Journées Scientifiques URSI - France

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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

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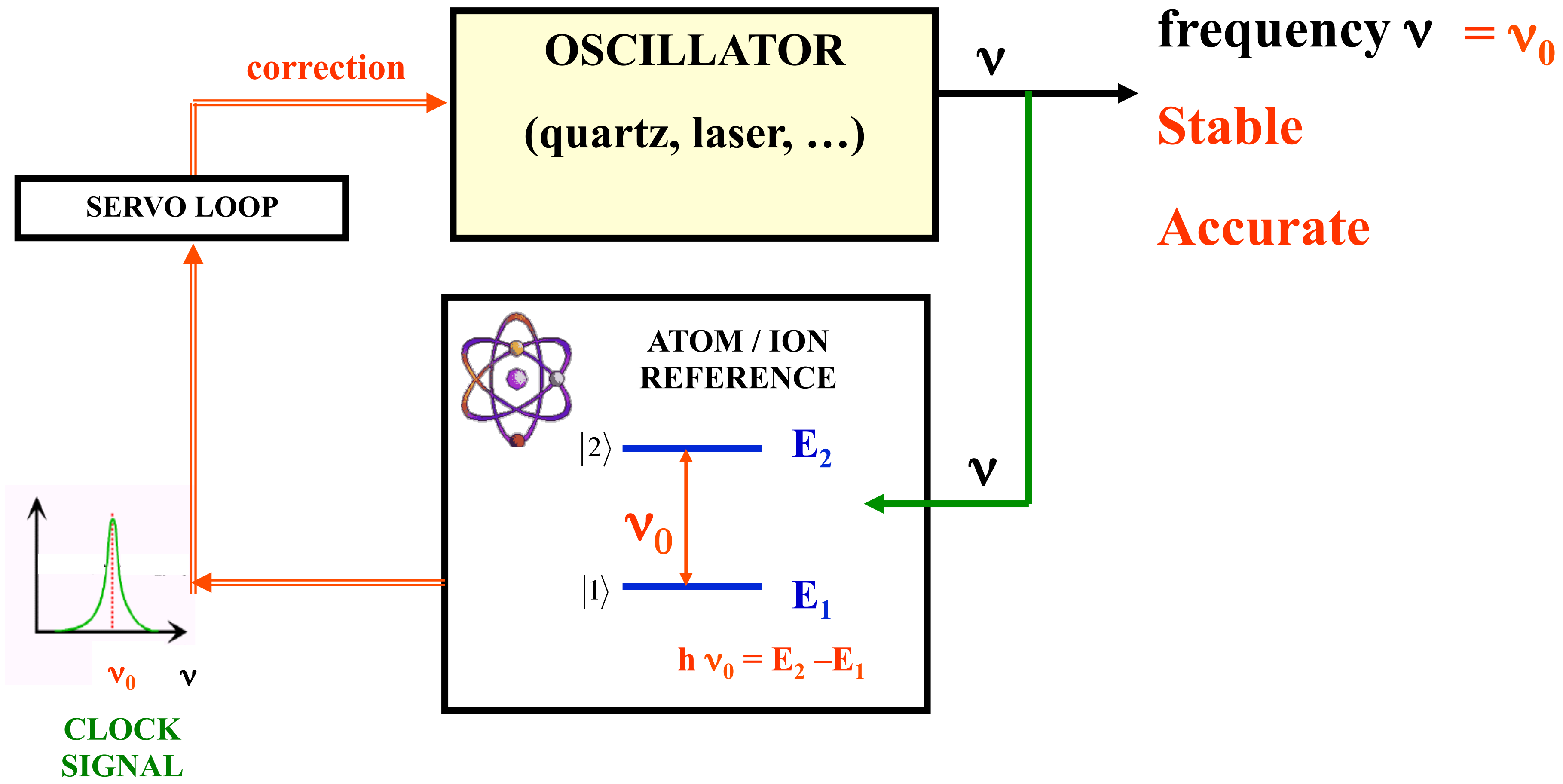
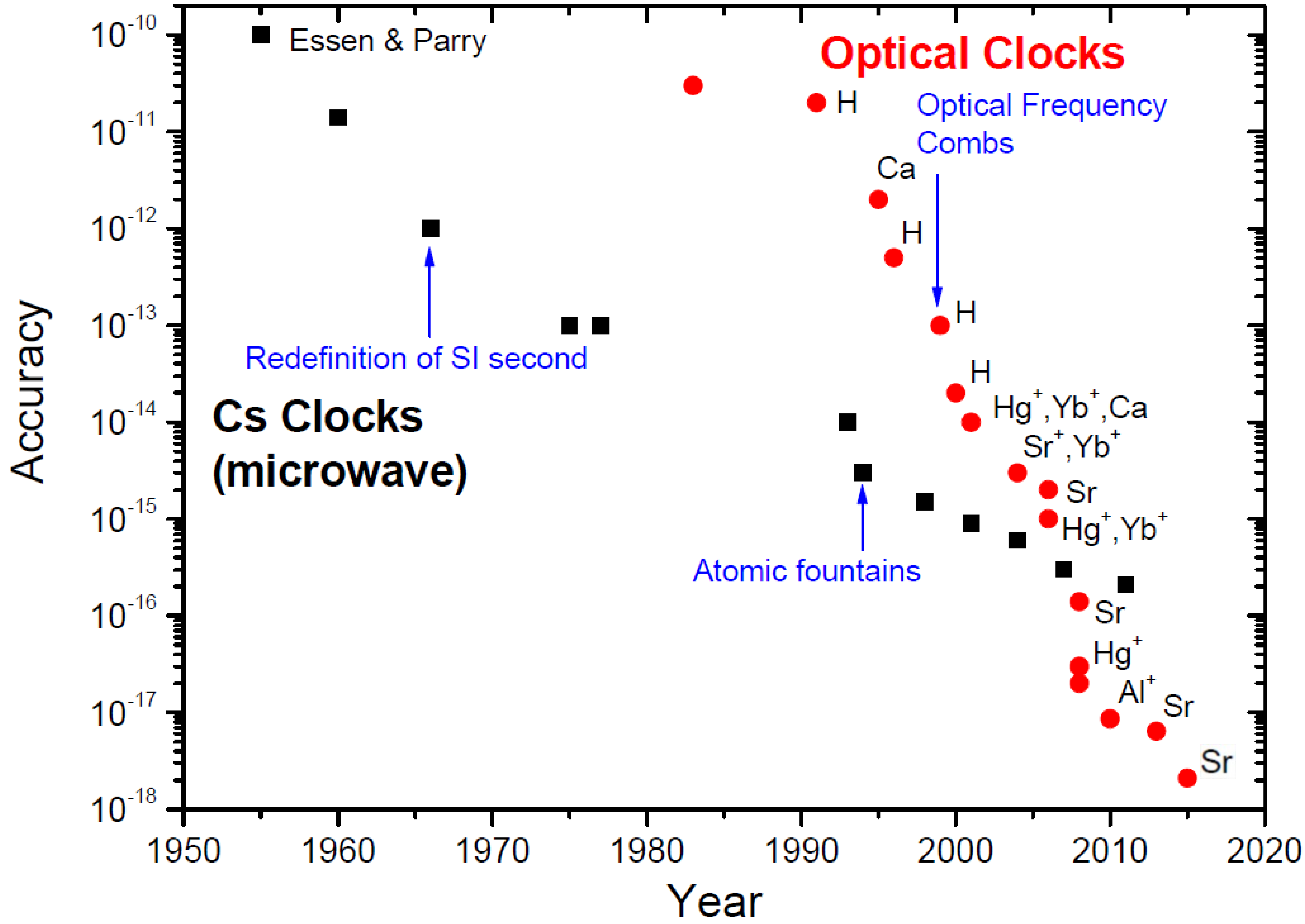
Basic principle of atomic clocks / atomic frequency standards



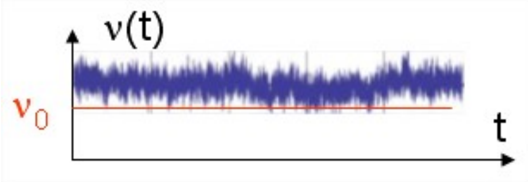
Improvement of clock frequency accuracy



Frequency / Phase / Time errors

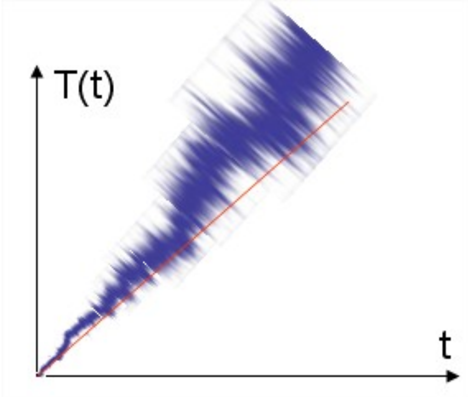
$$Signal = A.\cos\left(2\pi.\upsilon(t).t\right) = A.\cos\left(\varphi(t)\right) = A.\cos\left(2\pi.\upsilon_0.T(t)\right)$$

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



Phase : $\varphi(t) = 2\pi \int_0^t \upsilon(t')dt' = 2\pi.\nu_0 \left[\left(1 + \varepsilon\right).t + \int_0^t y(t')dt' \right]$

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



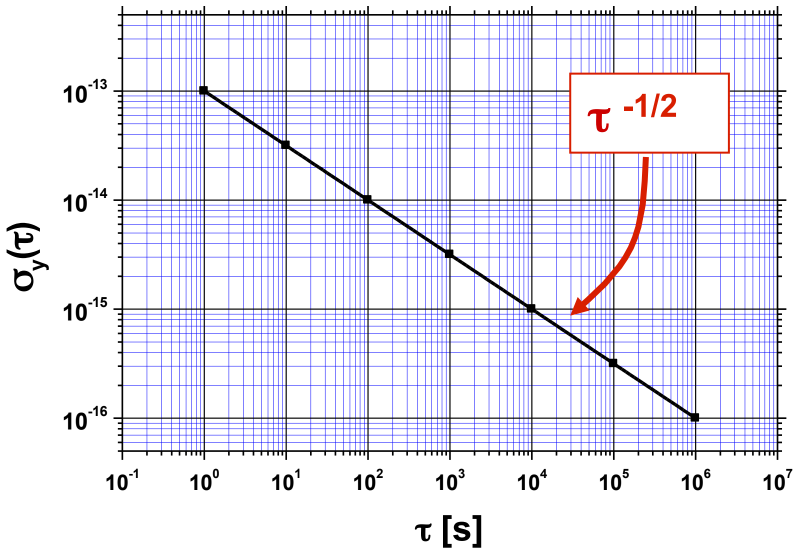
with $y(t) = \dfrac{dx(t)}{dt} \Leftrightarrow x(t) = \int_0^t y(t')dt'$

Frequency / Time errors

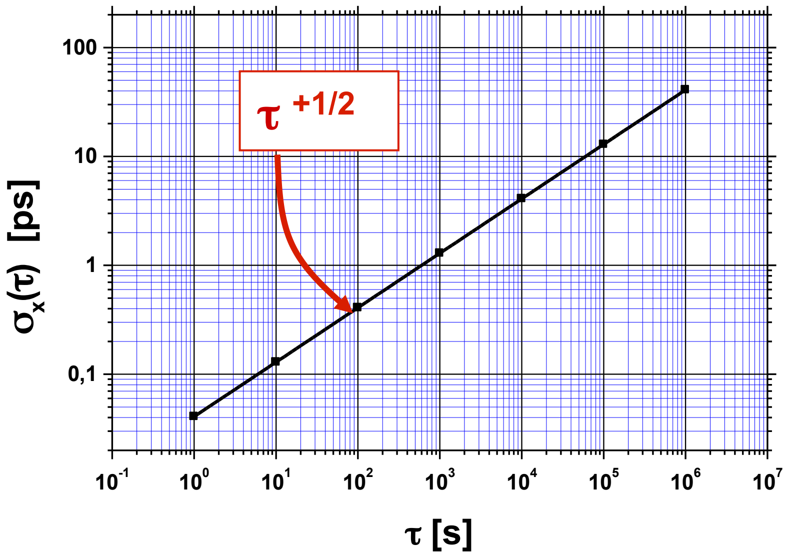
$$y(t) = \frac{dx(t)}{dt} \Leftrightarrow x(t) = \int_0^t y(t')dt'$$

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

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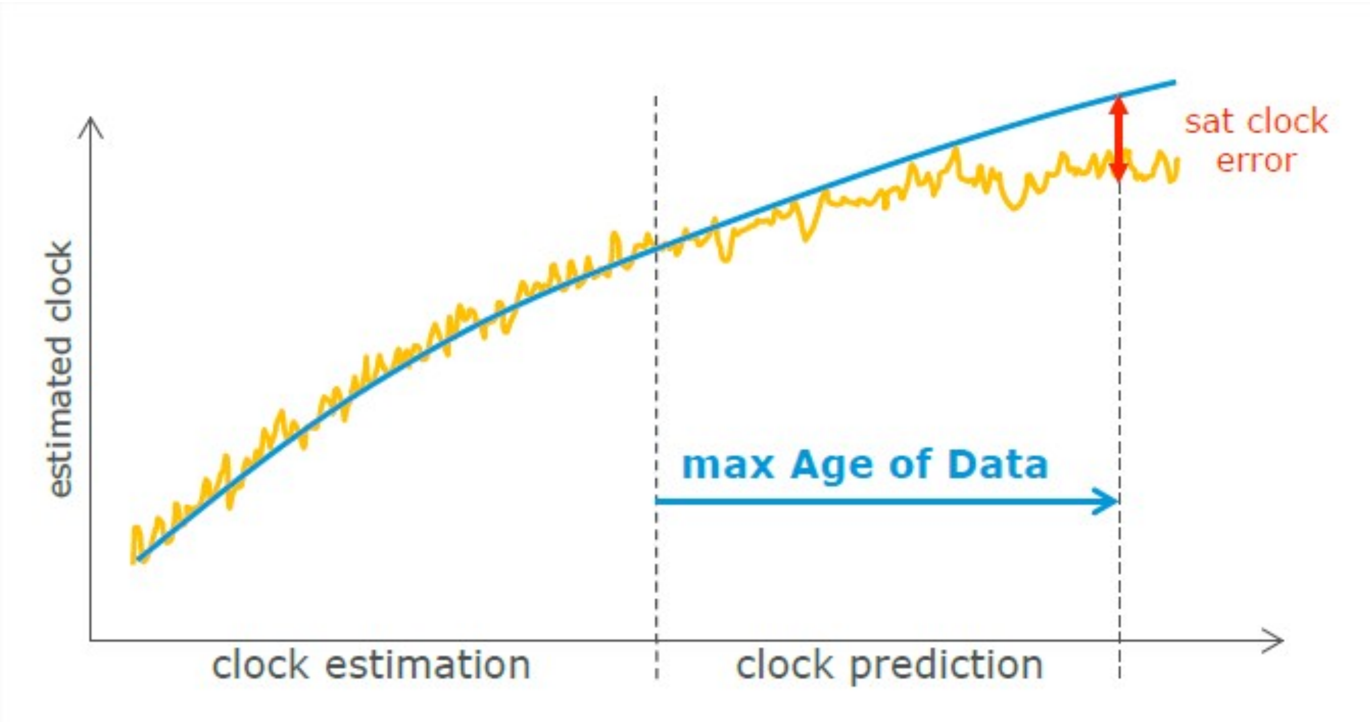
Clocks for space segment - Requirements

→ **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

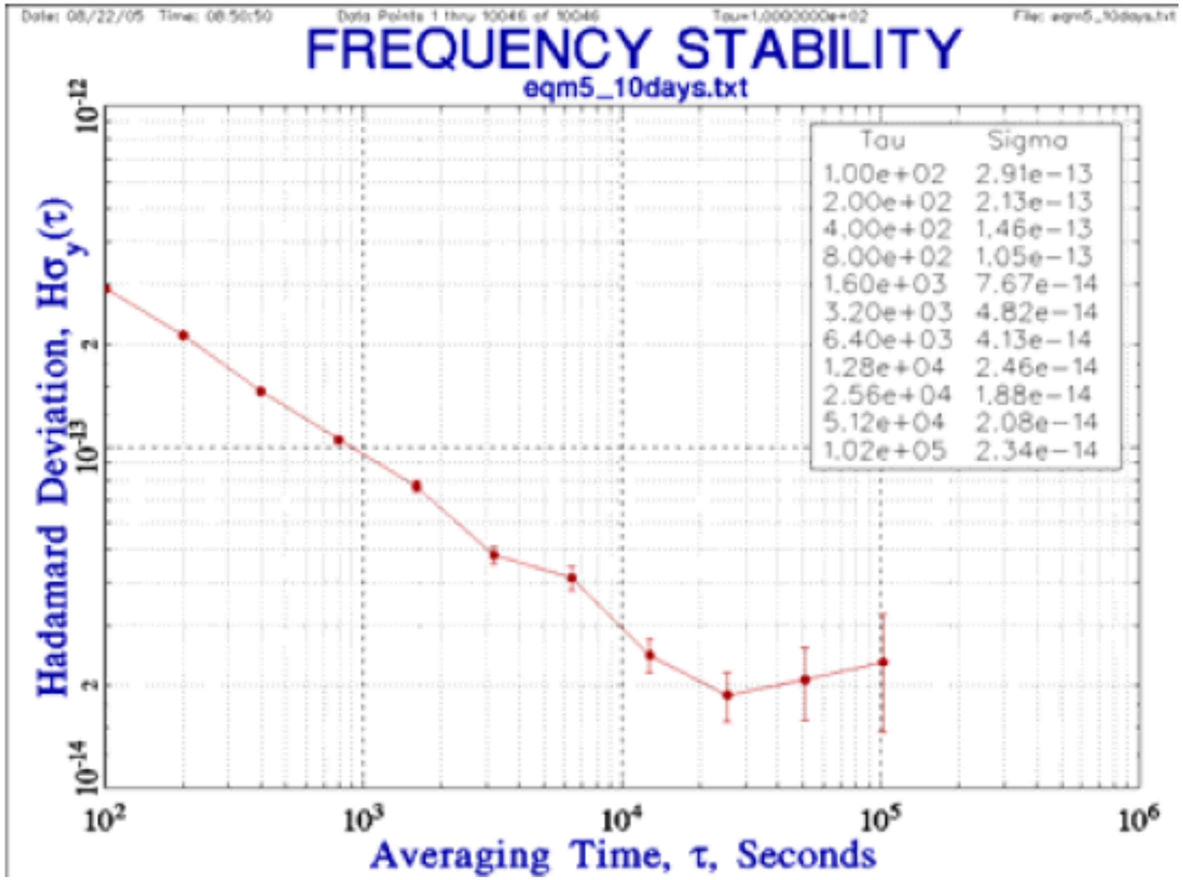
•Robust and reliable (12+ years, radiation…)



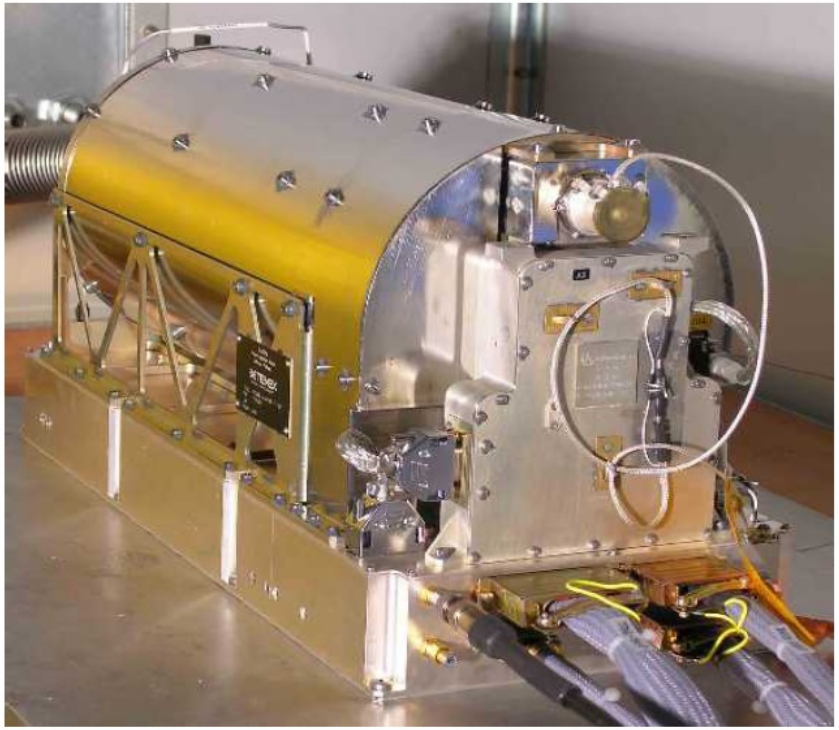
From P. Waller, ESA

RAFS – Rubidium clocks for GALILEO

SPECTRATIME
iPrecision Timing Solutions™



PHM – Passive H-Maser for GALILEO



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

Application: GALILEO

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

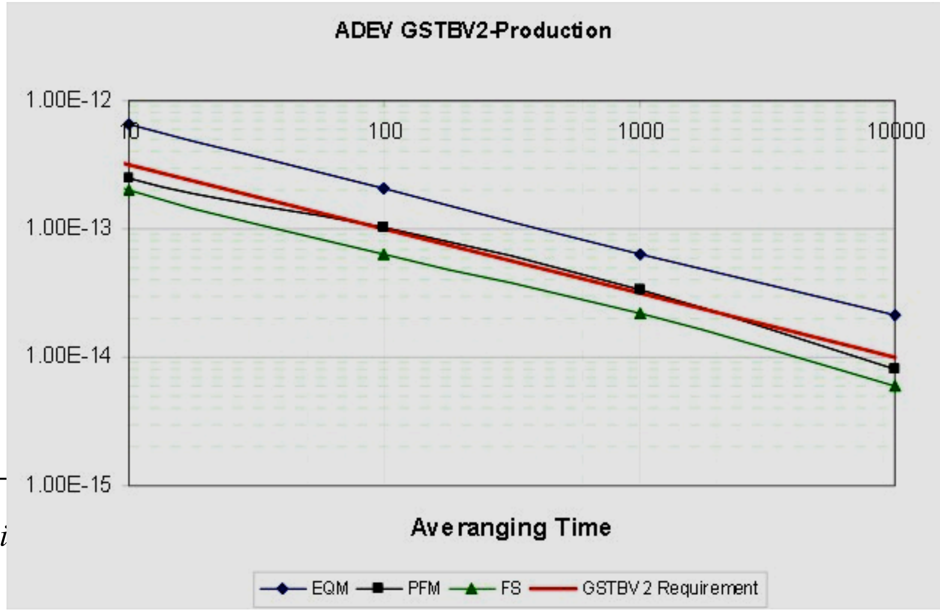
↓

30 cm position error

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

↓

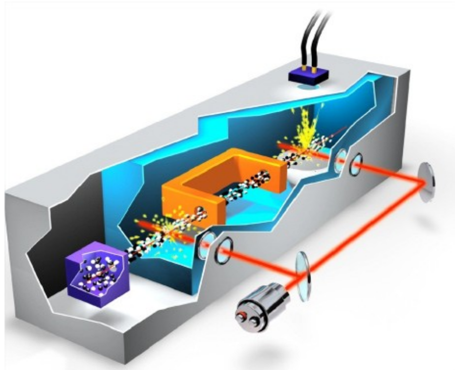
10^{-12} @ 1 s



Envisaged atomic clocks for next generations

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

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



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

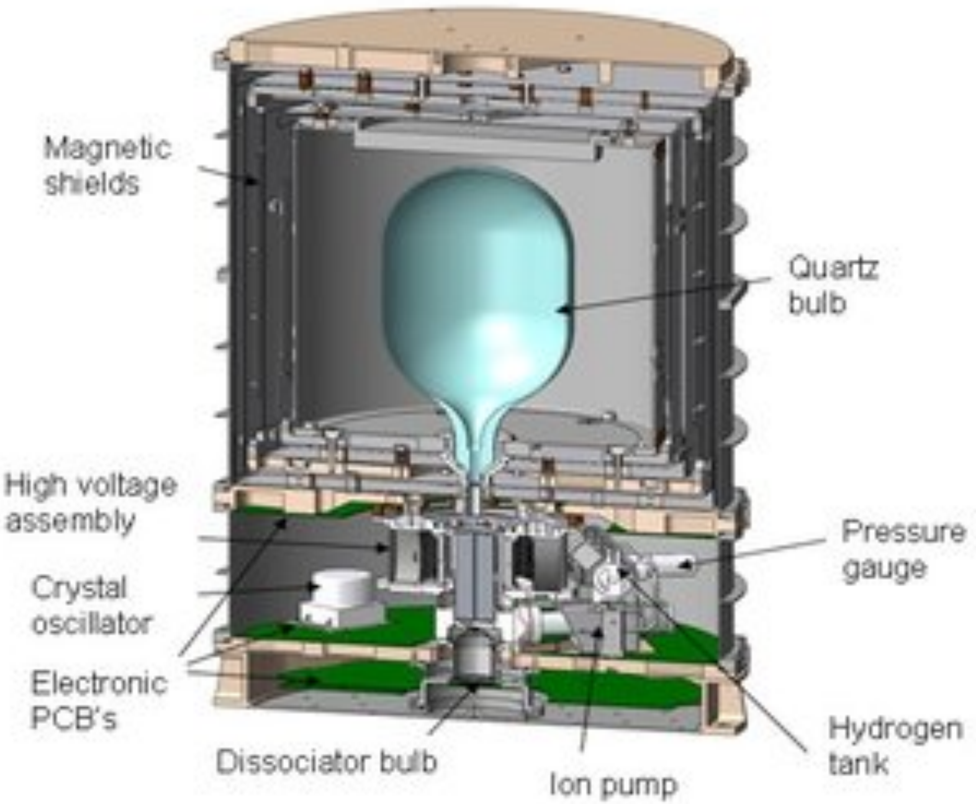
~ 1. 10^{-13} $\tau^{-1/2}$ + long term drifts (collisions with buffer gas)

→ **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 mm^3
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

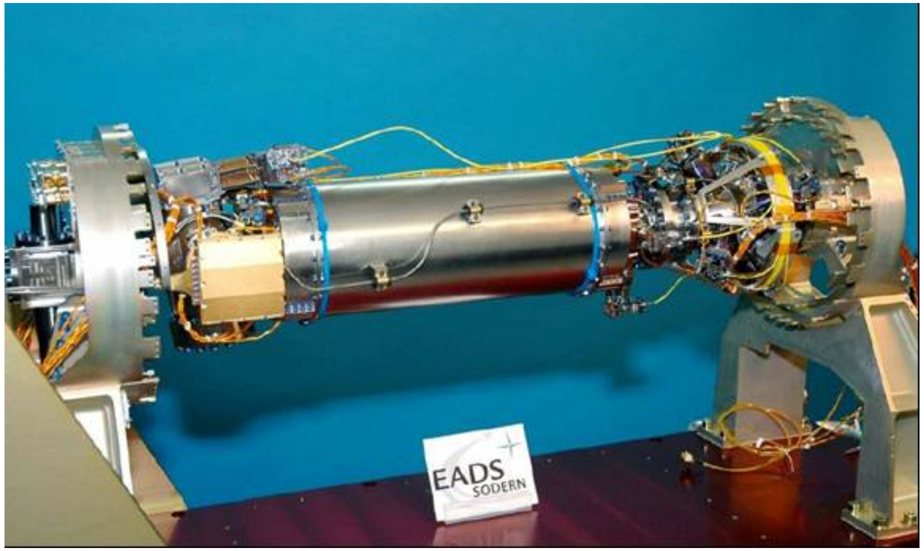
Design solution

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

SpectraTime iPrecision Timing Solutions™

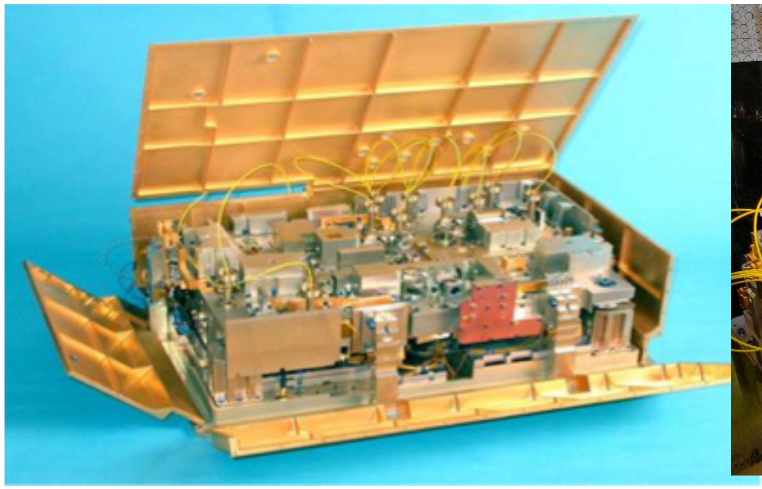
Very high stability space atomic clocks

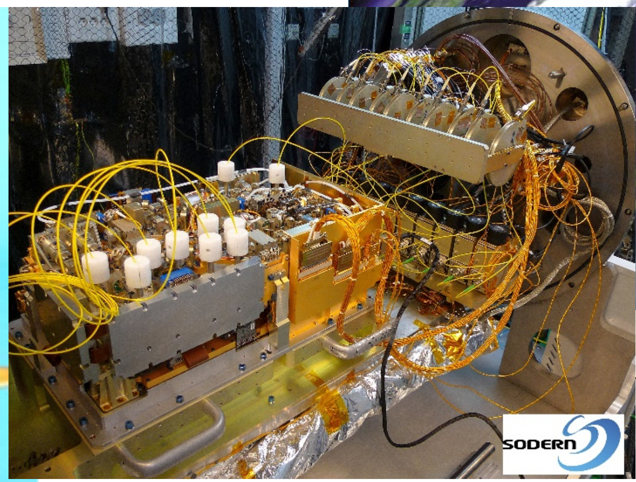
Cold atom clock PHARAO (ACES mission on board ISS)



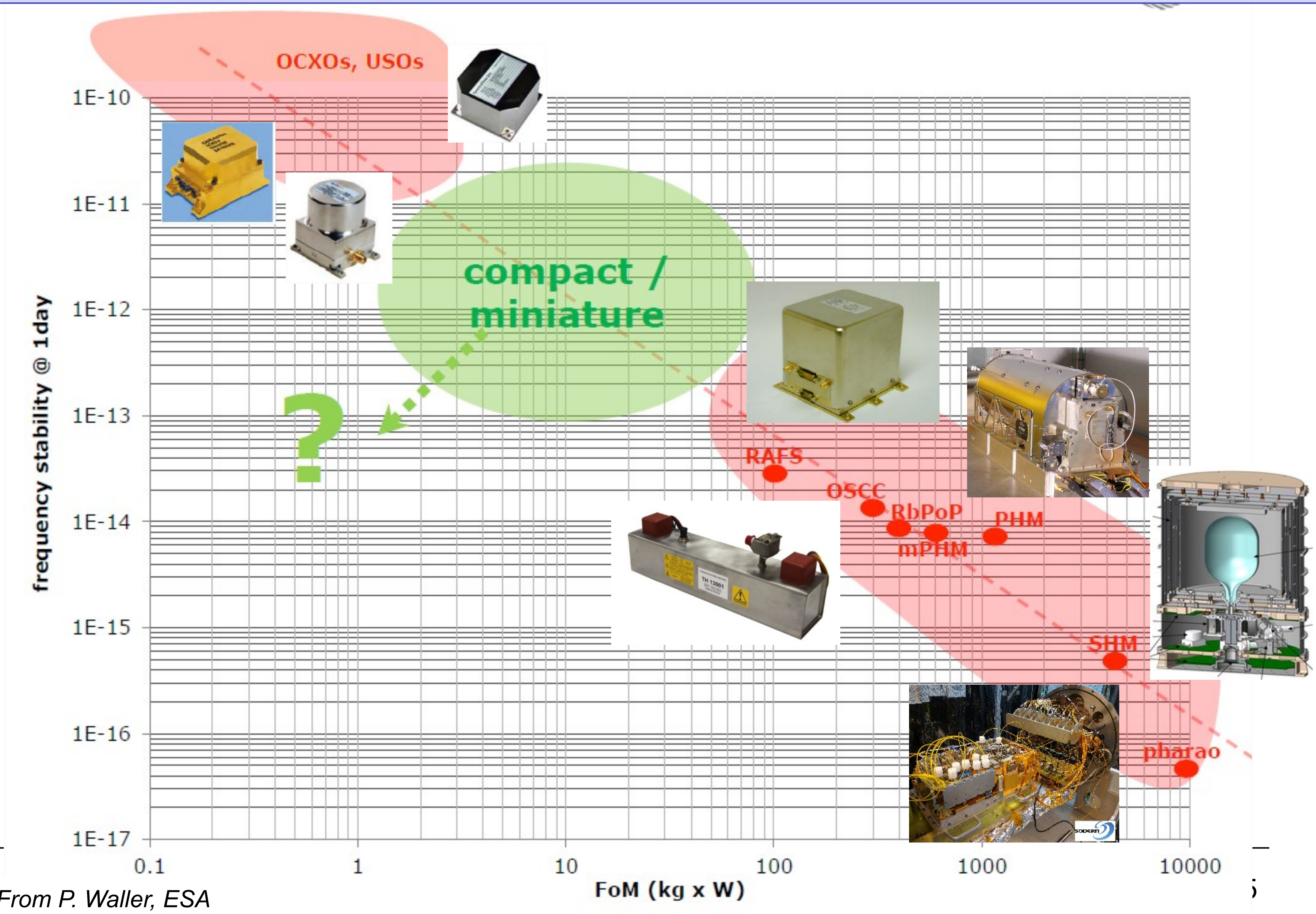
$\sigma_y(\tau) < 10^{-13}\ \tau^{-1/2}$

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





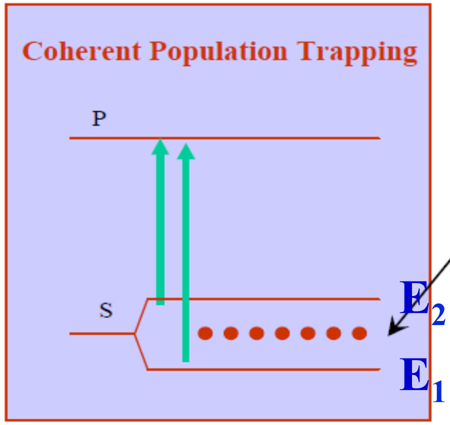
Clocks for space segment



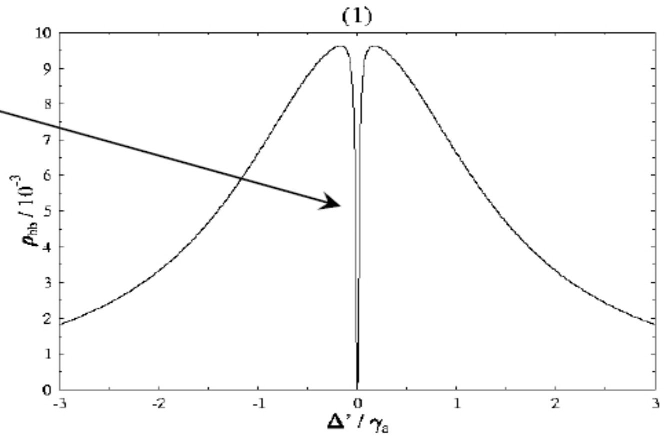
From P. Waller, ESA

An efficient way for miniaturization

→CPT – Coherent population trapping

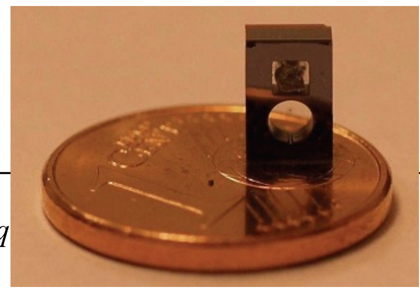


"dark" state

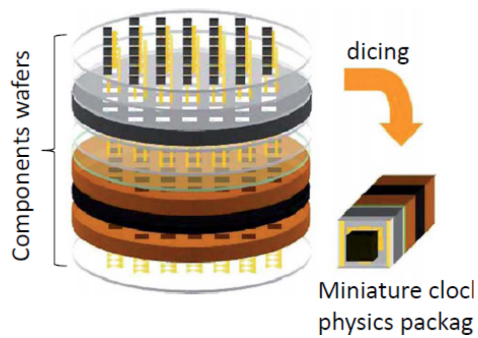


Potential advantages of using CPT:

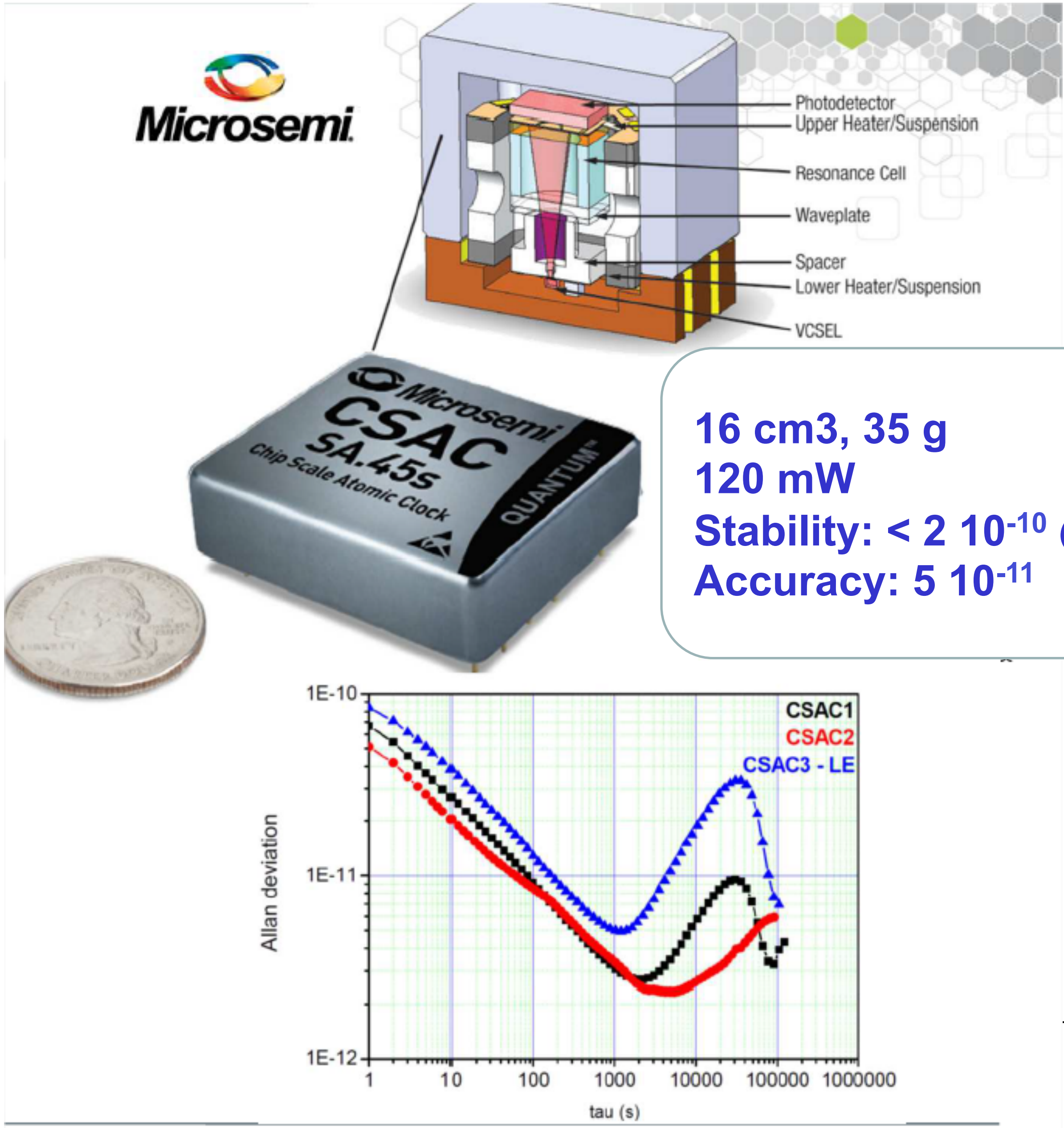
- No microwave cavity
- Reduced light-shift



Wafer-level assembly of all components:



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)

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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)**

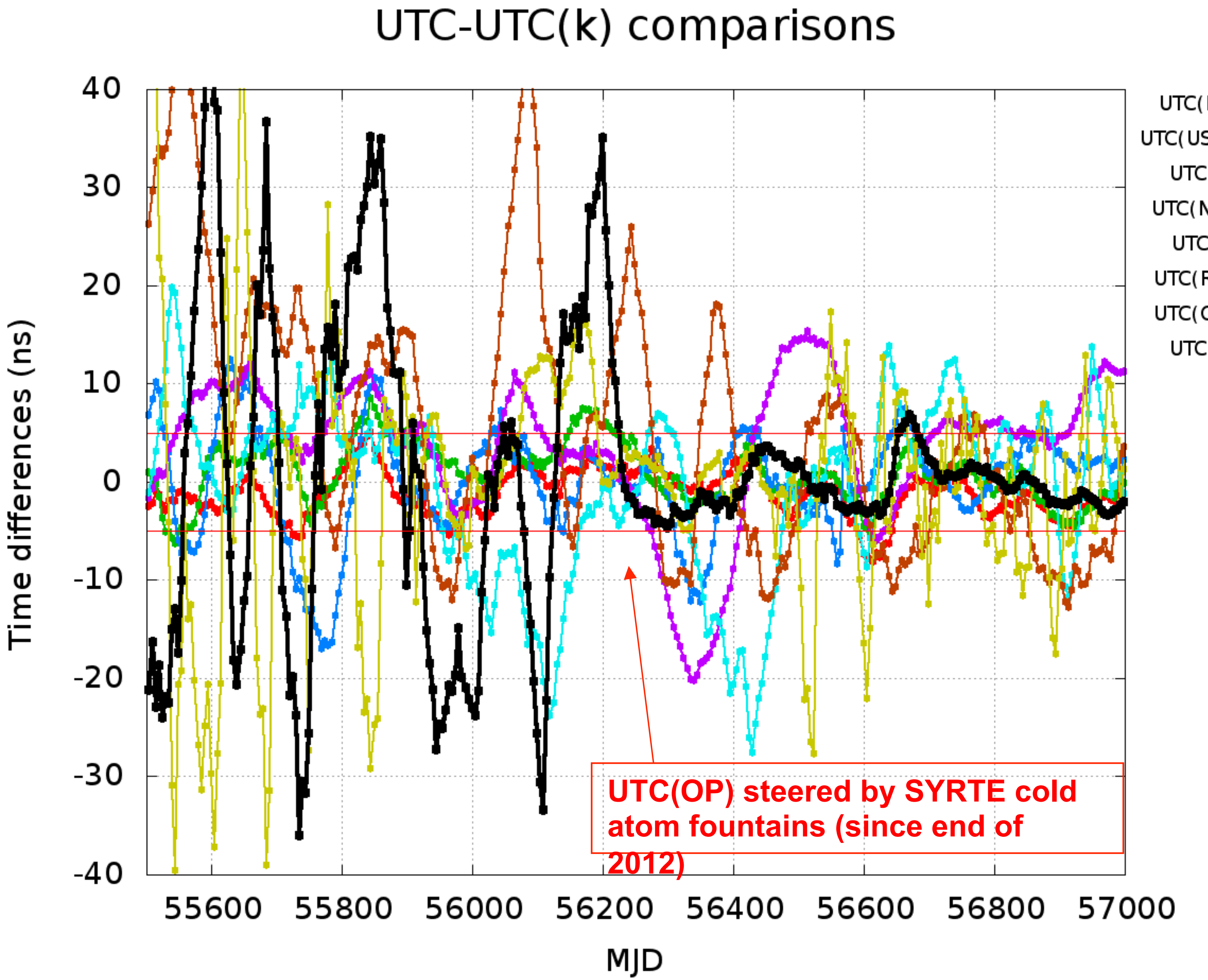
  Remark: difference between time scale at ground user level and GST < 30 ns, 95 % of time

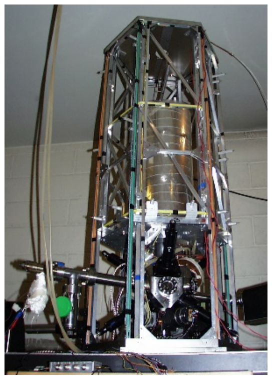
- **Ensure interoperability between GALILEO and GPS (difference between time scales < 20 ns, 95% of time)**

→ 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)





Industrial cold atom clock: Mu-Clock

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

▸ Frequency stability

1 s	≤ 3.0 10^{-13}
10 s	≤ 9.5 10^{-14}
100 s	≤ 3.0 10^{-14}
1000 s	≤ 9.5 10^{-15}
10000 s	≤ 3.0 10^{-15}
1 day	≤ 2.0 10^{-15}
Flicker floor	≤ 2.0 10^{-15} (@ 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

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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