GIOVE-A APPARENT CLOCK ASSESSMENT AND RESULTS

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Abstract

The performance of the Galileo space-borne clocks is of highest importance for navigation and integrity at the corresponding user level. Clock estimation and prediction errors driven by the onboard clock's frequency stability and drift are directly mapped into the User Equivalent Range Error (UERE), which has to be kept below its specified limits. The clock quality also affects the integrity performance of the Galileo system: clock "feared events," such as frequency and phase jumps, have to be characterized and adequate barriers built against them. In addition, the clocks operate in a rather harsh MEO-orbit radiation environment, and performance has to be guaranteed in all satellite mission phases, including eclipses.

Two Rubidium Atomic Frequency Standard (RAFS) units developed by Spectratime (former Temextime) were launched on the first experimental Galileo satellite, the Galileo In-Orbit Validation Element A (GIOVE-A). The RAFS already demonstrated excellent performance during on-ground qualification and acceptance tests. To verify its performance onboard, an experiment was carried out as part of the GIOVE Mission Segment. Under this Mission, an infrastructure was deployed, including a network of 13 Galileo Experimental Sensor Stations (GESS) monitoring continuously the GIOVE-A signals. Using dedicated network adjustment techniques, the processing of these observables allows the restitution of the phase difference between the onboard clock and a ground reference. Such restitution, however, is affected by the noise of the measurement system (e.g., onboard and averaged on-ground group delays, orbit residuals, etc.), therefore the "apparent" clock denomination.

This paper will present the GIOVE-A apparent clock results obtained since the ground infrastructure became operational for both the nominal and the redundant onboard clocks and for various signal configurations. These results will be complemented by relevant onboard telemetry data. Finally, the assessment of the onboard clock performance will be discussed, together with the contribution of the measurement system noise.

1 INTRODUCTION

In preparation for the deployment of the Galileo System, the European Space Agency (ESA) initiated in the late 90s the development and industrialization of two onboard clock technologies: Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM). In 2004, both technologies successfully passed ground environmental qualification tests (including vibration, shock, radiation…). In 2005, six RAFS and two PHM flight models were delivered for first in-orbit validation.

In parallel, ESA began development in 2002 of an experimental Ground Mission Segment, called Galileo System Test Bed Version 1. Within the GSTB-V1 project, tests of Galileo orbit determination, integrity, and time synchronization algorithms were conducted in order to generate navigation and integrity core products based on GPS data.

In 2003, the second step of the overall Galileo System Test Bed (GSTB-V2) implementation began with the development of two Galileo In-Orbit Validation Element (GIOVE) satellites: GIOVE-A (launched on 28 December 2005) and GIOVE-B (to be launched first half of 2008). In order to mitigate programmatic and technical risks of the Galileo IOV phase, the main objectives of the GSTB-V2 or GIOVE Mission are:

- Secure use of the frequencies allocated by the International Telecommunications Union (ITU) for the Galileo System
- Validate Signal in Space performance in representative environment (Radio Frequency Interference and multi-path) conditions
- Characterize the Onboard Clock (RAFS and PHM) technology in space
- Characterize the Radiation Environment for the Galileo Medium Earth Orbit (MEO)
- Collect lessons learned on Ground Mission Segment development, deployment, and validation, especially as far as Galileo Sensor Station are concerned
- Collect lessons learned on Space Segment onboard units pre-development and in-orbit operations.

The overall GIOVE system architecture with the necessary components to achieve the above-mentioned objectives are as listed here:

- The space segment is composed of GIOVE-A and GIOVE-B satellites
- The Ground Control Segment is composed of both GIOVE Ground Satellite Centers (GSC), in Guildford for GIOVE-A and in Fucino for GIOVE-B
- The GIOVE Mission Segment infrastructure.

1.1 SATELLITE AND PAYLOAD

GIOVE-A, built by Surrey Satellite Technology, is based on a three-axis stabilized platform. The attitude monitoring is based on Earth and Sun sensors, and gyroscopes; attitude control is based on reaction wheels, de-saturated thanks to magneto-torquers (normal operations) and thrusters. With about 600 kg of mass and 700 W of power (provided by two 4.55-meter solar panels), the satellite can transmit, thanks to its triple-redundant payload chains, two of the three Galileo frequencies (L1+E5 or L1+E6) at a time.

GIOVE-A payload consists of a timing section, including two RAFS (Flight Model 4 and 5) and an internally redundant Clock Monitoring and Control Unit (CMCU), a signal generation and up-conversion section, including an internally redundant Navigation Signal Generation Unit (NSGU) and a Frequency Generation and Up-Conversion Unit (FGUU), and a transmit section, including three Traveling Wave

Tube Amplifiers (in a 2/3 redundant scheme), Output Multiplexers (OMUX), and an L-band phased array antenna. The satellite payload is complemented by two radiation monitors (CEDEX and MERLIN) and a laser retro-reflector. The most sensitive payload units (in particular, the RAFS) are located on a temperature-controlled base-plate. Onboard resource limitations inherent to small satellite platforms caused the RAFS to operate above its nominal temperature range and within larger than specified temperature excursions, especially during eclipses. These limitations were recognized and accepted before launch, as they were well beyond the RAFS temperature limits. Furthermore, it was recognized that the potential impact of such environment on RAFS performance could be easily removed by analysis.

1.2 GIOVE MISSION SEGMENT

The GIOVE Mission Segment provides all the necessary facilities and tools for the requested experiments, covering the data acquisition (also from external providers such as IGS, IERS, BIPM, and ILRS) and archiving, the operations of the major processing facilities, and the management and wide dispatching of the results to internal and external users. The GIOVE Mission Segment includes:

- GIOVE Processing Center (GPC) located in ESTEC (Noordwijk, The Netherlands), composed of the Data Server Facility (DSF), the interface with the GIOVE-A and -B Ground Control Centers (GPCI), and the Experimental Orbit & Synchronization processing facility (E-OSPF)
- A worldwide network of 13 Galileo Experimental Sensor Stations (GESSs) and a Communication Network.

1.3 EXPERIMENTATION SETUP

The GIOVE signal in space is acquired by the GESS network, together with GPS signals. The DSF acquires periodically the data files and converts them to standard RINEX 3.00 format [1]. In addition, the GIOVE flight dynamics data and the telemetry and telecommand processed by the GSC-A and -B are also archived in the Data Server, through the GPCI. These data are the basis for the offline experimentation process.

The reference clock for the GIOVE experimentation is a free-running Active Hydrogen Maser (AHM) connected to the GIEN station, a GESS at the Italian national metrological laboratory (INRiM) in Turin. All clocks in the GIOVE segment are synchronized to the INRiM master clock through ODTS (see Section 2). The AHM output signal, both 10 MHz and 1 Pulse per Second (PPS), is fed to the GIEN station as an external reference time scale. The clock is continuously monitored versus the ensemble of atomic clocks of INRiM and also compared versus external reference time scales, such as the Universal Coordinated Time (UTC) realized by the BIPM.

In the Figure 1, the colors indicate the Depth-of-Coverage (DOC), which is the number of GESSs in view of the GIOVE satellite when flying over a particular location. In order to reduce the estimation uncertainty, the GIOVE-A clock is calculated when at least DOC-2 is available. The GESS network has been designed as to minimize the extent of DOC-1 areas (in red in Figure 1).
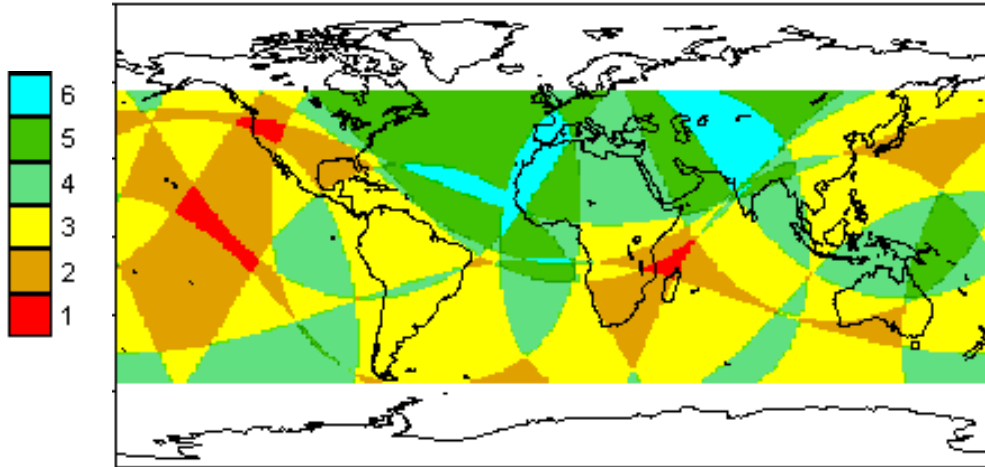
Figure 1. Coverage of the 13-GESS network (colors indicate the number of stations in view of GIOVE).

In parallel to this experimentation, a near-real time processing is performed continuously in routine mode: On a 2-hour basis, the E-OSPF evaluates the orbit and clock parameters needed for the generation of the GIOVE navigation message. Once generated, this navigation message is sent to each of the GSC for uplink to the respective GIOVE satellites.

The results of the data acquisition process, the results of the experimentations, the status of the mission, and other important information are distributed to the GNSS community via the GIOVE Web page **[2]**.

2 THE OBSERVATION SYSTEM

The technique used for clock characterization is called Orbit Determination & Time Synchronization (ODTS), a batch least-squares algorithm that processes undifferenced iono-free GIOVE-A and GPS code and phase combinations, together with GIOVE-A SLR measurements. The 1-second code measurements are smoothed with phase using a Hatch filter.

The ODTS solves, for orbits (dynamics parameters), clocks, troposphere, and the so-called station inter-system bias (ISB), following a dedicated strategy in order to deal with different effects (ionosphere, troposphere, relativity, phase center offsets, phase wind-up, tides, site displacements, ocean-atmosphere loading, etc).

The Figure 2 below summarizes the main clocks, reference points and components of the Measurement System.

One particular aspect of the ODTS process is the usage of a simplified Solar Radiation Pressure (SRP) model for GIOVE-A and all GPS satellites adapted from existing GPS and GLONASS literature on the subject **[3,4]**. Based on the estimation of five coefficients that best fit the orbit, the model requires no *a-priori* information about the satellite geometrical and reflectivity properties. No other empirical accelerations are estimated in ODTS. In total, only 11 dynamic parameters are estimated per satellite (position, velocity, and 5 SRP coefficients).
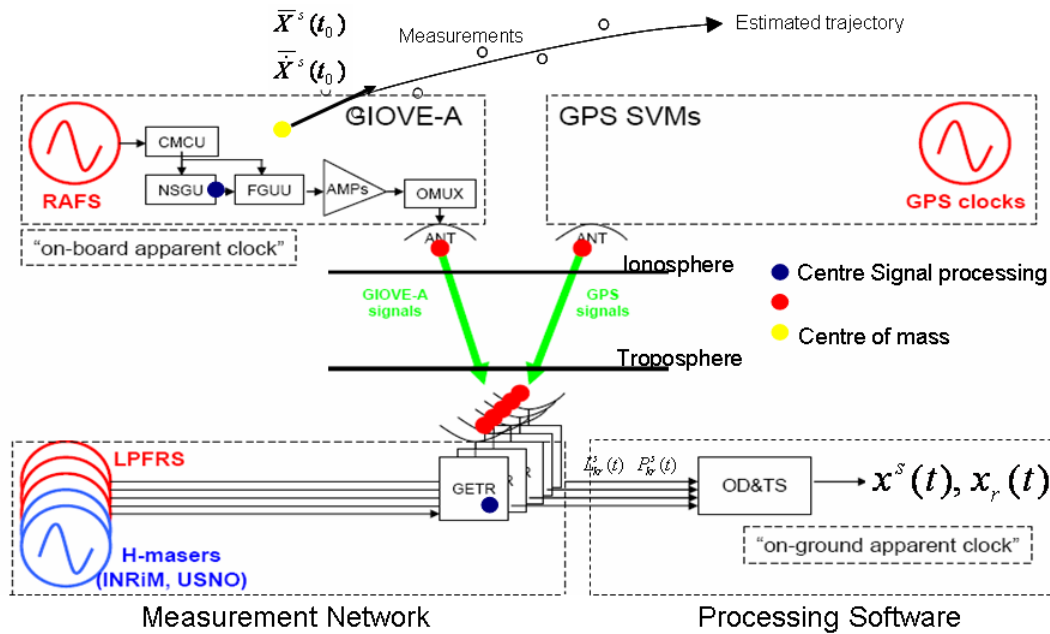
Figure 2. Schematic overview of the measurement system.

Together with the dynamics parameters, the main product from ODTS is the estimated clocks (for all satellites and all stations). The clocks are generated in clock-RINEX (CLK) format as phase offset relative to the INRiM reference clock, and at a nominal output rate of 5 minutes.

Table 1 describes the detailed configuration of the observation system that was used to generate the results presented in Section 5.

Table 1. Estimation strategy used by the ODTS.

PRE-PROCESSING	
GPS raw observables	Code: P1-P2, Phase: L1-L2
Galileo raw observables	FM5 →Code: C1C-C7Q, Phase: L1C-L7Q FM4 →Code: C1C-C6C, Phase: L1C-L6C
Basic observable	Undifferenced iono-free (code + phase)
Sampling rate of raw observables	1 Hz
Code smoothing	Hatch filter, interval 1000 s
Sampling rate after preprocessing	5 min
SLR	GIOVE-A (de-weighted)
PROCESSING	
Number of Stations	9-13
Processed Satellites	ALL (GPS+Giove)
Processed GSS clocks	ALL except GIEN
Basic observable	Un-differenced iono-free (code + phase)
Elevation cut-off angle	15 °
Weight of smoothed-code	30 cm
Weight of phase	10 mm
Weight of SLR	∞ (de-weighted)

Table 1 (cont'd). Estimation strategy used by the ODTS.

PROCESSING (cont'd)	
Weighting	Elevation-independent
Reference clock	GIEN (fixed to zero)
Reference ISB	GIEN (fixed to zero)
Inter-system bias estimation	Per arc
Ambiguity fixing	Float
Station Coordinates	Fixed to ITRF2000, a priori values computed by PPP using IGS products, then re-estimated by ODTS fixing GPS orbits (but not clocks) to IGS solutions
Orbits	5 days orbital arcs, initial orbit position and velocities, and 5 empirical SRP.
ERP	Fixed to IERS solutions
Iono-free	First order effect removed by iono-free combination.
Tropospheric refraction	Estimated at zenith as piece-wise constants at 2 hours interval, using Saastamoninen as *a-priori* model and Niell mapping function.
Satellite antenna Phase Center Offset	Fixed to latest IGS values
Satellite antenna Phase Center Variation (PCV)	No
Receiver antenna PCV	No

3 SYSTEM VALIDATION

A first indicator of the quality of ODTS results is measurement residuals, i.e. the difference between real data and the measurements as modeled by the processing algorithms. Optimally, residuals should be small and randomly distributed, showing only the unmodeled error contained in the data (for example, code multi-path). For example, a systematic elevation-dependent pattern can be observed on code residuals (an example is shown in Figure 3) that is believed to be due to a code/phase incoherence generated at the station antenna. Typical ODTS residuals RMS are 40 cm for code measurements, 1 cm for phase, and 3 cm (one-way) for SLR.

Although orbit results are not the primary subject of this paper, it is important to have an idea of the error in the orbit estimation, since this is largely correlated with the clock estimation error. The estimation errors are calculated to be at the level of 20 cm (RMS) in the radial direction for orbits, and 0.4 ns (1-σ) for clocks. These figures are consistent with GPS satellite orbit and clock comparisons against precise products from the International GNSS Service (IGS) **[5]**.

A successful determination of the GIOVE-A clock depends to a large extent on the correct determination of the station inter-system bias (ISB). This is essential in particular to avoid satellite clock jumps when GIOVE-A flies over different ground stations. Since the ISBs and the GIOVE-A clock are clearly correlated, it is not so obvious that the ODTS software should be able to correctly separate clock and ISB contributions from the GIOVE-A measurements. In spite of this, the ISBs calculated by ODTS over the data analysis period show a good stability. In addition, no phase jumps are observed on the GIOVE-A clock, which is also a good sign of correct ISB estimation.
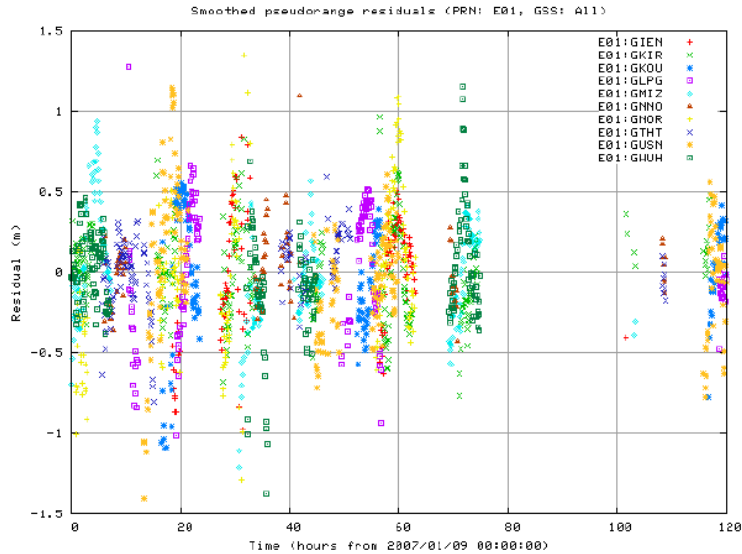
Figure 3. Elevation-dependant pattern observed on pseudorange residuals.

An alternative method based on a dedicated algorithm called IONO has been used to calculate station ISBs using geometry-free GIOVE-A and GPS code and phase. Geometry-free measurements contain ionospheric Total Electron Content (TEC) information and satellite and station inter-frequency bias (IFB). The IFB is the difference between the P1 and P2 code delays (for GPS), and between the L1 and E5 (or E6) code delays (for GIOVE-A), both at satellite and station level. The station ISB is calculated as the difference between the station L1-E5 or L1-E6 IFB (GIOVE-A chain) and the P1-P2 IFB (GPS chain), assuming that the delay on L1 codes (L1 and P1) is approximately the same for both systems. In order to calibrate the whole IFB system in the IONO software, the average satellite P1-P2 IFB (GPS) has been fixed to 5.4 ns (from the navigation message Broadcast Group Delay - BGD - values) and the satellite L1-E5 and L1-E6 IFBs (GIOVE-A) has been fixed to the values calibrated by the satellite manufacturer. The station ISB values calculated by IONO (every 2 days), depicted in Figure 4, show good stability and are in agreement with the values calculated by ODTS (at the ns level). The jump in the GIEN ISB around DOY 265 is due to an intentional hardware configuration change at the station.

An additional validation exercise consists of evaluating the behavior of the INRiM free-running H maser, to check that its level of noise and drift is well below the analogous quantities that are under evaluation for the onboard clock. This is done with two almost independent techniques. First, since two active H masers are included in the GIOVE mission network at INRiM, Torino, Italy (GIEN station) and at USNO, Washington, DC (GUSN station), the ODTS allows also the estimation of their phase offset. In addition, the NRCan Precise Point Positioning (PPP) algorithm **[6]** is used to process the GPS observables extracted from the two station data files, estimating also the clock phase difference. An example of results is reported in Figure 5 for the period 14-18 May 2007 (DOY 134 to 138).
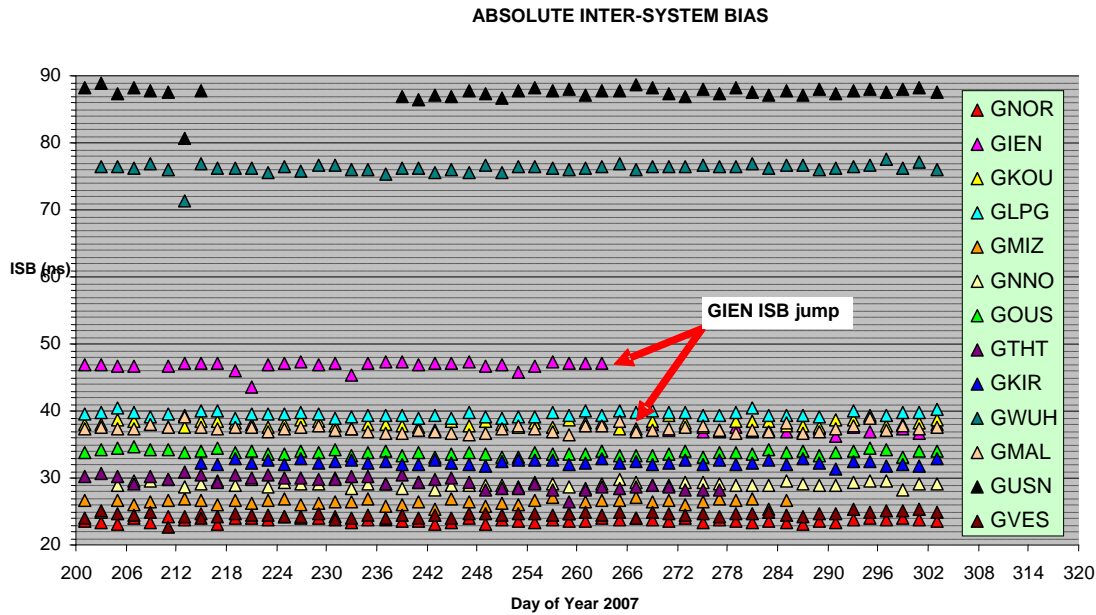
ABSOLUTE INTER-SYSTEM BIAS

Figure 4. The inter-system station biases for 13 GESSs as calculated with the IONO algorithm using geometry-free GIOVE-A and GPS code and carrier-phase combinations.
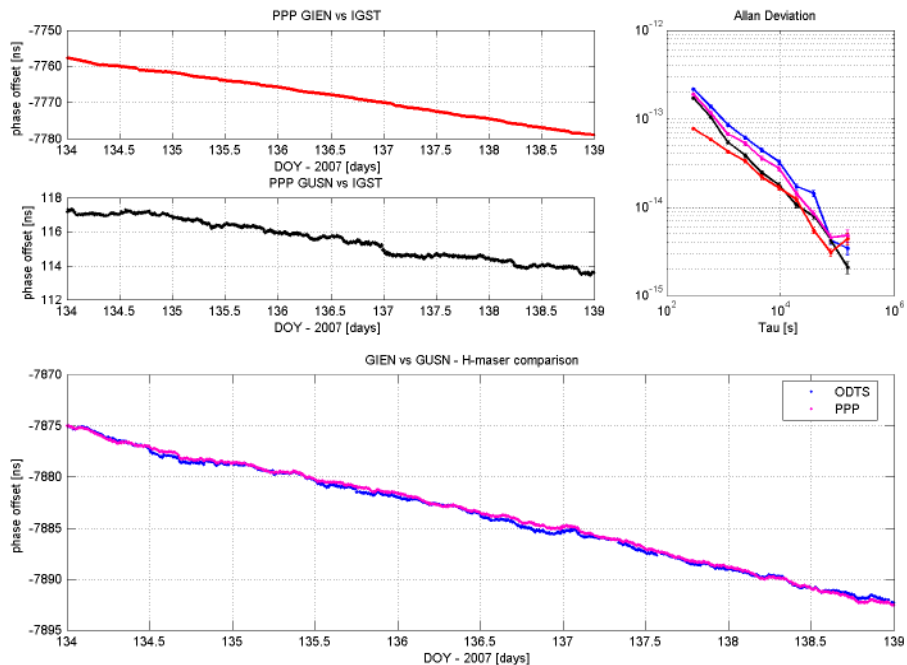

Figure 5. Phase offsets and stability analysis between the active hydrogen maser clocks at INRiM (GIEN) and USNO (GUSN), 14-18 May 2007, computed using Precise Point Positioning (PPP) and the Orbit Determination & Time Synchronization (ODTS) software.

A complementary analysis was done to evaluate the system noise using a new proposed One Way Carrier Phase (OWCP) technique for the 1 to 300 seconds interval **[7]** against the network adjustment solutions (IGS, ODTS) obtained in the 300 to 10^5 seconds interval. The two timing laboratories INRiM and USNO are hosting IGS (IENG, USN3) and GIOVE-M (GIEN, GUSN) stations connected to active hydrogen maser clocks. Note, IENG is attached to UTC (IT), which is a (daily) steered maser. Driven by the well monitored H masers, the results for these stations obtained with IGS and the ODTS maybe used as a quality control and as identification of the accuracy of the system. As the typical behavior of the H maser is below the value observed by the network solution, this can be considered as the noise floor of the measurement system. Additionally ground measurements from the qualification of the RAFS in thermal vacuum are available as a reference data set to compare the onboard results. In the 300 to 10^5 seconds interval, ODTS and IGS results are presented for all the nominal ODTS processed arcs in 2007 at the moment of this publication. It can be observed how the ODTS Allan deviations are worse than expected compared to IGS. Additionally, this solution is almost coincident with the WF noise observed for GIOVE FM4 and FM5 clocks. In the 1 to 300 seconds interval, OWCP results obtained for FM5 with all available signals using GIEN station for one typical day at the maximum elevation show a really good agreement with ground results and a clear difference with respect to ODTS solutions for FM5.

From this it can be concluded: it seems as if the noise floor of the measurement system composed by GIOVE-M Network and the ODTS software processing is impacting the clock estimations; the FM4 white FM noise is close to the measurements on the ground and only visible by the ODTS when over-passing this noise floor due to the onboard temperature effect.
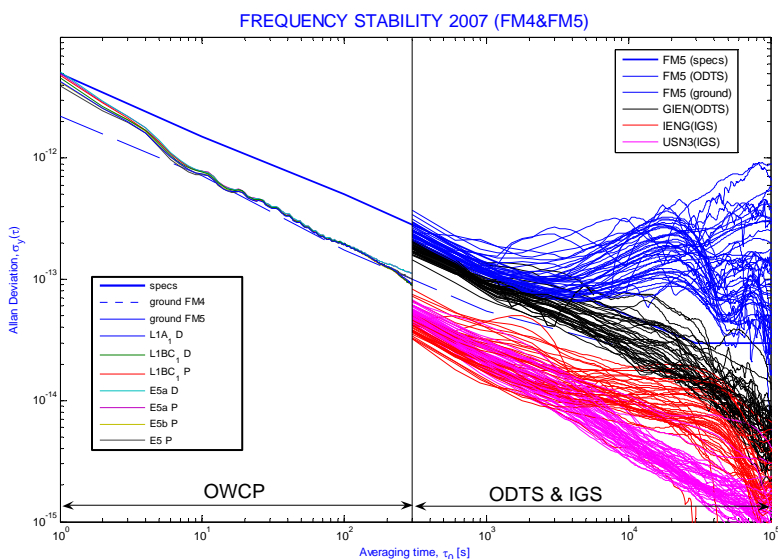

Figure 6. Comparison of OWCP technique **[7]** against ODTS and IGS solutions.

4 THE EXPERIMENTATION WITH GIOVE-A

Data from the GESS network, together with GIOVE-A SLR measurements from the International Laser Ranging Service (ILRS) **[8]**, have been processed since the beginning of the GIOVE mission until the end of October 2007. During some periods, the payload has been configured to transmit the L1 and E5 signals using the nominal payload chain (driven by RAFS FM4), and, during other periods, the redundant payload chain (driven by RAFS FM5). Other times, the payload is configured to transmit the L1 and E6

signals using the nominal payload chain. The Galileo Experimental Test Receivers (GETR) within the GESS stations are configured depending on the current payload configuration at each period.

The characterization of the onboard clock is significantly enhanced by the use of Satellite Laser Ranging (SLR), a high-precision technique for orbit determination that is independent of the navigation signal generation. The technique is described in **[9]**. Given the high GIOVE-A altitude and the reduced size of the laser retro-reflector on board, the satellite is regularly tracked by a limited number of stations (around 12).

5 RESULTS

The analysis of GIOVE A RAFS behavior (FM4 and FM5) has focused on three main areas:

- Deterministic behavior, including phase and frequency offset, and frequency drift
- Stochastic behavior, estimated by means of the ADEV, Hadamard deviation, and the dynamical ADEV
- Sensitivity to onboard environmental conditions.

The analysis in these areas was carried out for all the current experimentation period starting in Oct 2006 and ending at the end of Oct 2007. Over this period, the analysis of the data has been subjected to various constraints and limitations. First, onboard clocks were submitted to a number of ON/OFF cycles due to spacecraft and payload operations and changes from nominal to redundant chain. This is strongly limiting the RAFS performances, in particular the well-known equilibration process of the frequency drift **[10]**. Second, the satellite experienced two eclipse periods (March and September), during which an increase in the peak-to-peak temperature variation was observed, which obviously also affected the RAFS behavior. Finally, due to temporary limitations on the ground (e.g. intermittent interferences at some GESS, in particular the one hosting the reference clock), measurements are not continuously available, causing missing data in the restituted clock phase offset. This generates outliers in the estimated frequency. Therefore, two cases have been considered: a "best conditions" case, corresponding to periods with no missing dataand nominal clock behavior, and the "standard" case, corresponding to periods with missing data and (possible) anomalous onboard clock behavior.

Examples are reported in the following section, which is devoted to the FM4 and FM5 RAFSs, respectively.

5.1 FM4 RAFS Observed Behavior

The examples reported in the following section are devoted to the FM4 RAFS, which has been observed for two periods of 60 and 100 days, respectively. One eclipse season is included in these periods.

5.1.1 FM4 Onboard Clock, Main Results from the 1st Observation Period (from October 2006 to January 2007)
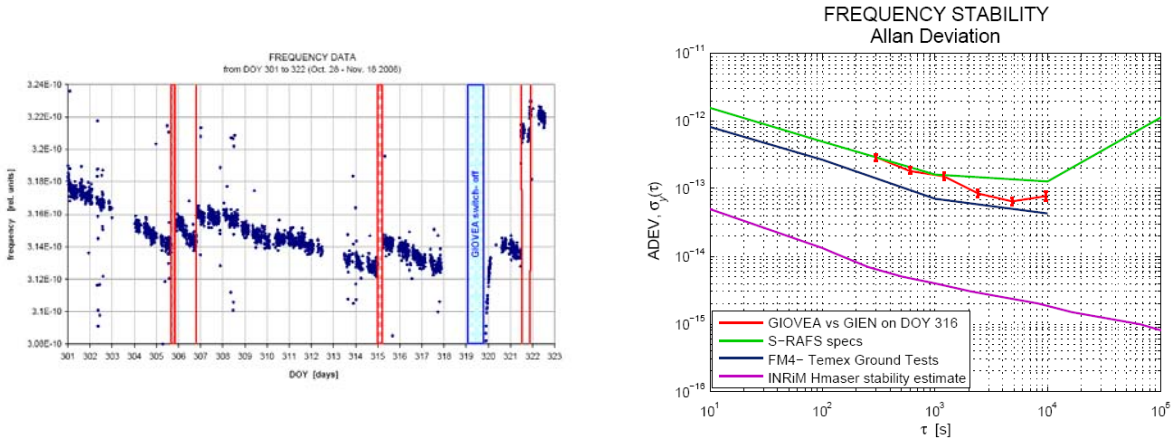

Figure 7. (left) GIOVE-A FM4 "apparent" clock frequency from October 28 to 18 November 2006. Vertical red lines indicate occurrence of apparent clock frequency jumps. (right) The stability of the GIOVE-A FM4 "apparent" clock with respect to the GIEN master clock on a "quiet" day (no anomalous behavior) compared to clock specifications, ground tests, and hydrogen maser performance.

5.1.2 FM4 Onboard Clock, Main Results from the 2nd Observation Period (from July 2007 to November 2007)
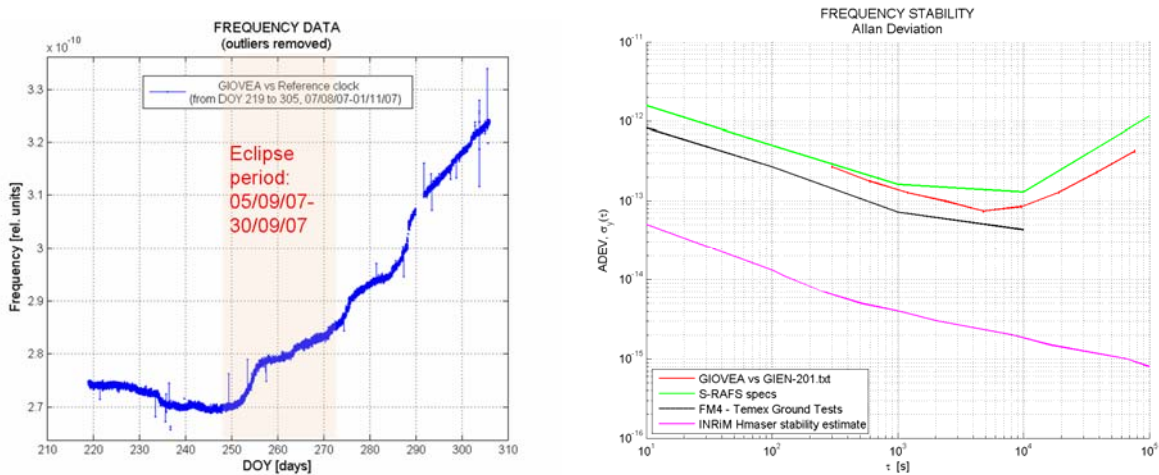
Figure 8. (left) GIOVE-A FM4 "apparent" clock frequency from August 7 to 1 November 2007. The spikes on the frequency estimates are outliers due to measurement noise and do not correspond to true clock behavior. (right) The stability of the GIOVE-A FM4 "apparent" clock with respect to the GIEN master clock on a "quiet" ODTS arc (no anomalous behavior) compared to clock specifications, ground tests, and hydrogen maser performance.

These results show that, apart from a few missing and outliers frequency data that are due to specific known events, the observation system and its reference H maser allow a good restitution of the apparent FM4 behavior. The first period indicates that the long-term trend of this behavior is in line with the expectation (frequency drift in the $5\cdot10^{-13}$ per day). This trend, however, is affected by frequency jumps (at the $1\cdot10^{-12}$ level) occurring over a time span of a few hours and that are not recovering. The second period shows a frequency drift that is varying substantially (from $-1\cdot10^{-13}$/day up to $+1\cdot10^{-11}$/day). In both cases, when selecting a "best condition" case (as defined above), the frequency short-term stability of the apparent clock (in terms of Allan deviation) is within specifications.

5.2 FM5 RAFS OBSERVED BEHAVIOR

The FM 5 was observed for a period of 90 days. One eclipse season is included in this period. GIOVE "apparent" clock frequency data for the FM5 onboard clock switch-on period are reported in the plot below.
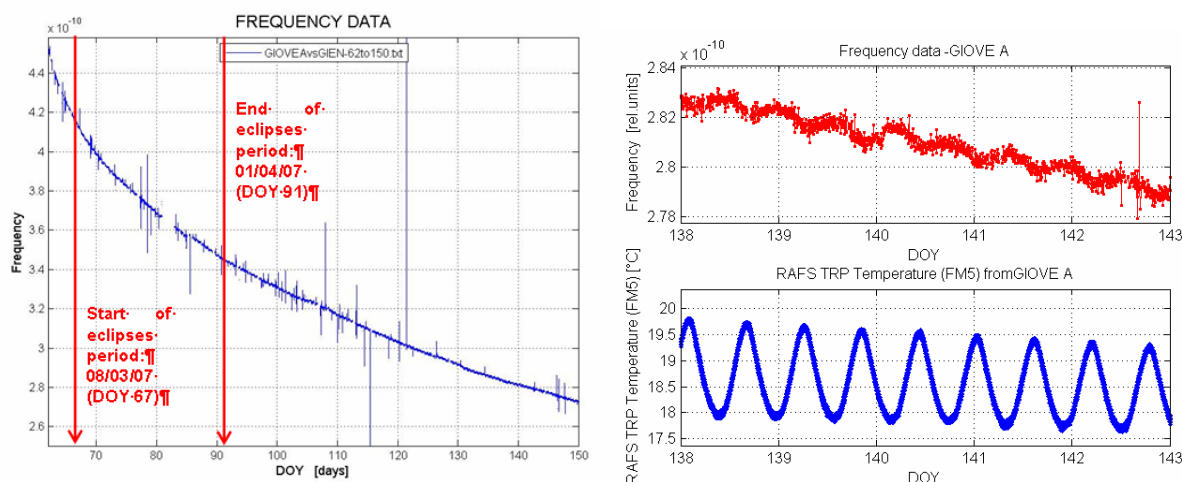

Figure 9. (left) GIOVE-A FM5 "apparent" clock frequency from 3 March to 30 May 2007. (right) GIOVE-A FM5 "apparent" clock frequency and RAFS TRP temperature, from 18 May to 22 May 2007. Example of periodic fluctuation and a frequency jump observed in the frequency data.

These results first confirm that despite few missing and outlying data, the observation system noise does not affect too much the good restitution of the apparent FM5 clock. Unlike in the first period of FM4, the FM5 long-term frequency trend shows a clear equilibration process, starting with a drift at the $-4\cdot10^{-12}$/day level, slowly stabilizing at the $-1\cdot10^{-12}$/day. This difference in behavior between FM4 (first period) and FM5 is explained by the fact that FM4 had been operating for 2 months before the data were measured while FM5 was measured just after switch on.

A closer look at the FM5 frequency behavior (after the drift has stabilized below $-1\cdot10^{-12}$/day) shows that a periodic fluctuation (with a periodicity of about 14 hours) is added to the linear frequency drift. This behavior has been attributed to the combined effects of possible unmodeled orbital effects and environmental sensitivities. As the first term is difficult to evaluate, and as it was known that the clock is operating outside of its nominal temperature range, possible correlation with temperature, as clearly indicated in Figure 9, was sought. The results of this analysis are presented in Figure 10 and 11.

Figure 10 shows that the removal of the temperature effects (and linear frequency drift) significantly reduces the observed fluctuations, which confirms that these effects are the main contributor to the observed frequency fluctuations. It has to be underlined that this high sensitivity to temperature was not unexpected as the RAFS operates outside of its nominal temperature range. This removal of deterministic effects also allows identifying a frequency jump (at the $3 \cdot 10^{-13}$ level) around DOY 140.
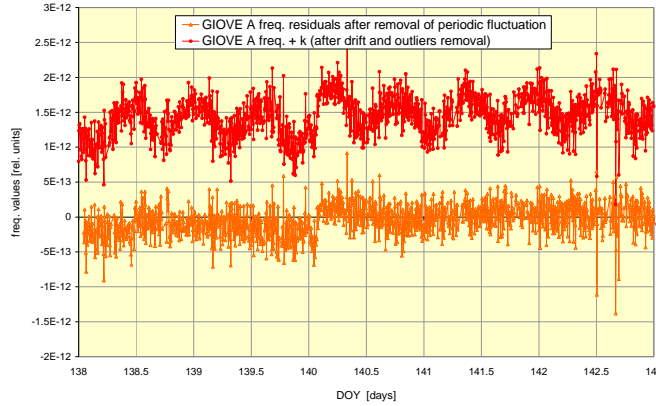
Figure 10. GIOVE-A FM5 "apparent" clock frequency (red dots) and residuals after removal of frequency periodic fluctuation (orange dots).

Figure 11 also shows the effects of temperature on the apparent clock short-term stability (in terms of Allan deviation with outliers removed using a median absolute deviation (MAD) filter). It shows that after removal of these deterministic effects, the apparent FM5 stability is within the specifications.
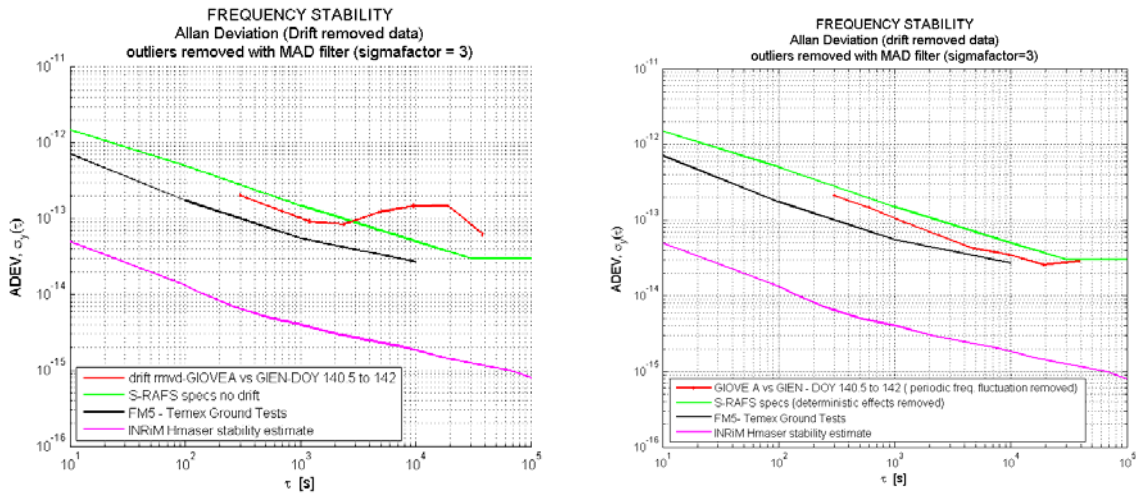

Figure 11. (left) The stability of the GIOVE-A FM5 "apparent" clock with respect to the GIEN master clock is corrupted by a periodic fluctuation due to the clock sensibility to temperature. (right) After removal of the frequency periodic fluctuation, the "apparent" clock stability meets the specs.

The sensitivity of the clock apparent frequency to the temperature has been examined for the different arcs, evaluating also if the eclipse season was giving some influence and the results are reported in the Figure 12 (right) where the eclipse season seems not to give significant influence. Evaluating the frequency drift value arc by arc (on batches of 5 days), it is possible to observe the evolution in time of the drift that goes towards stabilization. The frequency drift seems not particularly affected by the eclipse season, as shown in Figure 12 (left).
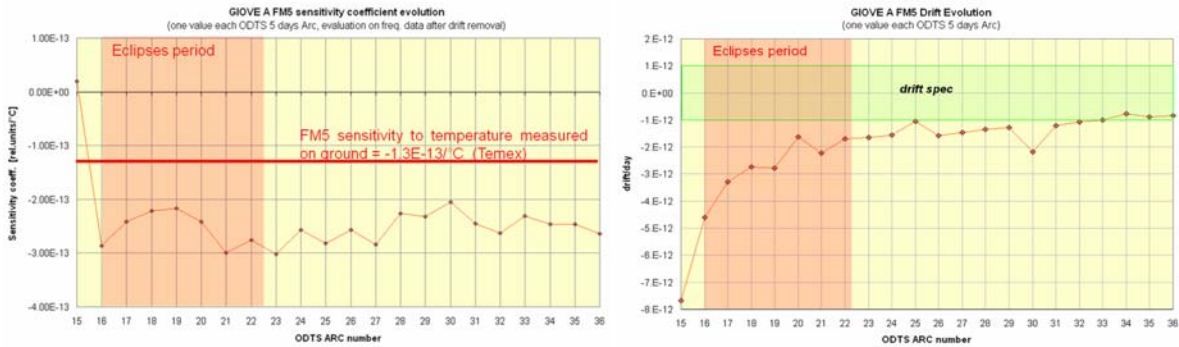

Figure 12. GIOVE A FM5 temperature sensitivity coefficient (left) and frequency drift evolution (right), from 3 March to 30 May 2007.

The effect of the periodic fluctuation on the Allan deviation, as well as the evolution in time of the Allan deviation has been also studied by using the Dynamical Allan deviation **[11]** that allows one to visualize possible nonstationary effects on the apparent clock behavior. An example of DADEV results is reported in Figure 13.
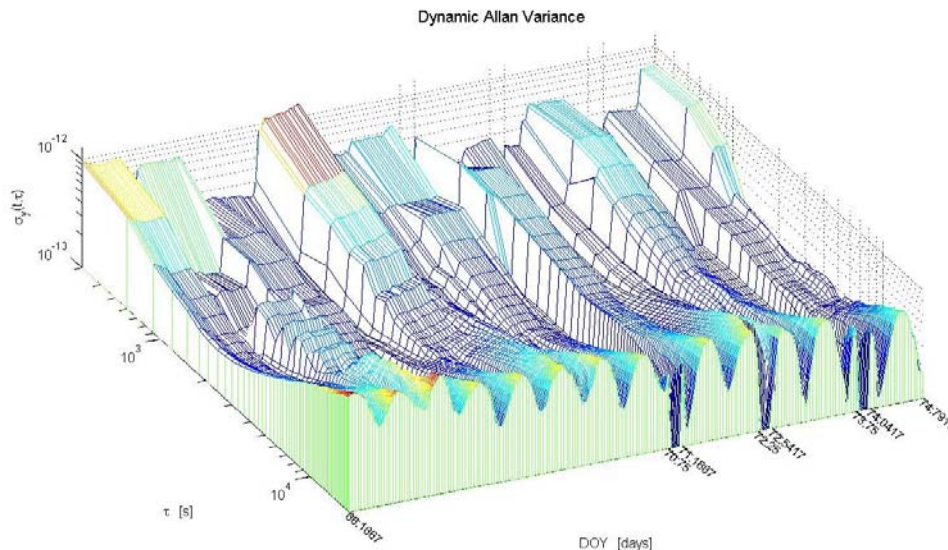

Figure 13. Dynamic Allan deviation, 7-15 March 2007.

An overall plot of temperature onboard and apparent clock frequency is reported in Figure 14, for the period from 1 January 2006 to 1 November 2007. The period in which FM4 or FM5 has been used are indicated by different colors (blue for FM4 and green for FM5, respectively).
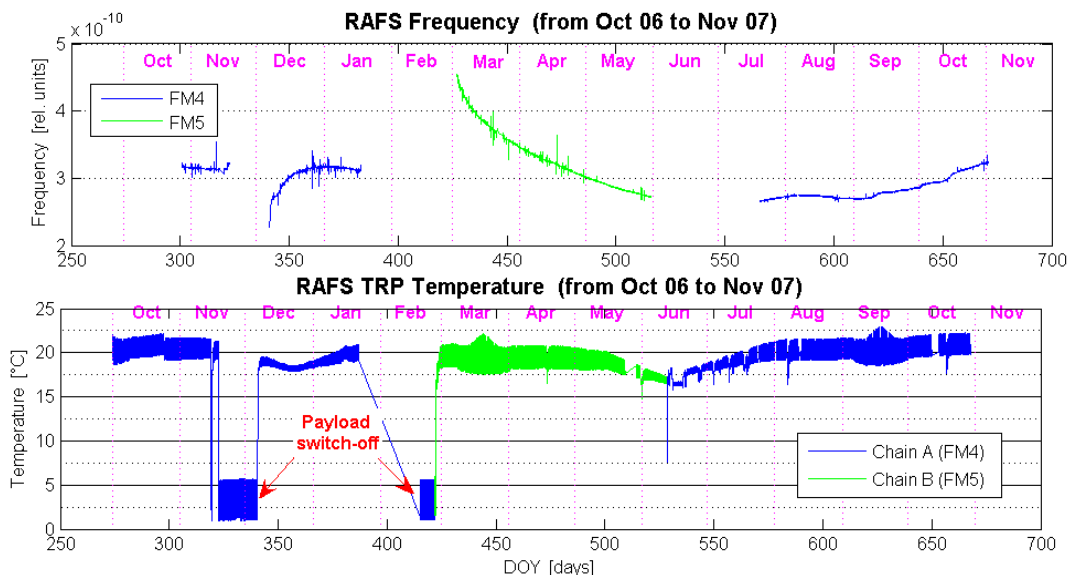

Figure 14. RAFS TRP temperature telemetry data and GIOVE A "apparent" clock frequency evolution, from 1 January 2006 to 1 November 2007.

6 TELEMETRY DATA ANALYSIS

RAFS onboard telemetries (TMs), as well as telemetries related to various onboard equipments and sensors (in particular temperature) are useful tools to analyze the behavior of the onboard clocks and to complement the frequency analysis. Further, as soon as the RAFS is switched on, TM data are available, which is not the case for frequency data, which strongly depends on signal transmission and availability of the ground network. Telemetry analysis has focused mainly in three areas. First, the analyses of RAFS switch-on sequences to verify the proper start up of the clock. Second, the long-term trend analysis to identify any possible anomalous behavior or ageing effects due to the space environment. Finally, *ad-hoc* analyses were performed to support the investigations of specific events like the frequency jumps, as reported in the previous section.

Figure 15 shows the evolution of the RAFS Rb light TM during a typical switch-on sequence. FM4 was used during most of the payload commissioning phase and during the frequency filings, requiring frequent signal reconfigurations. FM4 was, therefore, subject to a high number of on/off sequences. FM5 instead was switched-on only once. The Rb light telemetry is an indicator of the RAFS discharge lamp intensity and its signature is, therefore, a good sign of the various steps the lamp is undergoing during the start-up sequence. The analysis of several switch-on sequences indicate fully nominal behavior of the start-up sequences, with typical pronounced variation of lamp intensity during the so-called warm-up period, until it reaches a stable value. For both FM4 and FM5, this stabilized value was identical (at the 1% level) to the one measured on ground before launch. Typical time to stabilize varies between 10 minutes and 1 hour and depends on the internal temperature of the RAFS.
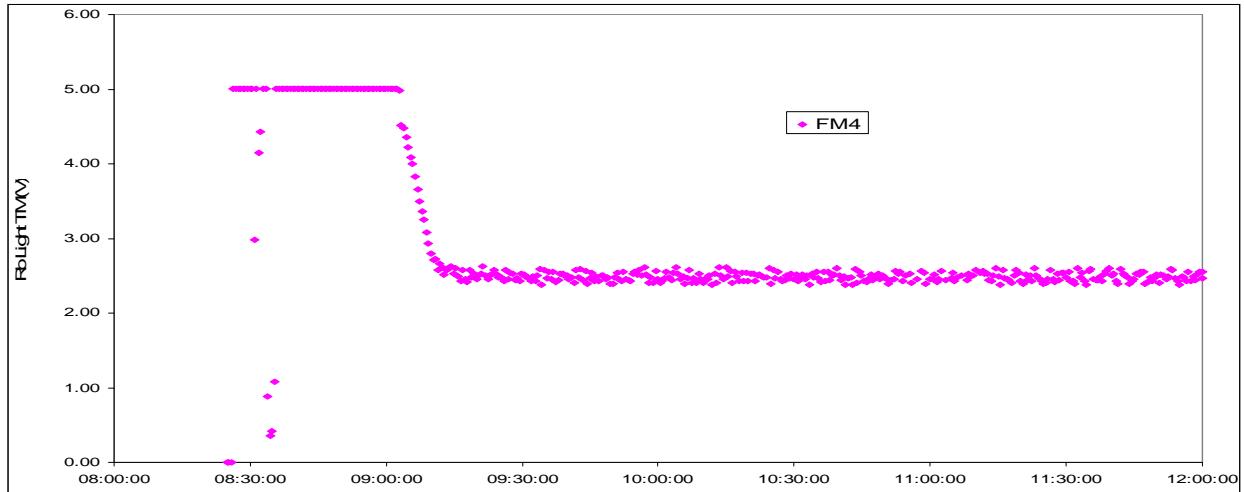
Figure 15. RAFS FM4 Rb light TM during a typical switch-on sequence.

Figure 16 shows the evolution of RAFS FM4 and FM5 Rb light TM over the period reported in the previous section.
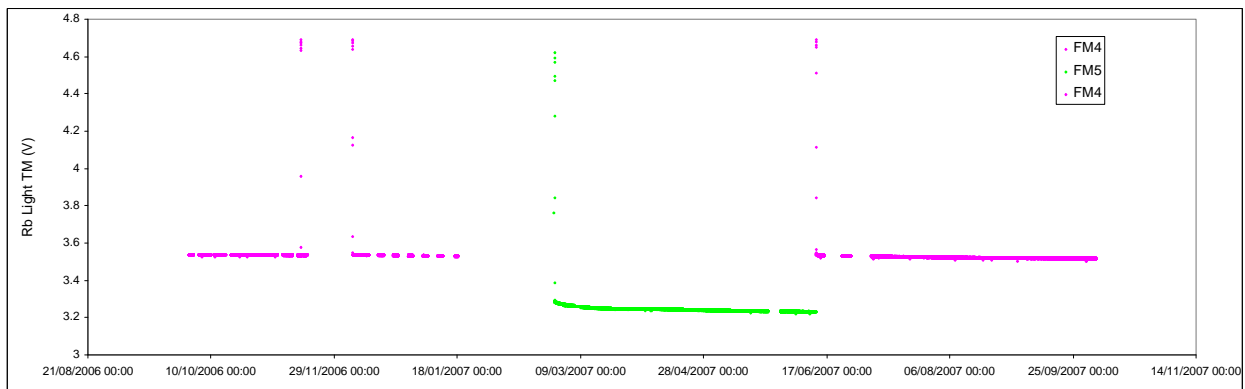

Figure 16. RAFS FM4 and FM5 Rb light TM over the reported period.

Data gaps indicate periods over which the RAFS was switched off and "jumps" of TM data to 5V indicate that the RAFS has undergone a switch-on sequence. The overall trend of this TM is expected to provide an indication of possible long-term degradation effects (in particular ageing) and can also be used to predict the expected lifetime of the clocks. Both figures indicate typical ageing behavior of the Rb light TM, with degradation in the few $1 \cdot 10^{-5}$ level per day. This is fully in line with figures obtained in RAFS units that are currently undergoing life tests on the ground **[12]**.

Finally dedicated TM analyses were performed to identify possible external causes of the RAFS frequency jumps reported in the previous section. A full review was undertaken, including the TMs of all navigation payload units (in particular the ones involved in the signal transmission), the TMs related to spacecraft operation (e.g., reaction wheels, magnetorquers, solar array mechanisms…) and temperature sensors, as well as TMs relative to the radiation environment both direct (through radiation monitors) and

indirect (e.g., through rate of Single Event Upset in the onboard mass memory). A deep analysis of all these data has concluded that there is clearly no evidence of correlation between the observed RAFS frequency jumps and a specific event onboard due to operation or environment. Detailed analysis of internal RAFS TMs during frequency jumps events has also been performed with similar conclusions, even though the results in this case are limited by the TM resolution.

7 CLOCK PREDICTION RESULTS AND IMPACT ON THE USER

7.1 BACKGROUND

During the GIOVE Mission experimentation, onboard clock predictions have been systematically computed by the E-OSPF in order to assess the clock performances for navigation. In order to do so:

- The E-OSPF calculates snapshot clock estimations over the whole observation arc of the Orbit Determination and Time Synchronization (ODTS) process. These clock estimations are obtained at every valid measurement epoch, and are directly referred to the reference time (E-GST). The estimates at different epoch are considered independent, in the sense that no dynamical filtering or clock modeling is applied to them. There is an implicit dependency, however, through the correlation with other parameters estimated simultaneously and averaged over time (e.g., satellite dynamic parameters).
- These estimations are then used to fit the clock model parameters. The model can only account for the deterministic clock behavior; therefore, a straight line or a parabola is typically used. The choice for one or the other will depend on the actual clock behavior and the desired prediction validity time. The prediction performances will depend also on the measurements' noise (i.e., the quality of the clock estimation).
- The so computed clock model parameters are used to predict GIOVE clock offsets in the future. Such offsets can be then compared to the estimations obtained in the following ODTS arc in order to assess prediction performances.

7.2 PREDICTION SETUP

The experimentation setup for the GIOVE Mission Clock Prediction assessment is as follows:

- The length of the ODTS determination arc is 5 days. Two consecutive ODTS arcs have a 1-day overlap. The comparison of the clock estimates from two consecutive arcs in the overlap period serves as a performance indicator for the clock estimations (estimation *consistency*). The clock estimation consistency computed this way is typically around 0.5 ns RMS.
- The clock estimates from the *last day* of the ODTS determination arc are used to fit the parameters of a *quadratic* model. This model is used to generate predictions for 1 day. The choice for the quadratic model is driven by the desired prediction validity (1 day).
- Predictions are compared with the estimations from the following ODTS arc to derive clock prediction performances.

7.3 PREDICTION PERFORMANCES

The prediction performances have been evaluated as described above along several ODTS arcs, covering the GIOVE-A operation period. In general, it can be concluded that the clock prediction error varies a lot from arc to arc and is quite unreliable. This makes producing clock prediction statistics difficult. The

main reason is the observed clock behavior, which is difficult to predict due to the frequency stability. A possible reason is that the clock has not reached the needed stabilization time (as there have been several clock switches during the GIOVE-A operation). An example is shown in the Figure 17, representing the GIOVE-A clock (FM4, second period) during two different ODTS arcs, with a parabola removed.
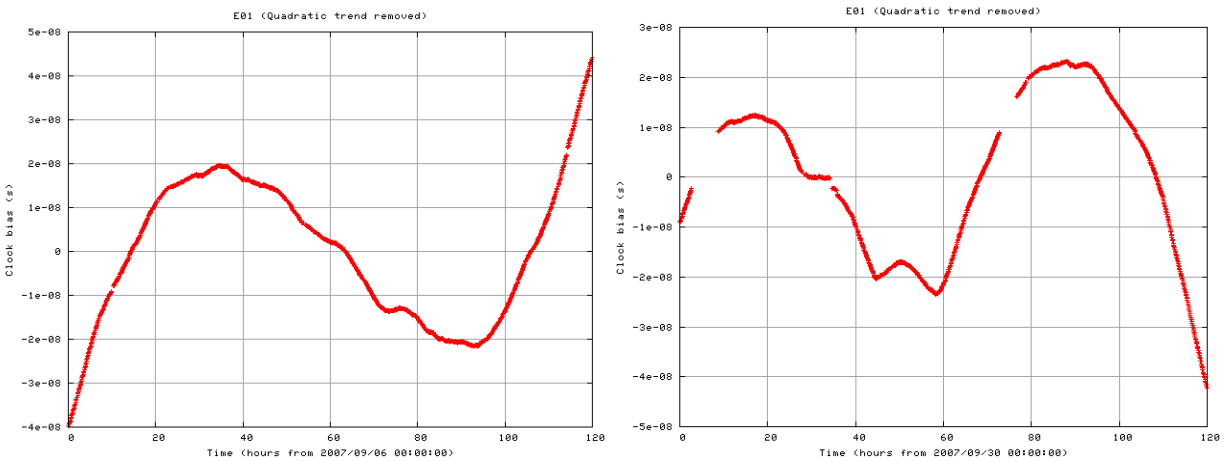

Figure 17. GIOVE FM4 apparent clock estimation examples (quadratic trend removed).

Consequently, the prediction error over 1 day has as significant variation among different arcs, depending on the existence of frequency changes during the prediction periods. Two examples are shown next in Figure 18 for FM5 (left) and FM4 (right).
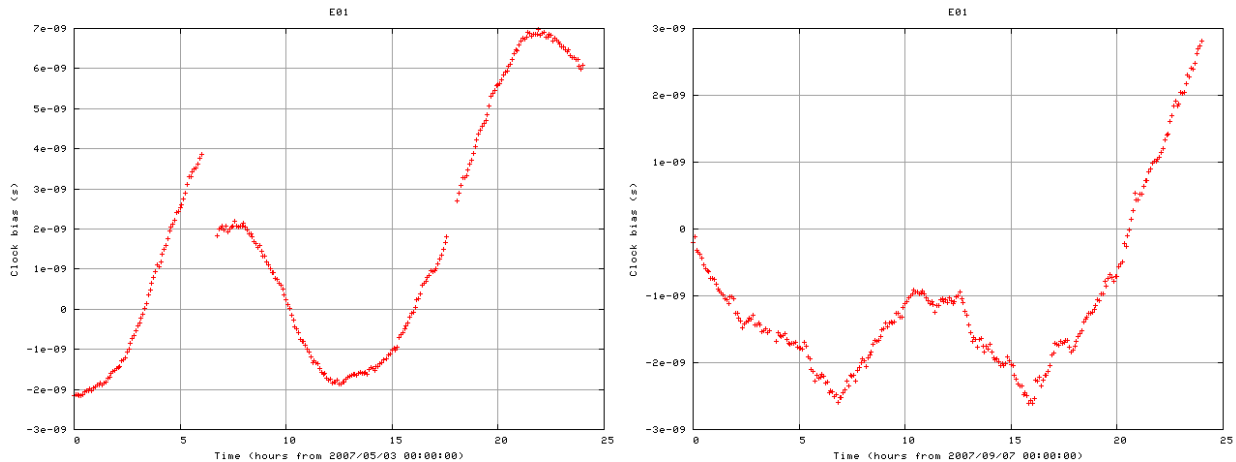

Figure 18. GIOVE Clock 1-day prediction examples (FM5 - left and FM4 - right).

Figure 19 picture shows:

- on the left, the clock prediction accuracy (clock prediction error mean and RMS over 1 day, per ODTS arc) for the second period of operation of FM4

- on the right, the prediction error *at* 100 minutes prediction time (i.e., not averaged over 100 minutes), for different ODTS arcs. It should be noted that the GIOVE Mission setup defines 1-day predictions according to the available upload rate for the navigation data. However, the operational Galileo setup foresees much more frequent updates of the navigation message, thus defining a target prediction validity time of 100 minutes. Despite the fact that this target would imply a different prediction setup (using probably a linear model and a different fit interval), the error at 100 min has been analyzed with the GIOVE setup.
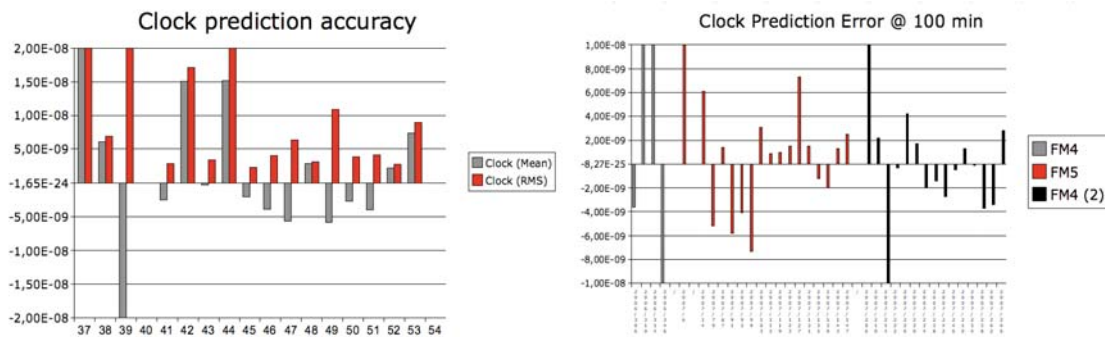

Figure 19. FM4 Clock prediction accuracy (left), and GIOVE clock prediction error @ 100 min (right).

The accuracy values for the first three arcs exceed the scale, and correspond to the period where the clock has been very recently switched on. After some initial stabilization, the RMS over 1 day remains normally below 10 ns, and typically below 5 ns, which is rather good especially considering the observed clock behavior. In the right plot, the values for the different clocks have been represented. Again, the initial values after clock switches exceed the limits of the y-scale; however, it can be seen that in many cases (especially in the second period of FM4) the *instantaneous* error is within 2 ns. This result is considered quite promising in view of the Galileo required navigation performances (130 cm for orbit and clock at user level, 95%).

8 CONCLUSIONS AND NEXT STEPS

The results of the GIOVE Experimentation as reported in this paper have met all their objectives. It was confirmed that the GIOVE experimental core infrastructure is able to restitute the onboard apparent clock. The limitation of the restitution technique due to system noise has been characterized in detail, using different techniques. The behavior of the apparent clock over almost 1 year of continuous data has been analyzed in detail. It was shown that in most of the cases, the apparent clock stability for both FM4 and FM5 meets the specifications. Furthermore, it was demonstrated that the ODTS is able to generate clock prediction products that are in good agreement with state-of-the-art results.

This experimentation has also allowed identifying some limitations both of the measurement system (elevation-dependent pattern of the GESS antennas) and of the onboard clocks (frequency jumps, sensitivity to temperature). The causes of these limitations have been well understood and recovery actions have been initiated and are currently under validation.

The GIOVE infrastructure is currently being updated to prepare for GIOVE-B experimentation. This will represent a major step forward in the building of the Galileo System, as it will extend the characterization of RAFS technology and it will allow for the first time the characterization of PHM technology.

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