SPACE PASSIVE HYDROGEN MASER FOR THE EUROPEAN NAVIGATION SYSTEM GALILEOSAT

P. BERTHOUD, I. PAVLENKO[1], Q. WANG, G. BUSCA[2], H. SCHWEDA, AND V. TEODORIDIS
Observatoire cantonal, Neuchâtel, Switzerland
[1]Visiting fellow from Vremya-CH, Nizhny Novgorod, Russia
[2]On leave for Keytime, Neuchâtel, Switzerland

Abstract

The Observatory of Neuchâtel, Switzerland, is developing an Engineering Model of a Space Passive Hydrogen Maser (SPHM) for the new Global Navigation Satellite System Galileo. Preliminary results on the partial Physics Package (PP) have proven that the SPHM design is suitable for this space application (15 kg, 80 W, $\leq 10^{-14}$ at 10'000 s). In addition this SPHM-PP has run without thermal vacuum with a representative frequency stability of $5.6 \times 10^{-13}\tau^{-1/2}$ for $1\,\text{s} \leq \tau \leq 1000\,\text{s}$.
Keywords : passive hydrogen maser, space application, global navigation system Galileo.

1 Introduction

Galileo is the new Global Navigation Satellite System under contract with the European Community and the European Space Agency [1]. This system will provide a highly accurate, guaranteed global positioning service under civilian control. It will be inter-operable with GPS and GLONASS, the two other global satellite navigation systems.

For the first generation of the space segment GalileoSat, the payload of each of the 30 satellites will gather two Rubidium Atomic Frequency Standard (RAFS) [2] and two Space Passive Hydrogen Maser (SPHM). The Observatory of Neuchâtel, Switzerland (ON) is currently developing an Engineering Model (EM) of the SPHM. As a prime contractor ON is concentrating on the development of a space-qualified Physics Package (PP), having Galileo Avionica, Milano, Italy (GA) as sub-contractor for the space-qualified Electronics Package (EP) and Temex Neuchâtel Time, Switzerland (TNT) as partner for the industrialization of the PP.

We report in these proceedings progress on the SPHM-EM with its Physics Package (PP) and its Electronics Package (EP) (2). Then we briefly discuss the results of the mechanical and thermal analysis (3). Finally a preliminary analysis of the main physical parameters and the first frequency stability measurements are presented (4).

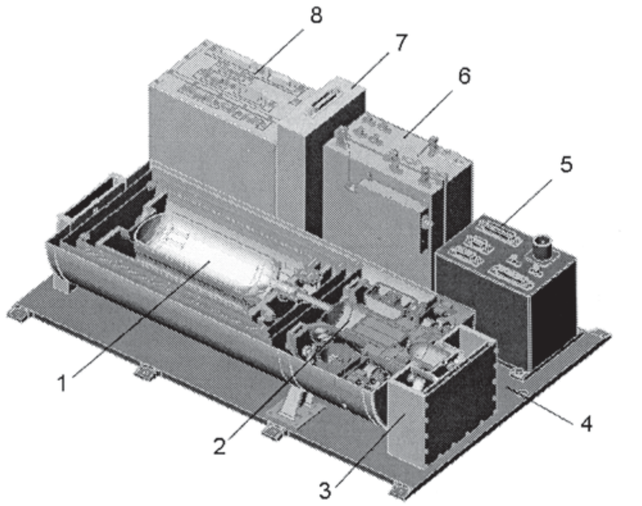

Fig. 1: Cut view of the Space Passive Hydrogen Maser. 1) Microwave Cavity and Shields Assy, 2) Hydrogen Beam Assy, 3) Hydrogen Dissociation Oscillator, 4) Structural base plate, 5) Hydrogen Supply Assy, 6) Radio Frequency Module, 7) High Voltage Module, 8) Power and Control Module.

2 The SPHM Instrument

ON has already developed a miniaturized (35 kg) Space Active Hydrogen Maser (SAHM) [3], but due to limitations in the GalileoSat navigation payload further mass and size reductions appeared necessary. The key to miniaturization is the use of smaller hydrogen storage bulb and microwave cavity, which results mainly in a maser no longer self-oscillating. However, the atomic resonator can still be used as a narrow band atomic filter leading to a variant instrument, the SPHM. Its frequency stability is an order of magnitude lower than that of the SAHM, but weighs only 15 kg, which fulfills the specifications of GalileoSat. The SPHM is a self-standing equipment composed of a PP and an EP, which are both assembled on a structural base plate (Fig. 1). The PP has been developed in collaboration with Vremya-CH on proved performance achieved with a Ground Passive Hydrogen Maser (GPHM) of industrial design.

The Physics Package The PP is composed a Microwave and Shields Assembly (MCSA), a Hydrogen Beam Assembly (HBA), and Hydrogen Supply Assembly (HSA).

Upon heating the hydride tank, a few bars of molecular hydrogen are released through a flow control device into the dissociator bulb. Molecular hydrogen is dissociated into atomic hydrogen by a plasma discharge maintained by an RF power oscillator (10 W). Atomic hydrogen escapes the dissociation bulb through a multi-holes collimator. The formed atomic beam crosses a quadrupole state selector which deflects off axis half of the beam while the remaining atoms enter a Teflon coated storage bulb (0.4 l). A hydrogen getter assembly combined with an ion pump (2 l/s) provide the necessary vacuum for this hydrogen beam assembly.

A magnetron-type microwave cavity resonant at a mode analogous to TE_{011} surrounds the bulb. This cavity is made of aluminum and silver plated for higher surface conductivity. Three coupling loops enter the cavity : one for interrogating both the hydrogen line and the microwave cavity, one for receiving the two output signals, and a third one for fine tuning the cavity through a varactor. A C-field coil provides the necessary static axial magnetic field (1 mG). The required overall shielding factor (10^5) is achieved by two concentric cylindrical magnetic shields around the cavity assembly and an additional shield around the whole PP. The cavity is temperature controlled at 45°C by a two-stage oven. As this temperature controller is not sufficient to reduce the cavity pulling effect, we actively control the cavity frequency with an Automatic Cavity Tuning servo loop (ACT).

The Electronics Package The EP currently developed by GA is composed of a Hydrogen Dissociation Oscillator (HDO), a High Voltage Module (HVM), a Power and Control Module (PCM), and a Radio Frequency Module (RFM).

The HDO provides the RF power needed to start and maintain the hydrogen plasma discharge in the hydrogen dissociation bulb. The HVM powers the ion pump by a continuous voltage of 3.5 kV. The PCM provides and manages all the SPHM external electrical interfaces except the RF outputs (DC/DC converters, active servo loops, controls and monitoring, telemetry and telecommand).

Finally the RFM processes the RF signal by phase locking an Ultra Stable crystal Oscillator (USO) to the hydrogen line. The input signal of the SPHM (1.42 GHz) is derived from the USO (10.028 MHz) with a direct multiplication by 142. It is frequency-modulated with a sinus wave at 12.5 kHz to allow a double servo system for both the USO and the ACT. The two output signals keep the same modulation frequency, but differ in phase by almost 90°. They are first down-converted to 20 MHz, then AM converted by an envelope detector. The two signals are finally fedbacked independently by their own synchronous detector.

3 Mechanical and thermal analyses

The SPHM instrument is required to withstand a continuous acceleration of $16g$ along the three axes, a random vibration up to $12g$ rms with a first mechanical resonance frequency > 100 Hz. The numerical analysis has shown high safety margins over these acceleration figures and frequency (> 250 Hz). Moreover the MCSA has successfully passed the qualification vibration tests.

The thermal analysis has considered two separate cases : the steady state and the transient analysis. In normal operation mode the power consumption is 70 W for an environment temperature range $[-12°C, +3°C]$. Most of the power is dissipated in the EP modules (80 %) and in the HSA (10 %). When the RF cavity is temperature controlled at 45°C its power consumption is < 0.5 W. The start-up power is < 80 W with a warm-up time of 24 hrs.

4 Preliminary results

During this SPHM-EM development phase, we test and characterize each sub-assembly separately. To qualify the SPHM-PP, we use a commercial GPHM-EP (Vremya-CH 1004) to drive the PP and an active hydrogen maser to provide the reference signal for frequency stability measurements. At this stage of development we are testing the space design of the new MCSA and HBA. The remaining items (HDO and HSA) are issued from a ground design. Note also that only the RF cavity and not the full instrument is kept under thermal vacuum.

Hereafter we discuss preliminary results of the main PP parameters and frequency stability. Their goal is rather to qualify the PP design, than to prove the performance of the full instrument. Full performance of the SPHM under real environmental conditions will require an appropriate fine tuning after the merging of both PP and EP.

Main physical parameters We have measured the RF power gain G_0 at resonance as function of the RF input power P_{in} for three different purifier currents I_p corresponding to three different atomic fluxes ϕ (Fig. 2). Following the detailed calculation of the operation of a passive hydrogen maser [4], we fit this data to deduce the unsaturated gain at resonance $G_{0,u}$ and the oscillation parameter α.

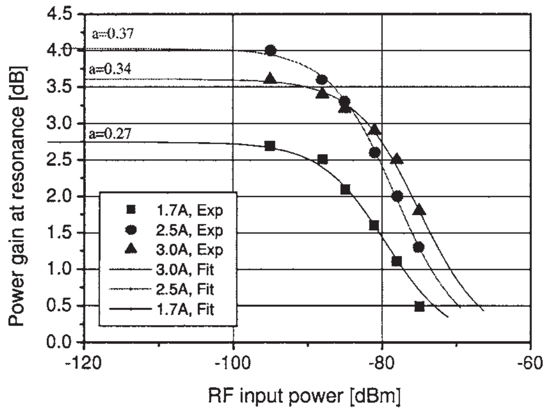

Fig. 2: Power gain at resonance G_0 vs. RF input power P_{in} for three different current of purifier I_p. By a proper fit we calculate the respective oscillation parameter α.

Purifier current I_p [A]	1.7	2.5	3.0
Unsaturated power gain at resonance $G_{0,u}$ [dB]	2.74	4.03	3.64
Oscillation parameter α	0.27	0.37	0.34
Useful at. flux ϕ [10^{13}s^{-1}]	0.11	0.78	1.38
Natural linewidth [Hz]	1.85	3.75	5.19
Spin-exch. broadening [Hz]	0.04	1.94	3.38
Geom.+wall broadening [Hz]		1.81	
Cavity filling factor η'		0.56	

Tab. 1: Main physical parameters the SPHM-PP calculated from Fig. 2 for three hydrogen fluxes.

A parallel measurement of the loaded cavity quality factor $Q_c = 7000$ and of the cavity pulling factor $\Delta\nu_H/\Delta\nu_c \simeq 1.6 \times 10^{-5}$ let us deduce the operational hydrogen linewidth for each I_p. We correct the effect of P_{in} and α to get the corresponding natural width. With at least two sets of data for different I_p, we deduce the corresponding useful atomic flux ϕ (flux of hydrogen atoms is the $|1,0\rangle$ hyperfine state) and the spin-exchange broadening contribution to the natural linewidth. The remaining contribution to the natural linewidth (geometrical and wall broadening) as well as the filling factor η' do not depend on I_p. Tab. 1 summarizes these main physical parameters for the three operating conditions.

We report on Fig. 3 the oscillation parameter α as function of the useful atomic flux ϕ. We fit these data and calculate its maximum value $\alpha = 0.41$ at a flux $\phi = 5.4 \times 10^{12}\,\text{s}^{-1}$, which almost corresponds to $I_p = 2.2$ A. Assuming that most of the noise for the short-term frequency stability is white frequency noise, we calculate the optimum interrogation power $P_{\text{in}} = -81$ dBm for the maximum value

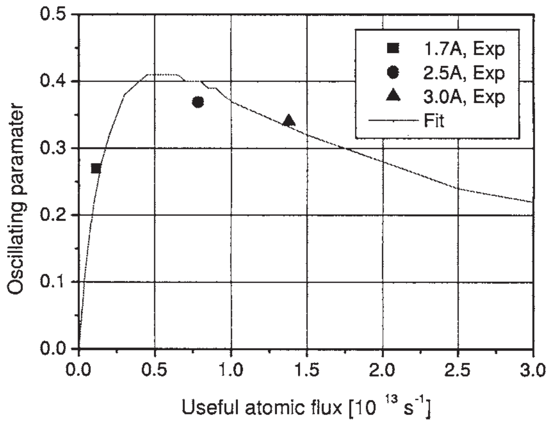

Fig. 3: Oscillation parameter α vs. Useful atomic flux ϕ. The optimal value of $\alpha = 0.41$ corresponds to a current of purifier $I_p = 2.2$ A. The calculated minimum value of Allan standard deviation is $\sigma_y(\tau) = 4.6 \times 10^{-13}\tau^{-1/2}$.

of α which minimizes the Allan standard deviation $\sigma_y(\tau) = 4.6 \times 10^{-13}\tau^{-1/2}$.

Frequency stability We have measured the frequency stability of the SPHM, where only the RF cavity is kept under vacuum with a specially designed bell-jar. The purifier current $I_p = 2.2$ A as well as the RF input power $P_{\text{in}} = -81$ dBm are the optimal figures determined above. The frequency data shows an important drift $D = 7.85 \times 10^{-18}\,\text{s}^{-1}$, which is actually not so surprising in our experimental conditions where we only control the temperature of the cylinder of the cavity (1 over 4 heaters) and where only 2 over 3 magnetic shields are used (no external magnetic shields). Fig. 4 gives the corresponding Allan standard deviation after drift removal.

The short-term frequency stability $\sigma_y(1\,\text{s}) = 5 \times 10^{-13}$ is 2 times better than specification and very close to the expected figure $\sigma_y(1\,\text{s}) = 4.6 \times 10^{-13}$. Up to 1000 s, the increase of stability perfectly follows a $\tau^{-1/2}$ rule without frequency drift removal. The Allan standard deviation already reaches the Flicker floor specification $\sigma_y(\tau) \leq 1 \times 10^{-14}$ for $\tau = 1'500\,\text{s} < 10'000$ s. We can conclude that our new space design of hydrogen atomic resonator (MSCA and HBA) is perfectly suitable for GalileoSat. Moreover, we observe a very low current of the ion pump, which suggests very good perspectives for the lifetime requirements (10 years).

We have also measured the frequency stability of the SPHM without any thermal vacuum around the RF cavity (Fig. 5). To compensate the decrease of its resonance frequency (−300 kHz), we have tuned

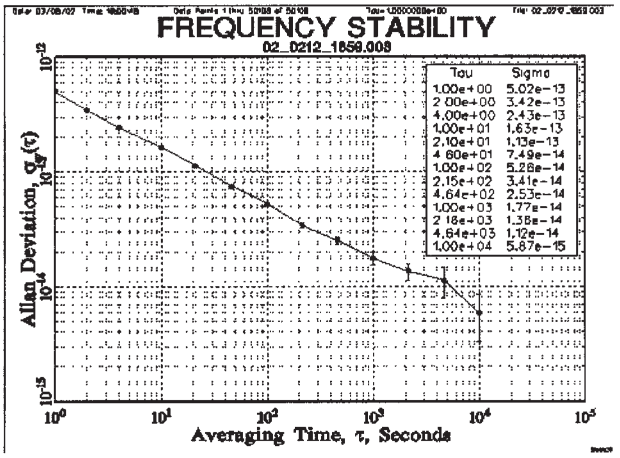

Fig. 4: Allan standard deviation $\sigma_y(\tau)$ of the SPHM under thermal vacuum and after frequency drift removal.

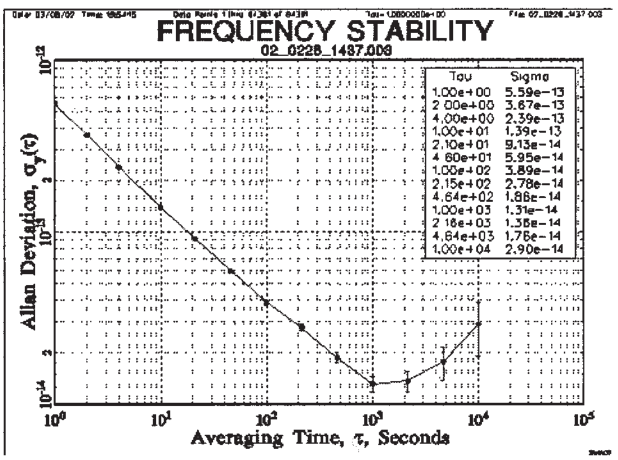

Fig. 5: Allan standard deviation $\sigma_y(\tau)$ of the SPHM without any thermal vacuum around the RF cavity.

it both mechanically and thermally. These adjustments have only a negligible effect on the cavity quality factor. For short-term measurements, the behavior of the SPHM under pressure is very close to vacuum conditions ($\sigma_y(\tau) = 5.6 \times 10^{-13} \times \tau^{-1/2}$ for $\tau \leq 1000$ s). It almost reaches the long-term frequency stability specification of 10^{-14} after 1000 s. This good behavior under atmospheric pressure is mainly due to the efficient active servo on the cavity frequency (ACT) which can strongly reduce the environment temperature change (0.6°C).

5 Conclusion

We have reported progress on the development of the Engineering Model of the Space Passive Hydrogen Maser. This instrument is designed to fulfill the GalileoSat specifications ($m \leq 15$ kg, $P \leq 80$ W, $\sigma_y(\tau \geq 10^4\text{s}) \leq 10^{-14}$). Preliminary vibration tests and frequency stability measurements on the PP have proven it suitable for this space application. A theoretical model can predict accurately the optimum tuning parameters in order to minimize the short-term frequency stability. In addition, preliminary frequency stability measurement has shown that the SPHM can be operated with reduced performances without any thermal vacuum around the RF cavity. This last result should be of course confirmed and completed with several environmental tests (humidity, barometric pressure), but it opens interesting perspectives for the procedure to be defined for the final testing of the SPHM during its integration on the satellite platform.

Acknowledgements

ON team would like to thank ESA for supporting the development of this Space Passive Hydrogen Maser program.

References

[1] J. Hahn and H.-H. Fromm. *Design baseline and importance of accurate time keeping.* In 15^{th} European Frequency Time Forum, 6–8 March 2001, Neuchâtel, Switzerland, pp. 3–14.

[2] F. Droz, P. Rochat, and F. Emma. *Rubidium Atomic Clock for Galileo.* In 15^{th} European Frequency Time Forum, 6–8 March 2001, Neuchâtel, Switzerland, pp. 499–502.

[3] 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 12^{th} European Frequency Time Forum, 10–12 March 1998, Warsaw, Poland, pp. 121–125.

[4] J. Vanier and C. Audoin. *The Quantum Physics of Atomic Frequency Standards.* Adam Hilger, Bristol and Philadelphia, 1989.