MEASUREMENT OF TIME & FREQUENCY, ATOMIC CLOCKS AND APPLICATIONS

Gaetano Mileti

Laboratoire Temps - Fréquence (LTF)

Institut de Physique, Faculté des Sciences

Université de Neuchâtel, Suisse

OUTLINE

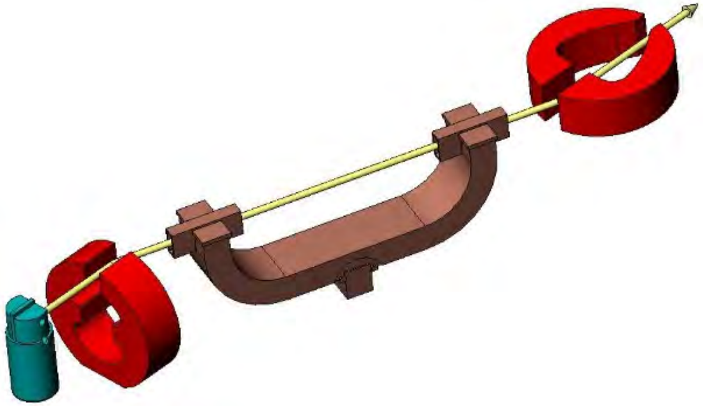
<u>Part 1:</u> Introduction and historical background

The evolution of Time & Frequency

<u>Part 2:</u> Atomic frequency standards

General aspects and applications

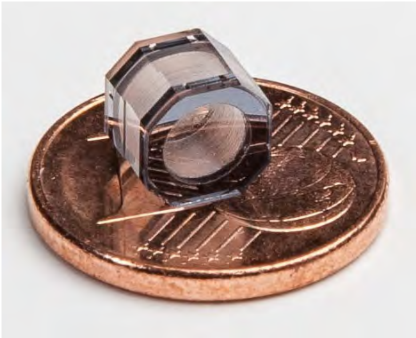
Examples of frequency standards



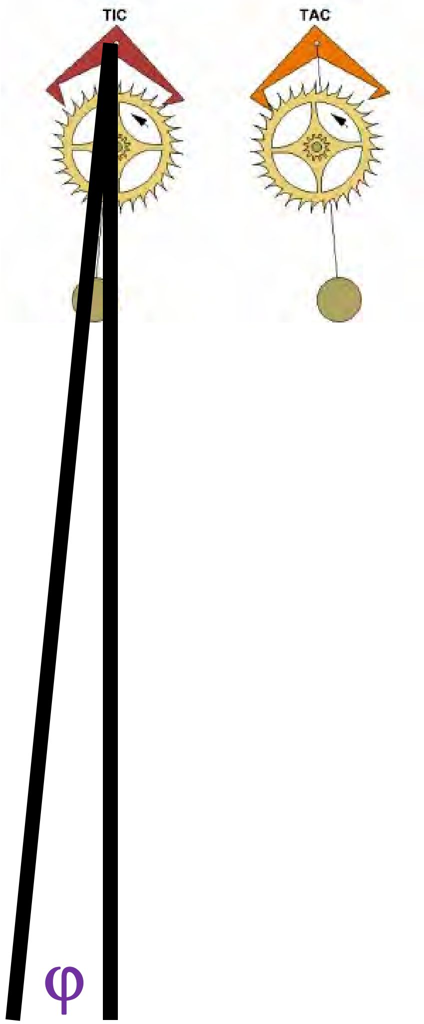
<u>Part 3:</u> Rubidium standards and miniature atomic clocks

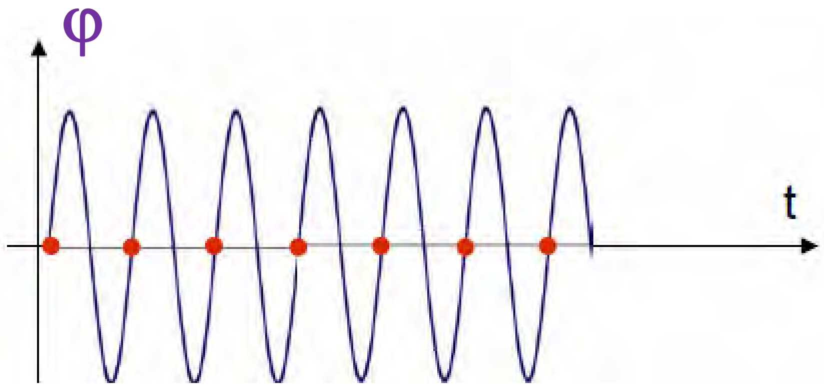
Rubidium frequency standards

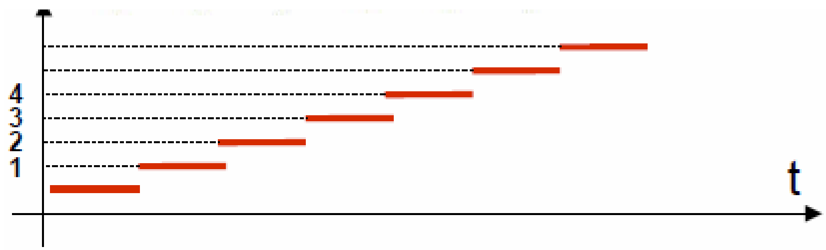
Miniature atomic clocks



MEASUREMENT OF TIME AND OSCILLATIONS







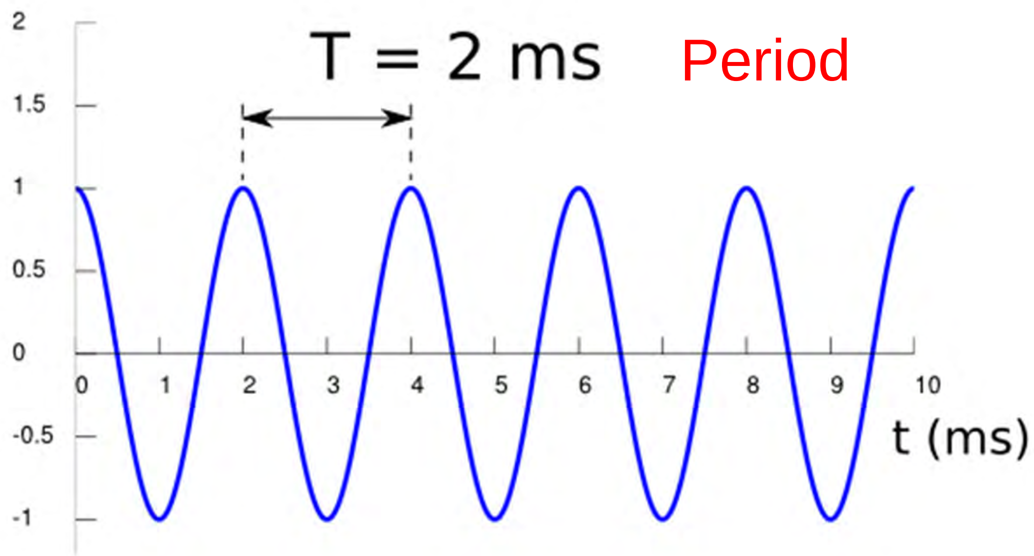
MEASUREMENT OF TIME AND «COMPLICATIONS»

Technological aspects, scientific aspects, societal aspects (applications)

PERIOD AND FREQUENCY OF AN OSCILLATOR

Oscillation

Periodic phenomenon



Frequency

$$f = \nu = \frac{1}{T} = \frac{1}{0.002\ s} = 500\ \text{Hz}$$

Electrical network: 50 Hz

Radio FM: 30 to 300 MHz

Wifi and microwave: 3 à 30 GHz

Laser (CD player): 100 à 400 THz

Frequency standard

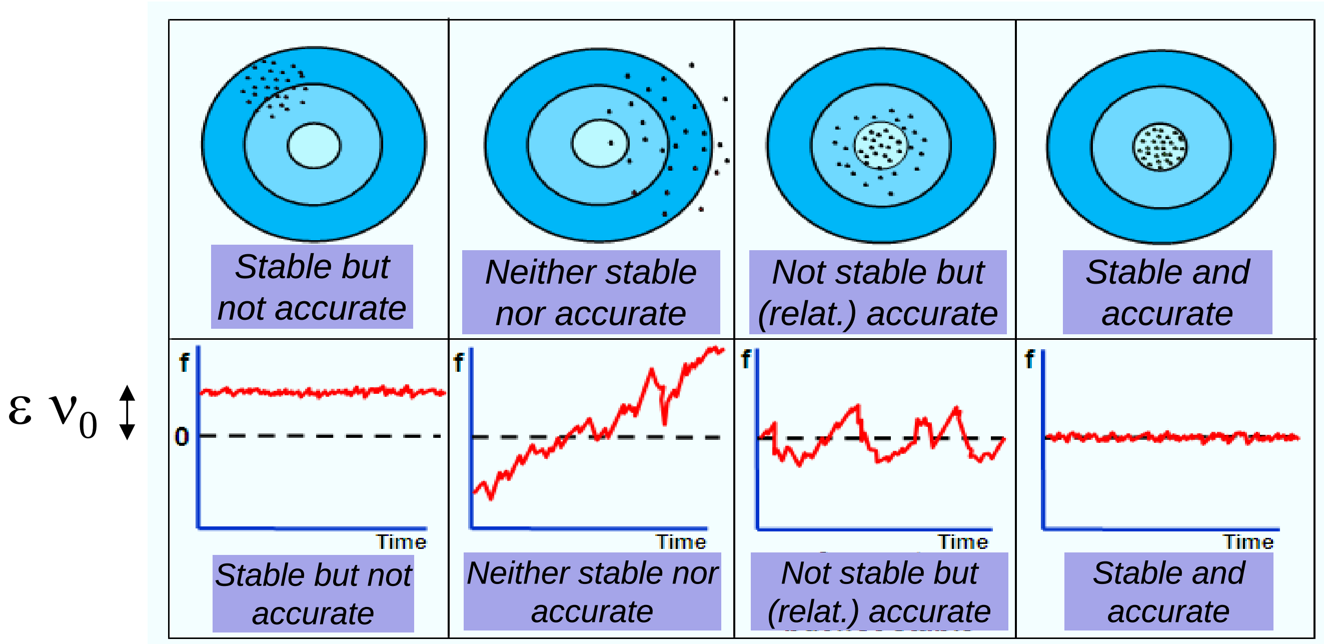
STABILITY AND ACCURACY (OR PRECISION)

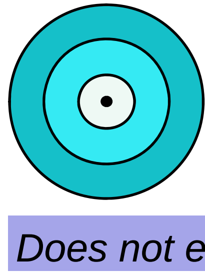
Frequency of the oscillator (real one): $\nu(t) = \nu_0 \left[1 + \epsilon + y(t)\right]$

Nominal frequency (ν_0)

Normalised systematic bias (ϵ)

Normalised instability (statistical fluctuations) ($y(t)$)





But approaching it as much as possible constitute one of the objectives of our research

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

How to measure / evaluate the stability and the accuracy of an oscillator (or a clock)?

- By comparing it with a more stable and/or accurate oscillator (reference, standard, etc.)
- Thanks to statistical and metrological studies

EXAMPLES OF NORMS: WRISTWATCHES

Reference: **ISO 3159** norm

Daily rate ~ daily inaccuracy (in s)

Source: COSC CONTRÔLE OFFICIEL SUISSE DES CHRONOMÈTRES

Minimum Requirements (for balance spring wristwatches) - Type I

Symbol	Criterion	Limit [s/d]	
		Category 1	Category 2
Avg R	Average daily rate	-4 +6	-5 +8
Avg V	Mean variation in rate	2	3.4
Max V	Greatest variation in rates	5	7
D	Difference between rates in horizontal and vertical positions	-6 +8	-8 +10
P	Largest variation in rates	10	15
C	Thermal variation	+/- 0.6	+/- 0.7
R	Rate resumption	+/- 5	+/- 6
The minimum requirements are considered absolute limits and no calculation result is rounded up or down.			

Minimum Requirements (for Quartz Oscillator Wristwatches) - Type IV

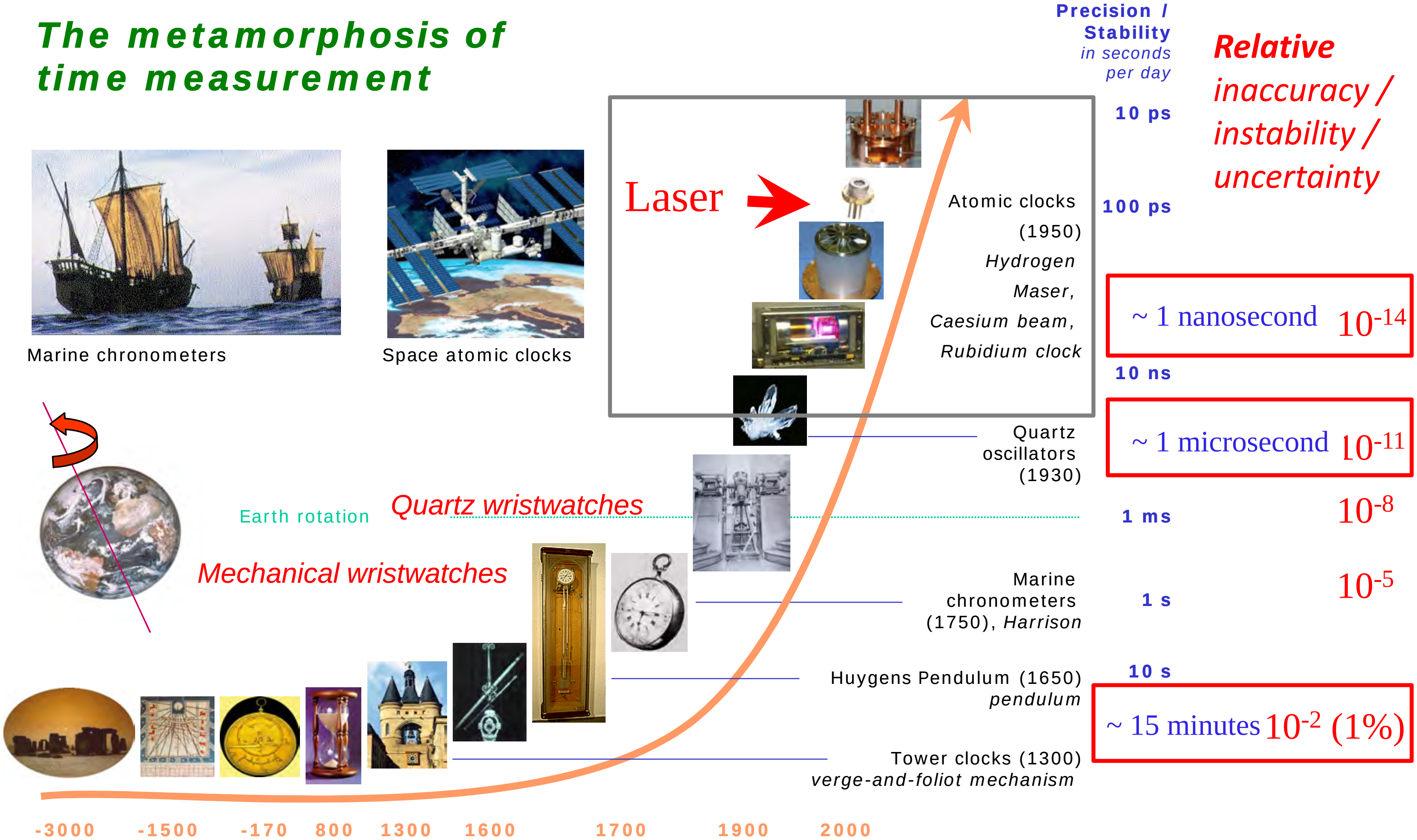
Symbol	Criterion	Limite[s/d]
Avg R	**Average daytime rate at 23°C**	**± 0.07**
M_{T8}	**Rate at 8°C**	**± 0.20**
M_{T38}	**Rate at 38°C**	**± 0.20**
SM	**Rate stability**	**0.05**
R	**Rate resumption**	**± 0.05**
Ht	**Humidity – temporary effect**	**± 0.10**

Best: **~ 0.001 s /day**, corresponds to **10^{-8}**

Best: **~ 0.1 s / day** corresponds to a **relative instability** of approximately **10^{-6}**

RESEARCH AND MEASUREMENT OF TIME

The metamorphosis of time measurement



RECENT NOBEL PRIZES IN PHYSICS

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.)

MEASUREMENT OF TIME IN NEUCHÂTEL

Souvenirs from Observatoire Cantonal de Neuchâtel

1750

-

1850

A. L. Breguet

F. Berthoud

1883 A. Hirsch

VERHANDLUNGEN

SIEBENTEN ALLGEMEINEN CONFERENZ

DER EUROPÄISCHEN GRADMESSUNG

A. HIRSCH. TH. v. OPPOLZER

CENTRALBUREAU DER EUROPÄISCHEN GRADMESSUNG.

COMPTES-RENDUS

SEPTIÈME CONFÉRENCE GÉODÉSIQUE INTERNATIONALE

A. HIRSCH. TH. v. OPPOLZER

BERLIN, 1884.

ANNULÉ

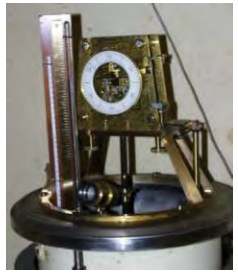
1920

C. E. Guillaume

ASTRONOMICAL TIME – MECHANICAL OSCILLATORS

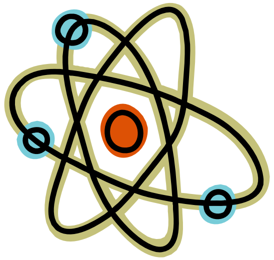
unine UNIVERSITÉ DE NEUCHÂTEL

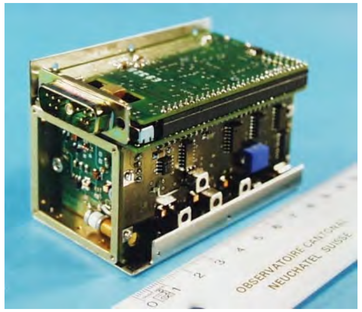
Observatoire de Neuchâtel (1858 – 2007)

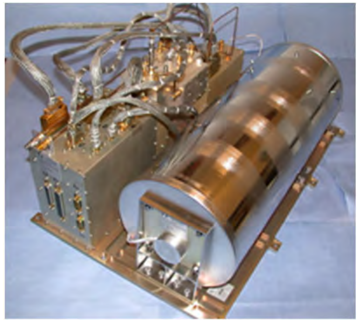


ATOMIC TIME – QUARTZ OSCILLATORS

Observatoire de Neuchâtel (1858 – 2007)







FIRST ATOMIC CLOCKS IN NEUCHÂTEL

UNIVERSITÉ DE NEUCHÂTEL

L´Express | vendredi, août 06, 1954 | 1

1954

UN JOURNALISTE FRANÇAIS DANS NOTRE VILLE

L'horloge atomique va naître à Neuchâtel

Grâce à nos savants, les hommes mesureront le temps avec encore plus d'exactitude

Le « Figaro littéraire » du 17 juillet a publié un fort intéressant article de M. Pierre de Latil, écrivain scientifique connu par son ouvrage sur « La cybernétique ». M. de Latil a fait le voyage de Neuchâtel, d'une part, pour admirer les automates Jaquet-Droz — que chacun connaît — et d'autre part, pour se renseigner sur la construction, au Laboratoire suisse de recherches horlogères, d'une horloge atomique — ce qui sera une révélation pour le profane de notre ville.

Fonds. Adepte de la cybernétique, nous n'étions pas sans quelque dédain pour de tels jouets qui, réglés une fois pour toutes, n'ont aucun degré de liberté.

Mais si le « dessinateur » et l'« écrivain » n'ont de souplesse que dans la main, la joueuse de clavecin est, elle, d'une grâce absolument étonnante. Certaines de ses révérences sont véritablement féminines. Non, la came poussant un ergot relié à un levier ne pourra jamais rien donner de moins méca-

elles plus ni balanciers ni roues dentées. Elles sont électroniques.

— Celle-ci, nous dit M. Quellet, ingénieur électronicien du laboratoire horloger, ne varie que d'un cent millième de seconde par jour. Et, comme le jour compte près de cent mille secondes, cela signifie que, sur la seconde, la précision est de l'ordre du dix milliardième. Une puissance moins dix, pour parler plus mathématiquement.

Nous étions dans les sous-sols du laboratoire. L'horloge n'avait rien

~ 0.01 ms /day, corresponds to $\mathbf{10^{-10}}$

L´Express | mardi, mars 18, 1958 | 6

1958

Instrument d'une extrême précision

L'horloge moléculaire est née à Neuchâtel

Après son exposition au pavillon suisse de Bruxelles, elle fonctionnera dans notre observatoire

Depuis les temps les plus anciens, l'homme a mesuré le temps d'après la rotation de la terre sur son axe. De la durée du jour, il a déduit la seconde. A cette unité se rapportent encore toutes les mesures du temps de la science et de la technique. Or, il y a vingt ans environ, on a constaté que la terre ne constitue pas une horloge absolument exacte. En effet, elle subit des variations de marche de l'ordre du millième de seconde par jour.

cylindre des oscillations accompagnées d'une émission d'ondes radio. La fréquence de ces ondes est la même que la fréquence des oscillations des molécules, environ 24 milliards à la seconde. Ce dispositif, produisant des ondes radio à l'aide

L´Express | mercredi, juillet 15, 1959 | 20

1959

Au Laboratoire suisse de recherches horlogères : d'intéressantes recherches

A l'occasion de son assemblée annuelle, tenue sous la présidence de M. Sydney de Coulon et en présence des représentants des organisations horlogères, le Laboratoire suisse de recherches horlogères (L.S.R.H.) de Neuchâtel, a rendu compte de ses activités.

Des crédits spéciaux ont permis notamment l'acquisition d'un microscope électronique, qui pourra également se transformer en une microsonde électronique d'une conception nouvelle, et la mise en chantier d'une horloge atomique à cesium, qui viendra s'adjoindre à l'horloge moléculaire à gaz d'ammoniac déjà en service depuis deux ans.

Le L.S.R.H. sera ainsi le seul laboratoire au monde à posséder ces deux types d'étalon de fréquence assurant une précision du cent-millième de seconde par jour.

1963

L'OBSERVATOIRE CANTONAL À LA POINTE DU PROGRÈS

La première horloge atomique au thallium jamais construite fonctionne au Mail

Autre innovation : la mise en service d'une chambre sous pression constante pour l'observation des chronomètres

L'Observatoire de Neuchâtel doit sa réputation à son heure. Cette heure est actuellement parmi les meilleures du monde. Aujourd'hui, il « produit » une heure d'une précision — tenez-vous bien et réglez votre montre — de quelque dix-millionièmes de seconde par jour. Et cela grâce à sa nouvelle horloge atomique au thallium, qui est la première de ce genre à avoir jamais été construite et à fonctionner.

Créé il y a un peu plus de cent ans, notre Observatoire était conçu, à l'origine, comme un service public et non comme un institut de recherche. Maintenant, il remplit cette double fonction, car la détermination de l'heure et sa conservation mobilisent les plus récentes applications de la physique moderne. Naguère, les horloges à quartz avaient remplacé les horloges mécaniques à pendule. Ces dernières réglaient leur marche sur celles des étoiles. Aujourd'hui, c'est la marche des étoiles qui est contrôlée par les horloges. Et à l'horloge à quartz a succédé l'horloge atomique.

Record mondial de précision

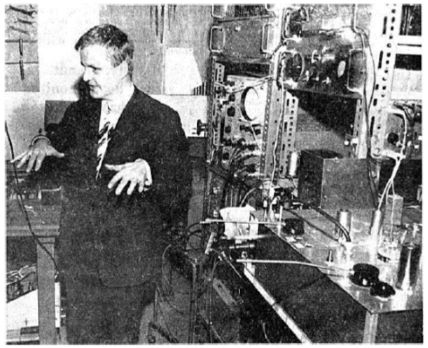
Les horloges atomiques, qui existent depuis environ six ans, utilisent les propriétés de certains atomes d'osciller à des fréquences très élevées et constantes. Ces vibrations peuvent être comparées aux oscillations de l'organe réglant de la montre, le balancier-spiral. Mais ici, on est dans le domaine de la physique poussée et de l'électronique. Les horloges atomiques existantes sont pilotées généralement par les atomes de césium, de rubidium ou encore les molécules du gaz ammoniac. Leur précision se situe autour de 2 millionièmes de seconde par jour. Le nouvel élément utilisé dans l'horloge atomique de l'Observatoire, à savoir le

et où les atomes de thallium sont projetés et leurs vibrations enregistrées électroniquement. L'Observatoire, qui a travaillé en collaboration avec le Laboratoire des recherches horlogères, démontre que, dans le champ de la recherche, il est à l'avant-garde.

La pression atmosphérique jugulée

Nous avons eu hier également la primeur d'une autre nouvelle installation, celle-ci destinée au contrôle des chronomètres. Comme on le sait, une activité importante de l'Observatoire cantonal consiste dans l'observation des meilleurs chronomètres de l'industrie horlogère. L'observation de chaque chronomètre s'étend sur deux mois environ et comprend des mesures faites à plusieurs températures et dans plusieurs positions.

Jusqu'ici, un facteur non négligeable d'influence sur la marche des chronomètres restait incontrôlé, soit l'influence des variations de la pression atmosphérique. En effet, une variation de la hauteur de la colonne de mercure de 1 mm peut produire une différence de marche de 1/100 de seconde par jour environ. Or, chez nous, entre le Haut-Jura et la région des lacs, des variations de pression de plusieurs dizaines de mm de mercure sont fréquentes. Il en résulte des variations dans la marche des chronomètres, qui peuvent en avantager certains et en désavantager d'autres. Afin d'aboutir



M. Jacques Bonanomi présente la nouvelle horloge atomique de l'Observatoire de Neuchâtel.
(Photo Avipress - J.-P. Baillod.)

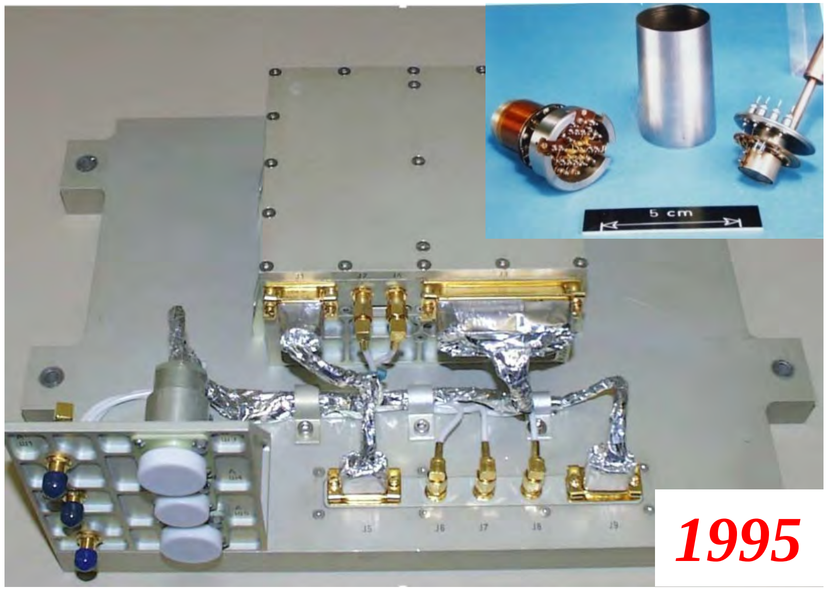
UNIVERSAL EXPOSITION OF BRUXELLES (1958)

L'horloge universelle (ainsi que l'étalon moléculaire et l'horloge à quartz) dans la section horlogère

Crédit: Johann Boillat

SPACE ATOMIC CLOCKS IN NEUCHÂTEL

UNIVERSITÉ DE NEUCHÂTEL



1995

L'Impartial | mercredi, mars 09, 1988 | 19

1988

Nouveau directeur de l'Observatoire

Giovanni Busca remplacera Jacques Bonanomi

M. Giovanni Busca remplacera M. Jacques Bonanomi à la tête de l'Observatoire cantonal de Neuchâtel. M. Busca est l'homme de la situation. Docteur en sciences physiques, spécialisé dans le domaine temps et fréquences, il sera précisément chargé de développer cette discipline, une nouvelle orientation qui bénéficiera de l'appui et de la collaboration de la Confédération.

M. Busca, neuchâtelois d'adoption, de nationalité canadienne, est âgé de 49 ans, marié et père de deux filles. Il prendra ses fonctions le 1er juillet pour succéder à M. Bonanomi, atteint par la limite d'âge, auquel M. Pierre Dubois, chef du Département de l'économie publique, a rendu un vibrant hommage.

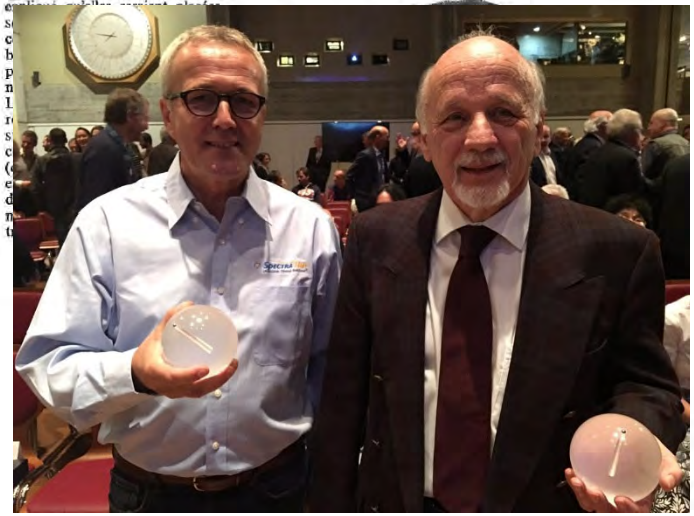
M. Bonanomi a passé 29 ans de sa vie à l'Observatoire et a joué un rôle important dans des développements industriels tirés de recherches fondamentales et qui se sont traduits par la création il y a moins d'une année de la société Précitel S.A.

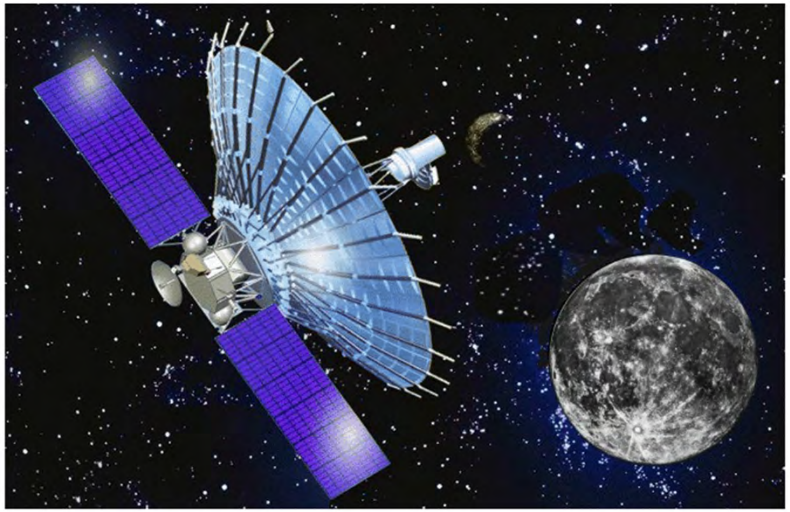
SON DOMAINE

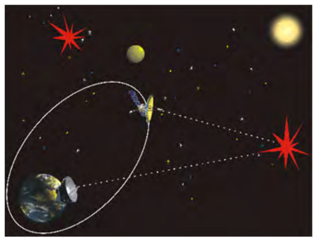
Présentant les orientations futures de l'Observatoire, M. Busca a

mentale, l'Observatoire entend participer à des recherches appliquées en aidant des entreprises. L'Observatoire sera en quelque sorte un atout supplémentaire à la promotion de l'économie neuchâteloise. Car selon M. Busca, «vendre le temps» est possible et représente un marché important. L'Observatoire travaillera en étroite collaboration avec l'Office fédéral de métrologie (construction d'un étalon économique), office qui assurera une partie du financement des activités de l'Observatoire.

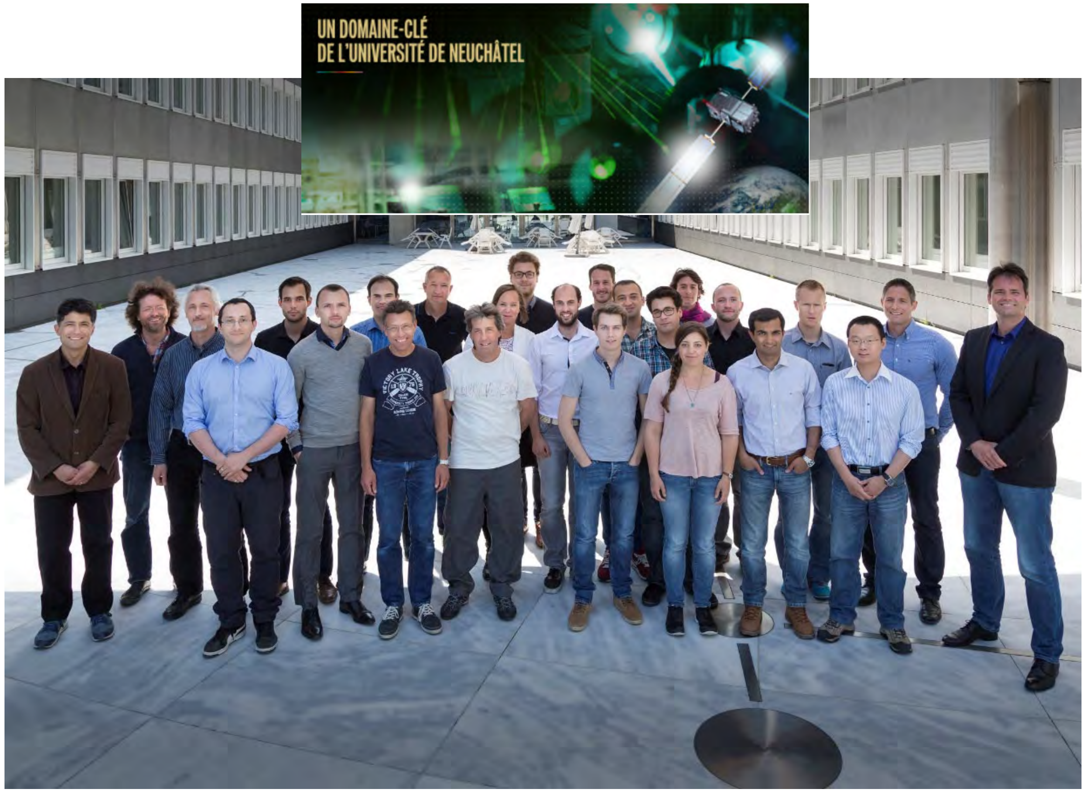
P. Ve





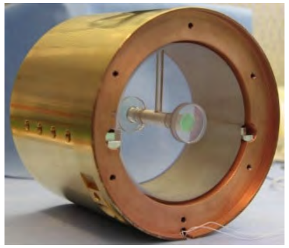


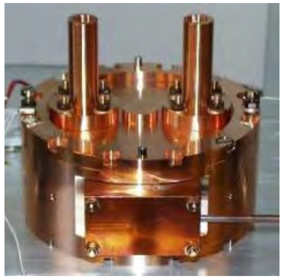
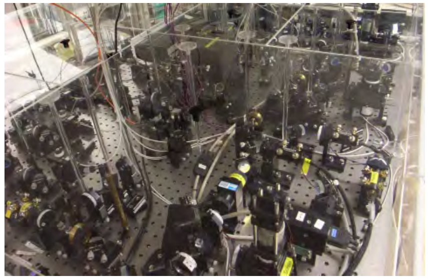
LABORATOIRE TEMPS – FRÉQUENCE (LTF) – 2007









Time & Frequency metrology

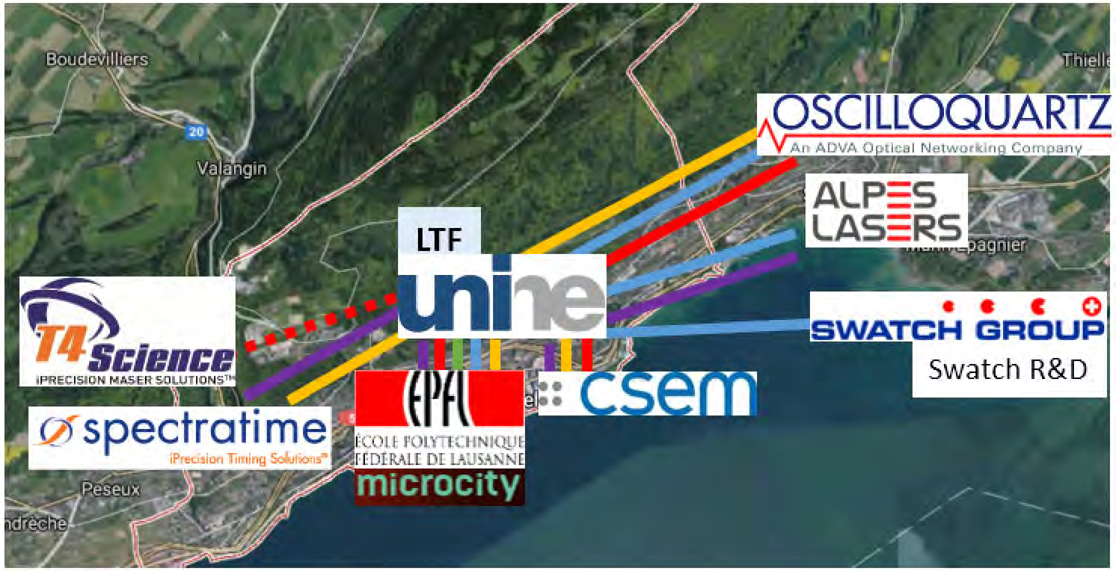
Atomic spectroscopy
Primary standards
Optical clocks
Cell standards
Space clocks

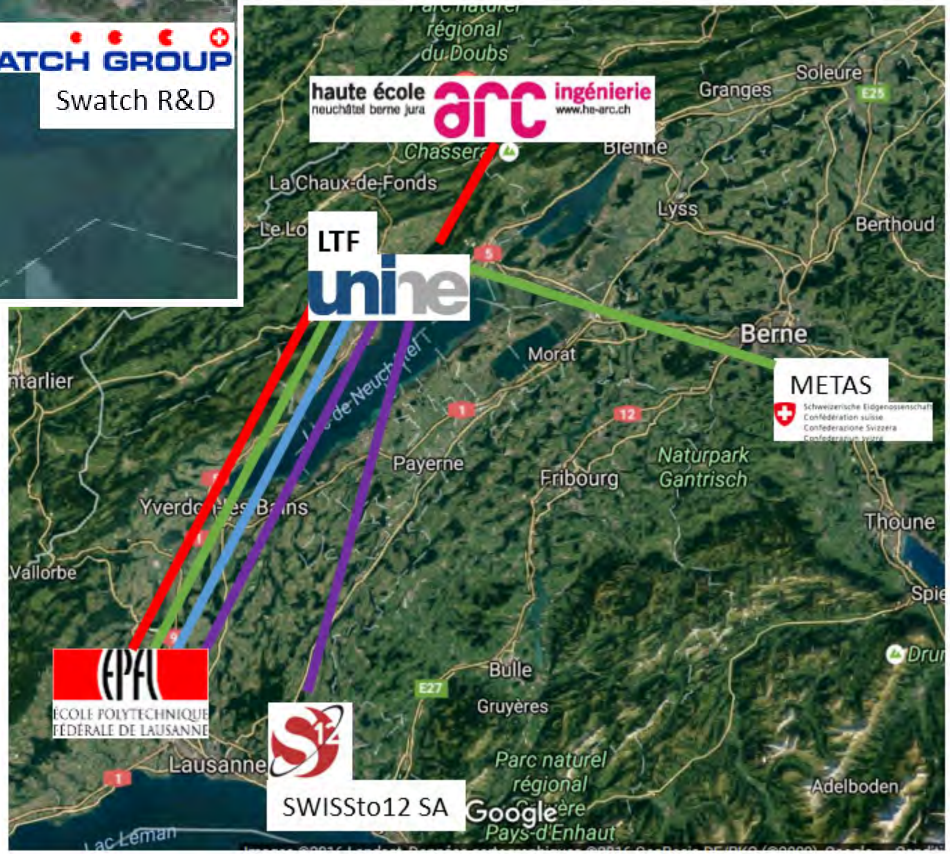
Optical metrology

Optical combs
XUV frequency combs
Stabilized lasers
Laser characterisation
Laser instruments

UNIVERSITÉ DE NEUCHÂTEL

TODAY: UNIQUE NETWORK WORLWIDE





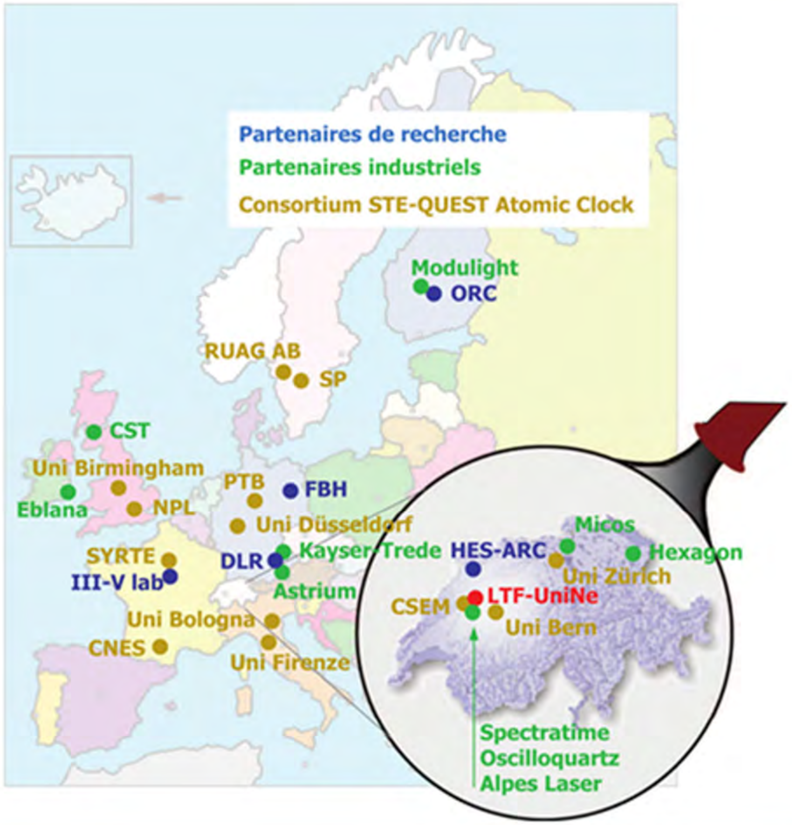
Private companies and research laboratories working in the domain of atomic clocks and stabilised lasers

SPECIALISED INTERNATIONAL NETWORK

UNIVERSITÉ DE NEUCHÂTEL

Domaine des horloges compactes (haute-performance et miniature)

Domaine des lasers stabilisés



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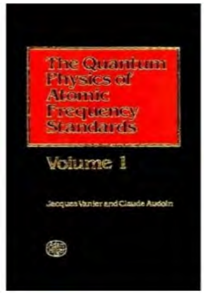
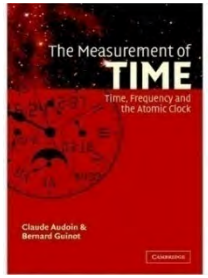
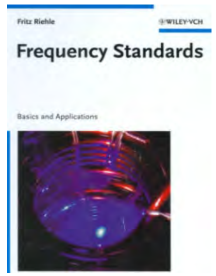
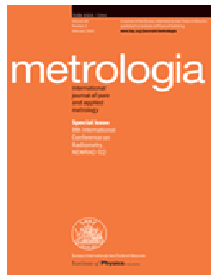
- Claude Audoin, Bernard Guinot, Stephen Lyle, ***“The Measurement of Time: Time, Frequency and the Atomic Clock ”***, Cambridge, (Original in french: Masson, 1998).
- Fritz Riehle, **“*Frequency standards – Basics and applications*”**, Wiley-VCH, 2005.
- Special issue of Metrologia: **“*Special issue: 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)
www.pptimeeting.org	(on subscription)
www.ieee-uffc.org/main/publications/fcs/index.asp	(on subscription)
Symposium on Frequency Standards and Metrology	(~ every 6 years)

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

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

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

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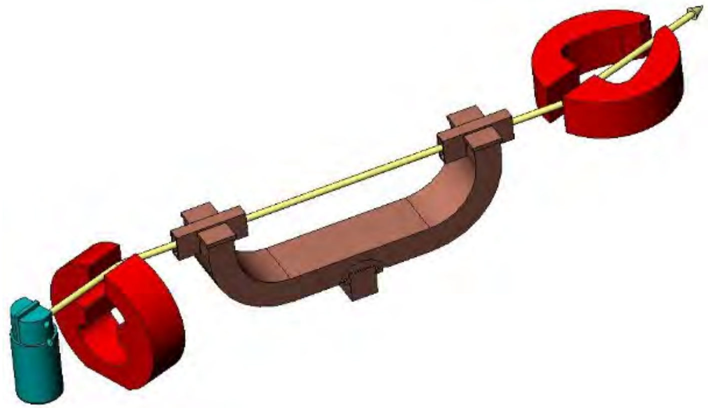
The evolution of Time & Frequency

Part 2: **Atomic frequency standards**

General aspects and applications

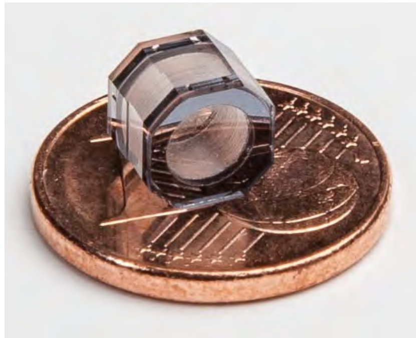
Examples of frequency standards



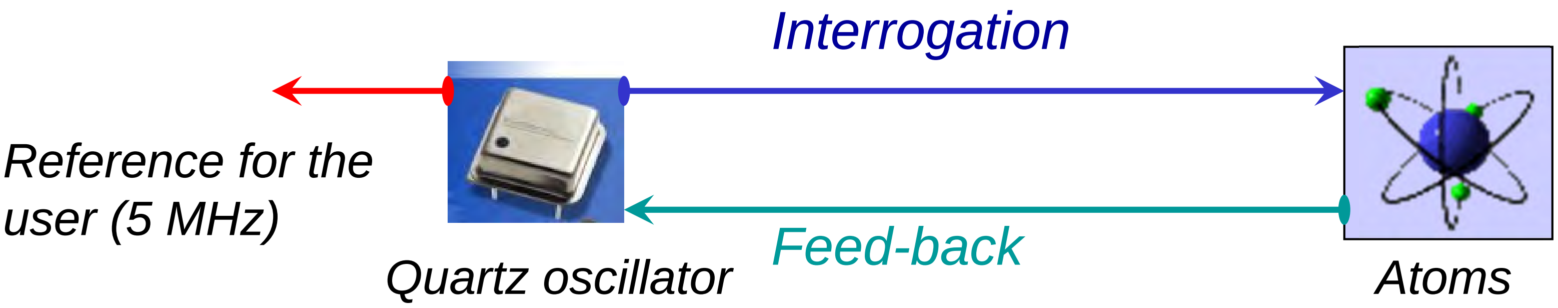
Part 3: **Rubidium standards and miniature atomic clocks**

Rubidium frequency standards

Miniature atomic clocks



ATOMIC CLOCK BASIC PRINCIPLE

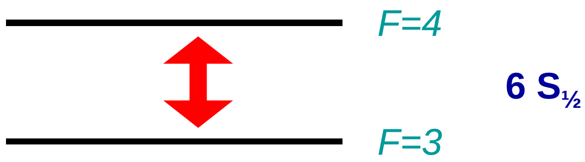


Definition in SI system

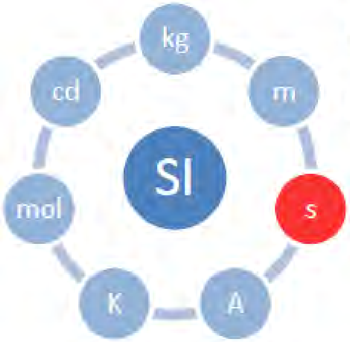
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of cesium 133 (1967)

The unperturbed ground state hyperfine transition frequency of the cesium 133 atom is 9 192 631 770 Hz (2019)

$$Frequency \quad \nu_0 = \frac{E_2 - E_1}{h} = 9\,192\,631\,770\ Hz \qquad \Delta\nu_{Cs}$$



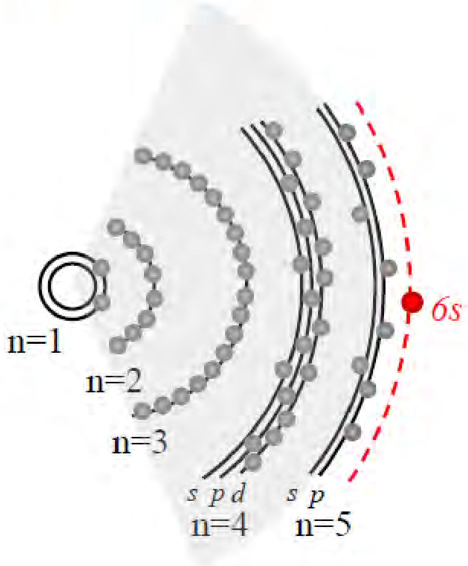
The Planck constant h is 6.626 070 15 × 10−34 J s,

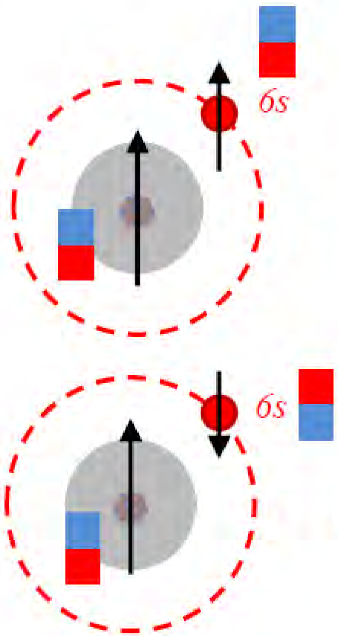


Césium 133

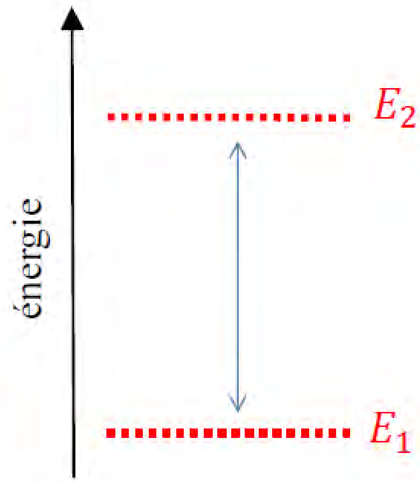
Structure électronique :

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 5s^2\ 5p^6\ 6s^1$ ⇔ [Xe] 6s1





Interaction entre
spin du noyau – spin de l'électron 6s



$$E_2 - E_1 = h\,f$$

$$f = 9'192'631'770 \text{ Hz}$$

INTERNATIONAL SYSTEM OF UNITS

The International System of Units, the SI, is the system of units in which

- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,
- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_A is $6.022\,140\,76 \times 10^{23}$ mol^{-1},
- the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W,

Table 1. The seven defining constants of the SI and the seven corresponding units they define

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant	h	$6.626\,070\,15 \times 10^{-34}$	J s
elementary charge	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant	k	$1.380\,649 \times 10^{-23}$	J K^{-1}
Avogadro constant	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

INTERNATIONAL SYSTEM OF UNITS

Table 2. SI base units

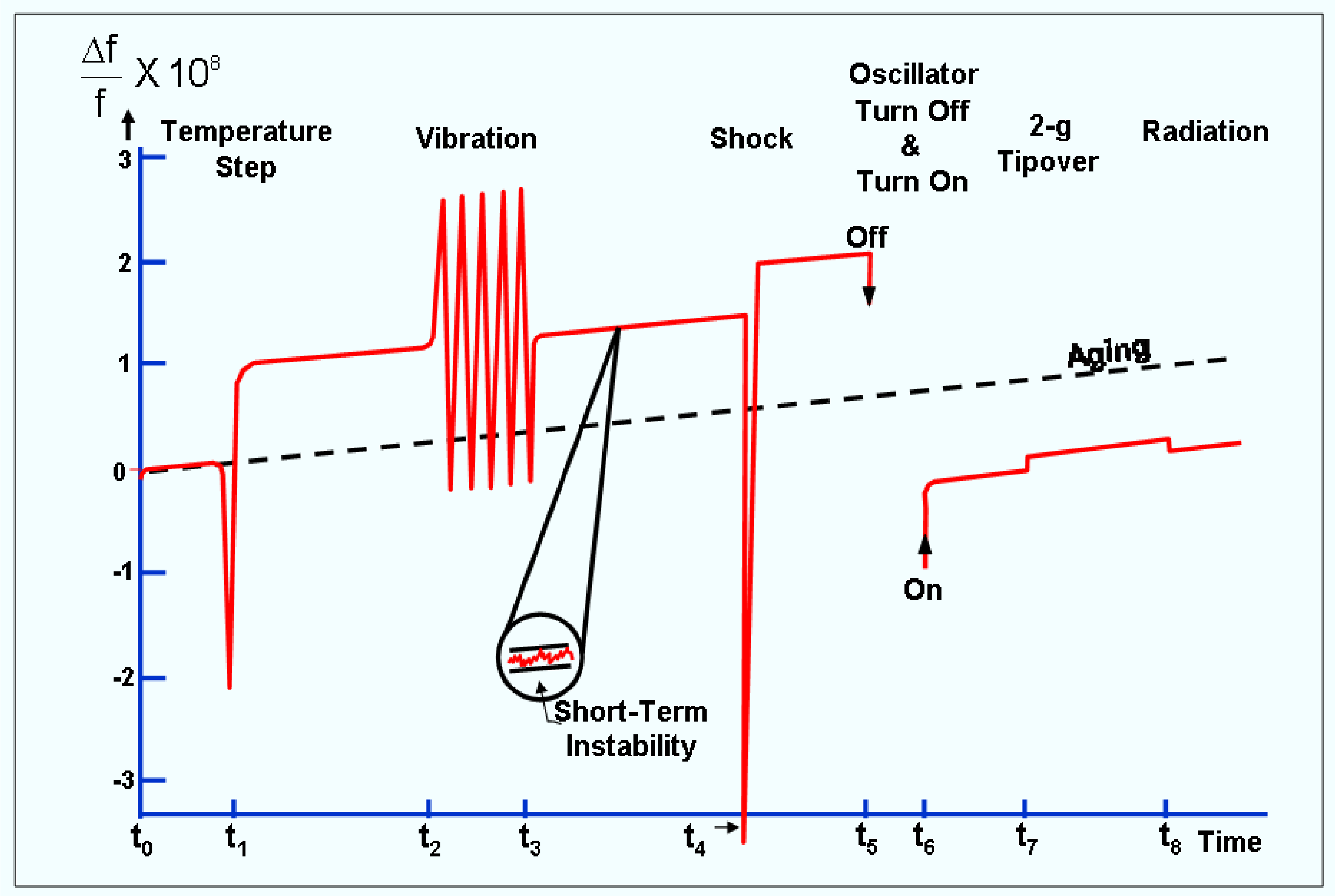
Base quantity		Base unit	
Name	Typical symbol	Name	Symbol
time	t	second	s
length	l, x, r, etc.	metre	m
mass	m	kilogram	kg
electric current	I, i	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

The symbols for quantities are generally single letters of the Latin or Greek alphabets, printed in an italic font, and are *recommendations*.
The symbols for units are printed in an upright (roman) font and are *mandatory*, see chapter 5.

Bureau International des Poids et Mesures

$$1\,\text{Hz} = \frac{\Delta\nu_{\text{Cs}}}{9\,192\,631\,770} \quad \text{or} \quad 1\,\text{s} = \frac{9\,192\,631\,770}{\Delta\nu_{\text{Cs}}}$$

WHY DO WE NEED TO STABILIZE THE QUARTZ?



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

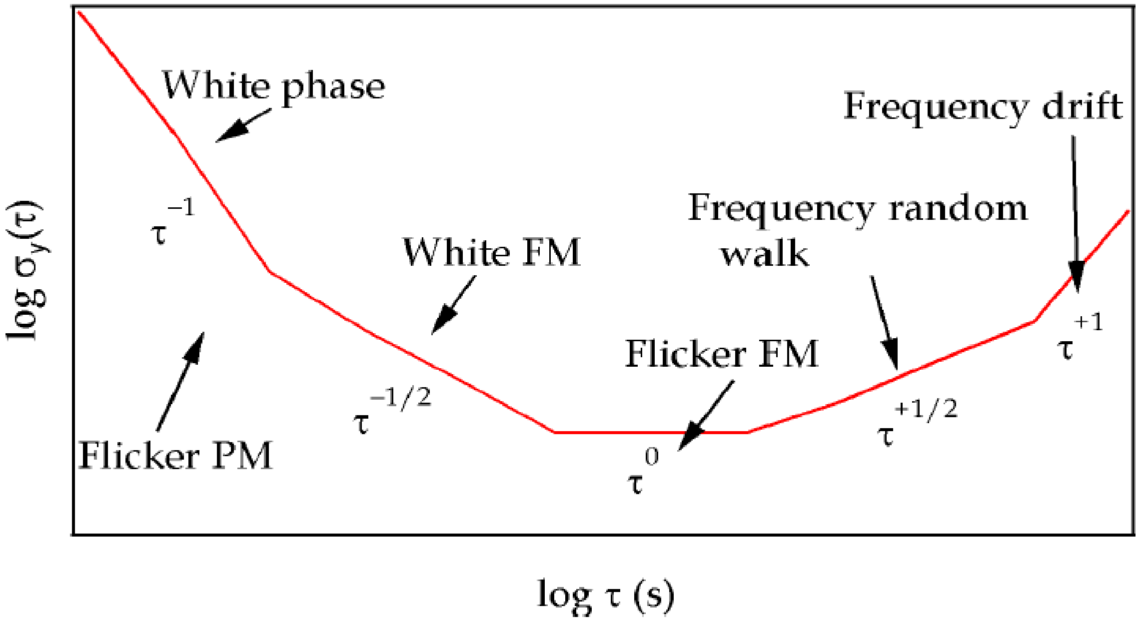
ALLAN DEVIATION (TIME DOMAIN)

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

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

$$\sigma_y^2(\tau) = \tfrac{1}{2}\overline{(y_{k+1} - y_k)^2}$$

$\sigma_y(\tau)$: *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

PHASE NOISE (SPECTRAL DOMAIN)

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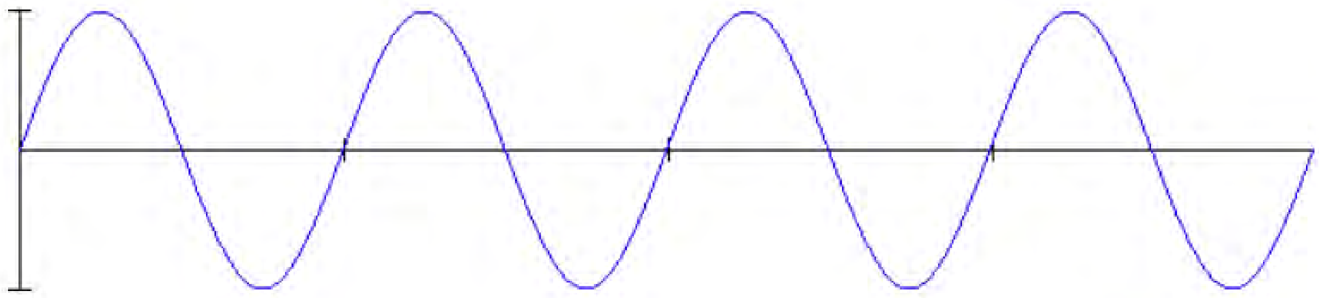
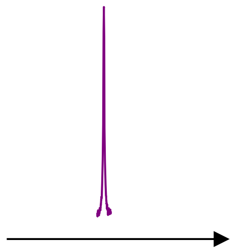
Ideal oscillator

$$A \cdot \cos(2\pi\nu_0 t)$$



Spectral domain



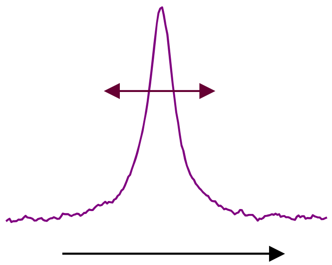
ν_0

Real oscillator

$$Signal(t) = \mathrm{Re}\left(A\gamma(t)e^{j2\pi\nu_0 t}\right)$$

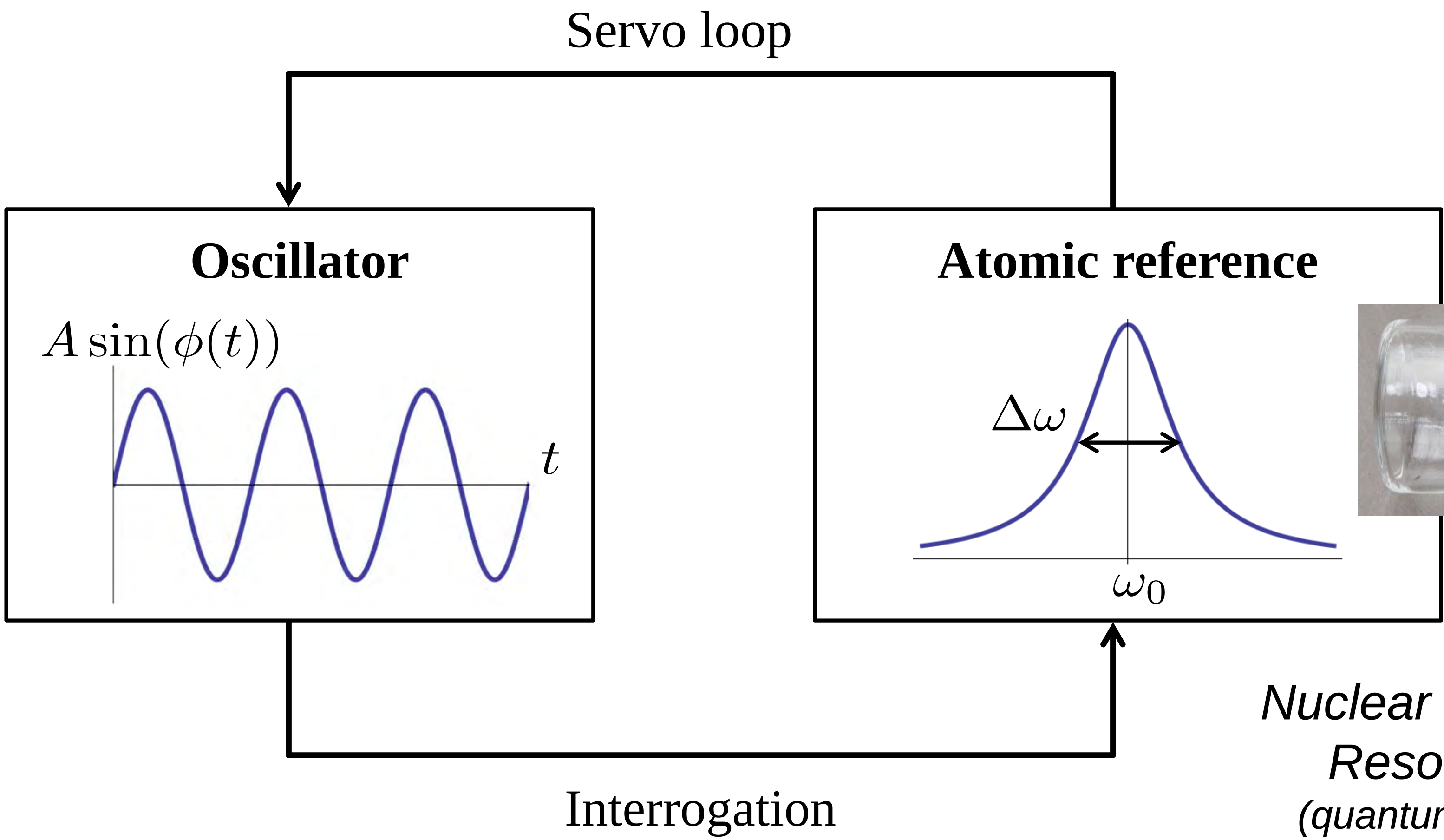
$$\gamma(t) = p(t) + j \cdot q(t) = (1 + \varepsilon(t)) \cdot e^{j\Phi(t)}$$

Spectral domain



$\nu_0 + bias$

GENERAL SCHEME OF AN ATOMIC CLOCK



Nuclear Magnetic Resonance
(quantum sensor)

DIFFERENT TYPES OF ATOMIC CLOCKS

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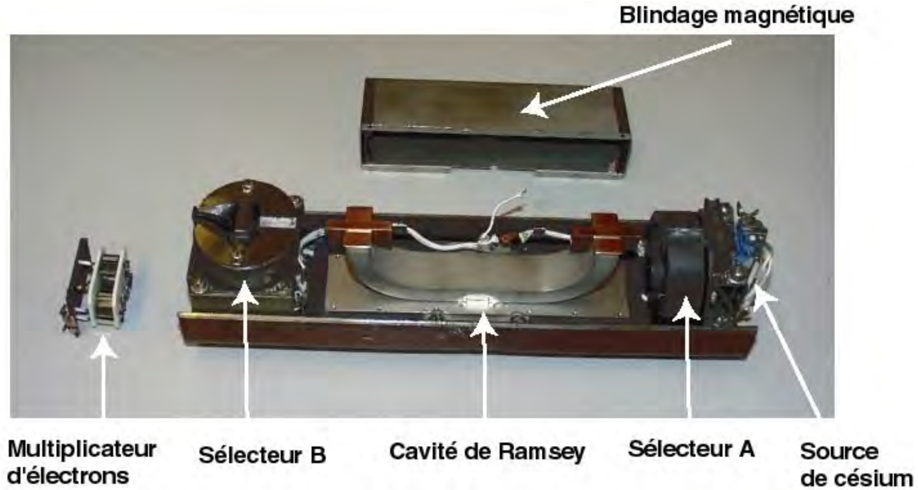
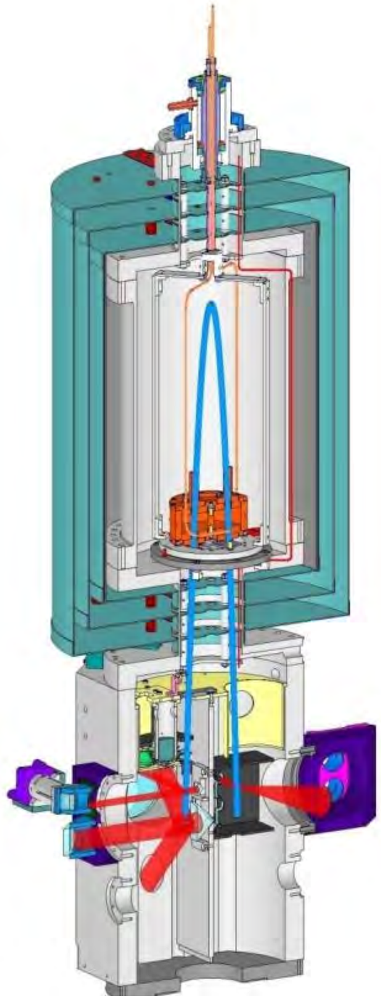
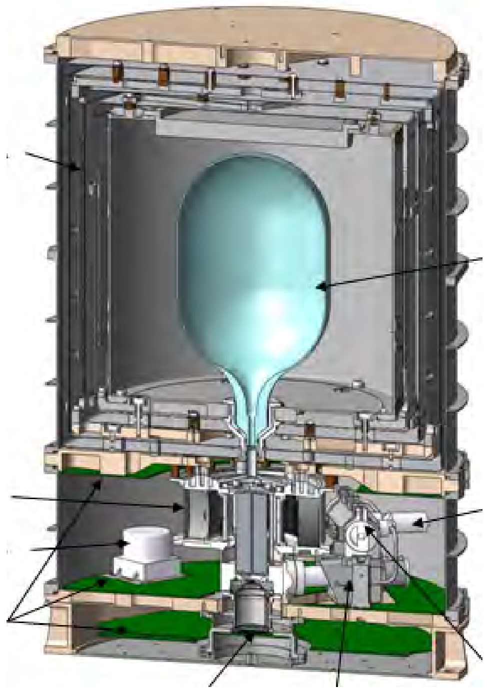
Thermal Caesium beam



Cold Caesium primary fountain



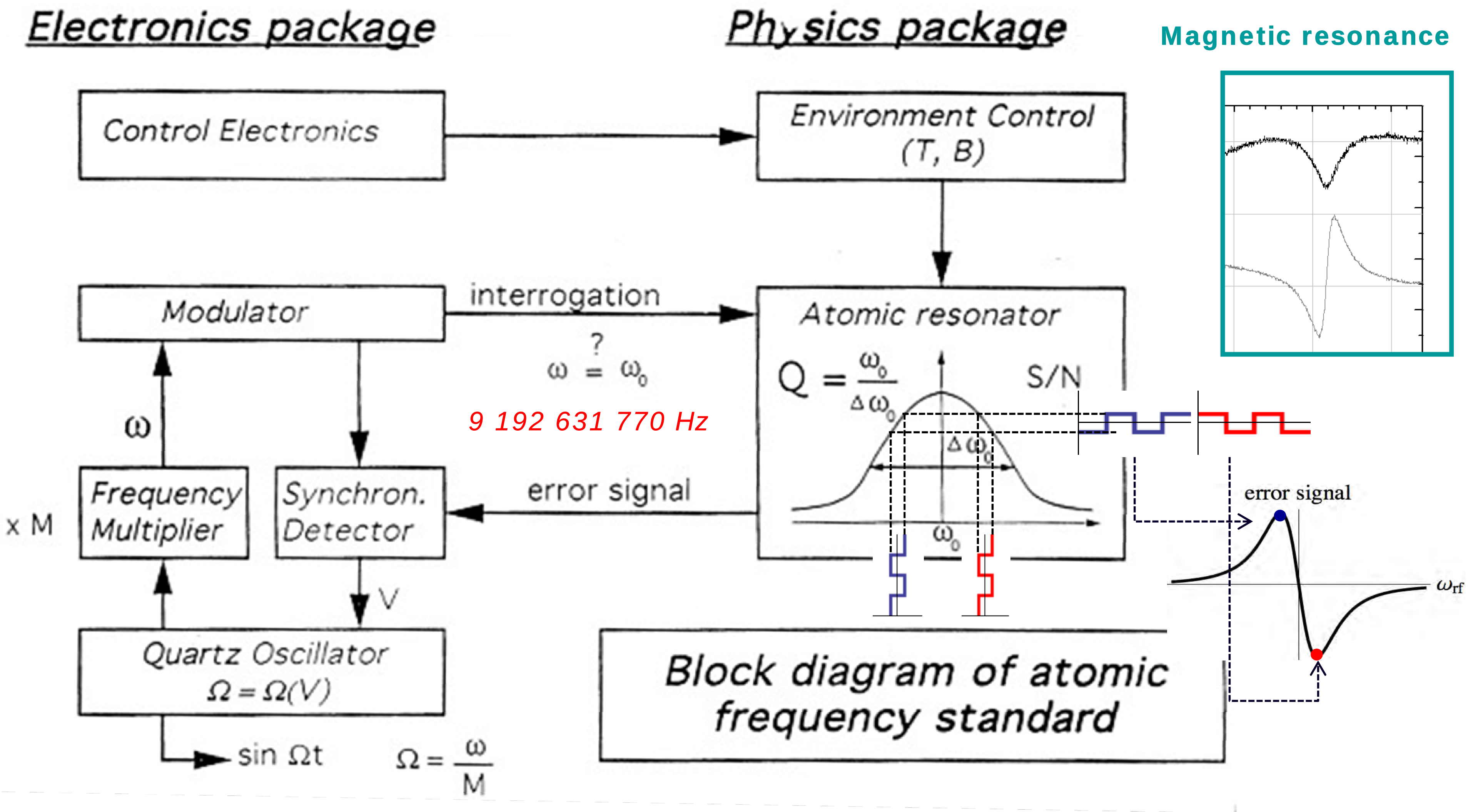
Hydrogen MASER



Rubidium vapour cell atomic clock

Atomic clock with microfabricated cell

BLOC DIAGRAM OF AN ATOMIC CLOCK

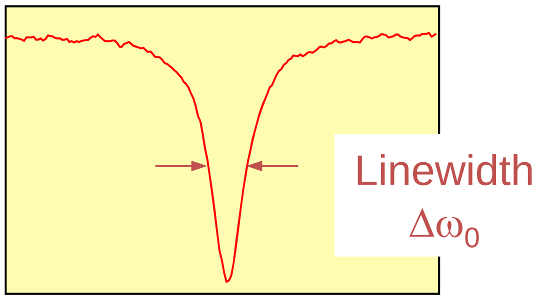


Typically 5 or 10 MHz

FREQUENCY STABILITY AND MAIN TRENDS

Resonance signal

Signal



Probing frequency

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

T_R: resonance «duration»

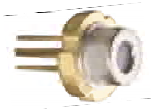
$$Q = \frac{\omega_0}{\Delta\omega_0} = \omega_0 \cdot T_R$$

Q: quality factor

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

S / N : Signal to noise Ratio

Long term stability depends on the sensitivity of the “clock” transition (metrological work)

Main novelties: use of lasers  **and micro-fabrication techniques**

Cold atoms

Increase T_R :

From ms to seconds

Optical standards

Increase ω_0:

From 10^9 Hz to 10^{14} Hz

Miniaturisation

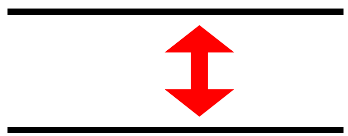
Reduce the «***SWAP***»

Size, Weight And Power

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 - …

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



APPLICATION 1: NAVIGATION

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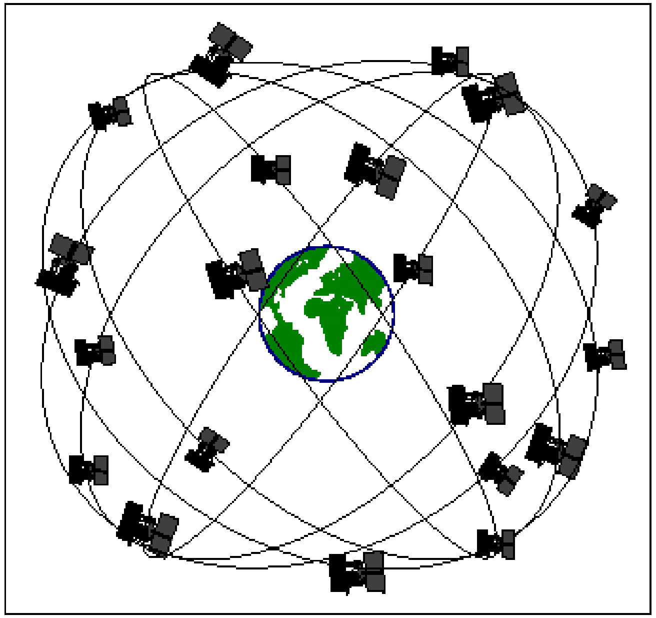


Determination of the longitude:

1 second
error in time
~
500 m error in position (equator)

Satellite positioning:

1 nano second
error in time
(0.000’000’001 s)
~
30 cm error in position

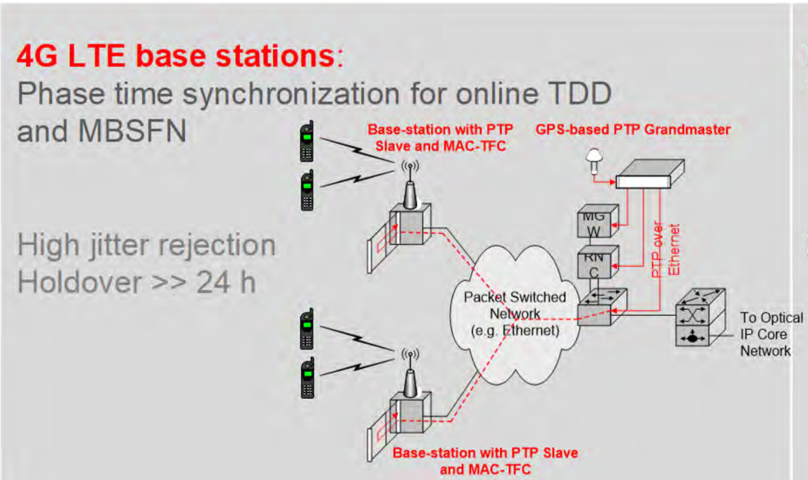
APPLICATION 2: NETWORKS SYNCHRONISATION

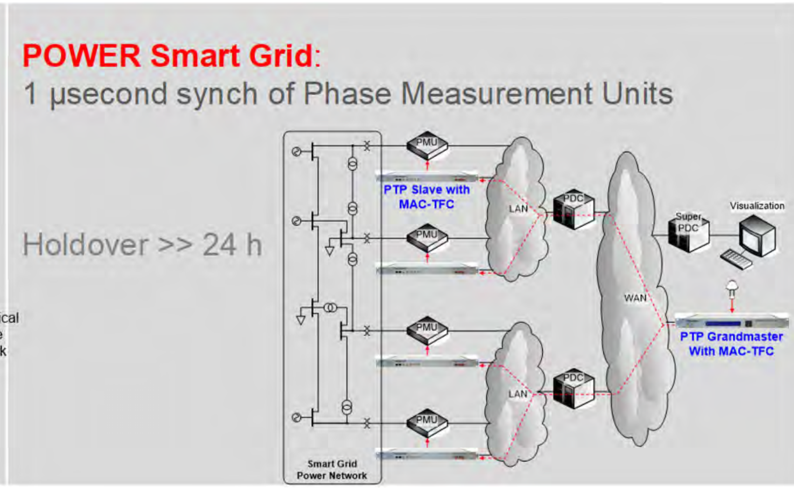
Telecommunications power distribution networks (smart grids):

Require a synchronisation of approximately

1 microsecond

(0.000’0001 s)





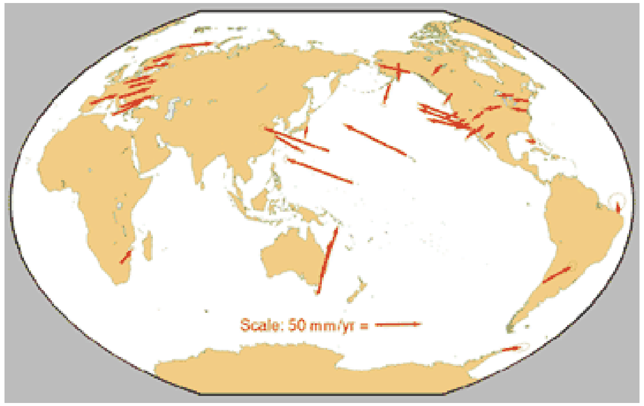
3: VLBI (VERY LONG BASE INTERFEROMETRY)

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

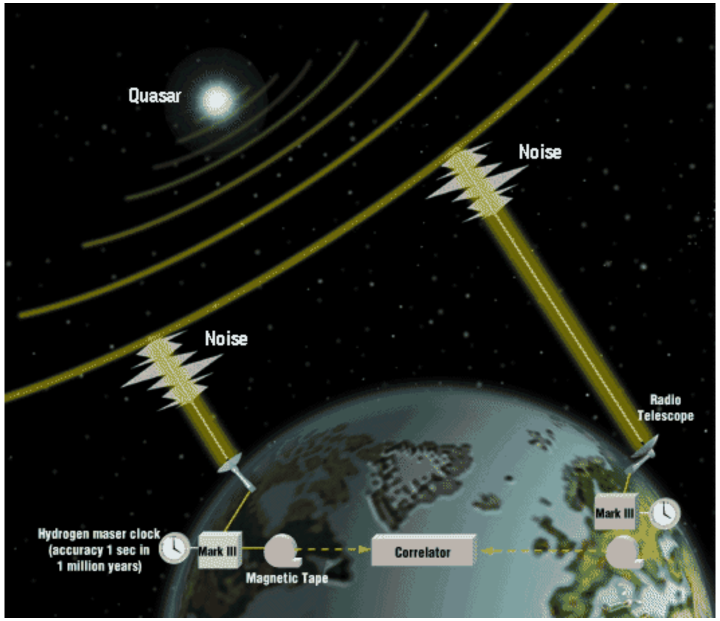
Angular resolution: ~ λ / Diameter

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

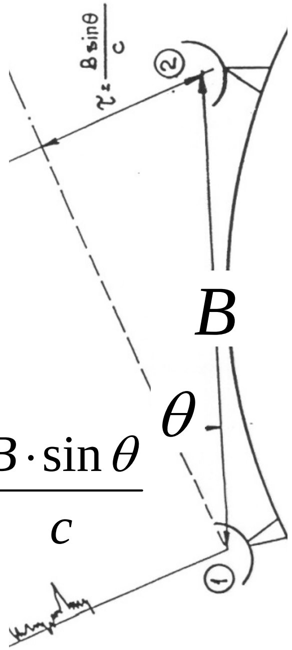
2 radio-telescopes: ~ 1 nrad (10^{-9} rad)

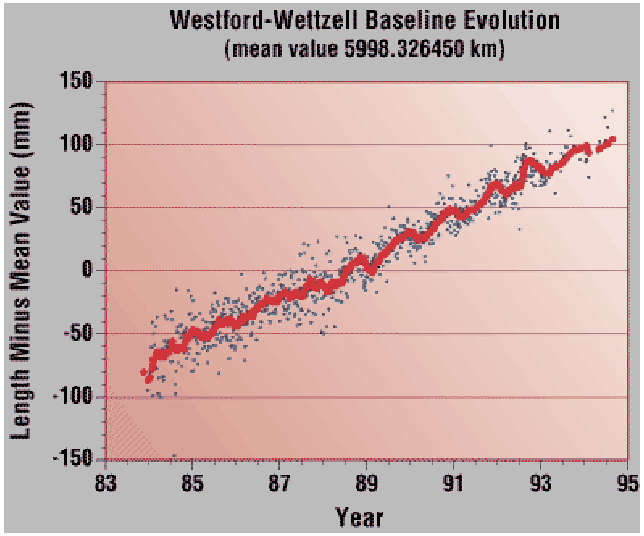


Earth rotation: 1 mrad → 6 km → 14 s

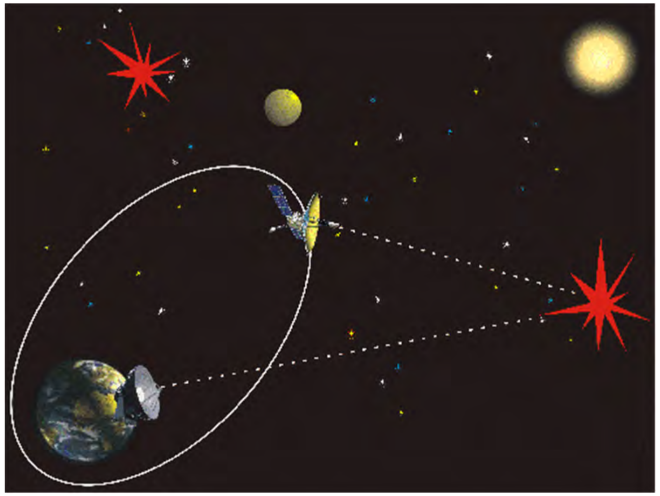


$$\tau = \frac{B \cdot \sin\theta}{c}$$

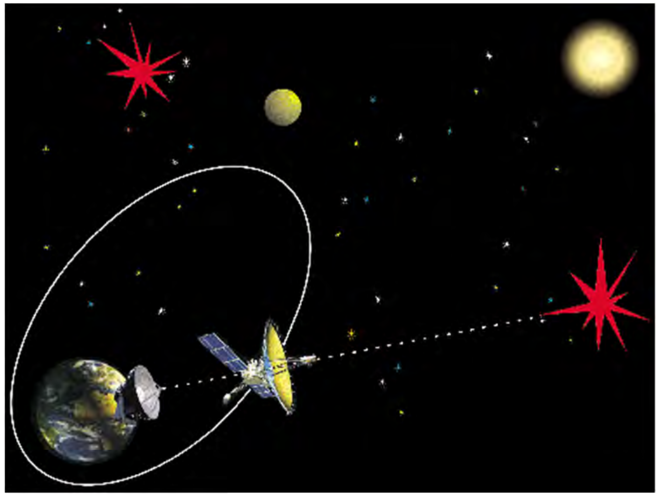


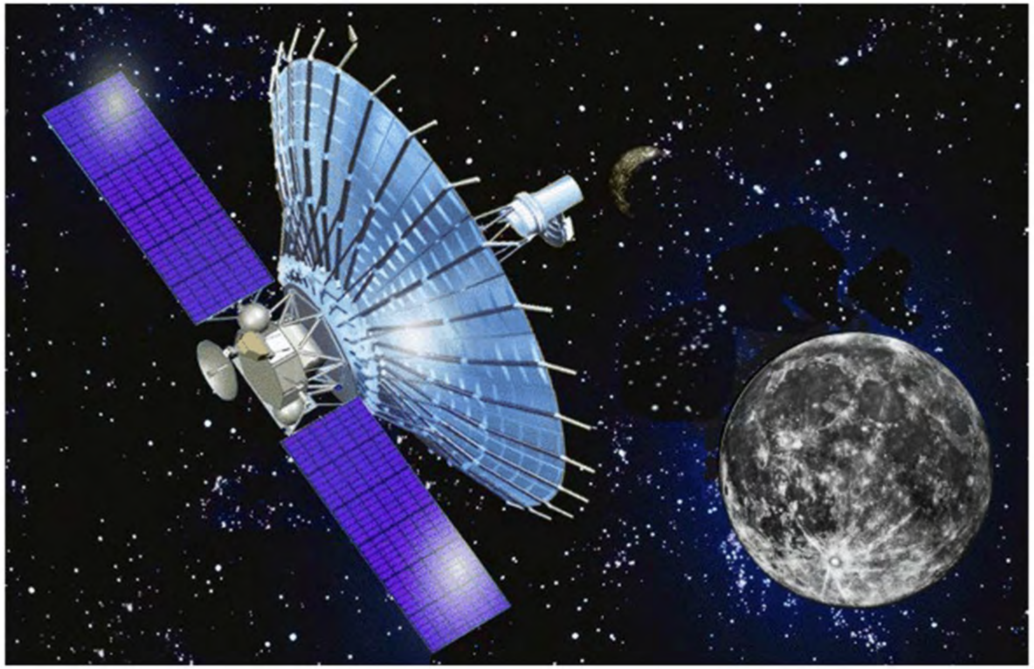


RADIOASTRON MISSION (SPACE VLBI)



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





DETECTION OF BLACK HOLE (M87)

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THE ASTROPHYSICAL JOURNAL LETTERS, 875:L2 (28pp), 2019 April 10
https://doi.org/10.3847/2041-8213/ab0c96

First M87 Event Horizon Telescope Results. II. Array and Instrumentation

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
Received 2019 February 11; revised 2019 March 5; accepted 2019 March 5; published 2019 April 10

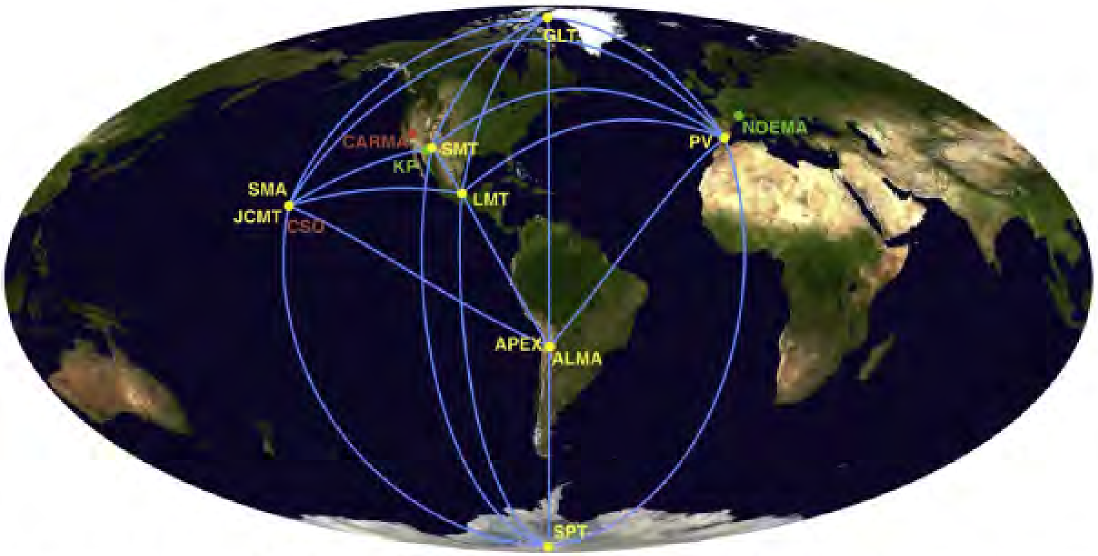


Figure 1. Map of the EHT. Stations active in 2017 and 2018 are shown with connecting lines and labeled in yellow, sites in commission are labeled in green, and legacy sites are labeled in red. Nearly redundant baselines are overlaying each other, i.e., to ALMA/APEX and SMA/JCMT. Such redundancy allows improvement in determining the amplitude calibration of the array (Paper III).

DETECTION OF BLACK HOLE (M87)

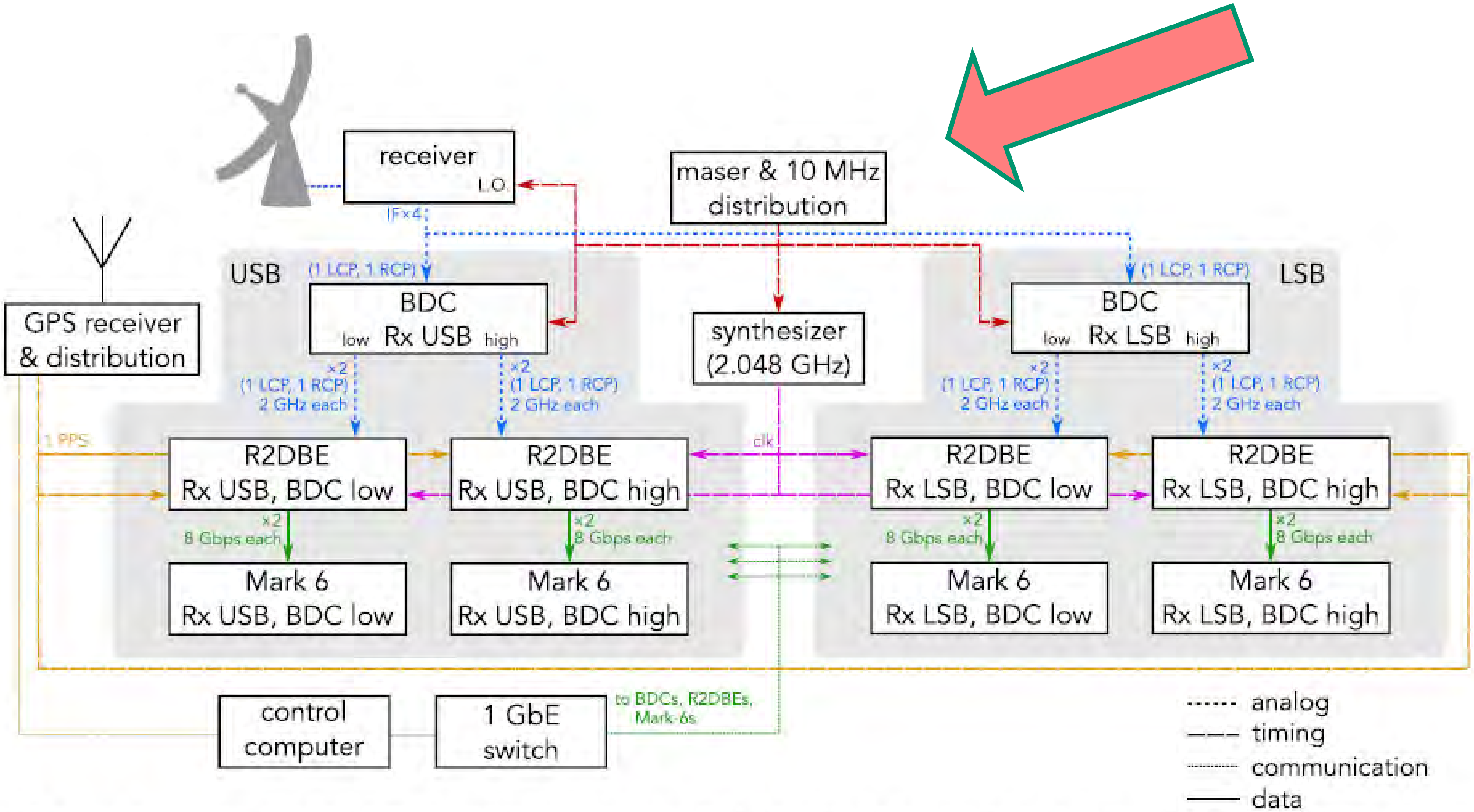
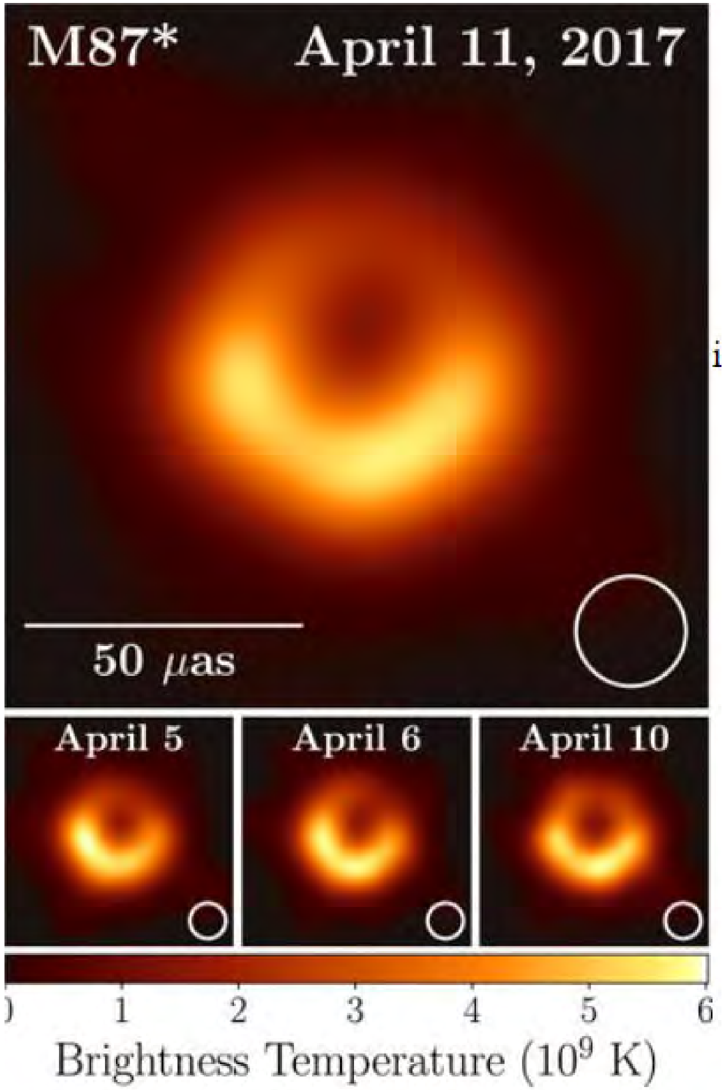
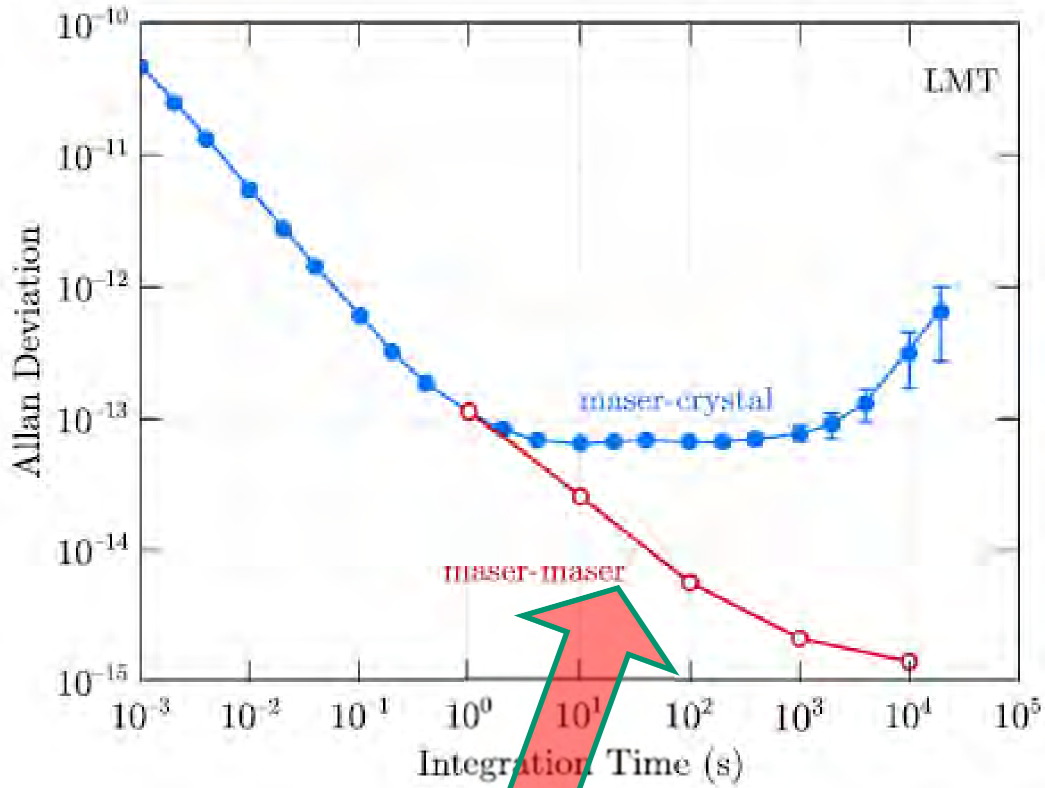


Figure 4. System diagram at a single-dish EHT site with 64 Gbps capability. Dual-polarization (left and right circular polarization (LCP and RCP)) and upper- and lower-sideband (USB and LSB) analog IF signals are sent from the receiver. The receiver local oscillator is locked to the station hydrogen maser 10 MHz reference. Block downconverters (BDCs) mix these signals to baseband. R2DBEs sample the analog signals and distribute packetized data to Mark 6 recorders over a 10 GbE network. All timing is locked to a 10 MHz maser reference and synchronized with a pulse-per-second (PPS) Global Positioning System (GPS) signal. The components are controlled through a 1 GbE network. See Figure 8 for a photograph.

DETECTION OF BLACK HOLE (M87)





~1.5 10^{-14} @ 10s

FUNDAMENTAL PHYSICS IN SPACE

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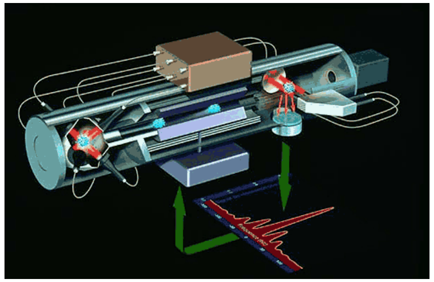
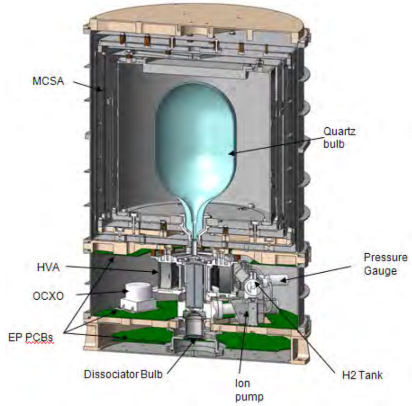
ACES

Atomic Clock Ensemble in Space



SPECTRATIME

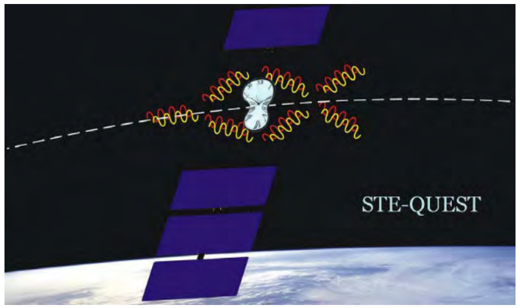


Micro-gravity

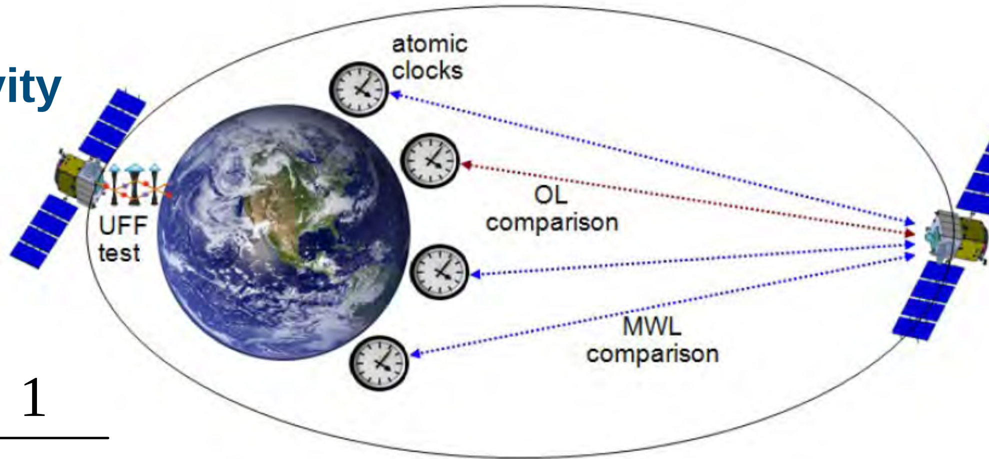
STE-QUEST

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

A class M mission proposal for Cosmic Vision 2015-2025



Relativity



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

APPLICATIONS OF ATOMIC CLOCKS: OVERVIEW

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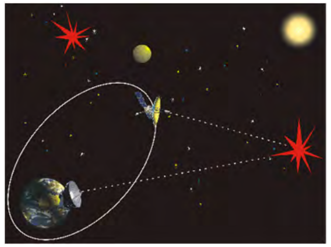
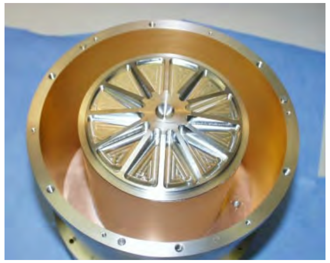
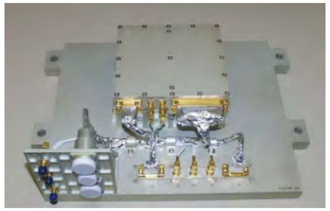
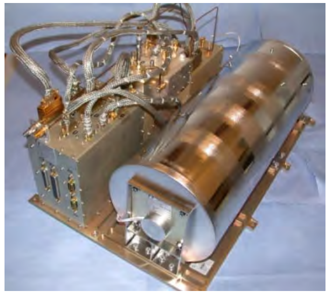
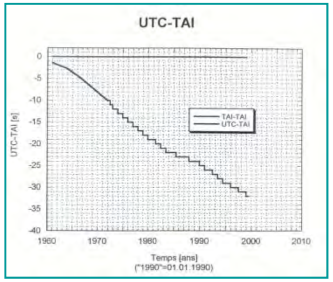
- *Radioastronomy, Geodesy*
  (VLBI, Radioastron, etc.)
- *Scientific Research, Instrumentation*
  (Microgravity, ACES, HYPER, etc.)
- *Navigation & Positioning*
  (Galileo, GPS, GLONASS, etc.)
- *Telecommunications*
  (Networks synchronisation, etc.)
- *Power distribution networks*
  (Smart power grids.)
- *Metrology, Time scales*
  (Primary and secondary standards, H-Masers)











EXAMPLE OF ATOMIC CLOCKS: CESIUM BEAM

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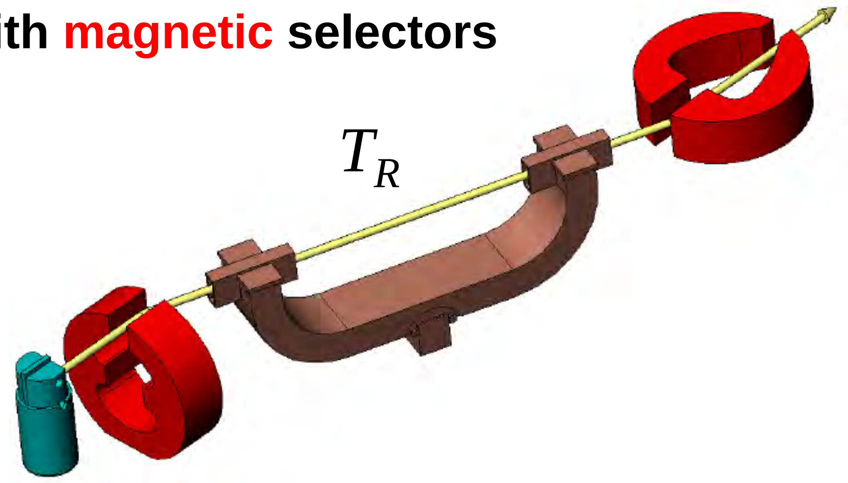
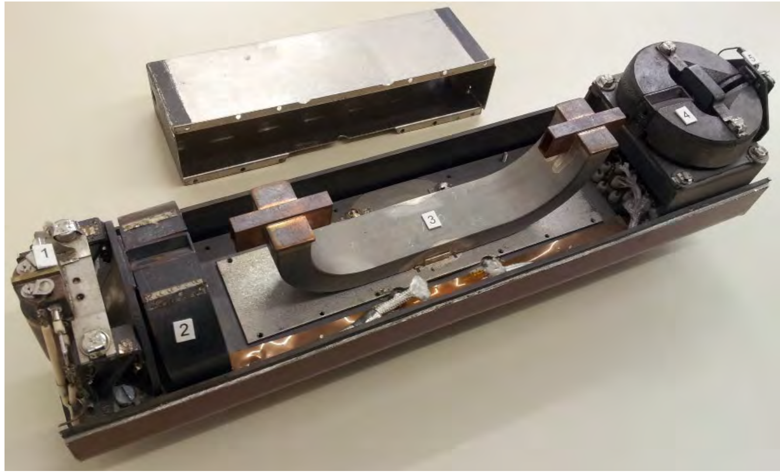
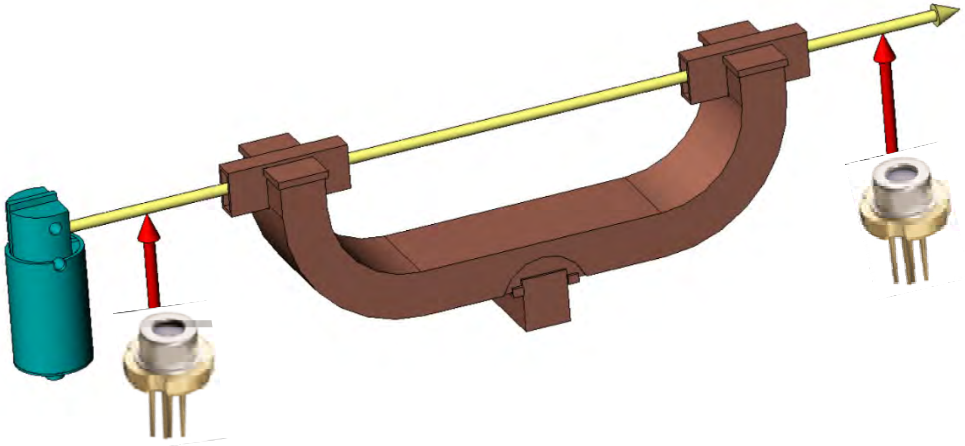
With magnetic selectors



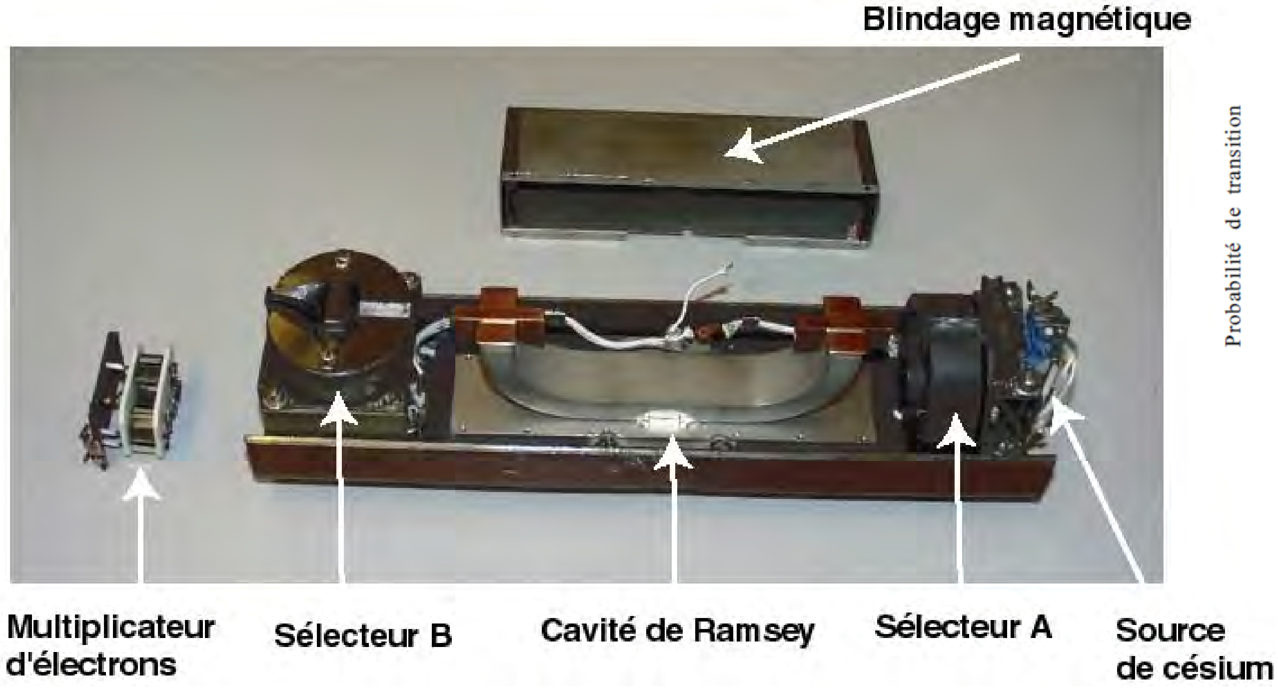


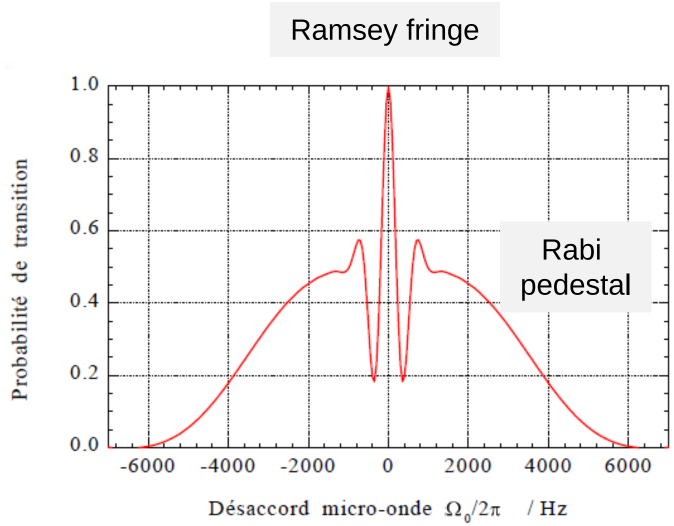
With laser diode optical pumping and detection



OSCILLOQUARTZ
An ADVA Optical Networking Company

CESIUM BEAM STANDARD



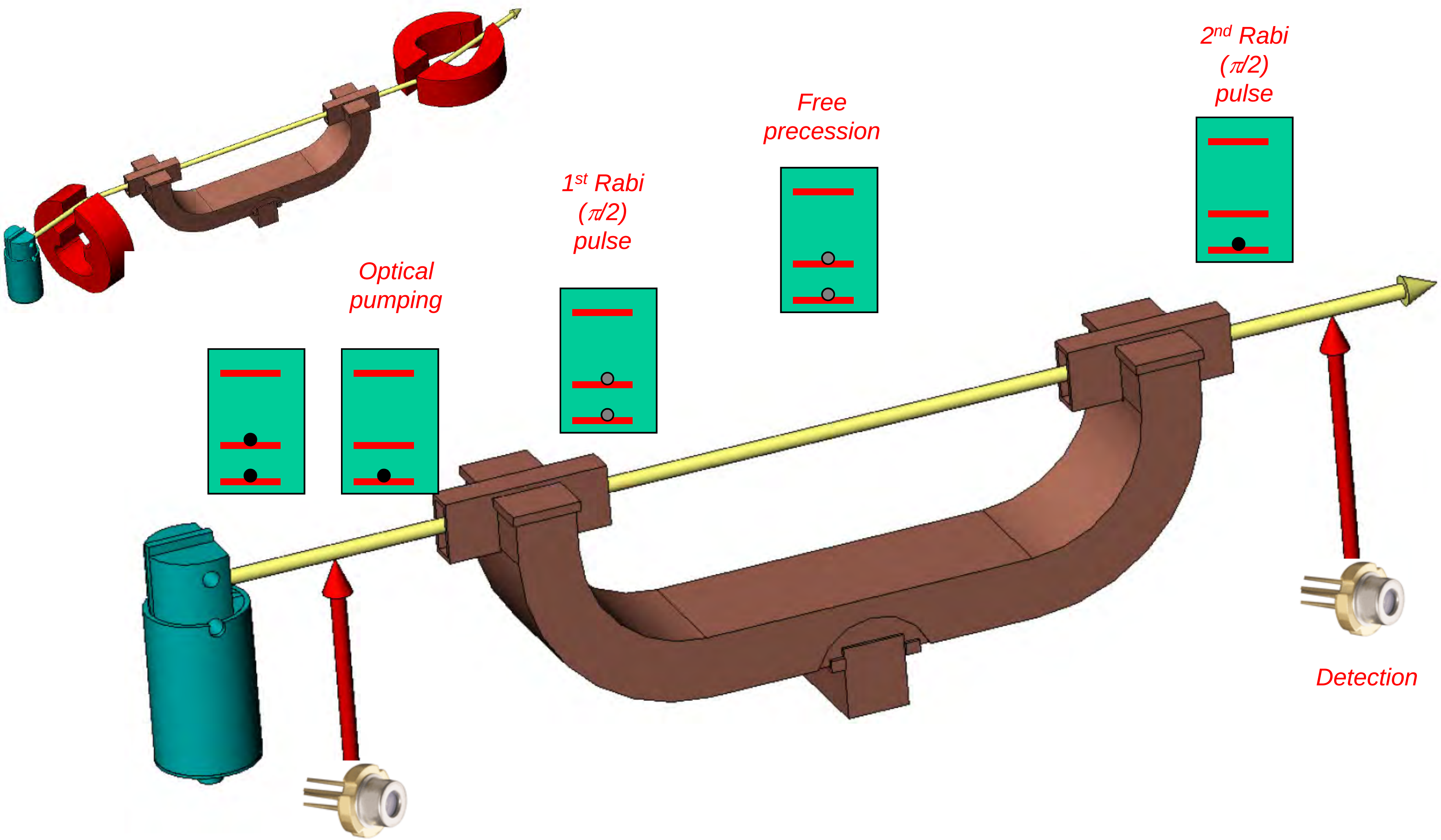


$$Linewidth \;\; \Delta\omega_0 \propto \frac{1}{T_R}$$

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

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

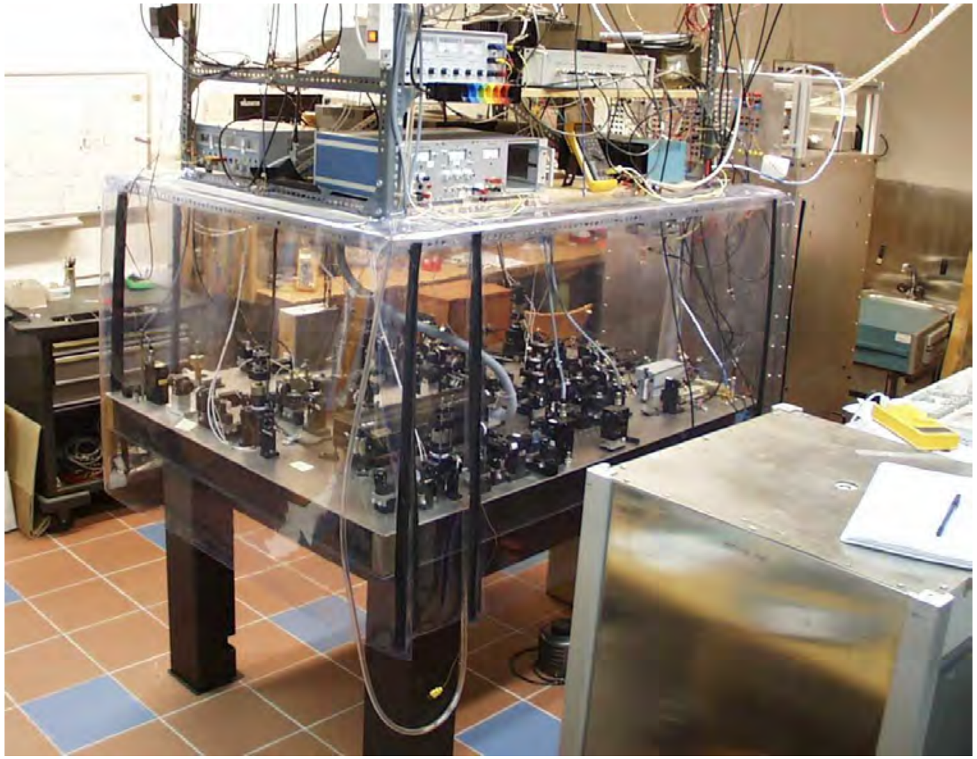
LASER-PUMPED BEAM STANDARDS

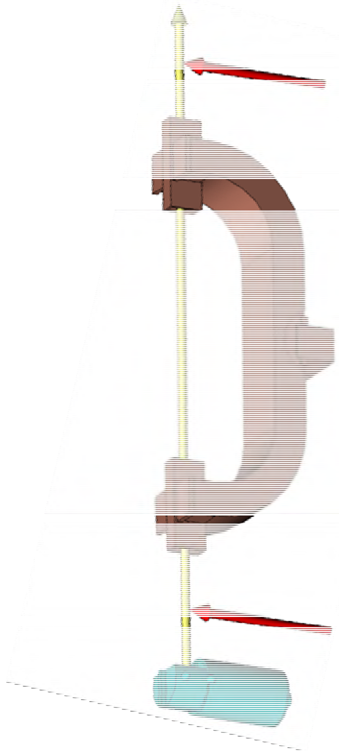


PRIMARY COLD (SLOW) ATOMS FOUNTAIN

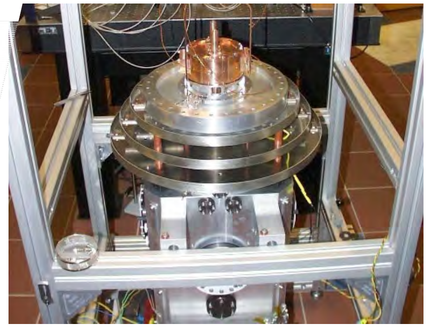
$$Q = \omega_0 \cdot T_R$$

T_R ~ 1 millisecond





T_R ~ 1 second

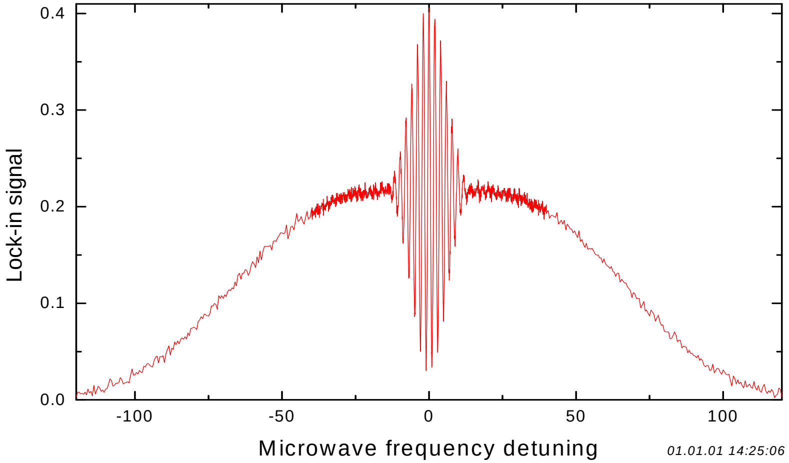


COLD ATOMIC BEAM CLOCKS (FOUNTAINS)

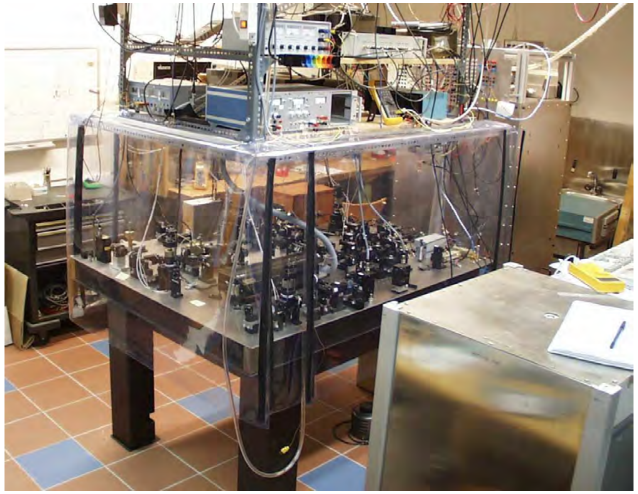
$$Linewidth \;\; \Delta\omega_0 \propto \frac{1}{T_R}$$

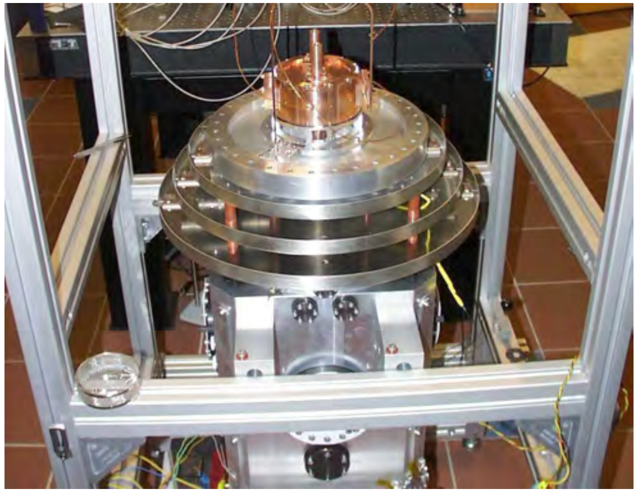
- Thermal beam: v = 100 m/s, T_R = 5 ms
  $\Delta\omega_0$ **= 100 Hz**

- Cold fountain: v = 4 m/s, T_R = 0.5 s
  $\Delta\omega_0$ **= 1 Hz**

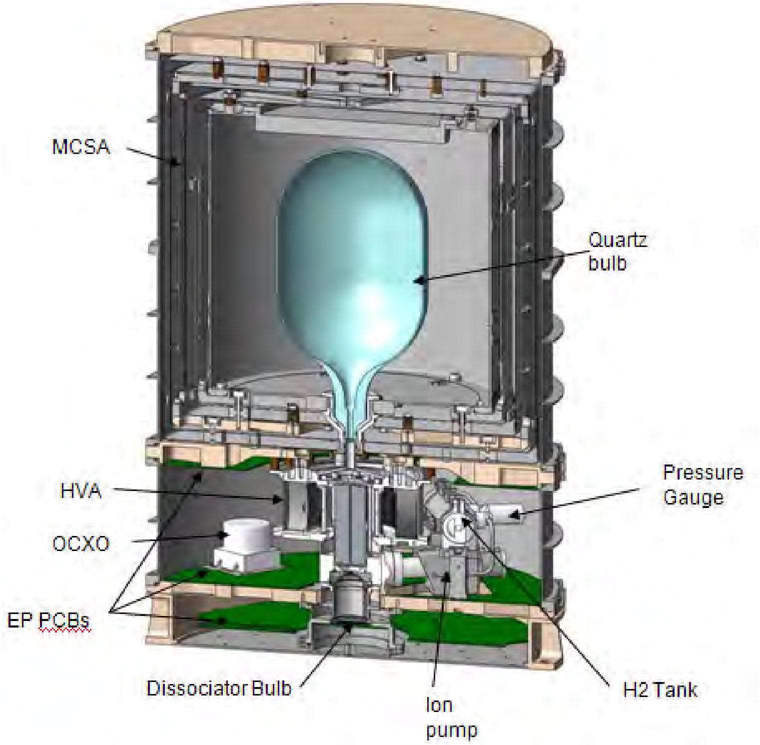


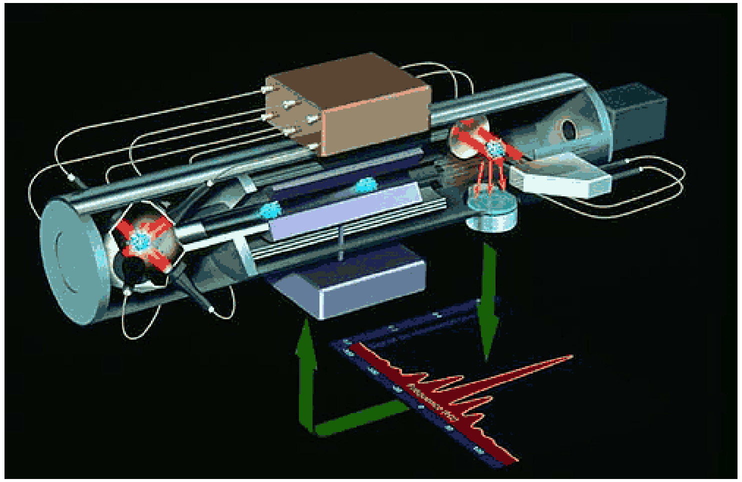
- Next step: microgravity (T_R = 10 s, $\Delta\omega_0$ **= 0.1 Hz**)





SPACE COLD ATOMS CLOCK





$$Q = \omega_0 \cdot T_R$$

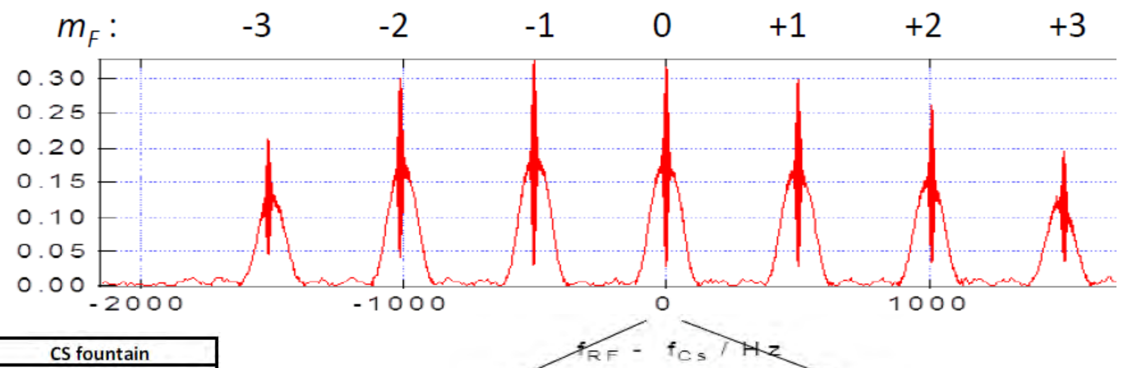
$$T_R \sim 10 \text{ seconde}$$

Atomic Clock Ensemble in Space

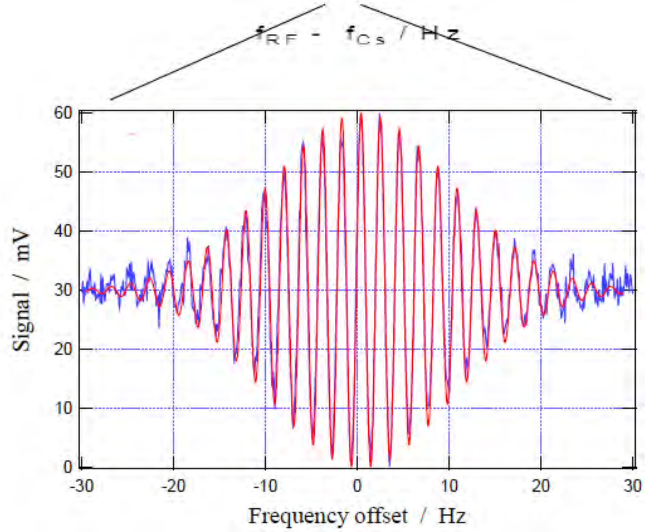
PRIMARY FREQUENCY STANDARDS

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

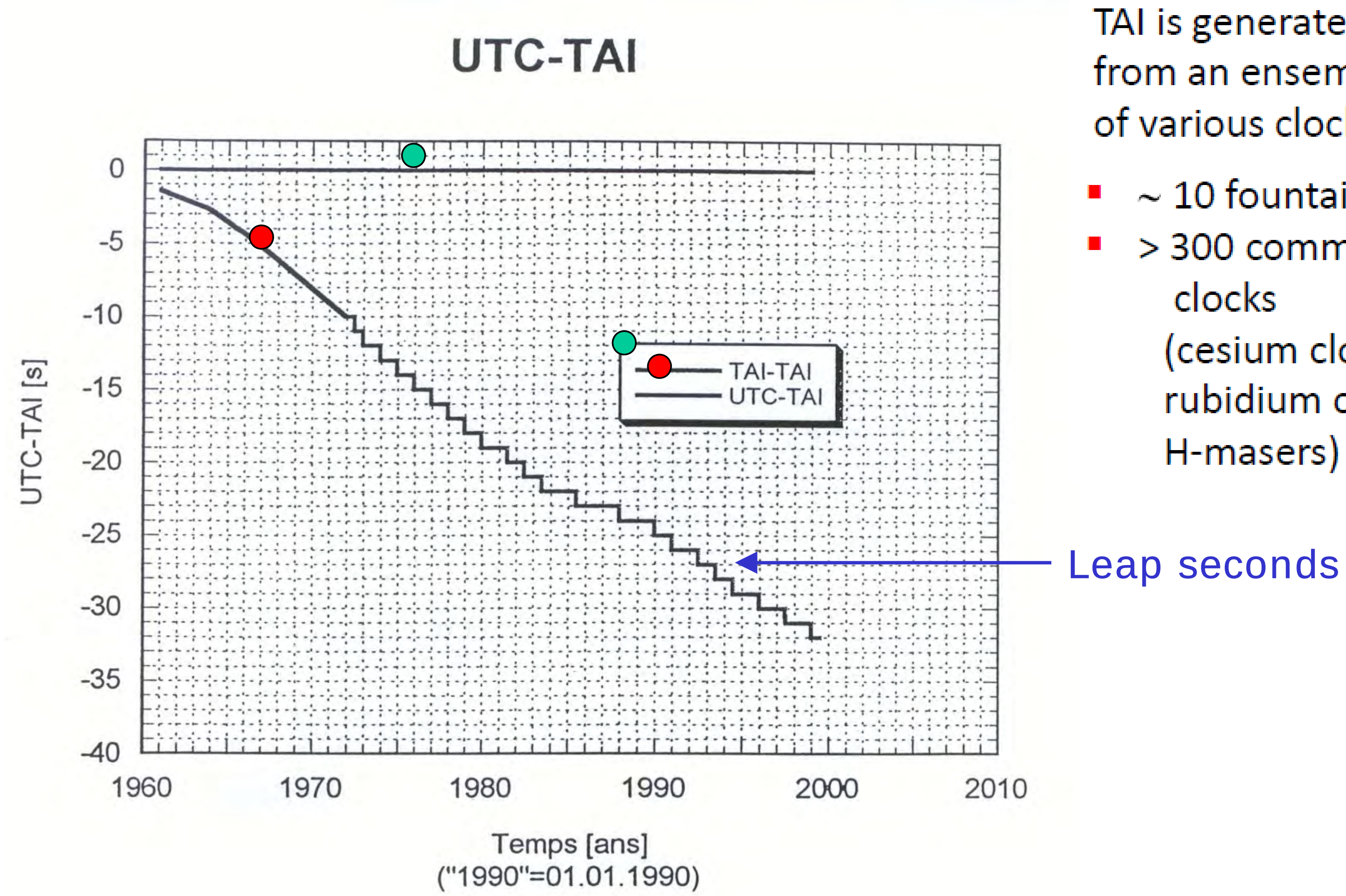
Systematic bias ←   → *Statistical fluctuations*



	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	$3.3\cdot10^{-10}$	$1\cdot10^{-15}$	$4.5\cdot10^{-14}$	$1\cdot10^{-16}$
2nd order Doppler	$5\cdot10^{-14}$	$5\cdot10^{-16}$	$< 1\cdot10^{-16}$	$< 1\cdot10^{-16}$
Cavity phase-shift	$2.5\cdot10^{-13}$	$6\cdot10^{-15}$	$< 1\cdot10^{-16}$	$< 3\cdot10^{-16}$
Gravitational pot.	$8\cdot10^{-15}$	$2\cdot10^{-16}$	$1.8\cdot10^{-13}$	$1\cdot10^{-16}$
Spin-exchange	-	-	$1\cdot10^{-14}$	$3\cdot10^{-16}$
Black body (AC Stark)	$2\cdot10^{-14}$	$5\cdot10^{-16}$	$2\cdot10^{-14}$	$3\cdot10^{-16}$
Other effects		$4\cdot10^{-15}$		$< 4\cdot10^{-16}$
Total uncertainty *D*		**$7\cdot10^{-15}$**		**$7\cdot10^{-16}$**



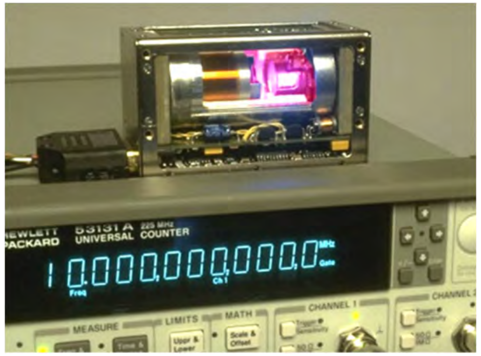
ATOMIC TIME (TAI) AND ASTRONOMICAL TIME (UTC)

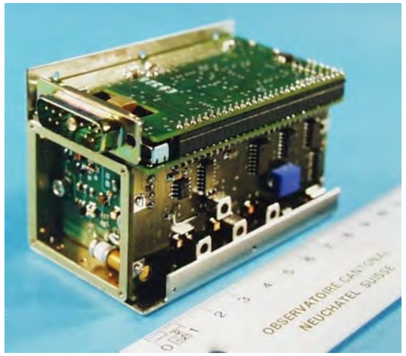


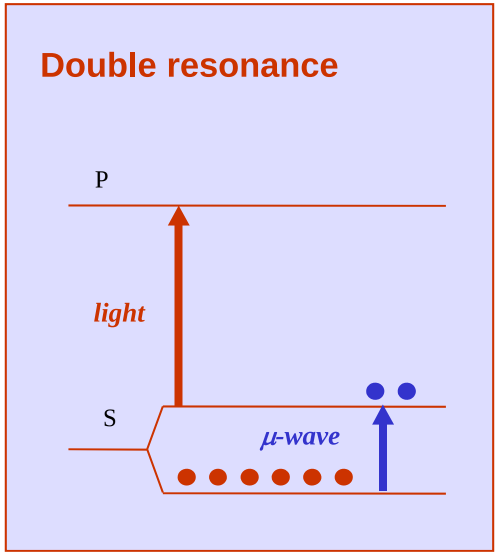
TAI is generated from an ensemble of various clocks :

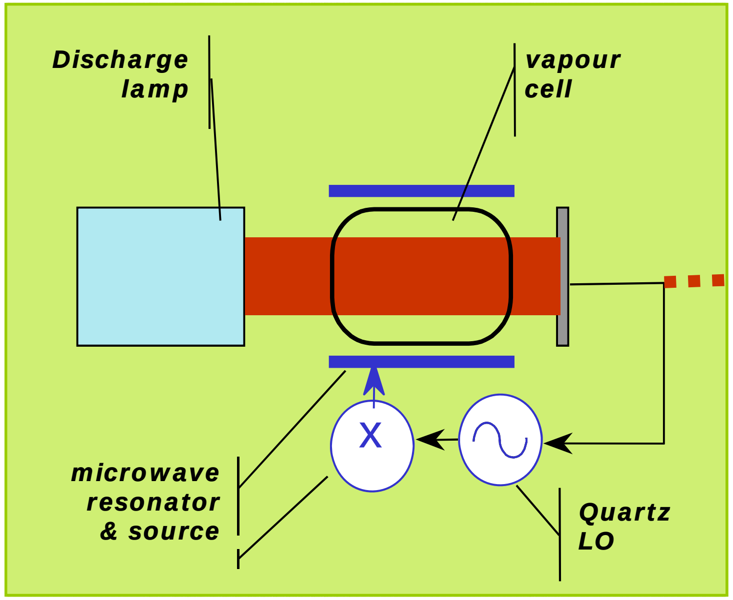
- ~ 10 fountains
- > 300 commercial clocks (cesium clocks, rubidium clocks, H-masers)

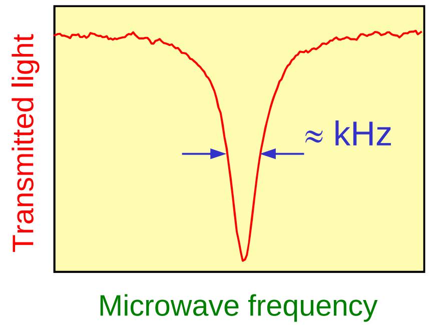
RUBIDIUM VAPOUR CELL STANDARD









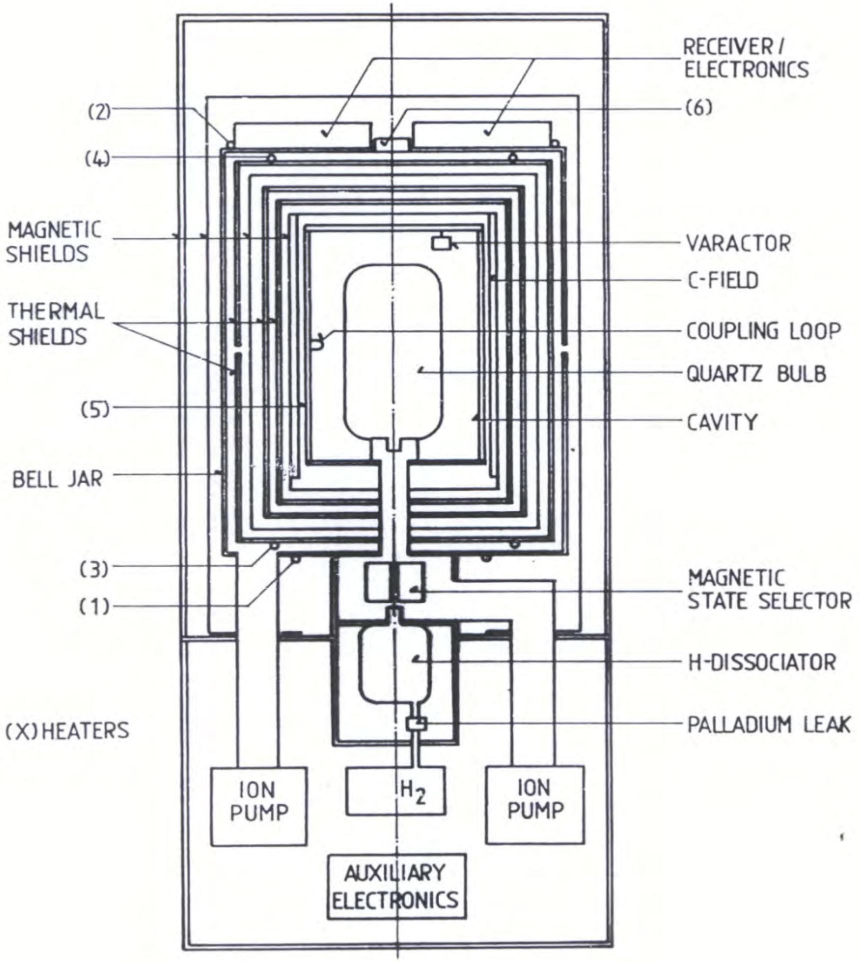


10^{-11} @ 1s

10^{-13} @ 10'000s

HYDROGEN MASER

microwave amplification by stimulated emission of radiation



10^{-13} @ 1s

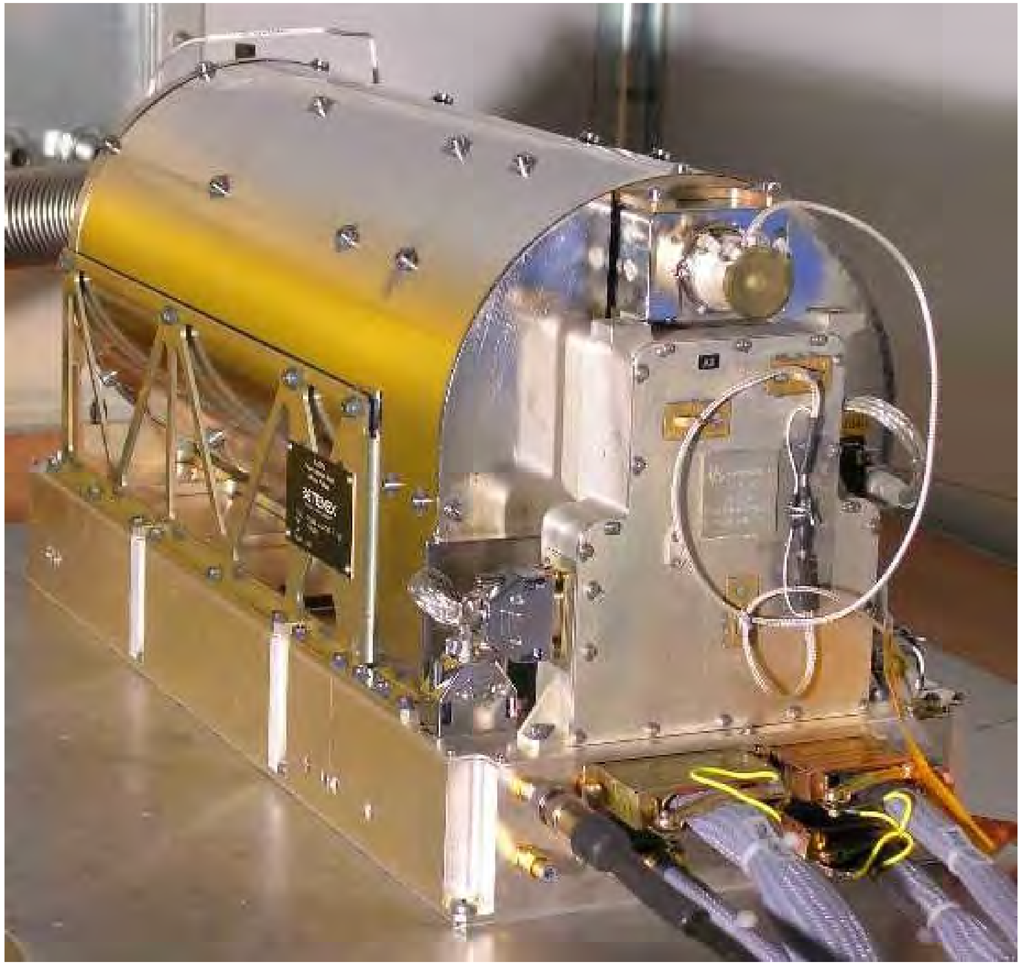
10^{-15} @ 100s

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

100 kg

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

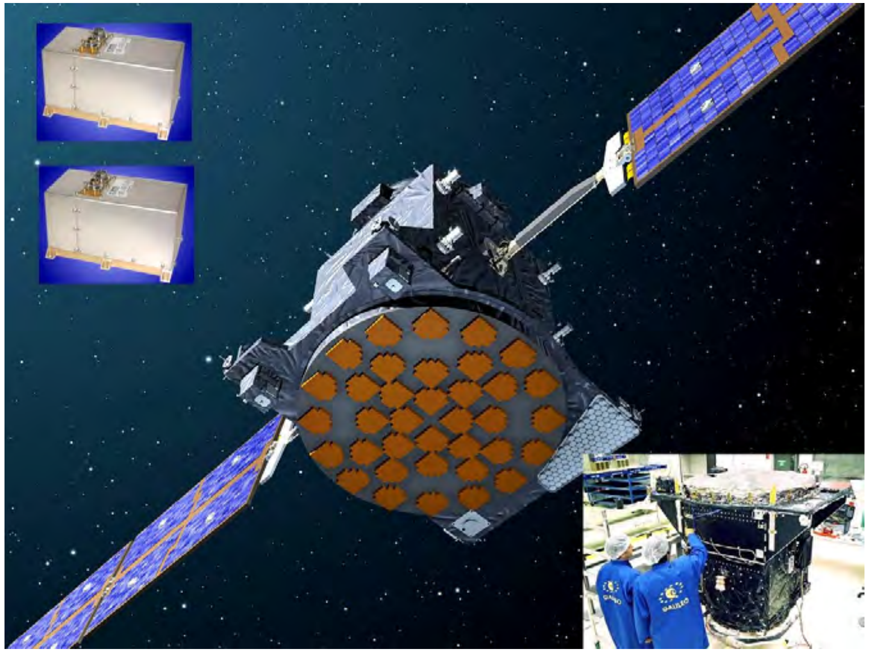
18 kg, 28 L, $7 \cdot 10^{-13}$ @ 1 s

GALILEO (GNSS = GLOBAL NAVIGATION SATELLITE SYSTEM)

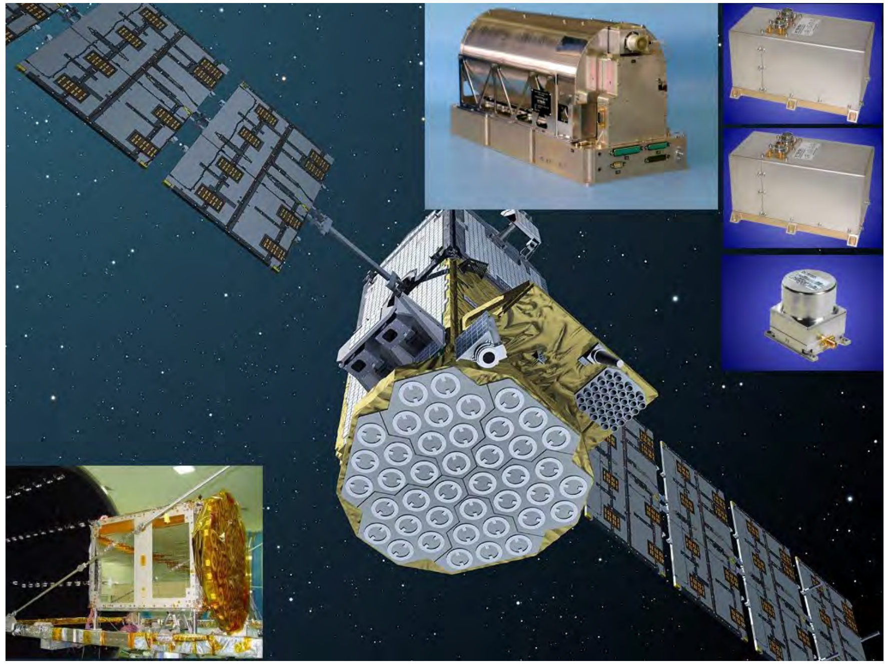
In space: Rubidium, passive Hydrogen Maser (1° generation)

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

GIOVE-A (launched 28 Dec 2005)

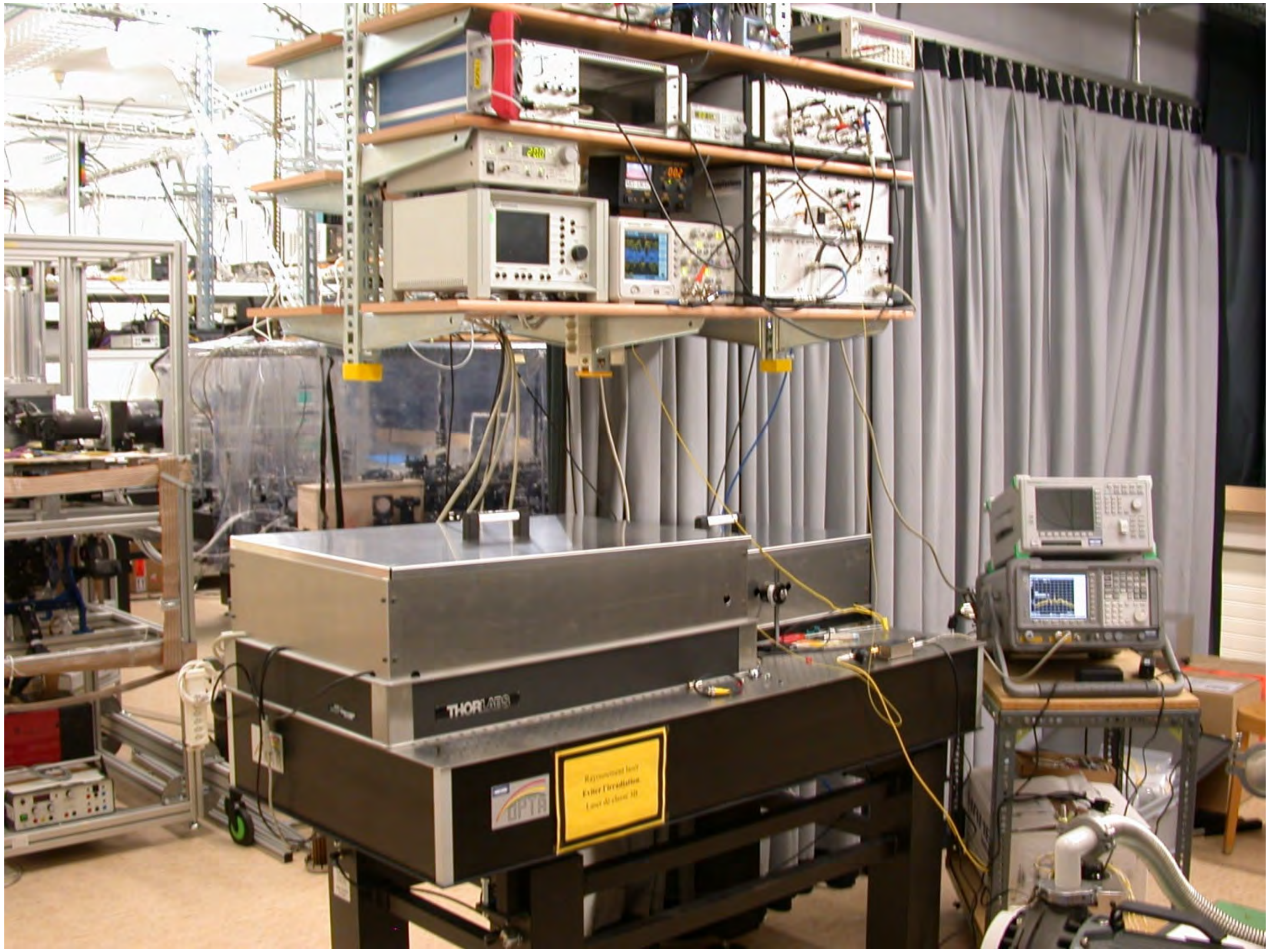


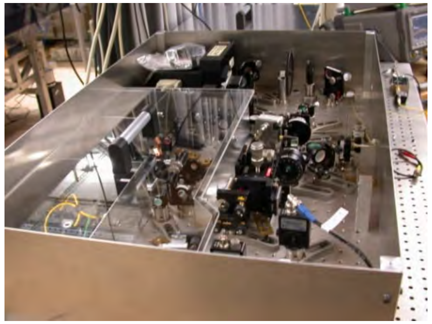
GIOVE-B (launched 26 April 08)



2011 and 2012: launch of first operational satellites (IOV – In Orbit Validation)
2014 – 2018: launches in view of the FOC (Full Operational Constellation).
Estimated number of Galileo-enabled smartphones: 1’000’000’000

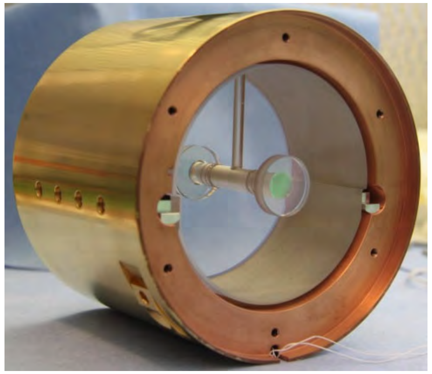
OPTICAL FREQUENCY STANDARDS



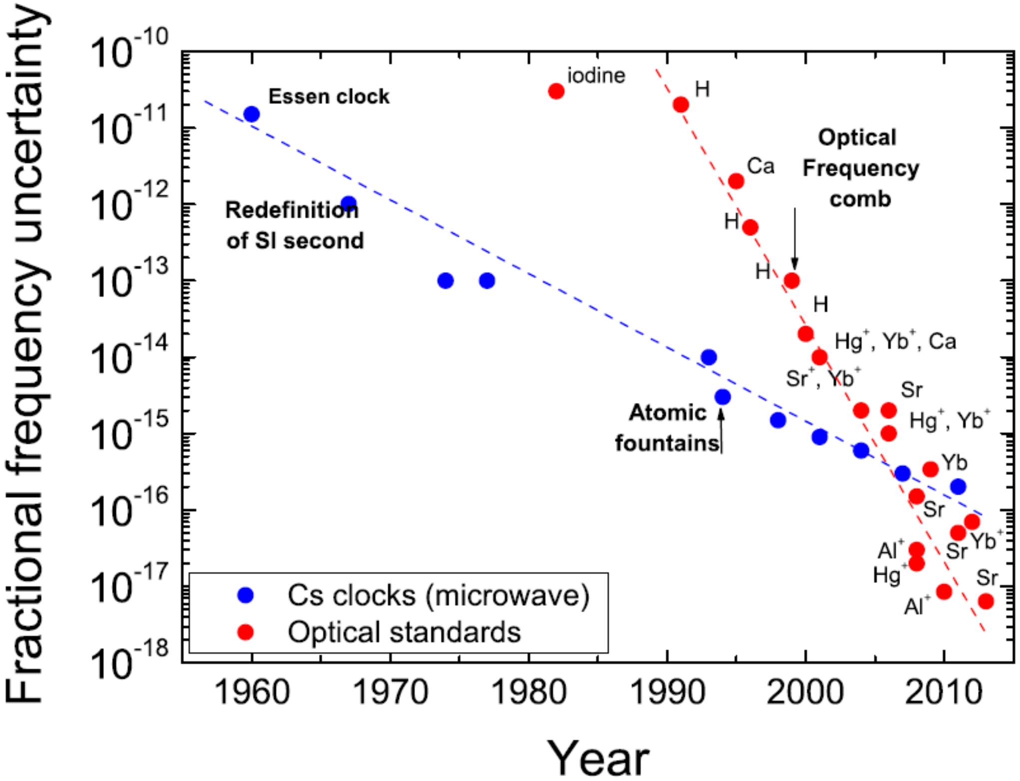


$$\frac{1}{Q} \propto \frac{1}{\omega_0 \cdot T_R}$$

$\omega_0 : 10^{10} \rightarrow 10^{15}$ Hz



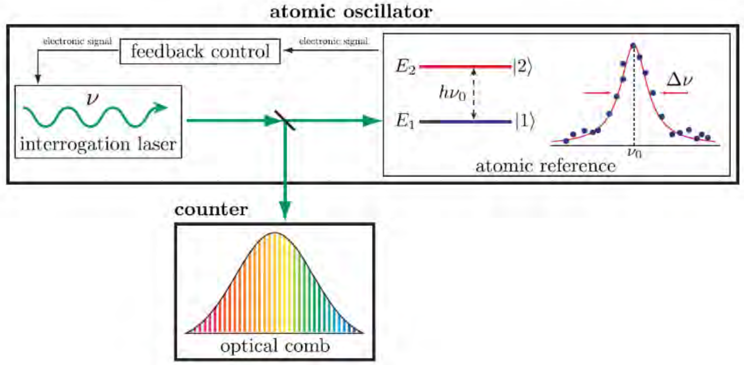
MICROWAVE AND OPTICAL CLOCKS

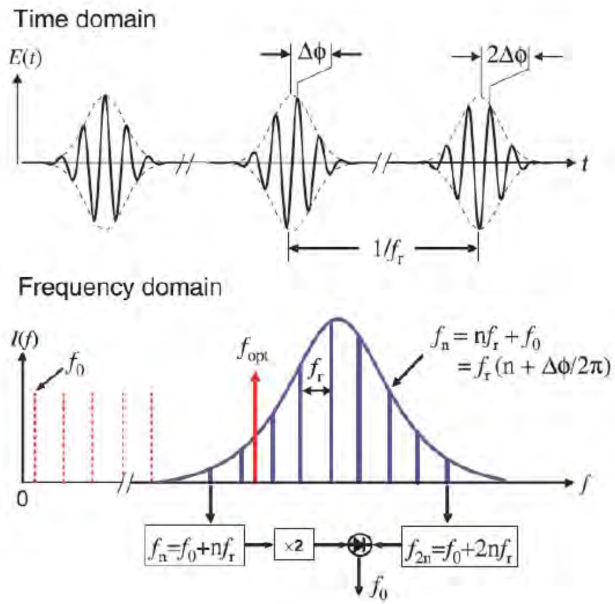


RIVISTA DEL NUOVO CIMENTO Vol. 36, N. 12 2013
DOI 10.1393/ncr/i2013-10095-x

Optical atomic clocks

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





OUTLINE

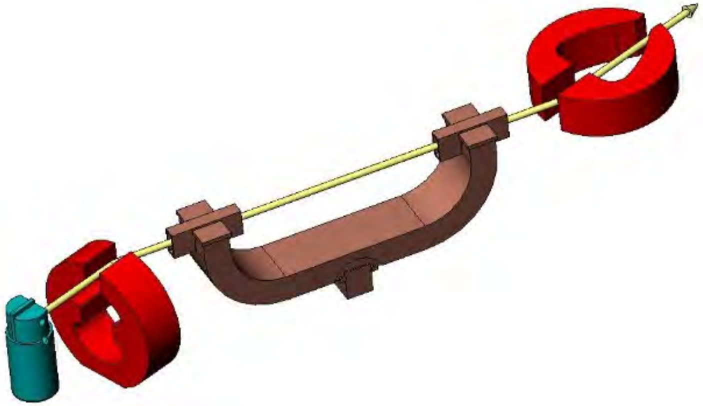
Part 1: **Introduction and historical background**

The evolution of Time & Frequency

Part 2: **Atomic frequency standards**

General aspects and applications

Examples of frequency standards



Part 3: **Rubidium standards and miniature atomic clocks**

Rubidium frequency standards

Miniature atomic clocks

RUBIDIUM VAPOUR CELLS

RUBIDIUM VAPOUR CELLS ATOMIC CLOCKS

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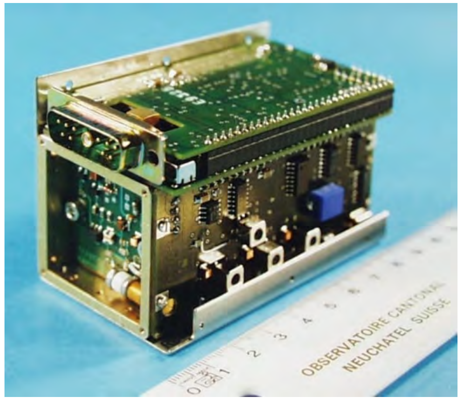


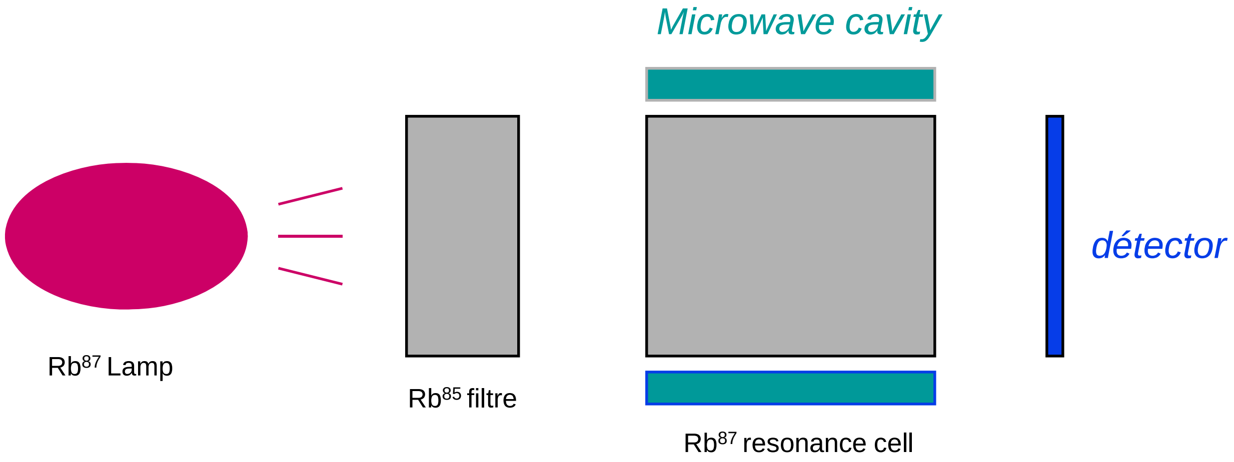
Rb partial pressure:

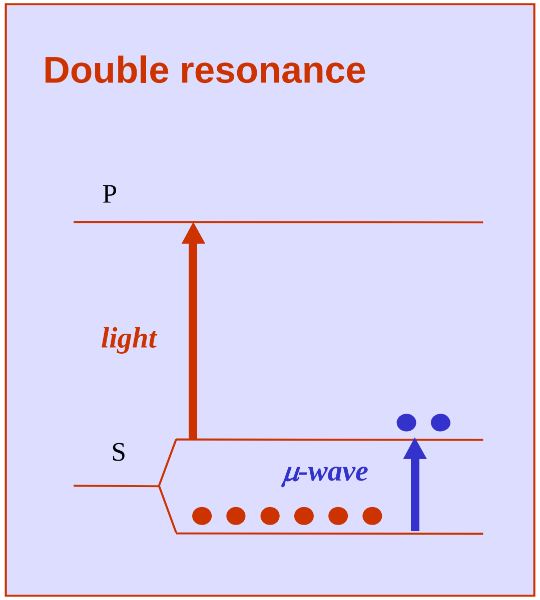
~ 10^{-5} torr

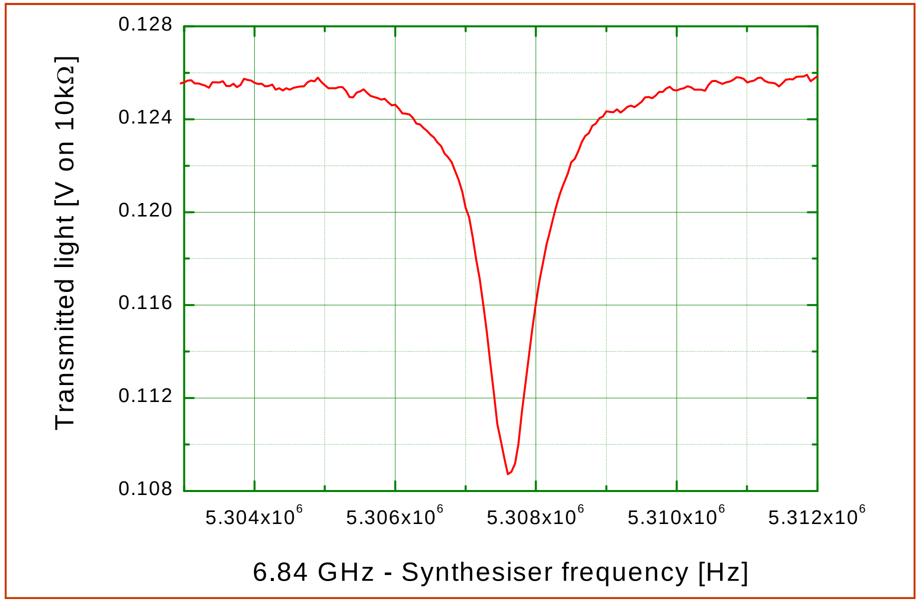
(10^{11}-10^{12} atoms)

10^{-10} - 10^{-14}

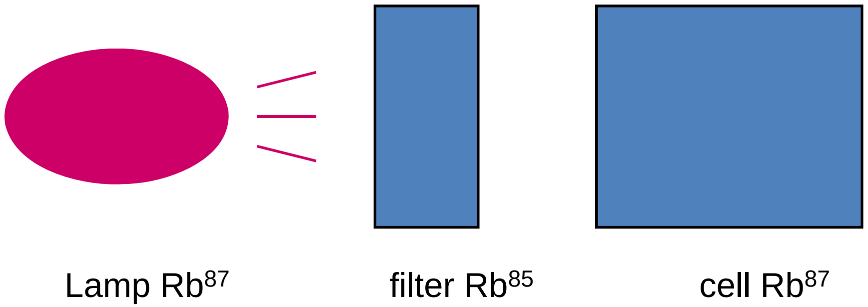
DOUBLE RESONANCE

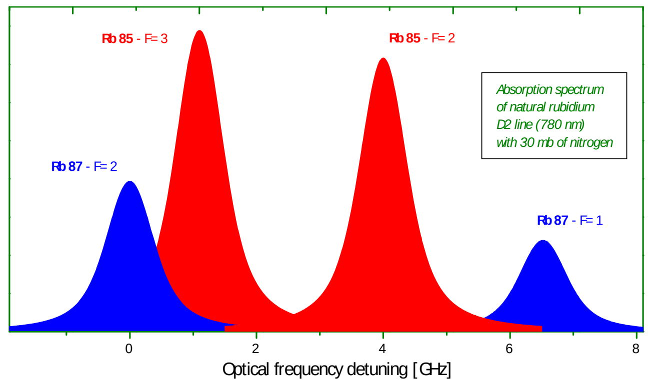


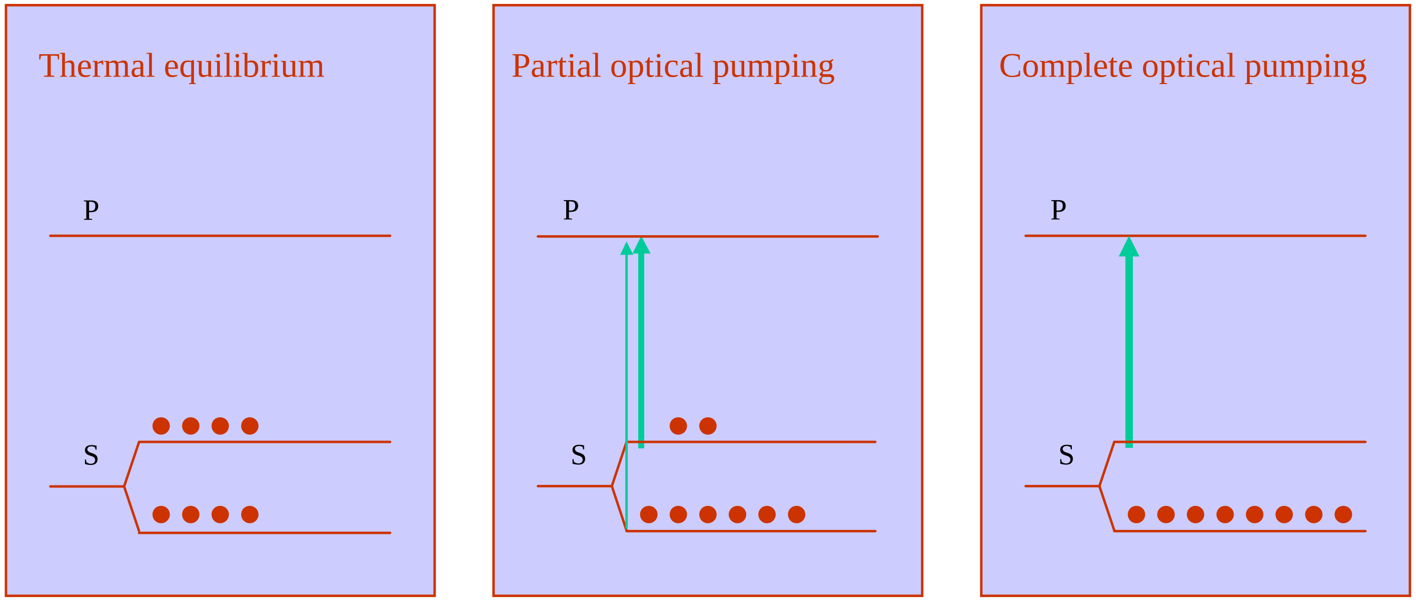




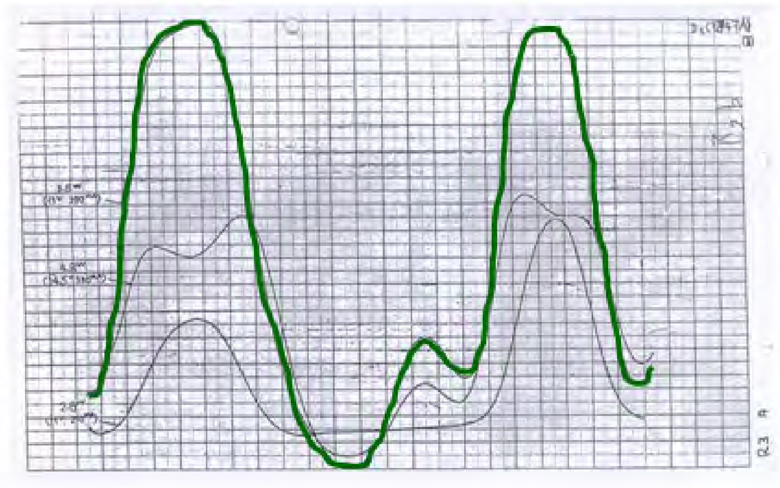
HYPERFINE OPTICAL PUMPING



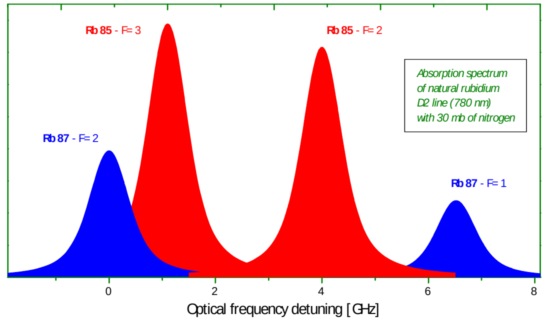


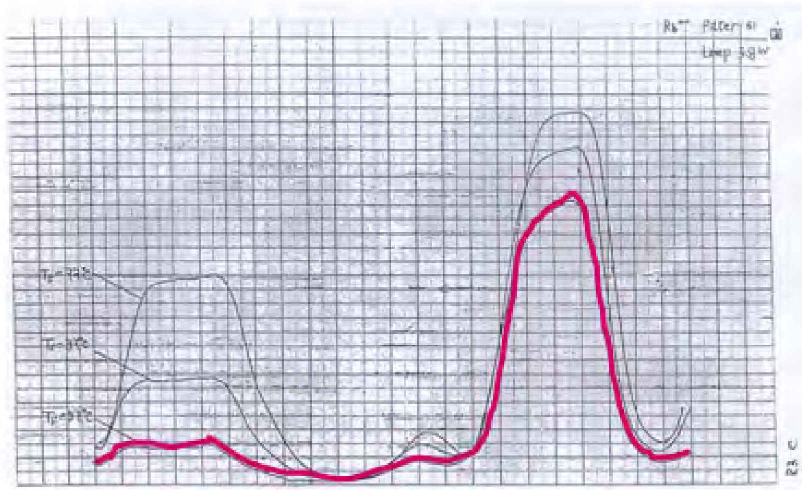


PLASMA DISCHARGE LAMP AND FILTER



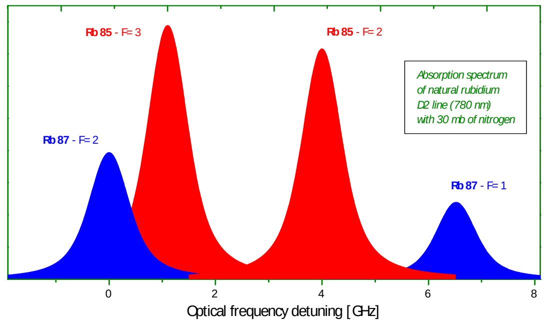
excitation of a ^{87}**Rb lamp** with an RF oscillator (~120 MHz)



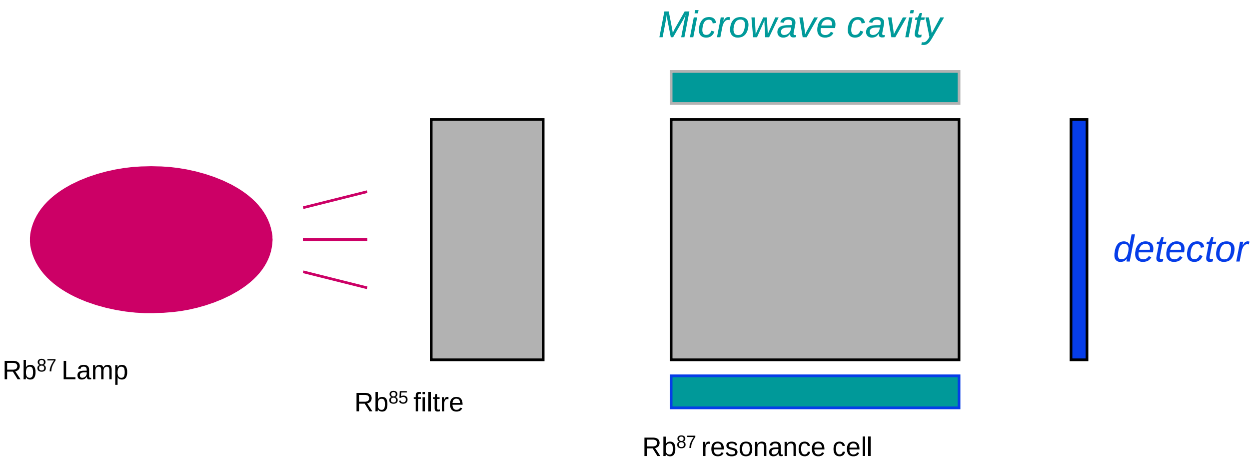


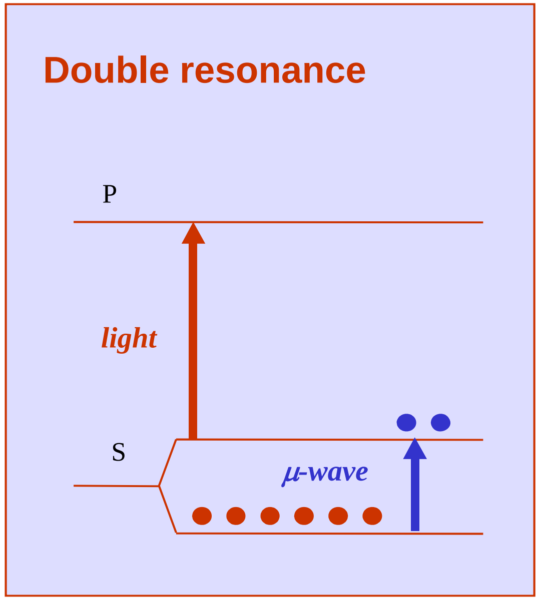
Isotopic filtering with a ^{85}**Rb cell**

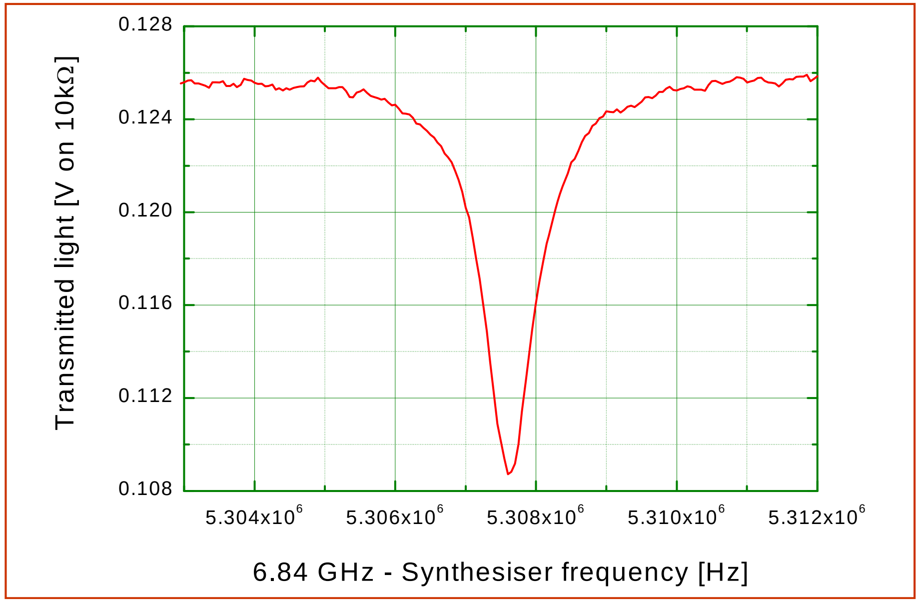
+



DOUBLE RESONANCE WITH A DISCHARGE LAMP







EXAMPLES OF RB CLOCKS (OBSERVATOIRE NE 1985-1995)

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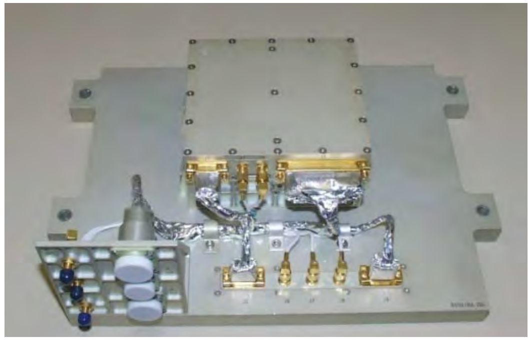
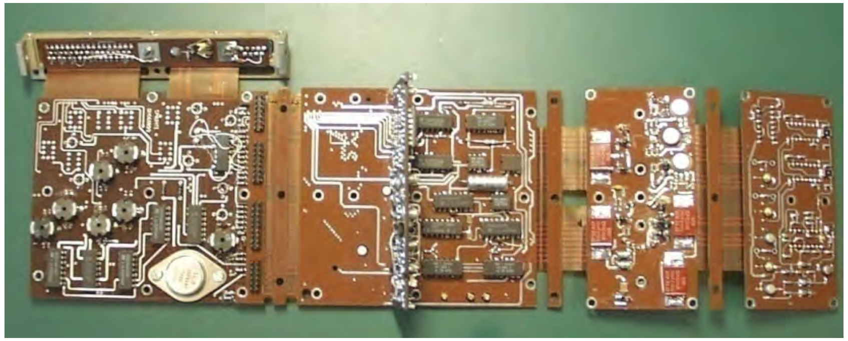
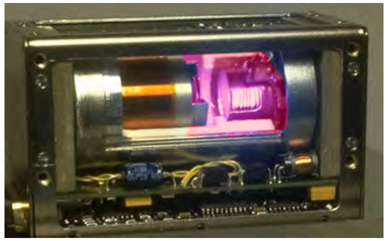
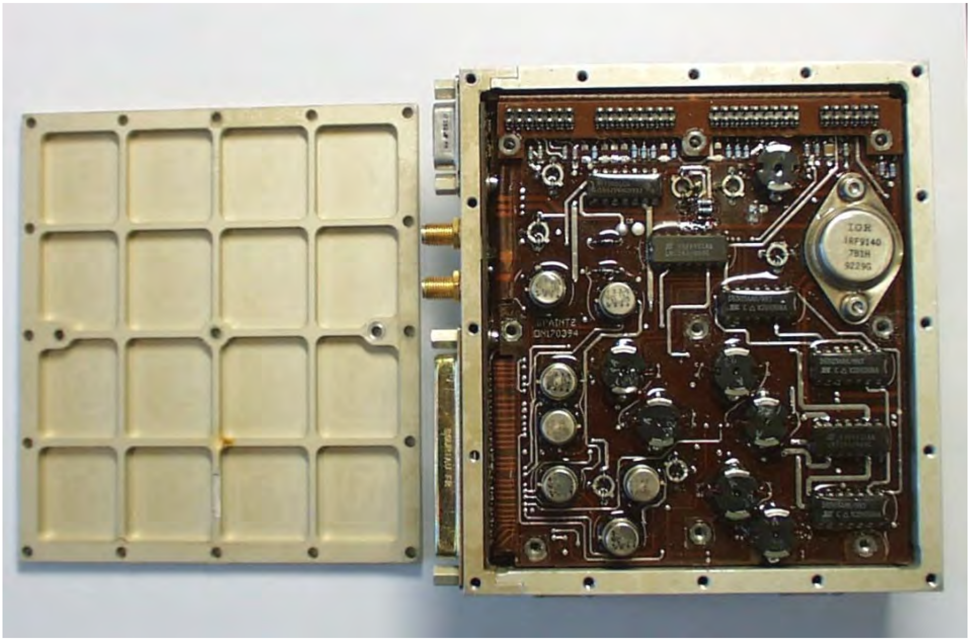
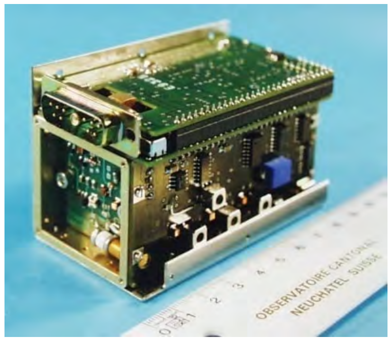


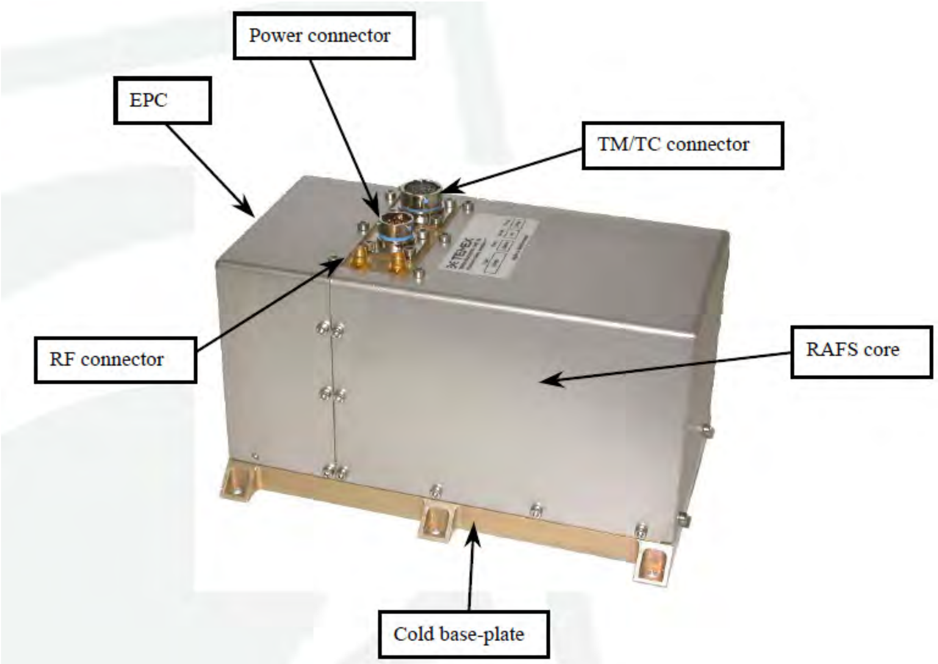


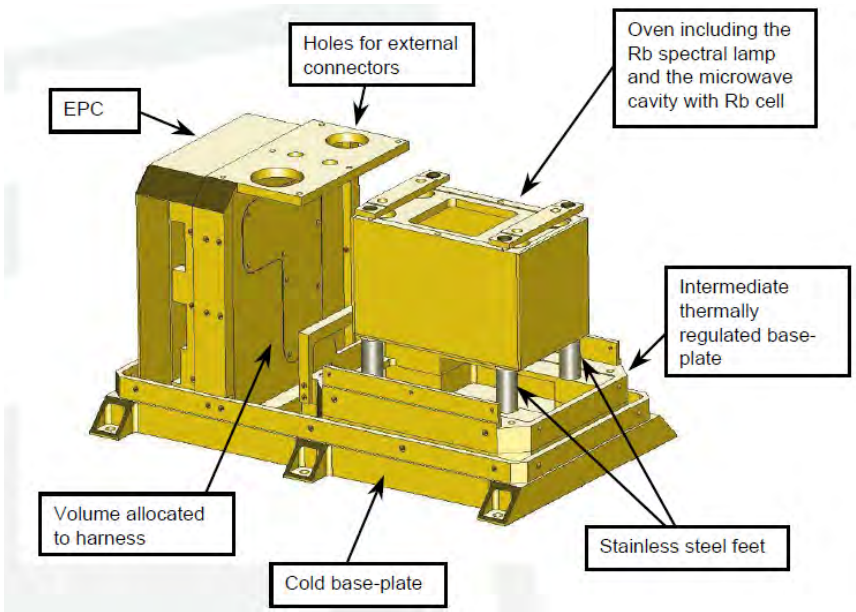






SPECTRATIME RB CLOCKS FOR GNSS





- ✓ **Frequency stability: $< 4\times10^{-14}$ @ 10'000 sec**
- ✓ **Flicker floor : $< 3\times10^{-14}$(drift removed)**
- ✓ **Thermal sensitivity: $< 5\times10^{-14}$ /°C**
- ✓ **Magnetic sensitivity: $< 1\times10^{-13}$ / Gauss**
- ✓ **Mass and volume: 3.2 kg and 2.4 lt**

Source: Pascal Rochat et al., SSOM meeting in Engelberg, 2007

OTHER APPLICATIONS OF RB CLOCKS

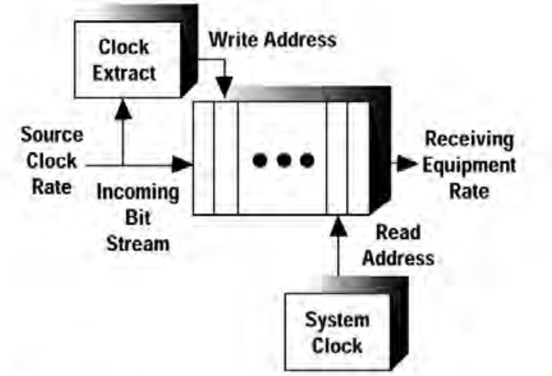
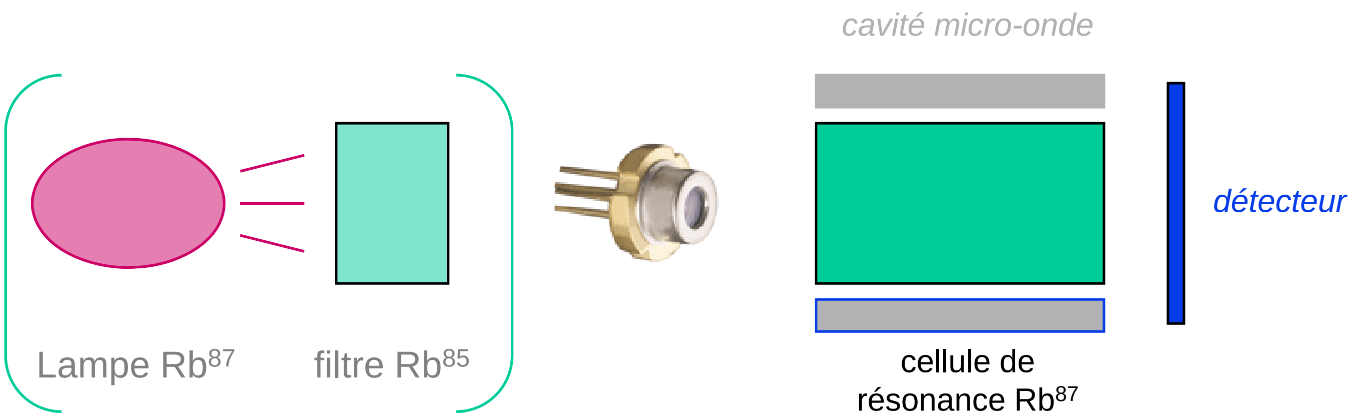


Figure 1.
Slip Buffer

- *Communications:*
  - SDH (Synchronous Digital Hierarchy) CCITT G811,G812
  - Mobile communications base stations reference clock
  - Spread Spectrum secure radio communication systems
  - Digital Radio&Video Broadcast systems (DRB , DVB)

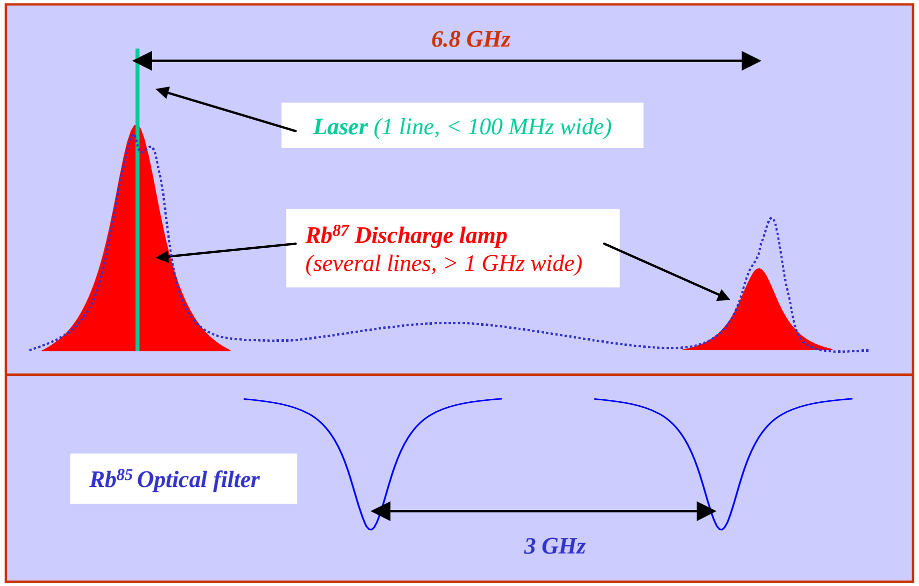
- *Instrumentation:*
  - Telecom SDH synch. Test sets , Cellular base stations test sets …
  - Synthesizers, Counters , Laboratory , Metrology
  - GPS time receivers.

USE OF A LASER DIODE (INSTEAD OF A LAMP)

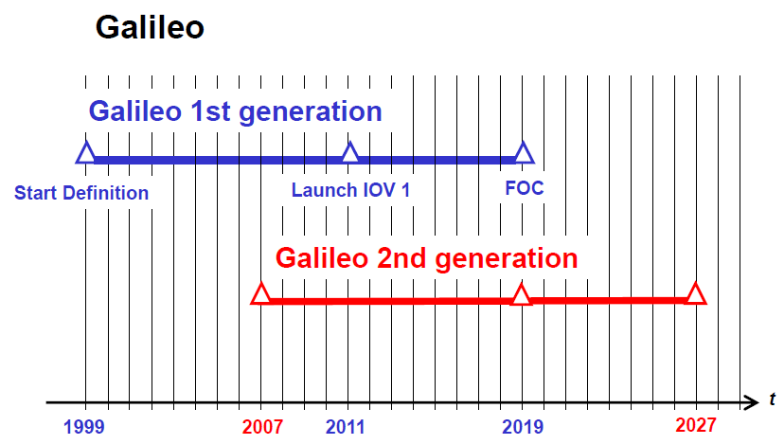


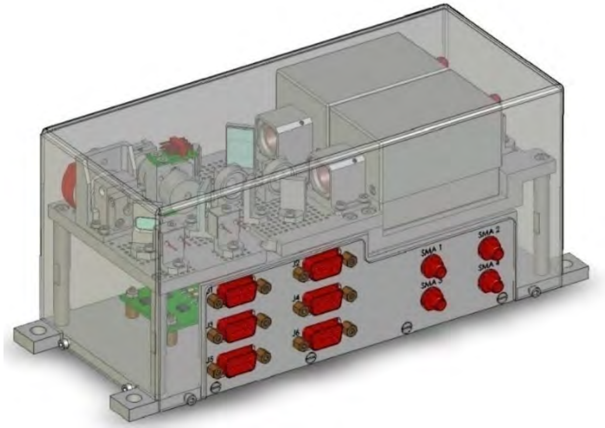
Potential advantages (in Rb clocks):

- More efficient pumping
- Improved S/N
- Long term stability
- Power / Weight / Volume
- Redundancy
- Use of other atoms (example: Cs)



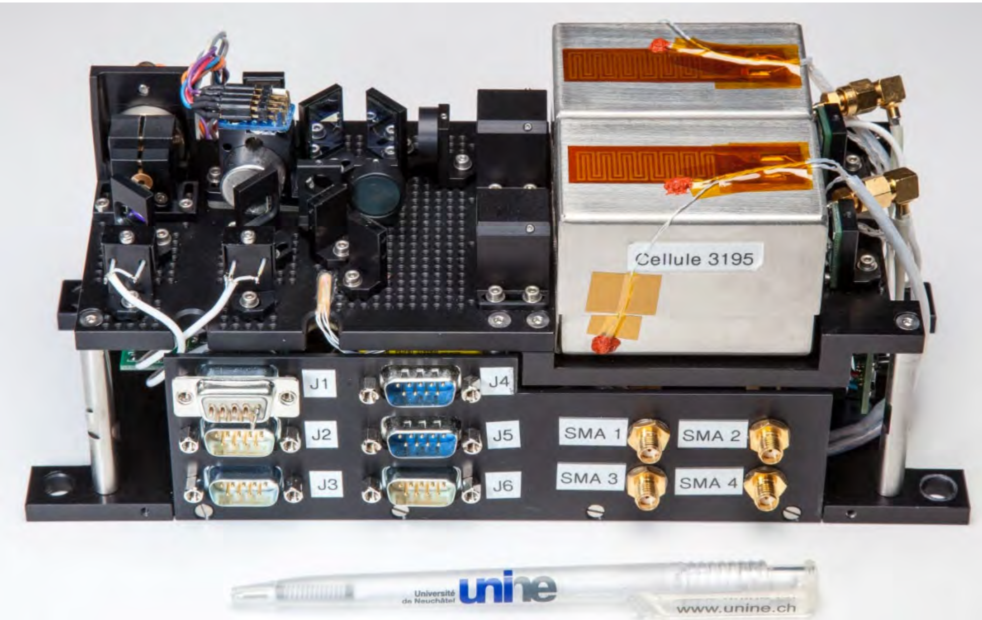
NEXT GENERATION SPACE ATOMIC CLOCKS



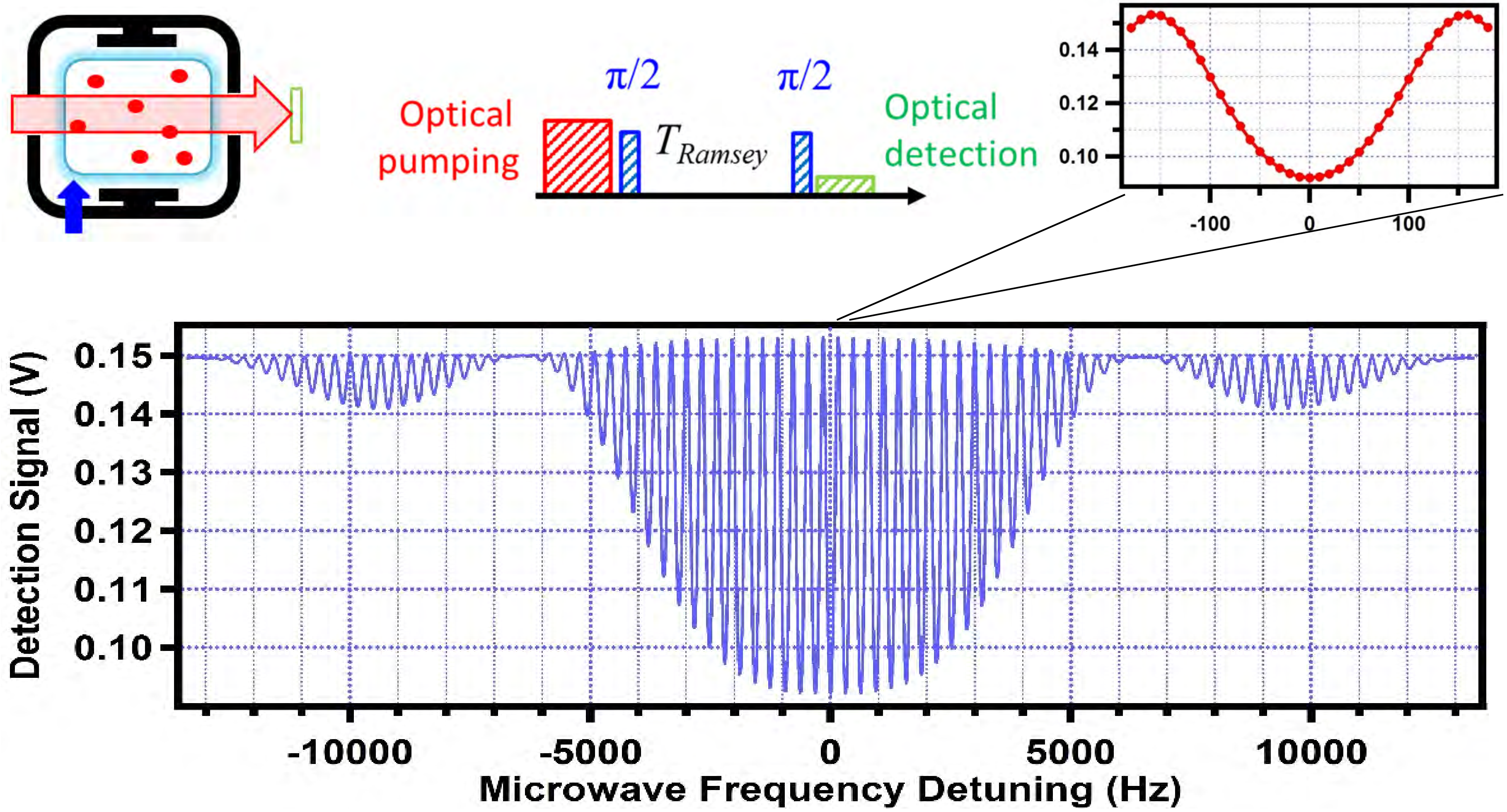


Example:

Laser-pumped Rb clock
(development at LTF-UniNe)



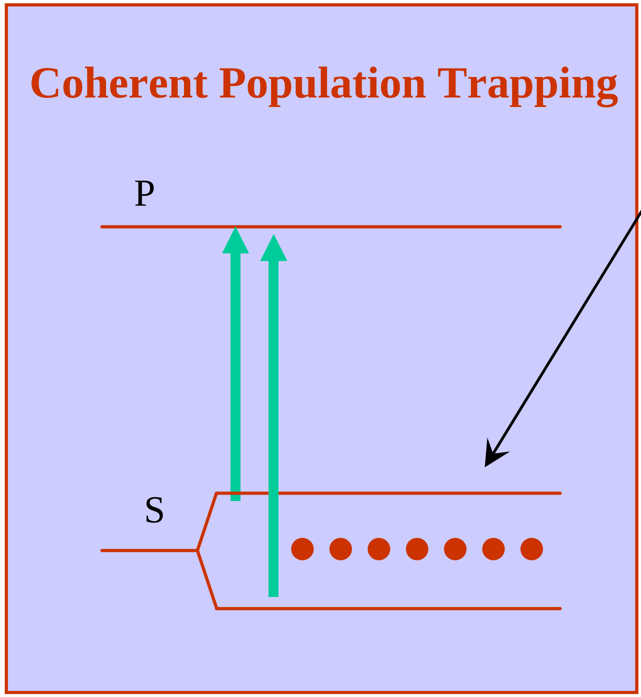
RAMSEY INTERROGATION IN A CELL STANDARD

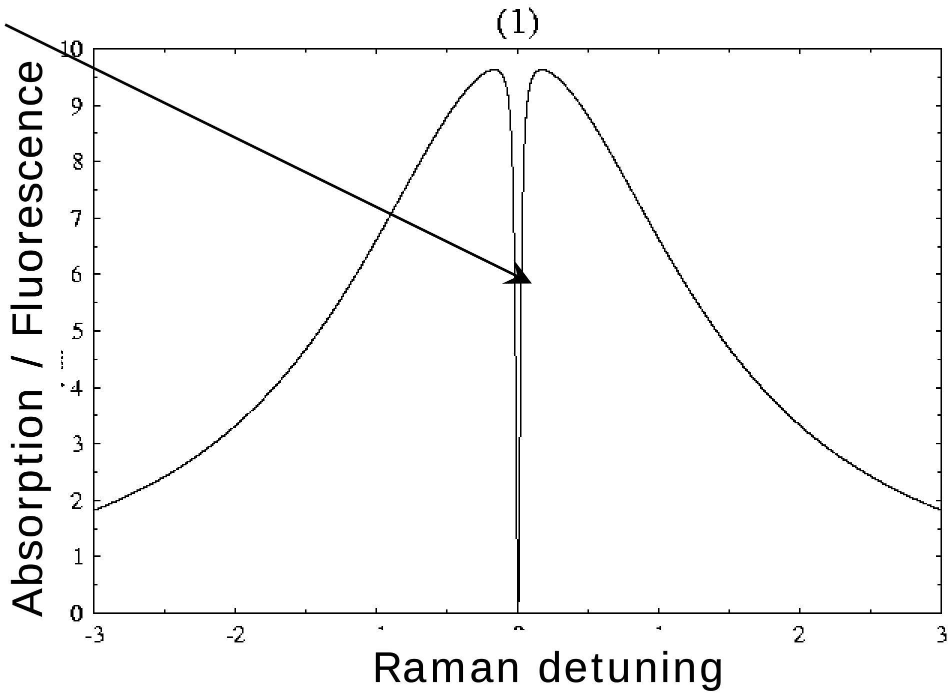


S. Kang, M. Gharavipour, C. Affolderbach, F. Gruet, G. Mileti, *Demonstration of a high-performance pulsed optically pumped Rb c based on a compact magnetron-type microwave cavity*, Journal of Applied Physics 117, 104510 (2015).

Coherent Population Trapping (CPT)

“dark” state





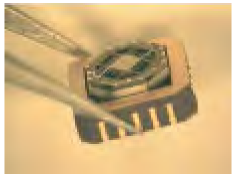
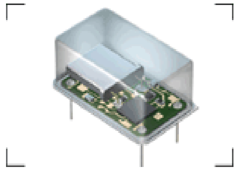
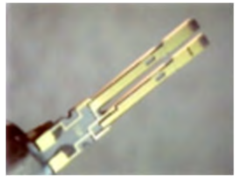
Potential advantages of using CPT:

- No microwave cavity
- Reduced light-shift

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

	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

MINIATURE ATOMIC CLOCKS

UNIVERSITÉ DE NEUCHÂTEL

Main goals

- small size ⇨ portable & mobile instrumentation
- low power cons. ⇨ battery-powered devices
- 10^{-11} stability ⇨ improvement compared to quartz (1μs timing)
- low unit price ⇨ parallel micro-fabrication techniques
- improved aging & shock behavior, compared to quartz

Applications

- network synchronization
- improved hold-over capabilities
- secure communication
- improved GNSS / positioning receivers
- mobile end-user equipment
- …

Ultimate development goals
(e.g. US DARPA CSAC project)

Stability:	$\leq 6\times10^{-10}\ \tau^{-1/2}$
	10^{-11} at $\tau > 3'600$s
Size:	1 cm^3
Power:	**30 mW**
Timing error:	1 μs/day

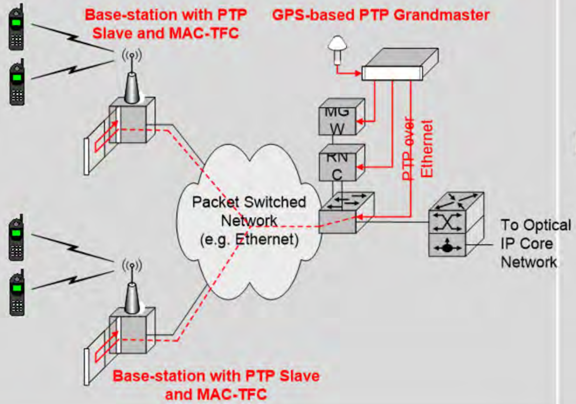
runs ≈ 7 days from a smartphone battery

MINIATURE ATOMIC CLOCK APPLICATIONS

UNIVERSITÉ DE NEUCHÂTEL

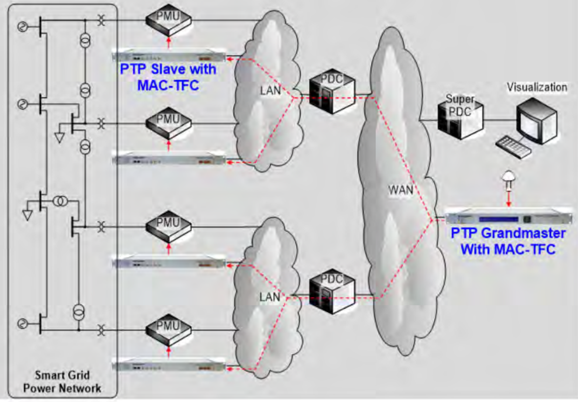
4G LTE base stations:
Phase time synchronization for online TDD and MBSFN

High jitter rejection
Holdover >> 24 h



POWER Smart Grid:
1 µsecond synch of Phase Measurement Units

Holdover >> 24 h

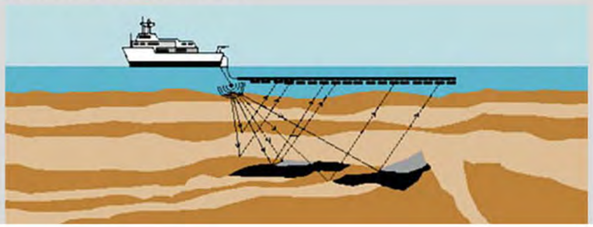


Professional Mobile Radio :
Phase time synchronization for online video

> 24 hours of Holdover
Low Power for Battery operation
Fast warm-up

Seismic exploration:
Net of free running independent clocks:

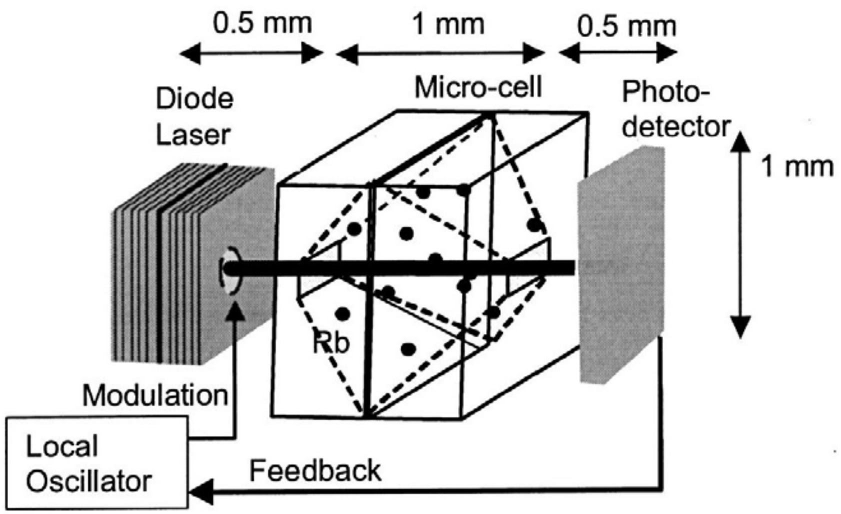
Higher frequency stability + Lower power
→ longer the undersea mission.



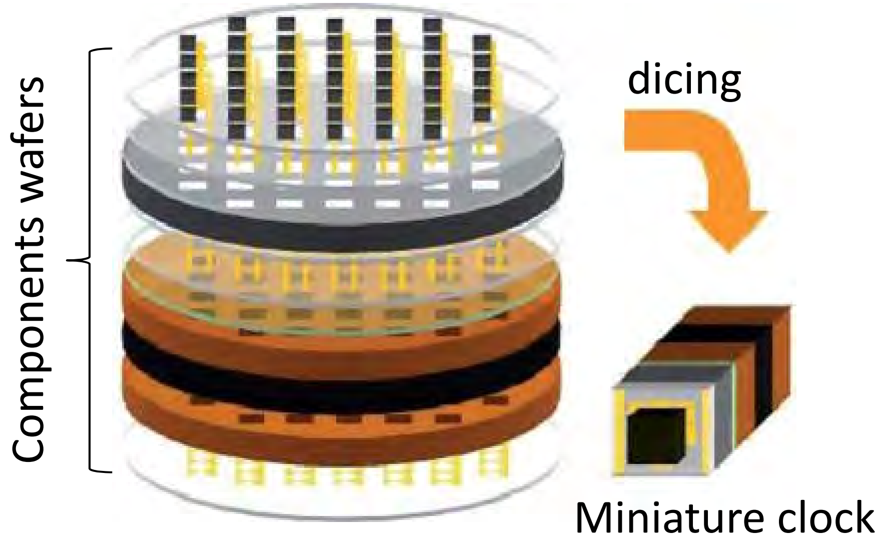
TOWARDS CHIP-SCALE ATOMIC CLOCKS

Proposal for a chip-scale atomic clock:

Use of micro-fabrication technology & CPT



Wafer-level assembly of all components:

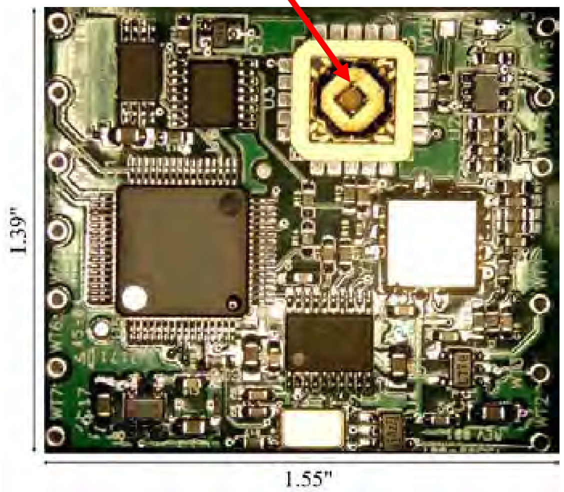


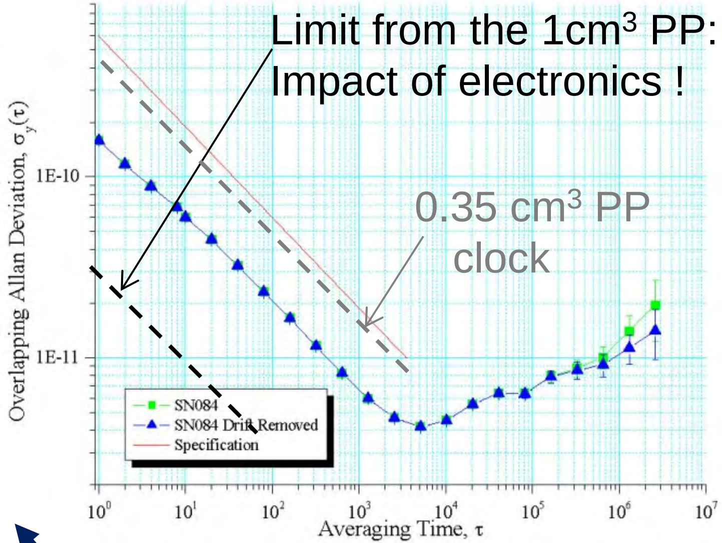
J. Kitching et al., Appl. Phys. Lett 2002.

SYMMETRICOM (MICROSEMI) CSAC PROTOTYPE

UNIVERSITÉ DE NEUCHÂTEL

Pcb with PP





Power budget

System	Component	Power
Signal Processing	MicroController	20 mW
	16-Bit DACs	13 mW
	Analog	8 mW
Physics	Heater Power	7 mW
	VCSEL Power	3 mW
	C-Field	1 mW
Microwave/RF	4.6 GHz VCO	32 mW
	PLL	20 mW
	10 MHz TCXO	7 mW
	Output Buffer	1 mW
Power Regulation & Passive Losses		13 mW
Total		125 mW

- 1 cm^3 PP volume
- 15 cm^3 total volume
- 125 mW consumption
- 10 MHz output

- 0.35 cm^3 PP volume
- ≈1 cm^3 total volume
- 30 mW consumption
- 4.6 GHz output (uncal.)
- No shields, etc.

R. Lutwak et al., Proc. PTTI 2007.

SYMMETRICOM CSAC PRODUCT

Symmetricom

SA.45s CSAC

Chip Scale Atomic Clock

KEY FEATURES

- Power Consumption <115 mW
- Only 16 cc in Volume, 1.6" x 1.39" x 0.45"
- Aging < 3.0E-10/month
- 10 MHz CMOS-compatible Output
- 1 PPS Output and 1 PPS Input for Synchronization
- Hermetically Sealed
- RS-232 Interface for Monitoring and Control
- Ultra-Low Power Mode for Power Consumption well below 100 mW

With an extremely low power consumption of <115 mW and a volume of <16 cc, Symmetricom's SA.45s Chip Scale Atomic Clock (CSAC) brings the accuracy and stability of an atomic clock to portable applications for the first time.

The SA.45s provides 10 MHz and 1 PPS outputs at standard CMOS levels, with short-term stability (Allan Deviation) of 2E-10 @ 1 sec, long-term aging of 3E-10/month, and frequency change over temperature of 5E-10 over an operating range of -10° C to +70° C. The unit can also be ordered with a wider temperature range (Option 002) of -40° C to +85° C, with slightly higher power

A standard CMOS-level RS-232 serial interface is built in to the SA.45s. This is used to control and calibrate the unit and also to provide a comprehensive set of status monitors. The interface is also used to set and read back the CSAC's internal time-of-day clock.

The SA.45s CSAC can also be programmed to operate in an ultra-low power mode. In this mode, the CSAC's physics package is turned off, and the unit operates as a free-running TCXO. The physics package is then periodically turned back on, and after warm-up (<120 sec), it re-disciplines the TCXO. This operating mode enables average power

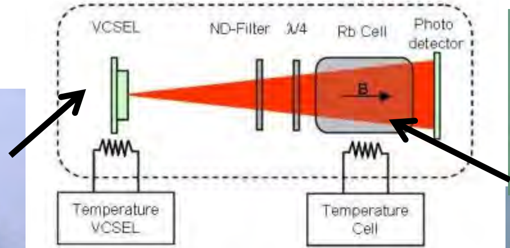
http://www1.symmetricom.com/csac/

ESA-PROJECT: MUSO

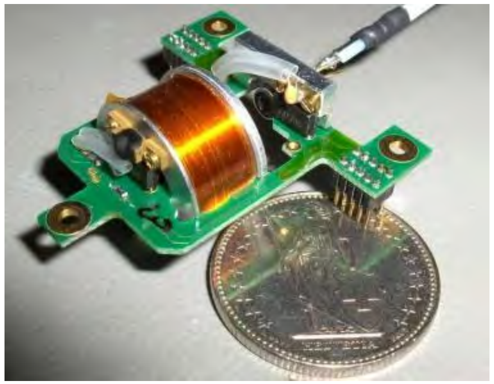
Miniature Ultra-Stable Oscillator

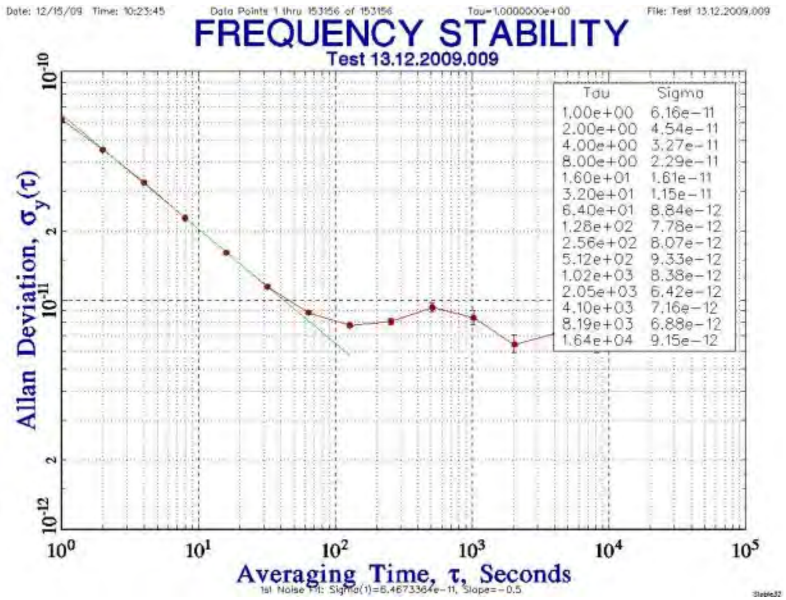
For secure satellite communication

- low-power VCSEL laser (795nm)
- miniature Rb cells



100% Swiss-Made !

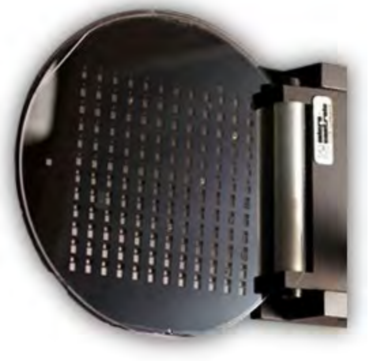




C. Schori et al., Proc. EFTF 2010.

EU-FP7: MAC-TFC

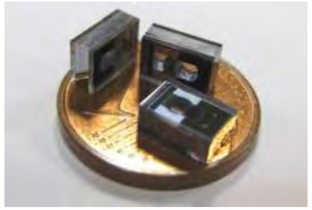
Miniature Atomic Clock for Timing, Frequency Control and Communication



- For ground-based applications
  - Low-power VCSEL on Cs D1-line (Ulm)
  - Miniature Cs cells (Besançon, Neuchâtel, Wroclaw)
  - Full miniature electronics (Neuchâtel)

All key components are developed within the project consortium !

www.mac-tfc.eu

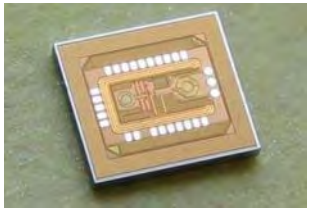


Cs-Cells

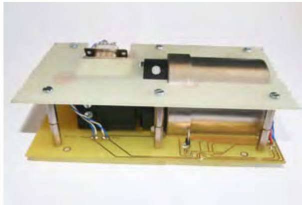
VCSEL-Laser

Packaging

Test setup



ASIC microwave electronics



Clock demonstrator

SINGLE-CHIP 4.6 GHZ SYNTHESIZER FOR CS CPT CSAC

Y. Zhao, S. Tanner, P-A. Farine, ESPLAB-EPFL

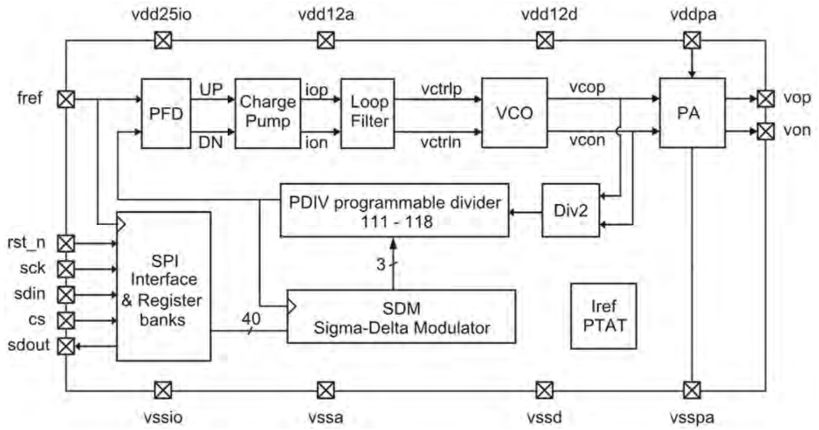
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITÉ DE NEUCHÂTEL

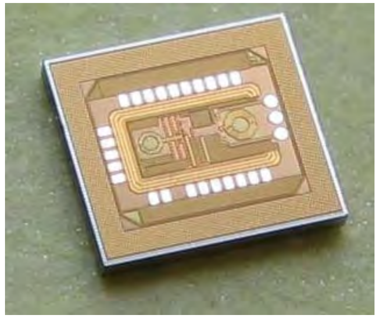
This low power, highly integrated and high performance frequency synthesizer is suited for realizing chip-scale atomic clocks.

Exp. Evaluation, LTF-UniNe :
L. Schneller, F. Gruet,
C. Affolderbach

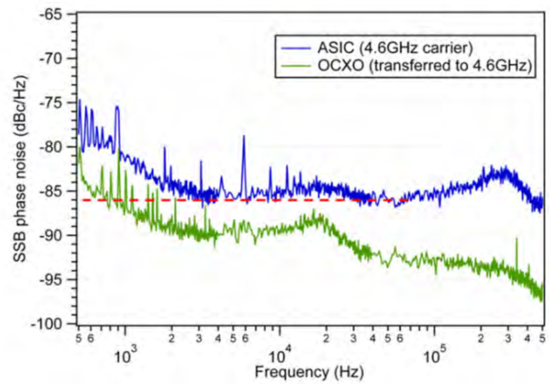
Circuit architecture

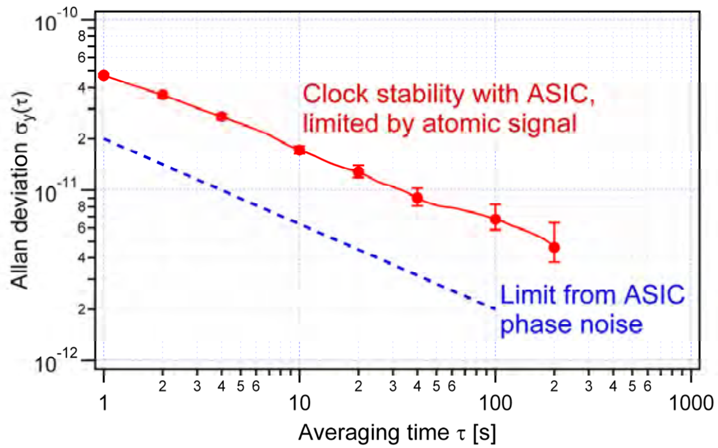


Chip photography



Phase noise @ 4.6 GHz





Stability with Cs micro-cell and ASIC

Obtained results

Fabrication process:	CMOS 130 nm
Chip size:	1.7 x 1.2 mm = 2 mm^2
Phase noise:	-86 dBc/Hz @ 5 kHz
Power consumption:	15 mW (vdd = 1.2 V)
Frequency tuning step:	0.5 mHz (10^{-13})
Output RF power:	0 dBm

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)

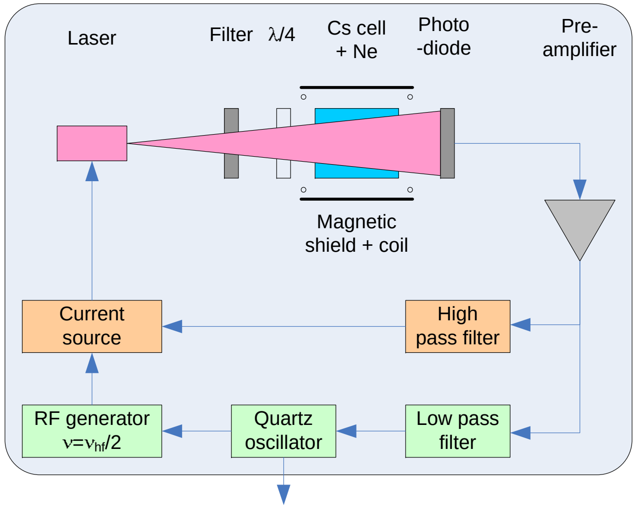
Product specifications

Superior frequency and time stability: 1 µs/day

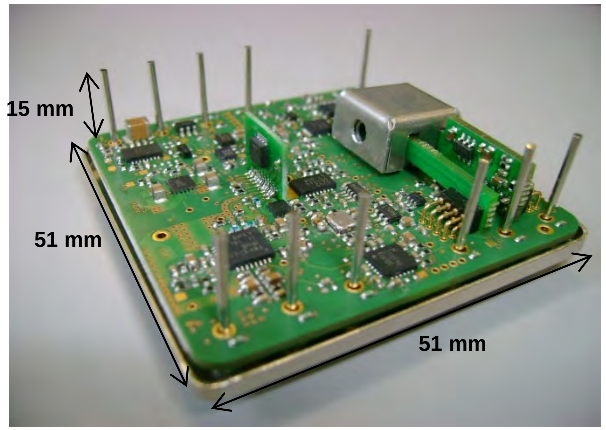
Compact size: 51x51x18 mm3

Low power: 2W

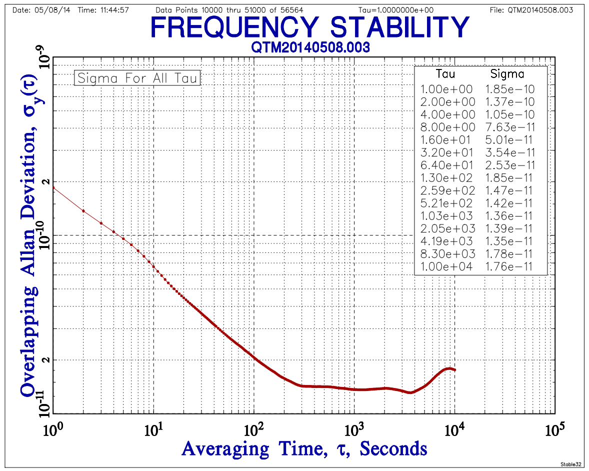
Lower price: 400 CHF



Clock implementation



Prototype picture



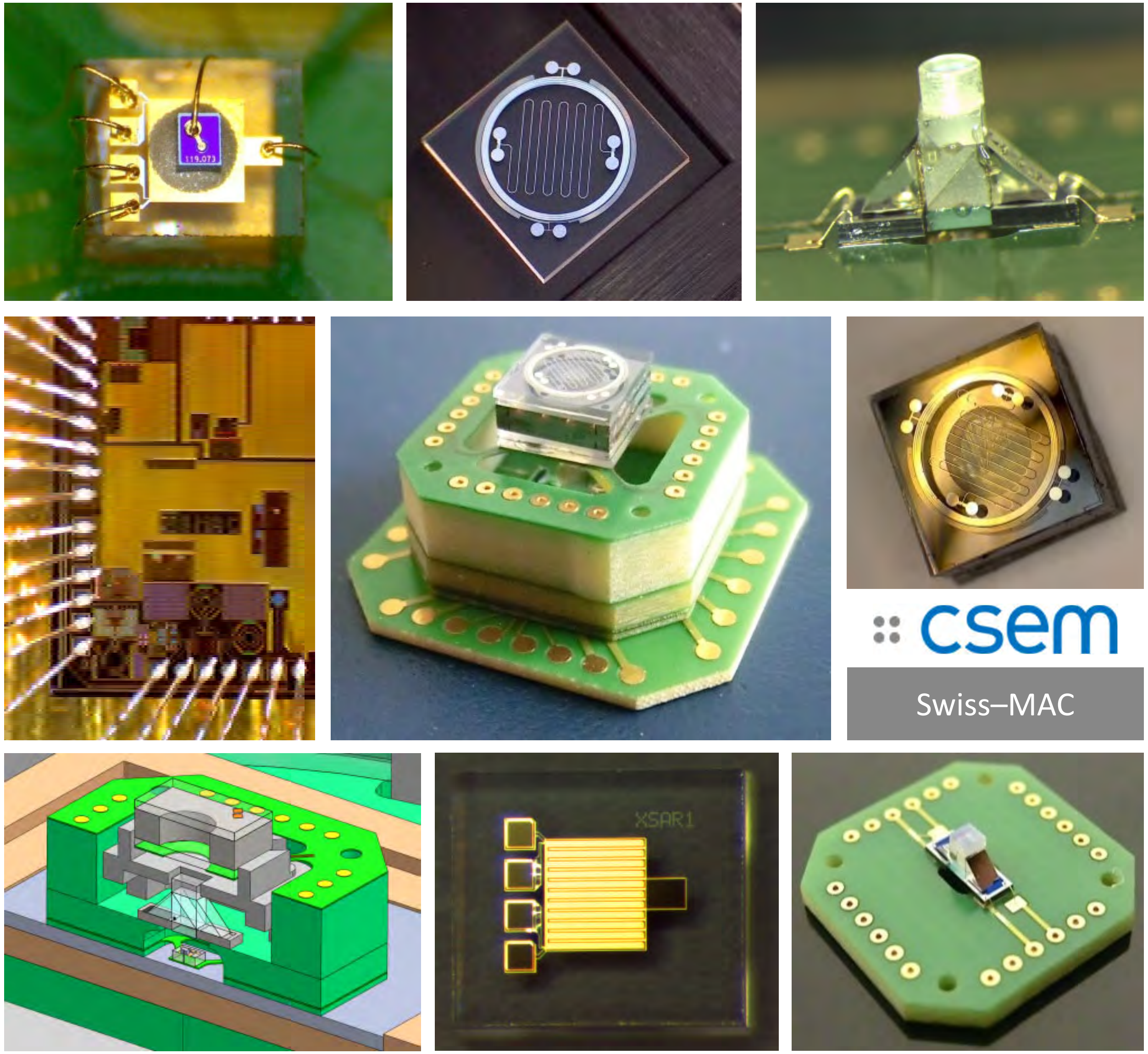
OSCILLOQUARTZ
An ADVA Optical Networking Company

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITÉ DE NEUCHÂTEL

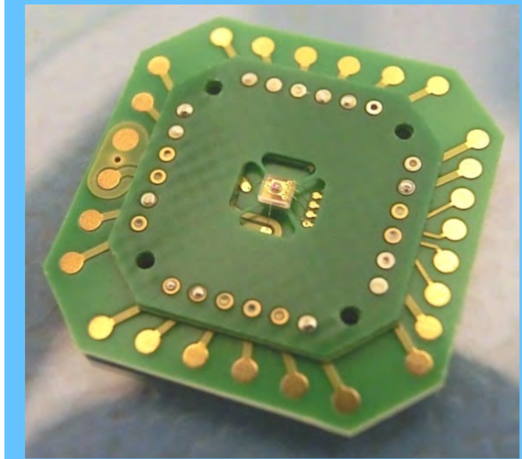
csem

Swiss Miniature Atomic Clock (Swiss–MAC)

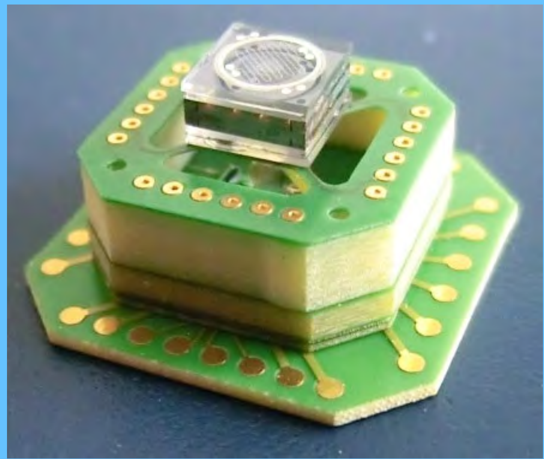


Swiss Miniature Atomic Clock (Swiss-MAC)

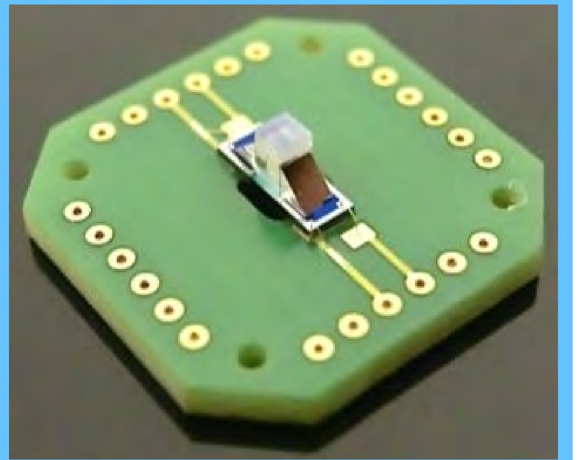
Physics Package components



VCSEL Assembly

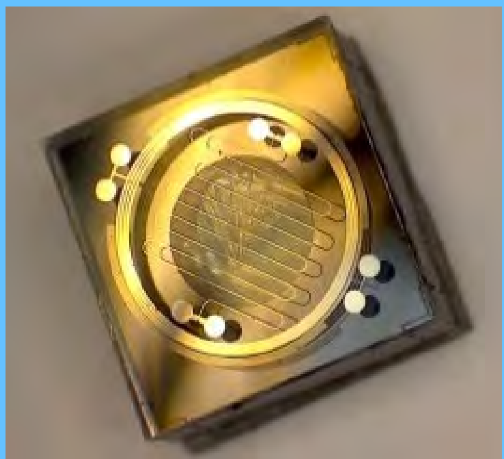


Physics Package Assembly

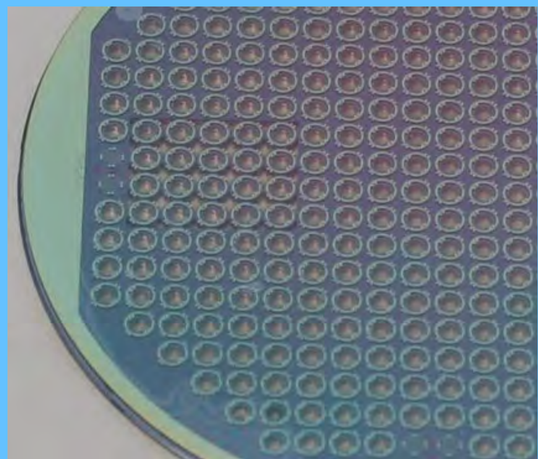


Optics/Photodetector Assembly

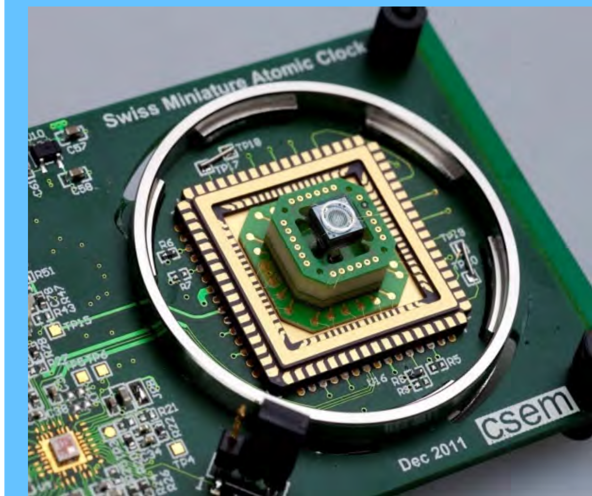
MEMS Atomic vapor cells



Integrated heaters, Tsensor and magnetic coil



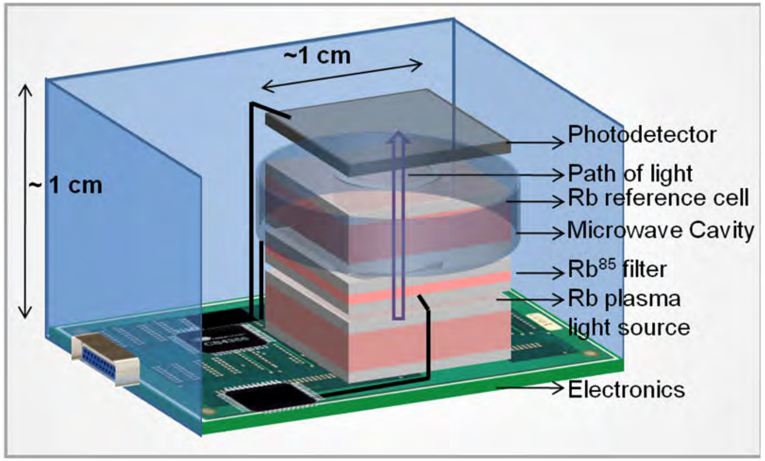
Wafer level fabrication

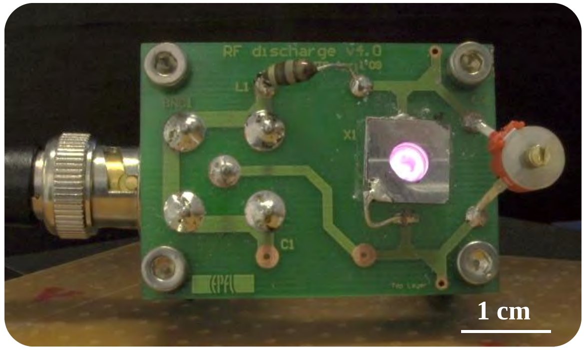


Assembled prototype

MINIATURE DISCHARGE LAMPS

UNIVERSITÉ DE NEUCHÂTEL
LTF
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LMTS+SAMLAB





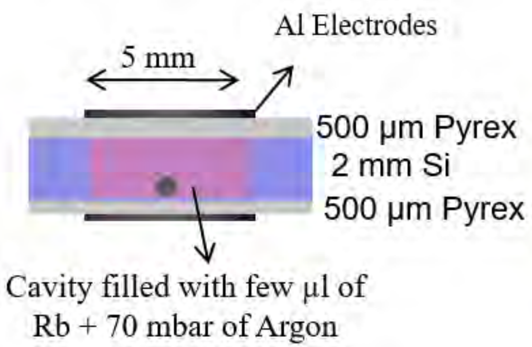
2 to 500 MHz RF drive

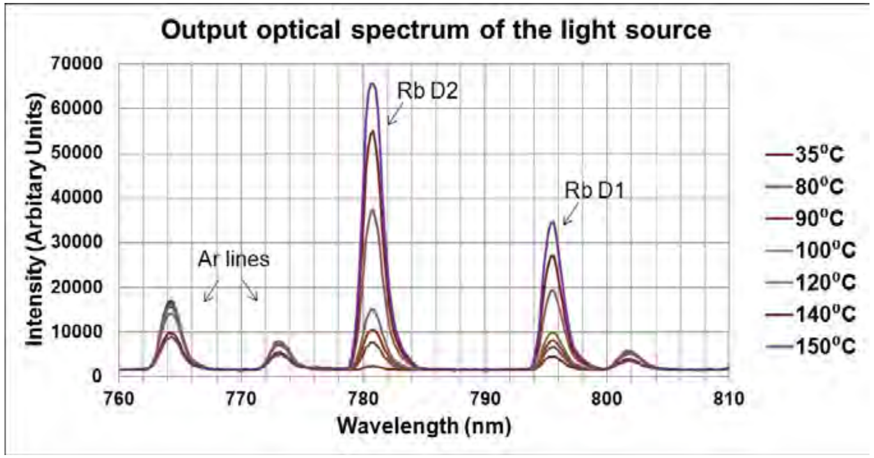
≈10 mW RF power coupled to the cell

⇨ 100µW light output

Dielectric Barrier Discharge (DBD)

- Micro-fabricated cell with Al-electrodes



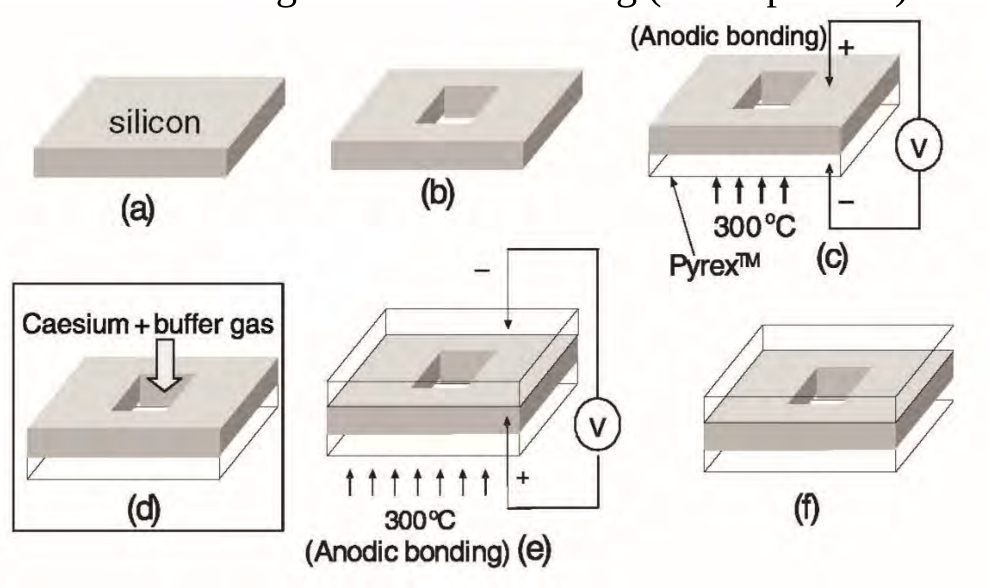


V. Venkatraman et al., Trans. UFFC 2012

MICRO-FABRICATED CELLS WITH ANODIC BONDING

UNIVERSITÉ DE NEUCHÂTEL

Glass-Si-glass anodic bonding (NIST process):



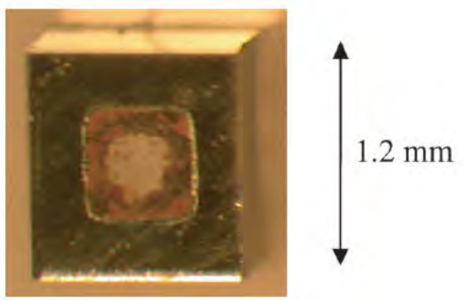
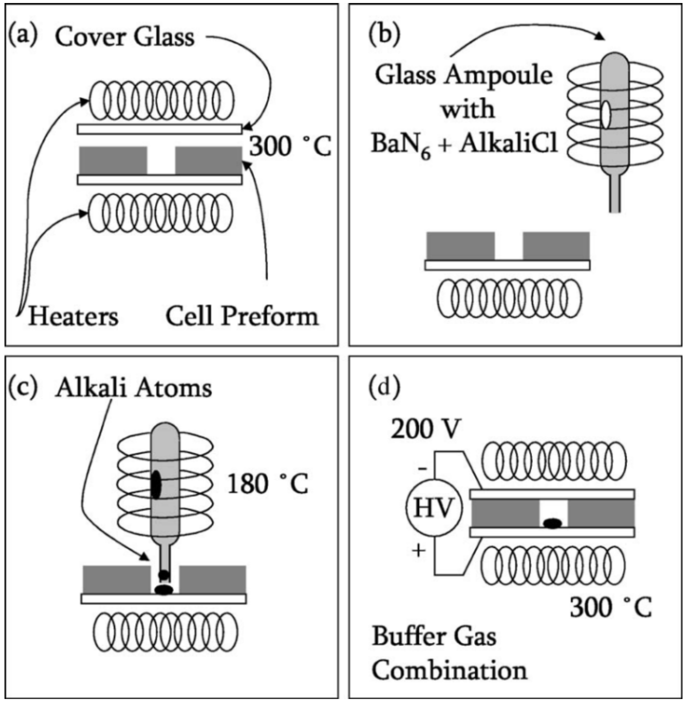


Figure 2. Photograph of a micromachined Cs vapour cell fabricated by anodic bonding.

Refined alkali filling:



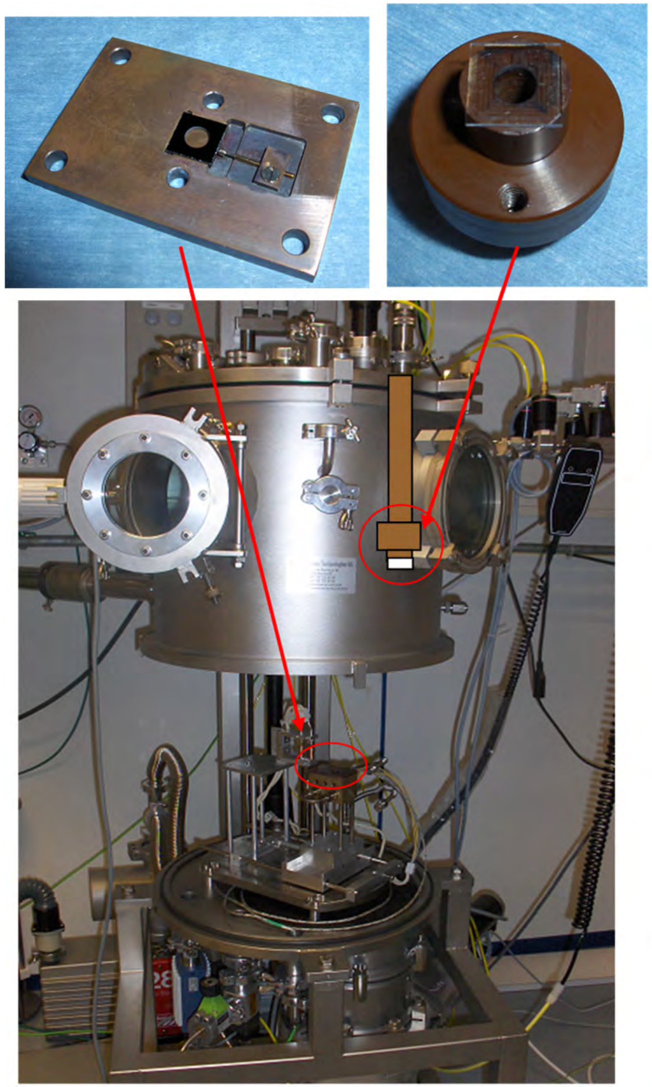
J. Kitching et al., Metrologia 2005,
S. Knappe et al., Opt. Lett. 2005.

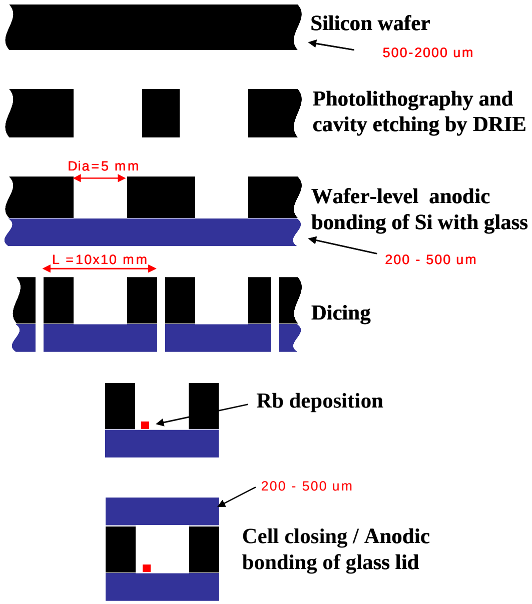
SWISS ANODIC BONDING TECHNOLOGY

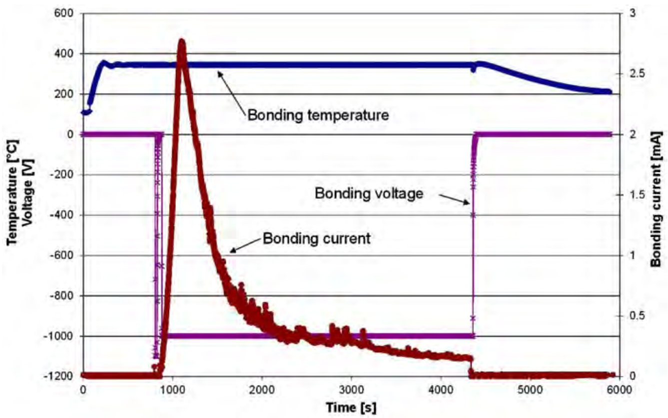
UNIVERSITÉ DE NEUCHÂTEL

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)

POST-ACTIVATED VAPOUR CELLS

J. Micro/Nanolith. MEMS MOEMS 7(3), 033013 (Jul–Sep 2008)

New approach of fabrication and dispensing of micromachined cesium vapor cell

L. Nieradko et al., FEMTO-ST (Besançon) & Wroclaw UT

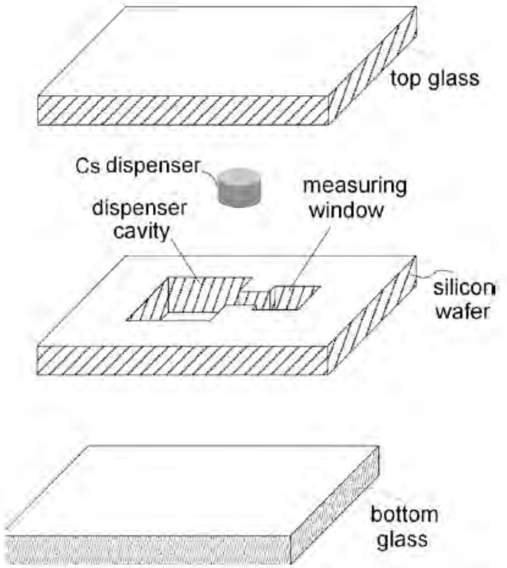


Fig. 3 Schematic of Cs microcell based on silicon etch, anodic bonding, and dispenser technology.

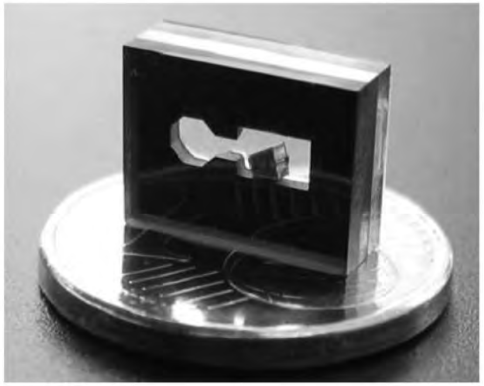


Fig. 1 *Cesium microcell on top of 1 euro cent*
Overall dimensions: 9 × 8 × 3.2 mm

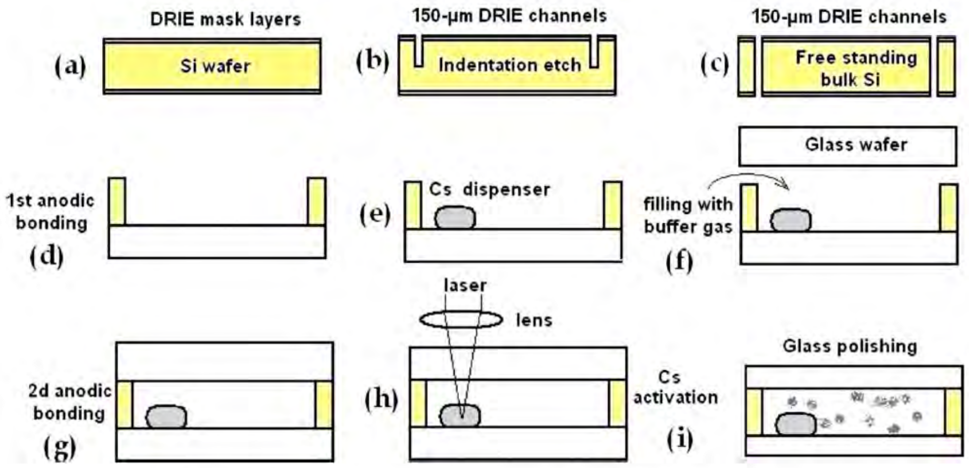


Fig. 4 Technology steps of micromachined cell with Cs dispenser.

SWISS SPECIAL MINIATURE CELLS

4-mm size Rb cells

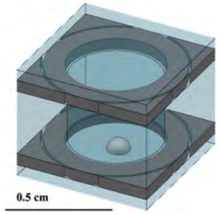
Micro-fabrication technology for precise control of cell geometry

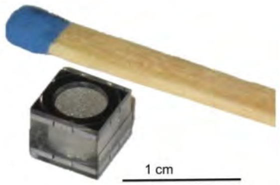
Multi-stack anodic bonding:

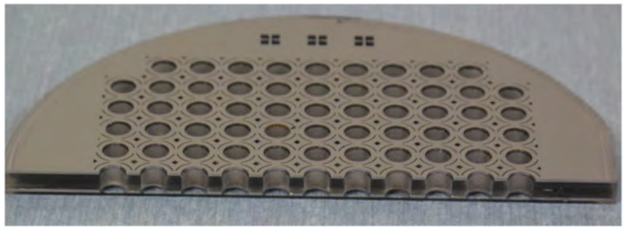
⇨ Thick glass core wafer

⇨ 2 Si layers + 2 glass windows

⇨ 4 steps of anodic bonding





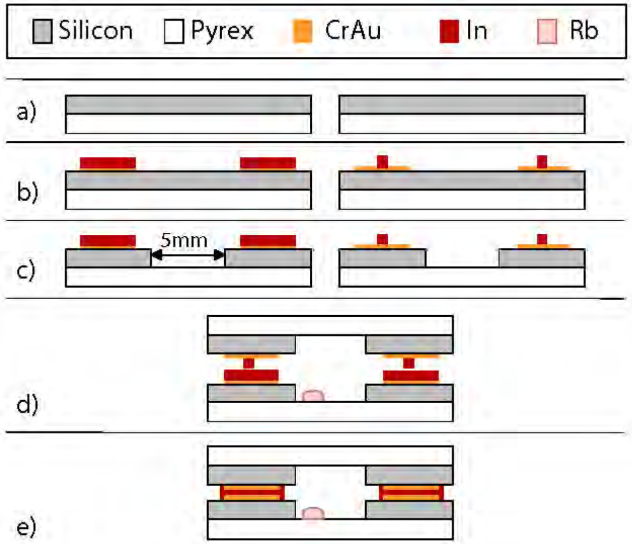


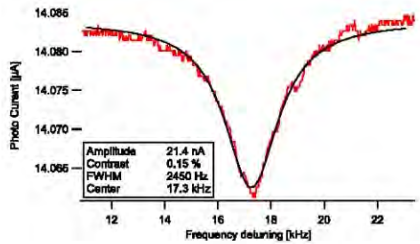
Y. Pétremand et al., JMM 2012.

Indium cell sealing

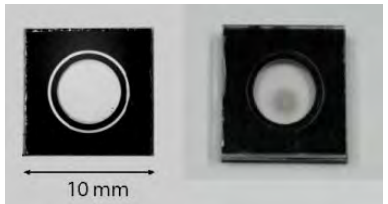
Low-temperature sealing (≤ 140°C)

⇨ alkali control & wall coatings





Working alkali cells



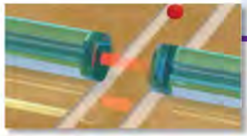
R. Straessle et al., MEMS 2012.

MACQSIMAL PROJECT

UNIVERSITÉ DE NEUCHÂTEL

O1: Miniature Optically Pumped Magnetometers (OPM)

- O1.1: Highly sensitive OPM for biomagnetic applications TRL 2-3 → TRL 4-5
- O1.2: Quantum-enhanced OPM concept TRL 1 → TRL 2-3



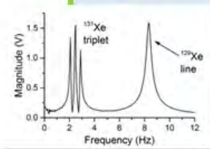
O2: Miniature Atomic Clocks (MAC)

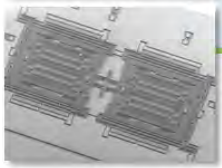
- O2.1: Flat form-factor, low-power CPT MAC TRL 4 → TRL 6-7
- O2.2: Quantum-enhanced MAC concept TRL 1 → TRL 2-3

Common platform: MEMS atomic vapor cells with integrated optics & electronics

O3: Miniature Atomic Gyroscopes (MAG)

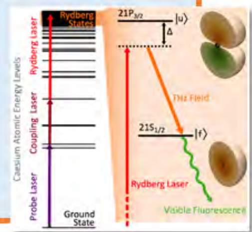
- O3.1: (Spin) Nuclear Magnetic Resonance Gyroscope TRL 2-3 → TRL 4-5
- O3.2: SERF Gyroscope TRL 1-2 → TRL 3
- O3.3: Quantum-enhanced MAG concept TRL 1 → TRL 2-3





O4: Atomic GHz & THz Sensors and Vector Imagers

- O4.1: Calibration-free detection and vector imaging of GHz and THz fields TRL 2-3 → TRL 4
- O4.2: Quantum-enhanced GHz sensor TRL 1 → TRL 2-3



O5: Rydberg based Gas Sensors

- O5: NO sensor TRL 1 → TRL 2-3

MEMS= Microelectromechanical systems

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 : by laser 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 & the Neuchâtel area makes crucial contributions to this domain

THANK YOU FOR YOUR ATTENTION

Prof. **Gaetano Mileti**

Gaetano.Mileti@unine.ch

https://www.unine.ch/gaetano.mileti

Laboratoire Temps – Fréquence (LTF)

http://www.unine.ch/ltf/fr/home.html

www.unine.ch

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