Lifetime of Space Passive Hydrogen Maser

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Abstract—**Accurate and ultra-stable space qualified atomic clocks represent critical equipment for the precision Global Navigation Satellite Systems (GNSS). The Passive Hydrogen Maser (PHM), with its excellent frequency stability performance, is the master clock for European Navigation satellite payload, and is the most stable clock ever flown for GNSS. Nine PHMs have been flying onboard Galileo satellites (GIOVE-B and four IOV satellites) since Apr. 2008. More than 35 PHM flight Physics Packages (PP) have been manufactured and characterized by Orolia Switzerland SA (Spectratime), under the industrial consortium led by Selex ES S.p.A.**

Besides radiation effects on electronic components, lifetime on PHM depends mainly on which of PP. In the frame of the "Lifetime Qualification of the PHM" supported by ESA, two Qualification Model (QM) units had been subjected to test under vacuum since 2008. After the first 1.5-year test period as reported in previously published papers [1][2], one QM has been extended for another 2-year lifetime test. This paper provides test results over the overall period of QM1, and gives further comparison and analysis of key PP parameters over 3.5 years of operation (or 4.1 years including the stay-alive period). The extended test enhances the on-ground test statistics and provides better confidences in the PHM lifetime evaluation, which shows the instrument capability to comply with the lifetime requirement of 12 years.

Keywords-Hydrogen maser; lifetime; space atomic clock; GNSS

I. INTRODUCTION

Accurate and ultra-stable space qualified atomic clocks represent critical equipment for the precision Global Navigation Satellite Systems (GNSS).

The Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM) are the baseline clock technologies for the European Navigation satellite payload. The adoption of a "dual technology" for the onboard clocks is dictated by the need to insure a sufficient degree of reliability (technology diversity) and to comply with the lifetime requirement of 12 years. The PHM with its excellent frequency stability performance has been chosen as the master clock.

After almost 10 years of continuous development in Europe the first space PHM has been launched onboard GIOVE-B (Galileo In-Orbit Validation Element) spacecraft on 27 April 2008. The mission of GIOVE-B has proved that PHM is the most stable clock ever flown in space for navigation applications and this clock technology is suitable for the harsh environment of space [3]. Four IOV (In-Orbit Validation) satellites were launched by pair on 21.10.2011 and 12.10.2012, each carrying two PHMs.

II. DEVELOPMENT HISTORY OF PHM

The development of the PHM has been funded continuously by ESA. The first space PHM development activity tailored to navigation applications was kicked off in 2000, led by Observatory of Neuchatel with Selex ES (SES) as subcontractor for Electronics Package (EP).

The industrialization activity aimed at PHM design consolidation for flight production was started in 2003. The industrial consortium is led by SES in charge of the instrument integration and EP design, and Spectratime is responsible for redesign and manufacturing the Physics Package (PP) [4][5]. The overall structure and design were reviewed in order to increase compactness and robustness. Strong efforts have been devoted to further improve both performances and manufacturing processes of the PHM from GSTB-V2 to IOV phases.

From 2009, the production and tests capability have been set up to 2 space PHM PPs per month at Spectratime. More than 35 flight PPs have been delivered, 9 of them have been flying onboard Galileo satellites.

A further development of a miniaturized PHM has been carrying out in the frame of the ESA European GNSS Evolutions Program. The main target is to preserve the excellent PHM frequency stability performance with reduction of the overall mass from present 18 kg down to 12 kg [6]. To achieve this goal, the physics package weight has been realized by Spectratime at 8 kg and demonstrated very similar performance [7].

III. LIFETIME TEST AND EXTRAPOLATION

Besides radiation effects on electronic components, lifetime on PHM depends mainly on which of PP. In order to highlight potential lifetime limitations, in the frame of the "Lifetime Qualification of the PHM" supported by ESA, two Qualification Model units (QM1 and QM2) were subjected to test continuously under vacuum from 05.06.2008 to 04.12.2009. The 1.5-year test results were published in papers [1] and [2], in which the comparison with related telemetries from the early 690-day in-orbit operation of GIOVE-B PHM demonstrated the consistency between the on-ground and in-orbit observations.

Seven months later QM1 was extended for a second 2-year lifetime test period (14.07.2010 – 13.07.2012). A third 1-year lifetime test on QM1 initiated on 06.02.2013 is in progress.

This paper provides test results over the first two test periods on QM1. Further analysis of key PP parameters over 3.5 years (1280 days) of operation (or 4.1 years if including the Stay-Alive period) is presented, which improves the statistical confidence for the lifetime extrapolation.

Fig. 1 illustrates the overall layout of the test bench. In addition to frequency stability performances, about 30 parameters have been measured. Most of them do not present measurable ageing effects. In this paper PP telemetries (Microwave cavity frequency, hydrogen supply tank temperature, high vacuum pressure), and master oscillator frequency, which are more relevant or affected by long term operation, therefore on which the lifetime of the PHM is more dependent, are discussed. The overall characteristics (atomic signal level, frequency stability) are also provided,

A. Microwave Cavity Frequency Drift

The cavity varactor, as part of Automatic Cavity Tuning (ACT) servo loop, is aimed at tuning the microwave cavity resonance frequency to the atomic transition frequency. For an easy and reliable comparison between the PHM units, the varactor voltage has been converted to the equivalent cavity frequency shift wrt the initial frequency.

Fig. 2 shows the cavity frequency shift observed on PHM QM1 during 1280 days (3.5 years) of operation, two curve fittings, and corresponding extrapolations over 12 years.

The least squares fitting of the cavity frequency shift consists in an exponential function of time, which has been also demonstrated during the PHM PP final tests. A square root fit is performed as well in the whole period in an attempt to estimate the drift trend in worse case.

It has to be noted that according the on-ground PHM PP acceptance tests, lifetime tests on QM1&QM2, and in-orbit data from GIOVE-B, the frequency drifts in all cases decease with time reaching an asymptotic value.

By two fitting models, the extrapolated values reach around 60 to 85 kHz in 12 years, which 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.

B. Hydrogen Consumption

Another key aspect that has been monitored is the hydrogen consumption over the time. PHM uses the hydride to store in a tank of 0.1 liters 25 bar*liter of hydrogen, with internal pressure below 5 bars. 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 a constant level required for maser operation. Therefore, the temperature

Figure 1. PHM QM Lifetime test bench

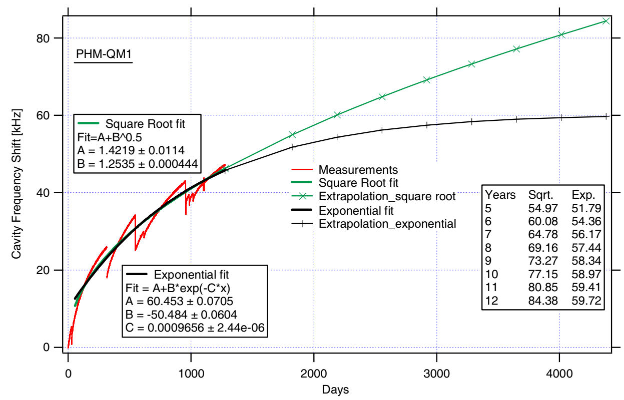

Figure 2. Cavity frequency shift measured during 3.5 years, curve fitting, and extrapolation over 12 year

variation over the time is a good indication of the Hydrogen consumption.

Fig. 3 shows the hydrogen tank temperature variations observed on PHM QM1 during 1280 days (3.5 years) of operation, the curve fitting and the trend extrapolation over 12 years. A square root fit has been used, which is a realistic approach based on hydride properties and its characterization. It can be noticed that the container temperature increasing rate is higher during first few weeks after the switch-on, which could be interpreted by the solid-state hydride transition phase.

The predication based on 3.5 years' data is remarkably similar as the results obtained during first 1.5-year period, which confirms the consistent behavior of the hydrogen tank.

As having highlighted in [1] and [2], the maximum reachable hydrogen tank temperature is limited to 50°C due to the available heating power. A recovery action has been carried out on all PHM models from QM2 on. A new type of hydride (higher purity LN5) achieving lower maximum pressure and more constant pressure plateau has been adopted. Thanks to this, the end of life temperature needed to keep the constant pressure is considerably lower than in the QM1, as demonstrated in the QM2 lifetime test [2].

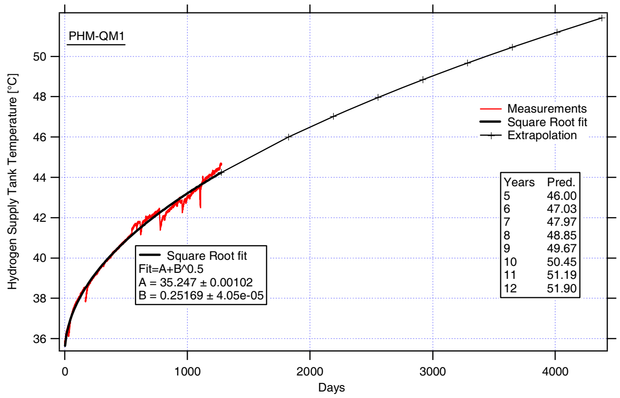

Figure 3. Hydrogen tank temperature measured during 3.5 years, curve fitting, and extrapolation over 12 year

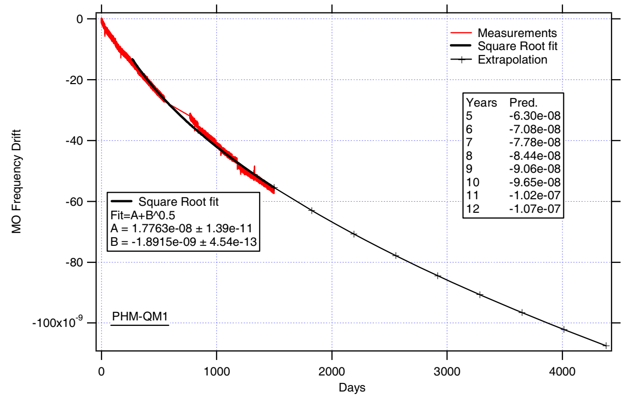

Figure 4. Master oscillator frequency drift measured during 3.5 years of operation (plus 7 months of Stay-Alive in-between), curve fitting, and prediction over 12 years

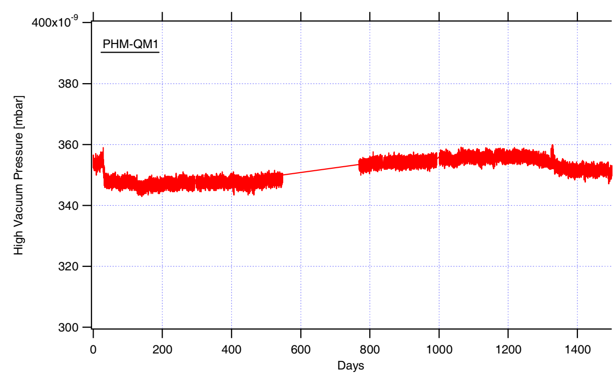

Figure 5. High vacuum pressure measured during 3.5 years of operation (plus 7 months of Stay-Alive in-between)

C. Master Oscillator Frequency Drift

The PHM 10 MHz output signal is provided by a crystal Master Oscillator (MO), whose frequency is locked to the atomic hyperfine transition by the varactor voltage. Therefore it is possible to assess the crystal frequency drift and servo loop capability in maintain the oscillator locked for the whole mission lifetime.

As done for the microwave cavity frequency drift, the varactor voltage change is converted to the MO fractional frequency drift.

Fig. 4 shows the MO frequency drift observed on PHM QM1 during 4.1 years, including the stay-alive period when the PHM QM1 was not operating. It's very interesting to note that even during this 7 months, the frequency drifting of the MO was still following the same trend. The figure shows also the simple square root fitting, which allows a very good confidence. The prediction over 12 years indicates the frequency change around -1e-7 in the end of the life.

The worst case analysis performed at PHM instrument level considers an overall frequency drift of the MO equal to ± 2.1e-7. As shown above, this limit is respected with almost 100% of margin. Besides such margin, further 2~3e-7 compensation can be achieved by telecommand. Therefore, the risk to lose a PHM as consequence of unexpected MO frequency drift is negligible.

D. High Vacuum Pressure

Fig. 5 shows the high vacuum pressure during 4.1 years (including the 'no-record' 7 months between two test periods). In this STAY-ALIVE mode, only external power was provided to the ion pump to prevent PHM performance degradation during long storage/ OFF periods. The high vacuum pressure had maintained at a reasonable level between 3.4e-7 to 3.6e-7 mbar over 4.1 years.

E. Atomic Signal Amplitude

The atomic signal amplitude telemetry provides the most relevant indication of PHM healthy operation.

This telemetry is sensitive to any degradation as internal coating, out-gassing, leakage, dissociation efficiency, quality factor of the microwave cavity, interrogation power instability, receiver electronic degradation, temperature instability, etc. It is therefore of primary importance to verify that its decay over the life time stays below acceptable limits.

Fig. 6 shows the atomic signal amplitude measured during 3.5 years of operation under the same operation condition. The data show a fairly stable behavior as expectation.

F. Frequency Performances

Frequency stability and trend evolution is the most fundamental aspect for a clock assessment. Fig. 7 reports the frequency data and the frequency drift evolution over 4.1 years. The frequency offset due to the cavity temperature change experiment during the 1st period [1][2] is corrected in order to compare the overall data under same operation condition. The values show that the frequency drift is improving with the continuation of the operation, finally stabilized below 1e-16/day.

Fig. 8 compares the frequency stabilities for every 3-month, which demonstrates the excellent flicker floor around 3e-15 from 1 day to more than 10 days.

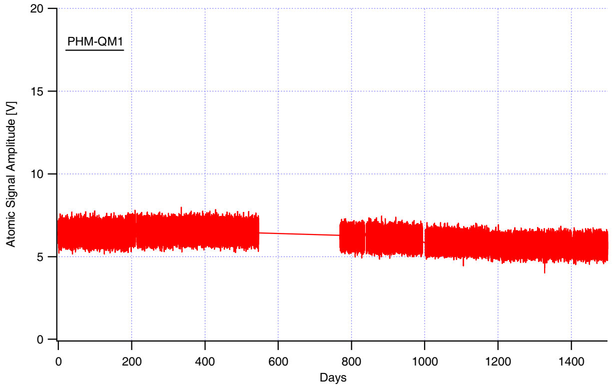

Figure 6. Atomic signal amplitude measured on OM1 during 3.5 years of operation (plus 7 months of Stay-Alive in-between)

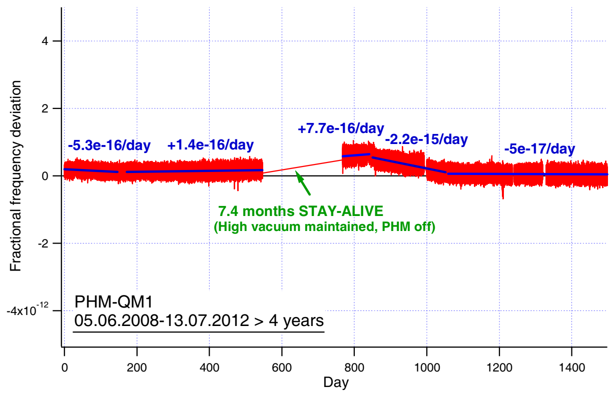

Figure 7. PHM frequency data and drift evolution during during 3.5 years of operation (plus 7 months of Stay-Alive in-between)

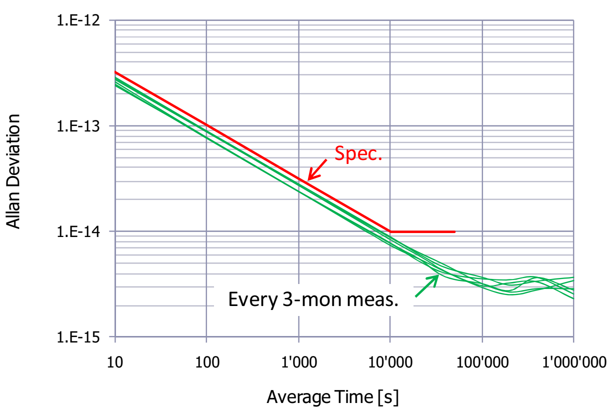

Figure 8. Frequency stabilities of every 3-month

IV. Conclusions

The extended 24-month test enhances the first 18-month test statistics. The comparison and correlation with previous data provides improved confidence in the PHM lifetime evaluation.

The life-demonstration testing on ground is confirming the capability of the PHM to operate in vacuum over the required life time of 12 years. The operational data so far collected for 30'700 h show no appreciable degradation.

Acknowledgment

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