DEVELOPMENT OF THE SPACE ACTIVE HYDROGEN MASER FOR THE ACES MISSION

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INTRODUCTION

The Atomic Clock Ensemble in Space (ACES) is composed of two atomic clocks: one cold Caesium clock (PHARAO) and one active Space Hydrogen Maser (SHM). PHARAO is necessary to ensure outstanding long-term frequency stability ($\tau \geq 3000$ s) and accuracy, while SHM is mandatory for its ultimate frequency stability in the mid-term range ($3\ s \leq \tau \leq 3000$ s). The combination of the two clocks via a double servo loop (short-term and long-term), will ensure an ultimate frequency stability. This configuration takes advantage of the best frequency stability for each integration time (PHARAO frequency locked to SHM for the short and mid-term, and SHM frequency steered to PHARAO for the long-term).

Hydrogen masers are atomic clocks based on the transition at 1.420 GHz between the two hyperfine levels of the ground electronic state of atomic hydrogen. Atoms prepared in the higher quantum state are directed into a storage bulb placed in a microwave cavity. When the atomic flux is high enough, the energy available from the stimulated emission of radiation overcomes the microwave losses of the microwave cavity and the maser action starts. The energy generated from this process, despite its very low power (in the order of 1×10^{-14} W), is detected by an antenna and converted into electrical energy, where it is further amplified and synthesized.

SpectraTime (SpT) is presently developing the Engineering Model (EM) of a 40kg lightweight active Space Hydrogen Maser (SHM) for the ACES Mission which will be flown on the International Space Station (ISS) in 2013. The main objective of the EM phase is to perform an end-to-end performance demonstration with representative hardware, to be used as a milestone for pursuing the development of the SHM and aiming at the delivery of the SHM Flight Model (FM) in 2012. The current design and the latest results are presented hereafter.

SHM DESIGN OVERVIEW

The SHM instrument is made of one physical unit, which includes both the Physics Package (PP) and the Electronics Package (EP). The PP provides the atomic oscillator, while the EP provides the atomic signal processing circuits, parameter control functions, telemetry and telecommand. The current design is presented in Fig.1.

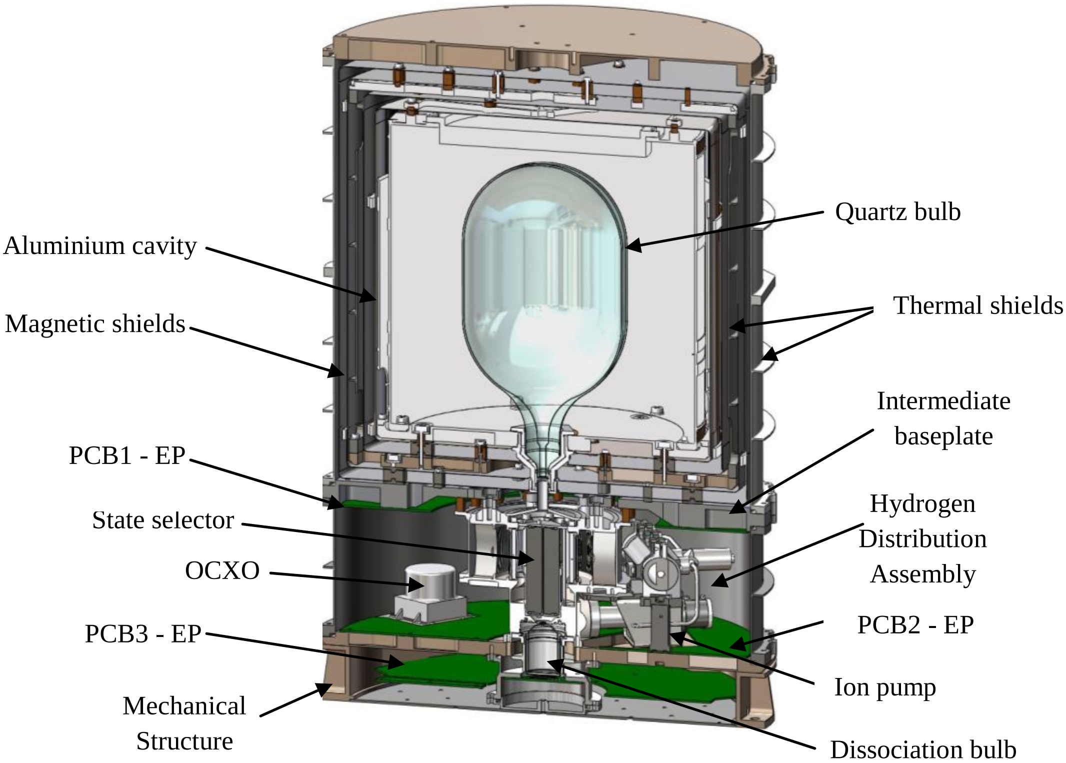

Fig.1: SHM Design Overview

The PP is constituted of a large cylinder, the MCSA (Microwave Cavity and Shielding Assembly) which is the heart of the maser. This main element contains the microwave cavity, the atomic storage bulb surrounded by 5 layers of magnetic shields and 2 thermal shields. It includes also the main structural elements that secure the MCSA cylinder to the spacecraft base plate. A low vacuum enclosure is built over the MCSA to limit the thermal with the surrounding air and to simulate the final flight conditions.

The microwave cavity is a full size unloaded metallic cavity. This cavity resonates at the hydrogen frequency f_0 in a mode analogous to the TE_{011} mode. The cavity is made of aluminium and coated with silver for higher surface conductivity and therefore higher cavity quality factor Q_c.

The quadratic dependence of the atomic transition frequency on the ambient magnetic field imposes shielding of the instrument from external magnetic influences by using several layers of magnetic shields (5 layers used in the present design). A stable and uniform magnetic field is maintained in the region of the atomic hydrogen storage bulb by the use of the static field solenoid (C-Field) placed inside the inner magnetic shield. An extremely high uniformity of the magnetic field is required in order to avoid magnetic relaxation.

Thermal control of the microwave cavity is essential for achieving the excellent frequency stability of the instrument. The frequency of the atomic signal depends on the resonant frequency of the microwave cavity. The pulling factor K i.e. the ratio between a change of atomic signal frequency produced by a change of cavity resonant frequency, is in the ratio of the microwave cavity quality factor, of about 3-4 $x10^4$, to the atomic line quality factor Q_{at}, of about 10^9. Thus, temperature fluctuations induce frequency fluctuations of the output through the temperature sensitivity of the microwave cavity.

A detailed mechanical model (of about 630’000 nodes) has been developed in Solidworks simulation software in order to design the SHM according to the stringent interface requirements. Stress, modal and random analysis has been conducted and will be consolidated in the FM phase. A dedicated thermal model has also been established and steady state as well as transient analyses have already been achieved.

SHM PP CHARACTERISTICS

After tuning adjustments, an atomic signal level up to -101 dBm was achieved (with a C-Field value of 600 μG).

It was also possible to measure the PP characteristics : Qc = 44'000, K = $4.39.10^{-5}$ Hz/Hz, which leads to an atomic quality factor of $1.0x10^{9}$. Moreover the cavity thermal sensitivity was measured at about 33kHz/°C between 50°C and 60°C. All these parameters correspond to the expected values.

Fig.2 presents the Technological Model (TM) which constitutes the experimental set-up used to test the EM cavity. The TM is made of the engineering cavity completed by standard components for Hydrogen Distribution Assembly (HDA). The goal of this intermediate set-up was to characterize and validate the cavity design itself.

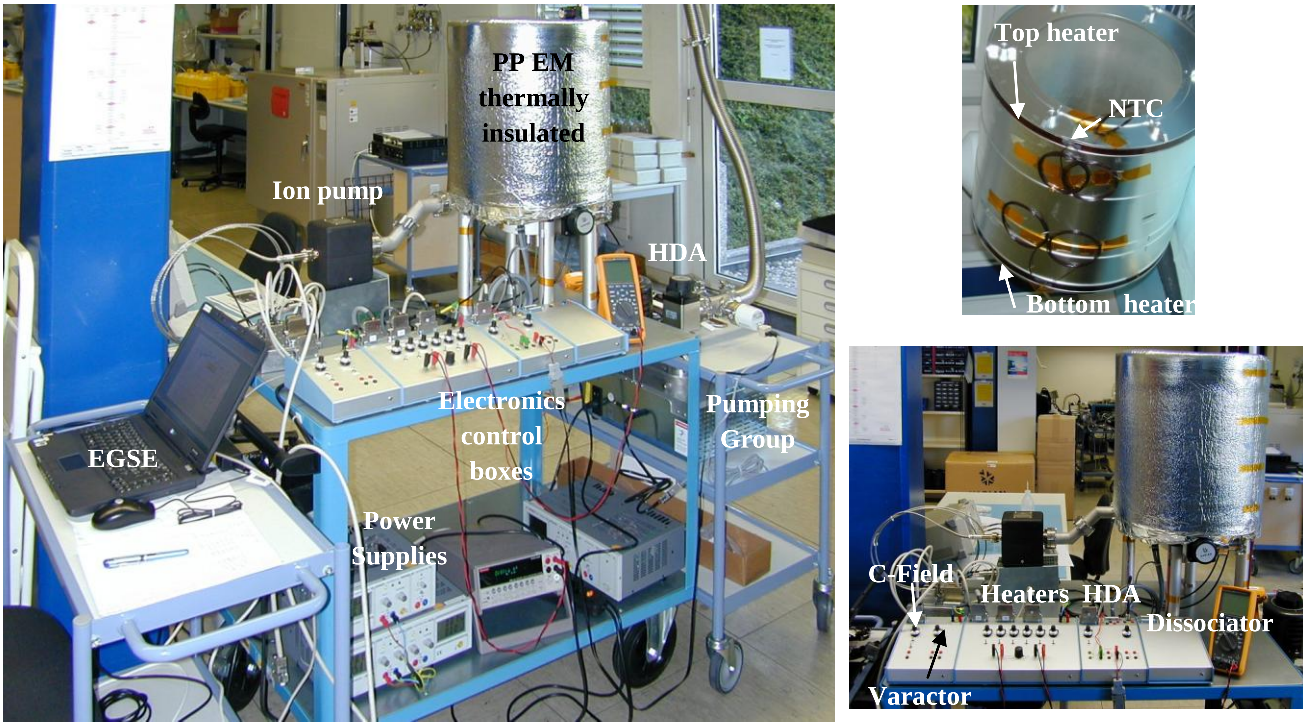

Fig.2: Technological Model Set-up and cavity view (top right)

The thermal control of the cavity is ensured by three thermal layers made of resistive heaters for the two inner ones (as shown on Fig. 2 for the cavity), and additional transistors for the outer one. The thermal gains of the different layers have been measured and an overall thermal gain of about 9300 was extracted. Nevertheless, in order to achieve the SHM ultimate performance of $1.5.10^{-15}$ relative frequency stability at 10'000s, the microwave cavity shall be actively stabilized at 0.1 Hz level, in order to compensate the cavity pulling effect. This is only possible with the Auto Cavity Tuning (ACT) function. The goal of the ACT is to increase the thermal stability of the cavity by several orders of magnitude. Fig. 3 presents the ACT principle.

The Cavity is interrogated by 2 continuous signals at 15kHz from central line, and the error signal defined as the amplitude difference of the 2 detected signals is used to generate a correction signal sent back to the varactor. The necessary stability of the error detection signal shall be of 2 ppm to ensure the required stability.

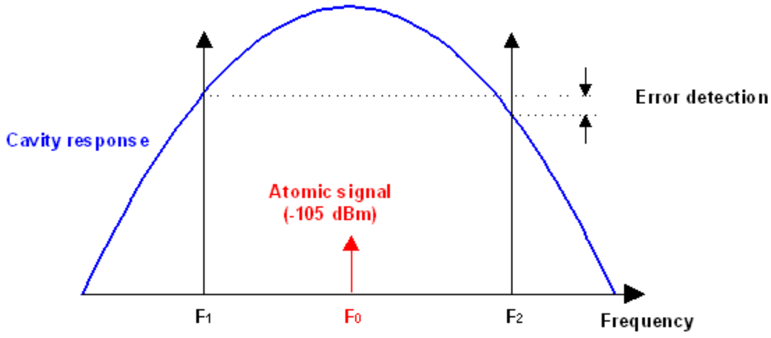

Fig. 3: ACT Principle

The next steps in PP development will be the assembly of the bottom part of the SHM EM made of the Hydrogen Vacuum Assembly (HVA) and the HDA. The HDA is based on a solid-state hydride storage container delivering molecular hydrogen gas through a nickel flow control valve into a low pressure gas bulb (0.1 mbar typical), where a plasma discharge dissociates the molecules into atoms.

SHM EP DESIGN

The objectives of the SHM EM phase concerning EP is to validate the critical electronics (in term of thermal sensitivity), i.e., the main RF electronics (down conversion chain and ACT electronics) as well as the heaters electronics. Therefore, these two functions will be integrated on PCB N°1 (see Fig.1) for final EM validation.

The main RF electronics is in charge of frequency locking the local quartz oscillator on the hydrogen clock transition frequency as well as frequency locking the microwave cavity using the ACT. It delivers the stable 100 MHz signal to the ACES payload. The heaters electronics regulates thermally the whole SHM PP at the m°C level in order to ensure the required frequency stability when combined with the ACT function.

The heaters electronics is based on proportional controllers, with 3 temperature setting points corresponding to the 3 heating layers. The system has been sized according to the thermal model and thermal testing.

Fig.4 presents the RF PCB layout which is currently under manufacturing process.

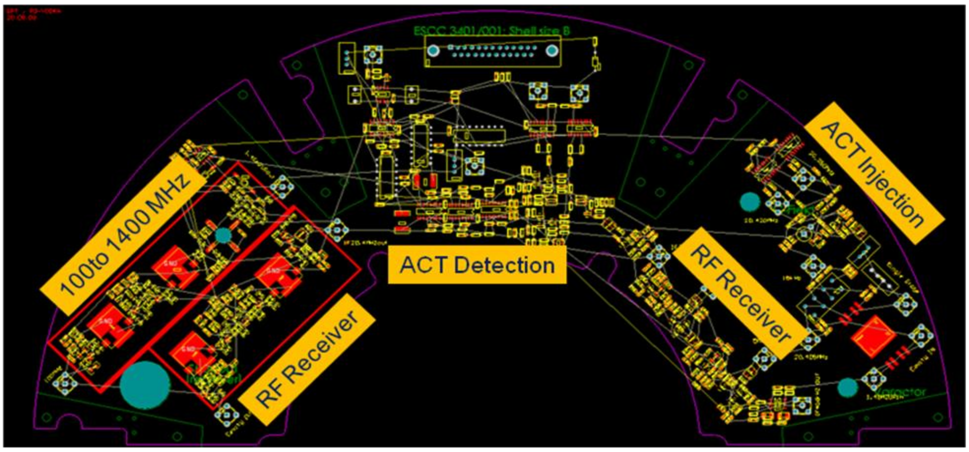

Fig. 4: RF PCB Layout

The other EP functions will be ensured either by laboratory equipment or by commercial parts. Nevertheless, their development have been started as advanced FM activities. For example, the power supply section is based on a PWM controller and is constituted of several DC-DC converters. Different prototypes have been realized and successfully tested (inrush current, load peak current, transient voltage, input filter, synchronization). A processor board based on a 80C32 processor is also under development. It is used to monitor and control various signals on the maser The processor board consists of a microcontroller with communication through RS422 and RS232. The RS422 channel will be connected to the ACES main computer crate for communication. The RS232 channel is used for local monitoring and control of signals of the maser. An ADC section is used for monitoring and control signals. a PROM, an EEPROM and a SRAM are used for bootloader, program code and data storage. There is also the possibility to download a new program onto the board, store it on the EEPROM, and execute it. A FPGA for necessary frequencies synthesis is under development, and a prototype is already under test.

SHM LATEST RESULTS

The ACT validation principle is on-going with a dedicated setup using an ACT prototype thermally regulated, and which is coupled to a ground active maser. The type of maser used is much less temperature sensitive than the SHM (ceramic cavity). Nevertheless, the goal is first to demonstrate that the ACT function does not perturb the behaviour of the maser and then it will be connected to the SHM PP for final validation.

Fig.5 presents the validation test bench currently used for ACT validation.

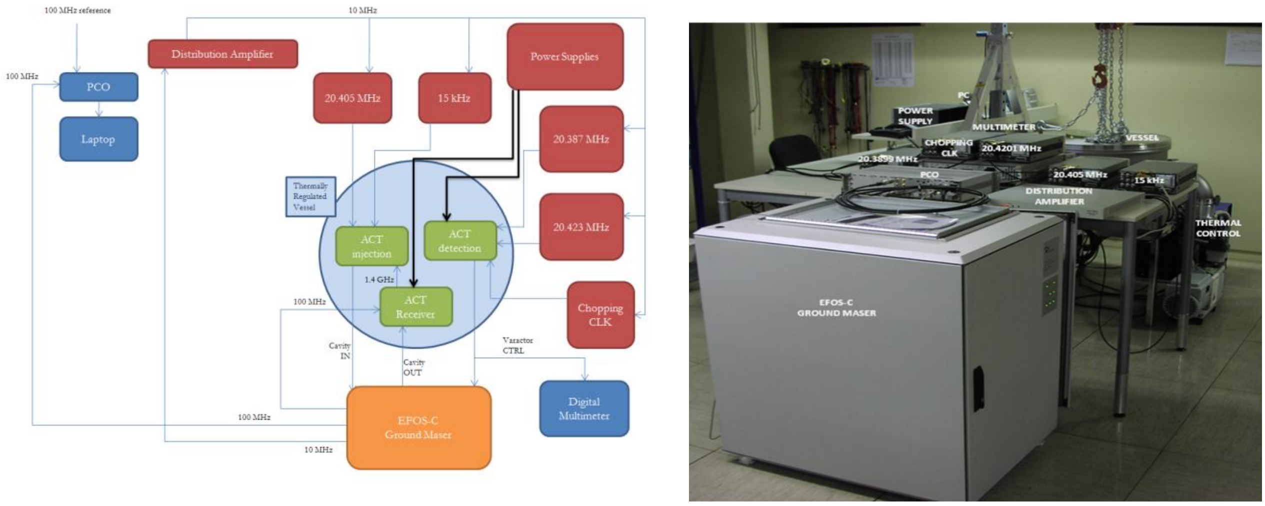

Fig. 5 : ACT validation test bench layout (left) and view (right)

The ACT thermal sensitivity has been measured and gives a value of 18 ppm/°C, which is compatible with the specification (2ppm) , as the ACT electronics will be implemented on the SHM intermediate base plate (see Fig.1), which will be thermally regulated at 0.1°C level.

Fig.6 presents the latest results obtained in the frame of the ACT validation campaign. The dashed green curve represents the SHM performance specification, the continuous green curve includes the contribution of the reference maser and measurement system (and thus constitutes the curve to which data shall be compared to) , and the red curve shows the actual performance achieved. The performance is in specification on the full range except for a small deviation around 1000s. This deviation is due to a small thermal residual effect which will be cancelled once the full RF electronics will be integrated in the SHM (see Fig.1).

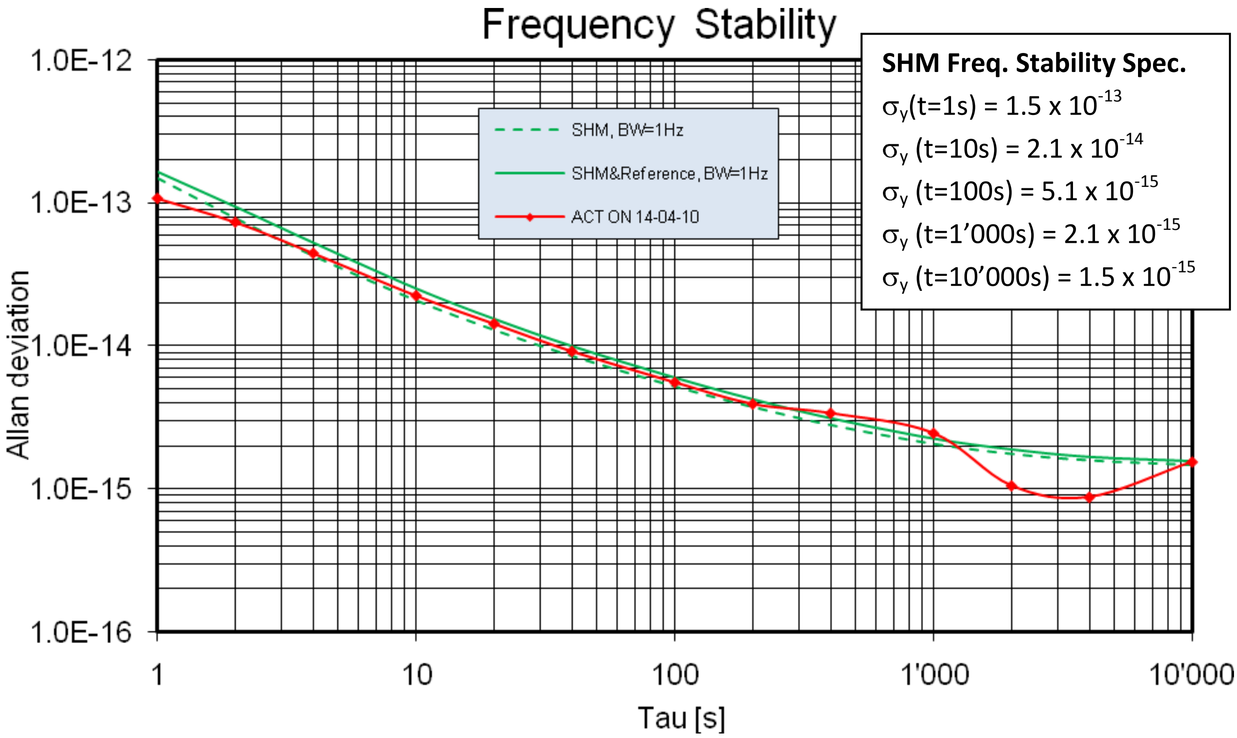

Fig.6 : Current SHM performance

CONCLUSIONS AND OUTLOOK

We have reported in these proceedings on the development of the Space Hydrogen Maser (SHM) for the scientific mission ACES. The Engineering Model of the SHM Physics Package has been successfully characterized and is currently under final assembly process (integration of final HVA and HDA). Moreover the functionality of the key electronic function (Automatic Cavity Tuning – ACT) is under finalization and the progress made in less than one year is very promising for the success of this new development. The next major milestone will be the end-to-end EM validation campaign, which will occur during summer 2010. The FM phase will be initiated in parallel and will lead to the FM SHM delivery in 2012.