Horloges atomiques - Etat de l'art et enjeux

Atomic clocks - State of the art and challenges

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Mots clés (en français et en anglais) : Horloges atomiques, Références de temps et de fréquence
Atomic clocks, Time & Frequency standards

Présentation en session plénière / Plenary session communication

Résumé / Abstract

Depuis leur invention au milieu du XXe siècle, les horloges atomiques n'ont cessé de s'améliorer pour atteindre aujourd'hui des niveaux exceptionnels de stabilité et d'exactitude dans la gamme des 10-18. Même si ce niveau de précision n'est pas encore nécessaire pour le positionnement et la navigation par satellite, le fonctionnement même des GNSS repose sur un ensemble d'horloges atomiques, embarquées dans les satellites ou fonctionnant au sol pour la construction de l'échelle de temps du système de positionnement considéré. L'exposé présentera un état de l'art des horloges atomiques fonctionnant dans les domaines micro-onde et optique, en décrivant de nouveaux types d'horloges atomiques en train d'émerger dans le monde industriel, dans le but d'améliorer les performances en fréquence ou la miniaturisation des dispositifs. Avec l'amélioration de la précision des horloges atomiques se pose la question de la synchronisation d'horloges distantes, qui sera aussi abordée au cours de l'exposé.

Since their invention in the mid-twentieth century, atomic clocks have continuously improved to reach outstanding levels of stability and accuracy in the 10-18 range. Even if this level of precision is not yet necessary for the localization and the navigation by satellite, the GNSS operation rests on a set of atomic clocks, embarked in the satellites or working on the ground for the construction of considered positioning system time scale. The presentation will give the state of the art of atomic clocks operating in the microwave and optical domains, describing new types of atomic clocks emerging in the industrial world, with the aim of improving the frequency performance or the miniaturization of the devices. With the improvement of the atomic clock precision, there is the question of the synchronization of distant clocks, which will be also addressed during the presentation.

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Atomic clocks State of the art and challenges

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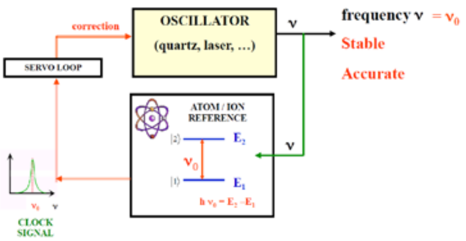
SYRTE – Systèmes de Référence Temps-Espace

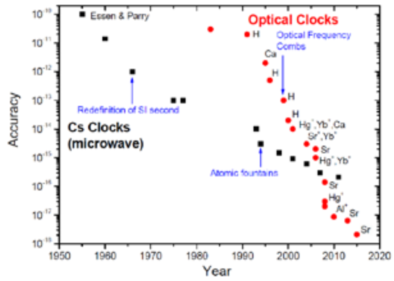
Atomic clocks - State of the art and challenges

- Introduction
- Clocks for space segment
- Clocks for ground segment
- Conclusions

Basic principle of atomic clocks / atomic frequency standards



Improvement of clock frequency accuracy



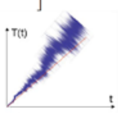
Frequency / Phase / Time errors

$$Signal = A.\cos(2\pi.\upsilon(t).t) = A.\cos(\varphi(t)) = A.\cos(2\pi.\upsilon_0.T(t))$$

Frequency : $\upsilon(t) = \upsilon_0 \times (1 + \varepsilon + y(t))$

Phase : $\varphi(t) = 2\pi \int^t_0 \upsilon(t')dt' = 2\pi.\upsilon_0 \left[(1+\varepsilon)t + \int^t_0 y(t')dt'\right]$

Time : $T(t) = \frac{\varphi(t)}{2\pi.\upsilon_0} = \frac{\varphi(t)}{2\pi}.\frac{1}{\upsilon_0} = (1+\varepsilon)t + x(t)$



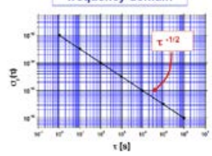
with $y(t) = \frac{dx(t)}{dt} \Leftrightarrow x(t) = \int^t_0 y(t')dt'$

Frequency / Time errors

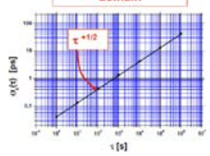
$$y(t) = \frac{dx(t)}{dt} \Leftrightarrow x(t) = \int^t_0 y(t')dt'$$

Case of white frequency noise:

Deviation in frequency domain



Deviation in time domain

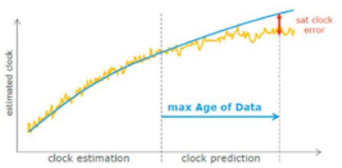


10^{-13} relative frequency error = 10 ns time error @ 1 day = 3 m position error

Clocks for space segment - Requirements

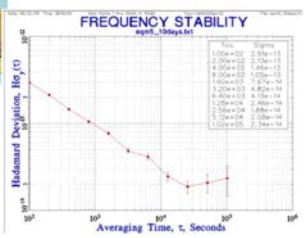
→ Requirements for clocks on-board Galileo Satellites:

- < few ns at max Age of Data = 100 min (future: extended to 1 - several days)
- Predictable frequency drift
- Robust and reliable (12+ years, radiation…)

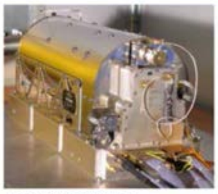


From P. Waller, ESA

RAFS – Rubidium clocks for GALILEO



PHM – Passive H-Maser for GALILEO



18 kg, 28 L, $7\cdot 10^{-13}$ @ 1 s

Application: GALILEO

1ns (10^{-14}) time error

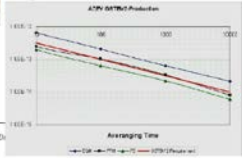
↓

30 cm position error

Goal: 10^{-14} stability @ 10'000 s (keeping 1 ns over one orbit)

↓

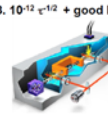
10^{-12} @ 1 s



Envisaged atomic clocks for next generations

→ **Cesium beam clocks (with optical pumping)**

~ 3. $10^{-12}\ \tau^{-1/2}$ + good long term stability



THALES

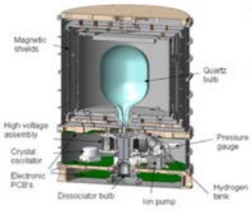
→ **Upgraded Rubidium cell clocks: spectral lamps replaced by lasers (LTF, Switzerland) or pulsed operation (INRIM, Italy)**

~ 1. $10^{-13}\ \tau^{-1/2}$ + long term drifts (collisions with buffer gas)

→ **Ion clocks in microwave domain**

~ 1. $10^{-13}\ \tau^{-1/2}$ + good long term stability

Very high stability space atomic clocks
Active hydrogen maser (ACES mission on board ISS)



Volume: 390x390x590 mm³
Mass: 42 kg

SHM role in ACES
- ACES flywheel oscillator
- PHARAO characterization

Technical challenges
- Low mass, volume, and power consumption
- Full performances:
  - $1.5\cdot 10^{-13}$ @ 1 s
  - $1.5\cdot 10^{-15}$ @ 10^{4} s

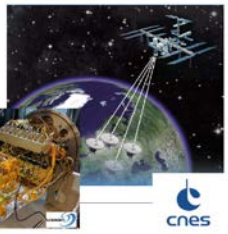
Design solution
- Full size Al cavity
- Automatic Cavity Tuning System (ACT)

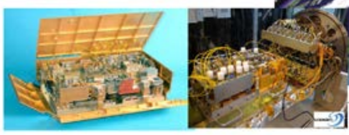
SpectraTime

Very high stability space atomic clocks
Cold atom clock PHARAO (ACES mission on board ISS)

$\sigma_y(\tau) < 10^{-13}\ \tau^{-1/2}$

Inexactitude $\delta\varepsilon$ au niveau de 10^{-16}





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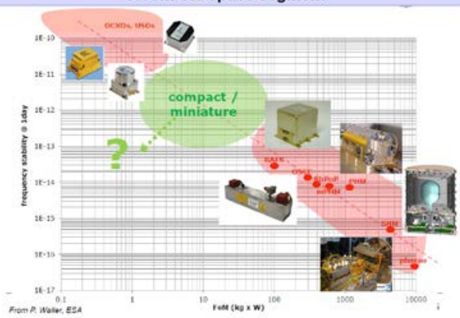
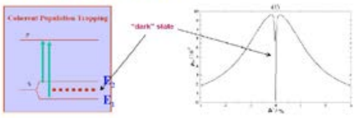
Clocks for space segment



From P. Waller, ESA

An efficient way for miniaturization

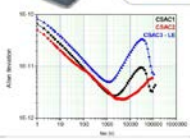
→**CPT – Coherent population trapping**



Potential advantages of using CPT:
- No microwave cavity
- Reduced light-shift

Miniaturized CPT clocks

16 cm3, 35 g
120 mW
Stability: < 2 10^{-10} @ 1s ; < 10^{-11} @ 1 jour
Accuracy: 5 10^{-11}



+ Current industrial development in France (Syrlinks)

Clocks for ground segment

Galileo System Time (GST)

Need to have a stable ground atomic time scale to:

- **Monitor et resynchronize space clocks with a time scale close to UTC (difference between GST and UTC < 50 ns, 95% of time)**

  Remark: difference between time scale at ground user level and GST < 30 ns, 95 % of time

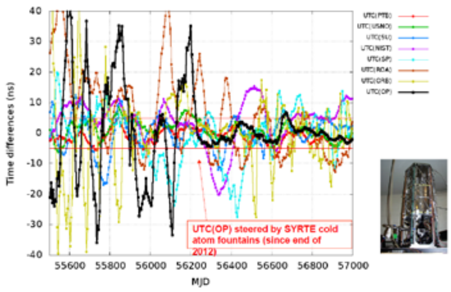
- **Ensure interoperability between GALILEO and GPS (difference between time scales < 20 ns, 95% of time)**

→ **Realization of GST in 2 Precise Timing Facilities (Germany, Italy) equiped with an ensemble of active H-masers and commercial Cs beam clocks.**

→ **Link between GST and European UTC(k) realized in T/F metrology institutes to ensure accuracy and provide a long term steering of GST (contributions of cold atom fountains in France and Germany)**

Improvements of UTC(k)

UTC-UTC(k) comparisons



Industrial cold atom clock: Mu-Clock

→ Objective: Replacement of H-maser + Cs beam clock

▸ **Frequency stability**

1 s	≤ 3.0 10[illegible]
10 s	≤ 9.5 10[illegible]
100 s	≤ 3.0 10[illegible]
1000 s	≤ 9.5 10[illegible]
10000 s	≤ 3.0 10[illegible]
1 day	≤ 2.0 10[illegible]
Flicker floor	≤ 2.0 10[illegible] (@ 10 days)

▸ **Power**

Operating power	200 W
Peak power	250 W

▸ **Physical characteristics**

Dimensions

Height	120 cm
Width	51 cm
Depth	40 cm
Weight	75 kg

Conclusions and future prospects

Today: only one European provider for GALILEO space clocks (Spectratime)

→Need to maintain and reinforce the developement in laboratories and in industry of new kind of clocks for space and ground segment: upgraded cell clocks, cold atoms free falling or trapped on a chip, Coherent Population Trapping, ion clocks, …

→Explore the possibility to install ultra stable clocks in geostationnary satellites (direct calibration in space of the constellation clocks, realization of a better atomic time scale with a lower uncertainty in the relativistic gravitational correction)

Importance of ultra stable frequency standards in T/F institutes (calibration of UTC, Galileo System Time)

→Calibration with cold atom fountains provides atomic time scales with high accuracy / high long term stability (SYRTE = 40 % of the calibration over years)

→Growing role of optical clocks in the construction of better atomic time scales (Stability: few 10^{-16} @ 1s, Accuracy: 10^{-18} – 10^{-17})

→With the improvement of clocks, need of upgraded T/F links (in microwave and/or optical range) for space and ground clock synchronisation

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