SHM Qualification for ACES: Performance and Environmental Tests

Qinghua Wang[1], Jacques Pittet[1], Antonio Perri[1], Hanka Ruedin[1], Sébastien Perrault[1], William Moreno[1], Didier Goujon[1], Thomas Niedermaier[2], Silvio Koller[2],
Luigi Cacciapuoti[3], Sophio Pataraia[3], Simon Weinberg[3], Jason Williamson[3], Thomas Peignier[3]
[1]*Safran Timing Technologies, Neuchâtel, Switzerland*
[2]*Airbus Defence and Space, Friedrichshafen, Germany*
[3]*European Space Agency, ESTEC, Noordwijk, The Netherlands*
Email: qinghua.wang@nav-timing.safrangroup.com

***Abstract*—We present the Space active H-Maser (SHM) qualification status for ACES based on the latest results of the SHM Proto Fight Model (PFM) test campaign performed after the refurbishment. They include the environmental tests (vibration, thermal vacuum cycle, EMC) for the verification of proper workmanship and the validation of the refurbishment, the full performance test under thermal vacuum, as well as the final SHM tuning performed after integration in the ACES payload to optimize SHM performances. The characterization of frequency sensitivities to the environment (e.g. temperature, magnetic field, voltage) and frequency stability is reported as well.**

Keywords— ACES, SHM, Hydrogen Maser, atomic clocks, space, ISS

I. INTRODUCTION

The Atomic Clock Ensemble in Space (ACES) is a pioneering mission led by the European Space Agency (ESA) to test Einstein's theory of general relativity. It will place high performance atomic clocks and links on the International Space Station to distribute a stable and accurate time base, thus establishing a global network to compare clocks in space and on ground [1, 2].

The active Space Hydrogen Maser (SHM), one of the two atomic clocks onboard the ACES payload, is developed by Safran Timing Technologies (STT, former Spectratime) under Airbus Defence and Space and ESA contract with the funding provided by the Swiss Space Office. SHM is the flywheel oscillator providing excellent medium-term stability to the ACES clock signal.

II. SHM DEVELOPMENT, REFURBISHMENT AND QUALIFICATION OVERVIEW

The design and development of the lightweight active hydrogen maser for space applications required 15 years at STT, starting from the development of engineering models [3].

TABLE I. SHM SWAP (SIZE, WEIGHT AND POWER)

Size	Ø40 * H60 cm
Weight	45 kg
Power consumption	85W @22°C

The Proto Fight Model (PFM) was firstly delivered in 2018 for ACES. In September 2020 during the ACES Integrated System Test (IST) 1, an anomaly in the SHM vacuum system was observed. The anomaly was impacting the clock lifetime, which could not be guaranteed for the envisaged ACES mission duration. Between April and September 2021, a design review of the SHM vacuum system was performed with the participation of ESA, Airbus and STT. The PFM refurbishment started in October 2021. The activities were carried out over the last two and half years and included:

- SHM dismounting
- Key parts manufacturing and refurbishment, mainly on the Physics Package (PP) specifically addressing the high vacuum assembly, e.g. ion pump and high voltage potting, getters and activation, pinch-off; hydrogen supply assembly, and hydrogen dissociation assembly
- Manufacturing and assembly process robustification for validation of the storage bulb assembly (with regard to the Viton joint permeation), handling and storage (especially to maximize the storage under vacuum to limit permeation), baking and getter activation, as well as additional assembly controls
- SHM re-assembling and integration of PP and Electronics Package (EP)
- SHM acceptance testing

In parallel, analyses and tests have been conducted to gain technical confidence by ruling out possible vacuum failure root causes, and to identify mitigation measures on potential risk:

- Vacuum analysis and test: Investigations were handled by ESA including X-ray Photoelectron Spectroscopy (XPS) test, and Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) of getter samples.
- Lifetime tests and analysis, including: Viton permeation coefficient measurements, permeation rate of o-ring joints and torque optimization, o-ring permeation measurements, and getter sorption measurements. The latter two tests were performed by ESA.

- Non-destructive inspection of critical structural parts, and update of fracture analysis with regard to new launcher environment.

Hereafter, we present the latest results of SHM acceptance test campaign after the refurbishment, from May to December 2023, including the functional and full performance test under thermal vacuum, the environmental tests, the performances checks, as well as the final SHM tuning in the ACES payload configuration to optimize SHM performances.

III. Functional and Full Performance Test

The test was performed at STT premises right after the PFM refurbishment.

The goal of this test was to demonstrate the SHM PFM functionality and performance under flight representative vacuum and thermal environments. It included the evaluation of the SHM sensitivity coefficients, the characterization of the 100 MHz frequency output, the Allan Deviation (ADEV) and the phase noise (Fig. 1) under different temperature settings.

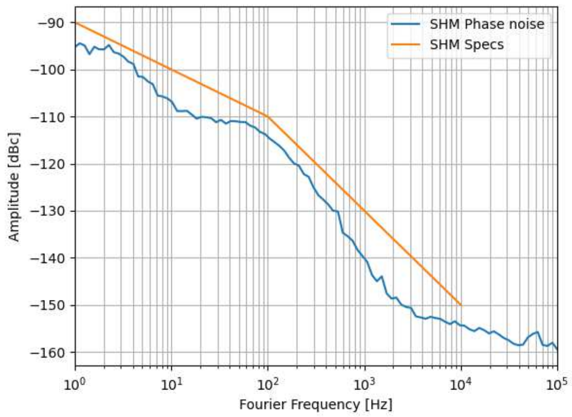

Fig. 1. Phase noise measurement at 100 MHz between the SHM and the reference maser

SHM sensitivity coefficients were characterized:

- Thermal sensitivity: 2.9e-14/°C and 1.8e-14/°C at thermal cycling periods of 5400 s (corresponding to the ISS orbital period) and 2000 s, respectively. Fig. 2 reports the SHM Allan deviation for a sinusoidal variation of the temperature of 1.5°C peak-to peak and a period of 2000 s.
- Magnetic sensitivity: 2.6e-14/G
- Voltage sensitivity: 2.6e-15/V

Compared to the SHM PFM performance measured before the refurbishment, we observed degradations of the Allan deviation (as shown below in Fig. 9) and of the thermal sensitivity.

The sensitivity to temperature and magnetic field has an impact on ACES science, but it can be efficiently measured. Calibrations can then be used on orbit to reduce temperature and magnetic perturbations on the SHM clock signal.

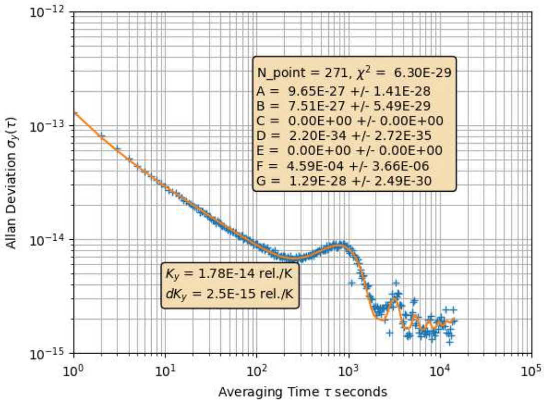

Fig. 2. Allan deviation of the SHM frequency under a sine temperature variation of 1.5°C peak-to-peak and a period of 2000 s. The best fit used to extract the sensitivity coefficient (red)

IV. Environmental Testing

The environmental testing of the refurbished SHM PFM composed of Vibration, Thermal Vacuum Cycle and Electromagnetic Compatibility (EMC) testing, was executed at Airbus Defence and Space environmental test laboratory in Friedrichshafen.

A. Vibration test

The objectives of this test were to determine the resonant frequencies, measure the random response, and verify the structural integrity of the unit after suffering the random vibrations (Fig. 3).

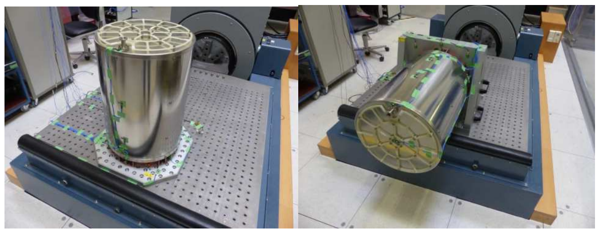

Fig. 3. Random vibration at acceptance levels: 5.26 g_{rms} and 5.76 g_{rms}, respectively, in the out-of-plane and in-plane directions

The measured eigenfrequencies were close to the ones determined by mechanical analysis and were higher than 100Hz, as required.

The ion pump current of SHM was checked after vibrating the clock along each axis. No degradation of the background pressure could be detected in the SHM.

B. Thermal vacuum cycle test (non-operational mode)

The objective of the test was to prove SHM survival and constant function behavior before and after non-operational temperature cycles under vacuum.

SHM was tested in the thermal vacuum chamber (Fig. 4) from 60°C to -35°C (Fig. 5).

In addition, the stay-alive subsystem (including ion pump, high voltage power supply and stay-alive DC/DC converter) was evaluated in operational mode at the lowest temperature. No anomaly or performance degradation could be observed after exposing the clock to the thermal cycle.

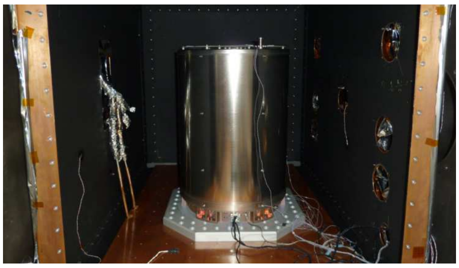

Fig. 4. Test setup in thermal vacuum chamber

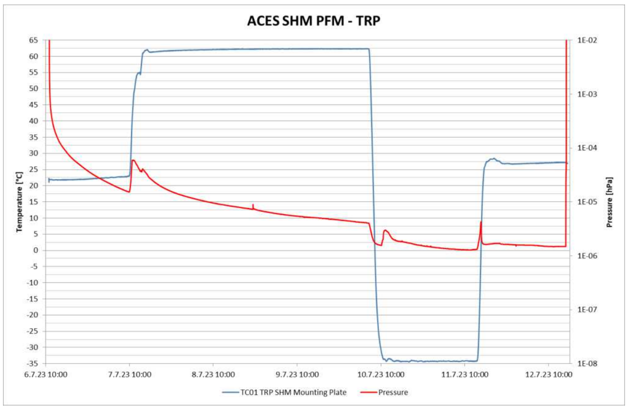

Fig. 5. Temperature measured at Thermal Reference Point (TRP) and pressure profile in thermal vacuum chamber

C. EMC test

The objective of this test was to verify the compliance of SHM to the EMC environment. SHM functionality and performance were tested under specified EMC disturbances.

The EMC test (Fig. 6) after the PFM refurbishment consisted of isolation and bonding, conducted emissions, and radiated susceptibility, while the testing of conducted susceptibility, radiated emissions and magnetic field which were performed previously were skipped due to time constrains.

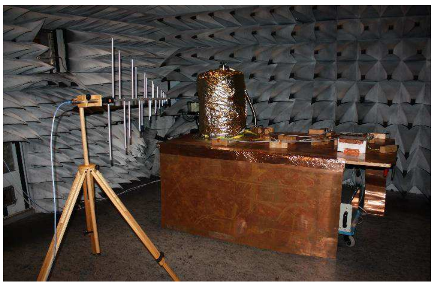

Fig. 6. Test setup inside EMC test chamber for radiated susceptibility test

Results were aligned with what had been measured prior to the refurbishment.

V. PERFORMANCE CHECKS AND DEGAUSSING

After each of the above environmental test, the SHM functionality and performance were checked.

The SHM functionality was fully kept. All performances have passed the criteria successfully. The linewidth of the atomic signal was measured to be narrower than 2Hz after each environmental test, showing an improvement with respect to the 2.3Hz ~ 2.6Hz obtained in 2018.

A degaussing function was implemented to remove the residual magnetization induced by mechanical constraints or thermal stress. Applied degaussing cycles could always efficiently recover the correct atomic signal for SHM operation after thermal and mechanical stresses.

To have access to the Airbus flight model of the degaussing box and test the degaussing function, SHM was installed temporarily in the ACES payload (Fig. 7).

Fig. 7. SHM installed (with holding tool) temporarily into ACES payload

Several degaussing cycles were applied on SHM with various degaussing cycle frequencies. The degaussing at 3.125Hz revealed to be very efficient, as in the C-field curves of Fig. 8 showing the amplitude of the atomic signal as a function of the current defining the bias field seen by H atoms:

- The maximum detected amplitude of the down-converted atomic signal was 2.68V. This value is lower than the ones observed in 2018.
- The width of the central notch of the C-field profile became narrower, from the 3uA to 1.25uA, equivalent as what obtained in 2018.

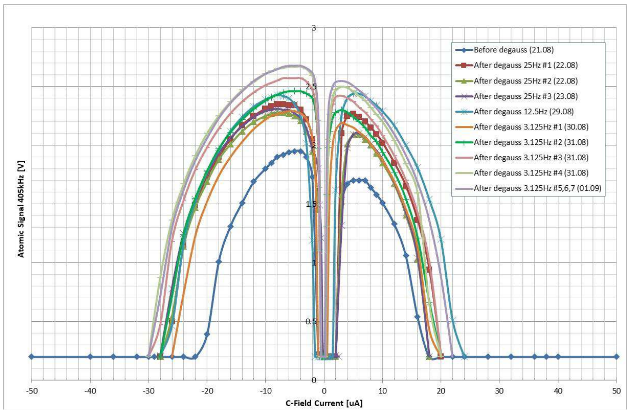

Fig. 8. C-field vs. atomic signal characteristics after degaussing

The degaussing proved to be effective in reducing the residual magnetization and improving the homogeneity of the magnetic field in the microwave cavity. However, it was not possible to fully recover the atomic signal observed before refurbishment. This degradation might be due to a permanent magnetization of the shields and/or a misalignment of the atomic beam path due to mechanical tolerances.

VI. Final tuning test

The final tuning, with SHM integrated in the ACES payload, was deemed necessary to achieve the best performance in final configuration. The objective was to optimize SHM frequency stability to compensate the degradation of the atomic signal, by tuning operational parameters through available EGSE commands.

Parameters setting was tuned on both:

- PP: cavity frequency, hydrogen flux, hydrogen dissociation oscillator power
- EP: Automatic Cavity Tuning (ACT) discriminator slope, ACT detection frequencies, fine spin exchange tuning, chopping mode

Fig. 9 shows the comparison of SHM ADEV measurement results compared with the active H-masers from T4Science as reference:

- In June 2023 during initial full performance acceptance test, the entire SHM was under a thermal vacuum chamber for 3 days at 22°C at STT premises. SHM ADEV was measured by comparison to the two reference H-masers in the lab with the three-cornered hat method.
- In December 2023 during 3 days in the ACES configuration at Airbus Defence and Space premises, the ACES payload was under vacuum. SHM ADEV was calculated after removing the contribution of the calibrated reference H-maser.

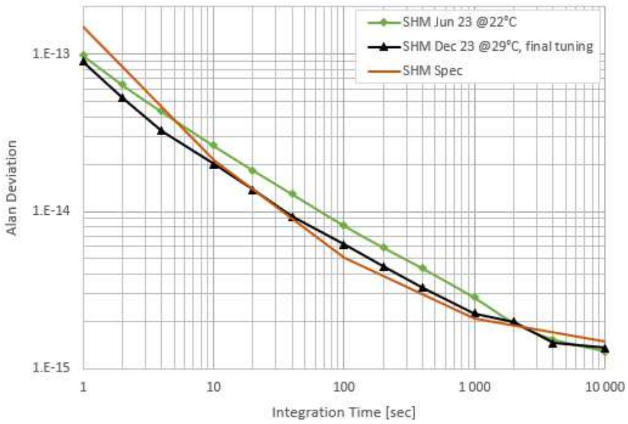

Fig. 9. Comparision of SHM ADEV measurements vs specification

As illustrated in Fig. 9, after the final tuning the frequency stability could be improved with respect to previous measurements up to an integration time of 1000 s, without any degradation of other parameters such as long-term stability and thermal sensitivity (i.e. 9.0e-14 at 1s, 2.0e-14 at 10 s, 6.2e-15 at 100 s, 2.3e-15 at 1000 s, and 1.3e-15 at 10000 s). Non-compliances to ACES SHM specification at 100 s and 1000 s can be considered as acceptable (5.1e-15 at 100 s and 2.1-15 at 1000 s according to the specification).

Conclusions

After the completion of the refurbishment, the PFM has been qualified by environmental tests at SHM unit level on ground. The SHM PFM performance under flight representative vacuum and thermal environments have been demonstrated.

The SHM PFM has been formally delivered with the successful acceptance review and released for the ACES IST campaign in the final configuration and under representative environmental conditions. The final acceptance of the SHM PFM will be concluded with the successful IST.

To mitigate the risk of SHM high vacuum degradation due to permeation, Airbus Defence and Space has equipped the ACES payload with vacuum pipe that will be used to depressurize the outer enclosure of SHM and reduce to the minimum the exposure of the clock to ambient pressure.

SHM is a lightweight, high-performance, high Technology Readiness Level (TRL) space atomic clock available today. Taking advantage of the ACES heritage with a 15-year lesson learnt, SHM offers good perspectives for technical and performance improvements, positioning itself as a good candidate for future space missions.

Acknowledgment

The authors wish to acknowledge all their colleagues at Safran Timing Technologies, Airbus Defence and Space, and European Space Agency for their substantial contributions and supports to these achievements, and the funding provided by the Swiss Space Office.

References

[1] L. Cacciapuoti, M. Armano, R. Much, O. Sy, A. Helm, M. Peter, et al., “Testing gravity with cold-atom clocks in space”, Eur. Phys. J. D 74, 264, 2020.

[2] L. Cacciapuoti, A. Busso, R. Jansen, S. Pataraia, T. Peignier, S. Weinberg, et al., “Atomic Clock Ensemble in Space,” to be published on 9th Symposium on Frequency Standards and Metrology, Kingscliff – AU, 2023.

[3] D. Goujon, P. Rochat, P. Mosset, D. Boving, A. Perri, J. Rochat, N. Ramanan, D. Simonet, X. Vernez, S. Froidevaux and G. Perruchoud, “Development of the Space Active Hydrogen Maser for the ACES mission,” 24th European Frequency and Time Forum, April 2010, DOI: 10.1109/EFTF.2010.6533730.