Atomic Clocks and Timing Systems in Global Navigation Satellite Systems

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ABSTRACT

Accurate and ultra-stable atomic clocks have been recognized as the critical equipment for the precision Global Navigation Satellite Systems (GNSS). SpectraTime (SpT) and T4Science (T4S) are space and ground clocks manufacturers of Rubidium Atomic Frequency Standard (RAFS) and Active & Passive Hydrogen Maser (HM) for various navigation systems (European, Chinese and Indian) and other programs. From Dec. 2005 to the beginning of 2012, both clock technologies have years of flight heritage through four Galileo and 11 Beidou satellites. Almost 90 SpT RAFS flight units and 25 Passive HM Physics Package flight units have been manufactured and characterized. As for ground application, more than 17 T4S Active HMs are involved in different ground segment worldwide, and one passive HM is in progress in the frame of a ground development program.

This paper describes for space RAFS and HM the on-ground performances and life-time tests, as well as onboard achieved clock performances. A short overview of the ground GNSS timing reference segment with its active Masers and associated disciplining algorithms will be given. Even these standard Rubidium and maser technologies have been proven to be highly reliable and robust those could be subject to perturbations and could exhibit some anomalies ,especially when exposed to single event radiations , magnetic field perturbations etc…. With those elements in hands, a presentation of novel onboard techniques to generate highly robust timing signal directly from the satellite onboard ONe CLock Ensemble (ONCLE) is presented. Performances achievements in presence of perturbations, and frequency jumps are also shown allowing a continuous and uninterrupted operation of the satellite navigation signals.

1 Introduction

Accurate and ultra-stable space qualified atomic clocks have been recognized as the critical equipment for the precision Global Navigation Satellite Systems (GNSS) – two current GPS and GLONASS, and upcoming systems as China's BEIDOU/COMPASS Navigation Satellite System, European GNSS (GALILEO), Indian Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS).

Space qualified atomic clock has to meet stringent requirements from launching to unattended operation for many years. It must assure satisfactory and reliable performances over overall mission life, meet constraints on mass, volume, and power consumption, survive launch environment (shock, acceleration and vibration) and survive operational environment (vacuum, thermal cycling, EMI/EMC, radiation, magnetic field and other space hazards).

The selection of the type of the space atomic clock for various missions is the trade-off between reliability, mass, performance and cost. Table 1 lists different types of onboard atomic clocks on different navigation systems. The adoption of a 'dual-technology' for Galileo onboard clocks is dictated by the need to insure a sufficient degree of reliability by flying 2 different technologies and to comply with the Galileo lifetime requirement of 12 years as well as superior navigation accuracy.

GPS	GLONASS	GALILEO	BEIDOU	IRNSS	QZSS
Rb	Cs	H	Rb	Rb	Rb
Cs (not GPS IIR)		Rb			

Table 1. Onboard atomic clocks on different navigation systems

SpectraTime (SpT, formerly Temex Neuchâtel Time) is a space clock manufacturer of Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM) for various navigation systems (Galileo, Beidou and IRNSS) and other space programs [1]. In addition, it provides high-performance synchronization modules and solutions for GNSS ground precise timing system and future onboard frequency system.

This paper will describe for space RAFS and PHM the on-ground and onboard achieved performances. Based on these results a short overview of the ground GNSS timing segment with key equipments and algorithms, and a novel robust onboard timing technique based on the onboard ONe CLock Ensemble (ONCLE) is presented.

2 Space RAFS and PHM

Both atomic clock technologies have now flight heritage of several years through Galileo In-Orbit Validation Element (GIOVE & IOV) experimental satellites which have been flying in orbit since Dec. 2005 or through Beidou since Apr. 2009.

More than 90 RAFS Flight Model (FM) units and 25 PHM FM units have been manufactured and characterized.

It has been recognized RAFS technology is the best choice in terms of performances versus mass ratio and no more lifetime limitation from mature clocks technologies available today. Rubidium technology applicable for navigation in space implies a very precise and high performances atomic line interrogation and detection circuitry to obtain very good short and mid-term stability while being capable to exhibit relatively poor atomic resonance quality factor (line Q ,Typically less than E+7).

On the other hands , passive maser technology is exhibiting very high atomic quality resonance factor of about 1E+9 requiring much less critical atomic resonance interrogation and detection circuitry compared to Rubidium and easily capable to meet the strongest navigation systems requirements' in terms of stability and autonomy.

The criticality on the RAFS can be easily explained from the ratio of the 5E-14 short term stability requested comparing the line Q which need a level of precision of detection of the center of the line of about 5E-7.

On the contrary, to achieve 5E-15 short term stability on the passive maser, the level of precision of atomic line center detection can only be 5E-6.(means 10 time less critical to obtain 10 times better stability)

Without entering deeply into technical details, this level of criticality is the principal raison why RAFS is more sensitive to most of the environmental parameters and could also exhibit some small frequency jumps when flying in MEO orbit and being exposed to radiations, micro-g , magnetic field changes or EMC. In addition , very small mechanical relaxation or Rb metallic drop shape or position change or Rb lamp plasma discharge instabilities could also lead to small frequency jumps. Such anomalies on GPS satellites has been reported.[11]

2.1 RAFS on-ground performance

SpT has started the RAFS for navigation (shown in Figure 1) development activities in 1996 based on previous development of Rubidium for Radioastron mission initiated in 1991.

Figure 1. Picture of space RAFS (3.2kg) for Galileo GNSS

The lifetime program running on five Engineering Qualification Model (EQM) units has provided useful results and demonstrated the capability of the RAFS to operate for 12 years under vacuum without significant degradation [2].

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

Since then, the overall behavior of the clocks has been improved. For various space programs, mainly in navigation satellite systems, more than 90 FMs have been delivered, among which, more than 30 have been flying in orbit.

In order to guarantee the performances of the clocks in-orbit, intensive tests on-ground are performed before delivery. As an update of [3], a statistics analysis over all FMs delivered since 2005 is performed regarding key performance parameters, such as short-term stability, thermal sensitivity and frequency drift.

The short-term frequency stability at the average time of 6000s is of great interest for Galileo navigation systems. Figure 2 shows values of Allan deviation at 6000s (drift removed) on about 90 delivered RAFS FMs numbered chronologically. The performance in short-term stability has been slightly improved during last 6 years. 80% of the total numbers demonstrate the excellent Allan deviation at 6000s between 2.0e-14 to 4.4e-14, which corresponds to the RAFS short-term stability of $1.5 \sim 3.4 \times 10^{-12}/\sqrt{\tau}$ dominated by the white frequency noise and limited by the photo-cell shot noise level.

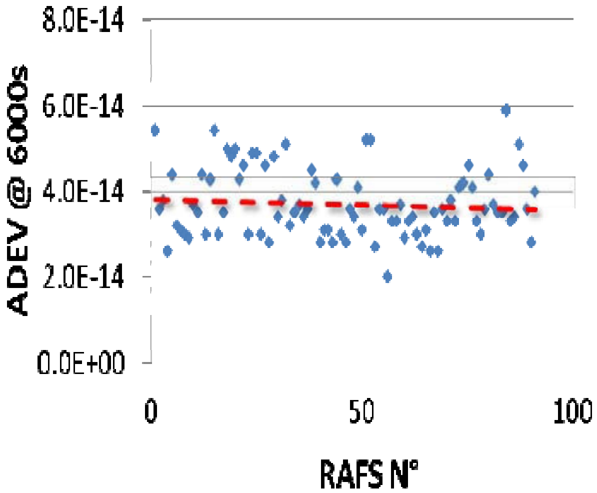

Figure 2. Allan deviation at 6000s on RAFS FMs

The frequency sensitivities to base plate temperature variations are compared in Figure 3 for these delivered FMs numbered chronologically. The thermal sensitivity has improved significantly by at least a factor of 2 from the earliest project to following projects. From following batches (since RAFS N° 7 in Figure 3), 80% of 90 FMs demonstrate the temperature sensitivity of less than 4.0e-14/°C.

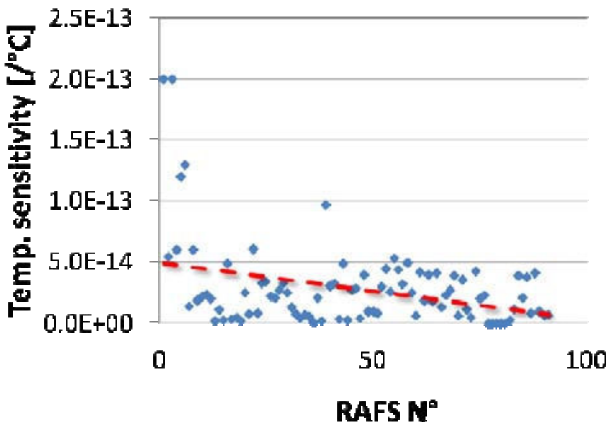

Figure 3. Temperature sensitivity on RAFS FMs

The performance overview of our space RAFS demonstrates continuous performance improvement along the production batches, which is allowed by improvements of process and adjustments during the production in large quantity. The ongoing technological and design evolutions with bigger cell and Rb85 filter cell allows further performance improvement, in particular the light shift coefficient (less sensitive to any Rb plasma changes) , the line Q (less sensitive to any interrogation & detection circuit instabilities and therefore less sensitive the radiations effects on the electronics. The figure 4 shows a typical short term stability of this improved performance RAFS design capable to exhibit stabilities below the 1E14 level.

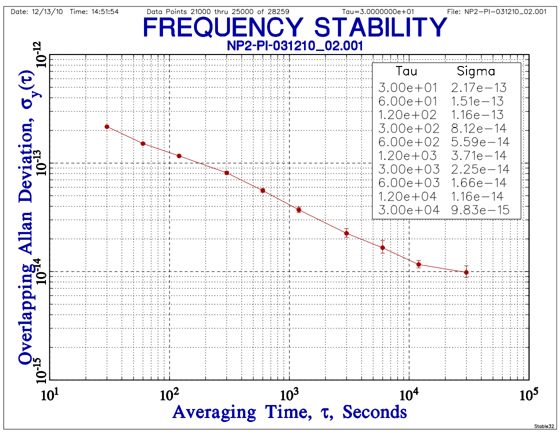

Figure 4. Short term stability of Improved RAFS

2.2 PHM on-ground performance

PHM (Figure 5) has been chosen as the master clock in the European navigation satellite payload, and is the first one of its type ever to fly with its excellent frequency stability performance.

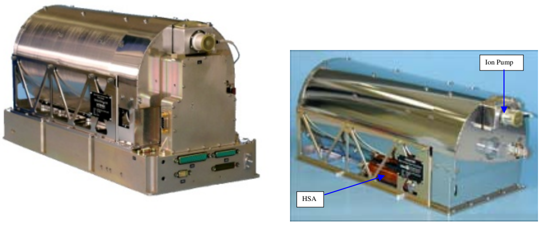

Figure 5. Picture of space PHM (18kg) & new 8Kg physics pacakge for Galileo GNSS

The industrialization activity aimed at PHM design consolidation for flight production was started in 2003, based on the Engineering Model (EM) design led by the Observatory of Neuchatel (Switzerland) since 2000. The industrial consortium is led by Selex Galileo (Italy) in charge of the instrument integration and Electronics Package (EP) design, and SpT is responsible for redesign and manufacturing the Physics Package (PP) [4]. 25 FMs physics packages have been delivered for the Galileo program These have demonstrated a production rate capability near to 1 PHM per month, with potential margins for improvement.

The excellent performance repeatability observed along the IOV production is illustrated in Figure 6.

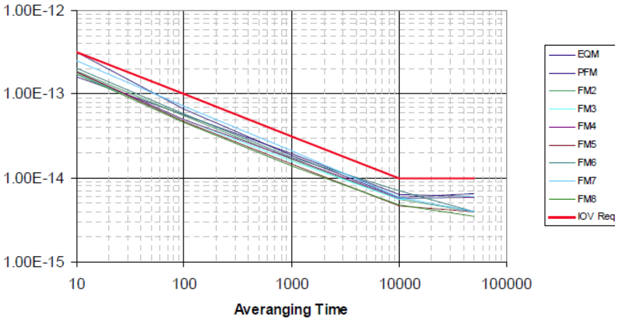

Figure 6. Allan Deviation for IOV PHM models (frequency drift included)

In the frame of the "Lifetime Qualification of the PHM", two PHM QMs have been subjected to test under vacuum in order to highlight any potential lifetime limitations. Both of them have completed the planned 18 months of test, and have shown PHM potential to operate for 12 years under vacuum conditions without significant degradation [5].

Frequency stability and trend evolution are fundamental aspects for a clock assessment. In the following figure the rough frequency data are reported (frequency spikes due to external perturbations from reference signal , thermal vacuum chamber or the acquisition system), including the estimation of the frequency drift. The frequency jump after 320 days is due to the 2°C cavity temperature set change (for experimental purposes). The observed frequency jump is in line with the theoretical expectation. During the life test period the PHM has been switched OFF and ON 3 times (a,b and c in Figure 7). The frequency drift has been stabilized at 3.3e-16/day. It is worth noticing that the output frequency retrace is better than 2e-13.

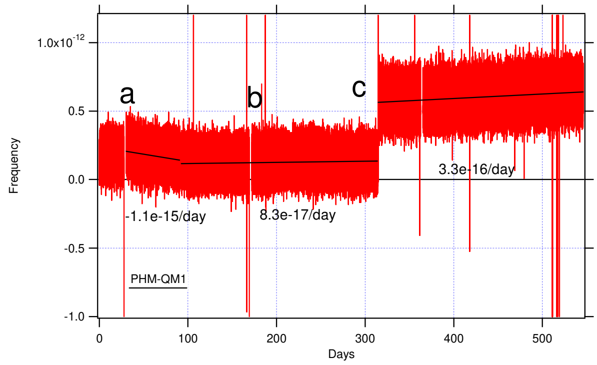

Figure 7. PHM QM1 freqeuency data and drift over 18 months

Figure 8 shows the frequency stability measurement performed on the PHM-QM1 over the last 3 months.

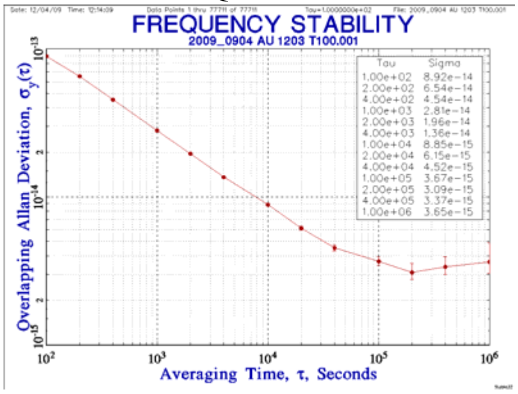

Figure 8. PHM QM1 freqeuncy stability

Table 1 summarizes the typical performances achieved during PHM ground tests.

Parameter	Measurement
Frequency stability	< 5e-15 @ 100'000 sec
Flicker floor	< 4e-15
Frequency drift	< 1e-15/day
Thermal sensitivity	< 2e-14/°C
Magnetic sensitivity	< 3e-13/G

Table 1. Typical space PHM performances

A further PHM technological program is on-going for the mass reduction of this instrument down to 12 kg without reduction of performance. To achieve this goal, the physics package weight realized by SpT is 8 kg and demonstrated very similar performance. A 'maintenance free' solution is also investigate to avoid performing switching ON periodically the redundant maser to make sure plasma discharge will always start in case of failure of the primary maser. At present, this 'maintenance' procedure is penalizing the whole system availability figure because of operational constraints. Therefore Spectratime will also investigate some alternate solutions to the present Selex Galileo Solution for the plasma discharge electronics.

2.3 GIOVE onboard clocks performance

The two Galileo baseline clock technologies are currently being validated onboard two experimental spacecrafts. RAFS technology has been operated in-orbit for five years onboard GIOVE-A and PHM technology for more than two-and-a-half years onboard GIOVE-B. The data accumulated over this period have been analyzed together with the long-term performances of these onboard clocks [6][7]. Both clocks have been operated continuously and do not show any sign of degradation, even after periods exceeding the original lifetime of the spacecrafts. The consistency among the on-ground and in-orbit observations and the ageing trends of key parameters provide good confidence on the instrument capability of meeting Galileo mission requirements.

On GIOVE-A, it is shown that the short-term stability of RAFS is not limited by the estimation noise and is below the specified limits (5e-12/SQRT(tau)). Over the medium term, the stability is affected by periodic oscillations at the orbital period that are mostly due to onboard thermal variations, as expected. Finally over the long-term, even if not always monotonous, the RAFS frequency drift is below the 1e-13/day level.

On GIOVE-B, it is shown that the GIOVE estimation noise by the Orbit Determination and Time Synchronization (ODTS) process limits the actual characterization of the PHM stability. However, its short-term stability, as estimated by the One-Way Carrier-Phase method is fully in line with the expectations (1e-12/SQRT(tau)). Over the medium-term (12~24 hours), the performance of the onboard clock is also affected by oscillations at the orbital period. Over the long term (> 1day), the PHM exhibits excellent frequency drift performances (below 1e-15/day).

3 Timing Systems

3.1 Ground Precise Timing Facility

The Precise Timing Facility (PTF) is one of the key facilities of the Galileo ground segment. Its scope is to provide an accurate, stable and precise Galileo System Time Master Clock (GST(MC)), the physical time scale of Galileo [8].

The PTF in Italy been coordinated by the Consorzio Torino Time (CTT), with the partnership and support of SpT and T4Science in Switzerland.

Two Active Hydrogen Masers (iMaser3000), a primary HM1 and a backup HM2, are externally steered via a precision PicoStepper, provide the physical realization of GST(MC), insuring the extremely high short-term stability required for the navigation functions, in particular to perform a reliable satellite clocks measurements and modeling.

The PicoStepper (i.e. micro-phase stepper), has been developed to provide phase or frequency correction of HM signals with a 0.1 ps high resolution and the negligible degradation of the HM signal phase noise and short term stability due to the reduction of output jitter.

Figure 9. Pictures of AHM and PicoStepper for PTF

The 'backup HM steering algorithm' [9] is implemented in order to allow a smooth switch-over between backup and primary HM in case of failure of the latter, without producing any significant effect in the GST continuity, uniformity, or short term frequency stability. Figure 10 shows the architecture of the steering system, forming a basic Phase-Locked Loop (PLL). The algorithm, based on a proportional-integral filter controller and an outlier removal, acquires the phase difference between two HM, and generates a steering correction to be applied to the backup HM via the PicoStepper.

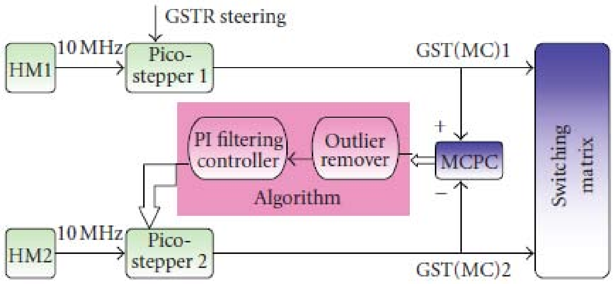

Figure 10. Architecture of the HM steering System

The steering system is capable of meeting the Galileo specifications to keep the backup HM close to the primary in phase and frequency allowing smooth switchover.

3.2 Onboard frequency system

The onboard timing system generates the Master Time Reference (MTR), whose performance has direct impacts on the navigation performance in terms of the Ranging Accuracy. When an abnormal behavior of the MTR is observed, the redundancy of atomic clocks in current timing system allows switching of the maser atomic clock. This operation requires however the isolation of the satellite from the constellation, which will degrade the system integrity and availability figures.

To overcome this limitation, novel onboard techniques to generate highly robust timing signal directly from the satellite onboard ONe CLock Ensemble (ONCLE) for future GNSS is described hereafter.

The proposed robust on-board frequency system will be a self-standing unit accepting as inputs up to 6 reference clocks signals and generate as output a frequency signal with improved performances and robustness. In order to insure a reliable frequency system, the preferred SpT solution is based on pure H/W solution where performance improvement is performed by a simple and efficient algorithm to be implemented on a FPGA without sophisticated and complex non reliable on board computer.

The preferred solution will allow:

- Clock failure detection and removal of the concerned clock without discontinuity (in phase and frequency) of the frequency system output signal
- Frequency jumps detection and compensation
- Averaging of the clocks (short-term frequency stability and drift improvement)
- Possible weighting of clocks to further improvement based on post-processing ground data (long-term frequency stability and drift improvement).

For these purposes, a simple ONCLE algorithm module based on weighted average, and the failure & frequency jump detection module [10] are implemented on a FPGA. To better illustrate the advantages of the ONCLE technique, 5 RAFS been measured over 7 days.

Figure 11 shows the frequency over time as well as some anomalies (Frequency jumps on RAFS 2 & RAFS 3).On this same graph, we can also shows the result of the ONCLE algorithm in ‘frequency’ which appears to be as good as the passive maser on this curve .

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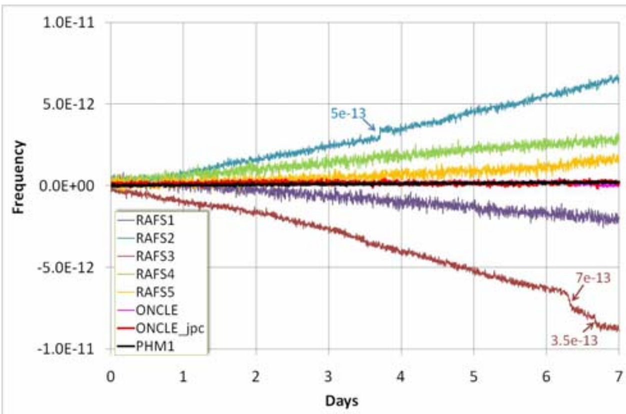

Figure 11. Frequency over time (including drift) for five individual RAFS and clock ensembles

From figure 12 (Allan deviation) we can see the ONCLE algorithm effect (RED curve with automatic jumps corrections) which also clearly shows an improved stability figure for the ensemble compared to any other individual clocks.

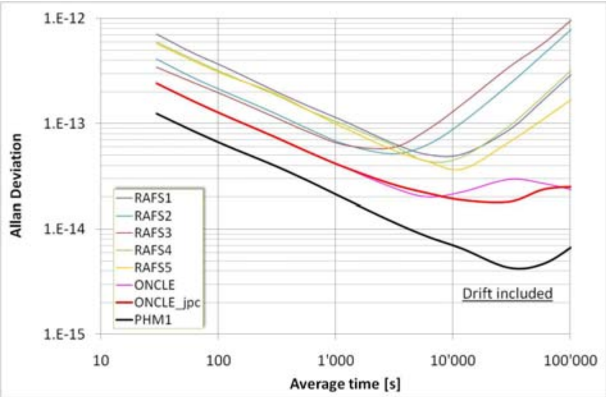

Figure 12. Allan deviation (including drift) for five individual RAFS and clock ensembles

The selected solution for onboard frequency system is based in the following diagram:

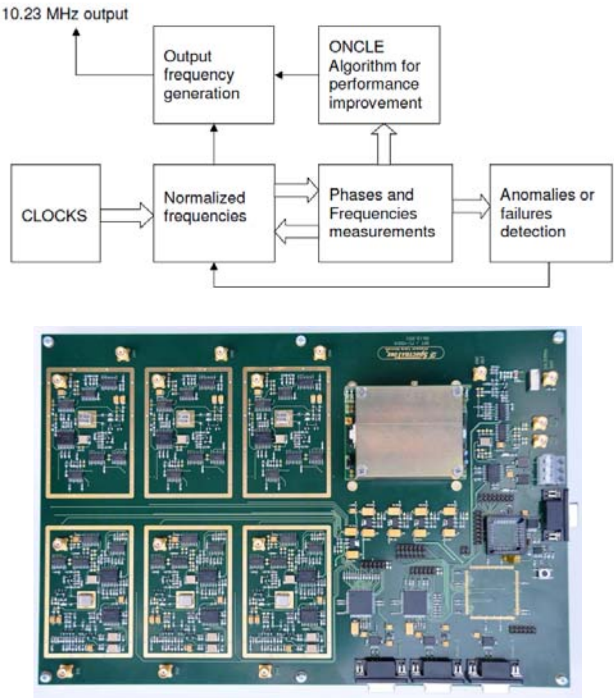

figure 13. Architecture & elegant breadboard model of onboard frequency system

- All the clock frequencies are normalized to the same frequency
- The normalization process allows the measurement of all clock relative frequencies and phases with few picoseconds resolution
- The phases measurements allow the anomalies or failures detection
- The frequencies measurements allow the implementation of an algorithm to generate a correction to the output frequency based on clock ensemble performance.

3.3 Benefits on ONCLE on Time Interval Errors

Navigation signal accuracy is mainly dependant on the time interval error of the on board clock or on board clock system compared to the uploaded clock model.

To better illustrate the role of the quadratic modeling of the phase, the graph of fig 14 is showing the phase-time deviation including drift of the 5 RAFS (some data as fig 11)

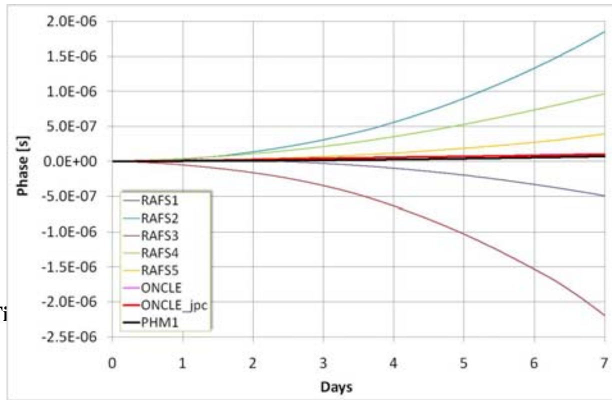

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Figure 15 represents the phase data after removal of a quadratic model computed over the full week of phase data. This in fact represents the possible TIE generated by those 5 RAFS when applying a clock model updated every week.

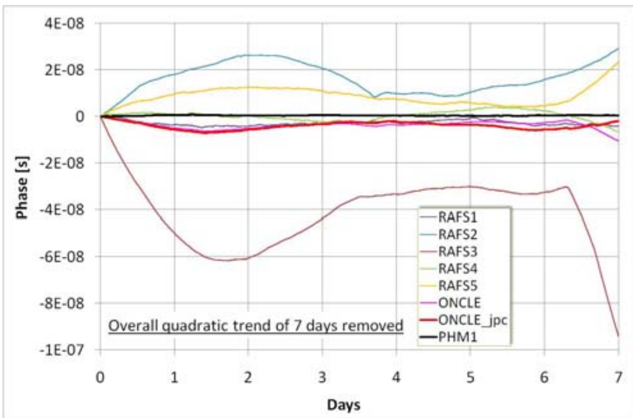

Figure 15. TIE over time afer overall quadratic trend over 7 days period removed,compared to ONCLE & PHM

From this figure, it can be clearly seen the effect of the frequency jumps of the RAFS 2 & RAFS 3, leading to phase deviations up to 100ns while the simple ONCLE algorithm without jumps correction able to maintain within 10 ns. Additionally, ONCLE equipped with RAFS only is able to 'remove' the jumps and maintain the phase within couple of ns, and this for about 1 week. The effect of the jumps removal is more visible within the figure 16 representing the SPHM, ONCLE & ONCLE with jump removal .

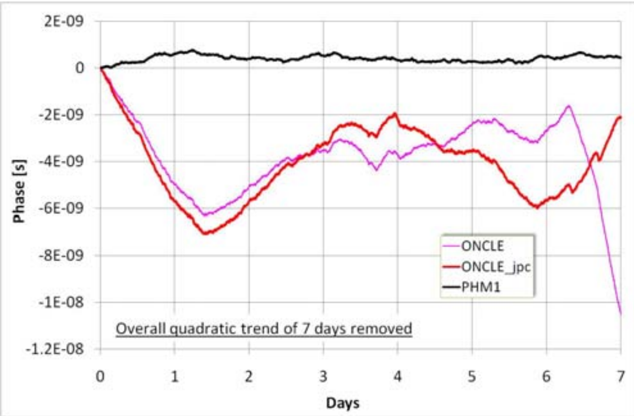

Figure 16. TIE over time afer overall quadratic trend over 7 days period removed (zoom of figure 15)

Quadratic trend removal by post processing is of course not applicable in real time GNSS sat clocks system because the quadratic trend shall be first computed during what we can call 'measurement time for the clock model fitting' **Tm** allowing a prediction of clock behavior for next period to come called 'prediction time ' **Tp**. It is obvious that the better the measurement and the better the clock fitting is realized, the better the fitting will be. Because of the errors induced by the signal transmission path & orbit modeling errors , Tm is generally as long as 1 day for minimum Tp of 100minutes .Figure 17 & table 3 shows the maximum time interval errors for the various clocks & clocks configurations (RAFS1 to 5 + ONCLE + SPHM) for Tp =24 hours .

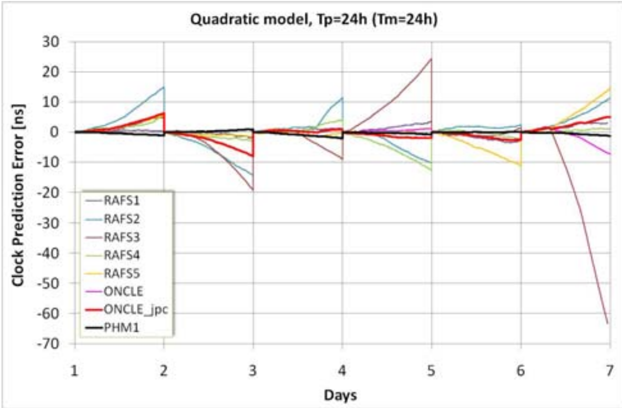

Figure 17. TIE over prediction time of 24 hours afer the previous 24 Hours quadratic trend

[ns]	RAFS1	RAFS2	RAFS3	RAFS4	RAFS5	ONCLE	ONCLE_jpc	PHM1
RMS(@24h)	2.42	11.55	30.34	6.08	7.88	5.29	4.85	1.17
Max	3.58	14.98	66.64	12.75	14.48	8.04	8.04	2.1

Table 3. TIE over prediction time of 24 hours afer the previous 24 Hours quadratic trend

From this result,it is clear that only the PHM or an ensemble of RAFS could lead to acceptable level of time error when need 24 hours or more autonomy of the system. (without taking into account of the availability figure) .The figure 18 & table 4 are showing the TIE over prediction time of 100 minutes (baseline for the Galileo system)

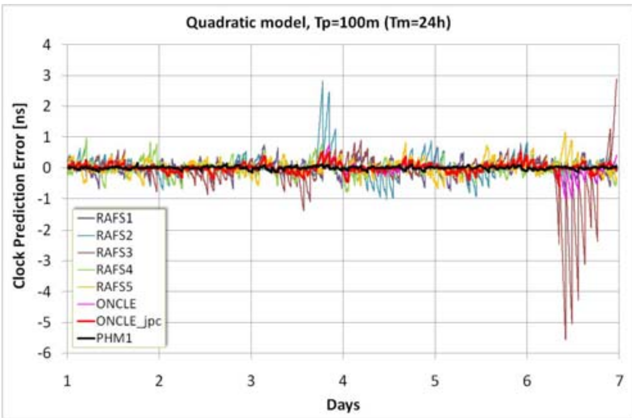

Figure 18. TIE over prediction time of 100 minutes afer the previous 24 Hours quadratic trend

[ns]	RAFS1	RAFS2	RAFS3	RAFS4	RAFS5	ONCLE	ONCLE_jpc	PHM1
RMS(@100m)	0.35	0.61	1.2	0.32	0.34	0.28	0.21	0.07
Max	0.79	2.83	5.56	0.97	1.16	1	0.6	0.16

Table 4. TIE over prediction time of 100 minutes afer the previous 24 Hours quadratic trend

3.3 Benefits on reference signal Availability:

A trade-off between mass of the complete satellite timing sub-system & signal availability been conducted taking into account the 2 SHM + 2 RAFS + CMCU configuration compared to the signal availability using the different clocks ensemble and using the ONCLE algorithm. (Called FRS as Frequency Reference Sub-system) .Figure 19 below is showing comparison of signal unavailability versus mass, taking into account failure rates of the clocks, probability of frequency jumps and reliability of the CMCU or FRS.

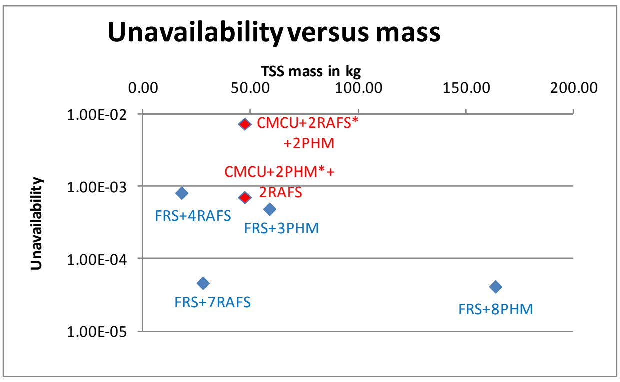

Figure 19. Signal unavailability & mass of various satellite timing sub-systems configurations.

It is very interesting to show a possible configuration constituted of 7 RAFS (4 running devices + 3 in cold redundancy) could lead to one order of magnitude better signal availability compared to the configuration constituted of 2 Maser + 2RAFS without ONCLE algorithm for about half of the mass.

4 Conclusions

- The GIOVE on-board clock performances during the normal operation of 5 years for RAFS and 3 years for PHM, validates the capability of meeting Galileo mission requirements for these two classical and mature space clock technologies.
- The on-going technological programs for both clocks offer room for improvement in terms of mass and performance for next generation of GNSS space clock.
- The ground timing system consisting of key equipments as AHM and PicoStepper, as well as the relevant steering algorithms generates and maintains the navigation timing signal with very high short-term stability.
- The novel onboard techniques to generate highly robust timing signal directly from the satellite clock ensemble will improve the system performance, system integrity and availability.

References

[1] P. Rochat, F. Droz, P. Mosset, G. Barmaverain, Q. Wang, D. Boving, L. Mattioni, M. Belloni, M. Gioia, U. Schmidt, T. Pike, F. Emma. The Onboard Galileo Rubidium and Passive Maser - Status & Performance. *Proceedings of Joint IEEE Frequency Control Symposium and Precise Time and Time Interval Meeting*, Vancouver (Canada), 29-31 August, 2005, pp. 26-32.

[2] F. Droz, G.Barmaverain, Q. Wang, P. Rochat, F. Emma, P. Waller. Galileo rubidium standard – lifetime data and GIOVE-A related telemetries. *Proceedings of the Joint European Frequency and Time Forum & IEEE Frequency Control Symposium*, Geneva (Switzerland), 29 May - 10 June 2007, pp. 1122-1126.

[3] F. Droz, P. Rochat, Q. Wang. Performance overview of space rubidium standards. *Proceedings of the 24th European Frequency and Time Forum*, ESA/ESTEC, Noordwijk (Netherlands), 13-16 April 2010.

[4] Q. Wang, P. Mosset, F. Droz, P. Rochat, G. Busca. Verification and optimization of the physics parameters of the onboard Galileo passive hydrogen maser. *Proceedings of the 38th Precise Time and Time Interval Meeting,* Reston (USA), 5-7 Dec. 2006, pp 81-94.

[5] M. Belloni, M. Gioia, S. Beretta, F. Droz, P. Mosset, Q. Wang, P. Rochat A. Resti, P. Waller, A. Ostillio. Space passive hydrogen maser - performances, lifetime data and GIOVE-B related telemetries. *Proceedings of the 24th European Frequency and Time Forum,* ESA/ESTEC, Noordwijk (Netherlands), 13-16 April 2010.

[6] P. Waller, F. Gonzalez, S. Binda, I. Sesia, P. Tavella, I. Hidalgo, G. Tobias. Update on the In-orbit Performances of GIOVE clocks. *Proceedings of the Joint European Frequency and Time Forum & IEEE Frequency Control Symposium*, *Besancon* (France), 20-24 April 2009, pp. 388-392.

[7] P. Waller, F. Gonzalez, S. Binda, D. Rodriguez, G. Tobias, A. Cernigliaro, I. Sesia, P. Tavella. Long-term performance analysis of GIOVE clocks. *42rd Annual Precise Time and Time Interval Meeting,* Reston (USA), 15-18 Nov. 2010.

[8] X. Stehlin, Q. Wang, F. Jeanneret, P. Rochat, E. Detoma, Galileo system time physical generation, *Proceedings of the 38th Annual Precise Time and Time Interval Meeting*, Reston (USA), 5-7 Dec. 2006, pp 395-406.

[9] Q. Wang, P. Rochat, X. Stehlin, Backup hydrogen maser steering system for Galileo Precise Timing Facility, *International Journal of Navigation and Observation,* Volume 2008, Article ID 730284.

[10] Q. Wang, P. Rochat. An anomaly clock detection algorithm for a robust clock ensemble, *Proceedings of the 41st Precise Time and Time Interval Meeting,* Santa Ana Pueblo (USA), 16-19 Nov. 2

[11] Marvin Epstein, Todd Dass, Dr. John Rajan, and Paul Gilmourn. Long-term clock behavior of GPS IIR satellites, *Proceedings of the 39st Precise Time and Time Interval Meeting (USA*) 26-29 Nov 2007, Long Beach, CA