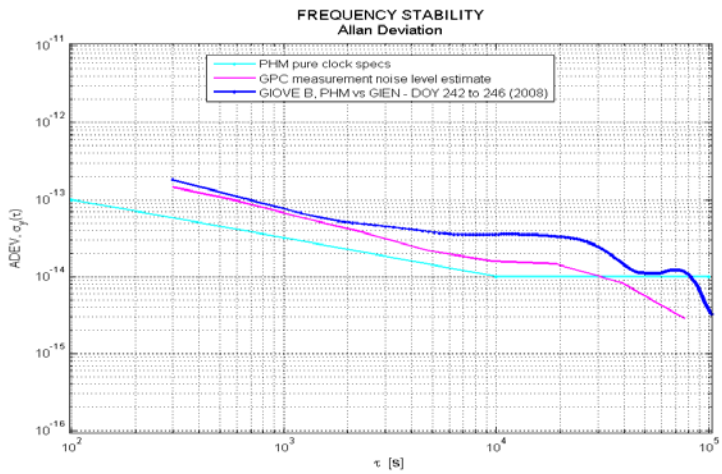

Figure 7. GIOVE-B (PHM) Allan deviation.

In the longer term (beyond ~6000 s), the Allan deviation is affected by two successive "bumps," which indicate the possible presence of long-term periodic oscillations in the fractional frequency data. This hypothesis is confirmed on Figure 8 that depicts a zoom on fractional frequency data over the last days of Figure 6. A periodic oscillation is clearly visible with a periodicity of about 14 hours, which is close to the GIOVE-B orbital period.

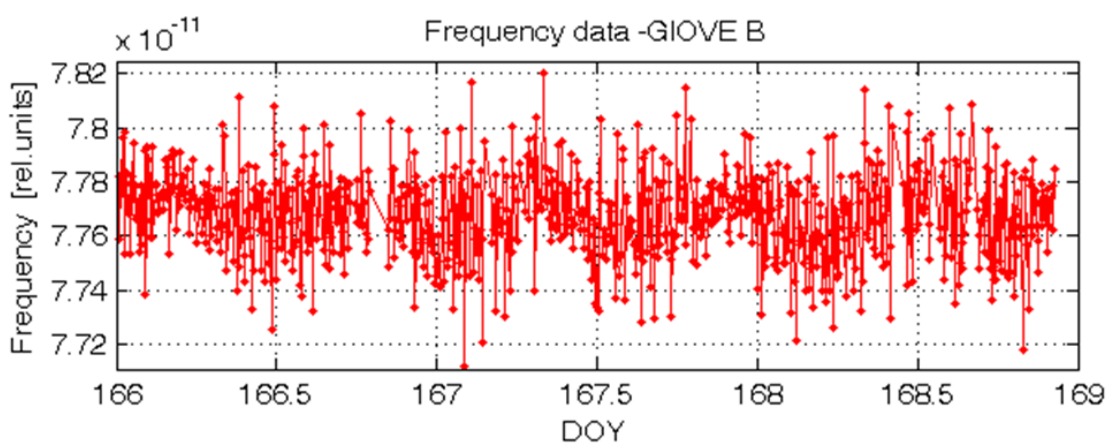

Figure 8. Zoom on GIOVE-B (PHM) estimated fractional frequency data.

In order to refine the analysis of this periodic oscillation on fractional frequency data, a Fourier analysis was performed and is reported on Figure 9. The main peak is estimated to be at $(1.97 \pm 0.05) \times 10^{-5}$ Hz, which corresponds to the GIOVE-B orbital period (14.1 hours). It has to be noted that one harmonic peak and one sub-harmonic peak are also visible on the plot.

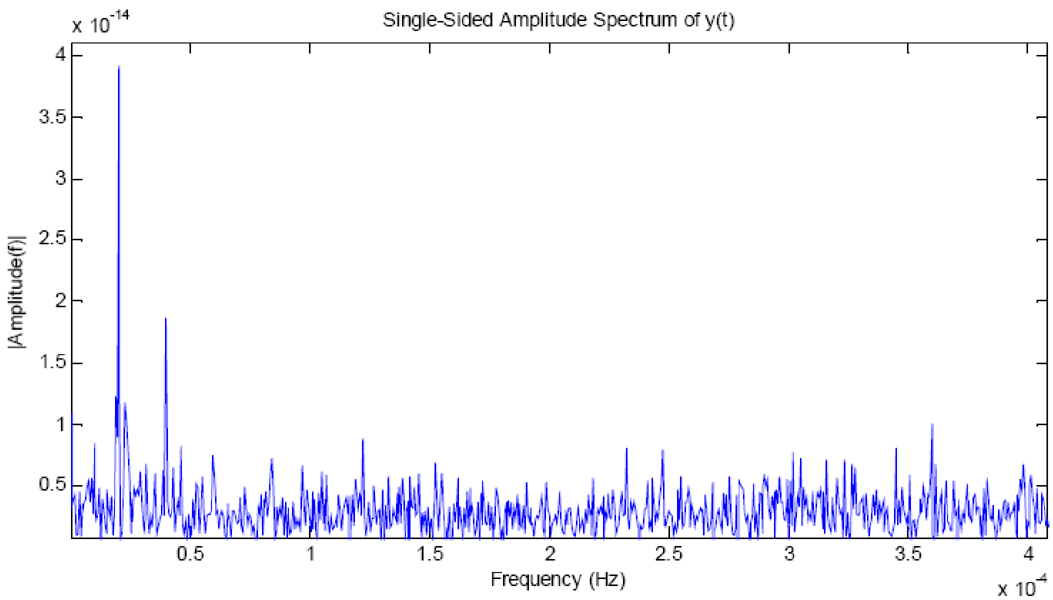

Figure 9. FFT Analysis on GIOVE-B (PHM) frequency data.

It shall be noted that over the whole period of analysis, all PHM internal telemetries have been fully nominal (including temperature) and did not show any periodic oscillation. It has been concluded that this periodic oscillation could not be caused by the PHM itself. The most probable causes are the combined effects of variation in the payload phase delays and possible limitations in the orbital models. Similar periodic oscillations with slightly lower amplitudes have been recently reported on GPS satellites **[9]** and are currently under investigation for the GIOVE ones.

GIOVE-A Results (RAFS)

The GIOVE-A spacecraft was launched on 28 December 2005 and the first onboard switch-on of RAFS occurred on 10 January 2006. During the year 2006, the GIOVE-A spacecraft was subject to a number of payload switch-on/off sequences due to payload and platform operations. Figure 10 depicts the operation of RAFS onboard GIOVE-A (FM4 in red, FM5 in blue) until 1 September 2008. Overall, FM4 and FM5 have been subjected to 13 and 3 switch-on sequences respectively and all have been fully nominal. FM4 has been mostly operated with more than two years of accumulated operation, while FM5 has accumulated about 7 months of operation. FM5 was last switched on 15 August 2008 and has been operating continuously since then.

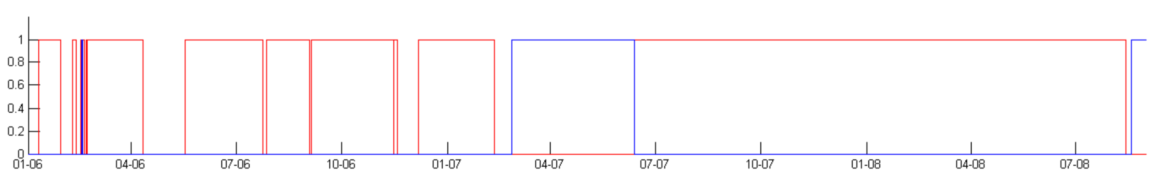

Figure 10. GIOVE-A RAFS ON-OFF status.

The GIOVE Ground Infrastructure, as described in a previous section, became fully available and operational late in 2006. As a result, the GIOVE-A RAFS performances could not be evaluated for most of the year 2006. Figure 11 presents all data available for GIOVE-A RAFS fractional frequency offset as estimated by the ODTS until 1 September 2008 (same color code as for Figure 10). It first shows that, while FM5 has been characterized over almost all its accumulated operation, FM4 was characterized over about 60% of its accumulated operation. It should be noted, however, that it has been characterized almost continuously over more than 1 year (Jun 07 to Aug 08).

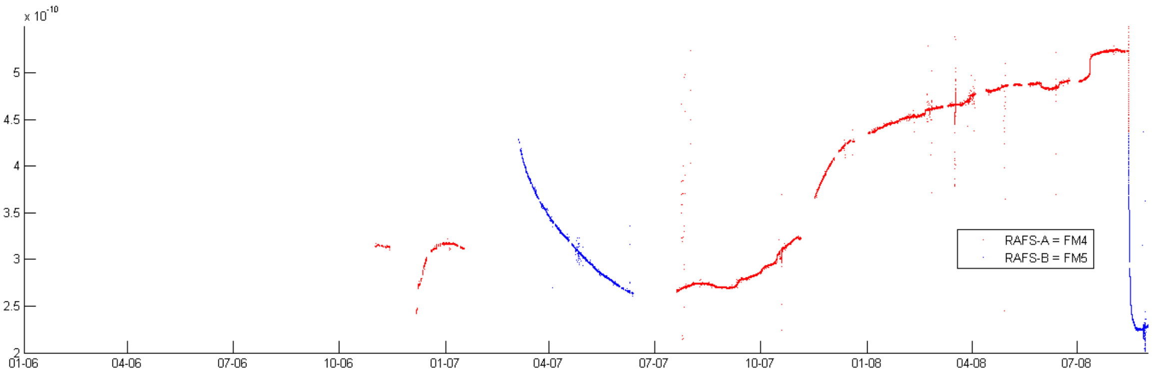

Figure 11. GIOVE-A estimated fractional frequency offset overview.

Due to the small number of available data in 2006, the GIOVE-A RAFS analysis focuses mainly on the years 2007 and 2008. Figure 12 presents the fractional frequency offset estimated by ODTS over the first three months of operation of FM5 onboard GIOVE-A. Over this period, the general trend follows a stabilization process that is typical of vapor-cell (rubidium) frequency standards and is very similar to what was measured on the unit on ground (including the sign). After 3 months of continuous operation, the fractional frequency drift has reached a value that is below 1×10^{-12}/day.

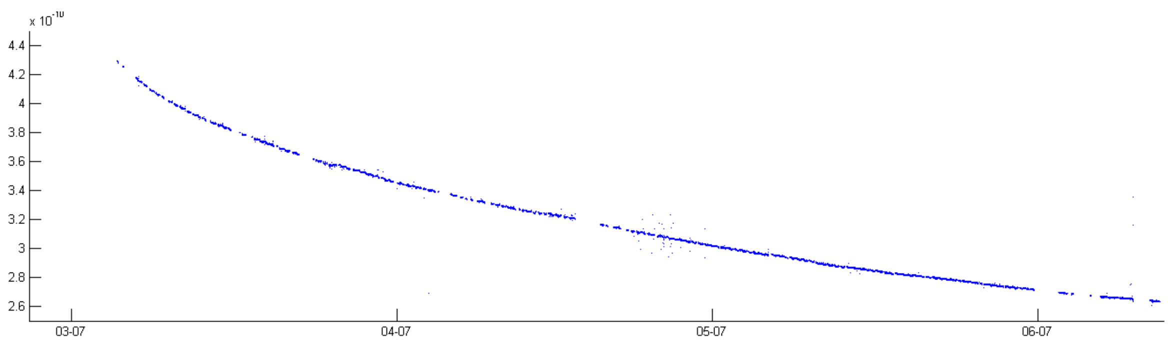

Figure 12. GIOVE-A RAFS FM5 estimated fractional frequency.

Over all this period, all RAFS telemetries have been fully nominal. However, as already reported **[10,11]**, due to limitations in the thermal control system of GIOVE-A, neither the nominal baseplate temperature, nor its variation could be guaranteed. This limitation was identified before GIOVE-A launch and was accepted since it was agreed that this would not damage the RAFS and would only cause minor performance degradation due to higher sensitivity to temperature variation.

Figure 13 is a zoom on the estimated fractional frequency offset of FM5. It indicates a clear periodic oscillation that could be easily correlated with the RAFS baseplate temperature. Unlike for GIOVE-B, the observed periodic oscillation on the GIOVE-A fractional frequency data are clearly attributed, at least at first order, to temperature variations.

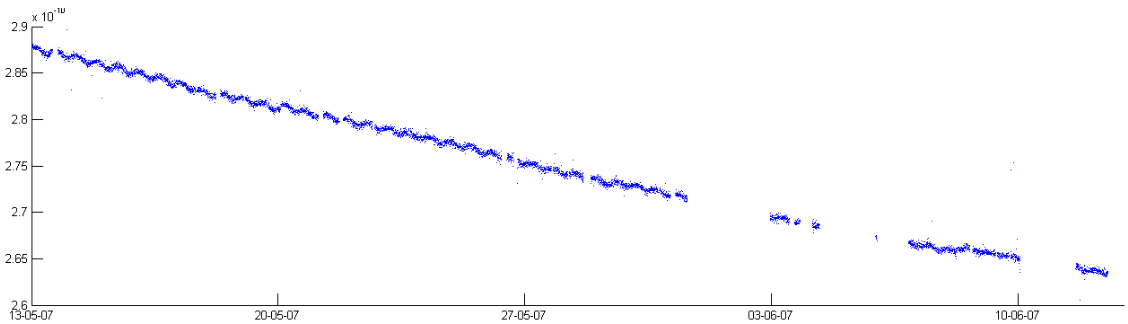

Figure 13. Zoom on GIOVE-A RAFS FM5 estimated fractional frequency.

This periodic oscillation is also well noticeable on the Allan deviation presented on Figure 14. A "bump" is clearly visible at a value that is close to half the orbital period. This plot also shows that, apart from the effect of this periodic oscillation, the estimated RAFS FM5 stability is very close to what was measured on the ground and is below the "true" clock specification for all values of tau.

Figure 15 presents the estimated fractional frequency offset of GIOVE-A RAFS FM4 over the period 12 June 2007-13 August 2008. The general trend of these data is rather unexpected, with non-monotonous and abrupt changes in fractional frequency data. Yet, outside of these changes, the stabilized drift averaged over several weeks reaches a few 10^{-13}/day.

Figure 16 also shows a few sporadic jumps in the estimated fractional frequency data, at the ~10^{-12} level. This was also reported earlier **[12]** and there are neither sign of improvement, nor of degradation as compared to this past report. In addition, the analysis of these additional data confirms that there is no clear correlation between these events and the clock environment (spacecraft operation, temperature, radiation environment, …).

As indicated earlier, some RAFS design limitations have been identified and solutions have been found and validated. The RAFS design has, therefore, been updated and new RAFS units tend to show a much better robustness during tests on ground. Furthermore, as indicated in the literature **[13-15]**, it is expected that such frequency jumps are not uncommon in rubidium atomic frequency standard technology.

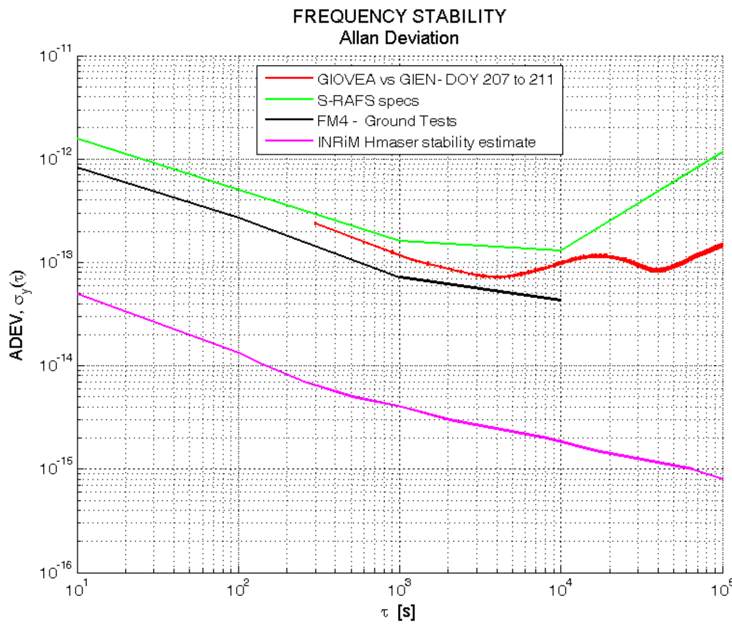

Figure 14. GIOVE-A RAFS FM5 Allan deviation.

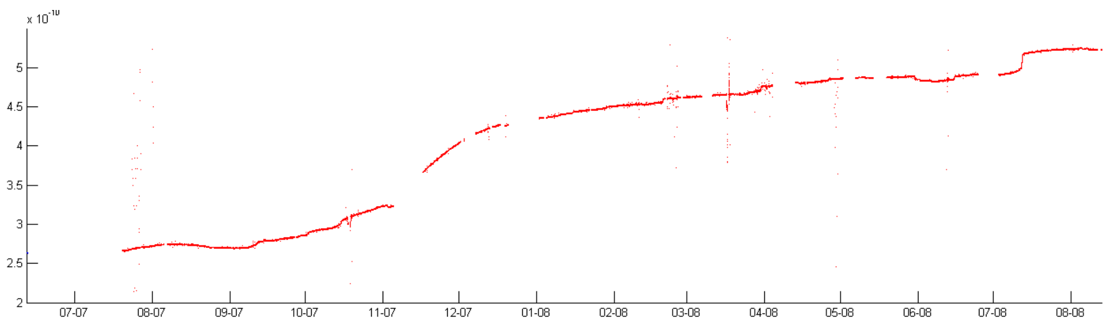

Figure 15. GIOVE-A RAFS FM4 estimated fractional frequency offset.

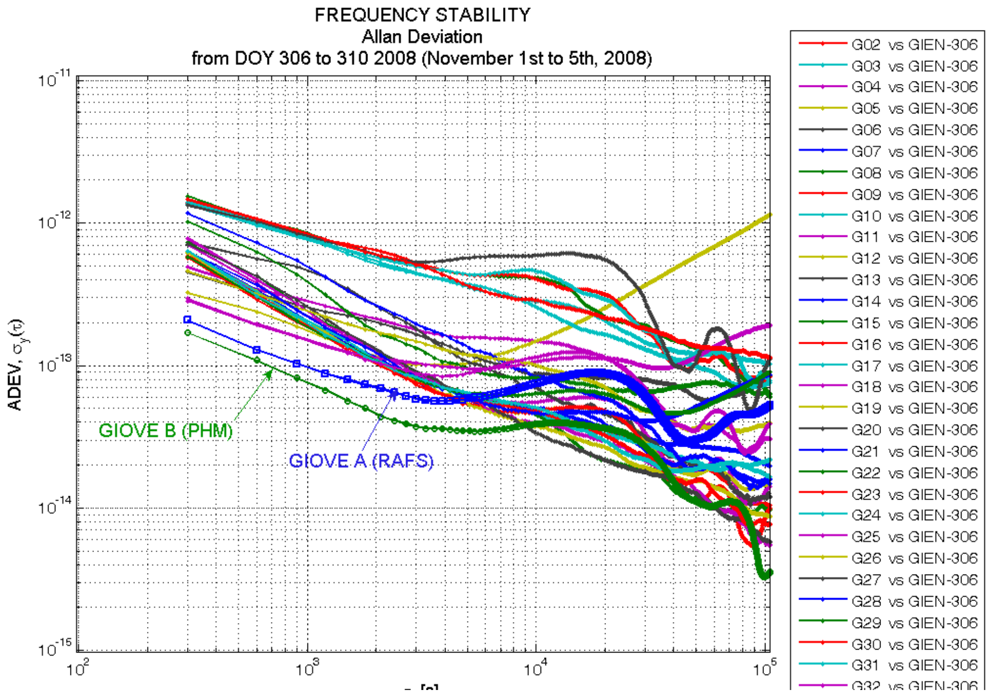

Figure 16. ADEV of PHM (GIOVE-B), RAFS (GIOVE-A) and GPS clocks.

As a summary of onboard GIOVE clocks performance assessment, Figure 16 presents the Allan deviation of PHM onboard GIOVE-B, RAFS onboard GIOVE-A, together with all GPS onboard clocks, as estimated by the ODTS over the period 1 November 2008 – 5 November 2008. It shows that at short-term (up to ~3 hours), the PHM is the most stable in-orbit clock. Beyond this limit, it is affected by a periodic oscillation that is also visible on several GPS clocks.

CONCLUSIONS AND NEXT STEPS

After almost 3 years and 8 months in orbit respectively, GIOVE-A and GIOVE-B have provided a large quantity of valuable data. It has been shown that the PHM onboard GIOVE-B is performing extremely well and that PHM is the most stable of all clocks currently in orbit. Furthermore, it has been shown that the estimation of the PHM onboard GIOVE-B is actually limited by the system noise (at short term) and by a combination of payload delays variation and orbital model errors at medium and long term.

On GIOVE-A, it has been demonstrated that RAFS technology is also performing extremely well, as its frequency stability is meeting its requirements most of the time. A non-monotonous variation of the estimated fractional frequency was noticed, as well as a few sporadic frequency jumps on one unit (FM4). This has been fed back into the RAFS design, which has been updated accordingly.

The onboard clock performance assessment of both GIOVE-A and GIOVE-B is an ongoing process. GIOVE-A mission has been extended until at least March 2009, well beyond the design lifetime of the spacecraft. Additional data on FM5 will be collected and analyzed. Additional PHM data onboard GIOVE-B will also be collected and analyzed, as well as RAFS data.

The GIOVE onboard clock assessment exercise has appeared to be extremely fruitful and beneficial for the next development and deployment phase of the Galileo Programme.

ACKNOWLEDGMENTS

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