The Onboard Galileo Rubidium and Passive Maser, Status & Performance

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Abstract—**Galileo program is approved by the European Commission and the European Space Agency (ESA). The activities related to GSTBV2 experimental satellite as well as the implementation of the In Orbit Validation 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. This article gives a general overview on the RAFS and the PHM developments and evolution up to now. It also provides updated information on the performance measurement results and qualification status.**

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 RAFSs and two PHMs. 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 Neuchatel (ON) from end of 1980s and Temex Neuchâtel Time (TNT) since 1995. These studies have been continuously supported by Switzerland 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. Two experimental satellites will be launched by the end of 2005 or beginning of 2006, 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 will be one PHM and two RAFS on board the satellite supplied by Galileo Industries and two RAFS on the satellite supplied by Surrey Satellite Technologies Ltd.

This article gives a general overview on the space RAFS and the PHM developments and evolution up to now, lifetime expectation and qualification status.

II. DEVELOPMENT ACTIVITIES OF ON-BOARD CLOCKS

A. Development & Qualification Activities of Rubidium Atomic Frequency Standard

The RAFS development milestones are chronologically listed as below:

1) The first development activity kicked off at TNT in 1997, and completed in 2000 with one Engineering Model (EM) RAFS1 produced [1].

2) The updated RAFS1 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. In this phase, the achieved activities include:

- Improved clock stability with inclusion of thermally regulated base plate. Fig. 1 is the picture of the updated RAFS1.
- Review of electronics package layout and components in view of flight production.
- Manufacturing of 5 Engineering Qualification Models (EQM) for lifetime qualification. Fig. 2 shows 5 EQMs without external cover and 5 vacuum chambers for life test with 'Picotime' measurement systems.
- Manufacturing of 1 Qualification Model (QM).

Besides the vibration and EMC/EMI qualification tests, two radiation tests were carried out at CNES in Toulouse: one test with Galileo orbit simulation, i.e. 4 cycles of 3rad per day during one week, and the other with total dose simulation over the mission duration, i.e. 30 krad continuous radiation @ 400 rad/h during 3 days. No frequency radiation sensitivity was observed during the former test. For the latter test no electronic failure or performance degradation was observed, but it showed the need for wider compensation of the drift of the crystal oscillator. The modification has been implemented on subsequent models. The stability achieved $<2.5*10^{-14}$/day in 'best temperature conditions' under vacuum of the RAFS1 model is shown in Fig. 3.

3) A third 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. Two main objectives were achieved [2]:

Figure 1. Picture of the updated RAFS1 once closed including the thermally regulated base plate

Figure 2. Five EQMs without external cover and vacuum chambers for life test with 'Picotime' measurement systems

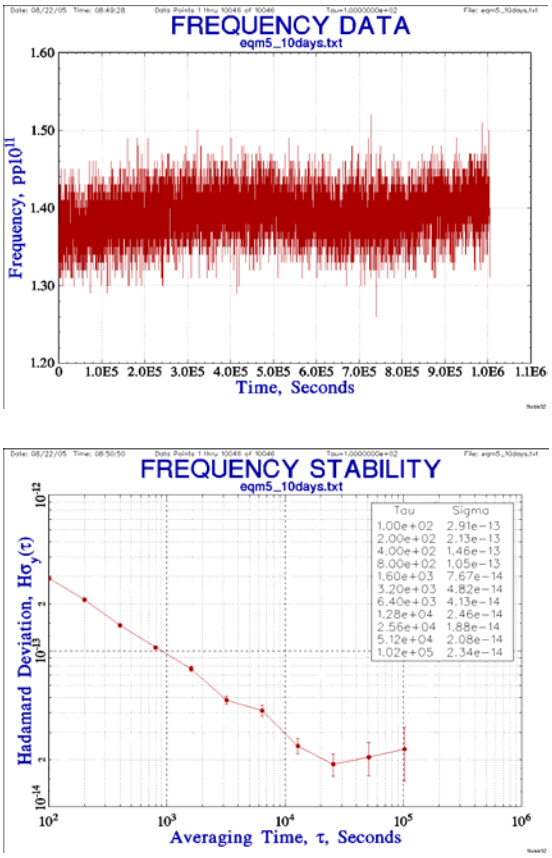

Figure 3. RAFS1 EQM frequency data and frequency stability

- Further optimisation of the physics package to reduce temperature sensitivity resulting better short/mid term stability with a temperature & vacuum environment similar to satellite platform environement (with +- 1°C temperature changes).
- Inclusion of a DC/DC converter and the satellite TT&C interface compatible with ESA's new requirements. Fig. 4 shows the performances achieved in term of frequency & time stabilities. Within this configuration RAFS2 shows capabilities to perform time stability close to 1 ns over 1 day.

Fig. 5 shows the internal construction consisting in RAFS core unit equipped with the thermally regulated baseplate & DC-DC converter.

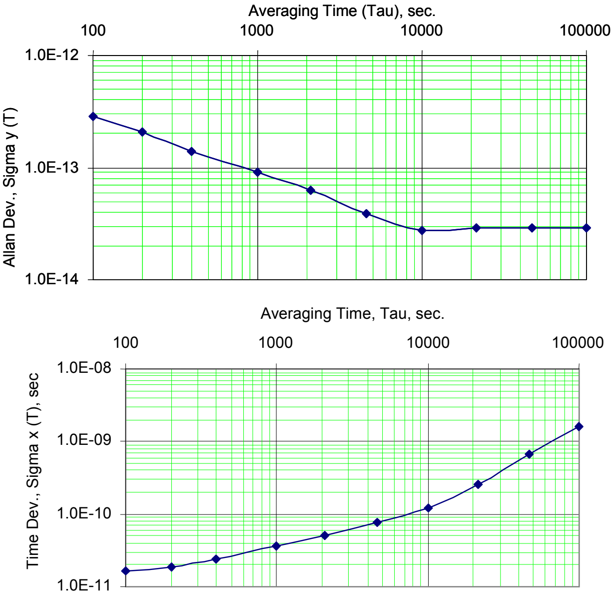

Figure 4. RAFS2 core model frequency and time stabilities

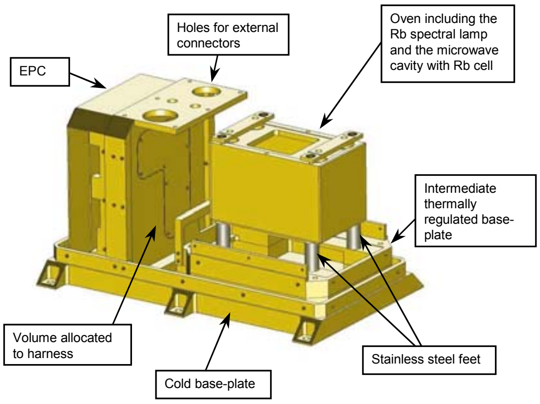

Figure 5. RAFS2 internal construction

4) In the frame of GSTB-V2, one EQM, one Proto-Flight Model (PFM) and three Flight Model (FM) units have been delivered (integration and tests on satellites are on-going). Two FM spare units are under test and ready to be delivered if required. Table I lists the achieved RAFS performance for GSTB-V2. Fig. 6 shows the measured frequency stability of GSTB-V2 PFM and FM1 to FM4.

5) Further investigations to improve the flicker floor and temperature sensitivity are under way . Beside the 'zero' temperature coefficient provided by the light shift and gaz pressure shift into the cell , the lamp has also been optimized and demonstrates 'zero' temperature coefficient. Nevertheless, still temperature coefficients of $5*10^{-14}$/°C have been observed. By improving the RF atomic interrogation signal stabilisation circuitry , RAFS has demonstrated stabilities in a range fo $7*10^{-15}$ for half of day (Fig. 7) or more observation time. Power shift coefficient has been measured arround $1*10^{-10}$/dB change in power. Therefore, few ppm / °C of atomic interrogation signal is required to reach stabilities within the 10^{-15} range. A carreful worst case analysis of possibles temperature drifts of parameters associated to the automatic gain control has been performed and demonstates the feasibility and possible repeatability of a RAFS having short term stability over one day lower than $1*10^{-14}$.

TABLE I. RAFS FOR GSTB-V2 PERFORMANCE ACHIEVED

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

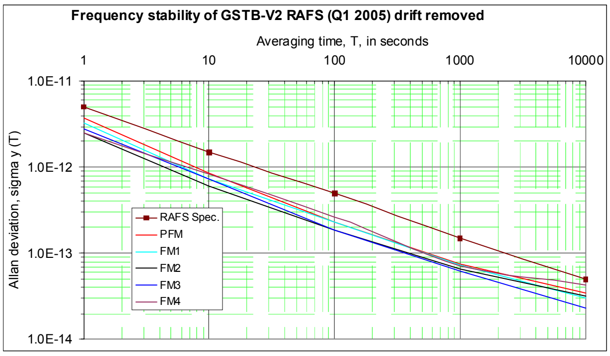

Figure 6. GSTB-V2 RAFS2 frequency stability

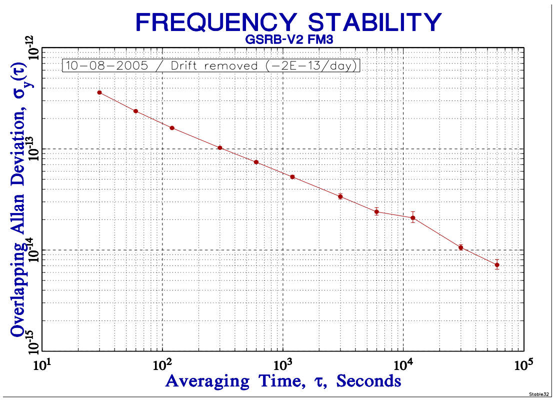

Figure 7. RAFS3 frequency stability

B. Development & Qualification Activities of Passive Hydrogen Maser

The space hydrogen maser will be the master clock on the Galileo navigation payload. The first maser development activity tailored to navigation applications was kicked off in 1998. It was initiated by the development of an active maser at ON However, at the Galileo definition phase, it became clear that the accommodation of the active maser on the satellite was too penalizing in term of mass and volume, and the excellent frequency stability performances of the active maser were not required. In 2000 it was re-orientated towards the development of a PHM based on the industrial design and ON heritage on active maser studies.

The development of the EM (Fig. 8) [3] was completed at the beginning of 2003, under the lead of ON with Galileo Avionica (GA) subcontractor for the electronics package and TNT supporting the activity in view of the future PHM industrialisation. The instrument has been under continuous test since June 2003 for assessment of long term performance and early identification of reliability and lifetime problems. This EM model (Fig. 9) shows the frequency and time stability at first stage. By comparison, about 5 years of design optimisation and intensive testing has been necessary to reach such level of performances with the RAFS.

The industrialization activity aimed at PHM design consolidation for future flight production was started in January 2003 [4]. The industrial consortium is led by GA designing the electronics package with TNT responsible for the manufacturing of the physical package and the ON supporting the transfer of technology. The overall structure of the instrument was reviewed to increase compactness and to ease the Assembly, Integration and Test (AIT) processes on the satellite by the inclusion of an external vacuum envelope. Main efforts in the industrialization frame focused on the definition of repeatable and reliable manufacturing processes and fixtures, particularly for the physical package:

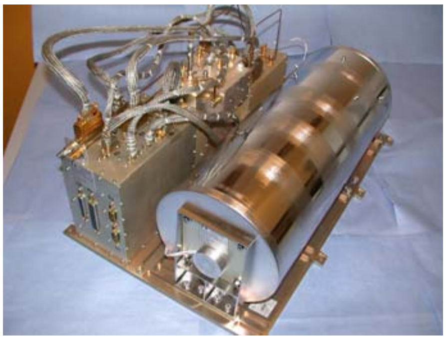

Figure 8. Picture of PHM EM. ON&GA

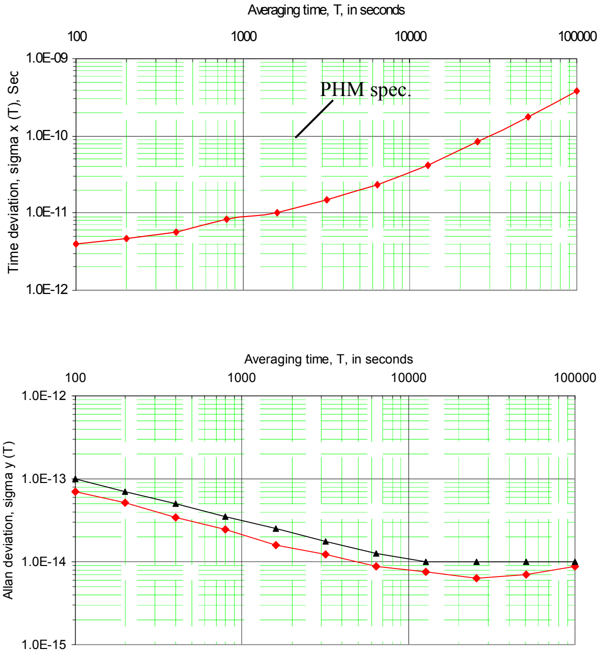

Figure 9. PHM EM frequency and time stabilities

- Teflonization of the quartz storage Bulb
- Hydrogen beam assembly
- Getters assembly
- Tuning of the microwave cavity
- H2 purifier assembly
- Magnetic shield assembly
- State selector assembly
- Hydrogen supply and dissociator

Fig. 10 shows the atomic response of the PHM physics package, measured with 15Hz span exhibiting atomic signal gain of 3.8dB and atomic line width of 2 Hz.

The new design of the physics package has been also focussed on parts count reduction. Less than one half individual parts has been used in the new design compared to the EM model.

For the electronics package and the whole instrument:

- Reduction of PHM volume and footprint
- Improvement of TM/TC interface
- Ground operability at ambient pressure
- Redesign of hydrogen dissociator
- Improvement of thermal and pressure controls
- Redesign of PHM and Purifier supply

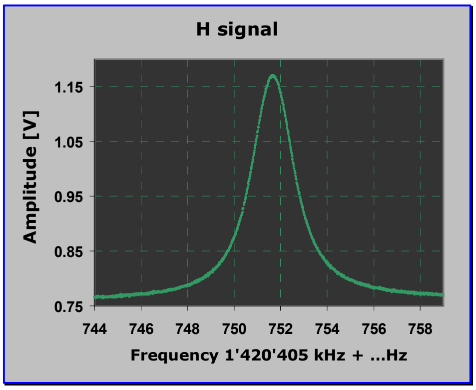

Figure 10. PHM atomic signal measured in FM1

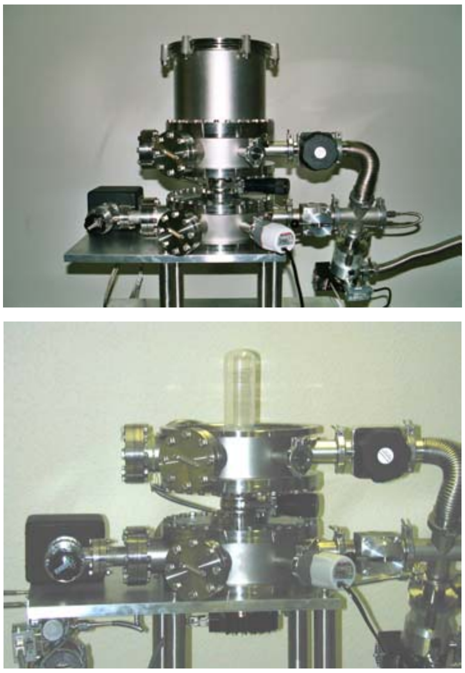

Figure 11. Technological models with/without cover

Two technological models (Fig. 11), a Structural Model and an EQM were built for these objectives and to qualify the new upgraded design. In addition, four EQMs for life demonstration are being manufactured and will be submitted to prolonged testing. In the frame of GSTB-V2, which is presently being tested at P/L level, one PFM (Fig. 12) has completed the proto-qualification testing and has been delivered. One spare FM will be delivered by the end of 2005. Table II shows the achieved performance of PHM/PFM for GSTBV2. Significant improvement has been achieved by a better silver coating process and surface polishing of the magnetron cavity (Fig 13). Fig. 14 is showing the performances improvements of the physics package of FM1 model before its integration, obtained by the quality factor improvement.

Figure 12. Picture of PHM PFM

TABLE II. PHM FOR GSTB-V2 PERFORMANCE ACHIEVED

Parameter	**Measurement**
Frequency stability	$< 1*10^{-14}$ @ 10’000 sec
Flicker floor	$< 7*10^{-15}$
Thermal sensitivity	$< 3*10^{-14}$ /°C
Magnetic sensitivity	$< 4*10^{-14}$ / Gauss
Mass and volume	18 kg and 28 liter

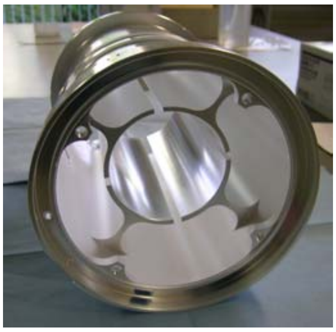

Figure 13. PHM magnetron cavity

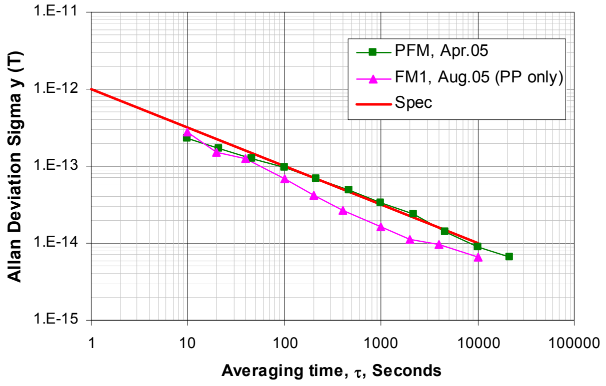

Figure 14. PHM performance improvement

PHM Lifetime

The PHM is being sized to guarantee 12 years of orbit life plus 1 year of ground storage, as well as the complete AIT program. The operational life is mainly limited by capacities of the hydrogen container (for H_2 supply), bulk getters (for H_2 sorption), ion pump (for pumping ungetterable background gases) and the total dose of ionising radiation. The lifetime is assessed by analysis and tests of subassemblies.

Fig. 15 shows the H_2 consumption test made in June 2005, which indicates the consumption of 1.53 bar*l/year at nominal flux, by measuring the pressure decay in the known volume of the high pressure pipeline. Taking account of the margin from the real consumption and the retrievable H_2 amount in the fixed pressure of the metal hydride, the H_2 container with the capacity of 30 bar*l is sufficient for the operational life time.

A novel custom built getter pump is developed for the PHM. The getter material provides high sorption capability and mechanical stability. The H_2 sorption test on the getter cartridge was performed in Sep 2003. Fig. 16 shows several cycles of the H_2 filling and pumping during the test. It has demonstrated that the getter pump is capable of sorbing the required amount of H_2 of 20 bar*l without embrittlement and the base pressure after the sorption was in the low 10^{-7} mbar range with only the getter cartridge pumping.

For the ion pump, the operating life at $5*10^{-6}$mbar is specified 8000 hours, corresponding to 400'000 hours (45 years) at the nominal high vacuum of 10^{-7} mbar. Moreover, accelerated lifetime tests of the pump in a gas composition as close to the PHM situation as possible will be performed to assure the pump life.

The total dose of ionising radiation over the mission lifetime on board of the Galileo Spacecraft was analysed on the PHM physics package and electronics package, respectively by the approach of 'sector'. The radiation test will be performed.

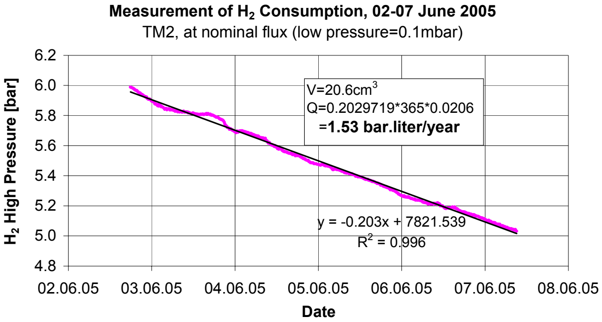

Figure 15. H2 consumption test

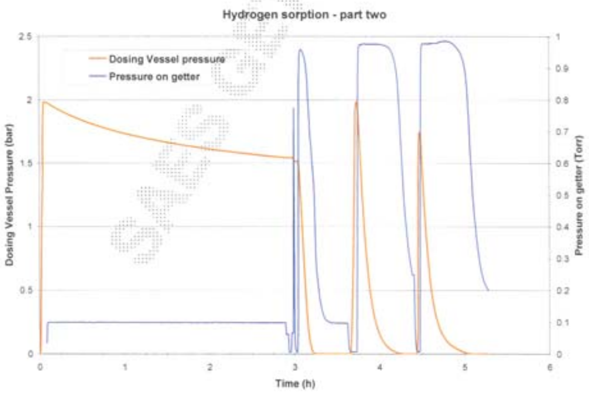

Figure 16. H_2 sorption test

In order to gain more field data on the reliability and lifetime of PP subassemblies four EQMs will be produced dedicated to the lifetime. The objective of the lifetime test is to monitor, during the scheduled two years, the critical parameters drift or degradation in order to predict the lifetime of the instrument and identify possible correction areas.

III. CONCLUSIONS

Table III summarizes the Galileo clocks status up to now. Both clocks are subjected to electrical (functional, thermal vacuum, EMC, etc.), as well as, mechanical tests (shock and vibrations). Nine flight models are being produced for GSTB-V2, which will provide the first flight opportunity for Galileo clocks qualification. With more than 10 years of efforts, two clock technologies for Galileo are qualified. Those clocks use reliable and mature technologies leaving room from further improvements in term of mass & performances.

TABLE III. GALILEO CLOCKS STATUS

Steps	**RAFS**	**PHM**
BB	Completed in 1995	BB activity and EM design started in 2000
EM	Completed in 2000	Completed in Q1/2003 (under life test since June 2003)
EQM	5 models built and under lifetime tests	4 models available in 2006 for lifetime tests
QM	1 model (RAFS1) fully qualified Rad. test Q1/2003	1 model
EQM for GSTB-V2	1 model delivered in August 2004	1 model completed in February 2005
FM for GSTB-V2	6 models (4 delivered, 2 by Q3 /2005)	1 model delivered, 1 model by Q4 /2005 as spare.

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