Space Passive Hydrogen Maser
- Performances and lifetime data-

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***Abstract*—Galileo navigation program is in progress under the technical supervision of the European Space Agency (ESA). The preliminary activities related to GSTBV2 experimental satellite 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 PHM, initial ground technological project related to lifetime possible limitation of the clock was initiated in parallel to satellite experimentation (GIOVE-B). Long duration frequency stability performance tests were recorded on ground demonstrating $2*10^{-15}$ clock stability at one day (including the drift). This article gives an overview on the ground lifetime data and performance of the PHM. Extrapolation for the 12 years Galileo mission duration is discussed.**

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's 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).

The activities related to Galileo System Test Bed (GIOVE satellites) experimental satellite as well as the implementation of the In Orbit Validation phase are in progress [1]. 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. The second experimental satellite (GIOVE-B) was launched 27th April 2008, and provide a more representative payload including the one PHM in addition to two RAFS. GIOVE-B satellite was supplied by Astrium. The four In Orbit Validation satellites are to be launched within the next two years.

II. Development & Qualification Activities of Passive Hydrogen Maser

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 Observatory of Neuchâtel (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 heritage on active masers studies.

The development of the EM was completed at the beginning of 2003, under the lead of ON with Selex Galileo (SG) (former Galileo Avionica) subcontractor for the electronics package and SpectraTime (SpT) (former Temex

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Neuchâtel Time) supporting the activity in view of the future PHM industrialisation. The instrument has been under continuous test for two years highlighting potential lifetime technological problems and performance limitations.

The industrialization activity aimed at PHM design consolidation for future flight qualification and production was started in January 2003. The industrial consortium was led by SG designing the electronics package and responsible for the integration of the whole instrument, with SpT responsible for the manufacturing of the physical package. The overall structure of the instrument was reviewed to increase compactness and to ease the Assembly, Integration and Test process on the satellite by the inclusion of an external vacuum envelope. The weak technological elements were fully redesigned too. Main efforts in the industrialization frame were focused on the definition of repeatable and reliable manufacturing processes and fixtures, particularly for the physical package:

- 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

and for the electronic 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

A technological model (Fig. 1), a Structural Model and an EQM were built for these objectives and to qualify the new upgraded design. In addition, four QMs for life demonstration are being manufactured and two of them are submitted to prolonged testing. In the frame of GSTB-V2, one PFM (Fig. 2) has passed the proto-qualification testing and was delivered together one other FM (i.e. Flight Spare, FS). The PFM and FS were delivered in mid-2005. Fig. 3 shows the improvement of the frequency stability performances observed along the GSTB-V2 models as resulting of the manufacturing process refining and consolidation of the alignment procedures. The FS is now operating on board of GIOVE-B since 1 year [2, 3].

Figure 1. Technological model

Figure 2. Picture of PHM PFM

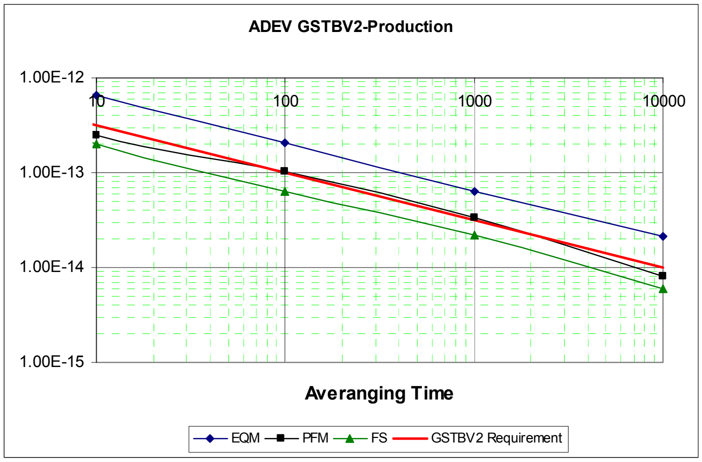

Figure 3. Allan Deviation for the GSTB-V2 models

III. PASSIVE HYDROGEN MASER ACTIVITIES FOR THE IN ORBIT VALIDATION

The IOV (In Orbit Validation) contract was signed in 2006. The scope of this Programme was the production and delivery of 8 Flight Units to be embarked on the first 4 satellites of the Galileo Constellation.

This contract has represented a new development phase for the PHM at sub-Unit level (i.e. Physic Package and Electronic Package) and Instrument level. Due to the changing of the environment and operating constraints with respect to GSTB-V2, strong efforts have been put in place in order to further improve both the PHM performances and the manufacturing processes. In particular:

- Increasing of the hydrogen storage capability
- Increasing of the storage temperature capability
- Extension of the storage time without maintenance
- Refining of the Physic Package manufacturing processes
- Improvement of the start-up logic in order to avoid any telecommand intervention
- Improvement of the PHM environmental sensitivity
- Improvement of the EMC robustness
- Improvement of the TT&C interface
- Refining of the electronic design in order to simplify the tuning and improve its reliability

An EQM has been successfully qualified against the new Galileo requirements in April 2008 and 6 Flight Units were produced and tested in December 2008, demonstrating a production rate capability near to 1 PHM per month with potential improvement margins.

The very good performance repeatability observed along the IOV production is illustrated in Fig. 4.

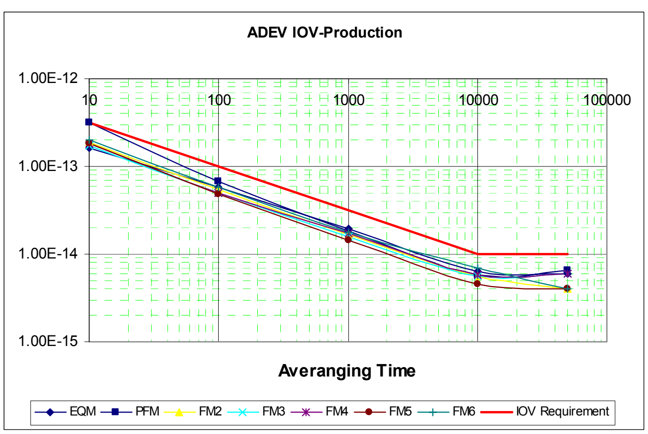

Figure 4. Allan Deviation for the IOV models with frequency drift included

IV. LIFETIME EXTRAPOLATION FROM GROUND TESTING

In the frame of the "Lifetime Qualification of PHM", two PHM QMs are contributed to the test under vacuum in order to perform the monitoring of the potential lifetime limitations of the PHM.

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

The two identical units consist of:

- the vacuum chamber with pumping system and gauge
- the base-plate connected with cooling system
- the frequency stability measurement system: Picotime measuring independently each unit
- the telemetry (TM) interface box
- the data acquisition system for additional TM
- the PC with automatic control and acquisition system
- the power supply and UPS

The common elements are:

- the QM life time test equipment, i.e. the man-machine-interface support including serial telecommand (TC) generation and main serial TM recording for both units
- the reference frequency system; H-Maser with GPS monitoring and the frequency distribution unit (common for all the SpT facilities)

The overall layout of the test bench is illustrated in Fig. 5. Most of the parts are off-the-shelf standard parts.

Figure 5. PHM QM Lifetime test bench

A total period of about 18 months of continuous measurement for each QM is required. One has been submitted to the life time test for 9 months and the other one to 1 year, respectively.

In addition to frequency stability performances, more than 20 parameters are measured:

- Atomic signal amplitude
- Cavity varactor voltage
- USO varactor voltage
- Hydrogen supply pressure and temperature

- Hydrogen dissociation oscillator voltage and current
- Dissociator optical sensor voltage
- Purifier supply setting voltage
- 10 MHz output level
- Cavity setting temperature
- PHM current (main bus)
- C-Field Current
- Ion pump voltage and current
- Cavity temperature
- Thermal plate temperature
- Vaccum container temperature
- Temperature sensor PP/EP interface
- Temperature sensor Thermal Plate/PHM interface

Most of them, do not present measurable ageing effects. The ones which are discussed below are the more relevant or affected by long term operation. Three typical records on QM1 (used as reference for this paper) are shown in Fig. 6.

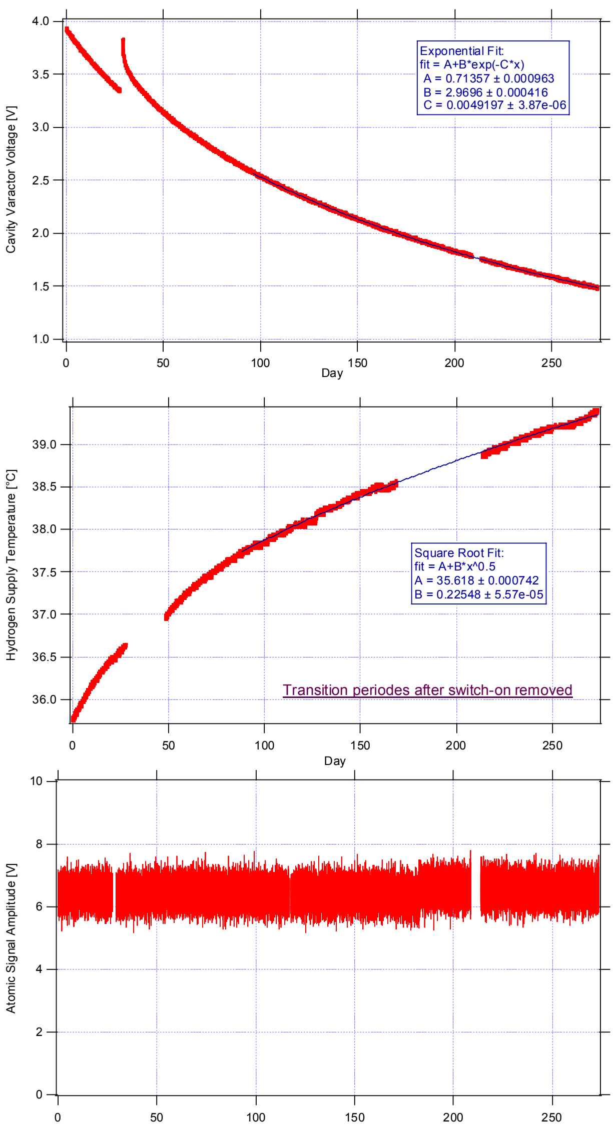

Figure 6. Nine months typical TMs (cavity varactor voltage, hydrogen supply temperature, and atomic signal amplitude) on QM1 lifetime test

The self frequency drifting of the microwave cavity used to amplify the atomic signal is highlighted by the varactor voltage variation over the time. This varactor maintains the overall microwave frequency centered to the atomic line (Automatic Cavity Tuning). For the cavity varactor voltage, the best fitting corresponds to an exponential function of time, which has been also demonstrated during the PHM physics package final test.

Another key element is the Hydrogen consumption over the time. About 25 bar*liter of Hydrogen are stored within a tank filled with hydride. By the use of the hydride, it is possible to store the 25 bar*liter within a volume as low as 0.1 liter with internal pressure below 5 bars at around 35°C temperature. During the life of the instrument, the hydrogen is consumed and the tank temperature must be increased in order to maintain the internal pressure constant. So, the temperature variation over the time is a good indication of the consumed Hydrogen. It has been observed that container temperature increasing rate is higher during first few weeks after switch-on, due to the solid-state hydride transition phase. This transition periods after switch-on were removed to evaluate the whole evolution of this parameter.

As most relevant parameter of what happen within the PHM is the atomic signal amplitude. The amplitude is sensitive to any degradation as internal coating, outgasing, leakage, dissociation efficiency, quality factor of the microwave cavity, interrogation power instability, receiver electronic degradation, temperature instability, … So, it is of primary importance to verify that the atomic signal amplitude do not decay over the life time below a reasonable limit.

Considering the measured curve, the expected behavior is very well confirmed as no noticeable ageing effect generates change in the atomic signal amplitude.

For the two remaining parameters, extrapolations for 12 years were performed, illustrated in Fig. 7 (QM1). The red curve is the measurement data during 9 months, and the blue line with dot markers is the extrapolation according to the fitting formula.

Table I provides the summary of these key parameters predicted evolution for QM1 submitted to life testing.

For the cavity varactor voltage, the predicted value is still within the adjustable frequency tuning range. Moreover, the decaying of this parameter could be compensated by increasing the cavity temperature by very small step of few m°C. Such implementation has been demonstrated by SG, without impacting on the PHM frequency stability.

For the hydrogen supply, the temperature in 12 years is about 50°C, which is in line with the expected H2 consumption. In fact, for later QMs and IOV FMs, a new type of hydrogen supply container of higher purity LN5, with lower maximum pressure and more constant pressure plateau, has been applied. In the end of life the final temperature at constant pressure will be lower than the present one for QM1, which will allow a comfortable margin for the safety reason.

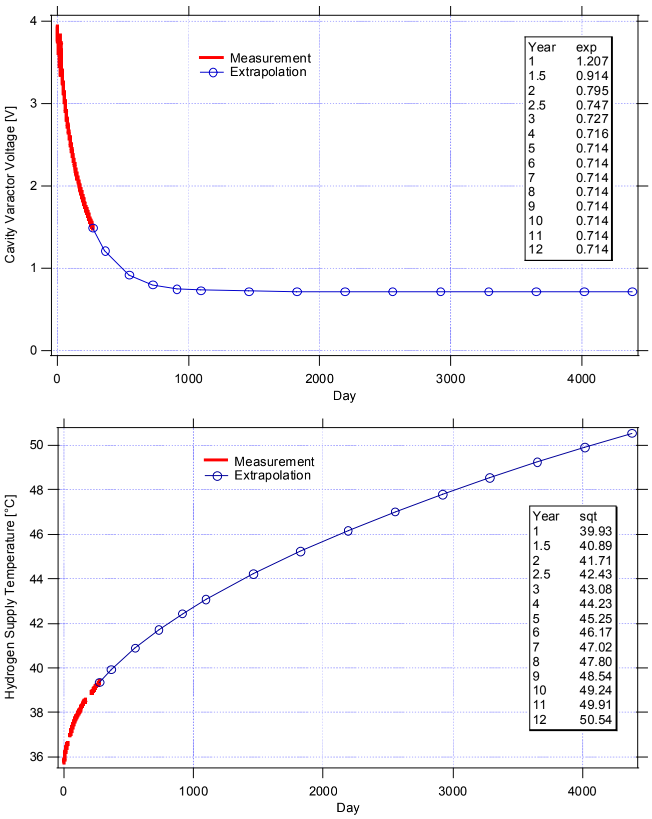

Figure 7. TMs (cavity varactor voltage and hydrogen supply temperature) on QM1 lifetime test with prediction on 12 years

TABLE I. EXTRAPOLATION OF AGEING DATA IN 12 YEARS (QM1)

TM	Extrapolation in 12 years
Cavity varactor votage	0.71V
Hydrogen supply temperature	50.5°C

The other important parameter, ion pump current is below 1mA all over the period, which indicates the high vacuum better than 10^{-7}mbar.

The prediction demonstrates that no major impact on performances is foreseen for a lifetime of 12 years.

Fig. 8 shows the QM1 frequency data and the frequency stability measured during recent last 3 months, the frequency drift was $<5*10^{-16}$/day.

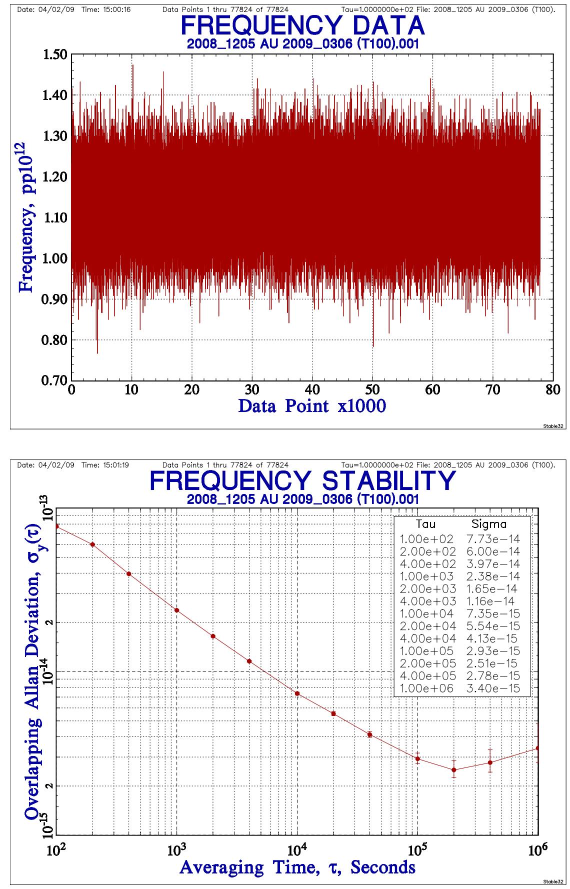

Figure 8. PHM QM1 frequency data and frequency stability (with drift)

Table II summaries the typical performances achieved in PHM ground tests.

TABLE II. SUMMARY OF PHM GROUND PERFORMANCES

Parameter	Measurement
Frequency stability	$< 7*10^{-15}$ @ 10'000 sec
Flicker floor	$< 3*10^{-15}$
Drift	$< 1*10^{-15}$ /day
Thermal sensitivity	$< 3*10^{-14}$ /°C
Magnetic sensitivity	$< 3*10^{-13}$ / Gauss
Mass	18 kg

V. CONCLUSIONS

The lifetime program has been providing useful results and demonstrating the capability of the PHM to operate for 12 years under vacuum without significant degradation.

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

VI. References

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