ATOMIC CLOCKS: BASIC PRINCIPLES, APPLICATIONS AND CURRENT TRENDS

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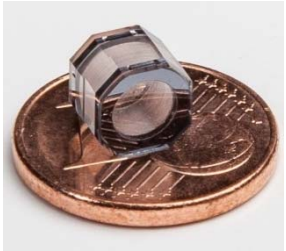
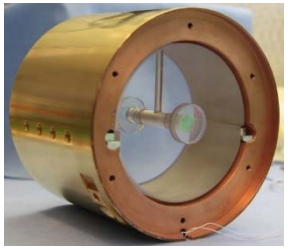
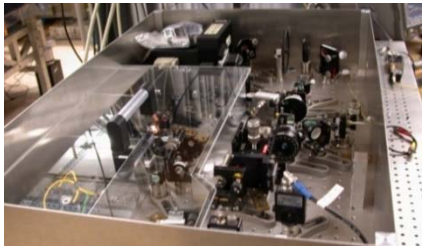
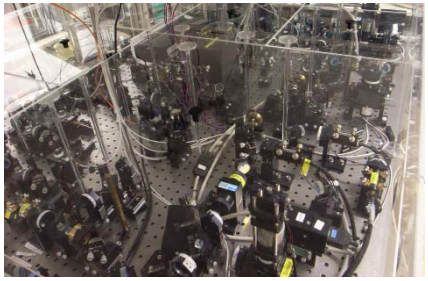
LABORATOIRE TEMPS – FRÉQUENCE (LTF)









<u>Time & Frequency metrology</u>
Atomic spectroscopy
Primary standards
Optical clocks
Cell standards
Space clocks

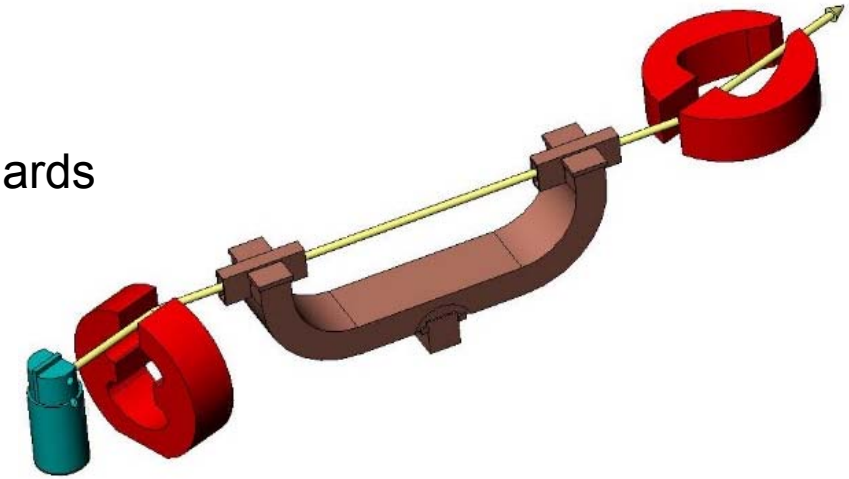
<u>Optical metrology</u>
Optical combs
XUV frequency combs
Stabilized lasers
Laser characterisation
Laser instruments

OUTLINE OF THE TALK

1) Introduction to atomic frequency standards

Basic (functional and physical) principles

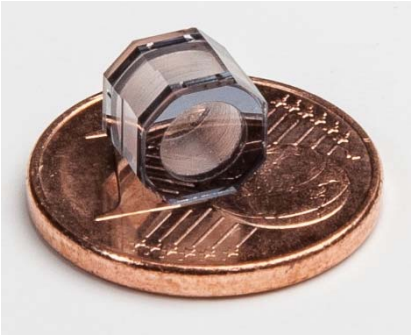
Examples and applications of frequency standards



2) Current trends in the field

Optical frequency standards

Chip-scale atomic clocks



RECENT NOBEL PRIZES IN PHYSICS RELATED TO THE FIELD

2012: **S. Haroche, D. Wineland**

Control of individual quantum objects. Photons and atoms

2005: **J. Hall, T. Haensch, R. Glauber**

Laser precision spectroscopy. Optical comb. Quantum optic

1997: **S. Chu, C. Cohen-Tannoudji, W. Philips**

Laser manipulation of atoms

1989: **N. Ramsey, W. Paul, H. Dehmelt**

Separated oscillatory fields method for atomic clocks.

Ion trap techniques

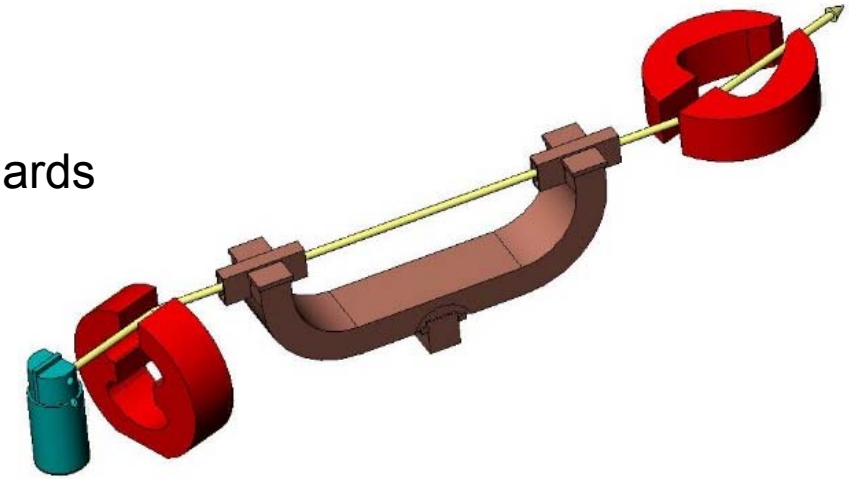
And several others in the previous years (Kastler, optical pumping, etc.)

OUTLINE OF THE TALK

1) Introduction to atomic frequency standards

Basic (functional and physical) principles

Examples and applications of frequency standards

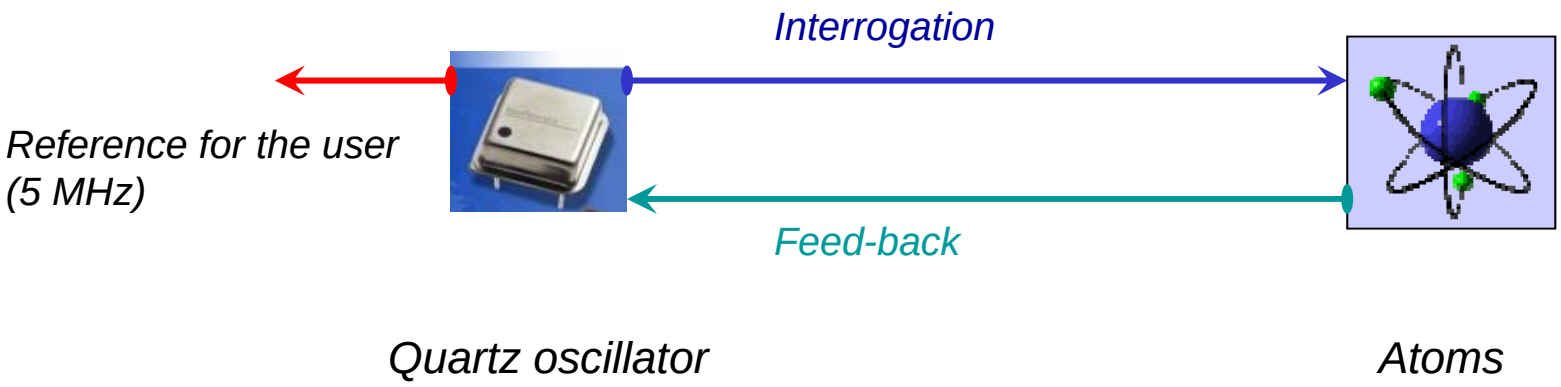


2) Current trends in the field

Optical frequency standards

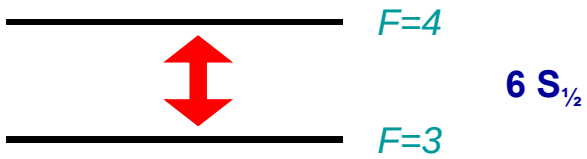
Chip-scale atomic clocks

ATOMIC CLOCK: FREQUENCY-STABILIZED OSCILLATOR



Definition in SI system

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of cesium 133 (1967)

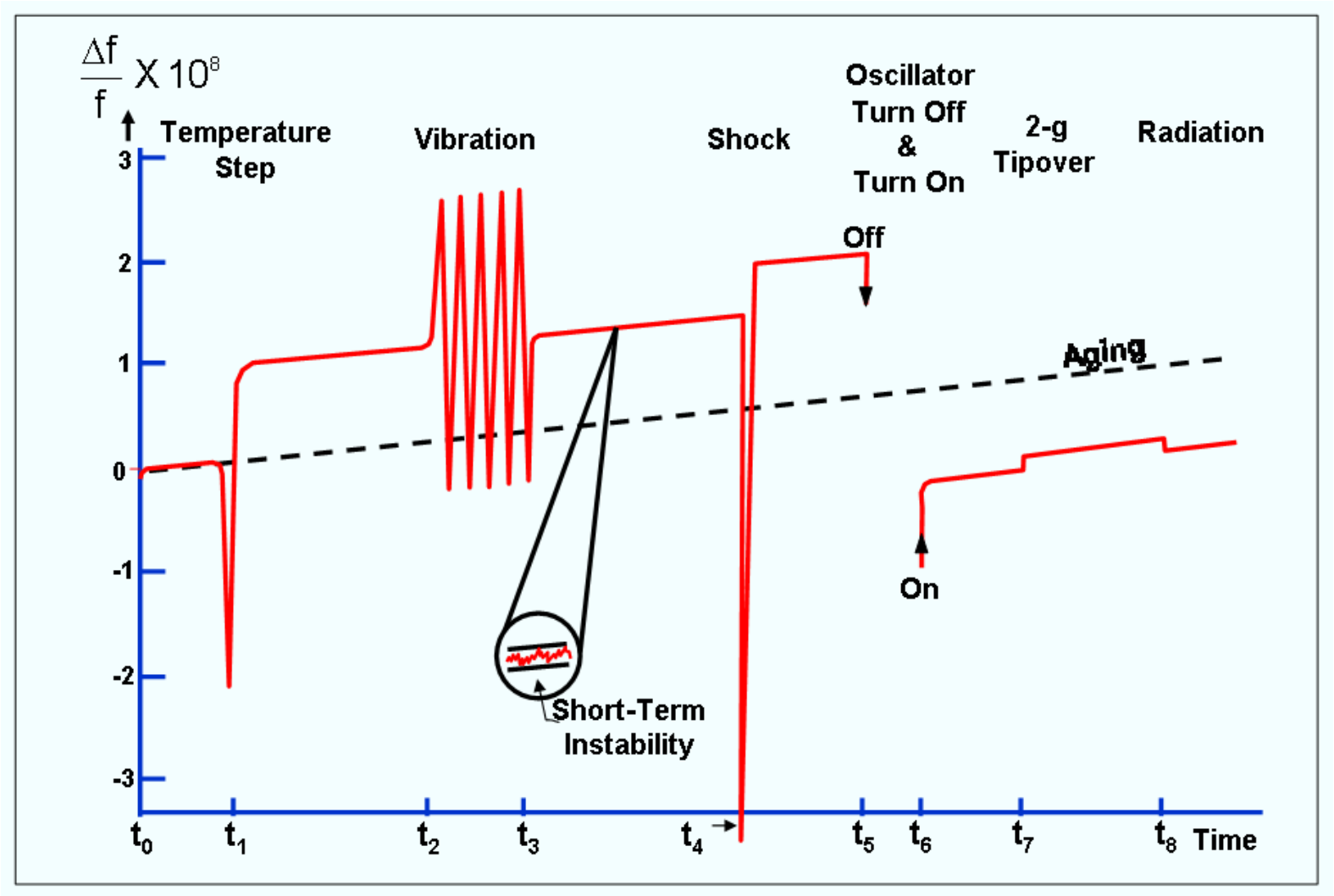


$$Frequency \quad \nu_0 = \frac{E_2 - E_1}{h} = 9192\,631\,770\ Hz$$

$$Period \quad T_0 = \frac{1}{\nu_0}$$

This would be the frequency of an atomic clock in which the atomic transition is not perturbed and the stabilisation "perfect"

WHY DO WE NEED TO STABILIZE THE QUARTZ?



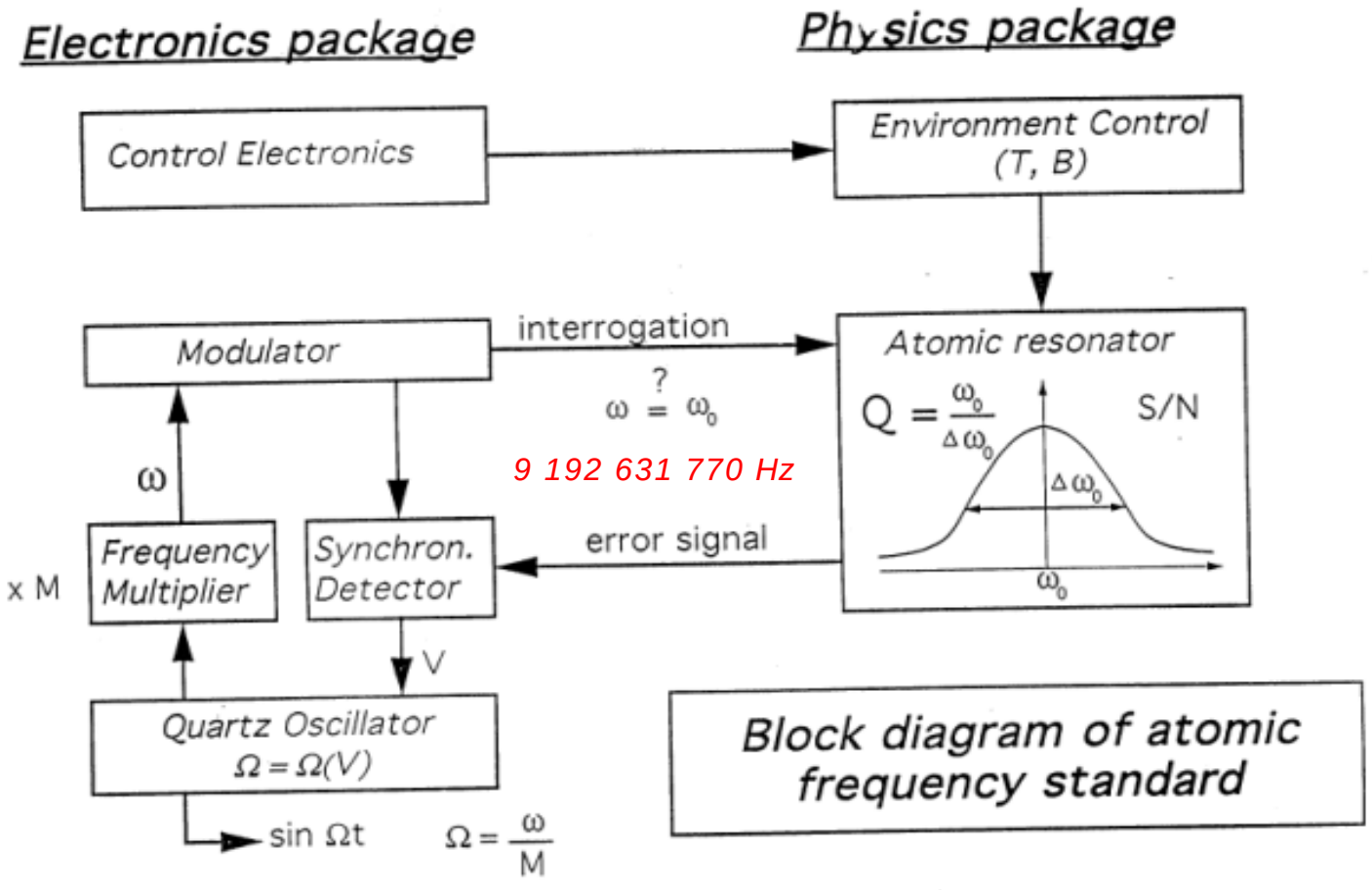
Slide from: **John Vig**, tutorial on «Quartz crystal resonators and oscillators»

FIRST OVERVIEW OF APPLICATIONS AND NEEDS

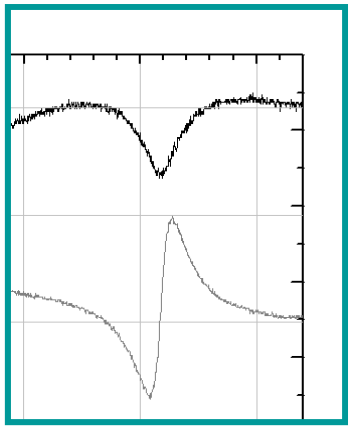
Agriculture (seasons)	~ 1'000'000 s	
Calendar (solstices, equinoxes)	~ 100 '000 s	
Daily activities (professional, social, etc.)	~ 1'000 s	
Determination of the longitude (sea navigation)	~ 1 s	
Common electronic and telecommunication devices	~ 0.01 s	
Advanced telecommunication devices	~ 0.000'001 s	10^{-11}
Satellite navigation	~ 0.000'000'001 s	10^{-14}
Scientific research and primary metrology	< 0.000'000'000'1 s	$< 10^{-14}$

Need of atomic clocks (in the device or to calibrate the device)

BLOC DIAGRAM OF AN ATOMIC CLOCK



Magnetic resonance



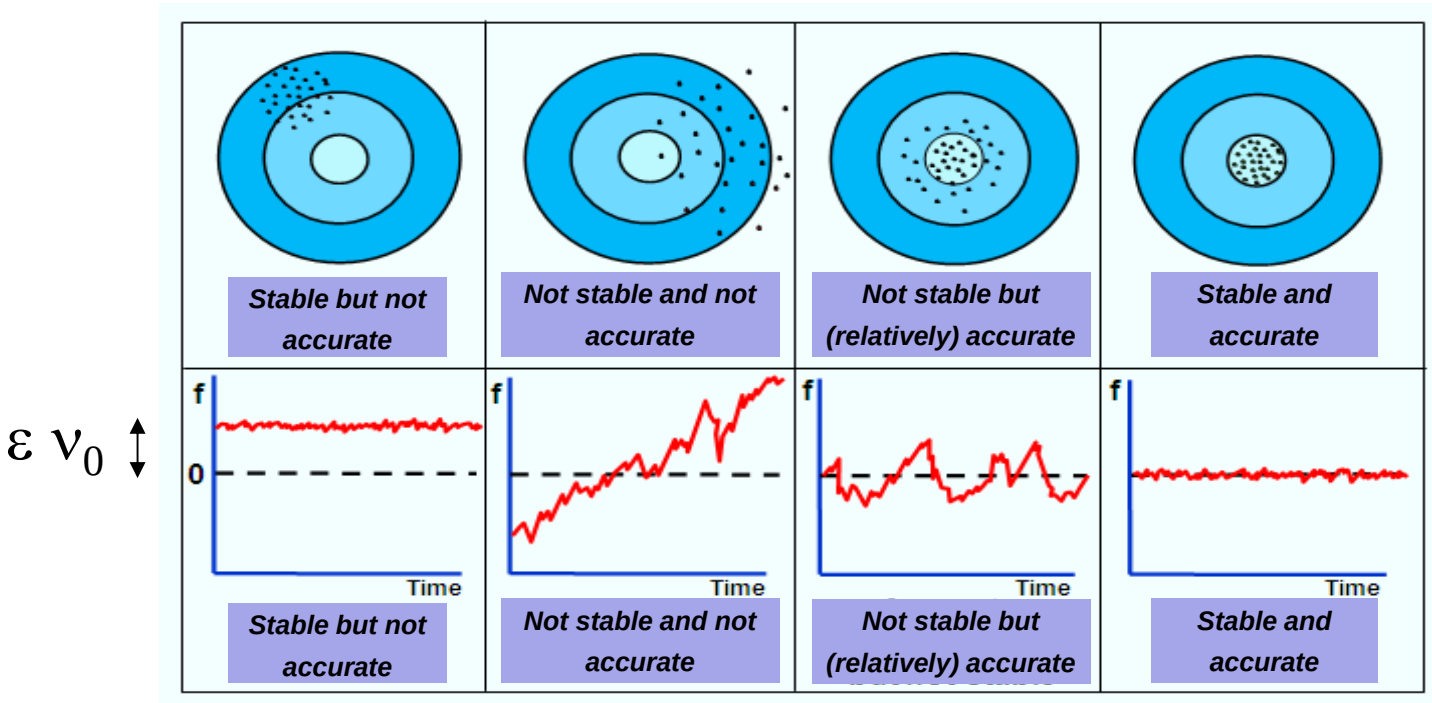
Typically 5 or 10 MHz

Adapted from: Jacques Vanier, Claude Audoin, "The Quantum Physics of Atomic Frequency Standards", Bristol: Adam Hilger, 1989.

STABILITY AND ACCURACY

Frequency of the oscillator: $\nu(t) = \nu_0 \left[1 + \epsilon + y(t)\right]$

Systematic bias ← ϵ $\quad$ $y(t)$ → *Statistical fluctuations*



Inspired by: John Vig, tutorial on «Quartz crystal resonators and oscillators»

How to measure / evaluate the stability and accuracy?

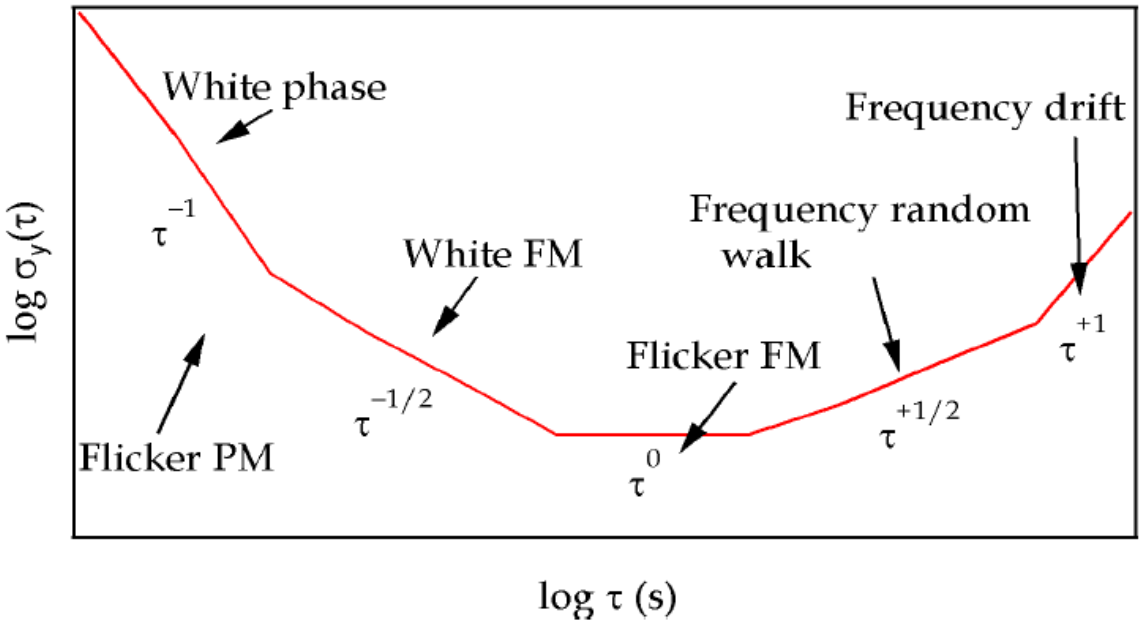
- By comparing to a more stable and/or accurate oscillator
- Statistical and non-statistical analysis

ALLAN DEVIATION

Frequency of the oscillator: $\nu(t) = \nu_0 \left[1 + \epsilon + y(t)\right]$

$$y_K = \frac{1}{\tau}\int_{t_K}^{t_{K+1}+\tau} y(t)\, dt \qquad \text{"True variance": } \sigma_y^2 = \overline{y_k^2} \text{ diverges in general}$$

$$\sigma_y^2(\tau) = \tfrac{1}{2}\overline{(y_{k+1} - y_k)^2} \qquad \sigma_y(\tau): \text{Allan deviation}$$

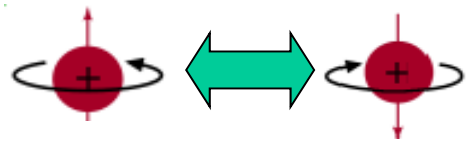


$\sigma_y(\tau)$ tells us how the oscillator under test compares to an ideal one over the timescale **τ**

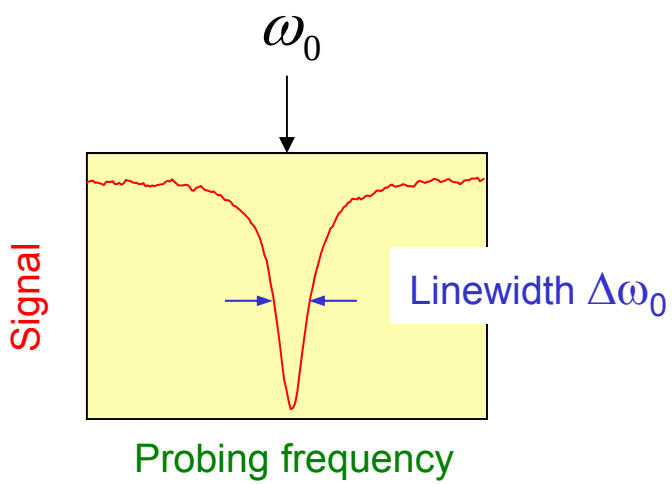
- Different types of noise processes affect differently the Allan deviation;
- Different applications require different (in)stabilities at given time scales

BASIC PHYSICAL PRINCIPLE: MAGNETIC RESONANCE

Magnetic resonance *allows "spin flip".*



Magnetic resonance is a ***frequency selective*** *phenomenon*



$$Q = \frac{\omega_0}{\Delta\omega_0}$$

$$\Delta\omega_0 \propto \frac{1}{T_R}$$

T_R : *resonance «duration»*

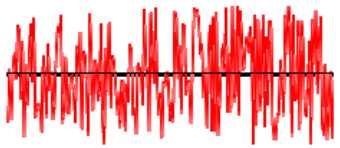
Allan deviation:

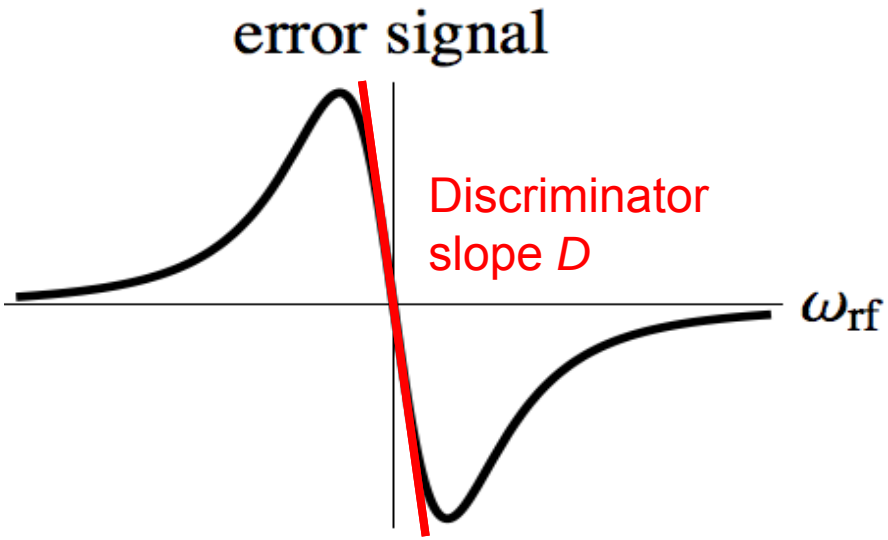
$$\sigma_y^I = \frac{0.2}{Q.(S/N)} \tau^{-1/2}$$

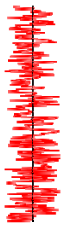
J. Vanier, L. Bernier, IEEE Trans. on Instr. and Meas., Vol. IM-30, No 4, Dec. 1981

RELEVANT PARAMETERS OF THE RESONANCE SIGNAL

Detection noise







Frequency noise

$$\sigma_y(\tau) \propto \frac{N}{D}\frac{\tau^{-\frac{1}{2}}}{\omega_0} \propto \frac{N\Delta\omega\,\tau^{-\frac{1}{2}}}{\omega_0 S} \propto \frac{\tau^{-\frac{1}{2}}}{Q(S/N)}$$

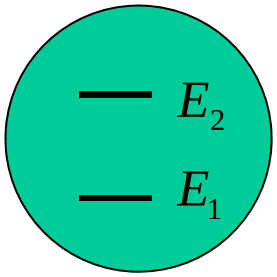
The most important parameters for the clock performances are:

- The resonance quality factor Q
- The signal to noise ratio S/N

$$\sigma_y(\tau) \propto \frac{\tau^{-\frac{1}{2}}}{Q(S/N)} \qquad Q = \frac{\omega_0}{\Delta\omega} \qquad \Delta\omega \propto 1/T_{\text{observation}}$$

BLOCH VECTOR FORMALISM (SEMI-CLASSIC)

Atom (or ensemble of atoms)



Interacting field (RF, microwave, optical)

$$e^{i\omega t}$$

$$\omega \approx \frac{E_2 - E_1}{\hbar}$$

Bloch vector (fictitious spin)

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} \propto \begin{pmatrix} \textit{atomic dipole in phase} \\ \textit{atomic dipole in quadrature} \\ \textit{difference of populations} \end{pmatrix}$$

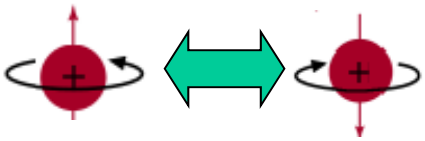
The state of an atom (2 levels) may be represented with a vector $\vec{S}$ ("Bloch vector", or "Fictitious spin") and its behavior when interacting with a resonant field as a magnetic moment in a magnetic field.

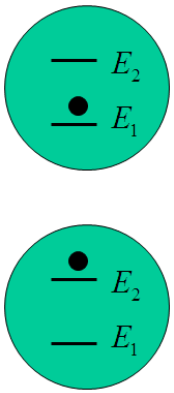
Microwave transitions, optical transitions, $\pi/2$ pulses, etc.

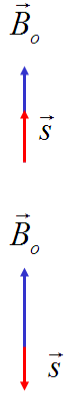
R. Feynman, F. Vernon, R. Hellwarth, "Geometrical representation of the Schrödinger equation for solving Maser problems", J. App. Phys, Vol. 28, p. 49, (1957).

WHAT HAPPENS IN AN ATOMIC CLOCK

Generalised magnetic resonance *allows "spin flips"*





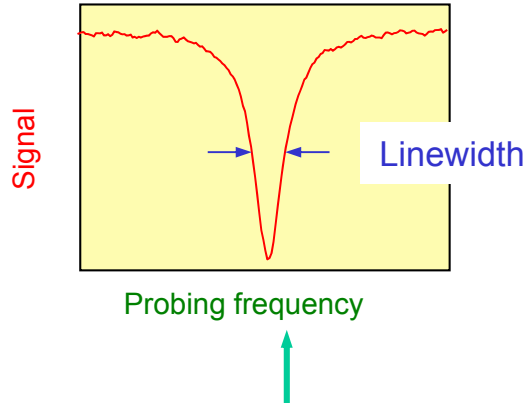


Or series of pulses such as The Ramsey scheme (π/2)

It is a ***frequency selective*** *phenomenon*

In an ***atomic clock*** *you exploit this phenomenon to frequency stabilise a quartz oscillator*

In each ***type of clock*** *it is realised on different species, in various configurations and with different detection techniques*



GENERAL SCHEME (OR SEQUENCE) IN ATOMIC CLOCKS

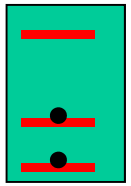
- Have the atoms available and as isolated as possible from the "outside" undesired interactions / perturbations;

- Put (or select) as many atoms as possible atoms in one (of the two) levels;

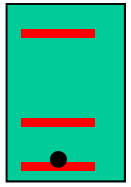
- Perform the "magnetic resonance" (in one or more steps);

- Detect the result of the "magnetic resonance" (level transition) ;

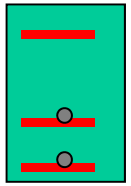
- Apply the necessary correction to the quartz oscillator



$$\vec{S} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

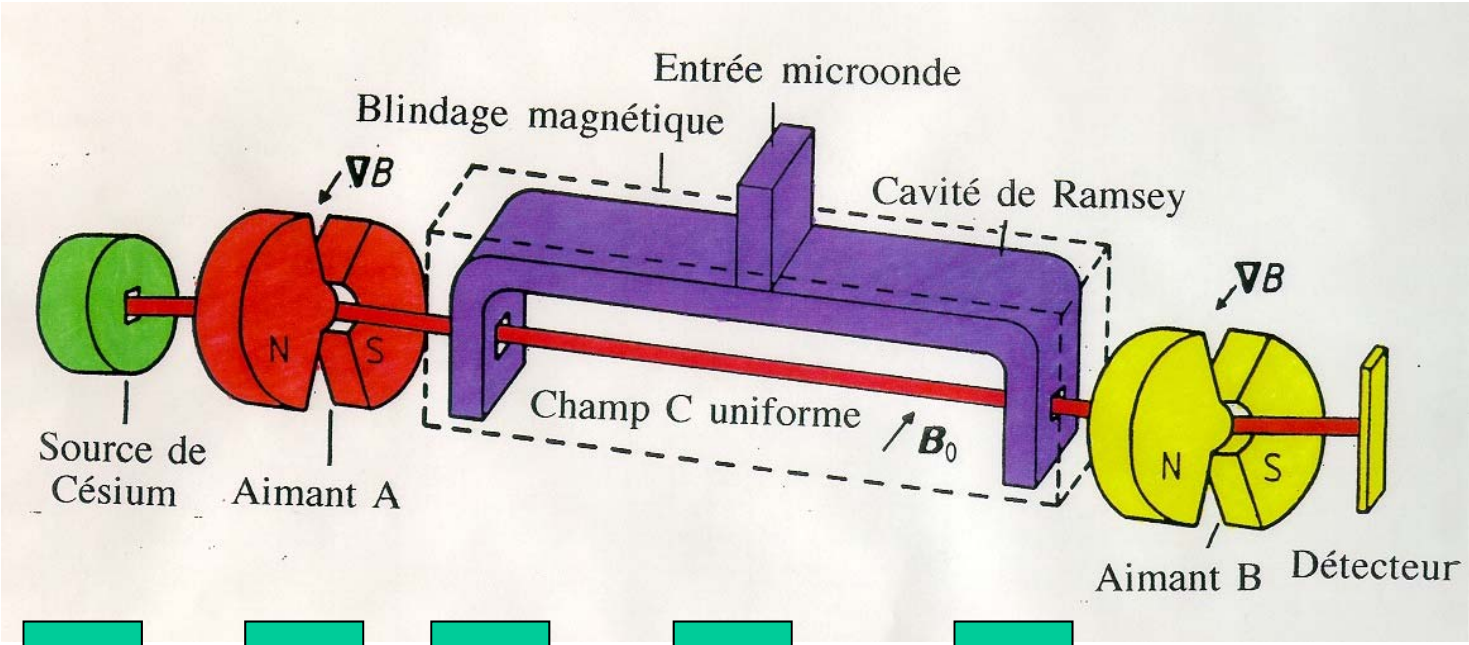


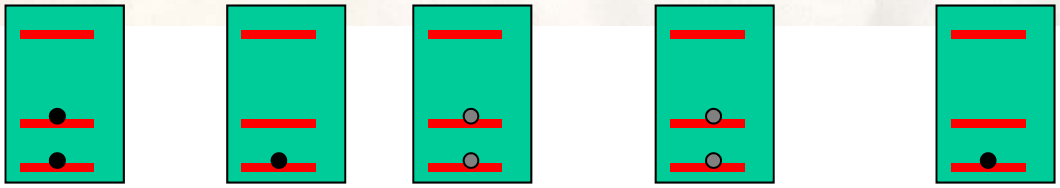
$$\begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$



ATOMIC BEAM FREQUENCY STANDARDS

Stern-Gerlach (State selection) and Ramsey interrogation



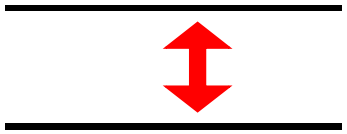


$$\vec{s} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad \begin{pmatrix} \sin(\omega_0 t) \\ \cos(\omega_0 t) \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

CATEGORIES OF ATOMIC CLOCKS

- Primary (Cs) – Secondary
- Passive – Active (H-Maser)
- Commercial (Rb, Cs, H)
- Ground or Space applications
- Laboratory – “In development”
- Microwave – Optical
- Neutral atoms – Ions – Molecules – Nuclear - …

$$\nu(t) = \nu_0 \left[1 + \epsilon + y(t)\right]$$



MAIN FIELDS OF APPLICATIONS OF ATOMIC CLOCKS

- *Radioastronomy, Geodesy*

  (VLBI, Radioastron, etc.)

- *Scientific Research, Instrumentation*

  (Microgravity, ACES, HYPER, etc.)

- *Navigation & Positioning*

  (Galileo, GPS, GLONASS, etc.)

- *Telecommunications*

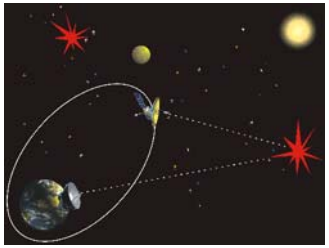
  (Networks synchronisation, etc.)

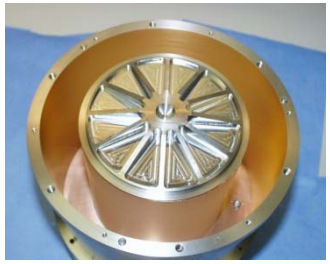
- *Power distribution networks*

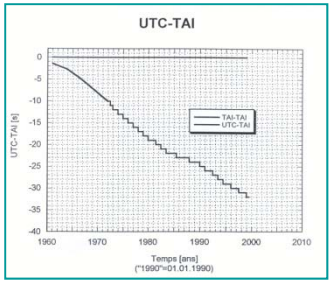
  (Smart power grids.)

- *Metrology, Time scales*

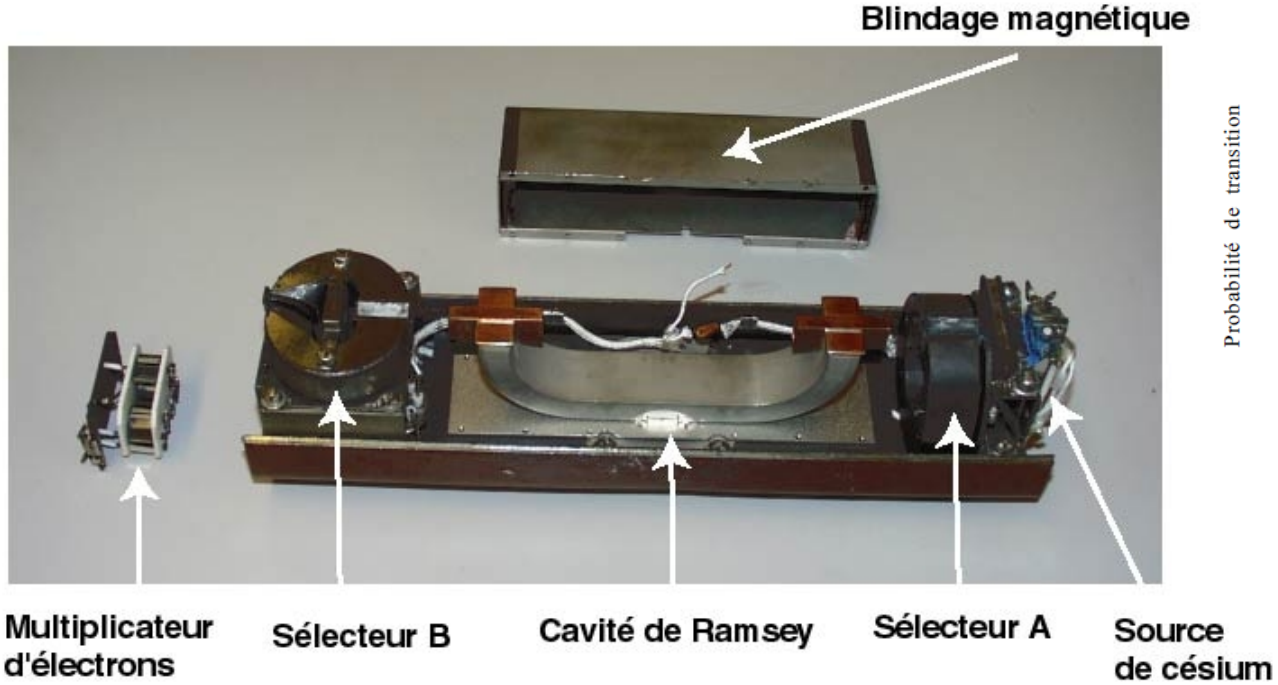
  (Primary and secondary standards, H-Masers)

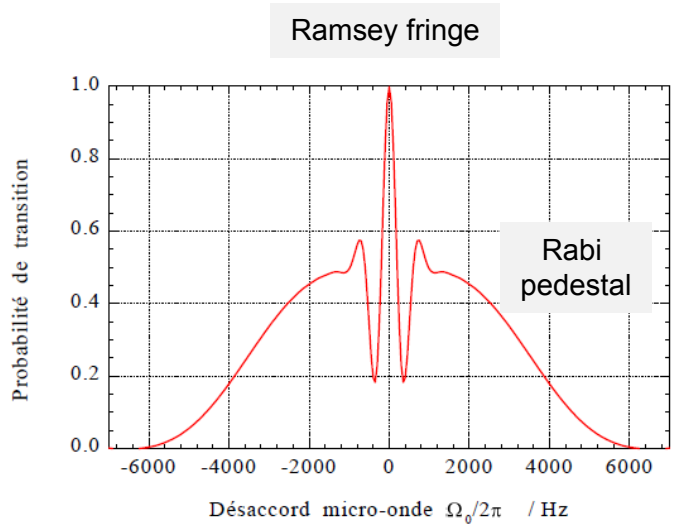






CESIUM BEAM STANDARD



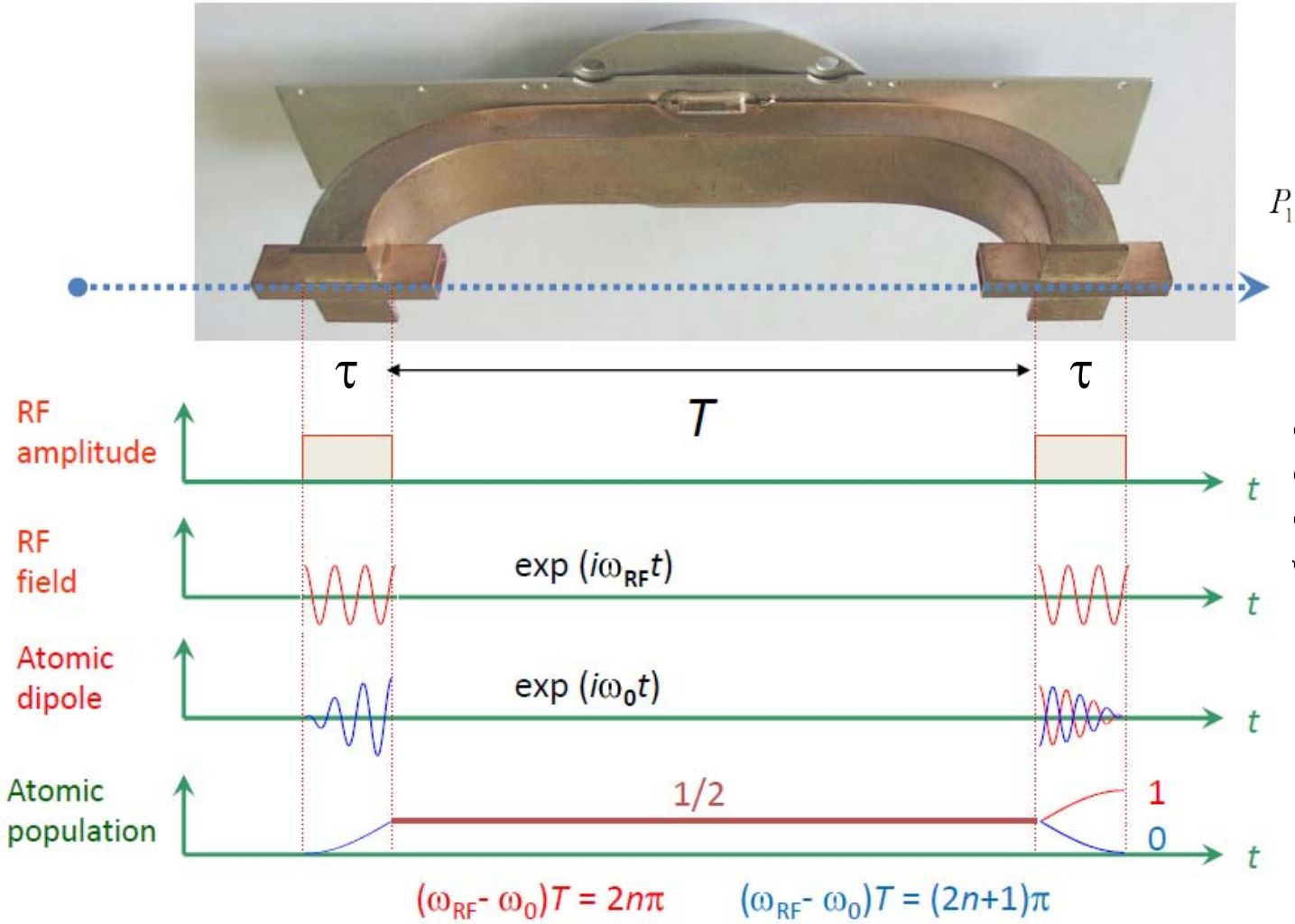


$$Linewidth \;\; \Delta\omega_0 \propto \frac{1}{T_R}$$

$$T_R = \frac{L}{\mathrm{v}} = \frac{Length\, of\; cavity}{speed\, of\; atoms}$$

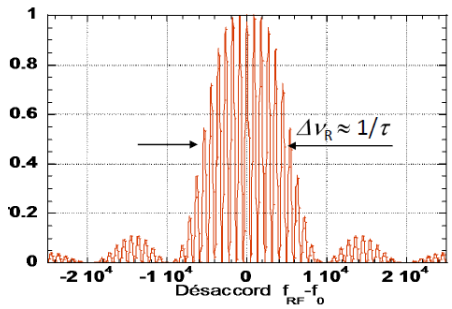
10^{-11} @ 1s but accurate and very stable in the long term

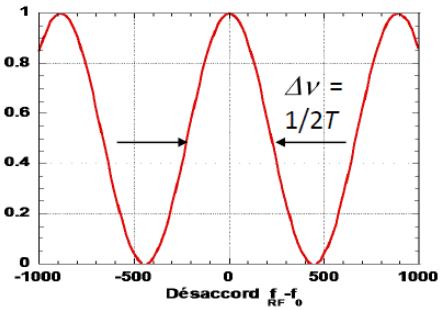
RAMSEY SCHEME (SEPARATED OSCILLATORY FIELDS METHOD)



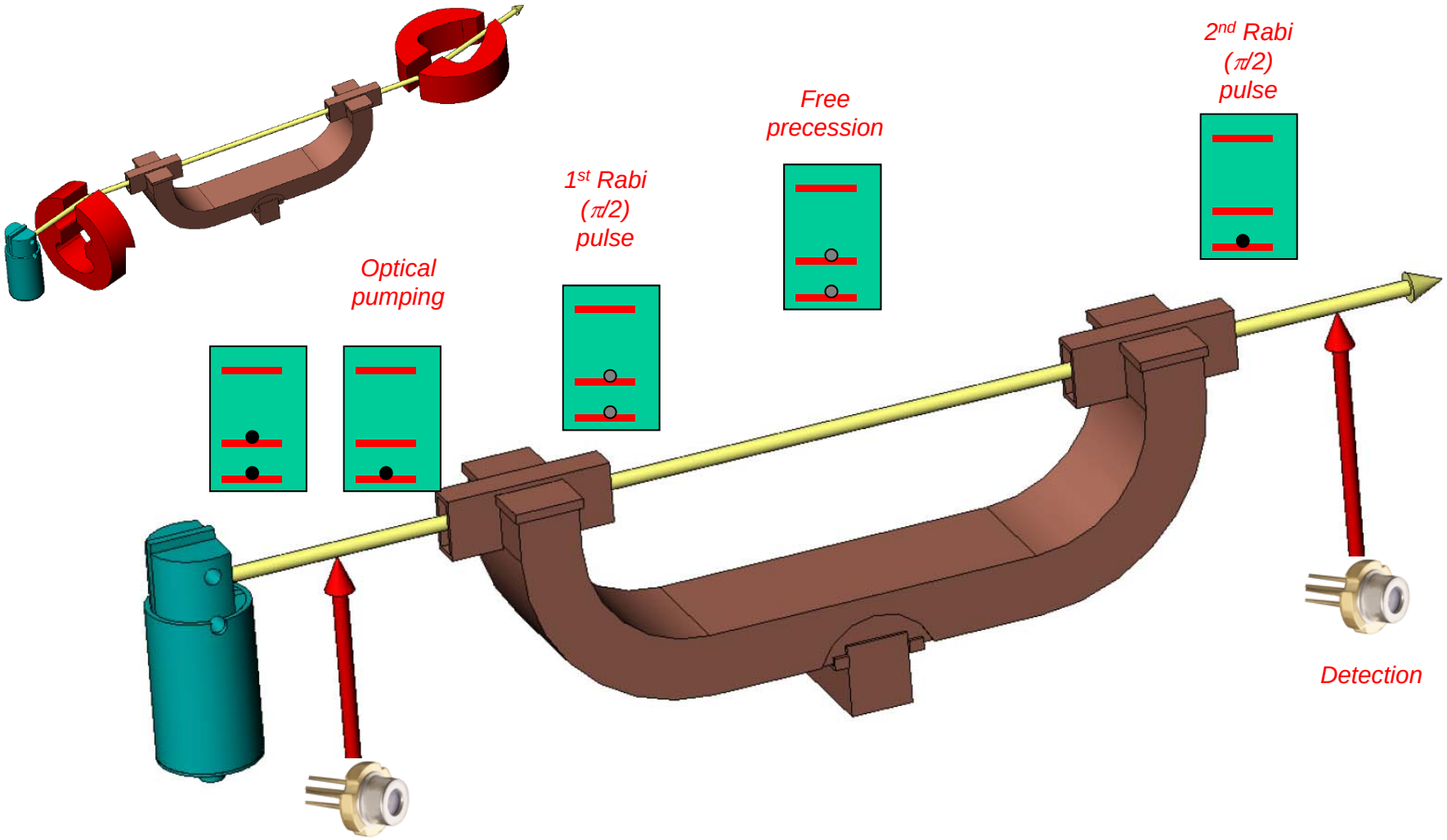
For a monokinetic beam

$$P_{12}(\delta) = \frac{1}{2}\sin^2 \Omega_{12}\tau \ \left(1+\cos \delta T\right)$$





LASER-PUMPED BEAM STANDARDS



LASER RADIATIVE FORCES

$$\vec{E}(\vec{r},t) = \hat{e} \cdot E_0 \cdot \cos[\omega_L t + \phi(\vec{r})]$$

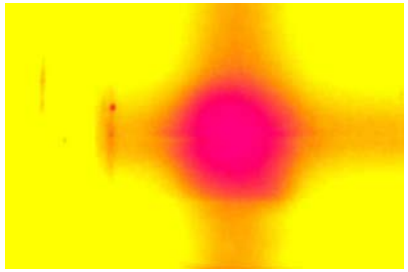
$$\vec{F} = \underbrace{\hat{e} \cdot d_{ab} \cdot u_{st} \cdot \nabla E_0(\vec{r})}_{\substack{\textit{reactive or} \\ \textit{dipolar force}}} + \underbrace{\hat{e} \cdot d_{ab} \cdot v_{st} \cdot E_0(\vec{r}) \cdot \nabla \phi(\vec{r})}_{\substack{\textit{dissipative or radiation} \\ \textit{pressure force}}}$$

~ light-shift

~ absorption

Optical trapping (lattice, tweezers, etc.)

Optical molasses



Motivations: reduce the Doppler effect, increase interaction time, etc. $\Delta\omega_0 \propto \frac{1}{T_R}$

COLD ATOMIC BEAM CLOCKS (FOUNTAINS)

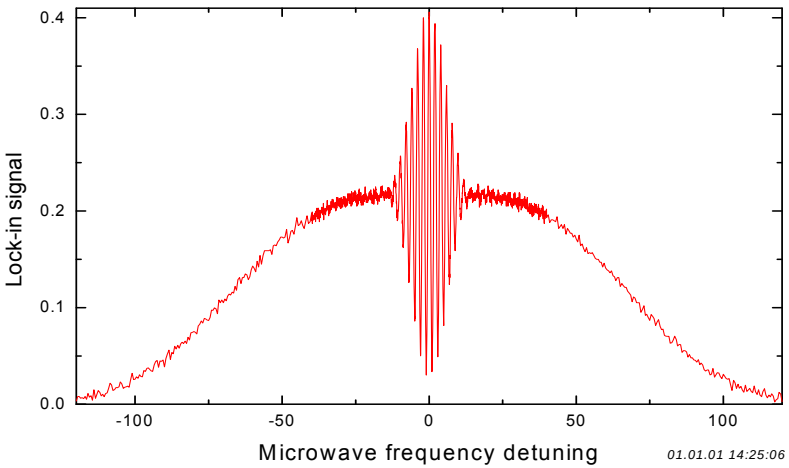
$$Linewidth\ :\ \Delta\omega_0 \propto \frac{1}{T_R}$$

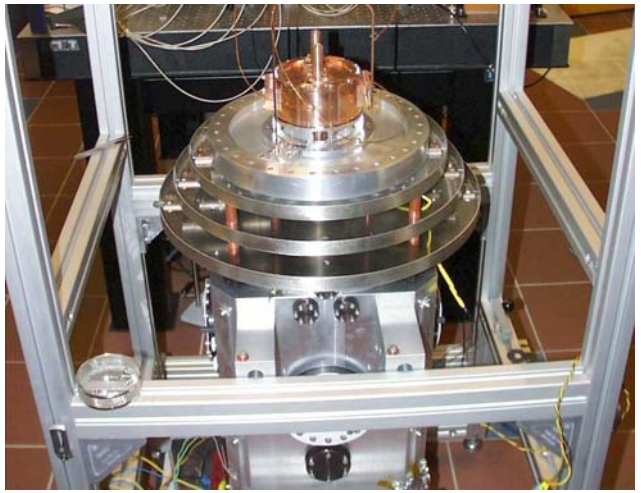
- Thermal beam: v = 100 m/s, T_R = 5 ms

$\Delta\omega_0$ **= 100 Hz**

- Cold fountain: v = 4 m/s, T_R = 0.5 s

$\Delta\omega_0$ **= 1 Hz**



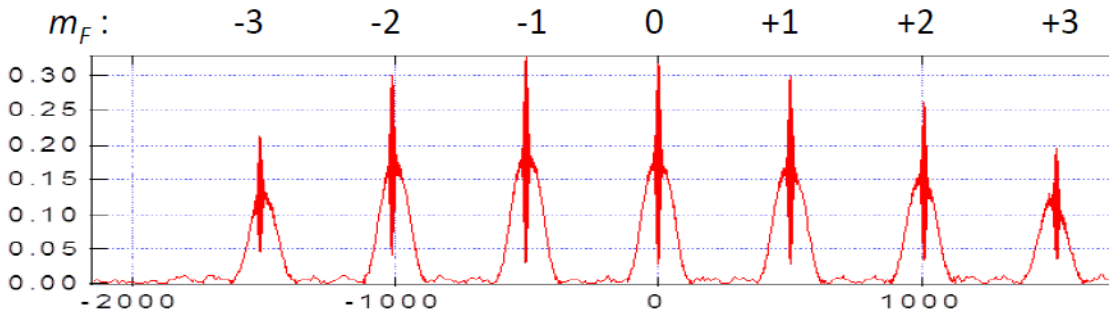


- Next step: microgravity (T_R = 10 s, $\Delta\omega_0$ **= 0.1 Hz**)

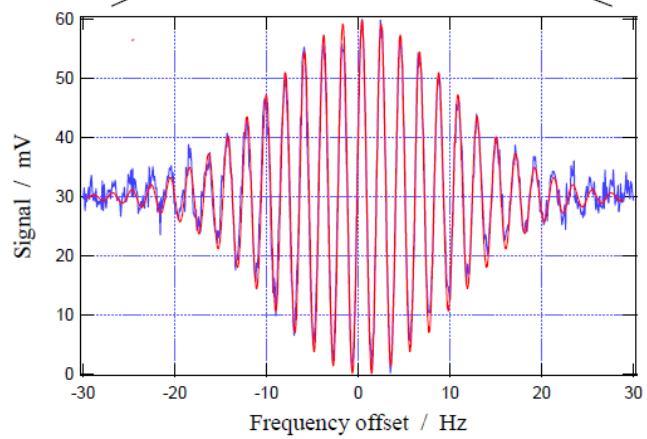
PRIMARY FREQUENCY STANDARDS

Frequency : $\nu(t) = \nu_0 \left[1 + \epsilon + y(t)\right]$

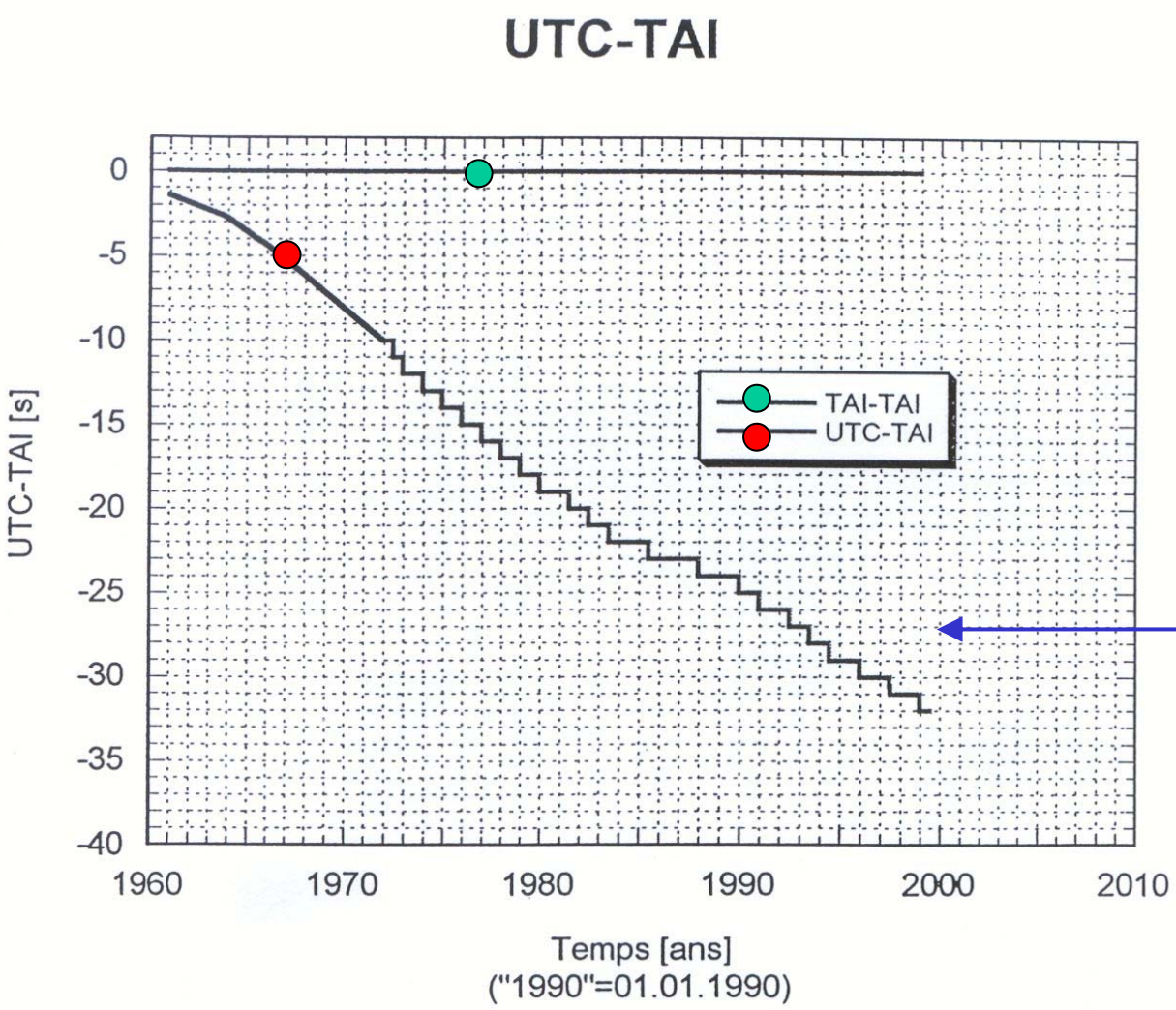
Systematic bias ← → *Statistical fluctuations*



	Thermal CS beam ($\Delta\nu$ = 50 Hz)		CS fountain ($\Delta\nu$ = 1 Hz)	
Type of shift :	*Freq. shift :*	*Uncertainty :*	*Freq. shift :*	*Uncertainty :*
2nd order Zeeman	$3.3 \cdot 10^{-10}$	$1 \cdot 10^{-15}$	$4.5 \cdot 10^{-14}$	$1 \cdot 10^{-16}$
2nd order Doppler	$5 \cdot 10^{-14}$	$5 \cdot 10^{-16}$	$< 1 \cdot 10^{-16}$	$< 1 \cdot 10^{-16}$
Cavity phase-shift	$2.5 \cdot 10^{-13}$	$6 \cdot 10^{-15}$	$< 1 \cdot 10^{-16}$	$< 3 \cdot 10^{-16}$
Gravitational pot.	$8 \cdot 10^{-15}$	$2 \cdot 10^{-16}$	$1.8 \cdot 10^{-13}$	$1 \cdot 10^{-16}$
Spin-exchange	-	-	$1 \cdot 10^{-14}$	$3 \cdot 10^{-16}$
Black body (AC Stark)	$2 \cdot 10^{-14}$	$5 \cdot 10^{-16}$	$2 \cdot 10^{-14}$	$3 \cdot 10^{-16}$
Other effects		$4 \cdot 10^{-15}$		$< 4 \cdot 10^{-16}$
Total uncertainty *D*		$7 \cdot 10^{-15}$		$7 \cdot 10^{-16}$



ATOMIC TIME (TAI) AND ASTRONOMICAL TIME (UTC)

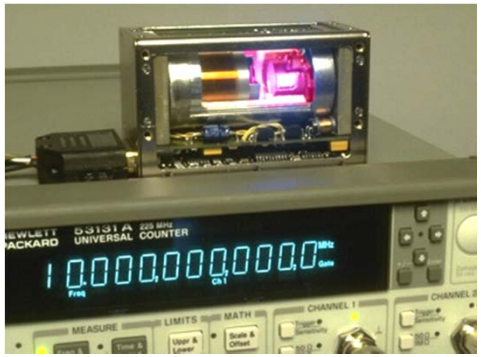


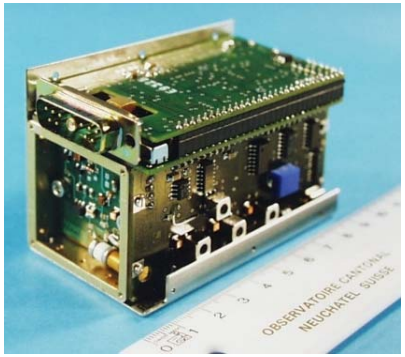
Leap second

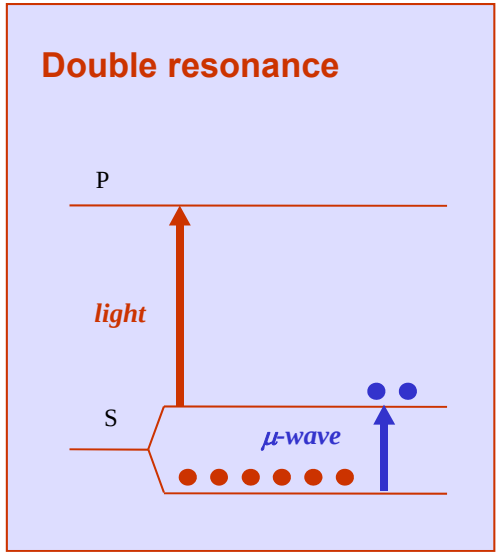
TAI is generated from an ensemble of various clocks :

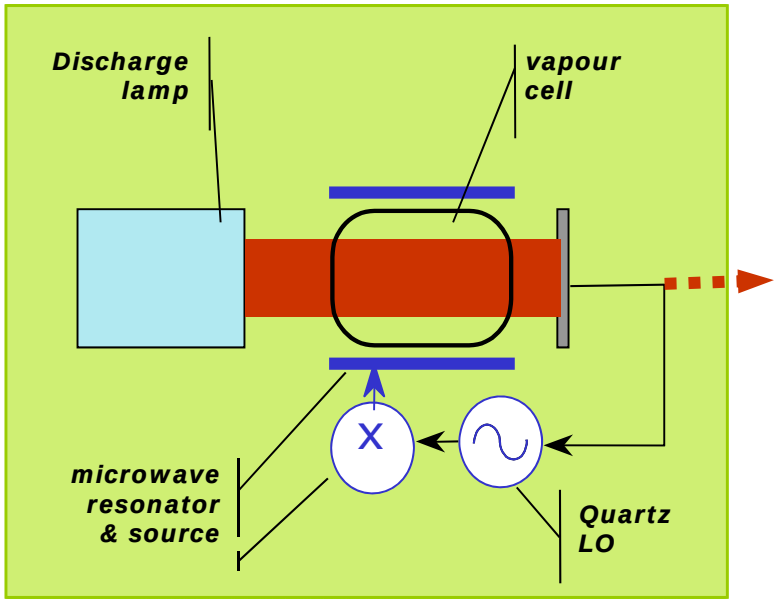
- ~ 10 fountains
- > 300 commercial clocks (cesium clocks, rubidium clocks, H-masers)

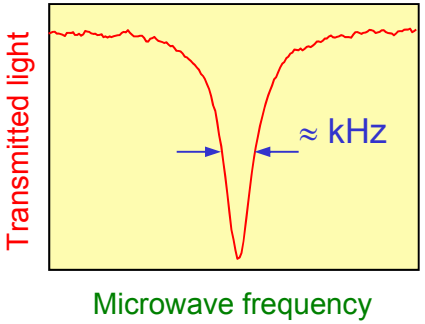
RUBIDIUM VAPOUR CELL STANDARD





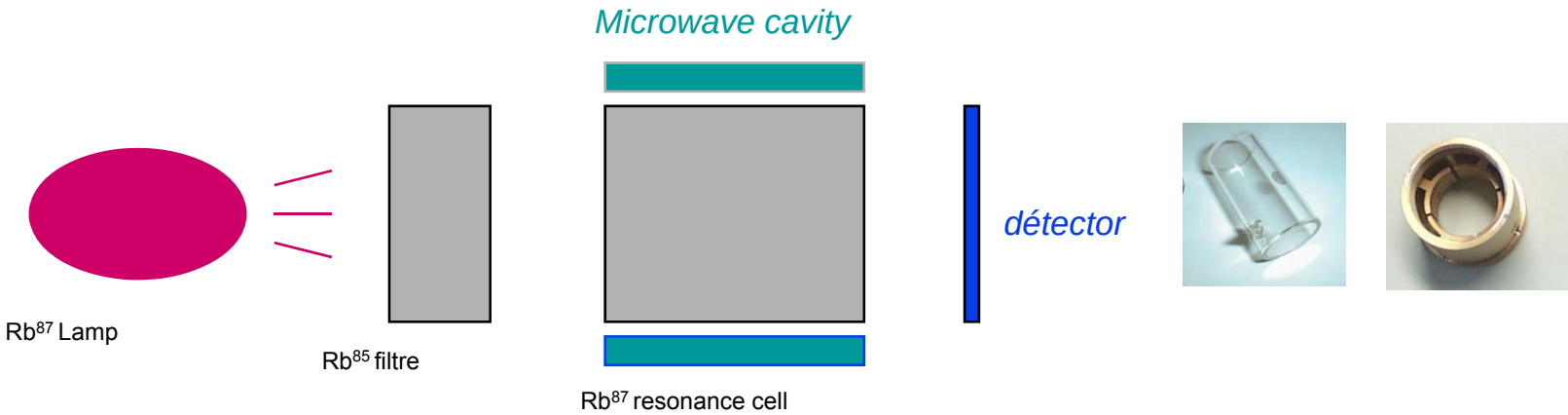


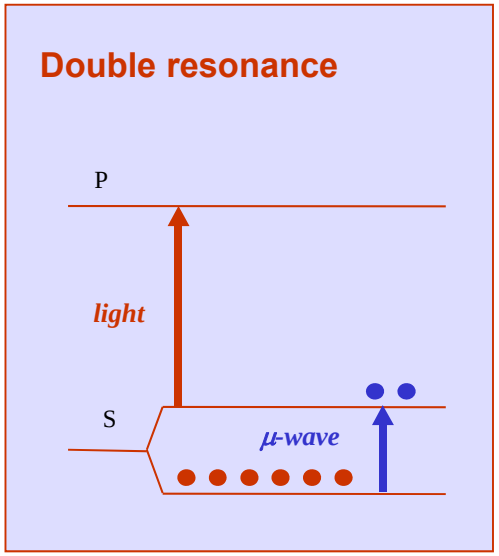


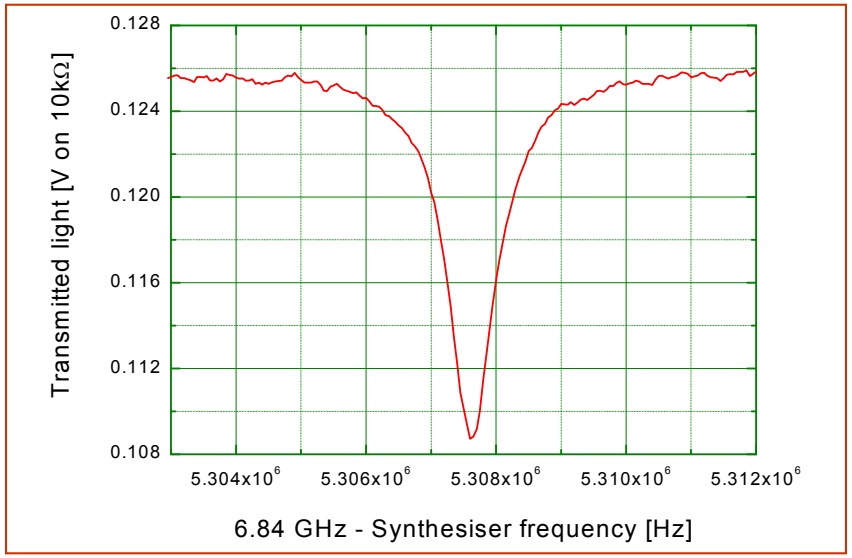


10^{-11} @ 1s
10^{-13} @ 10'000s

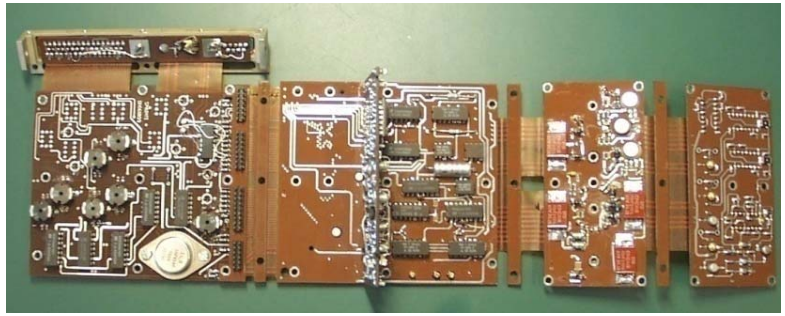
DOUBLE RESONANCE (WITH A DISCHARGE LAMP)

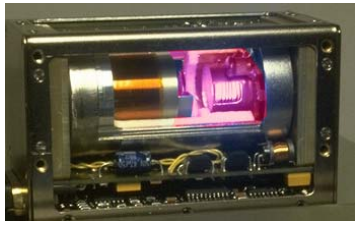


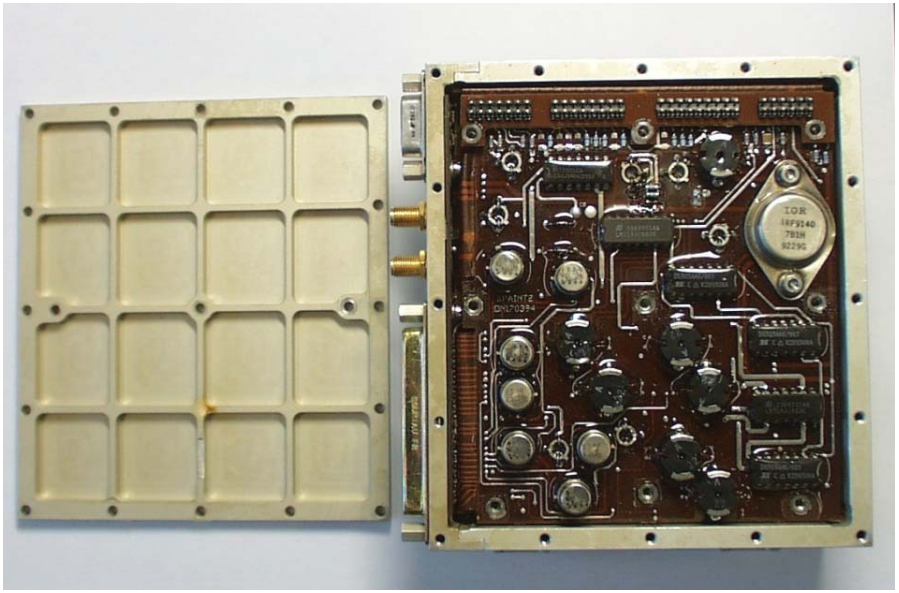


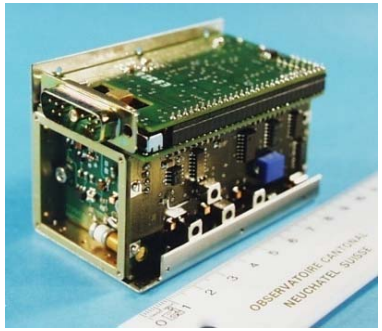


EXAMPLES OF RB CLOCKS (OBSERVATOIRE NE 1985-1995)





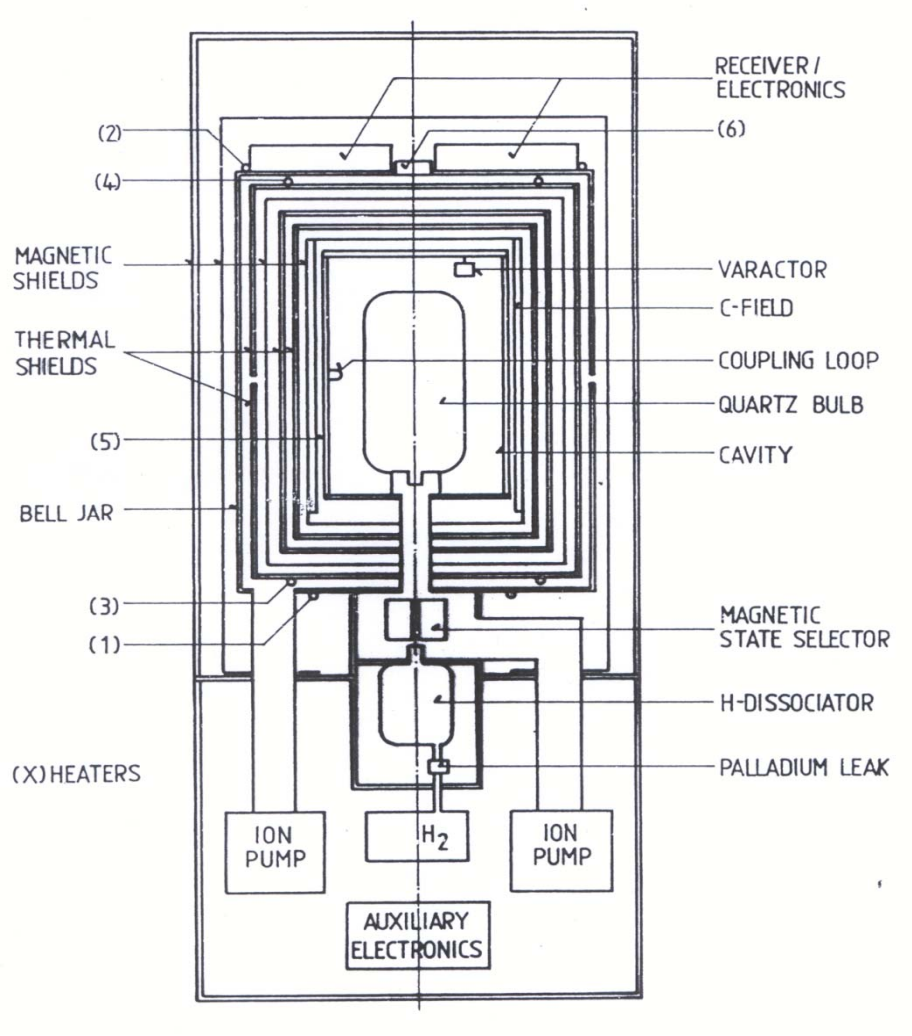




Currently commercialized by Spectratime-Orolia. Used in the GALILEO navigation system

Next generation: replace the discharge lamp with a laser for a more efficient optical pumping

HYDROGEN MASER



10^{-13} @ 1s

10^{-15} @ 100s

$\sigma(\tau) \sim 1/\tau$

100 kg

VLBI (VERY LONG BASE INTERFEROMETRY)

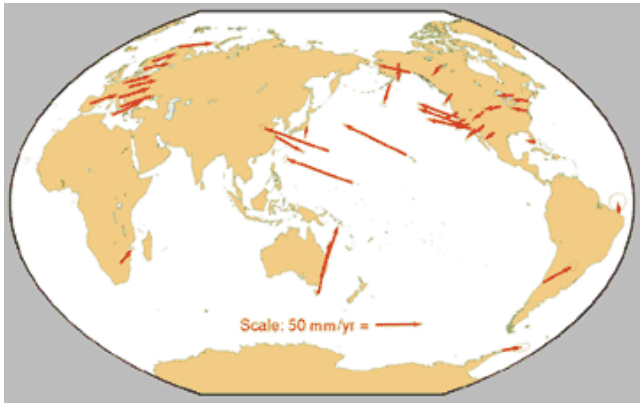
H-Masers (**10^{-15}** @ ~1000-10'000 s) are used to increase the resolution

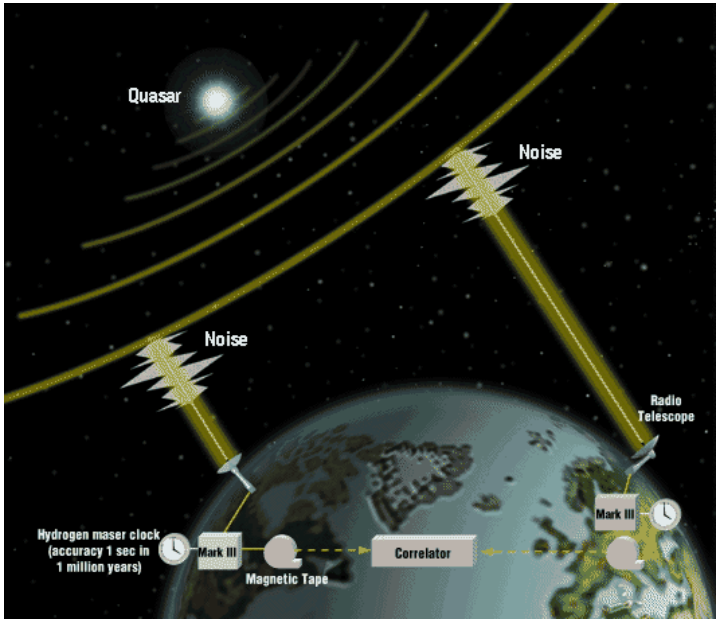
Angular resolution: ~ λ / Diameter

1 radio-telescope: ~ 1 mrad (10^{-3} rad)

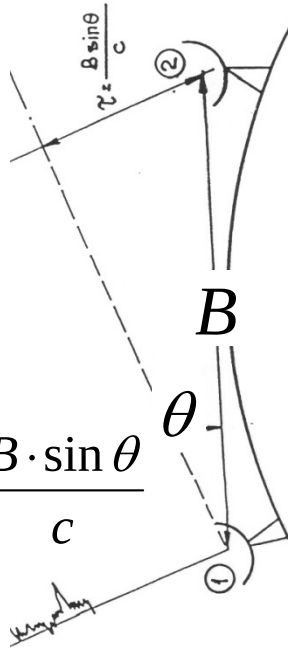
2 radio-telescopes: ~ 1 nrad (10^{-9} rad)

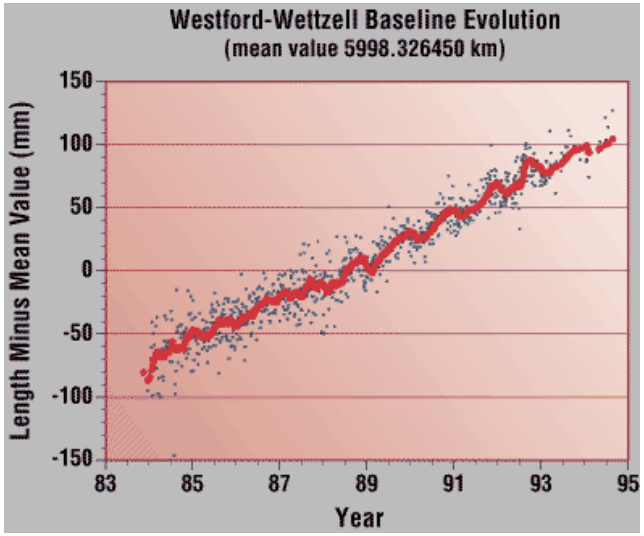
Earth rotation: 1 mrad → 6 km → 14 s



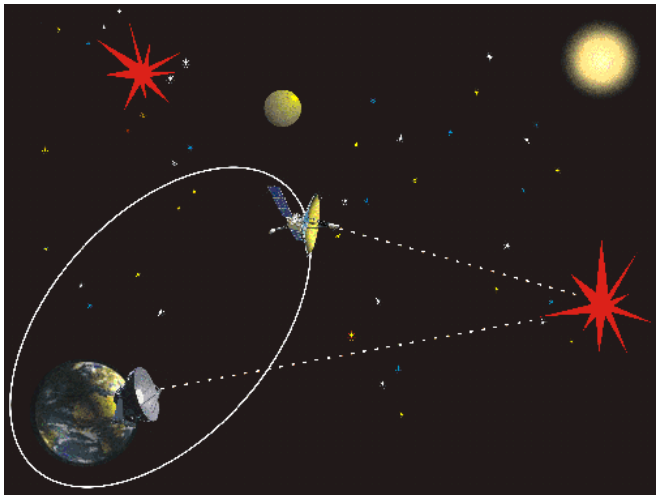


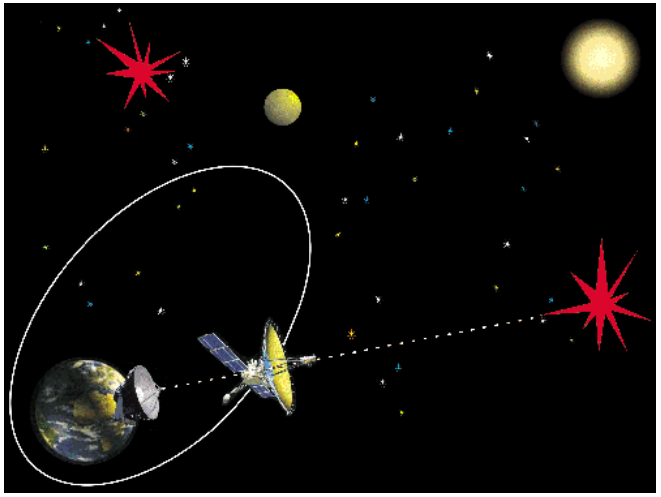
$$\tau = \frac{B \cdot \sin\theta}{c}$$



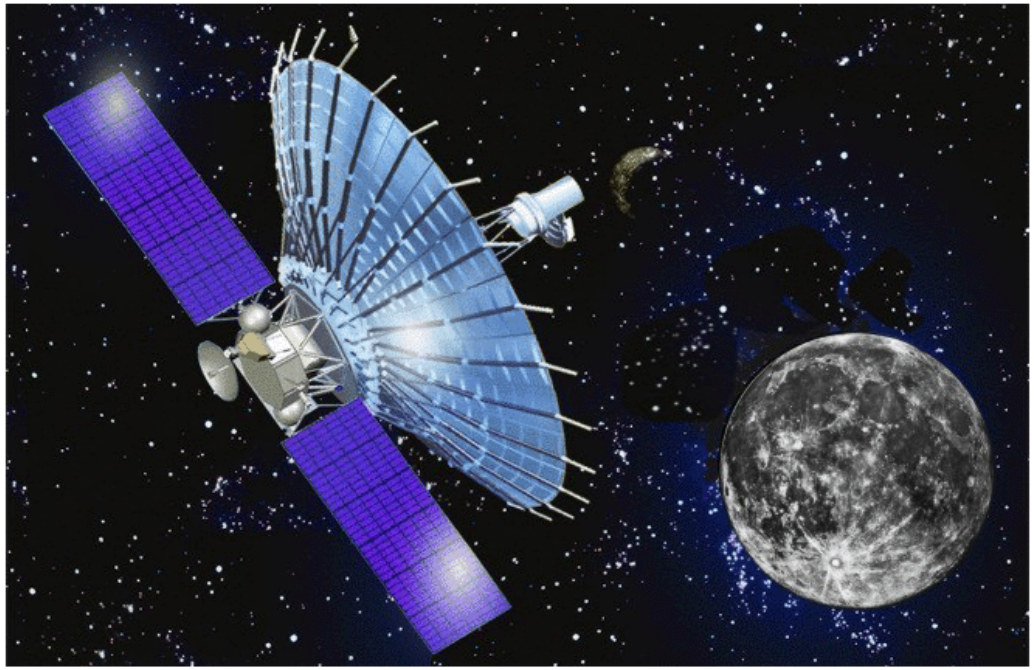


RADIOASTRON MISSION (SPACE VLBI)

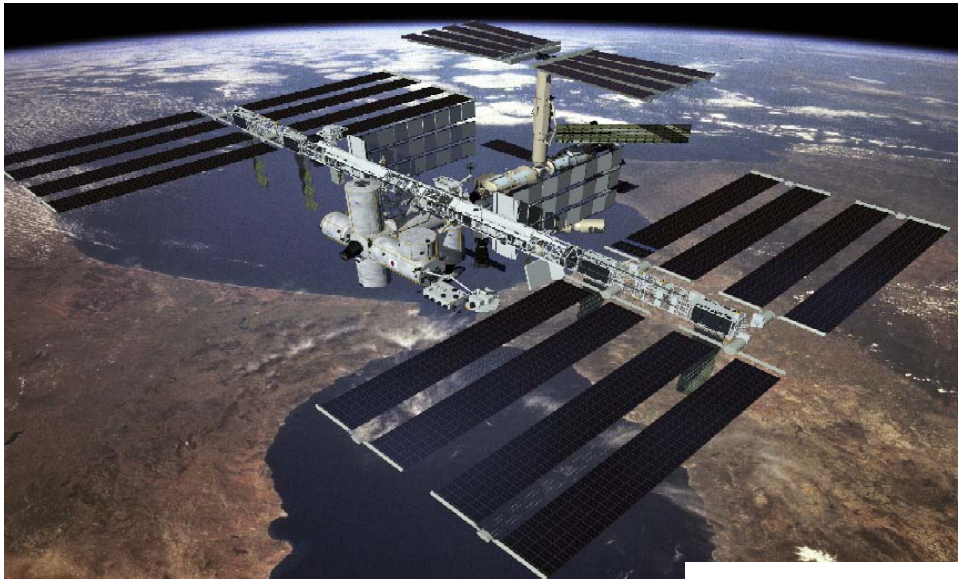




Increase the Baseline B from 30’000 to 300’000 km, by putting one of the telescope (and one Maser!) in space.

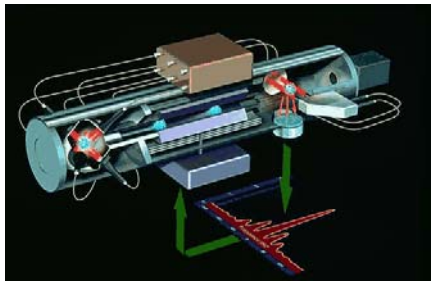


FUNDAMENTAL PHYSICS IN SPACE

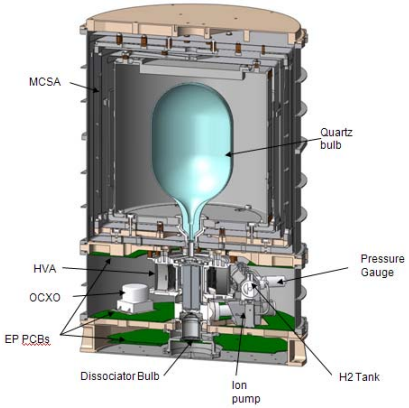


ACES

Atomic Clock Ensemble in Space



SpectraTime

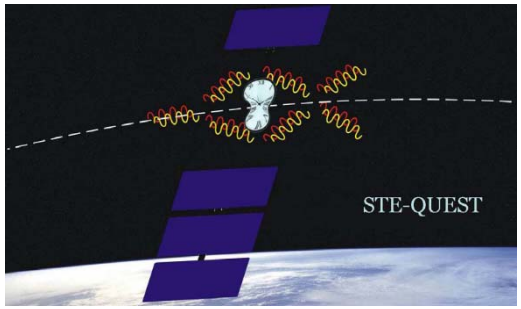


Micro-gravity

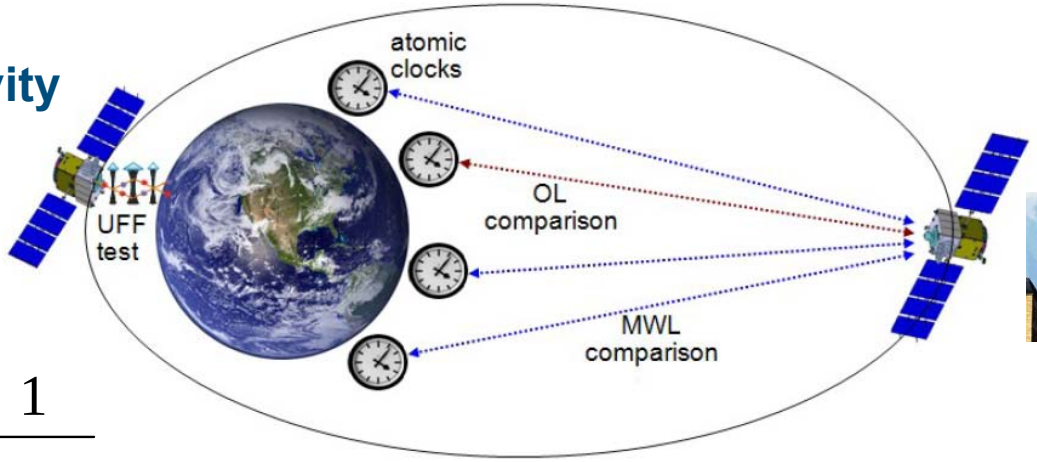
STE-QUEST

(Space-Time Explorer and
Quantum Equivalence Principle Space Test)

A class M mission proposal for Cosmic Vision 2015-2025



Relativity



$$\frac{1}{Q} \propto \frac{1}{\omega_0 \cdot \tau}$$

SPACE PASSIVE HYDROGEN MASER FOR GNSS

GNSS: Global Navigation Satellite System

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

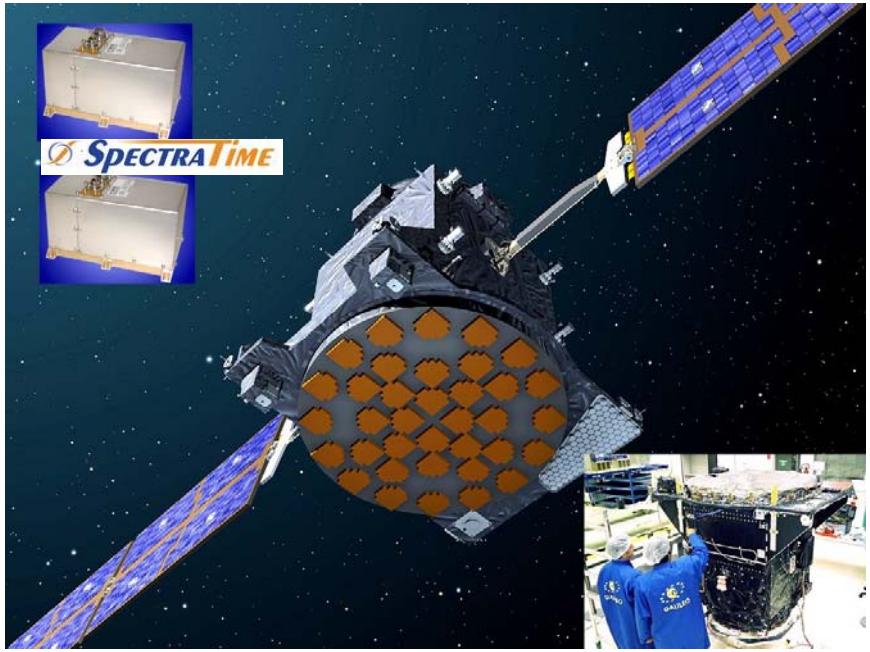
18 kg, 28 L, $7 \cdot 10^{-13}$ @ 1 s

GALILEO (EUROPEAN SATELLITE NAVIGATION SYSTEM)

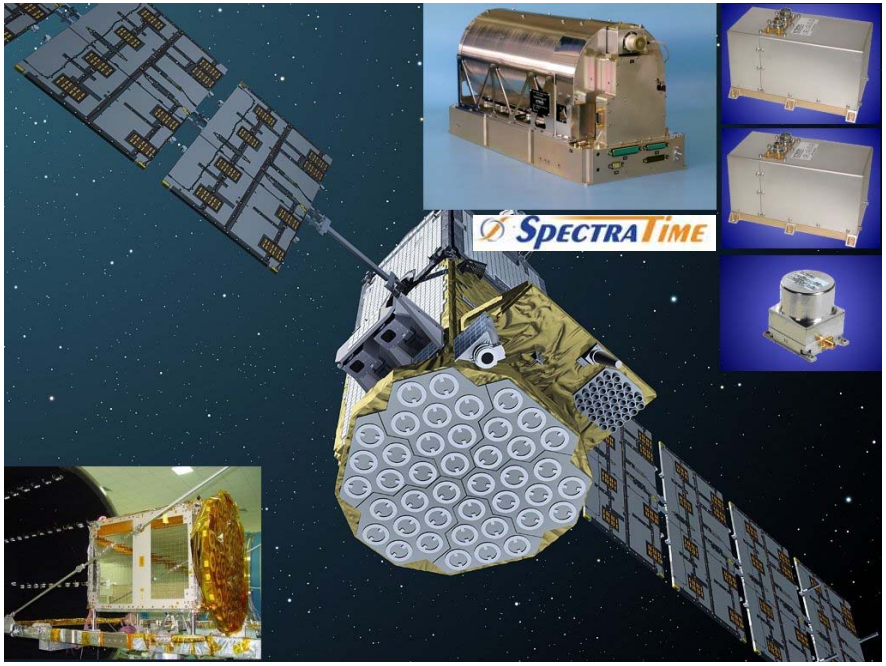
In space: Rubidium, passive Hydrogen Maser (1° generation)

On earth: (quartz), Rubidium, Cesium beams, active H Masers (1° generation)

GIOVE-A (launched 28 Dec 2005)

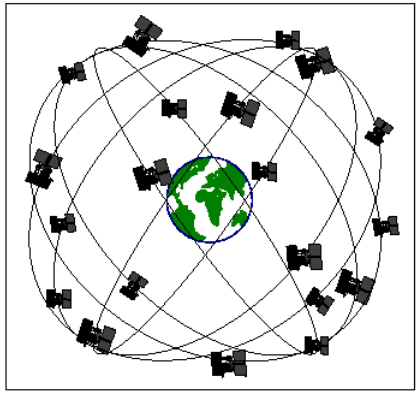


GIOVE-B (launched 26 April 08)



2011 and 2012: launch of first operational satellites (IOV – In Orbit Validation)

WHY RB CLOCK AND PASSIVE H MASER ON GALILEO?



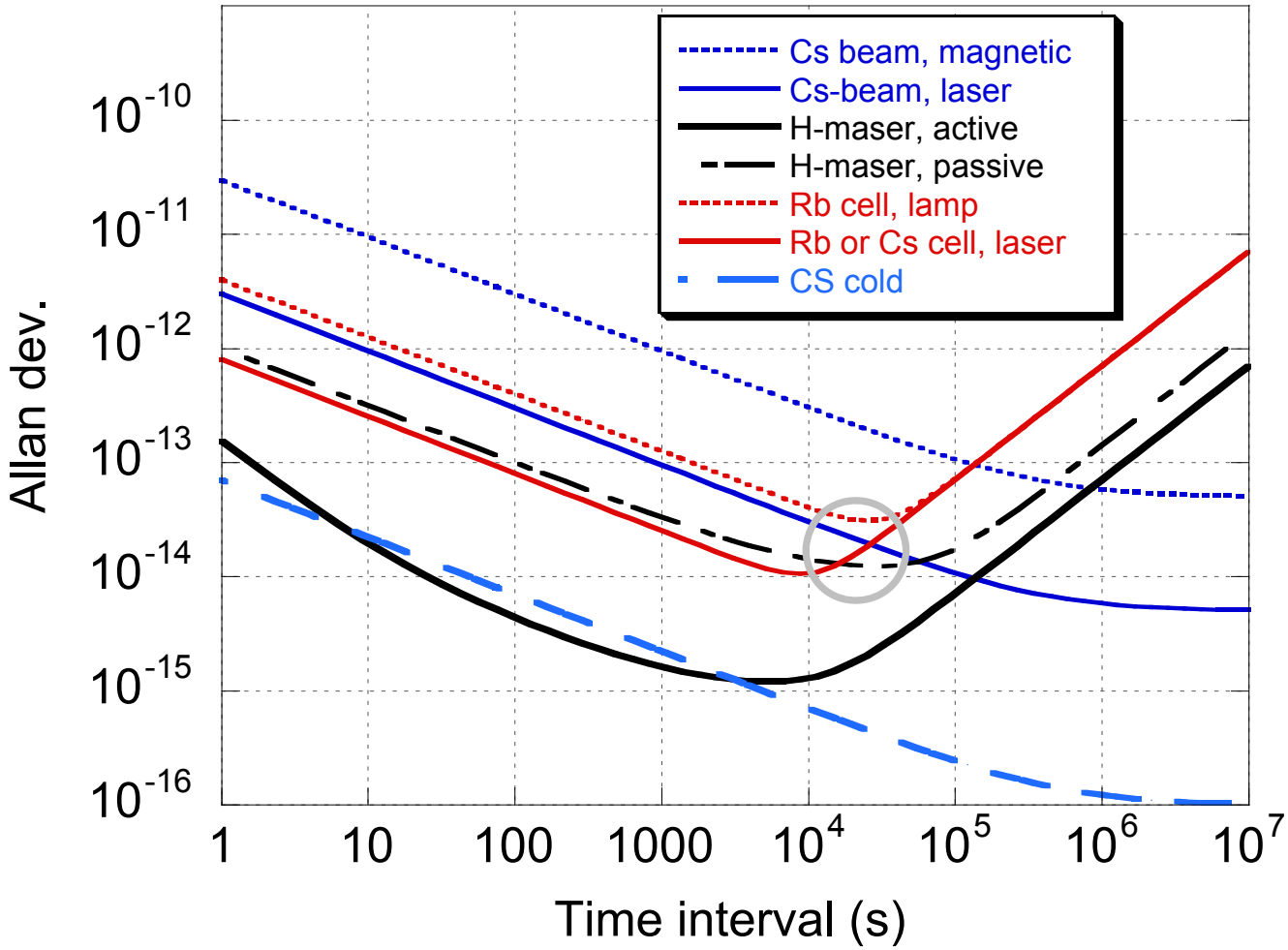
For 30 cm accuracy

Maximal Time error:

1 nanosecond for

1s < τ < 20’000 s

$$\sigma_y(20'000\,s) \approx 10^{-14}$$



OUTLINE OF THE TALK

1) Introduction to atomic frequency standards

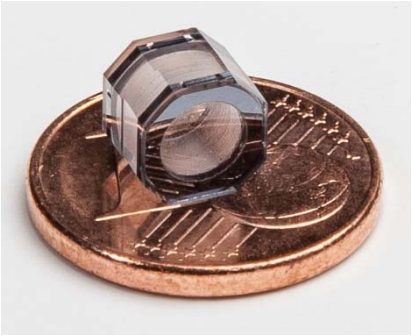
Basic (functional and physical) principles

Examples and applications of frequency standards

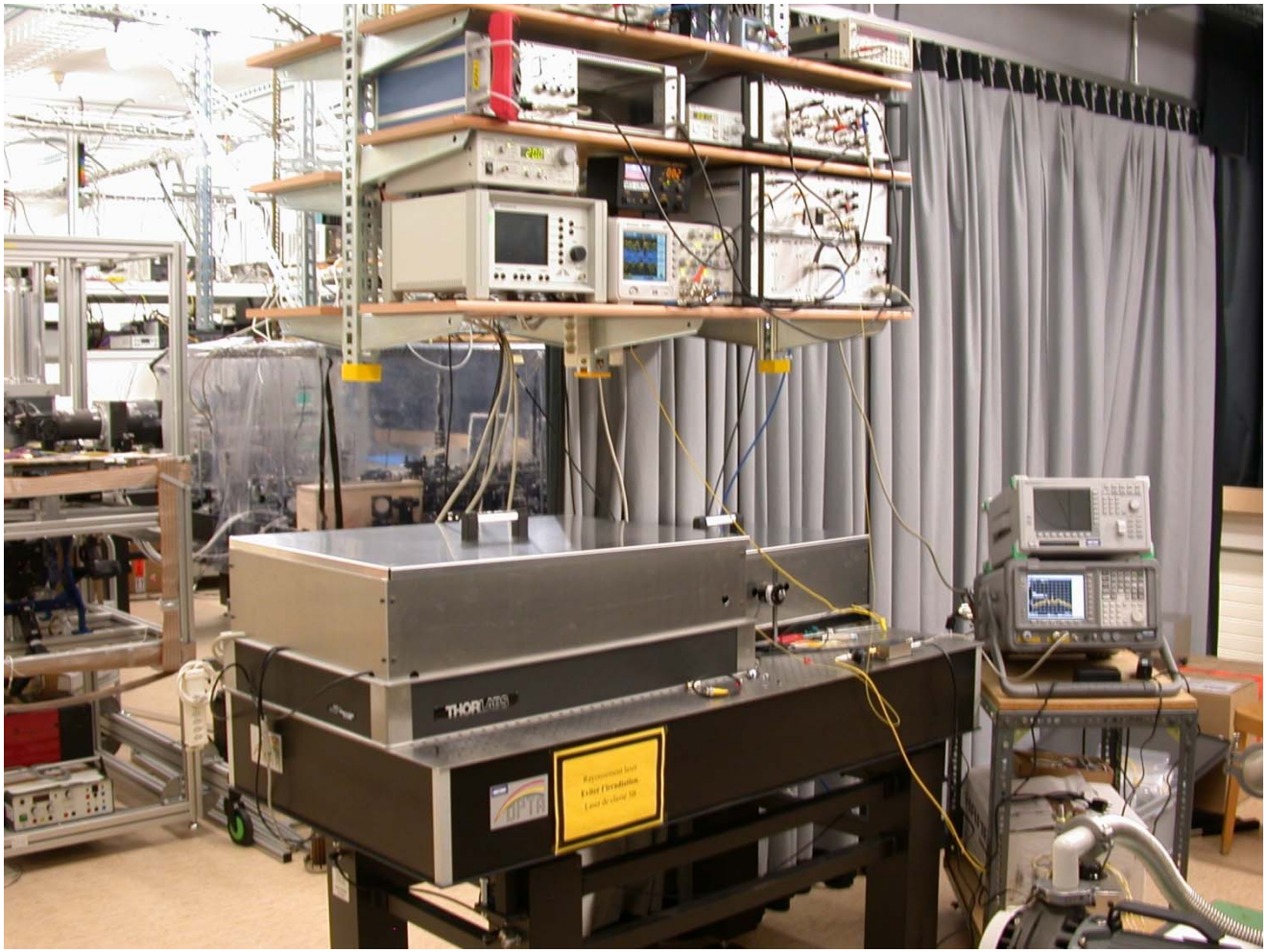
2) Current trends in the field

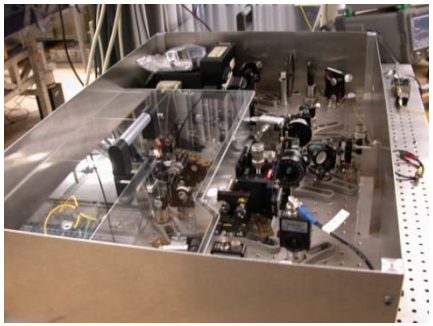
Optical frequency standards

Chip-scale atomic clocks



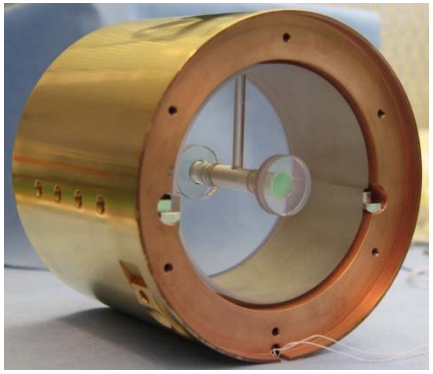
OPTICAL FREQUENCY STANDARDS



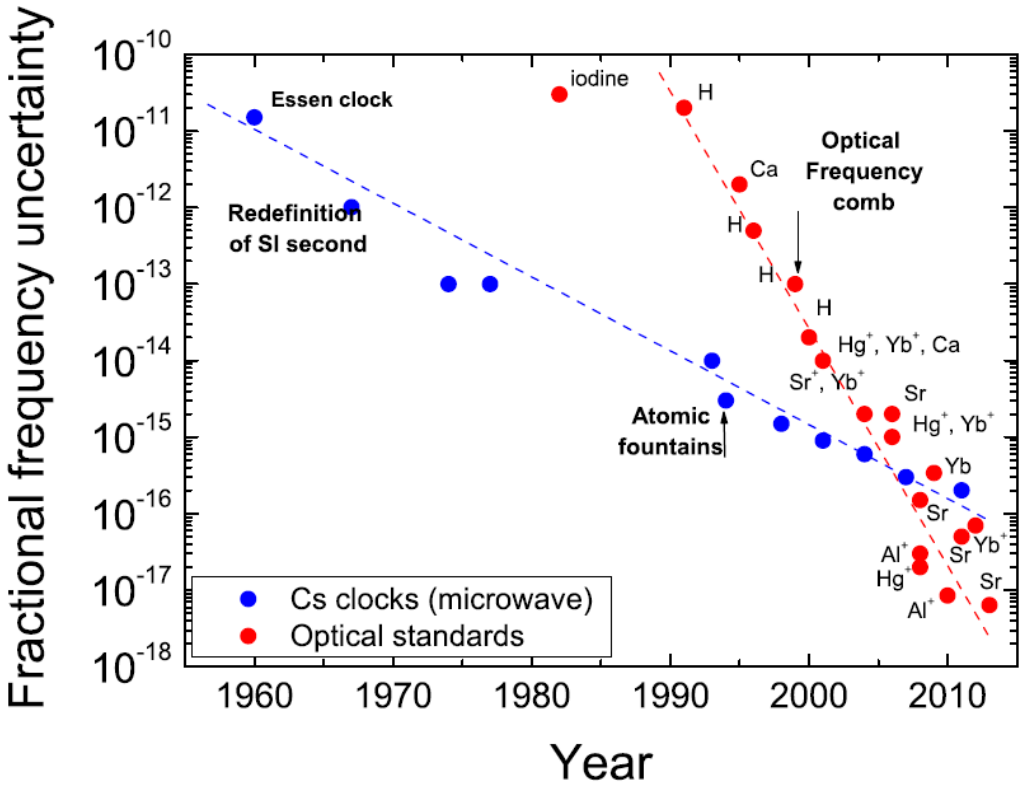


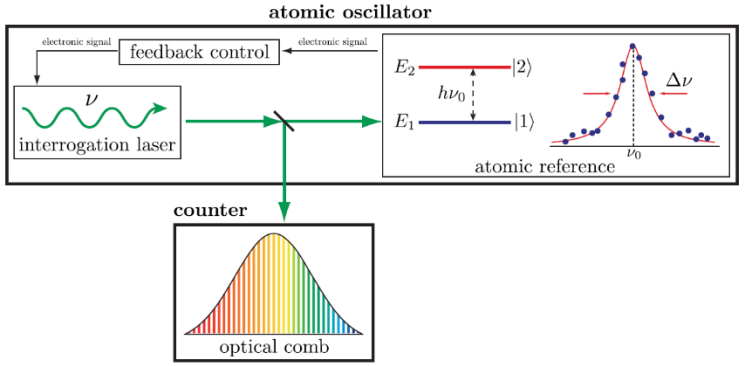
$$\frac{1}{Q} \propto \frac{1}{\omega_0 \cdot T_R}$$

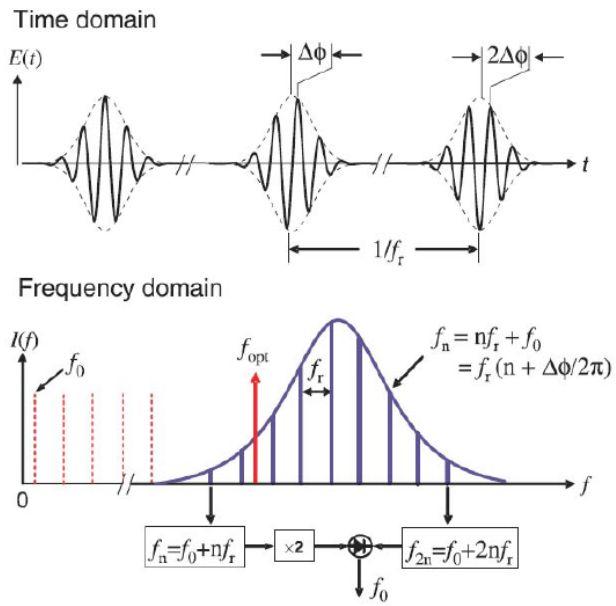
ω_0: $10^{10} \rightarrow 10^{15}$ Hz



MICROWAVE AND OPTICAL CLOCKS







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DOI 10.1393/ncr/i2013-10095-x

Optical atomic clocks

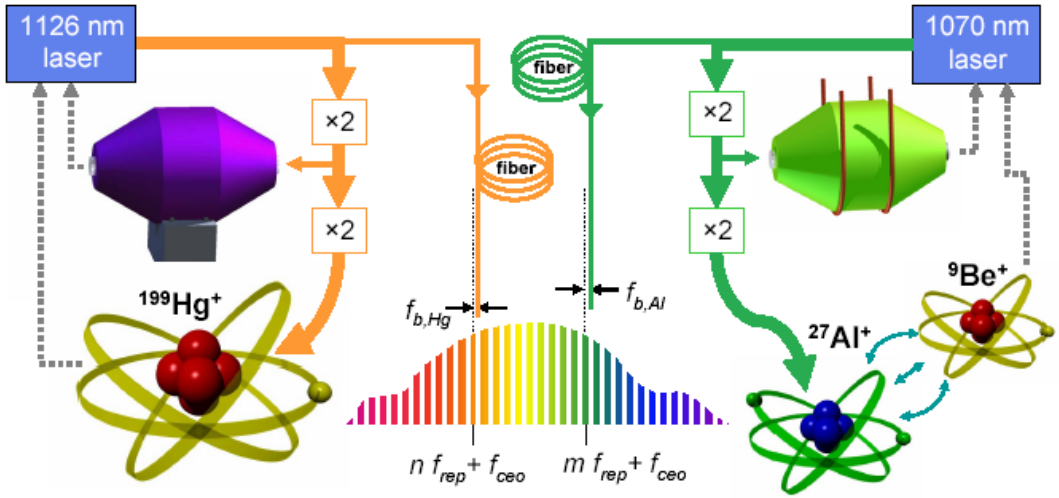
N. Poli(1), C. W. Oates(2), P. Gill(3) and G. M. Tino(1)(*)

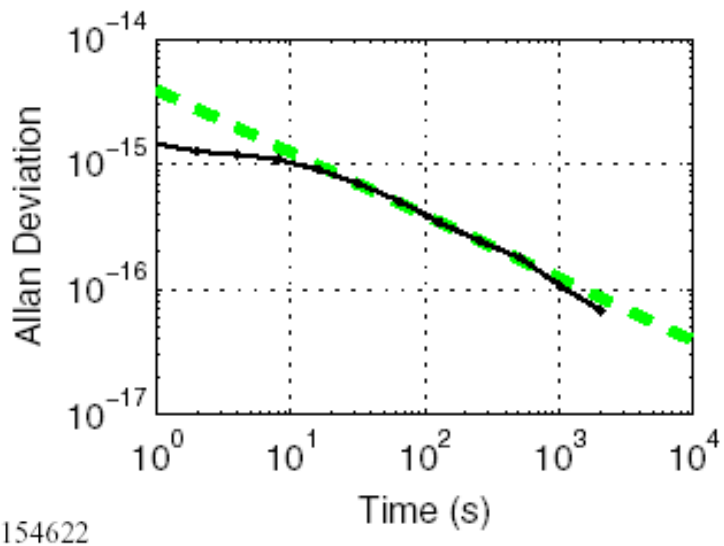
OPTICAL CLOCKS WITH SINGLE IONS AND QUANTUM LOGIC

UNIVERSITÉ DE NEUCHÂTEL

Frequency Ratio of Al^+ and Hg^+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

T. Rosenband,* D. B. Hume, P. O. Schmidt,† C. W. Chou, A. Brusch, L. Lorini,‡ W. H. Oskay,§ R. E. Drullinger, T. M. Fortier, J. E. Stalnaker,‖ S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist





Sciencexpress / www.sciencexpress.org / 6 March 2008 / Page 1 / 10.1126/science.1154622

EXAMPLE OF MORE RECENT ACHIEVEMENTS

Sciencexpress

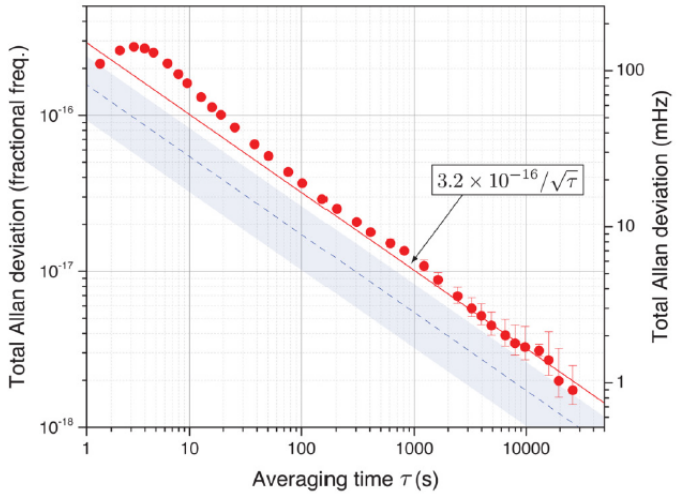
An Atomic Clock with 10^{-18} Instability

N. Hinkley,[1,2] J. A. Sherman,[1] N. B. Phillips,[1] M. Schioppo,[1] N. D. Lemke,[1] K. Beloy,[1] M. Pizzocaro,[1,3,4] C. W. Oates,[1] A. D. Ludlow[1]*

[1]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA. [2]University of Colorado, Department of Physics, Boulder, CO 80309, USA. [3]Instituto Nazionale di Ricerca Metrologica, Str. delle Cacce 91, 10135 Torino, Italy. [4]Politecnico di Torino, Corso duca degli Abruzzi 24, 10125 Torino, Italy.

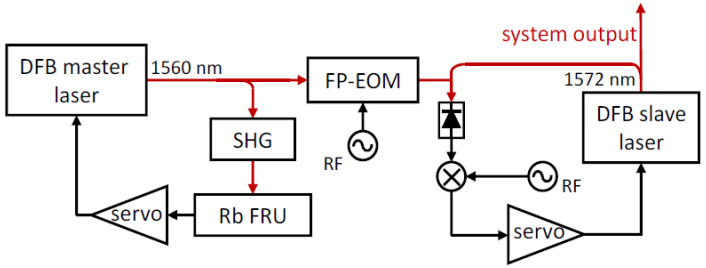
*Corresponding author. E-mail: ludlow@boulder.nist.gov

Atomic clocks have been instrumental in science and technology, leading to innovations such as global positioning, advanced communications, and tests of fundamental constant variation. Timekeeping precision at 1 part in 10^{18} enables new timing applications in relativistic geodesy, enhanced Earth- and space-based navigation and telescopy, and new tests of physics beyond the Standard Model. Here, we describe the development and operation of two optical lattice clocks, both utilizing spin-polarized, ultracold atomic ytterbium. A measurement comparing these systems demonstrates an unprecedented atomic clock instability of 1.6×10^{-18} after only 7 hours of averaging.



Sciencexpress / http://www.sciencemag.org/content/early/recent / 22 August 2013 / Page 1 / 10.1126/science.1240420

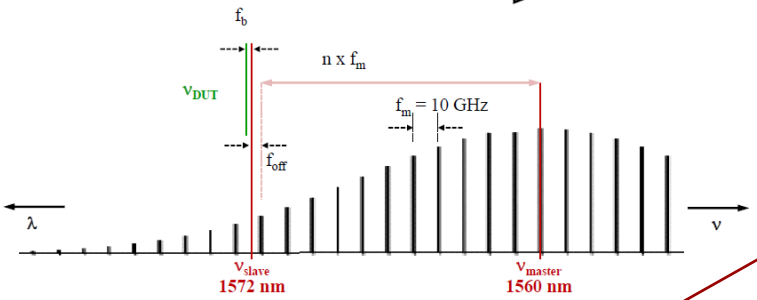
STABILISED LASERS & COMB FOR A (SPACE) CO2 LIDAR

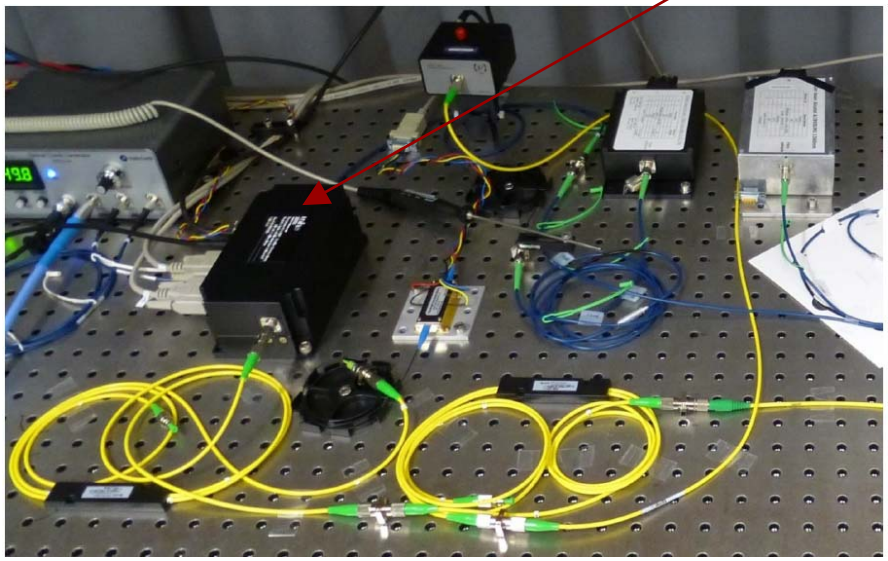


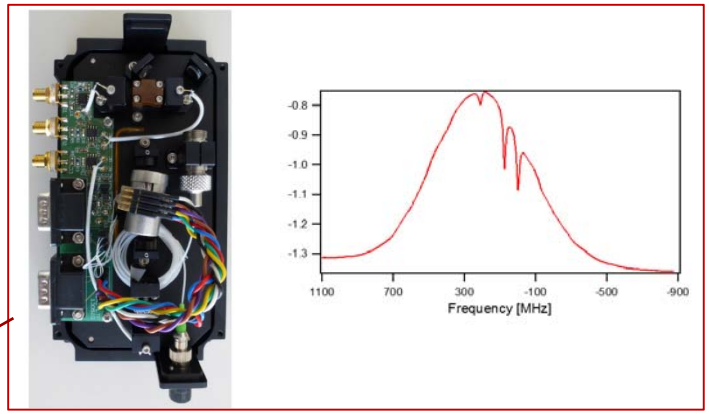
SHG: second-harmonic generation

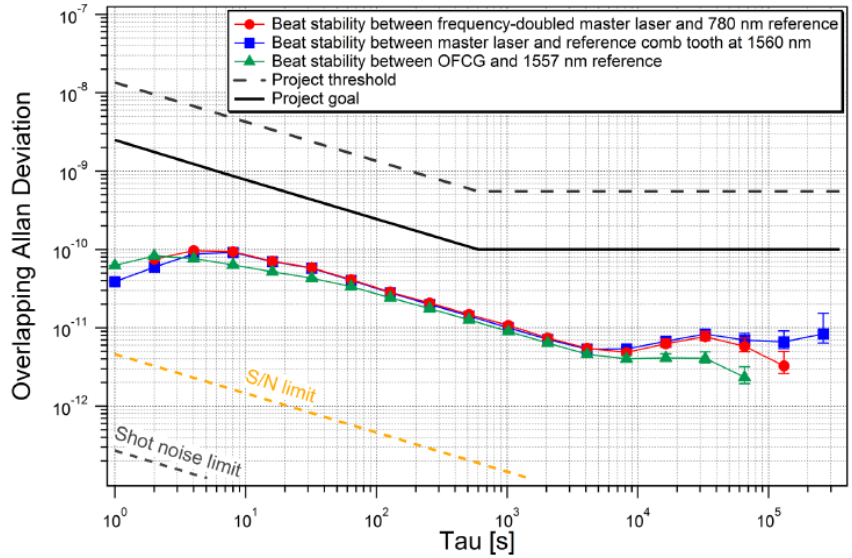
FP: Fabry Perot

EOM: electro-optical modulator





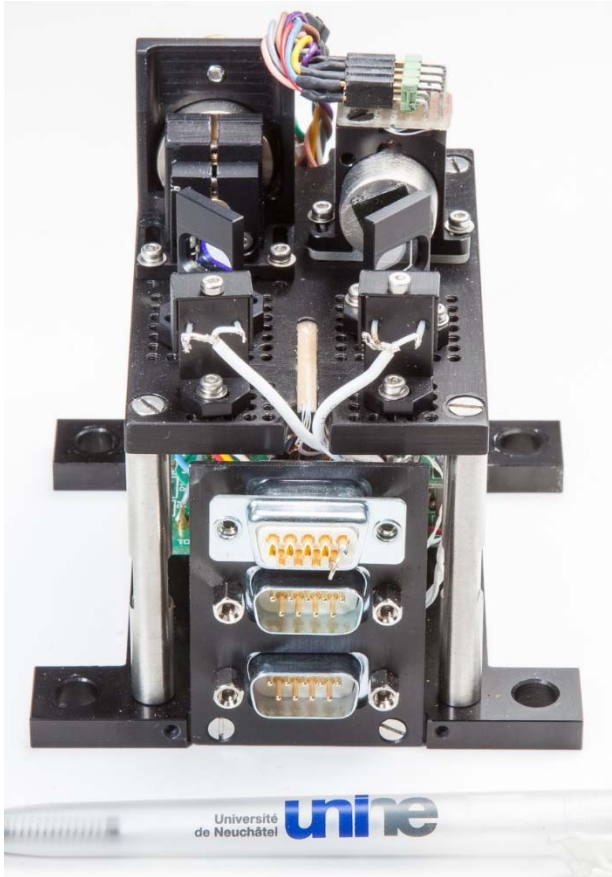


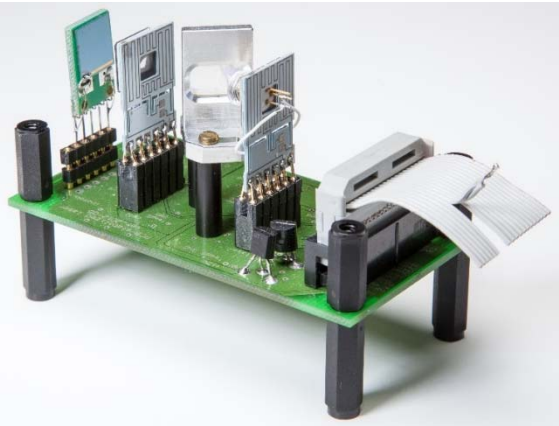


R. Matthey, F. Gruet, S. Schilt, G. Mileti, Rb-based Stabilized Laser System as Frequency Reference for CO2 Monitoring, Proceedings of the European Frequency and Time Forum (EFTF), Neuchâtel, June 23-27, (2014)

OTHER COMPACT AND MINIATURE STABILISED LASERS

R. Matthey, L. Stauffer, P. Giaccari, A. Pollini, L. Balet, G. Mileti, *Assembly Technique for Miniaturized Optical Devices: Towards Space Qualification*, Proc. of the International Conference on Space Optics (ICSO), Ajaccio, (2012)



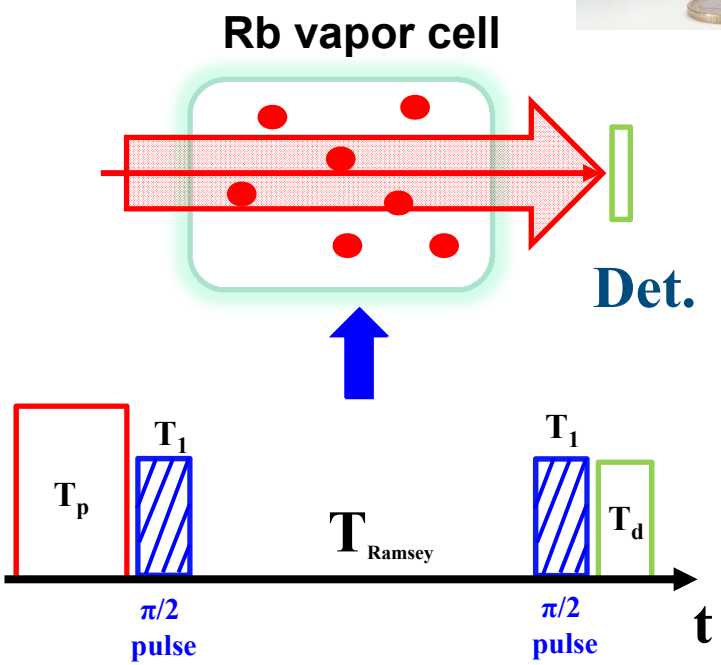


F. Gruet, F. Vecchio, C. Affolderbach, Y. Pétremand, N. F. de Rooij, T. Maeder, G. Mileti, *A Miniature Frequency-Stabilized VCSEL system emitting at 795 nm based on LTCC modules*, submitted to **Optics and Lasers in Engineering**, 51, 8, 1023–1027, (2013)

RAMSEY INTERROGATION IN A CELL STANDARD

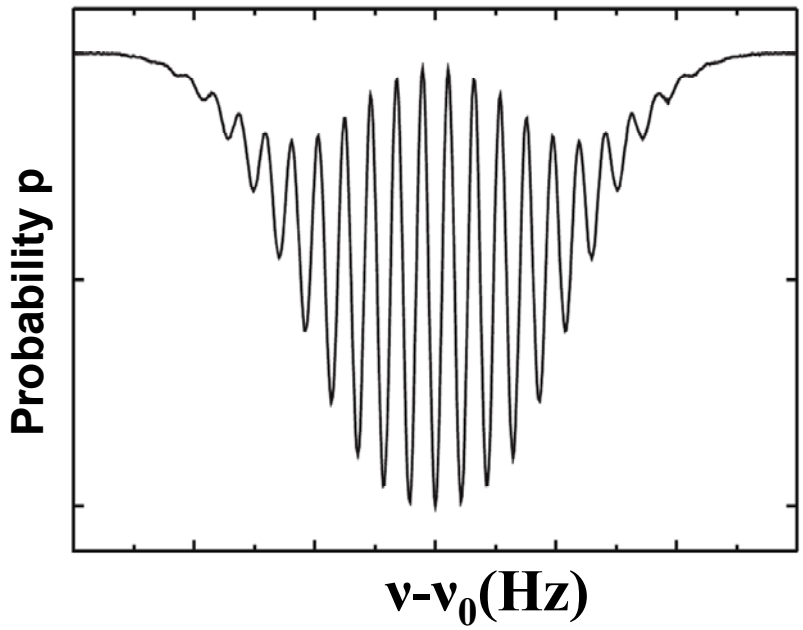
Time-domain Ramsey scheme:

- Optical pumping(T_P)
- Microwave pulse interrogation (T_1, T_{Ramsey})
- Optical Detection (T_d)



Advantages:

- ✓ Compactness
- ✓ Narrow linewidth
- ✓ Negligible light shift



S. Kang, C. Affolderbach, F. Gruet, M. Gharavipour, C. E. Calosso, G. Mileti, *Pulsed optical pumping in a Rb vapor cell using a compact magnetron-type microwave cavity*, EFTF-2014

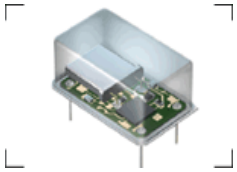
MINIATURE ATOMIC CLOCKS

⇨ Bring atomic timing precision to the size and power range previously covered by quartz oscillators

New clocks !








	Primary Standard	Commercial Beam Clock	Compact Atomic Clock	Miniature Atomic Clock	Precision Quartz	Wristwatch Quartz
Accuracy:	10^{-15}	10^{-13}	10^{-11}	10^{-10}	10^{-7}	10^{-5}
Timing error:	10ns/yr	1μs/yr	0.1μs/day	1μs/day	100μs/day	1s/day
Size:	10^7 cm^3	10^4 cm^3	100 cm^3	10 cm^3	1-10 cm^3	10 mm^3
Power:	kW	100's W	1 W	120mW	100 mW	10 μW
Cost:	>$1 M	$50 k	$2,000	$300	$100	$1

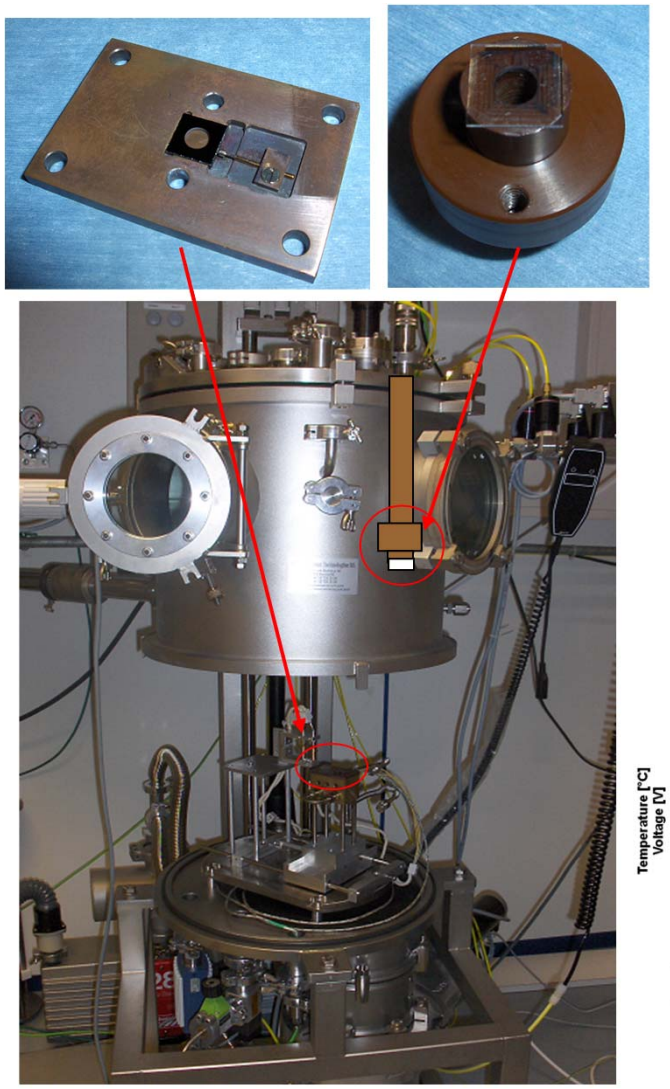
Decreasing performance and size/power/cost

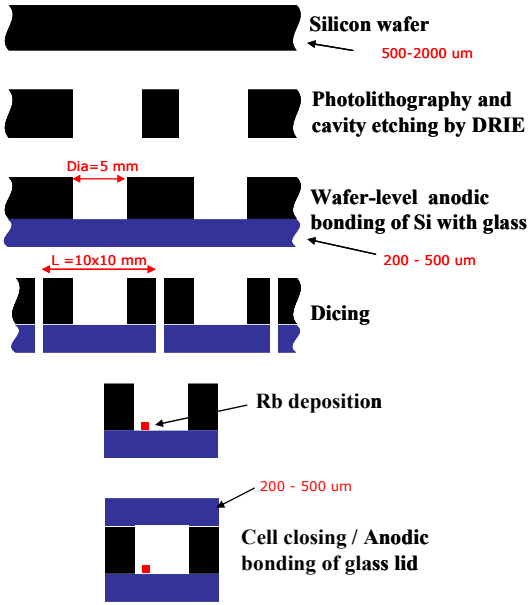
NEUCHÂTEL ANODIC BONDING TECHNOLOGY

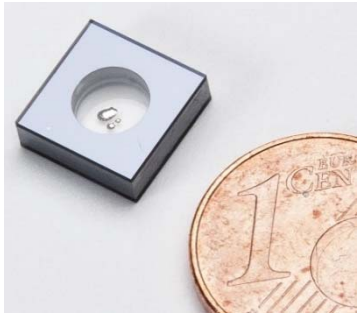
UNIVERSITÉ DE NEUCHÂTEL

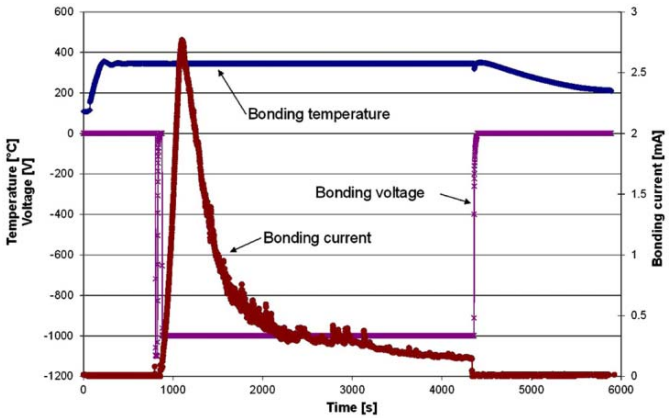
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IMT-SAMLAB









J. Di Francesco, F. Gruet, C. Schori, C. Affolderbach, R. Matthey, G. Mileti, Y. Salvadé, Y. Petremand, N. De Rooij, *Evaluation of the frequency stability of a VCSEL locked to a micro-fabricated Rubidium vapour cell*, SPIE Photonics Europe, Bruxelles, April (2010)

SPECIAL MINIATURE CELLS

4-mm size Rb cells

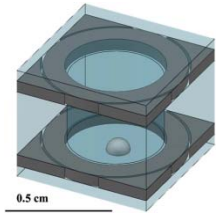
Micro-fabrication technology for precise control of cell geometry

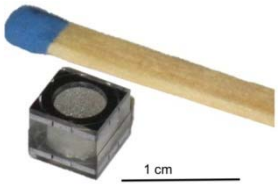
Multi-stack anodic bonding:

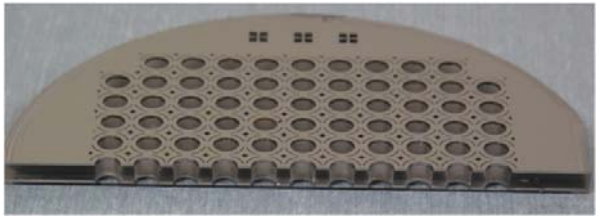
⇨ Thick glass core wafer

⇨ 2 Si layers + 2 glass windows

⇨ 4 steps of anodic bonding





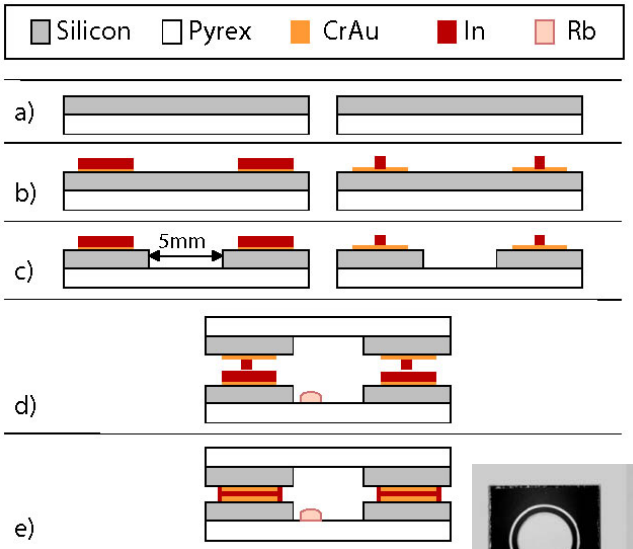


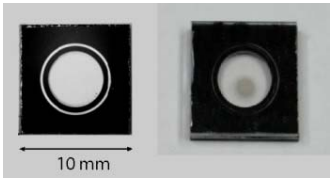
Y. Pétremand, C. Affolderbach, R, Straessle, M. Pellaton, D. Briand, G. Mileti and N. F. de Rooij, *Microfabricated rubidium vapour-cell with a thick glass core for small scale atomic clock applications*, **Journal of Micromechanics and Microengineering**, 22, 025013, (2012)

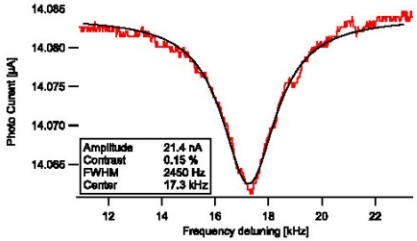
Indium cell sealing

Low-temperature sealing (≤ 140°C)

⇨ alkali control & wall coatings







Working alkali cells

R. Straessle, M. Pellaton, Y. Pétremand, C. Affolderbach, D. Briand, G. Mileti, and N. F. de Rooij, *Low-Temperature Indium Hermetic Sealing of Alkali Vapor-Cells for Chip Scale Atomic Clocks*, submitted to **Journal of Applied Physics**, 113, issue 6, 064501/1-8, (2013)

QUANTIME – A MINIATURE CESIUM ATOMIC CLOCK USING CPT TECHNIQUE FOR TELECOM APPLICATIONS (CTI REF. 13'818.2)

UNIVERSITÉ DE NEUCHÂTEL

Miniature cesium atomic clock

CPT (Coherent population trapping) technique

Applications

Telecom (4G LTE base stations)

Smart grid (power distribution)

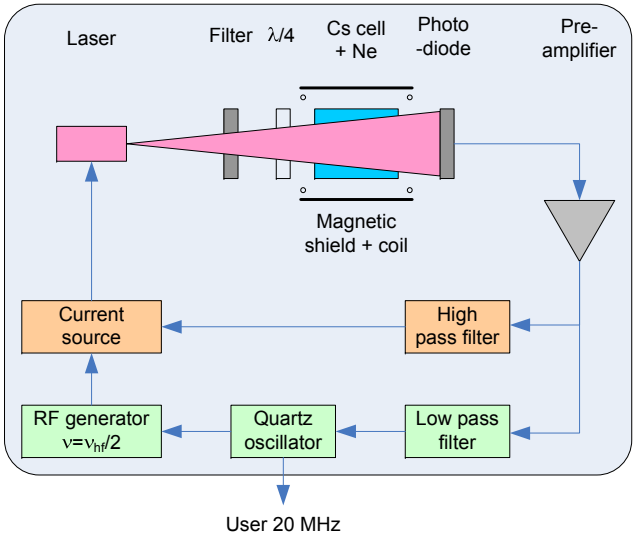
Product specifications

Superior frequency and time stability: 1 μs/day

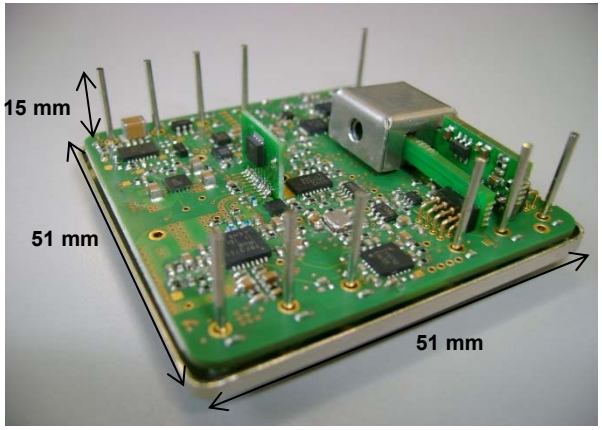
Compact size: 51x51x18 mm3

Low power: 2W

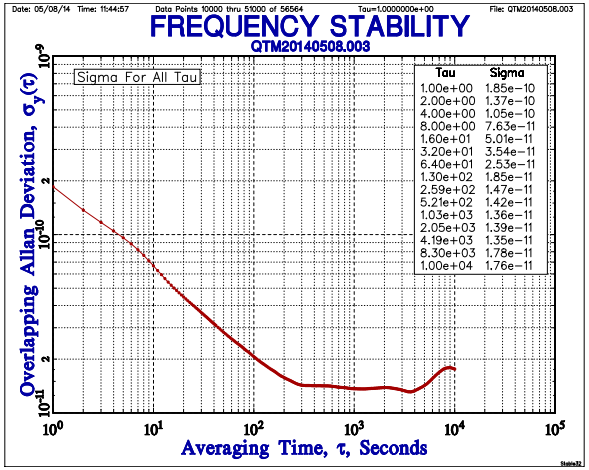
Lower price: 400 CHF



Clock implementation



Prototype picture



OSCILLOQUARTZ An ADVA Optical Networking Company

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITÉ DE NEUCHÂTEL

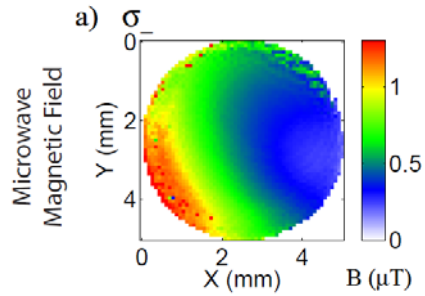
csem

Y. Zhao, S. Tanner, A. Casagrande, L. Schneller, C. Affolderbach, G. Mileti, P.-A. Farine, *A 4.6-GHz, 15-mW Frequency Synthesizer CMOS ASIC for Miniature Atomic Clocks*, **IEEE Transactions on Microwave Theory and Techniques**, (2014)

OTHER RECENT DEVELOPMENTS

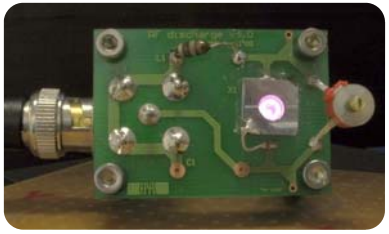
Imaging of microwave field and atoms relaxation time

A. Horsley, G.-X. Du, M. Pellaton, C. Affolderbach, G. Mileti, P. Treutlein, *Imaging of Relaxation Times and Microwave Field Strength in a Microfabricated Vapor Cell*, **Physical Review A**, 88, 063407, (2013)



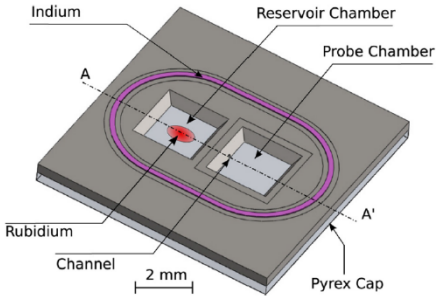
Microfabricated discharge lamps

V. Venkatraman, S. Kang, C. Affolderbach, H. Shea and G. Mileti, *Optical pumping in a microfabricated Rb vapor cell using a microfabricated Rb discharge light source*, **Applied Physics Letters**, 104, 054104, (2014)



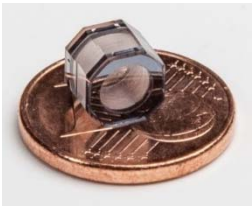
Microfabricated cells with wall coating

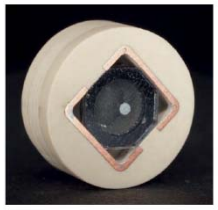
R. Straessle, M. Pellaton, C. Affolderbach, Y. Pétremand, D. Briand, G. Mileti, and N. F. de Rooij, *Microfabricated Alkali Vapor Cell with Anti-Relaxation Wall Coating*, **Applied Physics Letters,** 105, 043502 (2014)



Double resonance with miniature microwave cavity and Rb cell

M. Violetti, M. Pellaton, F. Merli, J.–F. Zürcher, C. Affolderbach, G. Mileti, A. K. Skrivervik, *The Micro Loop-Gap Resonator: A Novel Miniaturized Microwave Cavity for Double-Resonance Rubidium Atomic Clocks*, **IEEE Journal of Sensors**, 14, 9, (2014)





Summary

- Thanks to the latest discoveries in atomic physics and photonics (or photon engineering) the precision of atomic clocks is being improved down to **10^{-16} and beyond**;
- More precisely, it is the **manipulation of atoms photons** and the availability of **tunable laser sources** and **optical combs** which is allowing such dramatic improvements:

$$(In)stability \propto \frac{\Delta\omega_0}{\omega_0} \propto \frac{1}{\omega_0 \cdot T_R}$$

T_R : cooling
ω_0: going optical

- Atomic clocks (and stabilized lasers) are key instruments for **fundamental physics experiments** on ground and **in space**;
- Compact high performance and **miniature atomic clocks** find many applications in every day life (positioning, telecoms, etc.)
- **Micro-fabrication techniques** are crucial for extreme miniaturization
- With its tradition in Time keeping, precision mechanics, micro-technology, optical metrology and space science & technology, Switzerland makes crucial contributions to this domain

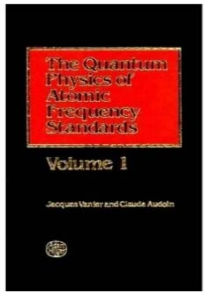
ESSENTIAL BIBLIOGRAPHY

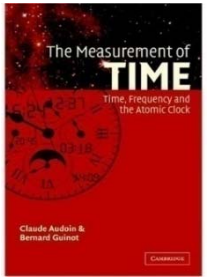
- Jacques Vanier, Claude Audoin, **"*The Quantum Physics of Atomic Frequency Standards*"**, Bristol: Adam Hilger, 1989.

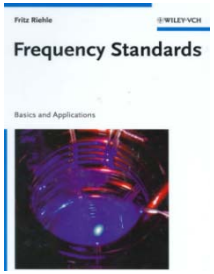
- Claude Audoin, Bernard Guinot, Stephen Lyle, ***"The Measurement of Time: Time, Frequency and the Atomic Clock "***, Cambridge, (Original in french: Masson, 1998).

- Fritz Riehle, **"*Frequency standards – Basics and applications*"**, Wiley-VCH, 2005.

- Special issue of Metrologia: **"*Special issue: fifty years of atomic time-keeping: 1955 to 2005"***, *Volume 42, Number 3, June 2005.*







<u>Time & Frequency conferences proceedings</u> (including tutorials)

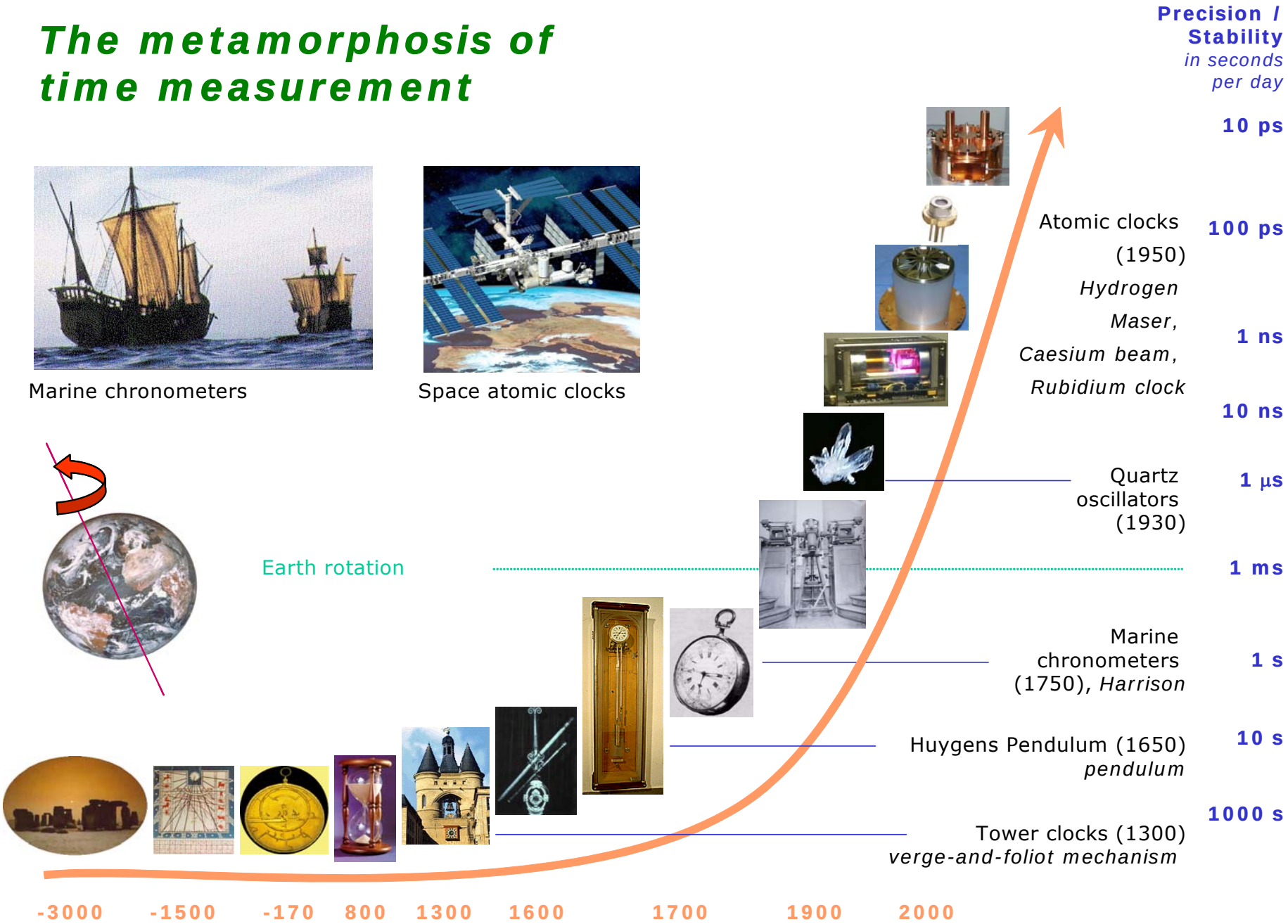
www.eftf.org (free) → EFTF-2014 in Neuchâtel (June 23-26 2014)
www.pptimeeting.org (on subscription)
www.ieee-uffc.org/main/publications/fcs/index.asp (on subscription)

European Time and Frequency Seminar (EFTS) – July 2014 in Besançon (F)

NIST Time & Frequency Seminar – June 2014 in Boulder (CO, USA)

CUSO doctoral school on atomic clocks (2010, 2012 & 2014)

The metamorphosis of time measurement



THANK YOU FOR YOUR ATTENTION !

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