Performance demonstration of the on-board active hydrogen maser for the ACES space mission of ESA

H. Schweda, H, S. Zivanov, G. Perruchoud, and C. Weber
Observatoire de Neuchâtel
CH-2000 Neuchâtel, Switzerland
Contact: hartmut.schweda@ne.ch

B. Thieme B and G. Baister
Oerlikon Space AG,
Oerlikon Components,
CH-8052 Zürich, Switzerland

***Abstract*—In view of the ESA scientific space mission "Atomic Clock Ensemble in Space" (ACES), aimed in particular at verifying fundamental general relativity laws, state-of-the-art atomic clocks are required. In order to overpass the medium term performance of the on-board primary cold Cesium beam frequency standard (PHARAO), a Space active Hydrogen Maser (SHM) is mandatory. Observatoire de Neuchâtel, Switzerland (ON) is currently developing this maser, focusing on the atomic resonator, while its partner Oerlikon Space AG (OSAG) is developing the control and frequency locking electronics.**

I. Introduction

Hydrogen masers (HM) are the most stable frequency sources readily available. They are however heavy and bulky laboratory instruments.

With the exception of the famous Gravitation Probe A (GP-A) experiment [1], in which a HM was launched on a 10 km altitude 2 hours ballistic flight, no HM has ever operated on a space platform. Early developments of HMs for NavSat GPS in USA have been discontinued in the late 1980s [10].

The Observatory of Neuchâtel has been involved in developing HMs for space applications on and off for more than a decade.

A prototype of a 50 kg space maser has been developed in 1999 for the orbital VLBI mission RadioAstron [2]. Due to financial problems this mission had been indefinitely postponed and the HM project was discontinued. With the advent of the GALILEO program a HM as principal on-board clock of the navigation satellites was considered. However payload restriction called for further miniaturization. A feasibility study led to the design of a 35 kg instrument, the smallest and lightest active maser ever conceived. For the GALILEO payload, which envisaged two HMs on board of each of the 30 satellites, this was still too heavy and a new approach with a passive HM (PHM) was realized. The detailed design and development of the Space Passive Hydrogen Maser (S-PHM) was completed with the manufacture and test of a 15 kg Engineering Model (EM) [11] [3]. Subsequently the S-PHM was handed over to industry for final qualification and flight hardware production. Meanwhile the first flight model has been delivered to the GALILEO System Test Bed (GSTB-2) and is currently integrated on the GIOVE-B satellite, to be launched later this year. In parallel several qualification models for long-term test have been realized.

The active SHM development has been revived after ESA's "Atomic Clock Ensemble in Space" (ACES) mission [4] took shape. An important part of this mission is to compare high-performance clocks in microgravity environment on a space platform. Newly developed cold atomic fountain clocks hold the potential of outperforming the HM but their performance is limited by the influence of gravitation. In the ACES mission the state-of-the-art cold cesium beam frequency standard PHARAO [5] will be compared with the SHM as reference on-board of the International Space Station [ISS].

II. SHM Instrument Overview

We will give here only an overview on the SHM design, since details have already been given in earlier presentations [9]. There are also two accompanying papers in these Proceedings, which focus on the Physics Package (PP) [6] and the frequency locking electronics [7], respectively

The prerequisite for space application of a HM is the miniaturization of its Physics Package (PP), which in turn is based on a size reduction of the microwave cavity. Along with the cavity goes a reduction of the magnetic shields, which present a large part of the instrument mass [10].

The heart of the PP of the SHM is a unique compound hydrogen storage bulb/microwave cavity construction. The cylindrical microwave cavity, which operates in the TEM_{011} mode is dielectrically loaded with a coaxial single crystal synthetic sapphire cylinder. Due to the high dielectric constant of sapphire the cavity volume could be reduced by a factor 4.5 as compared to a standard TEM_{011} cavity.

The SHM project is supported by Swiss Space Office and European Space Agency through the Swiss Prodex program and the other ESA programs

The cavity cylinder is made of titanium, whose inner surface is copper coated with an overlayer of gold. The sapphire cylinder is vacuum-tightly connected to the end faces of the cavity by a thermal diffusion bonding technique. Very close heat extension coefficients of sapphire and titanium allow a stress-free interface. The interior of the bottle formed by the cavity faces and the sapphire cylinder forms the hydrogen storage bulb, whose inner surface is coated with FEP Teflon.

Hydrogen is supplied from a solid-state hydrogen storage alloy and delivered to the maser by diffusion though a nickel membrane. A controlled flow is achieved by controlling the temperatures of both the storage container and the nickel membrane. A hydrogen atomic beam enters the vacuum section of the maser through a single-hole collimator at the exit of rf-discharge bulb where molecular hydrogen is dissociated.

Hydrogen is pumped by an array of 30 non-evaporable bulk getters (SAES ST-172). Two small appendix 2 l/s ion pumps (one for redundancy) remove other background gases.

The microwave cavity is surrounded by four coaxial magnetic shield cylinders and by a fifth shield enclosing the whole unit to reduce influences from external fields. An active magnetic field compensation system consisting of external flux-gate probe acting on a compensation coil placed between the two outer shields further enhances the shielding.

The nominal cavity temperature is 48°C. This temperature is stabilized by a three-stage control system. The thermal gain of this system is 1500, *i.e.* during the specified maximum variation of the baseplate temperature of 1.5 K per orbital revolution (90 min) the cavity temperature should stay within 1 mK.

In order to fulfill the frequency stability requirement for the ACES mission σ_y (τ =10000 s) = 1.5×10^{-15} [4], the cavity frequency has to be stabilized within 100 mHz. The oscillation frequency of the maser f_m is determined by the cavity pulling effect

$$f_m - f_H = \frac{Q_c}{Q_l}(f_c - f_H)$$

where f_H is the transition frequency of the hydrogen atom and f_c the cavity resonance frequency. Q_c and Q_l are the loaded quality factor of the microwave cavity resonance and the atom line quality factor, respectively. SHM design calculations predicted Q_C = (3–4) $\times10^4$, and $Q_l = 1.5\times10^9$, *i.e.* cavity frequency variations are transformed into maser frequency variations by a factor of 2×10^{-5}. The temperature sensitivity of resonance frequency of the sapphire loaded cavity, which is dominated by the temperature coefficient of dielectric constant, is about –40 kHz/K. Therefore, the cavity temperature needs to be stable within 2.5×10^{-6} K. This cannot be achieved by thermal control only. An Automatic Cavity Tuning (ACT) system is needed to reduce the cavity pulling by an additional electronic feedback system.

The SHM uses a novel ACT system based on a pulsed interrogation scheme [8]. Details are given in the accompanying paper [7]. The cavity resonance is alternately interrogated with two pulsed frequency signals synthesized at several kHz below (f2) and above (f1) the atomic frequency $f_R = F_H$ (Fig.1). The switchable synthesizer is adapted so that the two frequencies are centered on, and therefore symmetrical about the natural frequency f_R The difference between the responses of the cavity to these two signals generates an error signal, which suitably treated generates a correction voltage sent to the cavity varactor. If the average of these two frequencies corresponds to the resonant frequency fc of the cavity, this latter will be tuned to f_R and the amplitudes R1 and R2 will be identical and accordingly the value of the synchronous detector will be zero.

In terms of differential R2-R1 amplitude, a stability of 2 ppm is necessary to reach a detection error of 100 mHz.

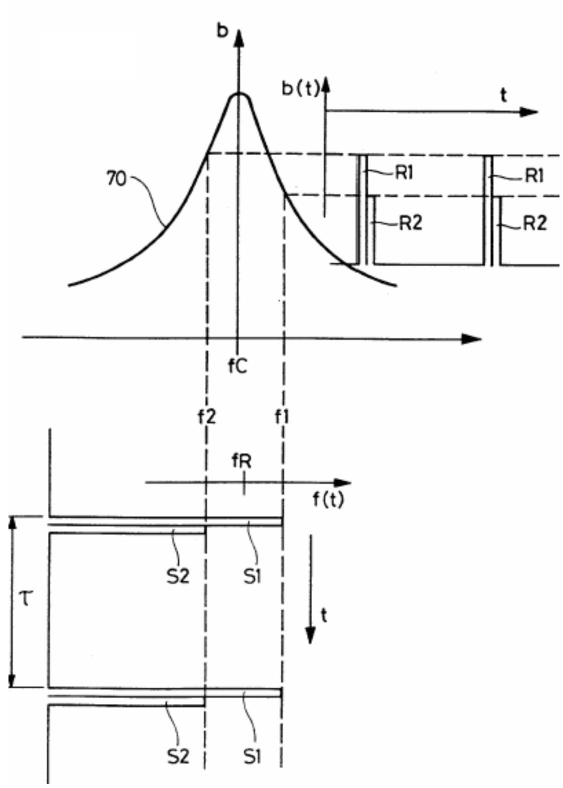

Figure 1. Pulsed frequency interrogation scheme [8]

Each of these pulses has a periodicity of τ and a predetermined pulse length τ_{ON}, which is substantially less than the interrogation period. Note that the residual frequency pulling caused by the interrogation is proportional to the duty cycle τ_{ON} / τ.

The interrogation is time multiplexed with the atomic signal detection: typically 50% of the time is used for the ACT and 50% for the main Phase-Locked Loop (PLL), which controls the local quartz oscillator by the atomic signal.

III. Hardware Status

The design verification and hardware evolution follows the philosophy of scientific payload developments for space missions. The framework of this plan foresees a number of consecutive hardware models starting from brass- and bread-boarding over an Engineering Model (EM), to the final Proto-Flight Model (PFM). In this frame the flight qualification is split between the EM and PFM.

Fig. 2 shows the design flow for the two principal parts of the instrument, the PP and the Electronics package (EP).

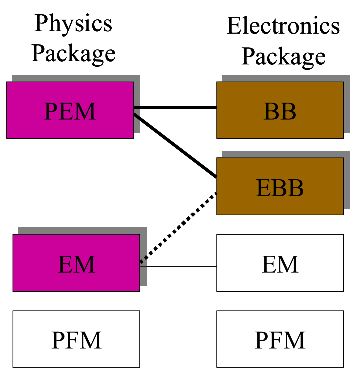

Figure 2. SHM harddware model evolution
PEM: Proto-Engineering Model (50 kg), EM: Engineering Model, PFM: Proto-Flight Model, BB: Breadboard, EBB: Elegant Breadbord

The first PP was a Pre-Engineering Model (PEM), which is the PP of the 50 kg version of the instrument originally developed for the RadioAstron mission. The core of this model, the Microwave Cavity and Shields Assembly (MCSA), is of the same design as in the Engineering Model (EM) realized afterwards. The principal difference between the two models is that for mass reduction the thermal vacuum enclosure was given up. This reduced the mass significantly from 50 kg to 35 kg. As a result the MCSA of the EM is less thermally isolated and cannot be operated in air. All performance tests have to be performed in a Thermal Vacuum Chamber (TVC). The base plate of the TVC is temperature-stabilized to ± 1 °C and adjustable within the full operation range of the SHM.

The PP-PEM was extensively used to characterize the SHM operation parameters with the first breadboard electronics. This breadboard contained all physical controls and a laboratory ACT demonstrator, built and tested at ON.

The Engineering Model (EM) of the PP has been designed and built being fully representative in form, fit and function to the final space design and to fulfill all requirements of the ACES mission. The first integration of PP-EM was completed in early 2006. The design has been mechanically and thermally analyzed. After measurements of the maser physics parameter, the PP-EM has been operated with the breadboard electronics including the ACT demonstrator.

These first PP tests have been performed in a simplified configuration (ion pumps, getters and HDA not implemented). Meanwhile the PP-EM is fully assembled. The next steps for the PP activities are to activate the getters, seal the vacuum and perform final characterization tests.

With the ACT proof-of-concept at the laboratory demonstrator level, this technology has been transferred from ON to Oerlikon Space AG (OSZ) for the development of the complete space-qualified EP. OSZ started their development with an Elegant Breadboard (EBB1). A second version (EBB2) was realized in 2006.

The complete EP consists of 5 boards, 2 FPGAs. It is packaged in 4 boxes: Controller and Power Unit (CPU), Radiofrequency Unit (RFU), Hydrogen Dissociator Oscillator (HDO) and the High-Voltage Supply (HVS) for the ion pumps. Fig. 3 displays the Radio Frequency Unit (RFU), which is composed of two separate boards, the Analog Module (AM) responsible for the frequency down conversion, and the Digital Module (DM) providing the digital frequency synthesis.

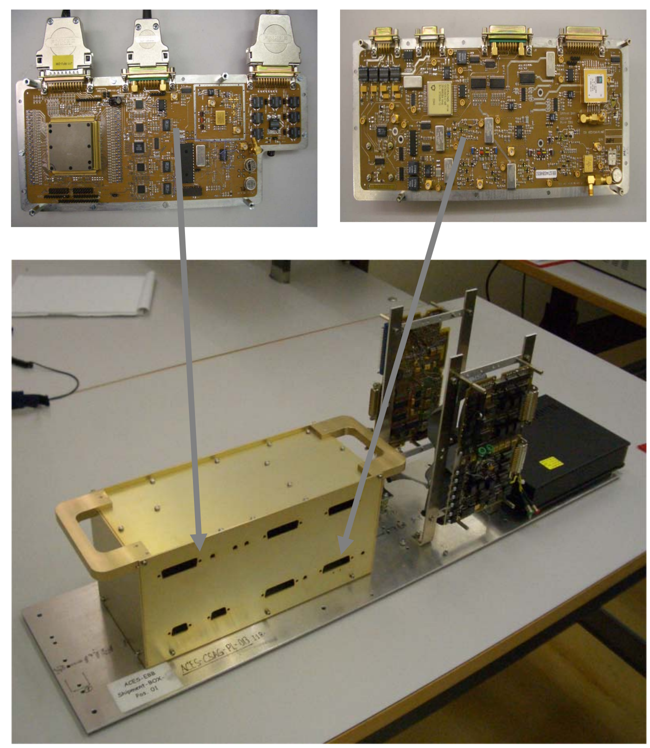

Figure 3. Radiofrequency Unit of EBB 2 of the SHM Electronics Package with the two boards RFU-DM and RFU-AM

For reasons of power dissipation and temperature control it was decided to split the electronics. Fig. 4 shows the envisaged packaging on the ACES baseplate with the CPU on a vertical platform.

The development of the Elegant Bread-Board model (EBB2) for the EP of SHM has been completed. While not yet being fully representative in form, fit and function to the final space design, the EBB allows to demonstrate the feasibility of the design for later space use being as representative as possible. A major challenge was the implementation of the Automatic Cavity Tuning (ACT) functionality into the RF receiver of the EP and to demonstrate the feasibility of the space design while having very stringent performance requirements.

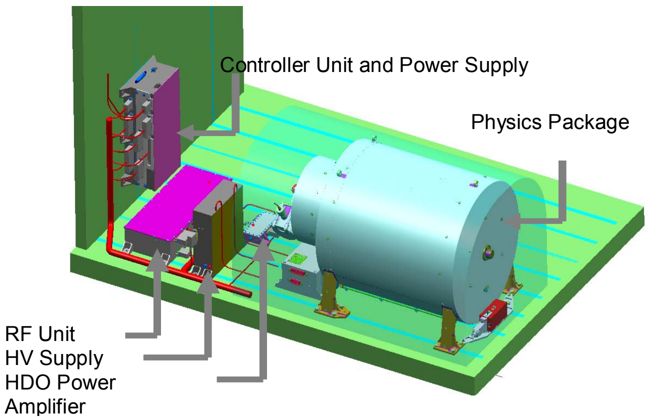

Figure 4. Packaging of SHM on ACES platform with Physics Package and split Electronics Package

IV. DESIGN VERIFICATION

A PP structural and thermal properties

A detailed structural analysis of the PP design has been performed based on a finite element model containing 66000 elements (shell+solid+bar), 75'000 nodes and 11 materials. The result showed compliance to

- quasi-static loads: 32 **g**
- random accelerations: 12 $\mathbf{g}_{\mathbf{rms}}$
- first mode frequency: 143 Hz

The Microwave Cavity and Shields Assembly (MCSA), which contains the compound cavity/bulb structure, the surrounding C-field solenoid as well as four magnetic shields with their supporting wheels and feet, is the most complex part of the PP. The MSCSA of the EM was already successfully tested for shocks (40 **g** shock response spectrum) and for random vibration (14 $\mathbf{g}_{\mathbf{rms}}$). An important result of these tests was also that the cavity resonance frequency detuning of 12 kHz after application of shocks and vibrations was small enough to be compensated by a few tenths of a degree in the cavity temperature. The magnetic shielding factor was measured before and after the tests and found unchanged within in the errors of measurement.

The thermal analysis of the PP based on a model with 48 nodes, 76 couplings, 7 fixed powers and 7 thermostats showed that the thermal regulation of the cavity within the operation temperature range (10°C to 35°C) appears feasible with acceptable variations for each transient, resulting in a PP start-up time of 1 day.

The thermal gain of >1500 of the three-stage control system for the cavity temperature has been confirmed by measurements, which showed that the cavity temperature stayed within 1mK during baseplate temperature variation of 1.5°C [6].

The measured power consumption at 10°C was with 21.2 W almost 50% higher than predicted by the model, which had to be re-adjusted.

B PP maser parameters

A number of tests have been performed to characterize the PP-EM and confirm various design parameters. Table I list the results, which are all in specification.

The measured magnetic shielding factor is twice as high as the design goal

TABLE I. MEASURED PHYSICS PACKAGE DESIGN PARAMETERS

	specification	measured
Cavity quality factor	> 30000	35500
Cavity temperature stability	0.001 °C	0.0005 °C
Magnetic shielding factor	>100000	199300
Atomic quality factor	$1.5\text{x}10^9$	$1.51\text{x}10^9$
Atomic signal output level	>-105 dBm	-103.5 dBm

C EP design parameters

A major design challenge was to reach the relative symmetry stability of the detected ACT interrogation signals of 2 ppm in order to improve the SHM cavity stability from about 100 Hz down to the 100 mHz level.. First tests at EP subsystem level showed instability of ± 17ppm/day and an out-of-spec thermal sensitivity. Optimizing the circuits and temperature control of the RFU brought this requirement into specification.

< ± 2e-6 for ± 15 kHz modulation over 1 day and stable temperature (0.1 K)

< ± 2e-6 / K for ± 15 kHz modulation

Thermal cycling of the RFU by about 1.7 K pp during frequency stability measurements with ACT activated operating on the PP-PEM led to significant stability deterioration at long-term.. Without changes in the current RFU design, the temperature variations of the boards are, when the environmental conditions are controlled about 1 K/orbit. It was found by analysis that the RFU needs a thermal stabilization of 0.2 K at board level.. During the performance tests this was achieved by a breadboard control with laboratory equipment.

V. PERFORMANCE DEMONSTRATION

A Frequency stability

Frequency stability measurements have been performed at various stages of the development. Fig. 4 shows measured Allan deviation plots of the PP-EM operating with the ON breadboard electronics when the ACT was on and off. The plots demonstrate the significant effect of the ACT for sampling times longer than 100s. This measurement not only proved the concept of the ACT system but also validated the PP-EM hardware.

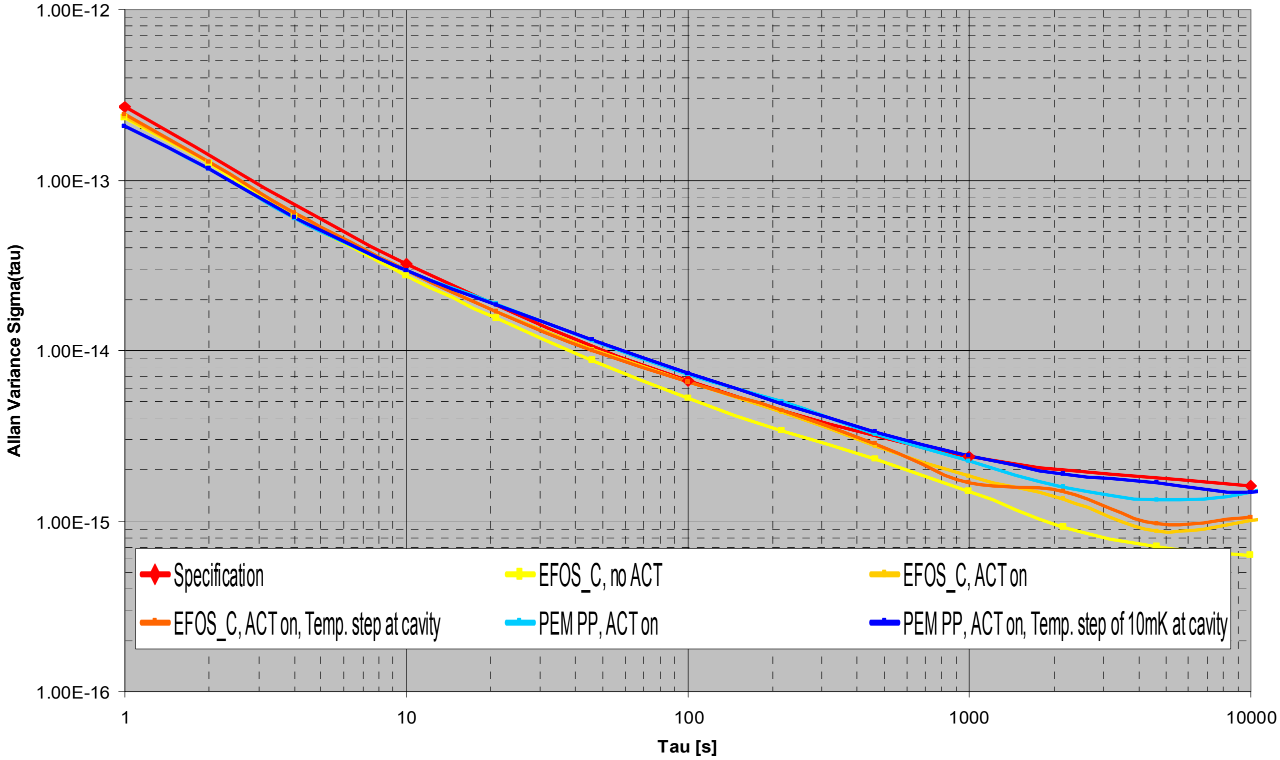

Figure 5 Frequency stability measurements results with EBB2 electronics with two PP configurations

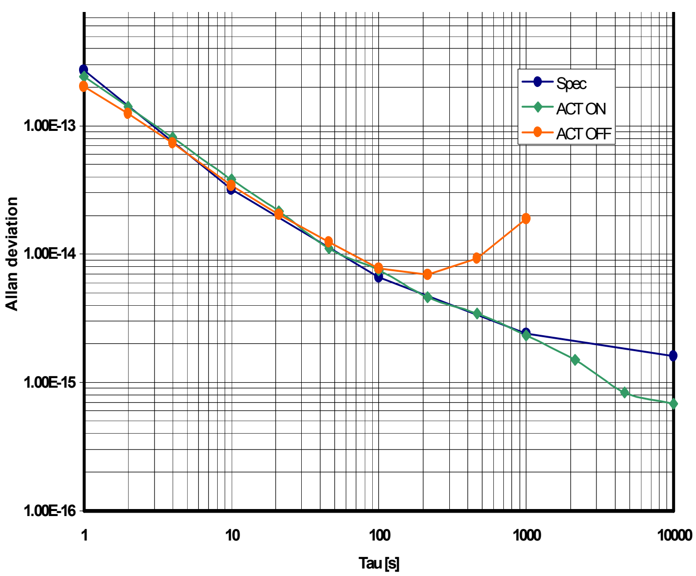

Figure 6. Measured frequency stability of PP-EM operating with ON breadboard electronics

A major achievement for the SHM project was the demonstration of the performance requirements with the EP at EBB stage, which are specifically frequency stability and phase noise. The main frequency stability requirement on SHM has been demonstrated with the EP-EBB2 on the microwave cavity of an (EFOS_C) maser and on the PP- PEM of the SHM. EFOS-C is a laboratory ground maser with full-size cavity, which shows excellent stability with no ACT. The performance is somewhat degraded when the ACT is acting on this cavity. The PEM requires the ACT functioning within specification to reduce the residual temperature instability of the PEM microwave cavity by a factor of 1000 to the 100 mHz level in order to achieve the SHM long-term frequency stability of 1×10^{-15}. Fig. 5 displays measurements with the EP-EBB2 operating on these two PP configurations. All results are essentially in specification. One measurement with the PEM was done while a cavity temperature step of 1 mK was introduced. One can see that he ACT almost fully compensated this cavity temperature variation.

In order to further characterize the system stability measurements with the PLL @ 50% and 100% and with the ACT interrogation signal on and off have been performed.

B Phase Noise

Table II compares the specified and measured phase noise for increasing frequency offsets from the carrier frequency

TABLE II. MEASURED PHASE NOISE

Frequency offset (Hz)	Specification (dBc/Hz)	Result (dBc/Hz)
1	−90	−89
10	−100	−101
100	−110	−113
1'000	−130	−130
10'000	−150	−152

The EP-EBB2 including the OCXO is in specification for all offset frequencies except 1 Hz where the noise level is about 1dB above specification. With the present constraints (-105dBm maser output, -88dBc/Hz OCXO phase noise @ 100Hz) this value cannot be improved electronically. There are two provisions, which could overcome this non-compliance, with possible detrimental consequences. An increase of hydrogen flow to get an output level >-105dBm would increase the spin-exchange broadening. The use of a better OCXO would likely lead to higher mass/volume/power consumption.

The phase temperature coefficient has been measured implicitly as ~ 2.0ps/K and it could be demonstrated that the Allan variance (short-term and long-term) is still in specification while thermally cycling the RFU box.

VI. CONCLUSION

The SHM for ACES has shown at its present development stage compliance with its principal performance requirements. The next development step will be the so-called "End-to-End" performance test in which the fully finished EP-EBB2 and the PP-EM operate together. This will be followed by the development of the vacuum-compliant EP-EM, after which the tests with the full instrument at Engineering Model level in vacuum will be possible.

ACKNOWLEDGMENT

We indebted to D. Goujon, D. Gritti and A. Jornod for their contributions to this work

REFERENCES

[1] R.W.F. Vessot *et al.*, "Space-borne hydrogen maser design," 8th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting p277-333 (1976)

[2] Busca, G.; Bernier, L. G.; Schweda, H.; Kardashev, N.; Andreianov, V.; Roxburgh, I. W.; Polnarev, S. "The CRONOS hydrogen maser clock redshift experiment on Radioastron", Advances in Space Research, Volume 32, Issue 7, p. 1421-1428.

[3] L. Mattioni, M. Belloni, P. Berthoud, I. Pavlenko, H. Schweda, Q. Wang,,P. Rochat, F. Droz, P. Mosset, and H. Ruedin, "The development of a passive hydrogen maser clock for the GALILEO navigation system", Proc. 34th Annual Precise Time and Time Interval (PTTI) Meeting, p.161-170, 2004

[4] L. Cacciapouti *et al.*, "Atomic Clock Ensemble in Space: Scientific Objectives and Mission Status" Nuclear Physics B (Proc. Suppl.), vol. 166, pp. 303–306, 2007.

[5] Ph. Laurent *et al*., "The PHARAO Space Clock: Results on the Ground Operation of the Engineering Model", EFTF 2007, these Proceedings

[6] S. Zivanov, H. Schweda, D. Goujon, D. Gritti and G. Perruchoud, "Physics Package of the 35 kg Active Hydrogen Maser for the ACES mision of ESA", these Proceedings

[7] C. Weber, M. Duerrenberger, H. Schweda, "Principles of Pulsed-Interrogation Auto-Cavity Tuning for the ACES Hydrogen Maser", these Proceedings

[8] G. Busca, L.-Gg. Bernier and P. Rochat, "Active hydrogen maser atomic frequency standard, United States Patent 5838206, filing date 1996

[9] P. Berthoud, D. Goujon, D. Gritti, A. Jornod, C. Weber, M. Dürrenberger, H. Schweda, M. Roulet B. Thieme, and G. Baister, "Development of the active space hydrogen maser for the ACES space experiment of ESA", Proc. 2006 20th European Frequency and Time Forum, 379-383

[10] R. Beard, W. Golding, J. White," Design Factors for Atomic Clocks for Space", Proc.IEEE. Symp. Freq. Contr. Vol. 56, pp.493-498 (2002)

[11] P. Berthoud, I. Pavlenko, Q. Wang, and H. Schweda, "The engineering model of the space passive hydrogen maser for the European global navigation satellite system GalileoSat," Joint IEEE International Frequency Control Symposium /17th European Frequency and Time Forum, 05-08 May 2003, Tampa (USA), pp. 90-94.