OSCC project : A space Cs beam optically pumped atomic clock for Galileo

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***Abstract*— Thales Electron Devices has been pursuing since 2003 frequency standards activities. In the framework of these activities, Thales established a consortium for the development of a space Cs atomic clock for Galileo. This consortium is composed by two of the best scientific laboratories in the European Time-Frequency community : the Observatoire de Neuchâtel (ON) and the SYRTE Observatoire de Paris, and by two space industrials : Oerlikon Space AG (OSAG) and Thales Electron Devices. The name of the project is OSCC for Optically pumped Space Cs Clock. The first phase (phase A) of this development started in June 2006 under an ESA contract.**

The purpose of this phase A is a feasibility study of Cs clock technology for Galileo with the manufacturing and the test of a new compact optically pumped Cs clock breadboard. This technology is well known in laboratories but it has never been industrialized, even for ground applications. This study starts with a strong background at SYRTE and ON, but also with new industrial developments realized at Thales during the last years. Frequency stability in order of 1 to $3x10^{-12}.\tau^{-1/2}$ has been already demonstrated in lab with different configurations.

This document will first synthesize the last results obtained by each Partner, followed by the results of the existing hardware analysis performed in the first step of the project. This analysis allowed Partners to share their know-how and to identify the limits of each existing breadboards with respect to the objectives of the project. As a result of this analysis, it was possible to define the atomic resonator best configuration for each sub-system. At least, this document presents a few design drivers of the new OSCC devices.

I. INTRODUCTION

In satellite navigation systems, the high performance atomic clocks take an important place. In particular the on-board clocks which are key components to reach the positioning performances. Since its creation, the GPS system has already used two different technologies : the current base line with the Rb clocks, and the Cs clocks. Concerning the GALILEO system, two technologies are specified for the first generation of satellites. The first one is also a Rb clock (RAFS) while the second is a passive H maser (SPHM), which has not been spatialized before.

These two clocks are based on the same concept of atomic vapor cell, which is particularly sensitive to the environment, limiting mid and long term stability performances. In the case of the Cs clock, the principle is different : the atoms are used in an atomic beam. This characteristic allows to reduce the effects of the environment and to reach better mid and long term stability performances.

The Cs Clocks on-board GPS satellites are based on the magnetic state selection technology. This very mature technology is used in all commercial Cs clocks. However, the frequency stability required for the Galileo space clocks can't be reach with the magnetic state selection technology. Then, the solution proposed for a space Cs clock is the optical pumping technology, well known in laboratories since the 90s but still never industrialized. Contrary to the magnetic deflection technology, the optical pumping allows to use much more atoms, improving the signal to noise ratio of the atomic resonator and consequently the frequency stability of the clock.

The topic of this document is a presentation of the OSCC project, acronym of Optically-pumped Space Cs Clock. The objective of the project is to develop and manufacture a space Cs clock for the Galileo's satellites. The first phase of the project (phase A) has started in June 2006 under the ESA contract 19908/06/NL/CH. The objective of this phase A is to demonstrate the feasibility of the performances required for the GALILEO program through the manufacturing of a new breadboard.

The OSCC project is funded by ESA

II. PROJECT PRESENTATION

A. *Main requirements & specifications*

The frequency requirements of a Cs for Galileo is a stability better than $3x10^{-12}.\tau^{1/2}$, but our ambitious goal is to demonstrate a short term stability in order of $1x10^{-12}.\tau^{1/2}$ and a flicker floor lower than 1.10^{-14}. To this high stability specification, it is necessary to associate the space constraints with very challenging requirements like the mass budget (<10 kg) or the lifetime (>12 years).

With respect to this specification, the optically pumped Cs is an alternative to the two based-line clocks of Galileo : the Rb (RAFS) and the passive H maser (SPHM). As it shown on Figure 1, the OSCC clock presents several advantages; it allows to reach a better frequency stability than the Rb clock for a weight lighter than that of the passive H maser. The OSCC specifications with regard to the required performances for the European navigation system show that this solution is in better equivalence with the Galileo specifications, while presenting sufficient margins for future evolutions of the system.

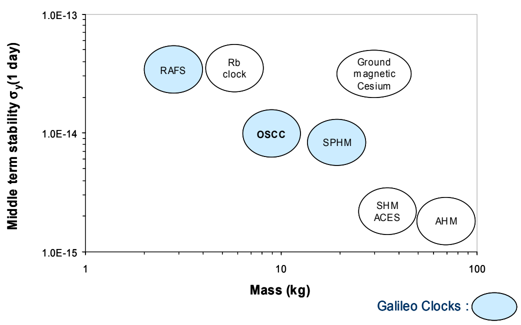

Figure 1. Comparative graph of existing atomic clock for ground and space applications.

B. *An European partnership*

The OSCC project, led by Thales, is based on a Swiss-French consortium composed by two of the best European Time-Frequency laboratories : Observatoire de Neuchâtel (ON) and SYRTE, and by two space industrials : Oerlikon Space and Thales Electron Devices (Thales ED). This consortium presents a strong know-how in the Time-Frequency domain and specially in Cs beam clocks.

Concerning ON, many Cs clock developments have been performed since 90's, with recently the OSCAR project for ESA. Connected to this, ON has developed few other space clocks (Rb for RadioAstron, SPHM for Galileo, SHM for ACES)

SYRTE has an important experience since 1981 in optically pumped Cs beam clocks with one primary standard (JPO), 4 compact resonators and many theoretical works. SYRTE has contributed in a pre-industrial development during the 90's.

Oerlikon Space is currently developing the electronic package for the Space Hydrogen Maser of ACES (SHM) and has performed some space optical developments.

Thales ED is currently developing Cs clocks for various applications. Thales ED has also a long experience in space products (world leader of space TWTs). Armed with those experiences, Thales is the prime of the project.

C. *Optically pumped Cs atomic clock principle*

The principle of the optically pumped Cs atomic clock has been well described in literature [1]. As every passive clocks, the frequency of a local oscillator (quartz) is locked on an atomic frequency resonance issued of an atomic resonator. For Cs, the atomic resonator presents 4 main functions : of course, the first one is the Cs beam generation by a Cs oven (rep.1), but the heart of the system is : the Cs optical preparation (rep.2), the interaction between the RF signal and the atoms (rep.3), and the optical detection (rep.4). These 4 functions are shown on Figure 2.

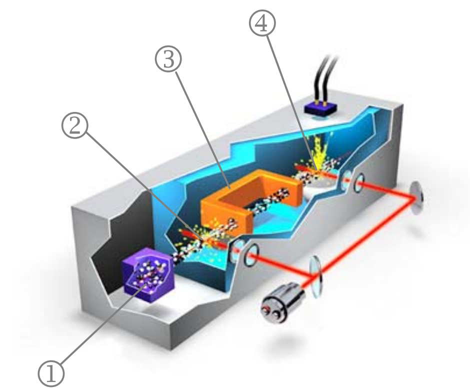

Figure 2. Scheme of an optically pumped Cs atomic resonator.

The RF interrogation is classically performed in a Ramsey microwave cavity (rep.3) but before, the atoms have to be prepared in a single hyperfine atomic state F=3 or F=4. This preparation is performed by optical pumping (rep.2) instead of the magnetic state selection. In this case, there is no spatial separation and all the atoms get through the laser towards the microwave cavity. That is why there is no lost flux and consequently a higher number of useful atoms. At last, the detection of the Cs atoms is performed with the same optical technique in the detection region (rep.4) : the Cs atoms which have changed of atomic state in the microwave cavity (clock transition) are pumped by the laser beam in the first excited state. The fluorescence photons of those atoms are then detected by a photodiode allowing the detection of the considered atoms.

III. PARTNERS BACKGROUND

As mentioned in the introduction, the partners of the project have an important background specially at SYRTE, ON and Thales ED which have developed several prototypes. The first step of the project was an existing hardware analysis to share the knowledge between partners. The objective of this work was to reach a better understanding of the noise limitations and to define the main design drivers of the new OSCC breadboard. Four prototypes were mainly studied : the OSCARino breadboard of ON, the breadboards Cs4 &

Cs4-NAV of SYRTE and the TOP-Cs prototype of Thales ED. The 5th prototype, PHACS, developed by SYRTE [2] was also taken into account in the analysis but its performances (telecom applications) are not fully compatible of our application.

A. Description and results of existing prototypes

The OSCARino experiment is the most recent breadboard. The last results obtained by ON are presented in the reference [3]. The frequency stability reach by this prototype is in order of $1.5x10^{-12}.\tau^{-1/2}$ with the single frequency optical configuration. These results are the best one obtained with this simple optical configuration but the counterpart is the high Cs flux, which could be not compatible with the long lifetime requirement of a Galileo development. The identified noise limitation is not yet the shot-noise of the atoms but mainly the stray light noise. Optimizations have been identified to increase the performances.

The Cs4 prototype was developed in the 90s at SYRTE for ground application. This well optimized atomic tube (2 litters) has not been modified since this period. It is continuously operating since 1992 excepted for 2 years between 2004 and 2005. The prototype has been exploited in two different optical configurations : the first one with a single frequency scheme called Cs4 and a second one called Cs4-Nav with the dual laser frequency configuration to reach higher performances. The best results obtained on Cs4 with the single laser frequency configuration were $4x10^{-12}.\tau^{-1/2}$ with a very low flux of atoms (oven temperature 90°C). In this configuration, the noise limitation was mainly the detection noise (limited by the photodiode) and the stray light noise [4].

To easily reach higher stabilities, the dual frequencies optical configuration has been implemented on the atomic resonator Cs4. This experiment, called Cs4-Nav, was performed in 2001 and a stability of $1.4x10^{-12}.\tau^{-1/2}$ has been measured [5]. The noise limitation in this configuration was mainly the noise of the laser, even if an Extended Cavity Laser (ECL) has been used, because of the cycling transition used for the detection.

The TOP-Cs prototype has been manufactured by Thales ED in 2005 in the framework of a Cs clock industrialization for ground applications. The atomic resonator is similar to its lab predecessor Cs4 but it was manufactured with industrial processes. The frequency stability of TOP-Cs was measured at $6.1x10^{-12}.\tau^{-1/2}$, also with the single laser frequency configuration [6]. The main limitation is electronic issues shown by a stability not consistent with the measured signal to noise ratio. Concerning the atomic resonator, the stray light noise is the main limitation followed by the detection noise, as for Cs4.

Tables below present the key functional parameters (Table 1) and the main experimental results (Table 2) of the existing prototypes manufactured by SYRTE, ON and Thales.

Parameter	Unit	OSCARino	Cs4	Cs4 Nav	PHACS	TOP-Cs
Theoretical consumption @ Cs pressure equivalent to 90°C	g/an	0.12	0.16	0.16	0.8	0.1
Cs oven operating temperature	°C	130	90	90	110	110
µ-wave cavity configuration		bright fringe	dark fringe	dark fringe	**dark fringe	dark fringe
Magnetic field in optical regions	*	1	6	6	1	6
Magnetic field in µ-wave region	*	same	1.3	1.3	same	0.7
Measured optical collecting efficiency	*	2	1	1	0.8	1
Type of laser		DFB	DBR	ECL	DBR	DBR
Measured laser linewidth	MHz	1,8	<3	#0.5	<3	<3
Optical transition		D2	D2	D2	D1	D2
Cs transition & laser polarization in detection		4-4' depolarized	3-3'σ	4-5'σ	3-4'π	3-3'σ
Cs flux contributing to the Ramsey fringe (mF=0)	at/s	1.6E+10	1.7E+9	2.0E+9	2.1E+9	2.2E+9

* Relative values ** cylindrical cavity

Table 1. Key functional parameters of existing prototypes at SYRTE, ON and Thales.

Parameter	Unit	OSCARino	Cs4	Cs4 Nav	PHACS	TOP-Cs
Ramsey fringe linewidth	Hz	858	650	590	2190	652
Atomic resonator Quality factor Q		1.1E+7	1.4E+7	1.6E+7	4.2E+6	1.4E+7
Ramsey fringe amplitude	nA	1.681	0.22	5	0.142	0.3
DC background	nA	2.12	0.4	1.5	0.017	0.3
PSD of the clock signal @ resonance	$fA/Hz^{1/2}$	41	17	-	14.5	19.5
PSD of the clock signal @ modulation depth	$fA/Hz^{1/2}$	-	18.6	130 to 200	15.3	24
Signal to noise ratio SNR	$Hz^{1/2}$	41000*	11800	25000 to 38000	9281	12500
Measured stability @ 100s		1.5E-13	4E-13	1.4E-13	1.2E-12	6.1E-13

* Different definition of the SNR

Table 2. Main experimental results of existing prototypes at SYRTE, ON and Thales.

B. *Existing hardware analysis conclusions*

The key parameters show that for the critical parts of the atomic resonator, French and Swiss teams have implemented different solutions. But the analysis of all the parameters and the tube's performances shows that the various existing breadboards lead to the same order of frequency stability when the atomic flux is similar.

The sharing of all those data has allowed SYRTE to complete its theoretical model of Cs beam clocks [7]. This model has shown a good coherence with the ON experimental results. It allowed to identify clearly the real noise limitations and the potential optimization criteria of the different breadboards.

IV. DESIGN DRIVERS OF THE NEW OSCC BREADBOARD

The analysis of the existing prototypes and theirs performances allowed us to identify the best configuration as well as improvement factors for each sub-systems of the clock. Partners have identified important design drivers to reach the frequency stability objective of $1x10^{-12}.\tau^{1/2}$ according to the space environment constraints.

The main choice concerns the optical configuration : single or dual laser frequencies. Even if frequency stabilities in order of $1x10^{-12}$ @1s have been already demonstrated with the dual laser frequencies configuration, we think that this stability goal could also be reached with the simplest optical configuration using a single laser frequency, and with the same low flux of Cs atoms. That is why, in opposite to other atomic beam clock developments [8][9], we chose to work on this simple optical configuration which is technologically more favorable for a space development with regard to the important space constraints. Indeed, the optical configuration with two laser frequencies requires the use of a laser source with a narrow line-width (ECL or very narrow laser diode) which are not well mastered, specially for a space application. This configuration also requires a supplementary active element as an acousto-optic modulator, which impacts consequently the criticality and the power budget.

In the same objective of simplicity, the depolarized laser pumping technique has been chosen. The ON's studies have shown that it is possible to cancel the dark states excitation by using a depolarized laser light [3] instead of using a high magnetic field in the optical interaction region [10]. This solution is technologically simpler than the implementation of 3 different C-field zones as it was implemented in the Cs4 resonator. This solution requires only an optical passive element to depolarize the light of the laser diode.

Regarding the frequency stability objective, the theoretical model of the SYRTE shows that the inversed Ramsey fringe configuration (dark fringe) presents advantages with respect to the regular Ramsey fringe (bright fringe) commonly used in commercial Cs clocks [7]. The inversed Ramsey fringe allows to reach frequency stability 10 to 30% better than the bright fringe (other parameters identical). The fringe configuration (dark or bright) depends on the phase shift between the two RF interaction regions of the Ramsey cavity (0 or π rad). Technologically it depends on the modal configuration of the microwave cavity (TE_{01m} with m odd or even). The dark fringe microwave cavity configuration has been implemented in all the compact atomic resonators developed by SYRTE since the 90s.

V. CONCLUSION

The phase A of the OSCC project has started in June 2006 with the objective to demonstrate the feasibility of an optically pumped Cs clock for Galileo through the manufacturing of a new breadboard. The first step was an analysis of the existing hardware at ON, SYRTE and Thales Electron Devices.

The share of the data and the theoretical model of the SYRTE, have allowed partners to identify different optimization criteria for each existing prototype. Consequently, this better understanding of the noise contributions make the OSCC Partners very confident in the development of a new atomic resonator, optimized to reach frequency stability level compliant with the ESA requirements for a space Cs clock, by using simple sub-system configurations. Today, the design drivers of the OSCC breadboard have been determined and the manufacturing of the new atomic resonator is ongoing.

ACKNOWLEDGMENT

Partners thank ESA, CNES (French national space agency) and SSO (Swiss Space Office) for their support.

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