

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

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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 56° 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 embark two RAFS's and two PHM's. The adoption of a "dual technology" for the on-board clocks is due to the need to insure a sufficient degree of reliability (technology diversity) in order to fulfil 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 the 28th 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 characterise the MEO environment. The second experimental satellite (GIOVE-B), developed by Astrium, was launched on the 27th April 2008, and its payload includes one PHM and two RAFS, 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 clock technology of GIOVE-B with the addition of one redundant PHM.

PASSIVE HYDROGEN MASER ACTIVITIES FOR THE IN ORBIT VALIDATION

The IOV (In Orbit Validation) contract was signed in 2006. Aim of this Programme is 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. 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 6 Flight Units were manufactured and tested by December 2008. This has demonstrated a production rate capability near to 1 PHM per month, with potential margins for improvement.

By almost the same time, radiation tests on electrical parts have showed 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 6 refurbished FMs and as well the production of the remaining two.



Fig. 3: Test facilities for the PHM alignment and testing

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

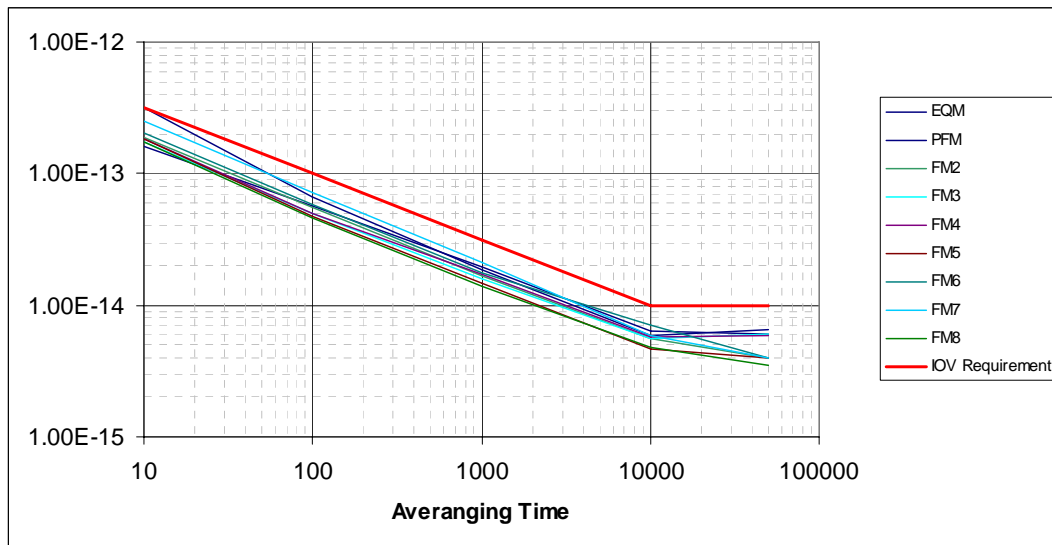


Fig. 4: Allan Deviation for the IOV models with frequency drift included

LIFETIME EXTRAPOLATION FROM GROUND TESTING AND GIOVE-B DATA

In the frame of the “Lifetime Qualification of the PHM”, two PHM QMs have been subjected to test under vacuum in order to highlight any potential lifetime limitations. The overall layout of the test bench is illustrated in Fig. 5.



Fig. 5: PHM QM Lifetime test bench

A total period around 18 months of continuous test for each QM was required. Both of them have completed the planned 18 months. In addition to frequency stability performances, more than 20 parameters have been measured.

| # | TLM description | # | TLM description |
|---|--|----|--|
| 1 | Atomic signal amplitude | 9 | PHM current (main bus) |
| 2 | USO varactor voltage | 10 | C-Field Current |
| 3 | Hydrogen supply pressure and temperature | 11 | Ion pump voltage and current |
| 4 | Hydrogen dissociation oscillator voltage and current | 12 | Cavity temperature |
| 5 | Dissociator optical sensor voltage | 13 | Thermal plate temperature |
| 6 | Purifier supply setting voltage | 14 | Vacuum container temperature |
| 7 | 10 MHz output level | 15 | Temperature sensor PP/EP interface |
| 8 | Cavity setting temperature | 16 | Temperature sensor Thermal Plate/PHM interface |

Table 1: Life test telemetry list

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

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

Most of the telemetries listed in Table 1 do not present measurable ageing 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][5]. The analysis summarized in the following pages includes the latest GIOVE telemetries and PHM-QM1 final data improving the statistical consistency for the lifetime extrapolation.

THE MICROWAVE CAVITY DRIFT

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 test and by the past models statistic.

The following pictures show the cavity resonance frequency shift observed on the PHM operating on GIOVE-B satellite and those measured on 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.

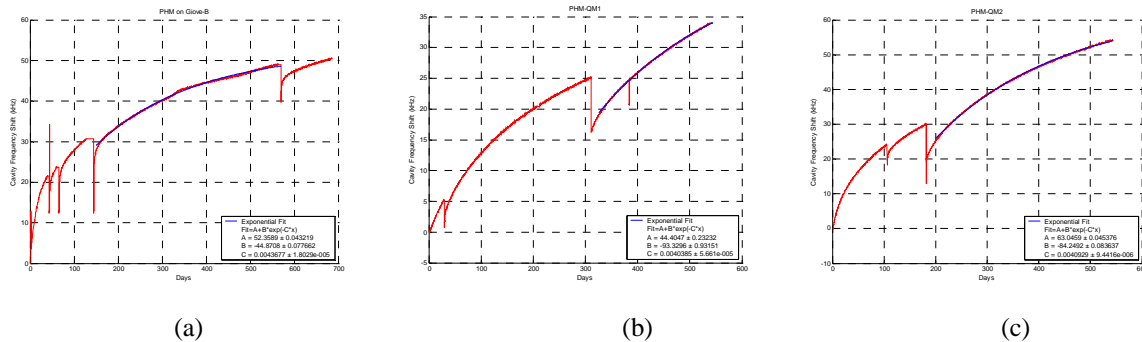


Fig. 6: Cavity frequency drift measured on GIOVE-B (a) on QM1 (b) and QM2 (c)

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

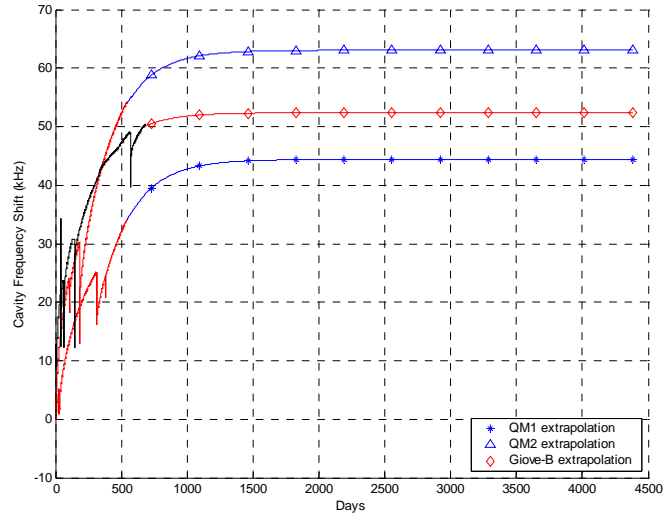


Fig. 7: Cavity frequency drift measured on GIOVE-B and QM models with prediction over 12 years

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 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 an hydride to store in a tank of 0.1 litres 25 bar*litre 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.

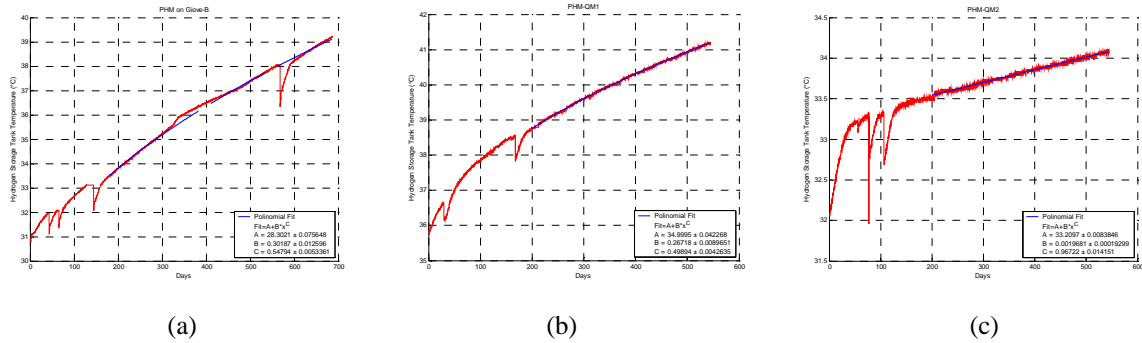


Fig. 8: Hydrogen Tank temperature measured on GIOVE-B (a) on QM1 (b) and QM2 (c)

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

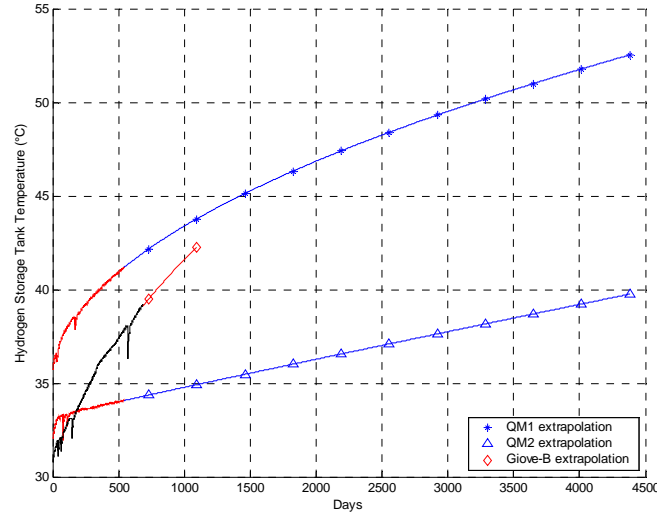


Fig. 9: Hydrogen Tank temperature measured on GIOVE-B and QM models with prediction over 12 years

Considering that the maximum reachable hydrogen tank temperature is limited to 50°C (because of the available heating power), it is predicted that QM1 hydrogen pressure will go out of regulation after almost 9 years of operation. However it is worth stressing that the impossibility to maintain the hydrogen tank pressure constant over lifetime affects the PHM frequency drift only, but not the frequency stability performance. This result is strongly affected by the adopted prediction model. With respect to the previous life test publication [5], a square root fit has been used. This is a more realistic approach based on hydride properties and its characterisation. 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 Fig. 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 one 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).

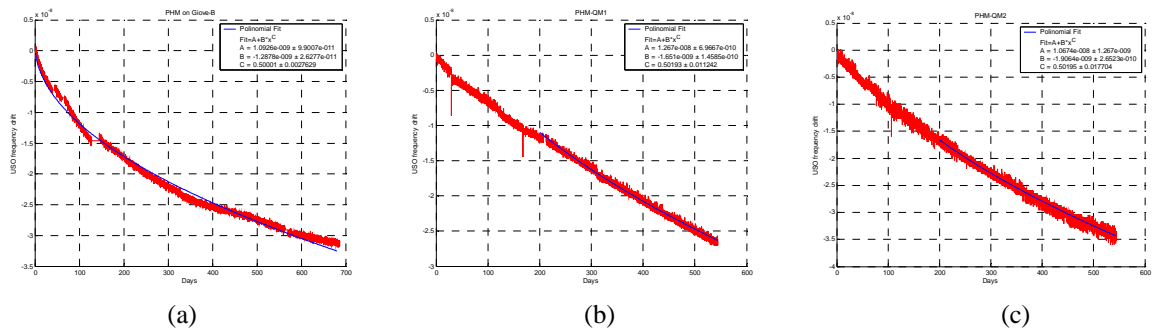


Fig. 10: Master Oscillator frequency change computed for GIOVE-B (a), QM1 (b) and QM2 (c)

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

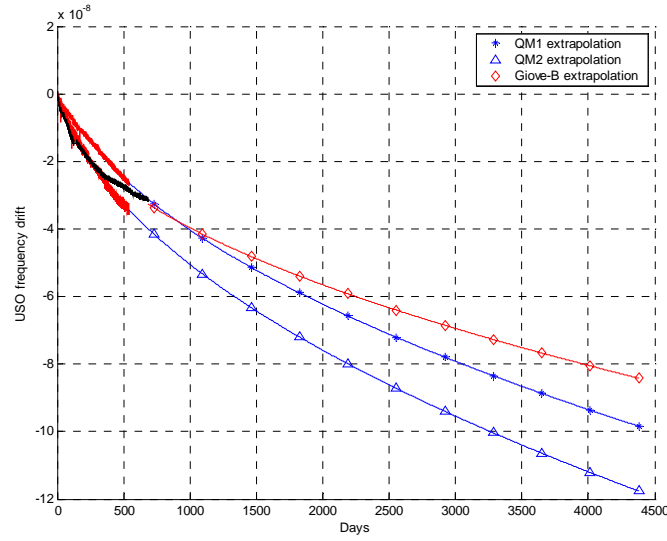


Fig. 11: Master Oscillator frequency change on GIOVE-B and QM models with prediction over 12 years

The polynomial fit adopted for the prediction, comes from the ageing trend observed on ground on 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 stabilised ageing effect.

The worst case analysis performed at instrument level considers an overall frequency drift of the master oscillator equal to $\pm 2.1 \cdot 10^{-7}$. As shown in Fig. 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 $2-3 \cdot 10^{-7}$ 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 behaviour observed on 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-ground).

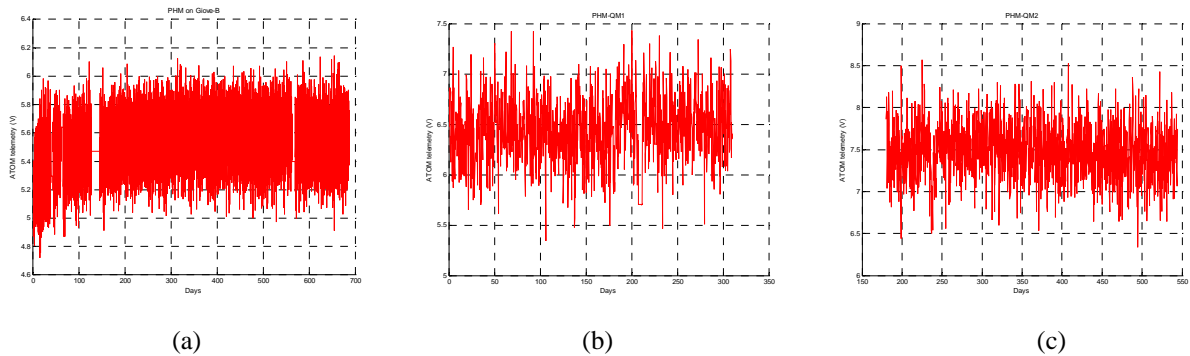


Fig. 12: ATOM telemetry measured on GIOVE-B (a), on QM1 (b) and QM2 (c)

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 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 behaviour observed on ground. This is particularly important because it implies negligible effects due to the Space radiations on both the RF electronics and Teflon coating properties.
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 ground and on Giove-B satellite [1].

THE FREQUENCY STABILITY

Frequency stability and trend evolution is another fundamental aspect for a clock assessment. In the following figure the rough frequency data are reported, including the estimation of the frequency drift. The frequency jump after 320 days is due to the 2°C cavity temperature set change (for experimental purposes). The observed frequency jump is in line with the theoretical expectation. During the life test period the PHM has been switched off and on 3 times (a,b and c in Fig. 13). It is worth noticing that the output frequency accuracy retrace is better than 2×10^{-13} .

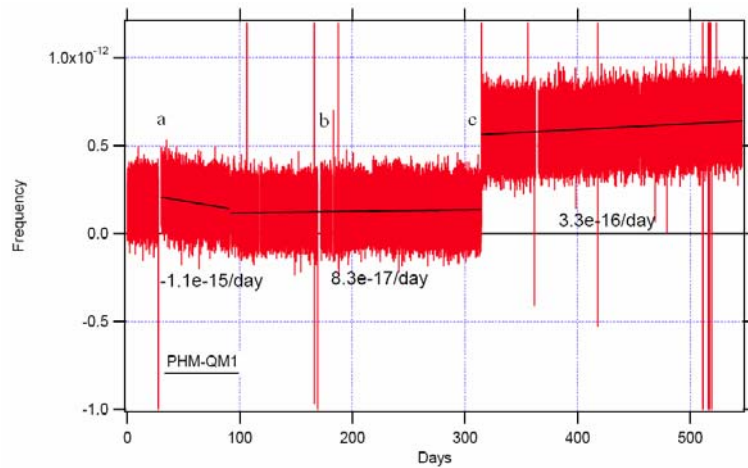


Fig. 13: PHM QM1 frequency data over 18 months of measurement

The following pictures show the frequency stability measurement performed on the PHM-QM1 over the last three months. Both the frequency drift and the Allan Deviation are very repeatable since the beginning of the life test campaign [4] [5].

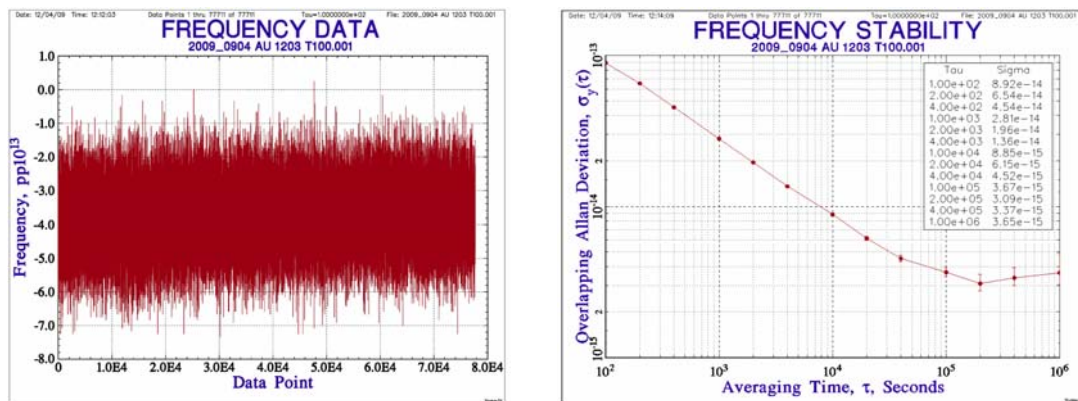


Fig. 14: PHM QM1 frequency data and frequency stability

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

| Parameter | Measurement |
|----------------------|------------------------------------|
| Frequency stability | $< 5 \cdot 10^{-15}$ @ 100'000 sec |
| Flicker floor | $< 4 \cdot 10^{-15}$ |
| Drift | $< 1 \cdot 10^{-15}$ /day |
| Thermal sensitivity | $\leq 2 \cdot 10^{-14}$ /°C |
| Magnetic sensitivity | $< 3 \cdot 10^{-13}$ / Gauss |

Table 2: typical PHM performances

CONCLUSIONS

On-ground measurements collected during PHM QMs life test have shown 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 ageing trends of the maser key parameters and the excellent frequency stability and performance provide good confidence on the instrument capability of meeting Galileo mission requirements.

ACKNOWLEDGEMENTS

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