SPACE PASSIVE HYDROGEN MASER – PERFORMANCES, LIFETIME DATA, AND GIOVE-B-RELATED TELEMETRIES

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Abstract

Galileo navigation program development is progressing under the responsibility of the European Space Agency (ESA). GIOVE-B, an experimental satellite, has already been launched and is providing the first results. The development of four In Orbit Validation (IOV) satellites is in progress. Atomic clocks represent the key technology for the success of any satellite navigation system mission, and their development has been continuously supported by ESA. PHM is a Passive Hydrogen Maser used as a master clock on Galileo navigation satellites.

In parallel with the in-orbit experimentation of GIOVE-B satellite, a technology project has been initiated to develop and test on the ground four PHM QMs with the aim of highlighting and overcoming possible PHM lifetime limitations, before starting the full production of the navigation satellite constellation. Preliminary results of this ground lifetime testing are already available, along with the complementary data collected from the orbit. This paper gives an overview of PHM performance and telemetry data collected so far. The most relevant telemetries and their lifetime trends are compared and discussed. Long-term frequency stability performance tests have achieved a clock stability at 1 day (including the drift) of 10^{-15}. The consistency among all the telemetry measurements, their aging trends, and the excellent frequency stability provide confidence in the capability of the instrument design of meeting Galileo mission requirements.

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 this, every satellite will contain two RAFSs and two PHMs. The adoption of a “dual technology” for the onboard clocks is due to the need to ensure a sufficient degree of reliability (technology diversity) in order to fulfill the Galileo lifetime requirement (12 years).

The activities related to Galileo System Test Bed (alias GIOVE) experimental satellite, as well as the implementation of the In Orbit Validation (IOV) satellites, are in progress **[1]**. The first experimental satellite (GIOVE-A) was launched on 28 December 2005. Its purpose was to secure the Galileo frequency filing, to test some of the critical technologies such as the atomic clocks, to experiment with Galileo signals, and to characterize the MEO environment. . The second experimental satellite (GIOVE-B), developed by Astrium, was launched on 27 April 2008, and its payload includes one PHM and two RAFSs, being therefore more representative of the GALILEO future constellation. The launch of four IOV satellites will follow soon. They will carry on board the same atomic clocks of GIOVE-B with minimum modifications.

DEVELOPMENT & QUALIFICATION ACTIVITIES OF PASSIVE HYDROGEN MASERS

The first maser development activity, tailored to navigation applications, was kicked off in 1998. It started with 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 terms of mass and volume, while the excellent frequency stability performances of the active maser were not necessary. In 2000, the activity was re-orientated towards the development of a Passive Hydrogen Maser (PHM), based on the heritage of 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 Neuchâtel Time) supporting the activity in view of the future PHM industrialization. The instrument has been continuously tested for 2 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, in charge of the electronics package design and responsible for the integration of the whole instrument, with SpT responsible for the manufacturing of the physics package. The overall structure of the instrument was reviewed in order to increase compactness and to ease the Assembly, Integration, and Test process on the satellite by the inclusion of an external vacuum envelope. The technologically weak parts 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 physics package **[3]**:

- 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 (Figure 1), a Structural Model, and an EQM were built to validate the design changes and to qualify the upgraded PHM.

The EQM clock was manufactured and qualified in the frame of GIOVE-B, one PFM (Figure 1) passed the proto-qualification testing and was delivered together with an FS (i.e. Flight Spare). Both PFM and FS were delivered in mid-2005. Figure 2 shows the improvement of the frequency stability performances observed along the GIOVE-B models as the result of manufacturing process improvement and alignment procedures consolidation. The FS is now operating onboard GIOVE-B for 1.5 years **[1,2]**.

In addition to these models, the manufacturing and on ground testing of four QMs, representative of the flight units, are currently in progress. They will be used for detecting and assessing potential PHM lifetime limitations. These QMs should be operated continuously under stable and well controlled thermal-vacuum conditions, while their telemetries will be monitored, collected, and logged for later processing. Figure 5 shows PHM QM Lifetime test bench.

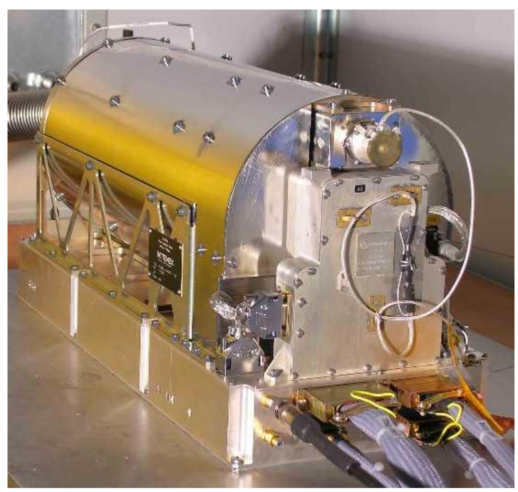


Figure 1. Technological model (on the left) and a picture of the PHM PFM (on the right).

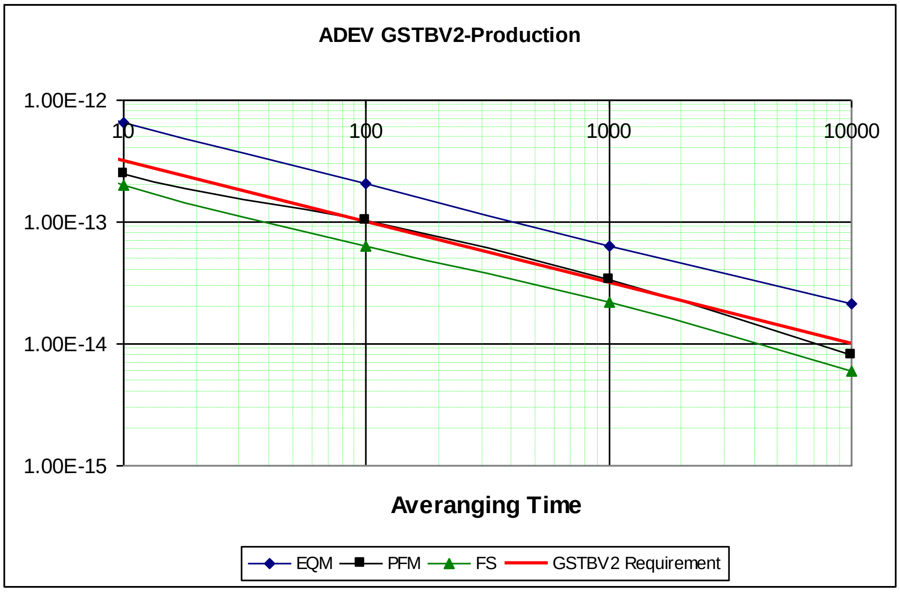


Figure 2. Allan deviation for the GIOVE-B models.

PASSIVE HYDROGEN MASER ACTIVITIES FOR THE IN ORBIT VALIDATION

The IOV (In Orbit Validation) contract was signed in 2006. The aim of this program is the production and delivery of eight Flight Units to be placed on the first four satellites of the Galileo Constellation.

This contract has represented a new development phase for the PHM, at sub-Unit level (i.e. Physics Package and Electronics Package) and Instrument level. Due to the different environment and operating constraints with respect to GIOVE-B, a strong effort has been devoted to further improve both performances and manufacturing processes of the PHM, in particular by:

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

IOV EQM was successfully qualified against the new Galileo requirements in April 2008 and six Flight Units were manufactured and tested by December 2008. This has demonstrated a production rate capability near to one PHM per month, with potential margins for improvement.

By almost the same time, radiation tests on electrical parts have shown the weakness of one component, requiring its replacement on all the PHM FMs already produced. The necessary activities for the selection, the procurement, the tests, and the substitution of a new component have unfortunately delayed at the end of 2009 the delivery of these six refurbished FMs, as well the production of the remaining two.

Figure 3. Test facilities for the PHM alignment and testing .

The excellent performance repeatability observed along the IOV production is illustrated in Figure 4.

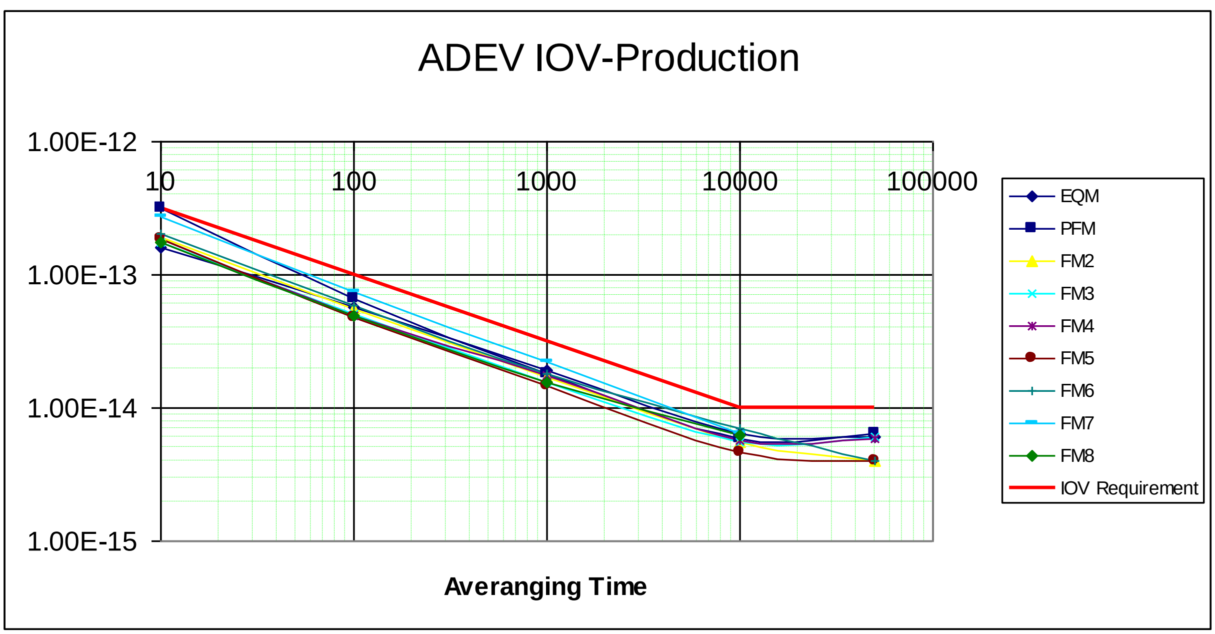


Figure 4. Allan deviation for the IOV models with frequency drift included.

LIFETIME EXTRAPOLATION FROM GROUND TESTING AND GIOVE-B DATA

In the frame of the "Lifetime Qualification of the PHM," two PHM QMs are subjected to tests under vacuum in order to highlight any potential lifetime limitations.

The overall layout of the test bench is illustrated in Figure 5.

Figure 5. PHM QM Lifetime test bench.

A total period around 18 months of continuous testing for each QM is required. One of them has already been subjected to a 15-month testing period, whereas the other one has completed the planned 18 months. 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
- Vacuum container temperature
- Temperature sensor PP/EP interface
- Temperature sensor Thermal Plate/PHM interface.

The availability of GIOVE-B data, in terms of PHM and Payload telemetries, can further improve the grade of confidence in the PHM lifetime for the following main reasons:

- It represents an additional statistical contributor
- It has been working for almost the same time period as for the QMs
- It is experiencing the actual operating conditions in terms of space environment.

The following subset of the above listed parameters is available from the GIOVE-B telemetries:

Table 1. GIOVE-B available telemetry list.

PHM Telemetries	Payload Telemetries
• Atomic signal amplitude • Cavity varactor voltage • USO varactor voltage • Hydrogen supply pressure and temperature • Dissociator optical sensor voltage • Purifier supply setting voltage • 10 MHz output level • Cavity setting temperature • PHM current • C-Field Current • Ion pump voltage and current • Cavity temperature	• HM current (from main bus) • Temperature sensor Thermal Plate/PHM interface

Most of them do not present measurable aging effects. Among them, either the more relevant telemetries or the ones affected by long-term operation are discussed in the paper.

Some preliminary life test results have been already published **[4]**. The analysis summarized in the following pages adds additional statistical element for the lifetime extrapolation.

THE MICROWAVE CAVITY AGING

The drifting of the microwave cavity resonance frequency, used to amplify the atomic signal, is highlighted by the varactor voltage variation over the time. This varactor, as part of Automatic Cavity Tuning (ACT) servo loop, maintains the microwave cavity resonance frequency tuned to the atomic line). For plotting purposes, the varactor voltage has been converted to the equivalent cavity frequency shift. This allows an easy and reliable comparison between PHM models. The rms best fitting of the cavity frequency shift consists in an exponential function of time, which has been also demonstrated during the PHM physics package final test.

The following pictures show the cavity resonance frequency shift observed in the PHM operated on GIOVE-B satellite and those measured in the two PHM QM1 and QM2 during the on-ground life tests. The curves reveal that in all cases the drift decreases with time, reaching an asymptotic value.

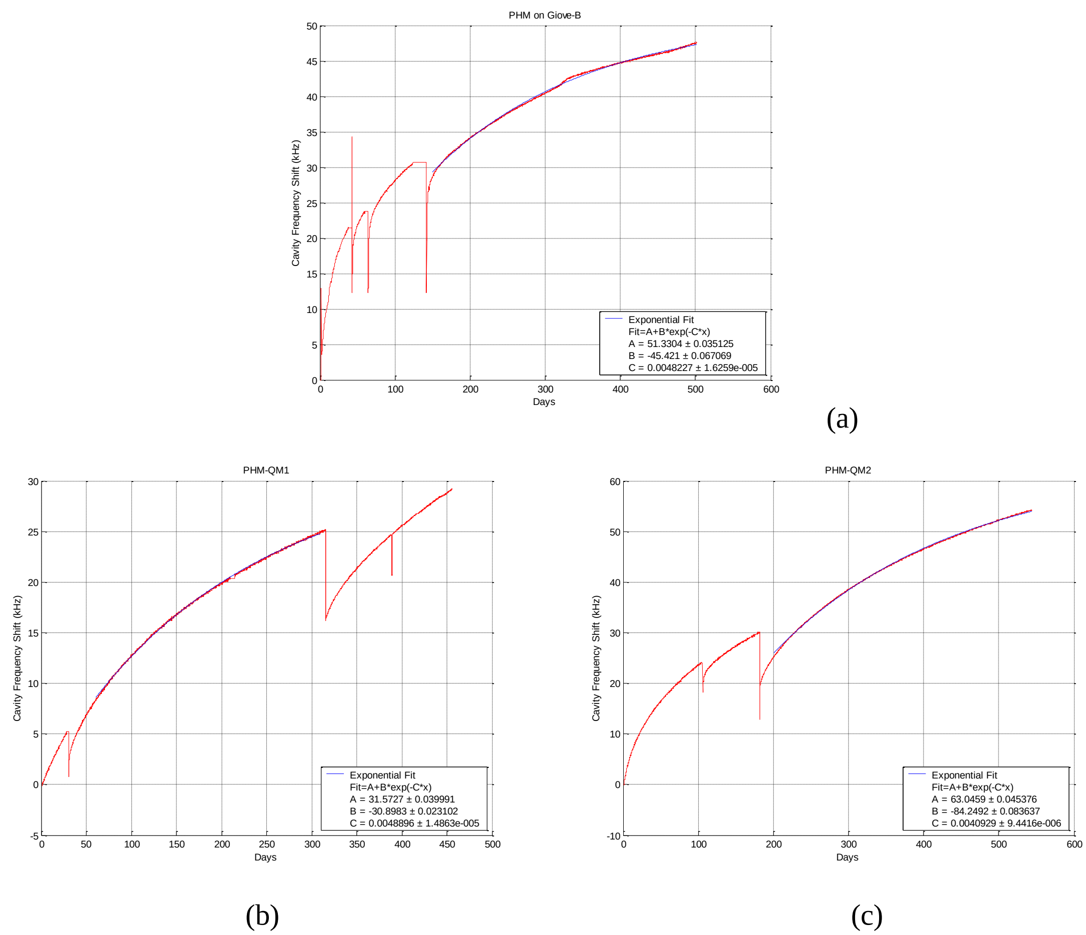


Figure 6. Cavity frequency drift measured on GIOVE-B (a) on QM1 (b) and QM2 (c).

A comparison between the trends and extrapolation over a Galileo lifetime (i.e. 12 years) is provided in the following figure.

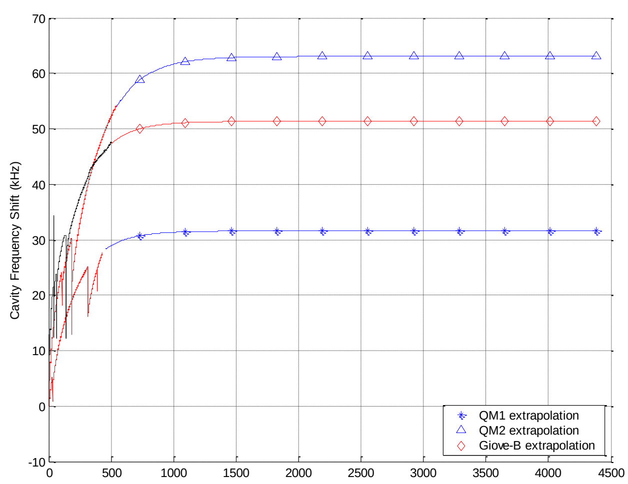


Figure 7. Cavity frequency drift measured on GIOVE-B and QM models with prediction over 12 years.

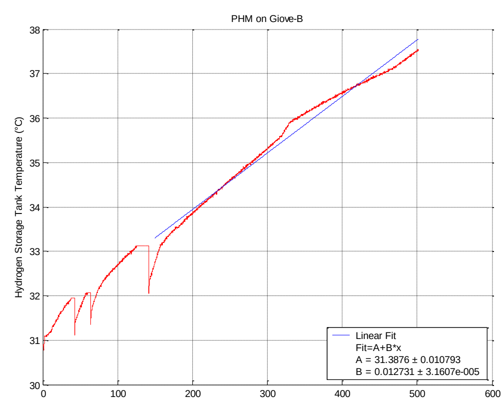
The predicted values are within the maximum adjustable cavity frequency tuning range, equal to 150 kHz. This considerable margin, with respect to the measured and predicted cavity drift, can be achieved by the combination of the ACT and the fine adjustment of the cavity temperature (by tiny steps of few mK each). Such an approach, as demonstrated by test, does not affect the PHM frequency stability.

THE HYDROGEN CONSUMPTION

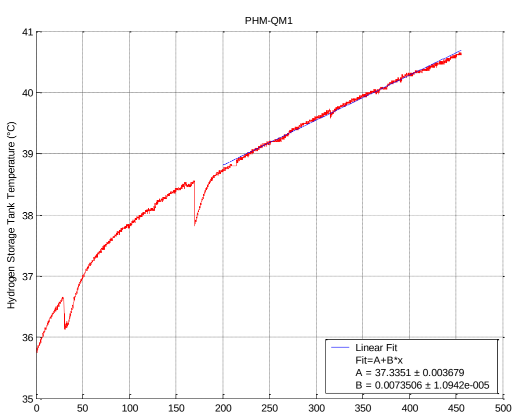
Another key aspect that has been monitored is the hydrogen consumption over the time. PHM uses a hydride to store in a tank of 0.1 liters 25 bar×liter of hydrogen, with internal pressure below 5 bars, at around 35°C temperature. During the instrument operation, the hydrogen is consumed and the tank temperature is automatically increased by a servo control loop in order to maintain the internal hydrogen pressure at the constant level required for maser operation. Therefore, the temperature variation over the time is a good indication of the hydrogen tank depletion.

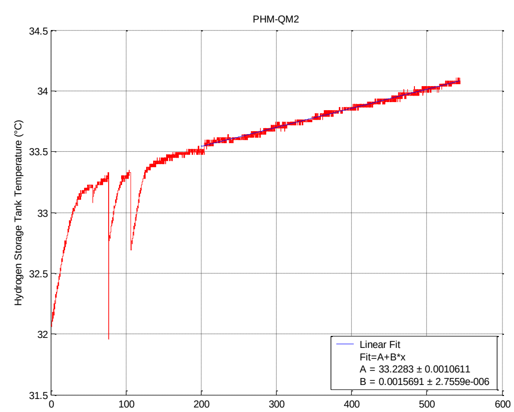
In the following figure, the measured data are reported together with the fitting equations. It can be noticed that the container temperature increasing rate is higher during the first few weeks after the switch-on. This is due to the solid-state hydride transition phase.

A linear prediction has been used even if it represents a worst-case hypothesis.



(a)





(b) (c)

Figure 8. Hydrogen tank temperature measured on GIOVE-B (a) on QM1 (b) and QM2 (c).

The trend extrapolation over 12 years is reported in the following figure.

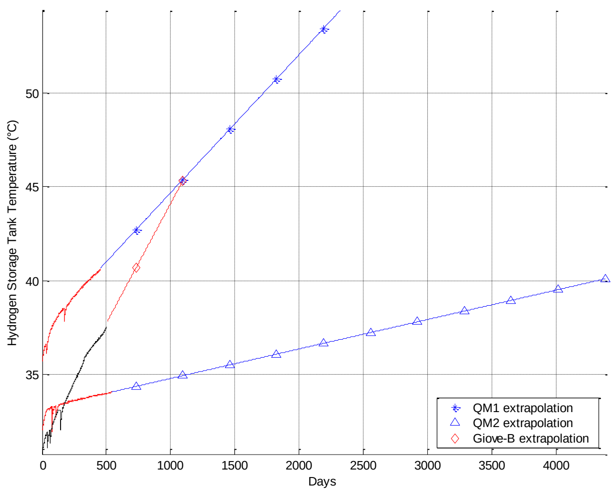


Figure 9. Hydrogen tank temperature measured on GIOVE-B and QM models with prediction over 12 years.

Considering that the maximum reachable hydrogen tank temperature is limited to 50°C (because of the available heating power), it is predicted that the QM1 hydrogen pressure will go out of regulation after 5 years of operation. However, the following aspects are worthwhile stressing:

1. The impossibility to keep the hydrogen tank pressure constant over the lifetime affects the PHM frequency drift only, but not the frequency stability performance.
2. This result is strongly affected by the adopted prediction model (i.e. linear). This is a worst-case approach that surely worsens the results of the prediction with respect to the actual trend.

A recovery action has been carried out on all PHM models from QM2 on. A new type of hydrogen supply hydride (higher purity LN5) achieving lower maximum pressure and more constant pressure plateau has been used. Thanks to this, the end-of-life temperature of the hydrogen tank needed to keep the pressure at the required constant value is considerably lower than in the QM1. This is clearly predicted in Figure 9 for QM2.

The trend analysis for GIOVE-B PHM points out that its hydrogen supply will meet the mission lifetime of 3 years with almost 1 year of margin.

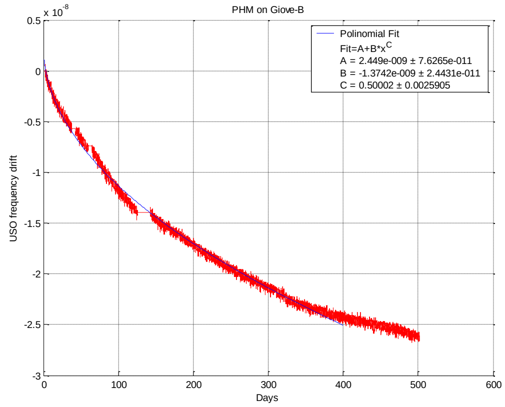
THE MASTER OSCILLATOR FREQUENCY CHANGE

The PHM 10-MHz output signal is provided by a crystal Master Oscillator (MO) that is frequency-locked to the hydrogen atomic hyperfine transition.

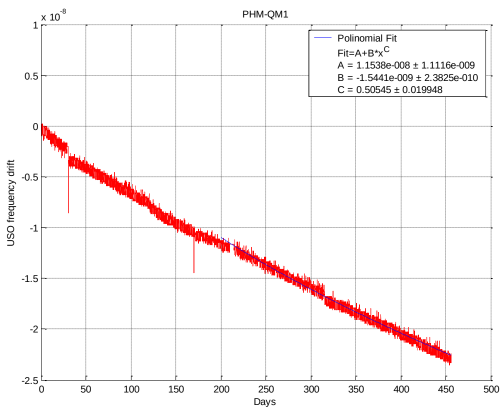
The varactor voltage that is used by a servo loop to keep the MO frequency locked to that of the hydrogen transition is monitored by the relevant PHM telemetry. Therefore, it is possible to assess the crystal frequency drift and the servo loop capability in maintaining the oscillator locked for the whole mission lifetime.

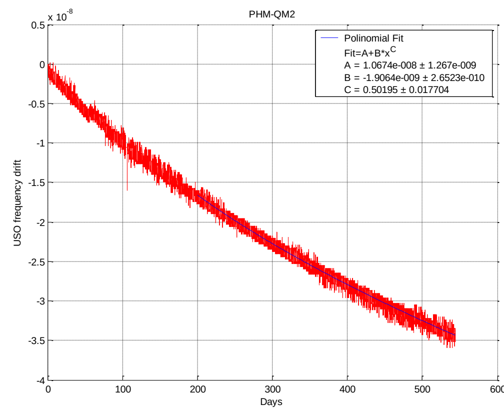
As done for the microwave cavity frequency drift, also in this case the varactor voltage is converted to the actual frequency change of the MO.

In the following graphs, the ratio between the measured frequency change with respect to the beginning of life value and the nominal output frequency (i.e. 10 MHz) is shown (Y axis) over time (X axis).



(a)





(b) (c)

Figure 10. Master Oscillator frequency change computed for GIOVE-B (a), QM1 (b) and QM2 (c).

The prediction over 12 years is reported in the following figure.

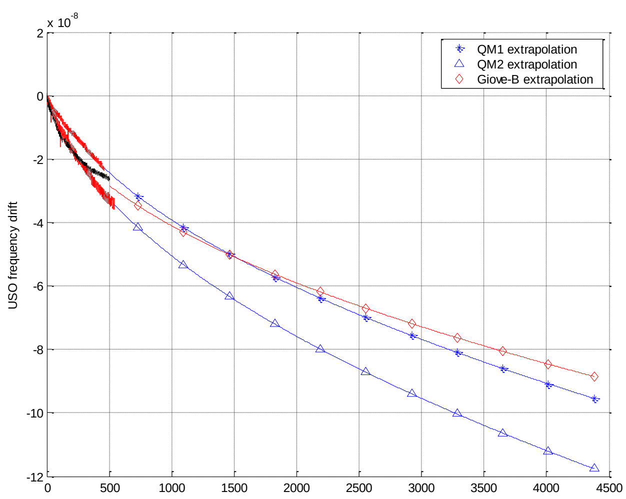


Figure 11. Master Oscillator frequency change on GIOVE-B and QM models with prediction over 12 years.

The polynomial fit adopted for the prediction, comes from the aging trend observed on the ground in several crystal oscillators. It gives a very good interval of confidence for both the trends measured on GIOVE-B and QM2. The QM1 seems to have a more linear trend, which is interpreted as an already stabilized aging effect. Lower drift observed on this model supports this interpretation.

The worst-case analysis performed at instrument level considers an overall frequency drift of the master oscillator equal to $\pm 2.1\times10^{-7}$. As shown in Figure 11, this limit is respected with almost 100% of margin. The following considerations are in order:

1. A further MO drift compensation in the order of $2\text{-}3\times10^{-7}$ can be achieved by telecommand, reducing to negligible the risk of an unexpected MO frequency change out of its control loop.
2. The MO frequency drift measured on GIOVE-B is in line with the behavior observed on the ground. The space environment (i.e. radiation effects) seems to have no effect on the actual trend.

THE ATOMIC TELEMETRY

The atomic signal amplitude telemetry provides the most relevant indication of PHM healthy operation. The following pictures show the relevant PHM telemetry measured on the GIOVE-B PHM (in space) and on QM1 and QM2 (on the ground).

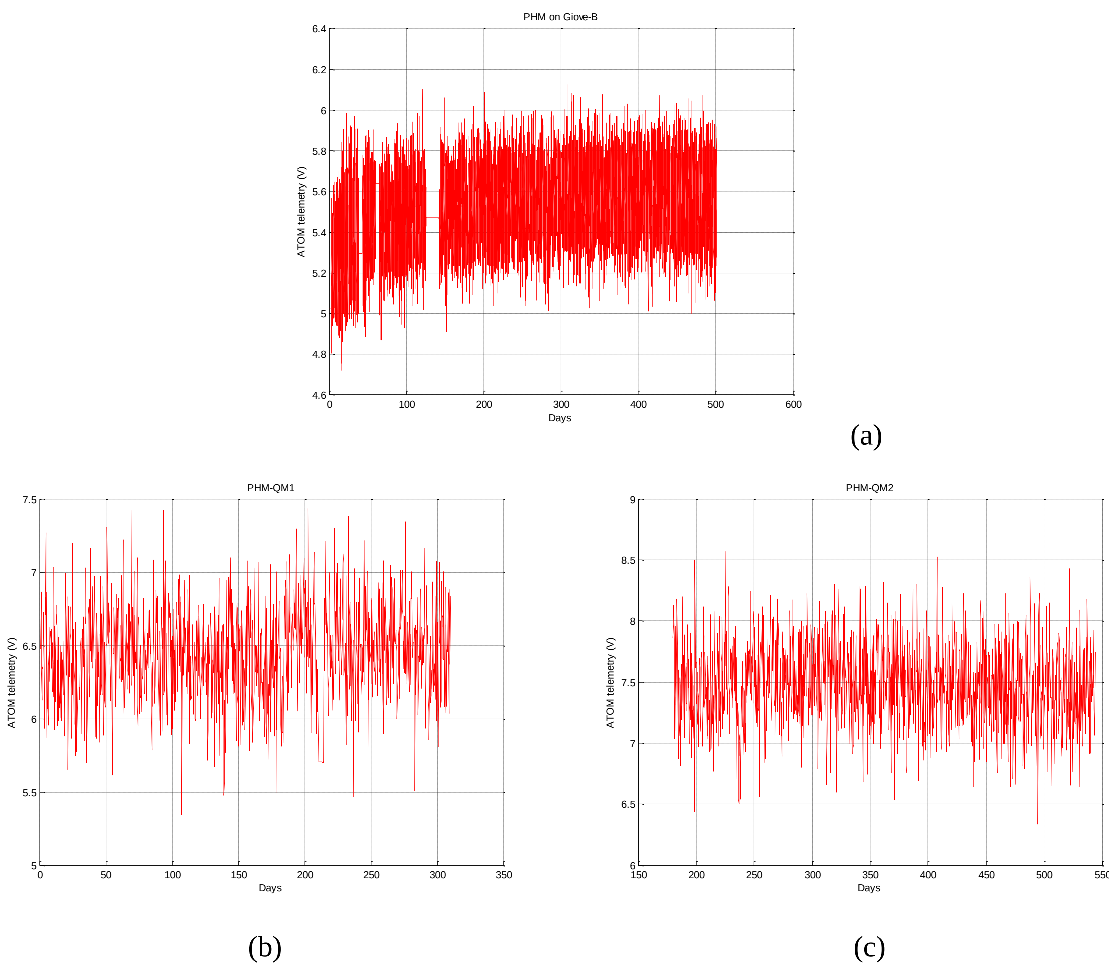


Figure 12. ATOM telemetry measured on GIOVE-B (a), on QM1 (b) and QM2 (c).

This telemetry is sensitive to many signs of degradation like changes in the internal coating of the hydrogen bulb, out-gassing of materials, vacuum leakages, loss of dissociation efficiency, decrease of the microwave cavity quality factor, interrogation power instability, receiver electronics degradation, temperature instability, etc. It is, therefore, of primary importance to verify that its decay over the life time stays below acceptable limits.

In all the three PHMs, no change in the atomic signal amplitude has been so far detected, confirming that no sign of degradation is observed after almost one-and-a-half year of operation. The following preliminary conclusions can be drawn:

1. The atomic telemetry coming from GIOVE-B is perfectly in line with the behavior observed on the ground. This is particularly important because it implies negligible effects due to space radiation on both the RF electronics and Physic Package materials.
2. A stable atomic telemetry implies proper maser operation, a necessary condition for good PHM frequency stability. This has been validated by the Allan deviation of the frequency measurements carried out on the ground and on the GIOVE-B satellite **[1]**.

The following picture shows the frequency stability measurement performed on the PHM-QM1 over the last 3 months. Both the frequency drift and the Allan deviation are very repeatable since the beginning of the life test campaign **[4]**.

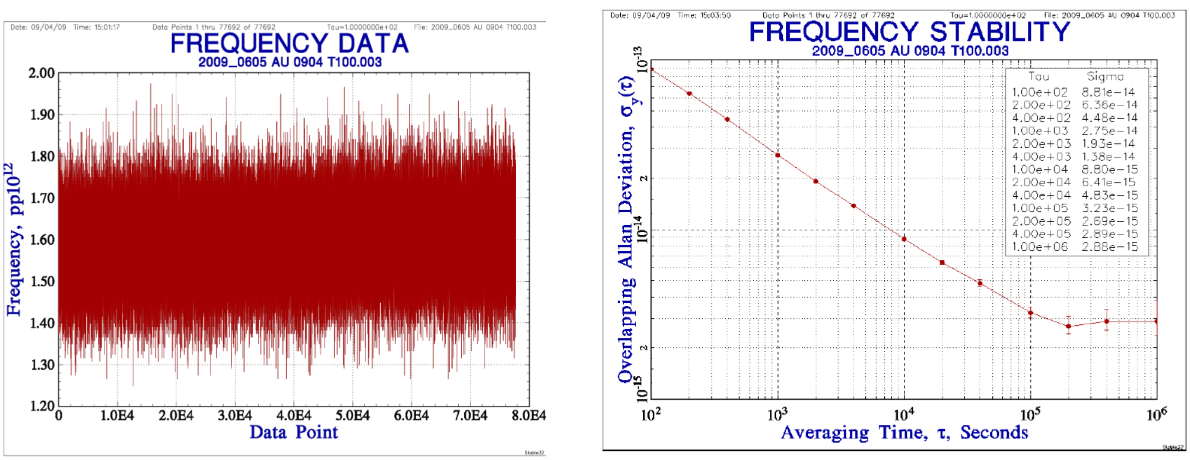


Figure 13. PHM QM1 frequency data and frequency stability (frequency drift equal to 3.72×10^{-16}/day).

The following table summarizes the typical performances achieved during the PHM ground tests.

Table 2. Typical PHM performances.

Parameter	Measurement
Frequency stability	$< 7\times10^{-15}$ @ 10'000 sec
Flicker floor	$< 3\times10^{-15}$
Drift	$< 1\times10^{-15}$/day
Thermal sensitivity	$\leq 2\times10^{-14}$/°C
Magnetic sensitivity	$< 3\times10^{-13}$/Gauss

CONCLUSIONS

On-ground measurements collected during the PHM QMs' life tests are already showing PHM capability to operate for 12 years under vacuum conditions without significant degradation.

These measurements are being complemented by the data collected from the in-orbit operation of GIOVE-B PHM. The data not only enhance the on-ground test statistics, but also confirm the instrument robustness to operate in the actual space radiation environment. The consistency among all the on-ground and in-orbit observations, the aging trends of the maser key parameters, and the excellent frequency stability and performance provide good confidence in the instrument capability of meeting Galileo mission requirements.

ACKNOWLEDGMENTS

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