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On-Board Galileo RAFS, current status and performances

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Abstract :
Galileo program is now approved by the European concerned government. The activities related to GSTBV2 experimental satellite as well as the implementation of the In Orbit Validation phase have been started. Atomic clocks represent critical equipment for the satellite navigation system and clocks development has been continuously supported by ESA. The first related ESA contract for a RAFS (Rubidium Atomic Frequency Standard) was first initiated in 1996. RAFS is today one of the baseline clock technology for the Galileo Navigation Payload. This presentation gives a general overview of the RAFS development and evolution so far. It also provides updated information on the measurement results regarding clock frequency stability under simulated space environment as:

- vacuum coupled with temperature variation
- electromagnetic perturbation
- radiation variation (orbit cycle simulation) and total cumulated dose.

Furthermore, measurement related to the capability of the clock to survive the vibration environment during launch without damage is addressed.

I. Introduction

Since 1996, the Temex Neuchâtel Time (TNT) space RAFS (Rubidium Atomic Frequency Standard) activities have been driven by the ESA program needs (GNSS-1, GNSS-2 and finally GALILEO). The clock performance potential was rapidly demonstrated but the capability of such a clock to fulfil the other objectives was much longer to achieve. In fact, speaking about space clocks, three main elements are to be considered:

- The performance of the clock must be compliant to the space system needs
- The clock must survive to the very aggressive environment of the initial and operational phases. This environmental condition includes vibration during launch, thermal stress, high radiation level and long term vacuum
- The clock must keep its performances under radiation and vacuum for the entire lifetime of the space system.

II. RAFS Development Steps

The different development steps are the followings:
- Initial *RAFS1* development and pre-qualification models for NAVSAT (GNSS-1 and GNSS-2 program)
- *Updated RAFS1* for lifetime demonstration and qualification model for GALILEO
- *RAFS2* development for improved performance and GALILEO payload interface compatibility

III. First Development and Pre-Qualification models for NAVSAT (GNSS-1 and GNSS-2 program)

The Agency has undertaken the development of space qualified rubidium clocks in the early 90s under its Technology Demonstrator Program. A first development activity of a RAFS suitable for Navigation Applications was initiated, by the Agency, in 1996 with TNT. This development contract was completed in the first half of 2000 with the manufacturing and test of an Engineering Qualification Model (EQM) *RAFS1* clock. The final frequency stability performances of this EQM *RAFS1* clock have been measured within the specifications up to 6000 sec. but limited by thermal effects mainly due to residual thermal sensitivity of the cell. The *RAFS1* EQM clock is shown on figures 1 and 2.

Fig 1: Picture of the *RAFS1* once closed
(before update)

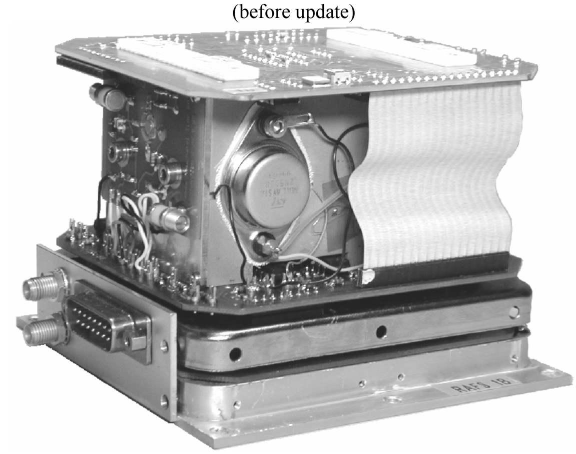

Fig 2: Picture of *RAFS1* without external cover
(before update)

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IV. *UPDATED RAFS1* FOR LIFETIME DEMONSTRATION AND QUALIFICATION MODELS FOR GALILEO

Updated RAFS1 Objectives

In view of the needs to improve the performances of the *RAFS1* for GALILEO, the Agency initiated, in June 2000, a development activity with a twofold objective:

- Develop an optimised clock (*updated RAFS1*) Qualification Model with reduced flicker floor
- Initiate a Lifetime Qualification program on this clock technology

For the development of the clock Qualification Model four aspects were considered of primary importance:

- To review and update of the Electronics Package design in line with the requirements for the manufacturing of space hardware
- To improve the thermal sensitivity performance of the clock (new geometry allowing temperature turning point on the cell)
- To include a thermally regulated base-plate in the clock
- To reduce the flicker floor

The main objective of the lifetime qualification program was the assessment of the reliability and lifetime capability of the *updated RAFS1* with respect to the Galileo requirements. This is particularly important as Galileo is a demanding mission which requires 12 years of continuous operations into space. In line with these requirements, the Agency has asked TNT to run a two-years life-test program during which the performances of five clocks will be continuously monitored under vacuum conditions. The program of work besides building up confidence on *updated RAFS1* will also serve to establish a database of fundamental performance characteristics of this clock, which will be compared in future with in orbit performances.

Collaboration within Updated RAFS1 frame

To achieve these objectives and in recognition of the importance to obtain a fully space-qualified product ready to fly on Galileo, TNT established a co-operation with ASTRIUM-D. In this co-operation ASTRIUM-D is in charge of Electronics Package update according to space rules and has, in fact, the mandate to manufacture the clock electronic modules for the flight production.

The main contribution of ASTRIUM-D in the optimisation of the clock Electronics Package can be summarised in the following points:

- Update the RAFS, Core Electronics with respect to usage of high rel. parts and manufacturing aspects.
- Implementation of the clock Digital Synthesiser developed by TNT into a FPGA.
- Re-design of the PCB layout design according to standards applicable in European space industry.
- Assistance to TNT in the selection and procurement of EEE parts for the QM model. The suppliers of the parts were selected according to their capability to manufacture radiation hardened in line with Galileo requirements (> 100 krad total dose).
- Perform limited, functional tests, on the electronic modules with regard to manufacturing failures and part defects.

Updated RAFS1 Qualification campaign

In parallel to the five clocks for lifetime demonstration, an *updated RAFS1* Qualification Model (QM) was manufactured. The initial performance tests on this QM clock were completed by a vibration test campaign whose results and conditions are reported in fig. 3. Furthermore, the QM was submitted to a complete EMC/EMI test campaign.

	Vibration Axis		
	X	Y	Z
Sine frequencies	5-100 Hz	5-100 Hz	5-100 Hz
Max sin. Level	20 g	20 g	20 g
Random frequencies	10Hz-2kHz	10Hz-2kHz	10Hz-2kHz
Random level max)	0.37 g^2/Hz	0.37 g^2/Hz	0.37 g^2/Hz
1st Resonance	>300Hz	>300Hz	>500Hz

Fig. 3 -Vibration Test Conditions and results

During this test campaign, one failure was detected. The origin of this failure was identified as a wire broken during vibration and correction will be implemented within *RAFS2* after validation in a complementary test campaign.

After these first tests performed under TNT's control, the QM clock was delivered to CNES in Toulouse.

CNES carried out several tests on a qualification model of an updated *RAFS1*. The test at constant temperature showed a good short and mid term stability ($\sigma_y(t) = 3.10^{-12}.\tau^{-1/2} + 5.10^{-14}$ after about 15 days of operation). The test with sine variations of temperature allowed to confirm that the temperature sensitivity is very low ($< \pm 2{,}3.10^{-14}$ at $2\ \sigma$).

CNES also carried out two radiation tests : one test with GALILEO-like variations of radiation and a cumulated dose test over the mission duration. The former allowed to establish that the RAFS has a very low sensitivity to low dose rate radiation. During the latter, the RAFS unlocked after 7 krad. Nevertheless, the test was performed up to a total dose of 30 Krad (at component level) which corresponds to an operation of 12 years in MEO orbit with a safety factor of 1.5.

The investigation demonstrates that the problem was due to a misalignment of the crystal compensation loop. ESA concurs with the classification of the reported NCR as minor and it is solved by a new alignment procedure for the crystal compensation loop. No degradation of the unit was observed beside reported problem and full initial performance was obtained after this new alignment. The radiation tests were therefore concluded as successful.

Updated RAFS1 Lifetime test campaign and performances

The five EQM clocks for lifetime evaluation have been built, as mentioned before, by TNT in parallel to the QM. These five clocks are under test for two years to assess their reliability and performance over time. To accomplish this task a special test bench has been designed by TNT that will be used to check the following main clock parameters:

- Control voltage of the internal VCXO; This parameter is very important to monitor in order to determine whether or not the crystal is drifting too much for the 12 years application requirement.
- Rubidium transmitted light level; This is to identify ageing phenomena on the spectral lamp.
- Rubidium signal level; This may depend on thermal gradient changes into the cell or variation of the light spectrum asymmetry
- Automatic gain control stability
- Output signal Phase / Frequency

Five test stations have been built for the tests of the clocks. These include a vacuum chamber connected to a Turbomolecular pump for the vacuum plus interfaces for the acquisition of the relevant data via computer.

The frequency stability performances of these EQM clocks and of the QM clock are shown in fig.3.4. The EQM#3 being still under adjustment at the time of the present article, its performances are not reported on this graphic. The five test stations used for lifetime demonstration are illustrated in fig. 3.5 while the *updated RAFS1* EQM's and QM clocks are illustrated in fig. 3.6 and 3.7.

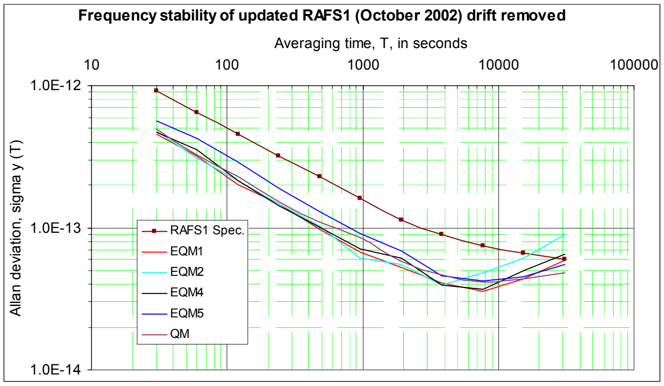

Fig. 3.4 *Updated RAFS1* performances (4 EQM's and QM)

Fig. 3.5 The five test stations for lifetime demonstration

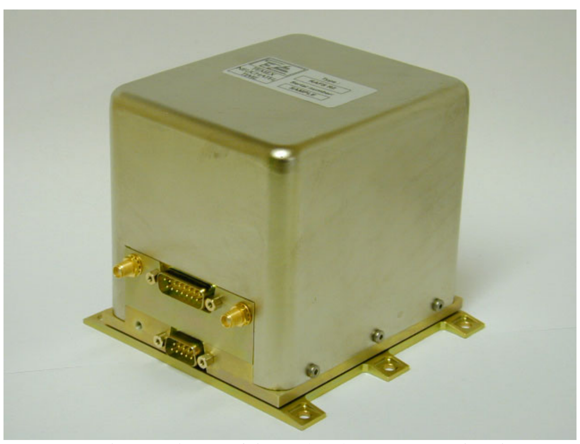

Fig 3.6: Picture of the *updated RAFS1* once closed including the thermally regulated baseplate

Fig 3.7: Picture of the 5 EQM *updated RAFS1* without external cover

V. *RAFS2* FOR IMPROVED PERFORMANCE AND GALILEO PAYLOAD INTERFACE COMPATIBILITY

The development of the *RAFS2* EM, QM and EQM clock started immediately after the initial results of the *updated RAFS1* with two main objectives:

- To improve the mid term frequency stability performance in the range of 10'000 to 50'000 sec.
- To include the DC/DC converter and the satellite interfaces within the clock equipment.

The need for an improvement in the stability performances was expressed by new specifications emitted by the Agency in June 2002. This work resulted in December 2002 in a clock with improved frequency stability performances. The frequency data with the corresponding Allan deviation (drift removed) are shown on fig. 3.8 and 3.9. These results are provided by an improved RAFS core module which not yet includes the DC/DC. This modified clock was well within the Agency requirements, in terms of frequency stability and constituted the first step in the design of the *RAFS2* Qualification Model clock and possible GSTB-V2 clocks.

The development of the DC/DC and satellite interfaces to be integrated within the *RAFS2* model is on progress with ASTRIUM-D in charge of the electronic and TNT for the mechanic. The first complete *RAFS2* model was carried out in April 2003. Corresponding *RAFS2* Flight Model are to be delivered for third quarter 2004.

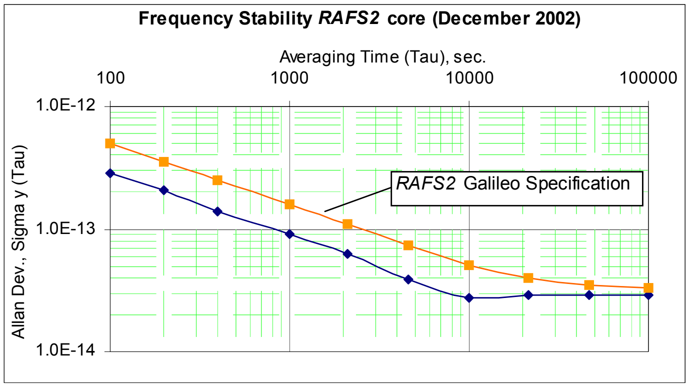

Fig. 3.8 *RAFS2* core module frequency stability performance

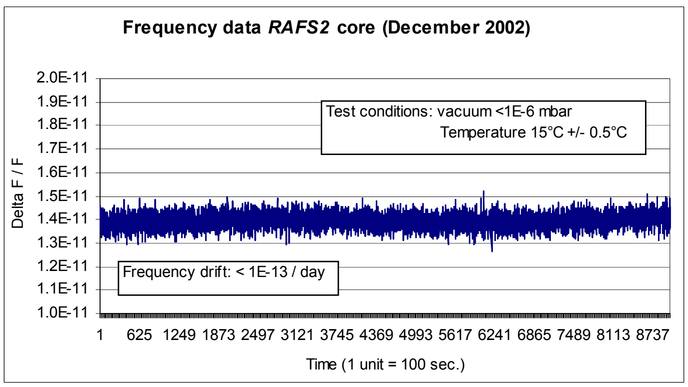

Fig. 3.9 *RAFS2* core module frequency data

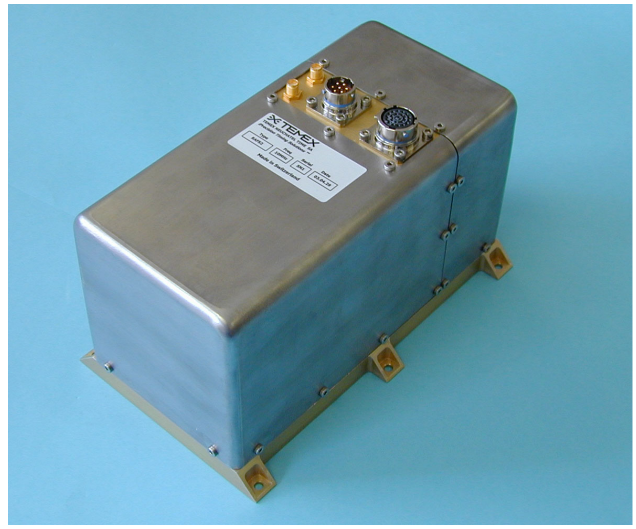

Fig. 3.10 *RAFS2* EM including DC/DC converter and satellite interface (mass: 3.0 kg, volume 2.5 litre)

VI. CONCLUSIONS

GALILEO RAFS has been successfully tested under space simulated environmental conditions (vacuum, radiation, vibration, EMC, …) and performances required for GALILEO system has been demonstrated on several units.

Three to six FM units are to be delivered for third quarter 2004 in the frame of GSTB-V2.

An intensive lifetime program is on-going and will be completed by the end of 2004. In parallel, a dedicated program has been initiated by ESA in order to improve a repeatable stability of the RAFS within $2x10^{-14}$ level. The actual stability is between $2x10^{-14}$ and $5x10^{-14}$.