A SPACE RUBIDIUM PULSED OPTICAL PUMPED CLOCK – CURRENT STATUS, RESULTS, AND FUTURE ACTIVITIES

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Abstract

Since the year 2000, Selex Galileo activity on Space Frequency Standards has been pursuing the development of a Passive Hydrogen Maser (PHM), presently the primary clock of the Galileo Navigation Constellation. A consortium has been established in 2007 with one of the best scientific laboratories in the European Time-Frequency community: the Istituto Nazionale di Ricerca Metrologica – INRiM (I) in order to demonstrate that the POP technique is suitable for space applications. The name of the project, Maser POP, comes from a very promising technique studied and refined by INRiM in order to achieve performance close to that of a passive hydrogen maser, but with dimensions and power consumption closer to a rubidium clock.

Under an Italian Space Agency ASI contract, a feasibility study has been completed in 2008 concerning the manufacture of a clock breadboard and the preliminary design of the three units composing the clock: Space Physics Unit, Optical Unit, and Electronic Unit. This paper summarizes the outcome of this study in terms of Breadboard (BB) results (where a frequency stability on the order of $1.2\times10^{-12}\tau^{-0.5}$ ***has been measured) and the critical areas that shall be correctly addressed for the project objective's full achievement.***

The development plan of the Maser POP is presented together with an overview of expected characteristics, in terms of mass and power consumption, realistically optimized taking into account the needs of the space market.

A preliminary schedule is also presented concerning future acivities aiming at the development of an Engineering Model (EM). This plan includes the qualification of the clock against the Galileo environmental requirements. Also, these further activities will be supported by the Italian Space Agency (ASI) in the frame of the Space Atomic Clock Development program.

INTRODUCTION

Traditional Optically Pumped Atomic Clocks are based on the physical principle of the double resonance. The atoms of a gas (typically cesium or rubidium) confined in a cell inside a microwave cavity are excited by an optical radiation generated by a lamp or a laser (optical pumping). The pumping inverts the atomic populations of two hyperfine levels of the fundamental state that have been chosen for the transition of the clock.

Once the atoms of the gas have been excited, the photons of the light are no longer absorbed by the gas and the cell containing the gas becomes transparent to the frequency of the optical pump.

A suitable microwave signal (at the resonance frequency of the microwave cavity) applied to the excited gas stimulates the decay of some of the excited atoms, so that the cell will loose its transparency, absorbing again the energy of the optical radiation. Consequently, a dip will be present on the intensity of the optical signal passed through the cell, corresponding to the gap between the two hyperfine levels of the gas.

This dip can be used to improve the stability of a quartz oscillator, making an atomic clock. The following three different phases, occurring at the same time, can be singled out:

- PUMPING: the atoms of the gas are excited by the light radiation.
- INTERROGATION: the microwave radiation stimulates the decay of some of the excited atoms.
- DETECTION: the dip of the light passed through the cell is detected (and used to lock an oscillator).

The main problem of an atomic clock based on the described principle is that these phases occur at the same time, which worsens the overall short- and medium-term stability of the system with respect to the theoretical limit (shot noise).

This is due to several physical phenomena[1], the most important one being the light shift, that consists of the transfer of the laser noise (in terms of amplitude and frequency fluctuations of the laser signal) to the hyperfine levels used for the clock transition, and consequently to the microwave signal (i.e. AM/FM amplitude-to-frequency conversion and FM/FM frequency-to-frequency conversion). This leads the stability of the clock to depend on the stability of laser's parameters.

PULSED OPTICAL PUMPED ATOMIC CLOCK

By adopting the Pulsed Optical Pumping (POP) Technique, the effects of the light-shift are strongly reduced, leading to an optically pumped atomic clock with better stability compared to classical optically pumped clocks. This is achieved by the separation in time of the three phases of pumping, interrogation, and detection, which is made possible by adopting the novel technique introduced by the studies carried out in the recent years at INRiM **[1,2]**.

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[1] Other phenomena affect the stability:

- Microwave noise, in terms of fluctuations of the amplitude and phase of the microwave field applied during the interrogation phase.
- Temperature variations that shift the hyperfine levels.
- Dependence of the clock frequency on the temperature due to microwave cavity drifts (Pulling effect).

The POP technique takes advantage of the today availability of laser sources for optical pumping, replacing the previously used lamp sources; in particular of laser diodes, which allow precise control of the emitted radiation. Such control is exploited in the POP, in order to separate in time the three working phases, which minimizes the mutual influences of the different signals and strongly reduces the transfer of laser's instabilities to clock transition.

This technique has been applied in this study program to a rubidium atomic clock, which is expected to guarantee stability (Allan deviation) of the clock signal:

$$\sigma y(\tau) \approx 1\times10^{-12}\ \tau\text{-}^{1/2}$$

where τ is the average time considered to assess the deviation.

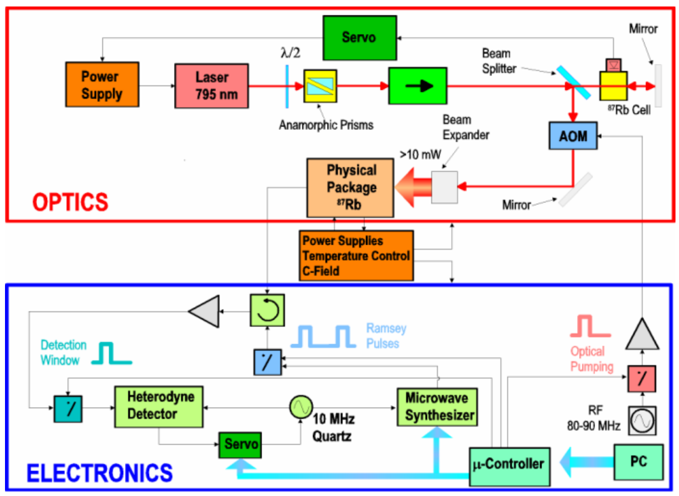


Figure 1. POP clock architecture.

PHASE A: THE FEASIBILITY STUDY

In the frame of an ASI contract, a POP clock feasibility study has been carried out with the following targets:

1. Definition of the Clock specification
2. Definition of the Clock Units' requirements
3. Preliminary design of the Clock taking into account the typical criteria adopted in space designs and technological assessment in view of its space application
4. Realization of a "Demonstrator" in order to validate the POP technique and its performances.

Concerning the last point, the demonstrator includes a prototype of the Physics Package (RF cavity containing the 87Rb vapor cell), interfaced to a devoted test setup simulating the remaining parts of the clock (electronic package and optical package).

FUNCTIONAL ARCHITECTURE

The POP clock is split in three units: the electronic unit, the physical unit, and the optical unit. The functions performed by each of these units are the following:

Physics Package Unit

- Acts as a frequency discriminator
- Receives the laser beam that inverts the atomic population in its rubidium vapor cell
- Receives the RF signal that stimulates the atomic transition
- Produces the microwave signal at the hyperfine atomic transition frequency.
- Includes cavity heaters and magnetic shields.

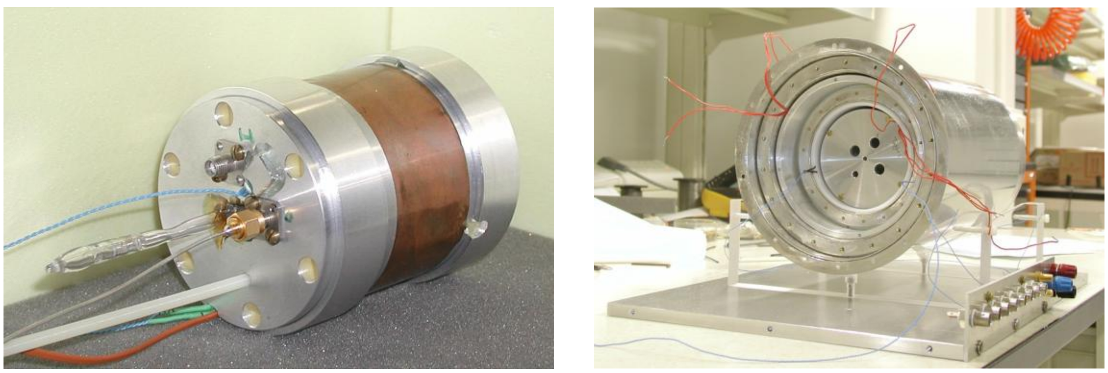


Figure 2. Microwave cavity assembly and with the thermal and magnetic shields mounted.

Optical Package Unit

- Creates the laser pulse
- Produces a high-stability, narrow-linewidth laser beam, with the correct wavelength and power for pumping the Physical Unit
- Receives the RF signal for modulating the laser beam.

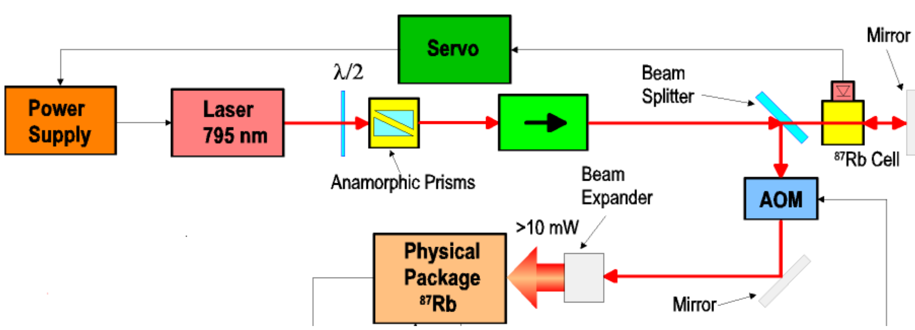
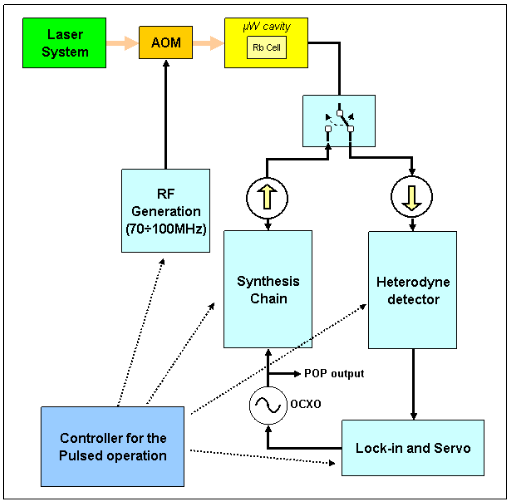


Figure 3. Optical Unit architecture.

Electronic Package Unit

- Provides the clock output signal (two outputs) to the payload
- Locks the USO to the atomic reference using the POP technique
- Processes the RF signals for atomic transition interrogation and detection
- Creates the RF signals for the AOM driving
- Achieves thermal stabilization of the POP clock critical functions (microwave cavity and electronics) and provides the QMF current source.
- Manages the POP phases with correct timing
- Provides the electrical power, telecommand, and telemetry interfaces to the spacecraft platform.
- Power supplies all POP Units with regulated lines.



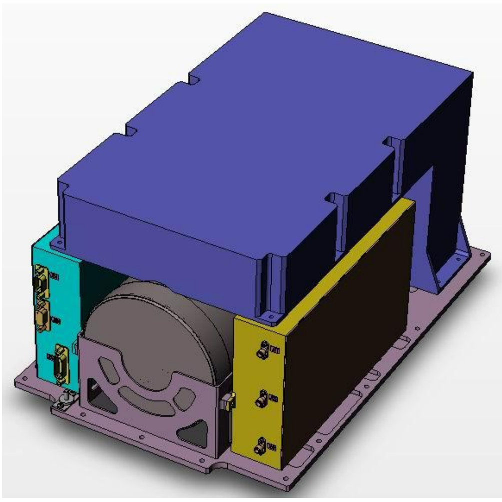


Figure 4. RF Signal Processing Blocks on the left and POP clock layout on the right (Optical Unit in blue, Physics Unit in gray, Electronic Unit in green and yellow).

TEST OF THE POP CLOCK DEMONSTRATOR

INRiM has realized and tested the demonstrator of the POP clock, to verify the capabilities of the POP technique at clock level.

This demonstrator is composed of a prototype of the Physics Package (RF cavity containing the ^{87}Rb vapor cell), which interfaces a devoted electronic test setup (with very low-phase noise) and an optical bench.

This demonstrator is representative of the whole POP clock even in terms of performance achievable by each Unit, according to the outcome of the feasibility study. It has allowed carrying out tests of stability in order to demonstrate the validity of the POP technique.

The following activities have been carried out in the frame of the test campaign:

a) Light shift measurement
b) Cavity pulling measurement
c) Ramsey fringes observation
d) Frequency stability measurement.

LIGHT SHIFT MEASUREMENT

The measurement of the relative frequency of a quartz oscillator locked to the hyperfine transition versus the laser intensity is reported in Figure5, the so-called AM-FM (amplitude modulation-to-frequency modulation) or off-resonance light shift.

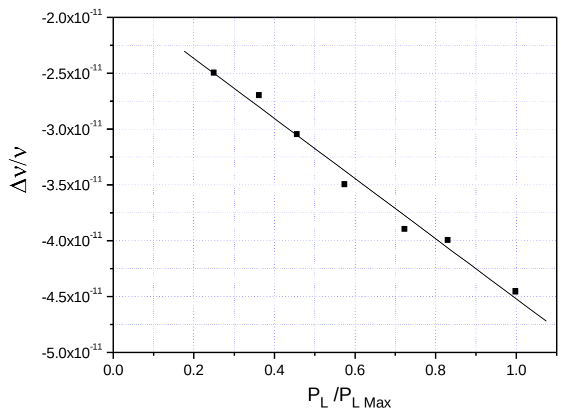


Figure 5. POP maser frequency vs. laser power (AM-FM conversion).

The slope of this straight line gives the amount of laser amplitude instabilities that are transferred to the clock frequency:

$$\left(\frac{\Delta\nu}{\nu}\right)\Big/\left(\frac{\Delta P_L}{P_L}\right)\approx 3\times 10^{-13}/\%$$

which should be compared with the value of few units of 10^{-11}/%, typical of traditional laser-pumped vapor cell clocks.

At the point of maximum laser power, the frequency modulation to frequency modulation (FM-FM or resonant light shift) has also been characterized, obtaining:

$$\left(\frac{\Delta\nu}{\nu}\right)\Big/\Delta\nu_L < 1\times 10^{-13}/\mathrm{MHz}$$

which is at least three orders of magnitude better than traditional continuous vapor cell clocks.

Definitely, these results show that the pulsed regime allows one to reduce in a significant way the light shift effect and this turns out in a major benefit for the medium-to-long term frequency stability of the clock, as will be shown later.

CAVITY PULLING MEASUREMENT

The following figure reports the dependence of the POP maser frequency vs. θ (Microwave Pulse area) for three different cavity detunings. This behavior is fully explained through the cavity pulling effect; in particular, the existence of a zero cavity pulling value at $\theta = \theta_0 = 1.05\ \pi/2$ is easily observed, as predicted by the theory. In practice, this effect is very useful for the fine tuning of the cavity, which can be achieved looking for the minimum slope of the curve.

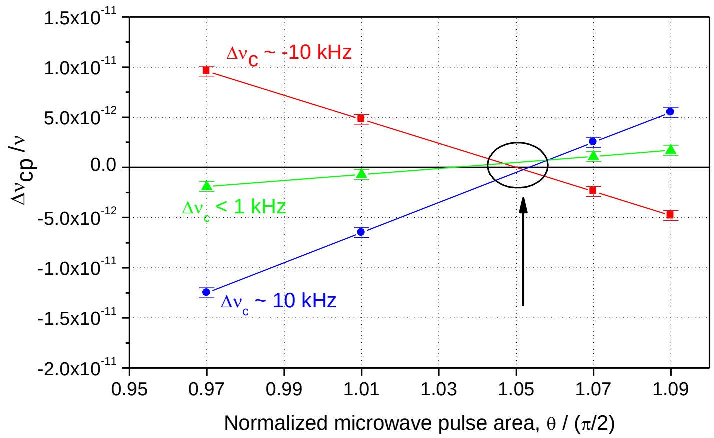


Figure 6. POP maser frequency versus θ. Inside the area of the ellipse indicated by the arrow, the zero cavity pulling point is highlighted.

RAMSEY FRINGES

Figure 7 shows the maser signal as observed in the frequency domain obtained by sweeping the frequency of the two consecutive microwave pulses around the clock frequency.

A quartz oscillator is frequency locked to this signal through a square-wave modulation.

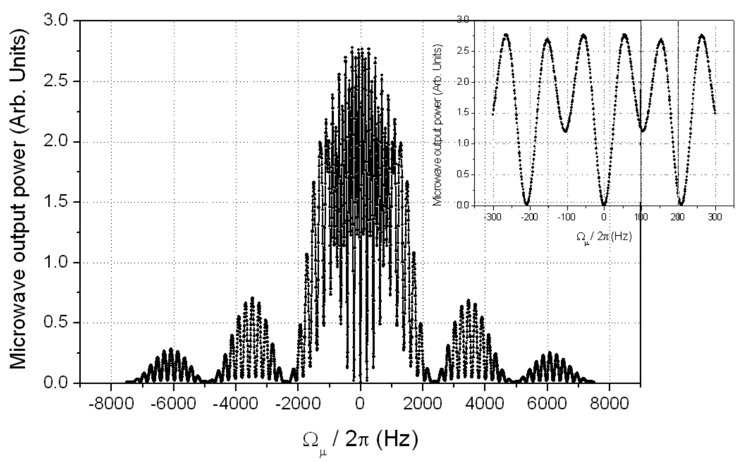


Figure 7. Full pattern of Ramsey fringes; in the insert the central fringe is shown.

The central fringe is about 50 Hz, according to the formula:

$$\Delta\nu = 1/(4 \cdot T)$$

where T is the period between the two Ramsey interrogation microwave pulses.

FREQUENCY STABILITY

The following figure shows the POP maser clock frequency stability, obtained with a quartz servo loop having a time constant of the order of 100 ms. The applied microwave has been modulated with a square wave signal with a modulation depth of ±10 Hz.

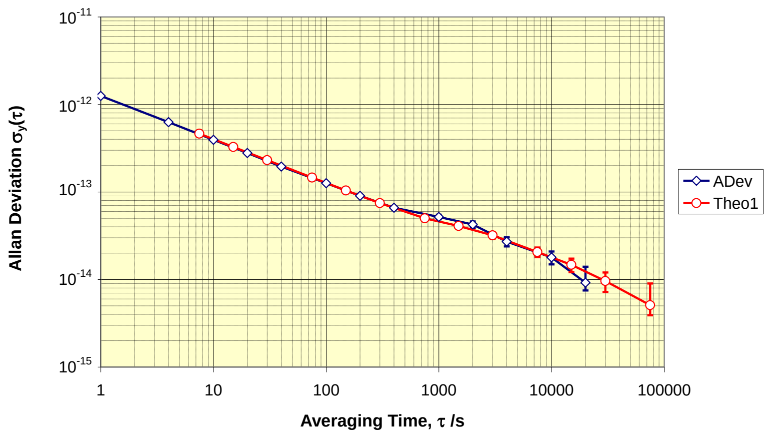


Figure 8. Frequency stability of the POP clock.

The short-term stability expressed as overlapping Allan (black diamond) and Thêo (red circle) deviations is 1.2×10^{-12} at 1 s, and it is limited by the Dick effect (7×10^{-13}) and by the thermal noise (1×10^{-12}).

A frequency drift of 8×10^{-14} per day has been removed from the raw data, and the resulting stability is $5x10^{-15}$ @ 100000 s.

In the medium- and long-term, no flicker floor has been observed until 10^5 s, highlighting the absence of any noise contribution coming from either the laser or the electronics.

Definitely, the POP maser stability is characterized by white frequency noise up to the region of 10^{-15} after drift removal.

This is a proof of the fact that, in the present structure, the main source of instabilities related to the temperature and to the laser are under control. This result is among the best achieved with state-of-the-art of secondary frequency standards based on rubidium or cesium vapor cells.

In addition, the stability characteristics of the current POP maser are very close to the requirement for the GALILEO PHM.

The following table compares GALILEO PHM requirement and POP test results.

Table 1. Comparison between GALILEO PHM ADEV requirements and POP demonstrator test results.

τ [sec]	**STABILITY $\sigma_Y(\tau)$**	
	GALILEO SPECIFICATIONS	**POP RESULTS**
1	1×10^{-12}	$\sim 1.3 \times 10^{-12}$
10	3.2×10^{-13}	$\sim 4 \times 10^{-13}$
100	1×10^{-13}	$\sim 1.3 \times 10^{-13}$
1000	3.2×10^{-14}	$\sim 4 \times 10^{-14}$
10000	1×10^{-14}	$\sim 2 \times 10^{-14}$
100000	-	$\sim 5 \times 10^{-15}$

PRESENT DESIGN BUDGET

This section presents the status of the present design, as far as mass and power consumption are concerned, and the possible improvements concerning the mass are explained.

MASS

Efforts aimed at reducing the mass have been concentrated with particular attention to the Physics Package that in the early assessments was responsible for more than 50% of the overall mass. Nevertheless, the Optical Package has also been considered, for mass reduction, with good results (1 kg of mass reduction is expected starting from the present structure, without compromising the stability required by the optical elements).

The resulting optimized mass is shown in the following table in the case of the lighter Physics Package (the mass reduction of the Optical Package has been already included).

Table 2. Optimized mass expected after Optical and Physics Packages' optimization.

Module	**Nominal mass [kg]**	**Design Maturity**	**Mass Uncertainties**	**Expected Mass [kg]**
Physics Package	3	calculated	10%	3.3
Electronics Package	2.5	estimated	20%	3
Optical Package	3	estimated	20%	3.6
Unit Baseplate	0.75	estimated	20%	0.9
TOTAL	9.3			10.8

It is worth noting that further mass reduction (0.5÷1 kg), would be possible by replacing the microwave cavity present design with a new design based on the use of a dielectric loaded type.

According to preliminary evaluations, the use of high dielectric constant materials (quartz) would halve the size of the microwave cavity, and even more importantly would reduce the dimensions of the magnetic and thermal shields around it.

POWER CONSUMPTION

The same classification concerning the maturity of the design, already adopted for the mass assessment, has been adopted to assess the power consumption. Considering the preliminary design phase for each unit, the 'Estimation' category has been selected with a correlated 10% of uncertainty.

In the table, the instrument power budget is reported.

Table 3. Power budget.

Module	Sub-Module	Nominal Power [W]	Design Maturity	Uncertainties	Expected Power [W]
PHYSICS PACKAGE		0	estimated	0	0
	RF signal processing	14	estimated	10%	15.4
ELECTRONICS PACKAGE	Physical controls	14.7	estimated	10%	16.1
	Power Supply Unit	5.4	estimated	10%	5.94
OPTICAL PACKAGE		7.1	estimated	10%	7.81
TOTAL		41.2			45.25

Almost 50 % of the overall consumption is due to the thermal stabilisation of the microwave cavity and RF critical parts. A detailed activity shall be done in order to find the best compromise between the isolation of the thermal regulated parts and the power needed to heat them. A correct dimensioning with respect to the Nominal operating temperature range will be necessary once the instrument layout is defined.

CRITICAL AREAS AND TECHNOLOGICAL ASPECTS

In the frame of the Feasibility Study, a technological analysis has been performed in order to highlight any issue should be anticipated in terms of development.

Only a few points have proved to be critical, thanks to the synergy that it is possible to put in place with analogous products already managed by Selex Galileo and its partners (e.g., PHM, laser sources for space applications, RF equipment).

The following points have been found out to be critical and requiring dedicated activity as risk mitigation actions:

1. Industrialization of the Rb-cell filling process in order to guarantee repeatability and improve yield
2. Optimization of the ACT (Automatic Cavity Tuning)
3. Qualification of the Laser Module (i.e. diode + sensors + cooler).

DESIGN AND DEVELOPMENT PLAN

The road map in order to achieve a qualified clock passes through the manufacturing of an Engineering Model (EM) aimed at full validation of the assumptions and preliminary design already performed in the frame of the Feasibility Study. Considering the long time required for the evaluation end qualification of parts for Space application, an Engineering Breadboard (EBB) of the Optical Unit shall be manufactured as soon as possible.

Three Phases can be defined starting from the present status:

- PHASE 1: Optical Unit EBB (15 months)
- PHASE 2: POP Clock EM (18 months)
- PHASE 3: POP Clock EQM and its qualification (TBD)

The reaching of the PHASE 2 is considered a priority for all the parties within the expected timelines.

CONCLUSIONS

It is straightforward to conclude that the POP clock is an extremely competitive clock which, for the expected characteristic and the relative simplicity, can play an important role in the scenario market of the time references for space applications. On the basis of the feasibility study outcome, it is expected that an EM of the POP clock, with the characteristics reported in the previous paragraph's table, can be realized in a short time.

As shown in the following diagram, the POP clock is a good compromise between the excellent performance achieved by the PHM and the simplicity of a typically less performing Rb cell frequency standard.

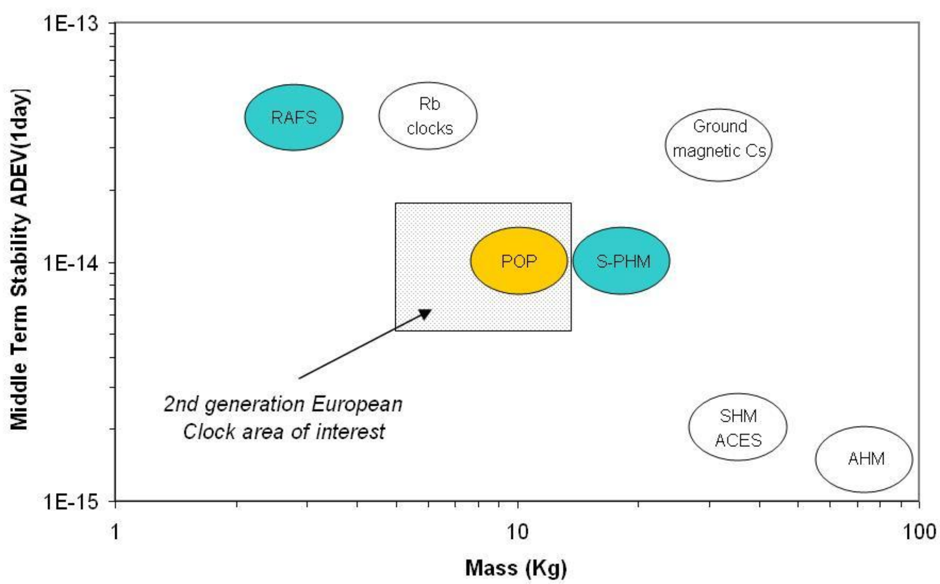


Figure 9. Area of interest for the POP clock.

Moreover, a design approach aimed at cost reduction would make it suitable for military applications, where a precise and user friendly clock is needed.

REFERENCES

[1] A. Godone, S. Micalizio, F. Levi, and C. Colosso, 2006, *"Physics characterization and frequency stability of the pulsed rubidium maser,"* **Physical Review A 74,** 043401.

[2] S. Micalizio, A. Godone, F. Levi, and C. Colosso, 2009, *"Pulsed optically pumped 87Rb vapor cell frequency standard: A multilevel approach,"* **Physical Review A 79,** 013403.