RUBIDIUM ATOMIC CLOCK FOR GALILEO

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Abstract

The overall performance of navigation payloads is dependent on the performance of the on-board clocks. Better stability leads directly to improved space segment autonomy and simplified ground segment operation. The European Space Agency supports the development of advanced atomic clocks in the frame of its Technology Demonstration Program and more recently under the GNSS-2 program. Two major activities are currently running with the aim fully space-qualifying a Rubidium Atomic Frequency Standard (RAFS) and a Space Hydrogen Maser (SHM). The development activity for the Rubidium clocks is driven by the following major design goals:

- ***Mass < 1 Kg***
- ***Short-term Stability (100s) < $5x10^{-13}$, flicker floor £ $5x10^{-14}$***
- ***Volume < 1 ltr***

Special emphasis has been placed on reliability for a 10-year mission. This article presents the status of the rubidium development program and focuses on the significant design goals and results obtained to date.

INTRODUCTION

The European Space Agency has continuously supported the development of better clocks for scientific applications in the frame of its Technology Demonstration Program and more recently, for navigation, in the GNSS-2 (Global Navigation Satellite System) program. The requirement for improved, space-qualified clocks became evident once the need for a European independent navigation system was established and materialized in the "Galileo" program. Galileo is an initiative of the European Union and the European Space Agency for the development and implementation of a global navigation satellite system. The high level of ranging accuracy (below 1 meter) specified in the Galileo system for some critical applications, requires the development of suitable ultra–stable frequency standards. Atomic clocks, with their unsurpassed performance in terms of frequency stability, are the best solution to fulfil these system requirements. Atomic clocks are used on-board of GPS and Glonass, the two currently operational satellite navigation systems. There is a continuous improvement of performance of these clocks, especially in the GPS constellation. GPS block IIR spacecraft will rely exclusively on an improved Rubidium Atomic Frequency Standard designed to fulfil the lifetime requirements of 10 years for block IIR satellites. Cesium clocks on Glonass satellites have a frequency stability of $1x10^{-13}$ for an averaging time of 1 day. The frequency stability of on-board clocks has a direct impact on the complexity and amount of work that has to be carried out by the ground segment,as this latter must take care of corrections of satellite clock data.

For a given ranging accuracy, the stability of on-board clocks determines the frequency of up-loads of correction data. To keep a goal accuracy of 0.5 meter, an up-load every 9 hours would be required for the ESA-specified rubidium clock and every week in case of the ESA-specified maser In this calculation the assumption is made that the specified frequency drift ($\leq 1\text{x}10^{-13}$/day for the rubidium and $< 10^{-14}$/day for the maser) is removed by a model. At system level a trade-off needs to be made in order to choose the optimum "ensemble" of clocks on the navigation payloads. The European Space Agency has undertaken a development program that will lead to the space qualification of a Rubidium Atomic Frequency Standards - work performed by Temex Neuchâtel Time (TNT) - and of a Space Hydrogen Maser (work performed by the Observatory of Neuchâtel).

RUBIDIUM ATOMIC FREQUENCY STANDARD (RAFS)

An initial development of a Rubidium Ultra-Stable Oscillator (RUSO) for space applications, was funded by ESA under its Technology Demonstration Programme (TDP-II) in 1993. The objective of such development was to manufacture and qualify a compact spaceborne RUSO for the Russian Radioastron mission (Radioastron is a Russian lead international mission to deploy a space-based radiotelescope for a Very Long Baseline Interferometry (VLBI) radiotelescope). The oscillator was supposed to be used for calibration purposes and as back-up of the main clock to be used on board (a maser or a quartz oscillator locked to ground masers via microwave links).

The development activity for the RUSO was completed in 1995 leading to the manufacturing of 3 flight models and one EQM. The EQM unit successfully underwent a series of qualification tests. These included random vibration, low frequency vibration, temperature, thermal vacuum radiation and EMC.

All the RUSO units manufactured under this development activity have shown short-term stability better than $5\text{x}10^{-12}\,\tau^{-1/2}$ when measured against a ground hydrogen maser. The units also underwent a long-term performance test lasting 5 months. Their long-term drift, which is typically below $4\text{x}10^{-11}$ per month , was measured against a cesium standard. Following this initial development for a space-qualified rubidium clock, the Agency placed, in January 1997, a contract on TNT for the development of an improved rubidium clock, which was suited for navigation applications. The initial contract, which falls under the GNSS-2 program, is still running and was complemented in 1998 by a second contract to build 3 additional RAFS units. Overall the two contracts will deliver one engineering qualified model, one protoflight unit, and three demonstrators. The main specifications of the RAFS for navigation are the following:

Parameters	Specifications
Frequency	10.23 MHz
Freq. Stability Long Term (goal)	$5\text{x}10^{-14}$ (per 24 hr.)
Freq. stability short term 1 sec	$5\ \text{x}\ 10^{-12}$
10 sec	$1.6\ \text{x}\ 10^{-12}$
100 sec	$5\ \text{x}\ 10^{-13}$
1000 sec	$1.6\ \text{x}\ 10^{-13}$
10000 sec	$5\ \text{x}\ 10^{-14}$
100000 sec	$5\ \text{x}\ 10^{-14}$
Power consumption at 25°C	< 18W
In the operating temp. range	< 35W

Parameters	Specifications
Temperature sensitivity	$1\ \text{x}\ 10^{-13}$ / °C
Operating temperature	10 to 40 °C
Phase Noise	
1 Hz	-90 dBc
10 Hz	-110 dBc
100 Hz	-130 dBc
1000 Hz	-150 dBc
10000 Hz	-150 dBc
Mass	1.3 kg
Volume	<1 ltr

The baseline design of the RAFS for navigation was completed in 1997. The unit is designed to withstand more than 10 years of cosmic radiation in geostationary orbit. A double-oven concept is utilized to provide a good thermal behavior. Before the definition of the final configuration of the RAFS, several tests were conducted by TNT on industrial units in order to determine what were the limiting parameters.

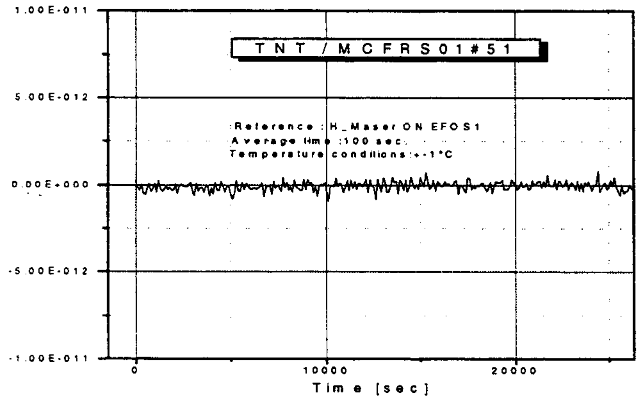
SHORT-TERM STABILITY

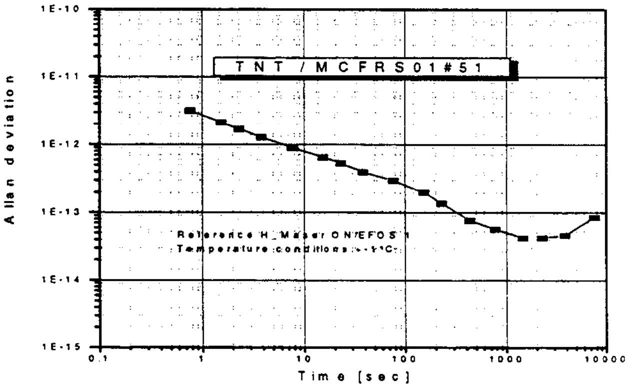
A short-term stability measurement was made at the beginning of the project on an industrial unit in order to prove the short-term stability capability of the very simple MCFRS configuration (integrated filter Cell). This MCFRS#51 was the first unit fully produced by TNT in 1995. Figure 1 represents the frequency record versus time over 25000 sec measured against the ON maser in stable temperature conditions (without-drift-removed algorithm). We can clearly see some drift in this figure of a few 10^{-13} per 10,000 sec of observation time. After several tests and analysis, we have clearly seen 3 limitation factors :

- The temperature sensitivity of the unit was much too high to reach $5x10^{-14}$ level. A long waiting time was necessary to thermally stabilize the unit before starting the measurement.
- The standard crystal resonator used in the industrial version was inducing too much frequency noise on the atomic resonance interrogation signal.
- The internal PLL-based synthesizer was too noisy.

Nevertheless, with some modifications, it has been possible to reach $4x10^{-14}$ level .

Figure 2 shows the test result of a modified MCFRS model equipped with a special crystal in order to reduce the interrogation noise along with an improved synthesizer. We can clearly see that the Allan deviation is limited by the drift. With a drift remove calculation, it is clear that this unit would be capable to stay below $5x10^{-14}$ (without temperature deviation).





At that time, since the temperature sensitivity of this unit was about $3x10^{-12}$ / °C, it was not possible to determine whether such deviation was a drift effect or simply the consequence a small temperature change during the measurement.

From that point it was then decided not change the basic configuration of the Physics; the original use of integrated filter cell surrounded by the patented magnetron microwave resonator had the capability to reach the specified stability level of less than $5 \times 10^{-12} \times \tau^{-1/2}$.

LONG-TERM STABILITY

The long-term stability is systematically measured before delivery on all the rubidiums produced by TNT (several thousands of units) . This parameter is time-dependent and decreases versus time.
However, industrial units are equipped with a natural rubidium lamp working at high temperature (~140°C). The systematic measurement has shown unit with a long-term stability of about 10^{-13}/day. This is the reason why the RAFS contains such a lamp. A significant improvement could by made in the future by using a lamp filled with Rb^{87} isotope.

RADIATION TOLERANCE

The loop synthesizer is built using standard rad-hard available components which have been chosen according to radiation data bases available from the manufacturers. A 4-point mount SC-cut 10MHz resonator for the local oscillator has been used. With a lower radiation shielding configuration, radiation sensitivity of such a crystal, produced by Temex, has been measured at less than 7×10^{-12}/Rad(Si) [8]. Such low sensitivity ensures the correct operation of the RAFS over the 10-year Galileo mission.

TABLE OF THE COMPUTED RADIATION DOSE VERSUS COMPONENT TOLERANCE					
ID #	Board	Part	Type	Applied dose (baseplate=2mm)	Radiation tolerance (Rad Hard, SOS)
U1	PCB2	IC	ACTS74MS	41.8 kRAD (Si)	1MRAD
U2	PCB2	IC	ACTS74MS	41.8 kRAD (Si)	1MRAD
U3	PCB2	IC	54AC00	41.8 kRAD (Si)	>200kRAD*
U4	PCB2	IC	HCTS393MS	41.8 kRAD (Si)	200K or 1MRAD
U5	PCB2	IC	HCTS393MS	41.8 kRAD (Si)	200K or 1MRAD
U6	PCB2	IC	HCTS161MS	41.8 kRAD (Si)	200K or 1MRAD
U7	PCB2	IC	HCTS161MS	41.8 kRAD (Si)	200K or 1MRAD
U8	PCB2	IC	HCTS161MS	41.8 kRAD (Si)	200K or 1MRAD
U9	PCB2	IC	HCTS74MS	41.8 kRAD (Si)	200K or 1MRAD
U10	PCB2	IC	HCTS74MS	35.4 kRAD (Si)	200K or 1MRAD
U11	PCB2	IC	HCTS00MS	41.8 kRAD (Si)	200K or 1MRAD
U12	PCB2	IC	HCTS00MS	41.8 kRAD (Si)	200K or 1MRAD
U13	PCB2	IC	HCTS00MS	41.8 kRAD (Si)	200K or 1MRAD
U14	PCB2	IC	HCTS11MS	41.8 kRAD (Si)	200K or 1MRAD
U15	PCB2	IC	HCTS00MS	35.4 kRAD (Si)	200K or 1MRAD
U33	PCB2	IC	HCTS390MS	41.8 kRAD (Si)	200K or 1MRAD
U34	PCB2	IC	HCTS390MS	41.8 kRAD (Si)	200K or 1MRAD
U40	PCB2	IC	HCTS74MS	41.8 kRAD (Si)	200K or 1MRAD
U24	PCB4	IC	SW-06	152 kRAD (Si)	up to 1MRAD
U26	PCB4	IC	OP15BJ	152 kRAD (Si)	up to 1MRAD

RELIABILITY

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System Mission Report     Page 1 / 1                                                     Date: 12/3/99  9:33 AM
================================================================================================================
RelCalc 2 Version 3.11-217F1.0   MIL-HDBK-217F-1 Part Stress
================================================================================================================
Company: Temex Neuchatel Time SA
================================================================================================================
System: RAFS     Records: 5    FileRev: 2
Description: Rubidium Atomic Frequency Standard - SPACE RUSO FOR GALILEO
Model Type: Serial      Mission Time= 87600.0000 hrs.
Basic: FR= 0.679285 f/million hrs.  MTBF= 1472136.5527 hrs.  R= 0.942230
Mission: MTBF= 1472085.5000 hrs.  R= 0.942230
================================================================================================================
Rec#  Part Number                  Part Type  File Name    DC    Qty   Ref Designator              Description

----------------------------------------------------------------------------------------------------------------
  1.  RAFS PCB1     Circuit    R1-PCB1     100%     1   R1-PCB1                   1st PCB at 40 degrees max
        TFR=    0.152235   [ 22.41% ]   FR=    0.152235                     BasicR= 0.986753  MissionR= 0.986753
        FileRev:16    Env:SF    T= 40C   Parts:82
----------------------------------------------------------------------------------------------------------------
  2.  RAFS PCB2     Circuit    R1-PCB2     100%     1   R1-PCB2                   2nd PCB at 50 degrees max
        TFR=    0.030055   [  4.42% ]   FR=    0.030055                     BasicR= 0.997371  MissionR= 0.997371
        FileRev:6     Env:SF    T= 55C   Parts:31
----------------------------------------------------------------------------------------------------------------
  3.  RAFS PCB3&5   Circuit    R1-PCB3     100%     1   R1-PCB3                   3rd PCB at 70 degrees max
        TFR=    0.245147   [ 36.09% ]   FR=    0.245147                     BasicR= 0.978754  MissionR= 0.978754
        FileRev:17    Env:SF    T= 70C   Parts:200
----------------------------------------------------------------------------------------------------------------
  4.  RAFS PCB4     Circuit    R1-PCB4     100%     1   R1-PCB4                   4th PCB at 70 degrees max
        TFR=    0.084748   [ 12.48% ]   FR=    0.084748                     BasicR= 0.992604  MissionR= 0.992604
        FileRev:7     Env:SF    T= 70C   Parts:73
----------------------------------------------------------------------------------------------------------------
  5.  SOLDER        Circuit    SOLDER      100%     1   SOLDERINGS OF THE 5 PCB    Solderings of the 5 PCB
        TFR=    0.167100   [ 24.60% ]   FR=    0.167100                     BasicR= 0.985469  MissionR= 0.985469
        FileRev:1     Env:SF    T= 82C   Parts:1671
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The life time of the lamp bulb has been evaluated by a measurement of the rubidium absorption rate (see `www.temex.ch`) by a microcalorimetric system measurement. Since the RAFS is using the same lamp as in the industrial rubidium, with the same bulb operating temperature, the life time is also longer than 20 years (50 years by design).

FLICKER FLOOR REQUIREMENT ($< 5 \times 10^{-14}$)

RAFS is equipped with a direct synchronous digital synthesizer which only generates spurious at known frequencies and does not degrade the signal purity. The very high accuracy local oscillator gives the capability to increase the overall Rb signal amplification factor before synchronous detection and, therefore, reduce the influence of loop integrator flicker noise by a very large amount. An efficient offset and noise cancellation scheme has also been implemented at the loop integrator level. The flicker floor of the heater controllers have also been verified to be compatible with noise floor requirements.

TEMPERATURE SENSITIVITY UNDER VACUUM

A Double-oven technique has been used in order to reach a thermal gain of 2000. Such a configuration is very useful because the lamp oscillator, crystal oscillator, and frequency multiplier can be thermally stabilized by the first oven. The RAFS has been designed to achieve operating parameters comparable either under pressurized or vacuum conditions in order to be able to optimize the working parameters in lab conditions and insure that the lamp bulb will not over-heat when operated in vacuum conditions.

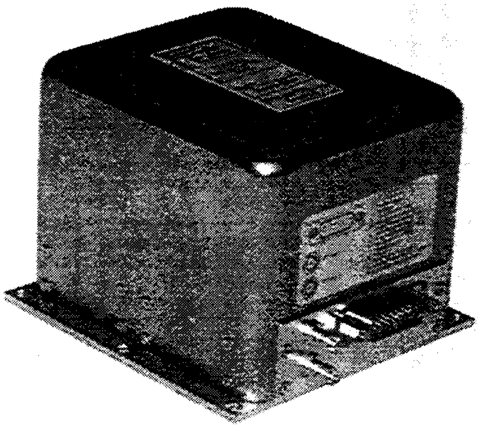


Fig 3: Picture of the RAFS once closed

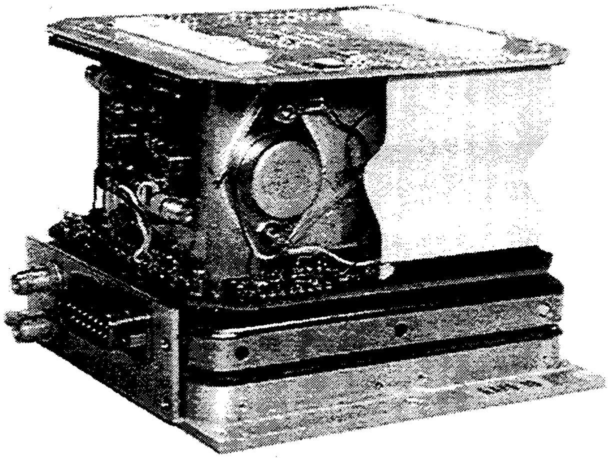
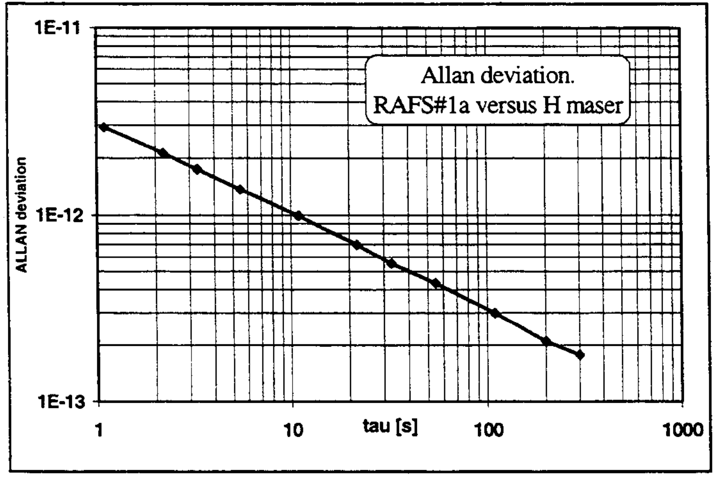


Fig 4: Picture of RAFS without external cover. .

The RAFS physics package enclosure is non hermetic in order to avoid any leakage problems. This forced us to find a solution for evacuating the RF power dissipated into the discharge lamp.

PROGRAMME STATUS

After the Baseline Design Review (BDR), an EM was manufactured which successfully underwent a preliminary functional test at the beginning of 1999. At the BDR, a preliminary short-term stability evaluation was made on the first prototype,which gave the following result and confirmed the capability to stay within less than $5 \times 10^{-12} \times \tau^{1/2}$ (seeFigure 5).



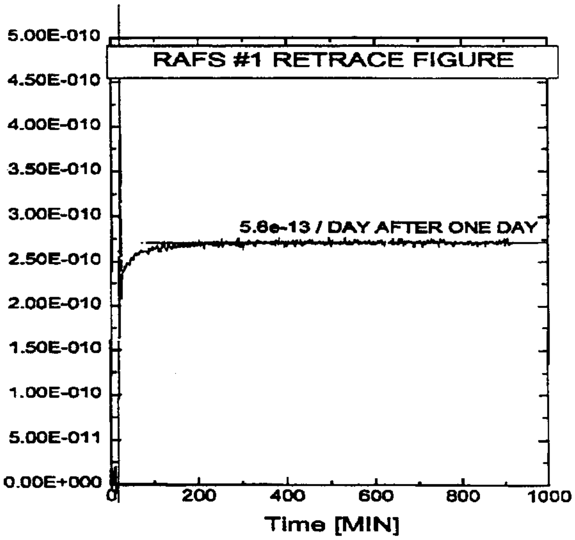


Fig 5. Measured Allan variance limited to 300sec under air and typical retrace figure of the RAFS. Fig 6: Retrace

Severe thermal dissipation problems of the discharge lamp have been solved after intensive testing and several iterative solutions. Figure 7 shows the various operational parameters (like the light level, signal level, various heaters, Automatic Gain Control…) when vacuum pumping. No significant frequency changes were detected except during the depressurization time. A transient frequency variation is due to the corona effect when passing through the critical pressure range.

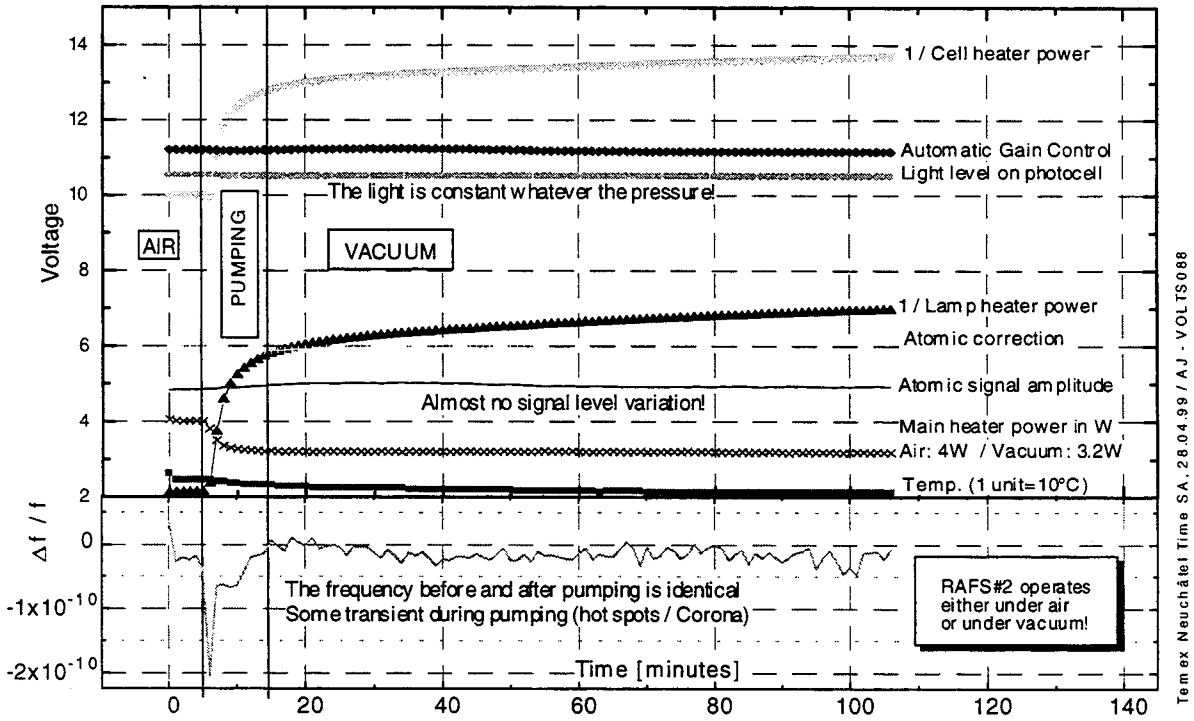


Figure 7: An overview of the operating parameters of the RAFS during the pumping process.

Parameter	Description	Analysis
Signal	Atomic signal amplitude	The signal amplitude variation during pumping is less than 5%
Temp	Base plate temperature	1 unit=10°C. The temperature is maintained at 23°C ± 3°C
Light	Light level on the photocell	The constant level validates the lamp design for air/vacuum operations
Lamp	Lamp oven heater (reverted)	Heating decreases under vacuum and keep stabilized both in air/vacuum
Cell	Cell oven heater (reverted)	Heating decreases under vacuum and keep stabilized both in air/vacuum
AGC	Automatic Gain Control	The AGC is stable, proving that the component thermal offset is low.
INT	Signal integrator (correction)	Except during transient, the crystal resonator does not need correction to stay locked on atomic signal. A thermal drift correction is visible under vacuum.
Pheat	Main oven power in Watt	The main heater power drops from 4W (air) to 3.2W (vacuum).

The above result is particularly interesting: the RAFS not being sensitive to pressure permits a precise adjustment of all the operational parameters under standard laboratory environment. This allows us to test new ways of improvement in a short period of time and still guarantee the perfect operation of the unit once under vacuum.

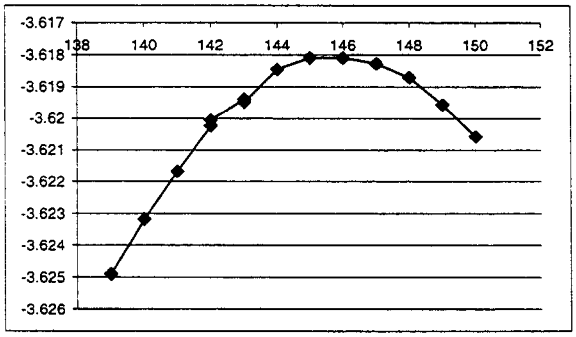


Figure 8: Lamp temperature sensitivity
Y units in 1×10^{-7}, X in °C, TOP at 145°C

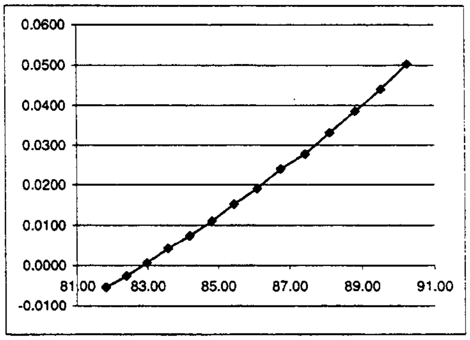
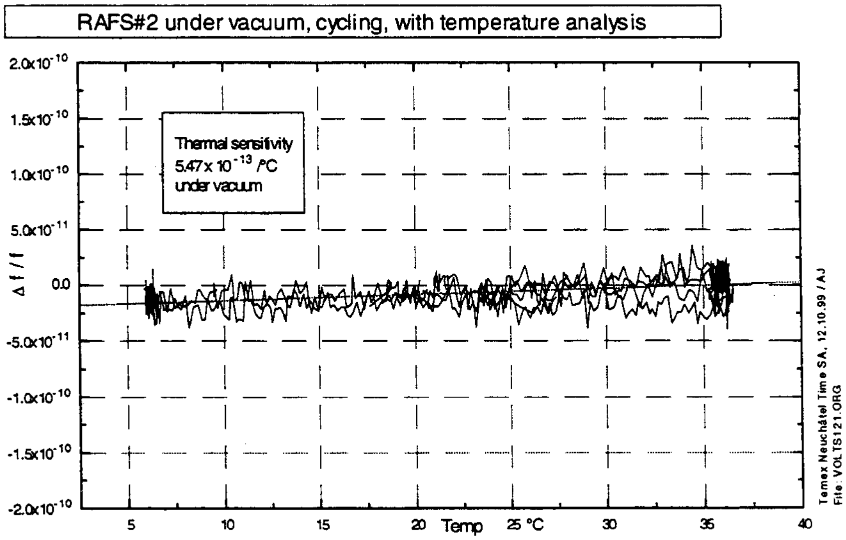


Figure 9: Cell temperature sensitivity.
Y units in 1×10^{-7}, X in °C, slope 6×10^{-10}/°C

The above Figures 8&9 show the sensitivity of the physics package under atmospheric pressure. Figure 8 is the result of nine months of design analysis, improvement and test, and 8 different iterations of lamp assemblies. The goal was to obtain a discharge lamp consuming less than 2W, providing a stable light level and wavelength within the whole range of specified operating pressure and temperature. The design of this lamp is now frozen and the repeatability of the characteristics have been verified. By placing the operating temperature right at the turn-over point (~145°C) and controlling the lamp temperature variations below 0.05°C, the effect of the temperature on the frequency can be dramatically reduced.



At the operating temperature the sensitivity of the cell is approximately on a 6×10^{-10}/°C slope. This relatively high sensitivity helped us to improve the temperature stabilization circuitry (flicker noise induced by heater controller amplifier). On such a cell, the pressure shift effect is not compensated by the light shift effect. With this type of cell, we reached an overall global temperature stability of 5×10^{-13} /°C for the complete RAFS, showing that our double-oven configuration has at least a thermal gain of 1200 (see Figure 9&10). Further improvement of this thermal gain is very difficult. For the next step we will reduce the thermal sensitivity of the cell by finding the right buffer gas mixture (argon and nitrogen) to get a turn-over point at the cell operating temperature. An improvement of a factor of five would be enough to meet the Galileo specification, but we expect to get at least a factor of ten.

SUMMARY OF THE PRESENT CONFIGURATION

Here is a summary of the present configuration:

- The RAFS is composed of 6 printed circuit boards connected by in-line connectors and a flat cable.
- The base plate supports the interface circuit, the voltage regulators, and heater drivers which need a good heat sink.
- The digital board is suspended and shielded at mid height.
- The analog and detection boards and the crystal resonator are fixed on the main oven and thermally stabilized.
- The physics package is placed inside the main oven into an additional large magnetic shield.
- The two RF boards for both cell and lamp are placed on both ends of the main oven.
- The thermal dissipation of the PP is sunk to the base plate through the four supporting posts.
- The cover is maintained by eight rivets into the base plate and four rivets at the top of the RAFS.
- The hyperstatic mounting improves the stiffness and limits the low resonance frequencies of the structure.

An EM unit has been tested and a formal qualification program will start after several units have been verified. Following this qualification, PFMs will be manufactured for flight experiments. In order to make a thorough assessment of the capabilities of the RAFS developed by TNT to fulfil the Galileo mission requirements, a follow contract will be given to TNT to manufacture and test a batch of ten RAFS. A laboratory test station, including a vacuum system and a computer-driven control system, will be set up to continuously monitor the performance of the ten RAFS over a period of three years. A cesium clock and a hydrogen maser will be made available and used as reference sources to check the performance of the ten RAFS.

CONCLUSION

The current results and analysis of the RAFS show that several important parameters for a clock operating in space have been achieved, such as the life time and the ability of the discharge lamp to work under pressurized or vacuum environment. A dedicated discharge lamp assembly has been successfully designed, proving that it is not necessary to place the physics package into an hermetic enclosure for proper operation. If the thermal sensitivity is not yet achieved (a factor of 5 must be gained), the way forward is identified. The thermal configuration being satisfactory for stabilizing the various ovens, the mechanical design has been frozen, and a set of RAFS will be assembled to prove the repeatability of the process.
The main advantage of the ability to work both under atmosphere and under vacuum is that it allows precise adjustment of the operating parameters under standard laboratory conditions.
Once the improvements in the thermal sensitivity is achieved, the RAFS, with its more than 20 years of life expectancy, will be a perfect candidate for being the on-board frequency reference of the Galileo satellite system.

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