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THE ENGINEERING MODEL OF THE SPACE PASSIVE HYDROGEN MASER FOR THE EUROPEAN GLOBAL NAVIGATION SATELLITE SYSTEM GALILEO

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Abstract - **In the frame of the new European Global Navigation Satellite System Galileo, the Observatory of Neuchâtel, Switzerland has developed the Engineering Model of the main clock on board, the Space Passive Hydrogen Maser. It weighs 15 kg, and it is 521 mm long, 355 mm wide and 251 mm high. Its steady state power consumption is 45 W in the middle of the environment temperature range (-5°C). After the initial performance tests, the frequency stability is 8.8×10^{-13} @ 1 s, but the white frequency noise follows a $5\times10^{-13}\ \tau^{-1/2}$ dependence from 20 s up to 1 hour. A Flicker floor of 7×10^{-15} is reached after 10'000 s. At 50'000 s the Allan standard deviation is 1.2×10^{-14}, mainly driven by the excessive residual frequency drift (2×10^{-14}/day). The frequency sensitivity to magnetic field variation is 1.3×10^{-14}/G, it is 2×10^{-15}/V to power supply variation and 5×10^{-14}/K to temperature variation due to non optimal temperature regulation of the microwave cavity.**
Keywords – Hydrogen Maser, Space Application, Galileo Navigation System

I. INTRODUCTION

The current developments funded by the European Space Agency (ESA) are grounded on early activities started in 1993 addressing the development of a 50 kg Active Hydrogen Maser (AHM) for space applications [1]. In 1998 this development was redirected to a 35 kg AHM [2] to be used as the master clock of the payload for the European Global Navigation Satellite System Galileo [3]. But, due to the payload restrictions in term of mass and volume, this activity was re-directed a second time towards the development of a Passive Hydrogen Maser (PHM) in the beginning of the year 2000, after the completion of the Baseline Design Review. It was recognized, at system level, that the excellent frequency stability performance of the AHM was not required, because the overall constellation design was driven by the need to guarantee the specified performances also when using the Rubidium Atomic Frequency Standard (RAFS) [4], and therefore no benefit could be obtained by the use of a much superior clock technology.

The objectives of this development was to provide the detailed design of a PHM in a relatively short period of time (2 years). The development risks had to be minimized. We had to meet all space requirements about materials, technologies, and suppliers. The design of this instrument had to be compact, robust, and reliable. To meet all the objectives we started from an industrial Ground Passive Hydrogen Maser (GPHM) with sufficient performances, mainly its frequency stability. In a first step we transferred the technology from Russia to Western Europe in order to master all processes. Then we have adapted this GPHM to fulfill all space requirements including mass add power limitations. A detailed analysis has been achieved with all partners to find the best available solutions for each sub-assembly.

The development phase of the Engineering Model (EM) of the Space Passive Hydrogen Maser (SPHM) had the following management structure : as prime contractor Observatory of Neuchâtel (ON) was concentrating on the development of a space-qualifiable Physics Package (PP), on the instrument integration and on its final tests, having Galileo Avionica, Milano, Italy (GA) as sub-contractor for the development and manufacturing of the space-qualifiable Electronics Package (EP) and Temex Neuchâtel Time, Switzerland (TNT) as partner for the industrialization of the PP.

We report in these proceedings the achievement of the SPHM EM. First we briefly review the design of both PP and EP (II), then we discuss the major verification tests including inspections, frequency stability and frequency sensitivities (III), and finally we discuss some important issues of the SPHM reliability and lifetime (IV).

II. DESIGN

The SPHM is subdivided into two principal functional packages, the Physics Package (PP), which provides the actual atomic oscillator, and the Electronics Package (EP), which provides the atomic signal processing circuits, parameter control functions, telemetry and telecommand (Fig. 1). Both subassemblies are screwed on a structural baseplate, which provides the mechanical and thermal interface with the spacecraft. Interconnections between EP and PP are made through a dedicated connector plate placed on top of the Hydrogen Supply Assembly. The SPHM external connections (input power, output frequency and telecommands / telemetries) are all grouped on the end face of the Power and Control Module.

The key to miniaturization of an Active Hydrogen Maser is the use of a smaller microwave cavity. This implies a lower quality factor preventing this maser to self-oscillate and a smaller hydrogen storage bulb, which limits the short-term frequency stability. However, the atomic resonator can still be used as a narrow band atomic filter. This mode of operation leads to a variant instrument, the Passive Hydrogen Maser, in which the atomic resonance needs to be interrogated with an externally generated microwave signal. Although the frequency stability of a PHM is an order of magnitude lower than that of an AHM, it is still sufficient to fulfill the specifications of the Galileo mission.

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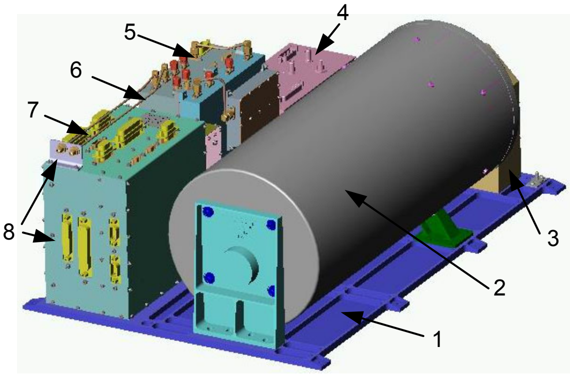

Fig. 1. Artistic view of the Space Passive Hydrogen Maser : 1: Structural baseplate; 2: H-Maser Assy; 3: H-Dissociation Oscillator; 4: H-Supply Assy; 5: RF Module; 6: HV Supply; 7: Power and Control Module; 8: Frequency, Power, and TTC interfaces. (Harness not represented).

Both AHM and PHM in their versions for ground application utilize two nested vacuum systems, i.e. the hydrogen vacuum, in which the actual physics of free hydrogen atoms takes place and a thermal vacuum enclosure around it, which serves as thermal insulation to support the high cavity temperature stability needed to reach the outstanding frequency stability. A hydrogen maser, which is designed to operate in orbit on a space platform, does not need the thermal vacuum enclosure, since it can utilize the surrounding space vacuum. This leads to an even more compact Physics Package, which allows the SPHM to meet the Galileo mass requirement (15 kg). The disadvantage of such a design is that this instrument is indeed only operable in space environment or in a vacuum test chamber.

The PP is composed of a major module, namely the Hydrogen Maser Assembly, and an auxiliary module, the Hydrogen Supply Assembly (Fig. 2). Molecular hydrogen gas (3 bar) is supplied from a solid-state hydride storage container and delivered through a nickel flow control valve into a low-pressure gas bulb (0.05 mbar), where a plasma discharge (10W) dissociates the molecules into atoms. By a differential pumping hydrogen atoms leave the dissociator bulb through a multi-hole capillary array (500 x 20 µm∅) and enter a vacuum chamber where they form a collimated beam. In order to create the necessary population inversion in order to detect the atomic oscillations, atoms pass through the high magnetic field gradient (1.8 T/mm) of a quadrupole state selector. Undesired atoms are deflected off the beam axis while remaining atoms enter downstream a storage bulb (0.4 l). This bulb is made of quartz and lined with an appropriate Teflon coating, which allows many collisions of the atoms with the wall without perturbation of their atomic state. The bulb is situated at the center of a small magnetron-type microwave cavity resonant at 1.42 GHz in an analog TE_{011} mode (loaded cavity quality factor Q_{lc}=7000). A weak static magnetic field (380 µOe) is applied parallel to the cavity axis by a solenoid to separate the magnetic Zeeman sublevels. To decrease the influence of a changing external magnetic field (e.g. Earth field) on the transition line frequency, the cavity is surrounded by three concentric magnetic shields providing the necessary shielding factor (10^5). The microwave cavity is operated around 47°C and temperature stabilized (1 mK) with by a two-stage temperature control system to reduce the influence of thermal expansion on the cavity frequency. The remaining frequency variation of the cavity is compensated by an active control, the Automatic Cavity Tuning (ACT), through a varactor diode inserted in the microwave cavity. Finally, the vacuum where the hydrogen beam propagates is maintained by an array of non-evaporable hydrogen getters. An additional ion pump (2 l/s) is required to absorb other background gases.

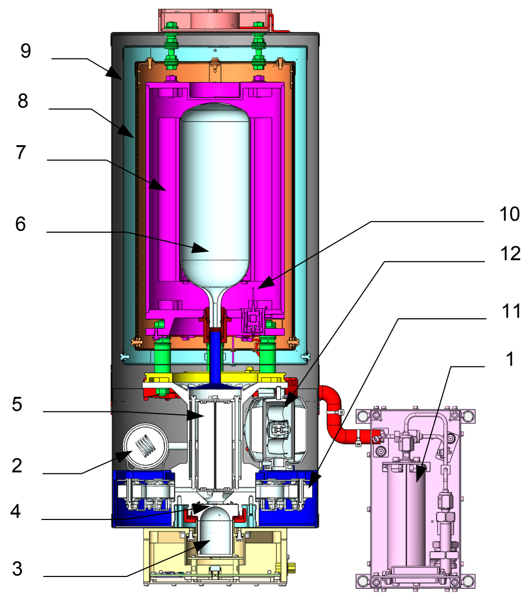

Fig. 2. Cut view of the SPHM Physics Package : 1: H tank; 2: Ni Flow Control Valve; 3: H dissociator bulb; 4: Multihole collimator; 5: State selector; 6: Storage bulb; 7: RF cavity; 8: C-field coil; 9: Magnetic shields; 10: RF cavity varactor diode; 11: Non-evaporable H getters; 12 : Ion pump.

The functional block diagram of the EP with their various connections to the PP and the instrument interface to the spacecraft or to the Electronics Ground Support Equipment (EGSE) is detailed in Fig. 3. The EP is composed of two main modules and two auxiliary modules. The main units are the Radio Frequency Module (RFM) in charge of phase locking an quartz oscillator to the hydrogen clock frequency (1.42 GHz), and the Hydrogen Dissociation Oscillator (HDO) which starts and maintains the plasma discharge in the hydrogen dissociator bulb. The auxiliary units are the High Voltage Supply (HVS) which powers the ion pump (3.5 kV), and the Power and Control Module (PCM) which provides all required power sources to drive other electronics modules (RFM, HDO, HVS), and also provides the necessary voltage and current sources for the PP (cavity and hydrogen container heaters, C-field coil, pressure sensor, and flow control valve).

Moreover the PCM interfaces the SPHM with the spacecraft for monitoring and housekeeping purposes.

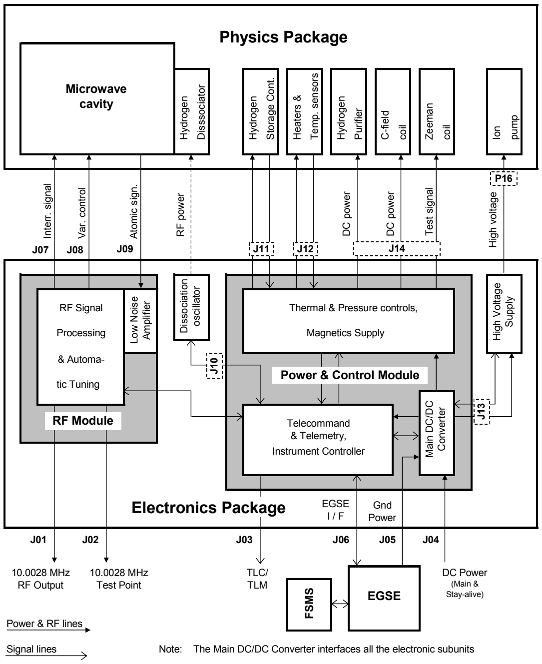

Fig. 3 : The functional block diagram of the SPHM Electronics Package.

The block diagram of the RFM is detailed in Fig. 4. The 10.0028 MHz of an Ultra Stable quartz Oscillator (USO) is directly multiplied by 142 to interrogate the hydrogen clock frequency (1.42 GHz). This carrier signal is modulated by a single sine wave frequency at 12.5 kHz (modulation index 1.4) to allow a double servo system for both the USO and ACT. The two output signals keep the same modulation frequency, but are almost in phase quadrature [5]. After the interaction with the hydrogen atoms in the RF cavity, the output signals are first amplified by a Low Noise Amplifier (LNA), then frequency down-converted to 20 MHz by a free running oscillator and AM converted by an envelope detector. Finally the two signals are split by a phase shifter and separately fed back to the USO and the ACT varactor diodes by their respective synchronous detectors.

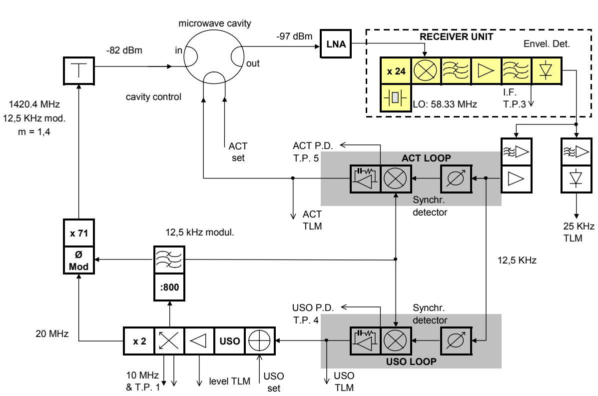

Fig. 4 : The functional block diagram of the RF module.

III. Verification

Before starting manufacturing of the SPHM, a number a ground sub-assemblies of similar design (storage bulb, microwave cavity, ion pump and dissociator bulb) have been successfully vibrated to the qualification levels (16 g_{XYZ}, and 12 g_{rms}). A detailed mechanical analysis by a Finite Element Method has demonstrated that all other elements can withstand such vibration levels, and that all resonance frequencies are higher than the required 100 Hz.

The fully assembled SPHM EM (Fig. 5) weighs 15 kg (excluding the structural baseplate). It is 521 mm long, 355 mm wide and 251 mm high. At -5°C, middle of the operating temperature range [-12°C, +3°C], and in vacuum conditions (< 10^{-5} mbar), the steady state power consumption is only 45 W. Probably due to insufficient loop gains in the microwave cavity and USO temperature controllers, the turn-on time to reach the optimal frequency stability is about 1 week. On the other hand, the maximum off-time of the instrument, which is limited by the ion pump switch off duration, is longer than two weeks. This indicates that the pumping efficiency of the hydrogen getters, which are still active even when the full instrument is off, is sufficient to maintain a good vacuum at least at the beginning of its life.

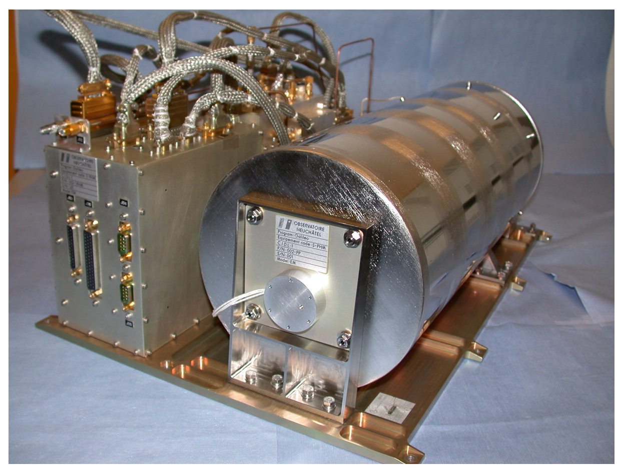

Fig. 5 : Achievement of the SPHM Engineering Model.

In order to improve the short term frequency stability, the hydrogen beam flux has to be optimized to get the biggest atomic gain while keeping a narrow atomic natural line width [6]. With an optimal atomic flux of 5×10^{12} at/s, the oscillation parameter is α=0.37 and the natural atomic line width is Δf=2.9 Hz. Considering the loaded cavity quality factor Q_{lc}=7000, we expect a short frequency stability of 5×10^{-13} @ 1 s. The Fig. 6 reports a frequency stability measurement of the SPHM EM versus an AHM. The Allan standard deviation is 8.8×10^{-13} @ 1 s, probably due to excessive noise of the USO loop filter. From 20 s up to 1 hr, the residual noise is typical of a passive frequency standard (white frequency noise). The corresponding Allan standard deviation follows a $5\times10^{-13}\ \tau^{-1/2}$ dependence. A Flicker floor of 7×10^{-15} is reached at 10'000 s. For longer integration time, a residual and excessive frequency drift is regularly observed (2×10^{-14}/day), but in some special environment conditions, this drift has been reduced by one order of magnitude. Even considering this excessive frequency drift, the improved performance of the SPHM at short term yields a long term frequency stability (1.2×10^{-14} @ 50'000 s) compliant with Galileo specifications.

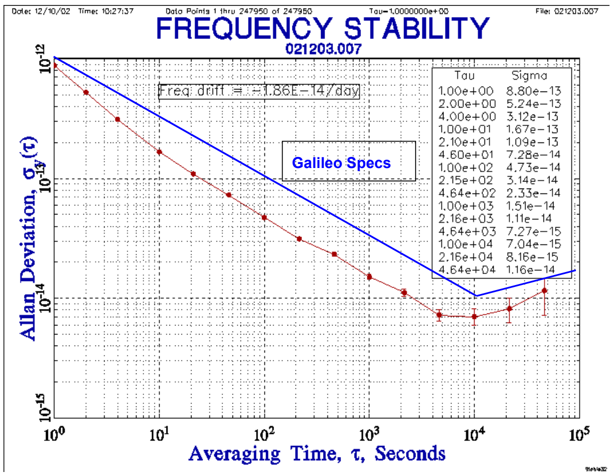

Fig. 6 : Frequency stability of the SPHM Engineering Model.

Concerning the SPHM frequency sensitivities to environmental parameters, we have measured its dependence on external magnetic field, power supply, and temperature variations :

- The magnetic sensitivity has been measured along the longitudinal axis of the atomic resonator (worst case) by inverting a ±0.4 G external magnetic field produced by Helmholtz coils. This sensitivity is 1.3×10^{-14}/G, which is compliant with Galileo specifications.
- The power supply sensitivity has been measured by changing the supply voltage of the instrument by the EGSE in the range [+47V, +57 V]. This sensitivity is 2×10^{-15}/V, which is also compliant with Galileo specifications.
- The temperature sensitivity has been measured over the full qualification range [-22°C, +13°C], with fast ramps (600 mK/min) and short integration time duration (12 hr). These experimental conditions are not those that the instrument will encounter onboard of the spacecraft (±1°C, 6 mK/min), but were considered necessary to detect the specified temperature coefficient (1×10^{-15}/K). The actual temperature sensitivity is far out of specifications (5×10^{-14}/K). Various possibilities are currently being investigated : first by better stabilizing the microwave cavity temperature (some temperature controllers are not working properly); second by defining a test procedure closer to environmental conditions that the instrument will encounter (reduced temperature excursion and slower temperature ramps).

IV. Reliability and Lifetime

A complete Failure Mode and Effects Analysis (FMEA) has been performed at EP and PP levels. The failure rate for the whole electronics components (EP and PP) is 2535 FIT (FIT = failure in 10^9 hr). As no redundancies are present in the instrument, the use of high reliability electronics components is mandatory. Among 34 identified failure modes, 29 have been classified as major and 5 as minor (none are critical neither catastrophic). Due to the expected reliability of the Galileo navigation system, a degradation of the clock performance is already considered as a major failure.

The lifetime goal of the SPHM is 12 years. A detailed analysis has been performed to assess the design choices. First of all, the molecular hydrogen consumption is 1.5 bar × liter / yr in normal operating conditions (see III). As the full hydrogen capacity is 18 bar × liter, the expected lifetime is achievable with respect to the hydrogen consumption. Secondly, the activation rate (50%) of the getters is compatible with the amount of hydrogen to be pumped (18 bar × liter). But, due to the getters brittleness when they become saturated in hydrogen, the activation rate will have to be reduced down to 20%, that will call for an increase of the getters number or a changing of the getter material (design update in progress). Finally, a hydrogen supply test bench including critical PP sub-assemblies (hydrogen tank, Ni flow control valve, dissociator bulb, and beam collimator) is running continuously with a 1 year database. Hydrogen getters and ion pump capacities will be studied by accelerated lifetime tests in the future.

V. Conclusion

We have reported the development of the Engineering Model of the Space Passive Hydrogen Maser for Galileo. One fully assembled and space qualifiable unit has been built and tested. Its mass is 15 kg, its dimensions are 521×355×251 mm^3, and its power consumption is 45 W in normal operating conditions (under vacuum and at –5°C).

An initial performance test demonstrated a frequency stability of 8.8×10^{-13} @ 1 s limited by an excessive noise in the local oscillator loop filter, an Allan standard deviation of $5\times10^{-13}\ \tau^{-1/2}$ from 20 s to 1 hr, a Flicker floor of 7×10^{-15} @ 10'000 s, and a long term frequency stability of 1.2×10^{-14} @ 50'000 s limited by a residual and excessive frequency drift. With this frequency stability improvement (factor 2), the long term stability is still compliant with Galileo specifications in spite of the residual frequency drift.

The instrument frequency sensitivities were also measured : apart from the thermal coefficient ($5\times10^{-14}/K > 1\times10^{-15}/K$), the SPHM is compliant with the Galileo specifications for the magnetic coefficient ($1.3\times10^{-14}/G < 2\times10^{-14}/G$) and the power supply coefficient ($2\times10^{-15}/V < 1\times10^{-14}/V$). Further investigations are under progress to minimize the frequency drift and the thermal coefficient.

Finally all stages of development are mastered by an experienced team (ON, GA, and TNT) and the first phase of the PP technology transfer to industry (TNT) has been completed.

ACKNOWLEDGMENT

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REFERENCES

[1] A. Jornod, L.-G. Bernier, H. Schweda, and G. Busca, "The SHM compact hydrogen maser for space applications report on the PEM physics package design verification" *in Proc. 12th European Frequency and Time Forum, 10-12 March 1998, Warsaw, Poland*, pp. 121-125.

[2] A. Jornod, D. Goujon, D. Gritti, and L.-G. Bernier, "The 35 kg Space Active Hydrogen Maser (SHM-35) for ACES" *in Proc. Joint Meeting 17th European Frequency and Time Forum and 2003 IEEE Frequency Control Symposium, 5-8 May 2003, Tampa, Florida USA*, these proceedings.

[3] J. Hahn and H.-H. Fromm, "Design baseline and importance of accurate time keeping" *in Proc. 15th European Frequency and Time Forum, 6-8 March 2001, Neuchâtel, Switzerland*, pp. 3-14.

[4] F. Droz, P. Rochat, G. Barnaverain, M. Brunet, G. Delporte, J.-F. Dutrey, F. Emma, T. Pike, and U. Schmidt, "On-board Galileo RAFS current status and performance" *in Proc. Joint Meeting 17th European Frequency and Time Forum and 2003 IEEE Frequency Control Symposium, 5-8 May 2003, Tampa, Florida USA*, these proceedings.

[5] A theoretical analysis yielding the optimum phase difference in the single frequency modulation phase discrimination scheme is given in :
G. Busca, Q. Wang, M. Belloni, and L. Mattioni, "Cavity Pulling in Galileo Passive Hydrogen Maser" *in Proc. Joint Meeting 17th European Frequency and Time Forum and 2003 IEEE Frequency Control Symposium, 5-8 May 2003, Tampa, Florida USA*, these proceedings.

[6] P.Berthoud, I. Pavlenko, Q. Wang, G. Busca, H. Schweda, and V. Teodoridis, "Space Passive Hydrogen Maser for the European Navigation System Galileosat" *in Proc. 16th European Frequency and Time Forum, 12-14 March 2002, St-Petersburg, Russia*, in press.