Galileo Rubidium Standard
- Lifetime data and GIOVE-A related telemetries -

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Galileo navigation program is in progress under the technical supervision of the European Space Agency (ESA). The preliminary activities related to GSTB-V2 experimental satellites provide the first results and the implementation of the In Orbit Validation (IOV) phase are in progress. Atomic clocks represent critical equipment for the satellite navigation system and clocks development has been continuously supported by ESA. The Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHM) are at present the baseline clock technologies for the Galileo navigation payload. For the RAFS, initial ground technological project related to lifetime possible limitation of the clock was already initiated in 2001. Telemetries of the operating RAFS on board of GIOVE-A provide highly valuable data to compare with the ground data and validate the selected method of 2001. This article gives an overview on the ground lifetime data of the RAFS in comparison with GIOVE-A data. Extrapolation for the 12 years Galileo mission duration is also provided.

I. Introduction

GALILEO is a joint initiative of the European Commission and the European Space Agency (ESA) for a state-of-the-art global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. It will probably be inter-operable with GPS and GLONASS, the two other Global Navigation Satellite Systems (GNSS) available today.

The fully deployed Galileo system consists of 30 satellites (27 operational and 3 active spares), stationed on three circular Medium Earth Orbits (MEO) at an altitude of 23 222 km with an inclination of 56º to the equator.

Atomic clocks represent critical equipment for the satellite navigation system. The Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM) are at present the baseline clock technologies for the Galileo navigation payload. According to the present baseline, every satellite will embark two RAFS' and two PHM's. The adoption of a "dual technology" for the on-board clocks is dictated by the need to insure a sufficient degree of reliability (technology diversity) and to comply with the Galileo lifetime requirement (12 years). Both developments are based on early studies performed at the Observatory of Neuchâtel (ON) from end of 1980s and Temex Neuchâtel Time (TNT) since 1995. These studies have been continuously supported by Swiss fundings within ESA technological programs especially since the set-up of the European GNSS2 program.

The activities related to Galileo System Test Bed (GSTB-V2) experimental satellite as well as the implementation of the In Orbit Validation phase are in progress. The first experimental satellite (GIOVE-A) was launched 28th December 2005, to secure the Galileo frequency fillings, to test some of the critical technologies, such as the atomic clocks, to make experimentation on Galileo signals and to characterise the MEO environment. There is two RAFS on the GIOVE-A satellite supplied by Surrey Satellite Technologies Ltd.

II. Development & Qualification Activities of Rubidium Atomic Frequency Standard

The RAFS development milestones are chronologically listed as below:

The first development activity kicked off at TNT in 1997, and completed in 2000 with one Engineering Model (EM) RAFS produced.

The updated RAFS development started in June 2000 and completed at the beginning of 2002. The industrial consortium is led by TNT with Astrium Germany as the subcontractor for the electronics package. The results of this development is applied clock design used for qualification and lifetime testing.

The last development and qualifications step was initiated at the end of 2001 and completed at the beginning of 2003 with the delivery of an EM, which is the baseline unit for the development of the flight models for GSTB-V2. The main contribution of this last development step is the Inclusion of a DC/DC converter and the satellite TT&C interface compatible with ESA's new requirements. It doesn't affect the lifetime sensitive parameters of the clock.

In the frame of GSTB-V2, one EQM, one Proto-Flight Model (PFM) and five Flight Model (FM) units have been delivered. The PFM and FM1 are integrated in GIOVE-B and ready for launch. The FM4 and FM5 are integrated in GIOVE-A and in orbit since 28th December 2005. In addition, the FM2 and FM3 are available as FM spare units.

RAFS for GSTB-V2 performance achieved are given in the table 1 and the plot in figure 1.

Parameter	Measurement
Frequency stability	$< 4*10^{-14}$ @ 10'000 sec
Flicker floor	$< 3*10^{-14}$ (drift removed)
Thermal sensitivity	$< 5*10^{-14}$ /°C
Magnetic sensitivity	$< 1*10^{-13}$ / Gauss
Mass and volume	3.3 kg and 2.4 liter

Table I : RAFS GSTB-V2 general performance achieved

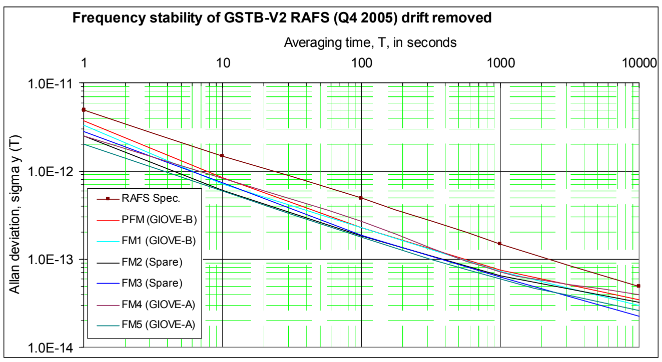

Figure 1. RAFS GSTB-V2 Allan deviation (ground measurements)

Figure 2. Picture of the GSTB-V2 RAFS

The detailed description of these units was published in previous EFTF paper [1].

III. LIFETIME EXTRAPOLATION FROM GROUND TESTING

In the frame of the "Lifetime Qualification of Rubidium Clock", five RAFS EQM's were manufactured and tested under vacuum in order to perform the monitoring of the potential lifetime limitations of the RAFS.

The test bench is composed of five identical units and some common elements.

The five identical units are composed of:

- the vacuum chamber with pumping system and gauge
- the cooled base-plate
- the frequency measurement system (including PC)
- the TM output terminals

The common elements are:

- the reference frequency system; H-Maser with GPS monitoring and the frequency distribution unit (common for all the TNT facilities).
- the frequency measurements instruments; five Picotime instruments measure independently each unit.
- the automatic TM measurement system; parameters with possible ageing are monitored.
- the power supply; five RAFS are connected on two 12V batteries in serie
- The cooling system; the five cooled base-plate are connected in serie

The overall layout of the test bench are illustrated below. Most of the parts are of-the-shelf standard parts.

Figure 3. The five vacuum chambers used for lifetime test.

From the validation of the test bench and the tuning of the 5 RAFS EQM's, a total period of about 12 months of testing/adjustment was performed. Then, a first period of one year of continuous measurement was performed. At the end of this first year of measurement, the units were dismounted and inspected. Then, the five re-assembled RAFS were submitted to the second year of continuous operation with parameters monitoring.

In total six parameters were measured:

- Output Frequency
- Rb spectral lamp light intensity emission
- Rb atomic response signal level
- Crystal control voltage
- Regulated internal reference voltage
- Interrogation power injected in micro-wave cell

Three typical records are shown in figure 4 to 6.

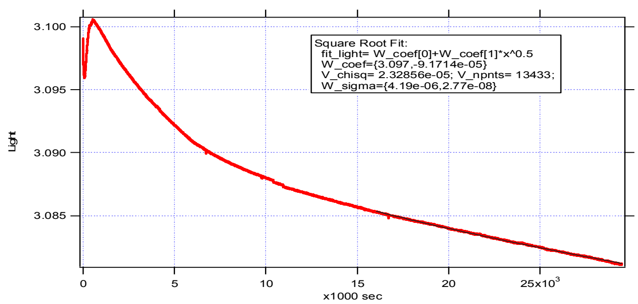

Figure 4. One year spectral lamp light intensity monitoring on "lifetime" EQM5

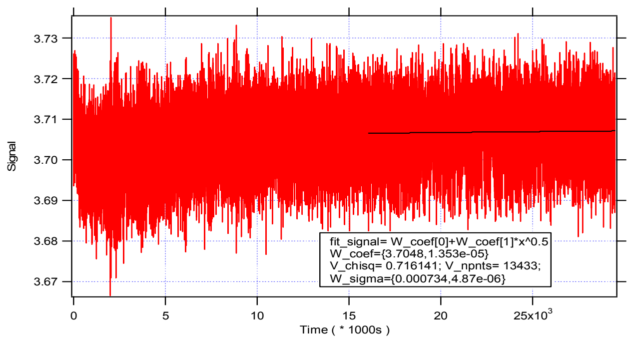

Figure 5. One year Rb atomic response signal monitoring on "lifetime" EQM5

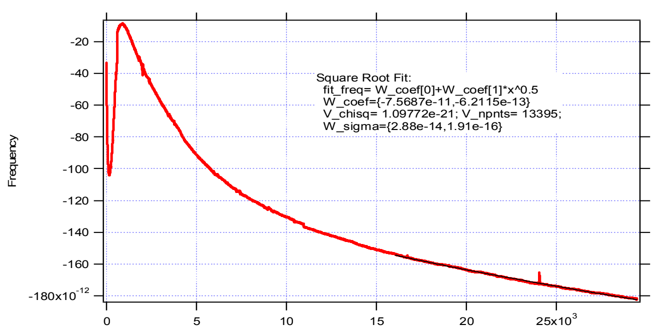

Figure 6. 1 years 10 MHz output frequency measurement on "lifetime" EQM5

Based on the records, an extrapolation for 12 years was performed. Different fittings were evaluated to generate the extrapolation formula.

For the Rb spectral lamp light intensity and the Rb atomic signal level the best fitting corresponds to a formula based on square root of time and is the one used for the prediction table (see table II). This result was predictable considering that the ageing effect on the lamp is related to the Rb diffusion in the surrounding glass. This phenomena is well known and was measured by several institutes with same results, in relation with square root of time [2]. The prediction demonstrates that no major impact on performances are foreseen for a lifetime of 12 years.

An example of Rb spectral lamp light intensity extrapolation is illustrated in figure 7 (EQM5). The red curve is the measurement data during one year, the black one is an exponential fitting curve, the blue one a linear fitting and the best fitting is the green curve in square root of time

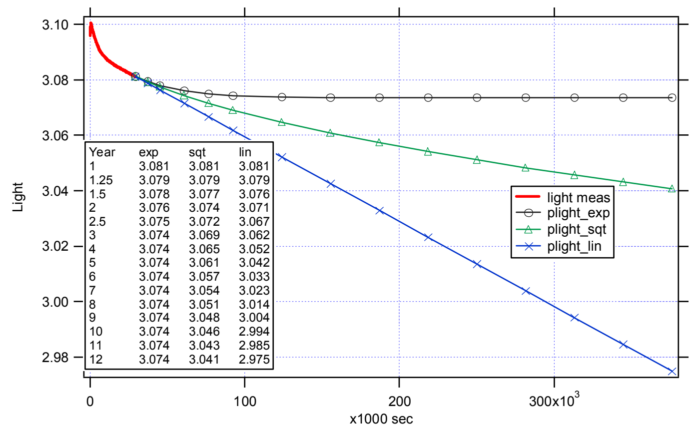

Figure 7. Spectral lamp light intensity TM on "lifetime" EQM5 with prediction on 12 years

A strong correlation between the spectral lamp ageing and the frequency drift is also clear. Papers were already published on this topic [3].

The table II provides the summary of these key parameters predicted evolution using square root of time for the five EQM units submitted to life testing. Such extrapolation is corresponding to the law of Rb absorption into the lamp walls.

Square root of time extrapolation on 12 years

	EQM1	EQM2	EQM3	EQM4	EQM5
Freq	-9.2E-10	+1.8E-10	-4.2E-10	-6.5E-10	-4.5E-10
Light	-15%	-18%	-20%	-11%	-6%
Signal	-11%	-1%	-7.5%	-2%	<-1%

Table II : Extrapolation of ageing data on 12 years

IV. GIOVE-A TM (January –October 2006)

In order to verify the in-orbit RAFS ageing, as demonstrated in the lifetime program, the main telemetries are related to the spectral lamp light intensity level and the atomic signal level.

The 10th January 2006, the RAFS FM4 was switched-on for the first time in orbit. The establishment of the internal TM was exactly in agreement with the ones recorded during laboratory test (figure 8).

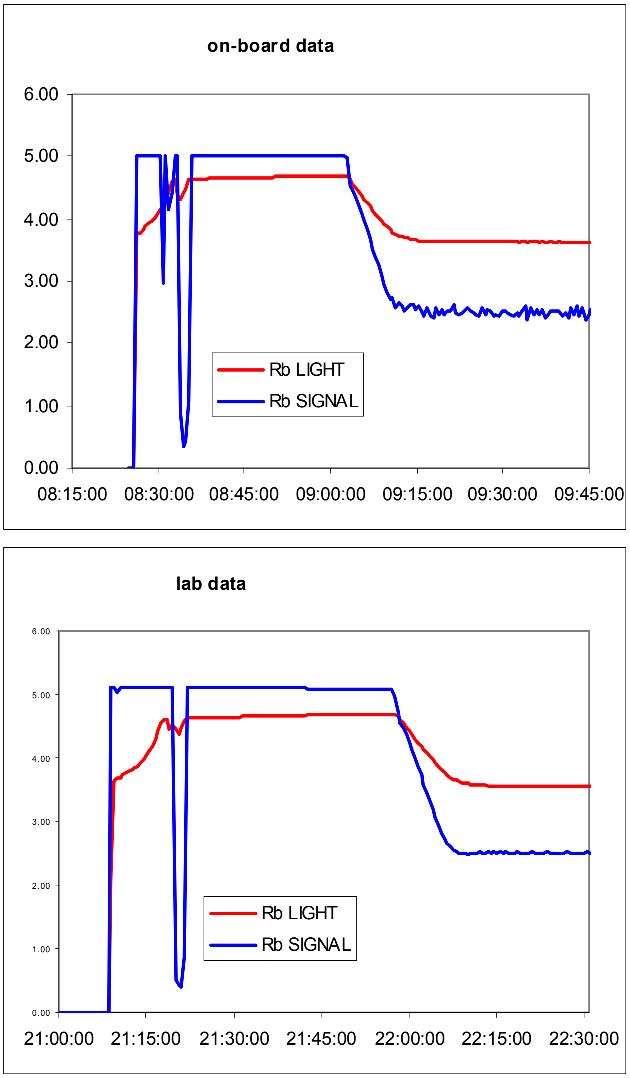

Figure 8. Comparison of the stabilisation process of the critical TM during the warm-up in orbit and on ground

Spectral Lamp Light Intensity TM

The spectral lamp light intensity level is collected through the photo-cell located inside the micro-wave assembly. When the lamp is switched-off, the reference level is 2.0V. The saturation is at about 4.8V. In nominal operation, the FM4 level was set at about 3.5V.

After an OFF period, the micro-wave assembly is cold and the vapor of Rb is at a very low density. By the way, no light is absorbed and the photo-cell is saturated (4.8V). After about one hour, the micro-wave assembly reaches its nominal temperature and the photo-cell indicates the operational level (about 3.5V).

In the figure below we observe several ON-OFF cycles including a long OFF period between the day 100 and 140.

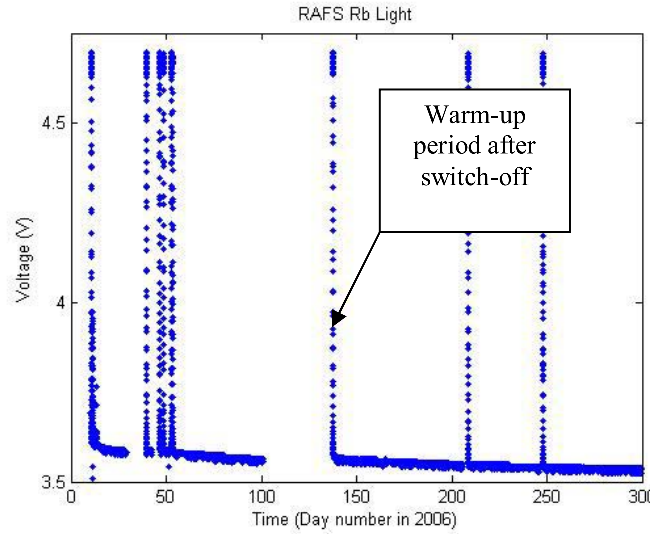

Figure 9. Spectral lamp light intensity TM from FM4 (GIOVE-A)

During the life of the clock, the spectral lamp light intensity will slowly decay due to the Rb diffusion in the surrounding glass. As observed during the lifetime test program, the decay of light intensity is a function which follow to the square root of time. The TM coming from the in-orbit FM4 is in line with the expectation coming out of the lifetime program. In addition, when the unit is OFF, the ageing process stops and the next ON level is equal to the last level in the previous ON period.

It must be noted that the frequency drift of the RAFS is nearly proportional to the decay of the light. So, the frequency drift value decays with time for a better performance.

As illustrated in figure 10, the FM4 light TM measurement is affected by the digitalisation noise due to the A/D converter low resolution (8 bit resolution).

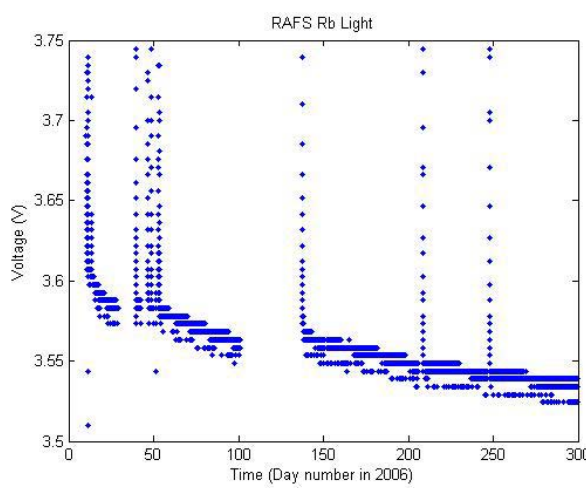

Figure 10. Zoom on Spectral lamp light intensity TM

Atomic Signal level TM

After the warm-up period (about one hour), the lower is the TM voltage, the higher is Atomic Signal level. When no signal exists, the TM provides 5V. The value of 5V is observed each time after a switch-off of several minutes (or more) as the density of the Rb vapor in the cell is too low to collect a signal.

For the FM4, the signal is nominal at 2.5V. The small ageing variation of TM is due to a decay of the Atomic Signal related to the decay of the spectral lamp light intensity. This low decay has no visible effect on the frequency stability.

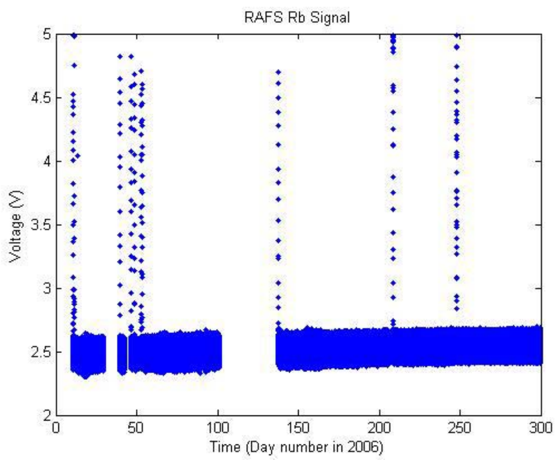

Figure 11. Atomic Signal TM from FM4 (GIOVE-A)

The noise measured on the Atomic Signal is related to the ripple of the analogue TM (+/-150 mV) and is nominal.

Here again, the in-orbit measurement results are similar to the ground measurement results coming from the lifetime program.

V. CONCLUSIONS:

The lifetime program running on five reference units has provided useful results and demonstrated the capability of the RAFS to operate for 12 years under vacuum without significant degradation.

Based on the TM from January to October 2006, the RAFS FM4 operates according to the expectation.

The small ageing trend observed is in line with prediction of the lifetime program results and is compatible with Galileo 12 years mission.

The numerous switch-on / switch-off sequences operated on the RAFS FM4 have not affected the overall clock behaviour.

The real environmental space conditions seem not to affect the ageing behaviour in comparison with the simulated one used for lifetime testing.

VI. REFERENCES

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