Performance Overview of Space Rubidium Standards

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INTRODUCTION

In addition to GPS and GLONASS, the two Global Navigation Satellite Systems (GNSS) available today, several other space navigation programs are currently in progress under the technical supervision of Space Agencies in Europe and Asia. Atomic clocks represent the critical equipment for precision satellite navigation systems. The SpectraTime (SpT) Space Rubidium clock was selected as on-board back-up clocks in two different global navigation satellites systems and as primary clock for one regional navigation satellite systems. This clock is manufactured together with Astrium-GmbH or Syderal for the electronic section. To guarantee the performances of the clocks in-orbit, intensive tests on-ground are performed before delivery.

This paper will give an overview of the performances of Space Rubidium Atomic Frequency Standard (RAFS) as obtained at SpT before delivery to customers. It will briefly recall the various development steps of this frequency standard, starting from the late nineties until the very recent Flight Model deliveries, and will emphasize the continuous performance improvement along these steps. Statistics over more than 40 Flight Models (FM) delivered will be presented regarding key performance parameters as short-term frequency stability, sensitivity to environmental effects and long-term frequency drift. It will be shown in particular that a detailed analysis of behavior on a large set of units is a key contributor to performance improvement validation. Finally, the paper will conclude on possible alternative applications of Rubidium Standard, as exemplified by its use in the GAIA Mission of the European Space Agency (ESA).

DEVELOPMENT, QUALIFICATION & PRODUCTION ACTIVITIES

SpectraTime (SpT) has started the Rubidium Atomic Frequency Standard (RAFS, shown in Fig. 1) development for navigation application since more than 10 years. The RAFS development milestones are chronologically listed as below [1]:

Fig. 1. Picture of SpT space RAFS for the Galileo navigation satellite system

The first development activity kicked off at SpT (former Temex Neuchâtel Time) in 1997, and completed in 2000 with one Engineering Model (EM) RAFS produced.

The updated RAFS development started in June 2000 and completed at the beginning of 2002. The industrial consortium was led by SpT with Astrium Germany as the subcontractor for the electronics package. The results of this development are applied in space clock design, which were used in the five Engineering Qualification Models (EQM) and one Qualification Model (QM) for space qualification tests (vibration, EMC/EMI and radiation) and lifetime testing. The lifetime program running on five EQM units has provided useful results and demonstrated the capability of the RAFS to operate for 12 years under vacuum without significant degradation [2].

The third development and qualifications step was initiated at the end of 2001 and completed at the beginning of 2003 with the delivery of an EM, which is the baseline unit for the development of the Flight Models (FM) for Galileo System Test Bed (GSTB-V2). The main contribution of this last development step is the inclusion of a DC/DC converter and the satellite interfaces compatible with ESA's new requirements.

In the frame of GSTB-V2, one EQM, one Proto-Flight Model (PFM) and five Flight Model (FM) units have been delivered, among which, two have been integrated in GIOVE-A experimental satellite (Galileo In-Orbit Validation Element) in orbit since 28th December 2005, and two have been flying in GIOVE-B satellite since 27th April 2008 [2,3].

In parallel to the activities for Galileo, another development and qualification was conducted with Syderal as supplier of the electronic section of the clock. These activities have allowed the production of a 100% Swiss Rubidium clock used for Compass as back-up clock.

Since then, the overall behavior of the clocks has been improved by the implementation of electronic improved filtering and isolation between the different sections of the clocks. The spectral lamp construction was also improved to be less sensitive to mechanical disturbance. For other various space programs than GSTB-V2, mainly in navigation satellite systems, 44 FMs have been delivered, among which, several have been flying in orbit.

PERFORMANCE STATISTICS

In order to guarantee the performances of the clocks in-orbit, intensive tests on-ground are performed before delivery. A statistics analysis over more than 40 FMs delivered since 2005 is performed regarding key performance parameters, such as short-term stability, thermal sensitivity and long-term frequency drift, based on the performance measurements on Space RAFS FMs as obtained at SpT before delivery to customers.

Short-term Stability

The short-term frequency stability at the average time of 6000s is of great interest for navigation satellite systems. Fig. 2 shows values of Allan deviation at 6000s (drift removed) on 44 delivered RAFS FMs numbered chronologically. The performance in short-term stability has been slightly improved during this last 5 years.

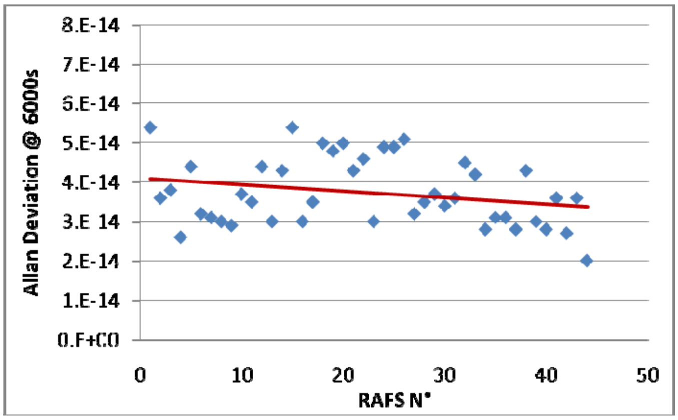

Fig. 2. Allan deviation at 6000s on RAFS FMs

Fig. 3 indicates the distribution of Allan deviation at 6000s with respect to the number of RAFS. 80% of the total numbers of 44 FMs demonstrate the excellent Allan deviation at 6000s between 2.0e-14 to 4.6e-14, which corresponds to the RAFS short-term stability of $1.5 \sim 3.6 \times 10^{-12} / \sqrt{\tau}$ dominated by the white frequency noise and limited by the photo-cell shot noise level.

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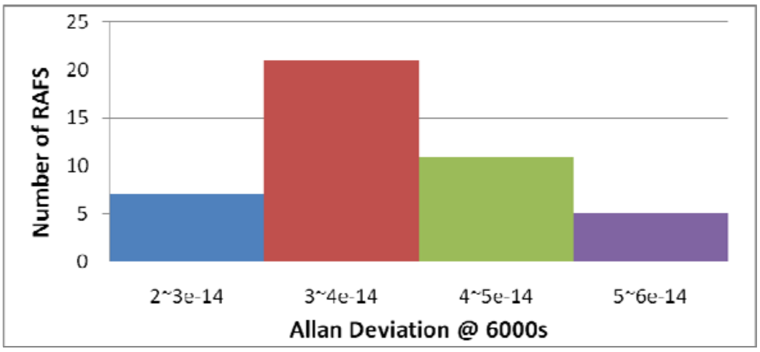

Fig. 3. Distribution of Allan deviation at 6000s with respect to the number of RAFS

Sensitivity to Temperature

The frequency sensitivities to base plate temperature variations are compared in Fig. 4 for these 44 delivered FMs numbered chronologically. The thermal sensitivity has improved significantly by at least a factor of 2 from the earliest project to following projects.

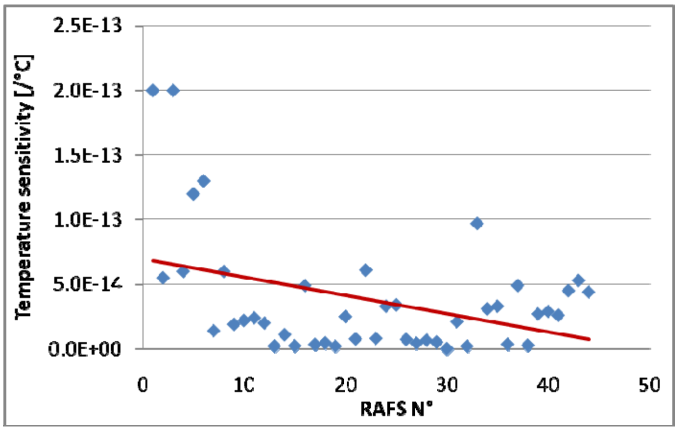

Fig. 4. Temperature sensitivity on RAFS FMs

Fig. 5 gives the distribution of the temperature sensitivity with respect to the number of RAFS in following batches (since RAFS N° 7 in Fig. 4). 80% of the total numbers of 38 FMs demonstrate the temperature sensitivity as less than 3.5e-14/°C, among which, 50% of RAFS has an excellent thermal stability lower than 1e-14/°C.

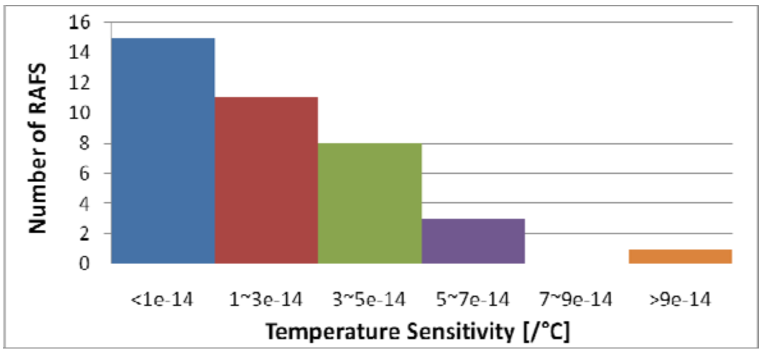

Fig. 5. Distribution of temperature sensitivity with respect to the number of RAFS

Long-term Frequency Drift

Fig. 6 shows the long-term frequency drifts for delivered FMs numbered chronologically. As the thermal sensitivity discussed previously, the frequency drift shows also an improvement trend following the earliest project. The level of 3e-13/day is representative in latest FMs, which is targeted for dedicated applications.

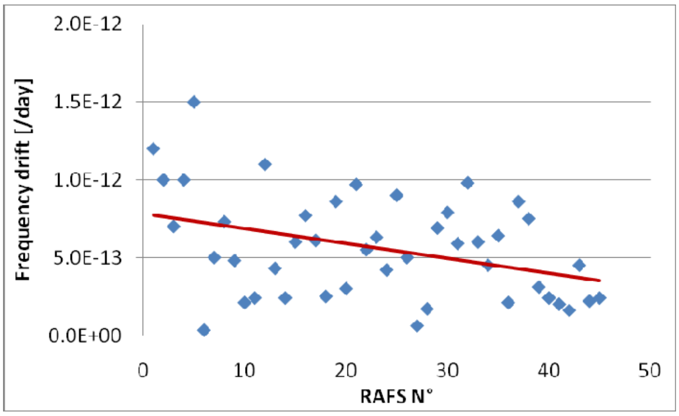

Fig. 6. Frequency drift on RAFS FMs

Fig. 7 gives the distribution of the frequency drift with respect to the number of RAFS in following batches (since RAFS N° 7 in Fig. 6). More than half of the total numbers demonstrate the frequency drift lower than 5e-13/day.

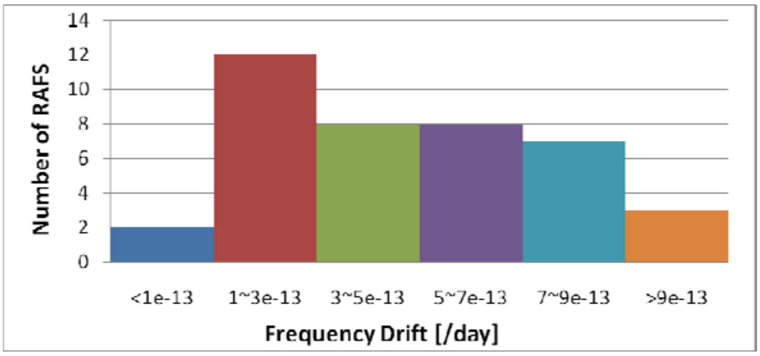

Fig. 7. Distribution of frequency drift with respect to the number of RAFS

ALTERNATIVE APPLICATIONS

Several other applications like scientific mission, military secure communication or astrophysics require the use of atomic clock. Thanks to its good trade-off between reliability, mass, performance and cost, the Rubidium clock technology is often selected for such missions. The typical mass of such device is between 1 and 5 kg for a frequency stability as good as $1x10^{-13}$ over several hours including environmental effect. The example of the use of Rubidium Standard, is given by its use in the GAIA Mission of the European Space Agency.

GAIA Mission

Gaia is a mission to chart a three-dimensional map of our Galaxy, the Milky Way. Gaia will provide unprecedented positional and radial velocity measurements of about one billion stars in our Galaxy. Combined with astrophysical information for each star, provided by on-board multi-colour photometry, these data will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way Galaxy.

The GAIA satellite is manufactured by Astrium.

Why an Atomic Clock on-board of GAIA?

Ultimate astrometrical performances of the GAIA mission deeply rely on the accuracy by which the payload data are time stamped on board.

Indeed, the expression into the International Celestial Reference Frame (ICRF) of the GAIA catalogue begins with the reduction to an internally consistent catalogue of positions and proper motions of stars and extra galactic objects observed from GAIA (the final link to the International Celestial Reference System being deduced from apparent proper motions of quasars observed by GAIA as well as positions of optical counterparts of radio sources compared to their radio positions in the ICRF). An internally consistent catalogue of positions and proper motions for the GAIA observations implies an accurate and internally consistent time tagging of payload and platform data.

Moreover, it is necessary to design an accurate correlation of the GAIA time scale to an Earth based, observable, time scale (Universal Coordinate Time, UTC) in order to obtain accurate astrometry for the solar system objects and to be able to program the on board mission time line for the control of the spacecraft.

Consequently, GAIA payload raw measurements are time stamped on the basis of an on board, ultra-stable Rubidium atomic clock, the stability requirement of which has been deduced from expected final astrometrical performances of the mission (a few µarc-sec for the bright stars). The atomic clock generates the On Board Time, realisation of the GAIA proper time. This clock also generates in phase sequencing signals used by the Focal plane assembly to schedule the CCD operations and time stamp resulting video acquisitions. This design insures the consistency and deterministic behaviour of the overall video acquisitions time stamping process.

Requirements for the Atomic Clock?

The on-board time tagging accuracy is directly link to the measurement concept of the GAIA satellite. The satellite is equipped with telescopes which will measure in a continue mode the stellar objects during one satellite self-rotation. According to of the accuracy expected, the round tour will be divided in µ arc-second and time tagging will allows the restitution of a measurement, performed at a given time, to an angular position.

In first estimation, the requirement of to the clock could be explained by the following elements:

- The satellite rotation of ***360°*** is completed in 6 hours (***21'660 sec***)
- The angle positioning resolution of each measurement is about ***1 µ arc-second***
- ***360°*** contents ***$1.296x10^{12}$ µ arc-seconds***
- So, the time error is defined by ***21'660 sec/$1.296x10^{12}$ = 16.7 ns***
- Considering some margin, the clock stability requirement (MTIE) is set at ***10 ns*** for an observation time of 6 hours including all effects cumulated, drift, stability and environmental effect.

It must be noted that the clock is integrated within the Clock Distribution Unit (CDU) equipment manufactured by Thales Alenia Space Espania.

GAIA Clock Performances

The ground measurement of the two delivered clock have provided the following results:

- Clock drift:
  - FM1: $-2.4x10^{-13}$ /day
  - FM2: $+2.0x10^{-13}$ /day
- Clock Stability:
  - FM1: $5x10^{-14}$ (Flicker)
  - FM2: $4x10^{-14}$ (Flicker)
  -
- Temperature Effect:
  - FM1: $-1.7x10^{-14}$
  - FM2: $-2.6x10^{-14}$

Overall Maximum Time Interval Error at 6 hours:
FM1: ***< 2.7 ns***
FM2: ***< 1.8 ns***

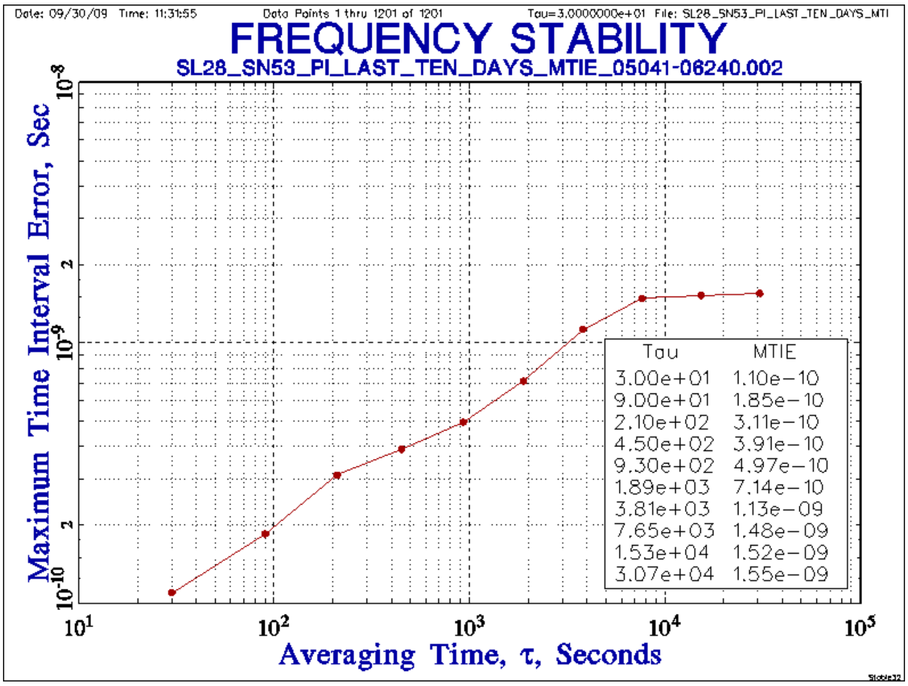

Fig. 8. Example of the Maximum Time Interval Error computed for the GAIA FM1

CONCLUSIONS

Thanks to its good trade-off between reliability, mass, performance and cost, the Rubidium clock technology is often selected for various missions as navigation, astrophysical cartography, scientific measurement or secure communication. The typical mass of such device is between 1 and 5 kg for a frequency stability below $1x10^{-13}$ over several hours including environmental effects.

With more than 10 years of efforts, SpT RAFS has been developed and qualified for space applications. More than 45 FMs have been delivered to various navigation satellite systems and other space programs, among which, several RAFSs have been flying in orbit, and operating with expected good performances.

The performance overview of our space RAFS demonstrates continuous performance improvement along the production batches. The detailed analysis of behavior on a large set of units is a key contributor to performance improvement validation.

REFERENCES

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[3] P. Waller, F. Gonzalez, S. Binda, I. Sesia, P. Tavella, I. Hidalgo, et al, “Update on the in-orbit performances of GIOVE clocks” *Proceedings of the Joint 2009 European Frequency and Time Forum & 2009 IEEE Frequency Control Symposium, Besançon (France)*, pp. 388-392, 20-24 April 2009.