CHARACTERISATION OF GALILEO CLOCKS ONBOARD AN EXPERIMENTAL SATELLITE

Christophe Bourga[1], Bruno Lobert[1], Michel Brunet[2]

[1] *Alcatel Space Industries - 26, avenue Jean-Francois Champollion - B.P. 1187 - 31037 Toulouse Cedex 1 - France*
[2] *CNES – 18, avenue Edouard Belin - 31055 Toulouse Cedex - France*
Contact : christophe.bourga@space.alcatel.fr

1. ABSTRACT

• An early flight experimentation of Galileo system has been proposed that could carry out performance characterisation of Galileo space clocks. This paper describes the system architecture proposed for this mission, with emphasis on the metrology aspects. This architecture relies on on-board phase comparisons, comparison of space clocks with ground ultra-stable time scales and monitoring of clock environment (radiation, magnetic field, temperature).
Finally, the performance of clock characterisation has been assessed as a function of system design (number of stations, error budget …) and of experimentation duration.

Keywords : Galileo, satellite, clock, experimentation.

2. INTRODUCTION

Galileo is the European satellite navigation system developed under the overall responsibility of the European Union. It consists of a constellation of satellites in Medium Earth Orbit (MEO) and its associated ground infrastructure.
In 2001, the French Space Agency (CNES) has awarded to Alcatel Space Industries the GEM study. This study was devoted to the identification of the potential missions for an early flight experimentation of the Galileo system. The main assumption used as the starting point of experimental satellite design, was the utilisation of the Proteus platform. This platform has been developed by Alcatel Space Industries in co-operation with CNES, and has been successfully flight-proven in the frame of the JASON mission. Other scientific missions are foreseen in the near future with this platform.
During GEM study, two missions of the experimental satellite have been deemed as essential for the success of Galileo. The first one is related to the protection of the frequency filings allocated to Europe for navigation services. The second one is the verification of the space atomic clocks that would be used as reference frequency standards in Galileo : this is the topic addressed in this paper.

3. MISSION OBJECTIVES CONCERNING SPACE CLOCKS FOR GALILEO

3.1 *Definition of the objective*

Atomic clocks are at the core of any satellite navigation system. The lack of experience in Europe in space atomic clocks thus fully justifies the need for an embarked experimentation.
The interest for an early experimentation derives from two classes of risk related to atomic clocks :

- Clocks fail during Galileo operation and lead to global system failure
- Performance is degraded compared to specs and ground test results, hence potential impact on ground segment design and on performance (OD&TS, integrity)

It must be clearly stated that ground test facilities are not fully representative of static and dynamic profiles of in-orbit environment, in particular radiation. Furthermore, environment conditions are reproduced independently in ground tests, e.g. radiation, magnetic field, temperature, and the impact of space environment where all these parameters vary together may be more important than the sum of the individual effects (because of unknown correlation effects).

The objective of an early flight experimentation is thus to verify in-orbit operation (at the same orbit as the one defined for Galileo) and characterise performance in actual space environment of reference clocks that could be considered in GalileoSat and that would be available in the near future (about 2004-2005), if possible at least one of each technology.
Performance in space will be assessed in the form of Allan variance (time intervals of interest between 15 minutes and 1 day) and in factor of sensitivity to space environment.

Three types of clock have been considered for the experimental payload :

- RAFS (Rubidium Atomic Frequency Standard) from Temex Neuchâtel Time (ESA development for Galileo)
- PHM (Passive Hydrogen Maser) from Observatoire Cantonal de Neuchâtel (ESA development for Galileo)
- SCOP (Space Cesium with Optical Pumping), which is proposed by a French consortium Tekelec/ Alcatel/ Sodern.

Another type of European space clock is the USO (Ultra Stable Oscillator) from C-MAC, which is a CNES development for DORIS. The DORIS USO is not retained as a clock to evaluate in the experimental satellite because its performance is not sufficient to meet Galileo requirements. However, since a quartz oscillator is needed for the other missions of the satellite, in order to make them independent of the clock mission in case of failure, it is deemed useful to embark a state-of-the-art USO of the DORIS type that would possibly allow to characterise the candidate frequency standards for Galileo on the short term.
Note that non-European clocks have not been considered.

3.2 *Performance objective*

The performance must be compared to the high level requirement on clock correction error exposed in [Ref.1] : a requirement of 1.5 ns (1 sigma) for the maximum clock error (initial error plus the degradation before a new correction becomes available).
Still in [Ref.1], the specifications of two clocks : RAFS and PHM, have been processed in order to compare the predicted error as a function of the refreshment rate of satellite clock corrections (see also [Ref.2] and [Ref.3]). These specifications are shown in Figure 1 : PHM stability is specified to be around 5 times better than RAFS. The results of the analysis have been refreshment rates of 100 minutes for RAFS and 8.3 hours for PHM.
This performance assessment must be carried out with the reproduction of Galileo satellite environment in order to evaluate the clocks in their true environment. If this turns out to be not possible because of a major impact on the experimental satellite, these constraints could be relaxed but the experimental satellite must then embark the instrumentation needed for fine characterisation of clock environment : it will allow to extrapolate results and to verify clock models established with ground measurements.
Furthermore, the precision of clock performance assessment must be such that the resulting relative uncertainty on Galileo

performance is small. A preliminary figure of 10% maximum uncertainty on stability estimation has been selected.
The Figure 1 shows the Allan standard deviation for the European RAFS and PHM, for SCOP and as a matter of comparison for one GPS clock : RAFS from Perkin Elmer. For this last clock, one curve shows the specification and the other one shows the results of CNES evaluation [Ref.6]. The characteristic stability of the DORIS USO has been added to the Allan standard deviation curve.

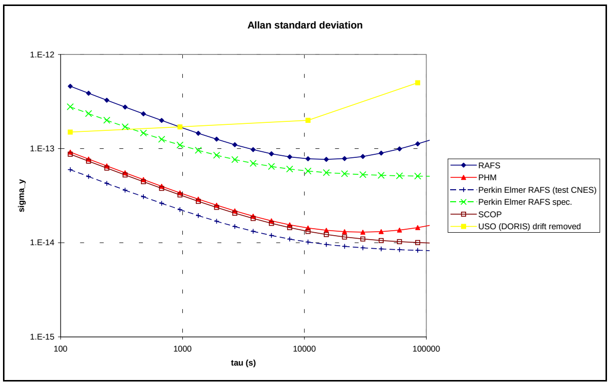

Figure 1 : Allan standard deviation for different clocks

4. GENERAL SYSTEM ARCHITECTURE

Clock performance assessment relies on the following points :

- reproduction of an environment similar to Galileo design (in particular the orbit shall be the one foreseen for Galileo)
- monitoring of environment parameters that can impact clock performance : temperature, magnetic field, radiation
- monitoring of internal clock parameters (e.g. output voltage …)
- continuous on-board comparison of clocks, which allows to use only one clock as the reference frequency for the payload and to characterise the other clocks from measurements on that reference clock; it allows also to use the three-corner hat method when this one is applicable, or to characterise a clock by another on-board clock of better stability
- comparison with clocks located in ground stations
- calibration and verification of measurements : the measurement campaign must start with system bias estimation and also continuously assess parameter drift
- Processing of measurements and analysis of results.

The comparison with clocks located in ground stations uses two different methods. Whatever the method, it requires a precise satellite position determination, an ultra-stable time-scale on ground and an earth/space link.
The first method relies on the emission of down-link navigation signal (in RF) by the experimental satellite and has been called CCNS (Clock Characterisation by Navigation Signal) within the study. It uses a ground network of sensor stations similar to the one foreseen in Galileo [Ref.1] and an algorithm similar to the ones used by IGS to characterise GPS clocks. However, as only one experimental satellite is expected to be launched, the ground network needed for navigation signal measurements needs to be synchronised by an independent means. This is achieved by combining GPS measurements with those of the experimental payload.
The second method uses a signal in optical frequencies and is based on T_2L_2 system. This concept relies on two-way measurements. It has been developed in the frame of the ACES project (part of the International Space Station) but has been recently abandoned for mass and volume constraints onboard the ACES payload. As it is an optical link, it suffers from poor availability due to the atmosphere (clouds) but is practically much more precise than RF links.

5. SYSTEM DESIGN AND EXPECTED PERFORMANCE

The baseline clock configuration defined in GEM study (and presented in this paper) is 1 RAFS + 1 PHM. Other options have been identified, e.g. 2 RAFS + 1 PHM, or 1 RAFS + 1 PHM + 1 SCOP, however it turns out that only one PHM can be accommodated due to platform constraints, also SCOP has a critical planning for the horizon 2004-2005 and thus cannot be retained in the baseline.

5.1 On-board phase comparisons

The phase comparisons between on-board clocks can be used in three different approaches, depending on the actual clock configuration :

- characterisation of a clock by another flying clock which is characterised from the ground
- characterisation of a clock by another flying clock whose stability is much higher
- characterisation of a set of clocks, with the three-corner hat method.

In any case, the quality of the phase comparator is a major issue. A simple calculation shows that its Allan variance specification shall be in the vicinity of $10^{-13}\,\tau^{-1/2}+10^{-15}$.
The first approach is made necessary when more than one clock is flying.

The second method can be envisaged e.g. if RAFS is flying with the PHM. However the possibility to characterise the PHM this way, e.g. with a GPS clock is questionable because of the high stability expected from the PHM.
This solution has been analysed with the GPS RAFS implemented on block IIR, produced by Perkin Elmer.

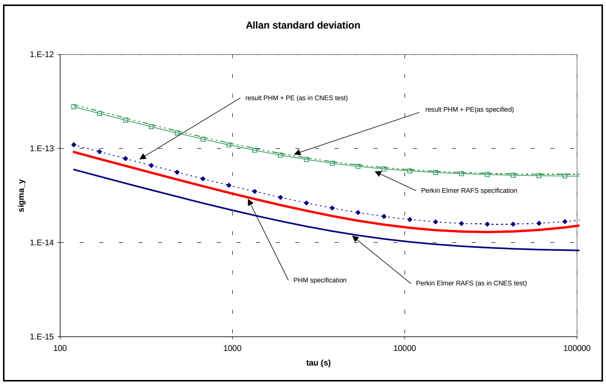

Figure 2 : PHM characterisation with Perkin Elmer RAFS

The Figure 2 shows the performance of this solution in terms of PHM characterisation in Allan deviation. It takes into account two different performance assumptions for Perkin Elmer RAFS : one is the manufacturer specification and the other one is the result of CNES tests on one unit [Ref.6].
It comes out that the risk exists to characterise Perkin Elmer RAFS rather than PHM itself. Furthermore, programmatic issues such as procurement of US sensitive equipment lead to turn down this solution.

The last method, as clearly expressed in its name, requires three or more clocks. Similar stability between the clocks seems to be the condition of the efficiency of the method.
This method has been analysed in the case of one additional RAFS, i.e. the 2 RAFS + 1 PHM option. To simplify the simulations, only 10 days of data sampled at 120 s have been generated (Figure 3). The solid line represents the actual clocks and the dotted line the estimated stability. RAFS are represented in blue and in green, whereas PHM is in red. While RAFS stability is well estimated, the PHM estimator clearly diverges.

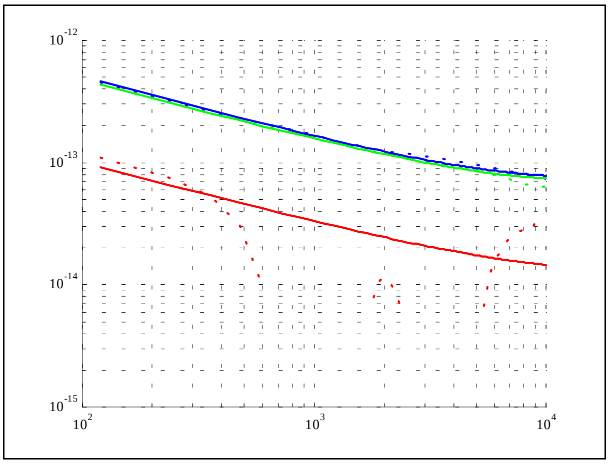

Figure 3 : simulation of three-corner-hat method with 2 RAFS + 1 PHM

A preliminary analysis has put in evidence theoretical limits of the method for this case. Further investigation is needed to assess the actual limits of the technique, which could else be of great interest for clock monitoring and estimation in the Galileo context.
However, from our current analysis, it seems unlikely to characterise one PHM on-board from phase comparisons, even with two RAFS.

5.2 Clock Characterisation with Navigation Signal (CCNS)

5.2.1 CCNS Design

The main issues concerning CCNS relate to the design of the navigation signal, the design of the ground network and the design of the algorithm.

Signal design for clock characterisation is driven by the capacity to make precise and accurate measurements. This condition must be examined in view of the need for combining measurements from the experimental satellite with GPS measurements.
In order to alleviate the critical issues related to the experimental receiver, in particular inter-channel bias calibration (cf. [Ref.7]) and development of brand new receiver model, a similar signal design to GPS has been proposed. This signal would be emitted on two frequencies L1 and L2, in order to correct ionosphere delay and to gain in precision, with the same carrier frequencies as GPS. Similar codes to GPS would be used. The impact on existing geodetic GPS receivers and availability for the experiment is still to be thoroughly investigated.

The design of the ground segment is based on a network of sensor stations, including one with an ultra stable time scale (denoted here as E-PTS : Experimental Precise Timing Station, in analogy with current GSTB projects).
There must be at least 12 standard sensor stations world-wide spread, close to the configuration defined in [Ref.1], since this configuration has proven to allow good clock estimation thanks to sufficient coverage and common visibility.
The E-PTS sensor station differs from the standard sensor station by the stability of its reference clock. Its function is to carry out a datation of the signals received from GPS satellites and experimental satellite, with respect to an ultra-stable time scale. Frequency stability must be higher than the specification of the best clock to characterise. A 10 factor is recommended, which leads to $10^{-13}\tau^{-1/2}+10^{-15}$ specification. This range of performance corresponds to an Active Hydrogen Maser, at least for τ<10000 s.

5.2.2 Experiment duration for CCNS

With confidence intervals calculated from [Ref.4] formulae, 42 days of continuous measurements are needed for clock characterisation with 10% error at 68% confidence level with the most efficient method (maximum overlap method), if the maximum τ interval of interest is one day.
Recent studies indicate a mean availability of IGS data of 70%. If this figure is retained as a worst case for the experiment, it leads to to increase the duration of the experiment, which would then be 42/0.7=**60 days**.

5.2.3 Expected performance with CCNS

The performance expected with CCNS is based on classical error budgets for dual frequency geodetic receiver measurements (pseudo-range and carrier phase). The baseline for algorithm design is to use carrier phase measurements in order to get the maximal precision.
The Figure 4 displays the error budget for the measurement noise term and compares it to specifications for both RAFS and PHM.
Three error curves are visible :

- the short term measurement noise for carrier phase
- the long term measurement noise for carrier phase; this component derives from the error in ambiguity resolution in combining several observation periods between stations and satellites; from IGS experience, this term amounts to 5 cm clock precision and behaves as a white frequency modulation noise (random walk phase noise)
- the short term measurement noise for pseudo-range.

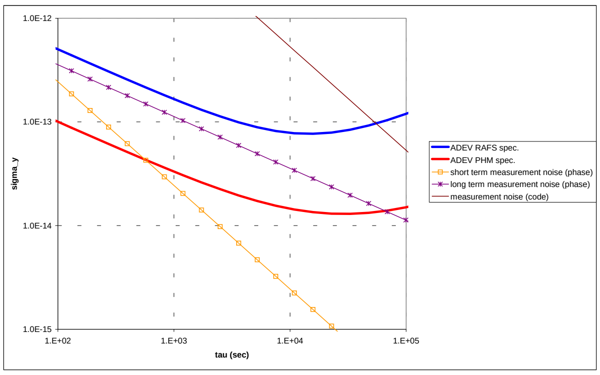

Figure 4 : expected performance for CCNS (measurement noise)

The second term (long term measurement noise for carrier phase) has a major impact for time intervals ranging from half the mean observation period duration (1e4 seconds) to one day. For shorter time intervals, this term could be removed by specific processing using only separated observation periods, without trying to combine them in order to get larger observation periods. This term is the most annoying for clock characterisation, namely for PHM and for time intervals from 1e4 to 1e5 seconds.

The third term (short term measurement noise for pseudo-range) intervenes for time intervals over one day, because ambiguity resolution has to be adjusted on the long term with non ambiguous measurements (in order to avoid biases in orbit determination), due to cycle slips, geometrical errors at ground station or in satellite position.

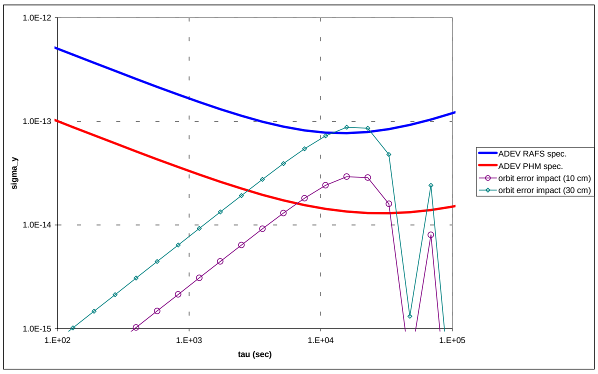

Figure 5 : expected performance for CCNS (impact of orbit error)

The Figure 5 displays the terms due to error on orbit determination and compares them to specifications for both RAFS and PHM.

The first error curve shows the case of 10 cm RMS error, with sine variation on the orbital period. This represents the optimistic case. Indeed, IGS post-processed data yield 5 cm precision with the whole ground station network and a well characterised network. With a more reduced network, precision is rather around 10 cm. With a new experimental satellite, such precision will likely not be obtained until late in the survey (one year maybe), after precise identification of satellite model parameters.

The second curve represents the more realistic case for the beginning of the experimentation, similar to GLONASS performance in IGS processing, i.e. 30 cm RMS orbit error.

Clearly, these terms are degrading PHM characterisation, at least for the interval $\tau \in$ [2 hours; 9 hours]. In the worse case (30 cm), the degradation affects PHM characterisation in the 1 hour/11 hours intervals and even affects slightly RAFS characterisation.

The Figure 6 shows the global estimation of clock characterisation, assuming only short-term measurement noise for carrier phase and 10 cm RMS orbit error. Therefore, even in the best case, it is clear that PHM cannot be finely characterised by CCNS. Conversely, CCNS allows to assess RAFS clock behaviour very well.

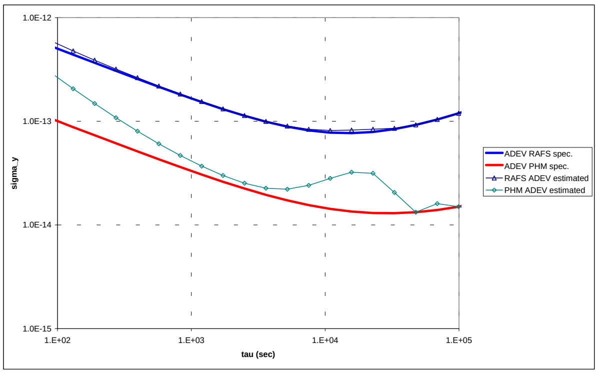

Figure 6 : expected performance for CCNS (final clock estimation in best case)

5.3 *Clock characterisation with T_2L_2*

The T_2L_2 system has been developed in the frame of the ACES project [Ref.5]. It is designed to allow the synchronisation of remote clocks on Earth and the monitoring of a satellite clock with a time stability of the order of 1 ps over 1000 s and an accuracy in the range of 100 ps.

5.3.1 T_2L_2 ground segment design

The stations retained for use of T_2L_2 must comprise of the following features :

- stations must be able to **track MEO orbit** (hence enough power must be provided on laser firing)
- measurement rate shall be **300 s** or less (Glonass tracking experience)
- they must comprise of frequency standard with specification $10^{-13}\tau^{-1/2}+10^{-15}$, which corresponds to **Active Hydrogen Maser performance**.

The Laser Ranging stations belonging to ILRS have been investigated in order to analyse their potential selection as T_2L_2 stations for the experiment.

The selection has been initiated with stations able to track GPS orbit day and night (because it indicates that the station will allow continuous tracking with Galileo orbit), if possible with a AHM collocated in SLR station, and with world-wide coverage.

From discussion with experts from OCA (Observatoire de la Côte d'Azur), 50% availability due to weather and operations must be expected for a given station.

Simulations have then been carried out to dimension the ground network, with several scenarios :

- different sizes of networks
- different values of operation duration per day granted by each SLR station to the experiment.

For each scenario, the number of measurements for Allan variance calculation and then the number of days needed for the experiment (from formulae in [Ref.4]) have been computed.

In conclusion, it turns out that in order to remain at the level of 3 months operation, there are two extreme solutions.

Either a large contribution is expected from ILRS, i.e. 12 stations. Anyhow, a minimum of 2 hours/day seems to be required. This kind of solution is currently difficult to take into consideration because LEO satellites are given the priority in ILRS (GLONASS satellites are tracked with a daily average of 35 minutes, for the best stations). Also, the implementation of T_2L_2 ground equipment and of frequency reference standard in each of the 12 SLR stations raises practical problems.

Or a limited network (3 stations) fully dedicated to the experiment is retained. It would be able to characterise the satellite clock on a reasonable duration (100 days) if the time interval of interest is not greater than 12 hours. This is the most reasonable approach.

5.3.2 T_2L_2 Performance

The Figure 7 shows the expected performance of clock characterisation with T_2L_2, assuming there are enough measurements. Errors due to earth rotation are considered as negligible.
It clearly comes out that both PHM and RAFS clocks can be safely characterised for the time intervals of interest.

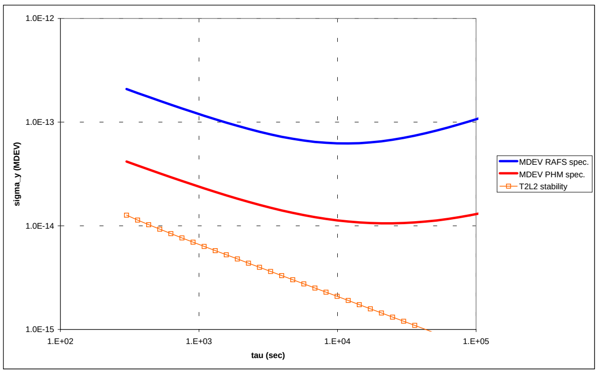

Figure 7 : expected performance for T_2L_2

6. CONCLUSION

For the clock characterisation mission defined in GEM study, the proposed architecture is based on :

1. **On-board phase comparisons**, in order to determine stability of a hot redundant clock from measurements performed on the payload reference clock. This method allows to carry out three corner hat method in case clock configuration changes and is more favourable to such a method (i.e. 3 clocks of similar stability). With the present clock configuration (1 RAFS + 1 PHM), only the RAFS can be characterised. Flying a Perkin-Elmer RAFS for PHM characterisation is not recommended, due to risks on the achievable performance and on procurement.
2. **CCNS** (Clock Characterisation by Navigation Signal), based on **use of GPS signal** transmitted by the experimental payload. It has been shown that performance of this method is **adequate for RAFS** but not for PHM.
3. T_2L_2 (Time Transfer by Laser Link), with a payload equipped with T_2L_2 on-board module and a network of existing ILRS stations (equipped with T_2L_2 ground module and Active Hydrogen Maser). This method allows to calibrate and verify CCNS, and above all **to fully characterise PHM**. From an operational point of view, T_2L_2 implementation raises several programmatic issues that need further investigation. The more realistic design comprises of a limited network (3 stations) fully dedicated to the experiment during 3 months.

From the analysis carried out up to now, it clearly turns out that RAFS characterisation is not a difficult issue, unlike PHM whose performance assessment cannot be firmly guaranteed.

7. ACKNOWLEDGEMENTS

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