La misura precisa del tempo
gli orologi atomici

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Le scale di tempo astronomiche

1. Tempo sidereo = angolo orario dell'equinozio vernale

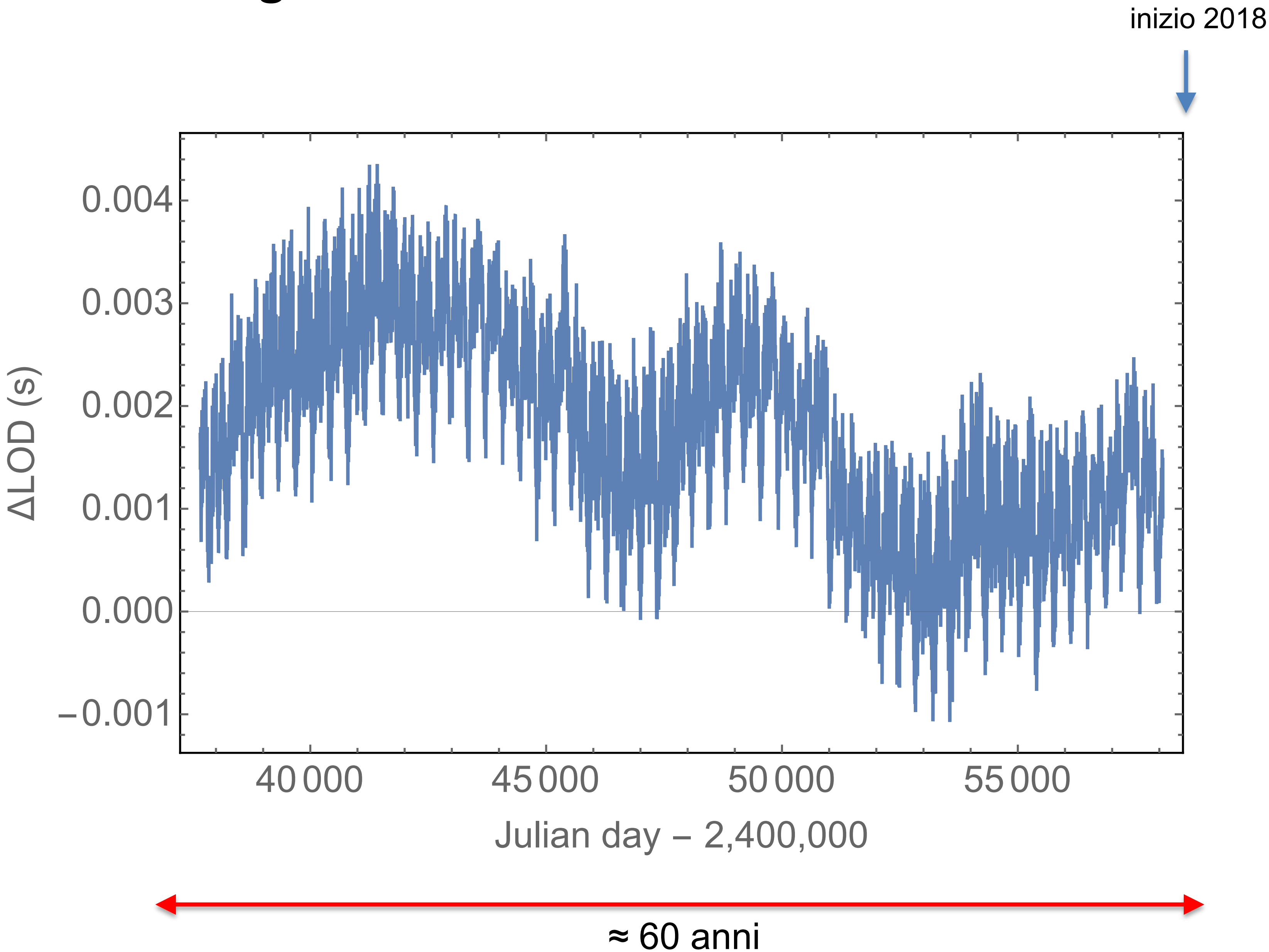
2. Tempo solare medio ≈ posizione angolare del sole medio

3. Tempo universale (UT) = tempo solare medio sul meridiano di Greenwich

- Il tempo astronomico non è affidabile (i fenomeni celesti non sono sempre osservabili)

- I fenomeni astronomici accessibili non sono sufficientemente precisi

Instabilità della rotazione terrestre: deviazione dal giorno solare medio in ms



- Cos’è un orologio?

... By “perfect clocks” ... I shall mean clocks ... that are perfect in the sense that the world’s best clock makers ... understand: Perfection is to be judged by comparison with the behaviors of atoms and molecules.

More specifically, perfect clocks must tick at a uniform rate when compared with the oscillations of atoms and molecules. The world’s best atomic clocks are designed to do just that. ...

Kip Thorne in "Black Holes and Time Warps"

Figure 1. The Riefler pendulum clock, which was the primary standard for time interval measurements from 1904 to 1929, is now on display at the NIST museum in Gaithersburg, MD.

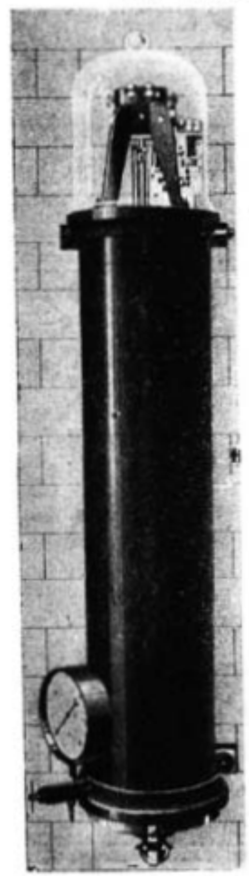
THE PERFECT CLOCK

ASTRONOMERS have now stated that the RATE of the "SYNCHRONOME" FREE PENDULUM at

GREENWICH OBSERVATORY

but for the very small growth of the Invar Rod which was known and forecasted, has been INVARIABLE. Over a period of nearly TWELVE MONTHS while it was under the closest observation,

NO CHANGE OF RATE COULD BE DETECTED.



THE SYNCHRONOME FREE PENDULUM

was designed by Mr. W. H. SHORTT, M.Inst.C.E., in combination with the Synchronome System, the invention of Mr. F. HOPE-JONES, M.I.E.E., F.R.A.S.

PROFESSOR W. de SITTER of Leyden, discussing in "NATURE" of Jan. 21st, 1928, this entirely new conception of the possibilities of clocks, asks—

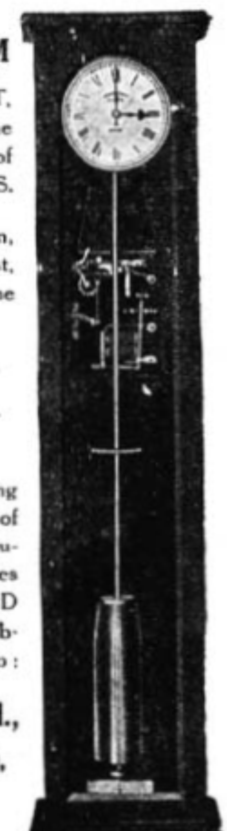
> *"Can these wonderful clocks be of use as a control upon the uniformity of astronomical time like the motion of the moon, the sun, and the planets? Can the handiwork of man compete with the heavenly bodies?"*

All who are interested in this astonishing achievement, and who wish to know more of the SYNCHRONOME SYSTEM, particularly its applications to commercial purposes in the supply of UNIFORM AND ACCURATE TIME for Industrial Establishments and Institutions, should apply to:

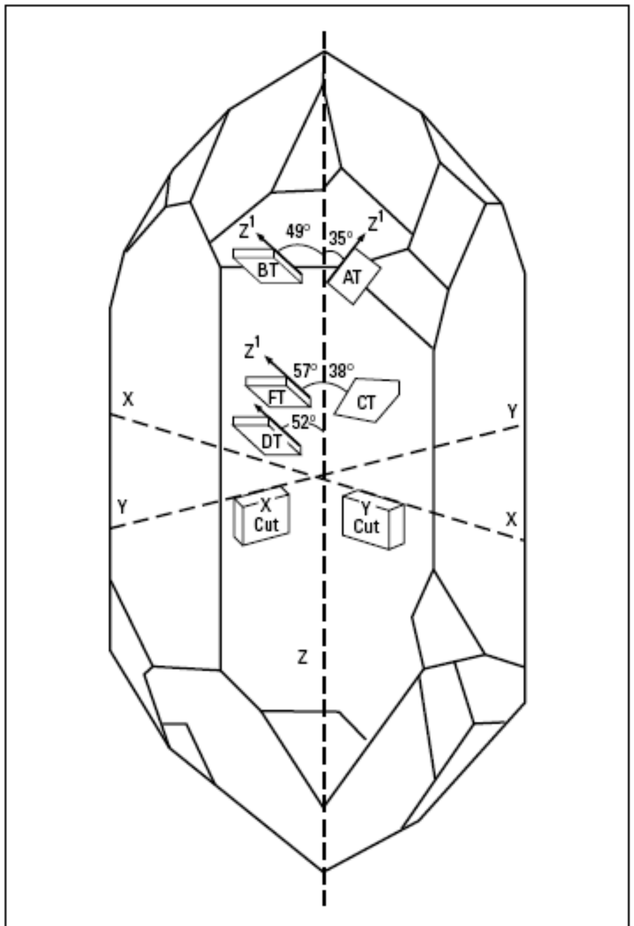
THE SYNCHRONOME Co., Ltd.,

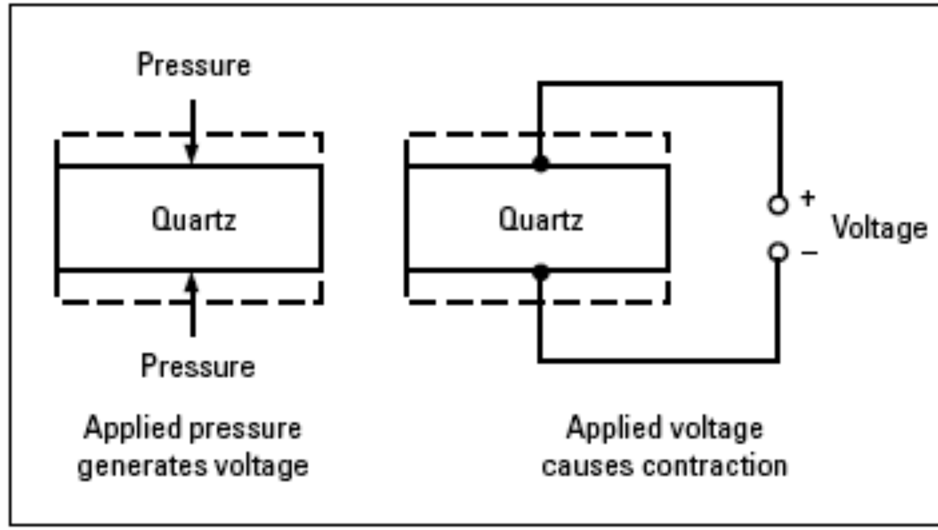
32 & 34, CLERKENWELL ROAD, LONDON, E.C.1.

Tel.: No. CLERKENWELL 1517.



Lo scopritore della piezoelettricità, Pierre Curie


Z1
49°
35°
Z1
BT
AT
Z1
57°
38°
FT
CT
52°
DT
X
Y
Y
X
X
Cut
Y
Cut
Z


Pressure
Quartz
Pressure
Quartz
+
Voltage
–
Applied pressure
generates voltage
Applied voltage
causes contraction

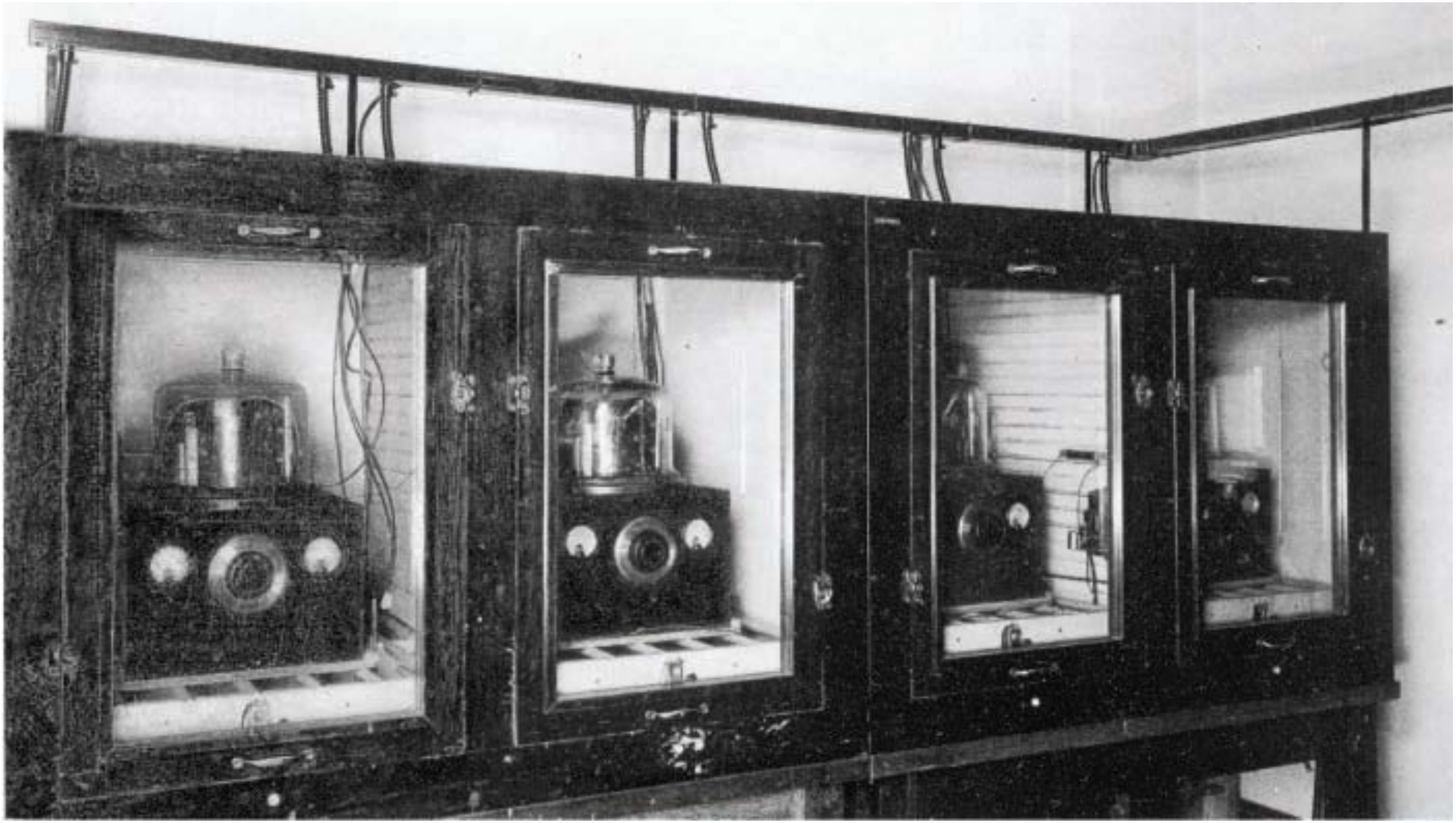
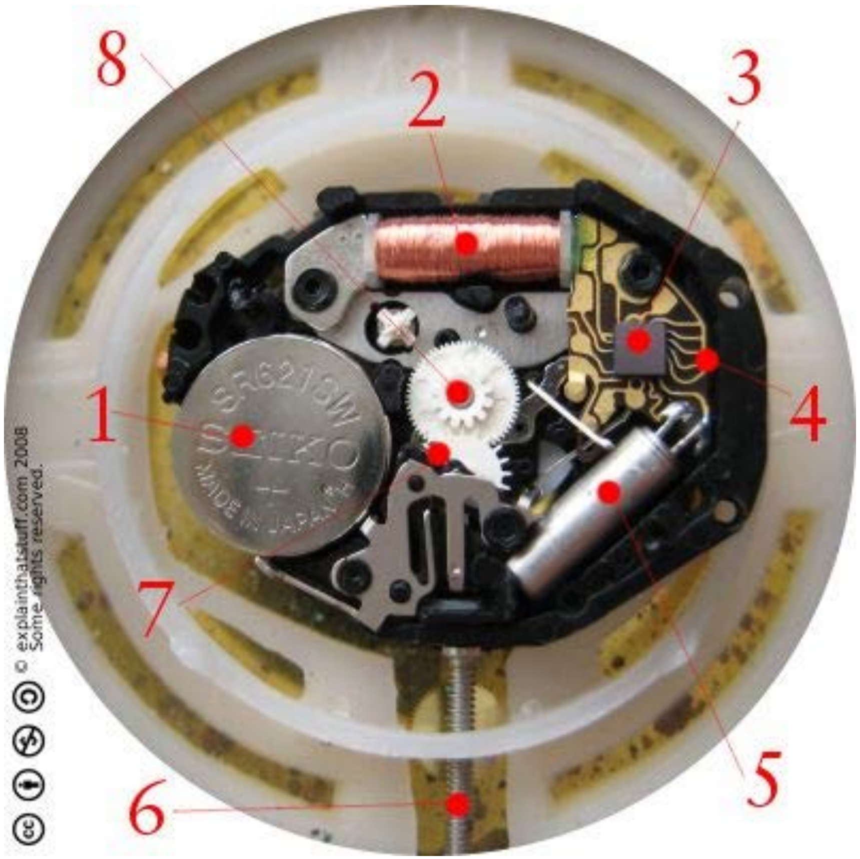


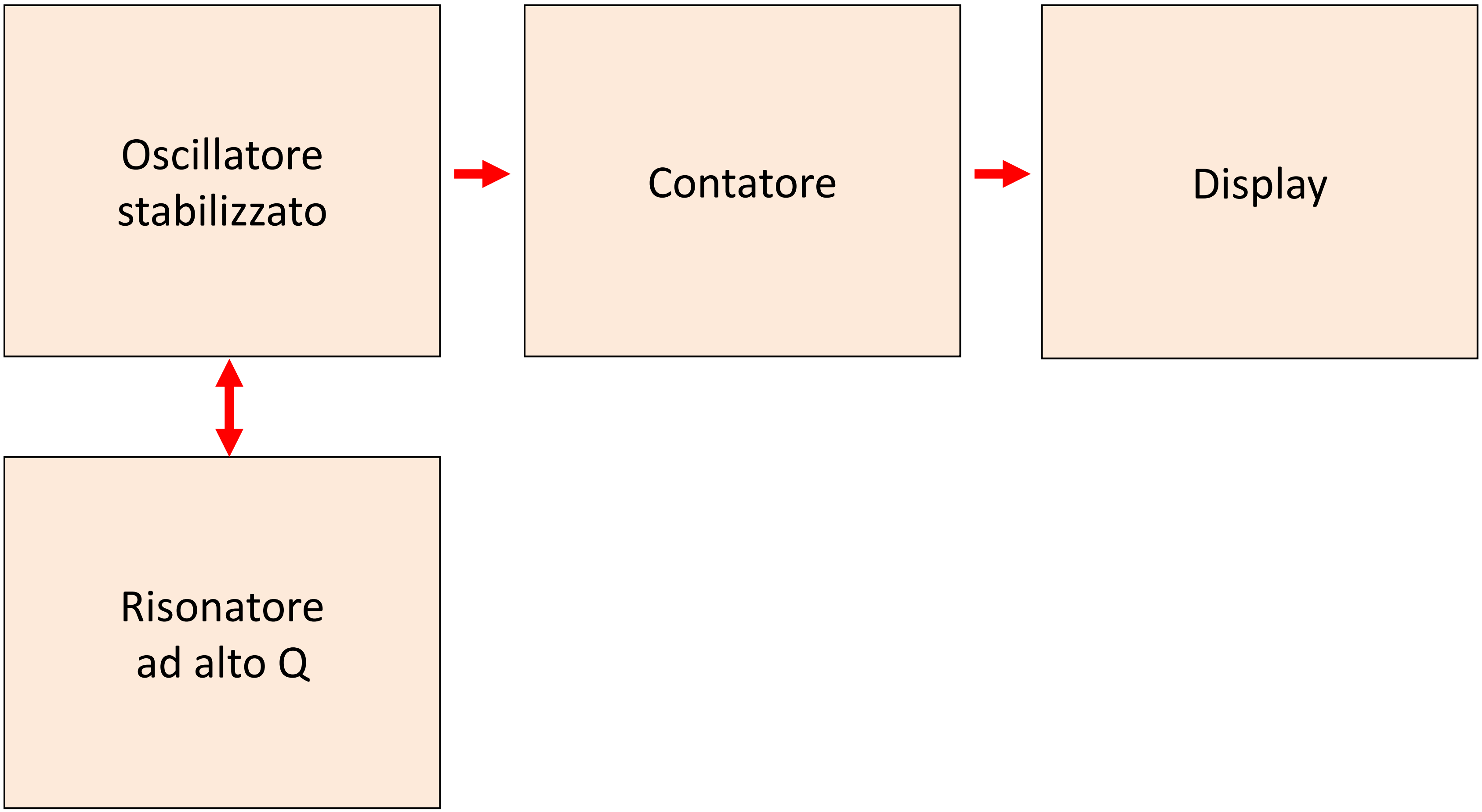
Figure 3. This group of 100 kHz quartz crystal oscillators served as the U.S. national primary frequency standard in 1929.

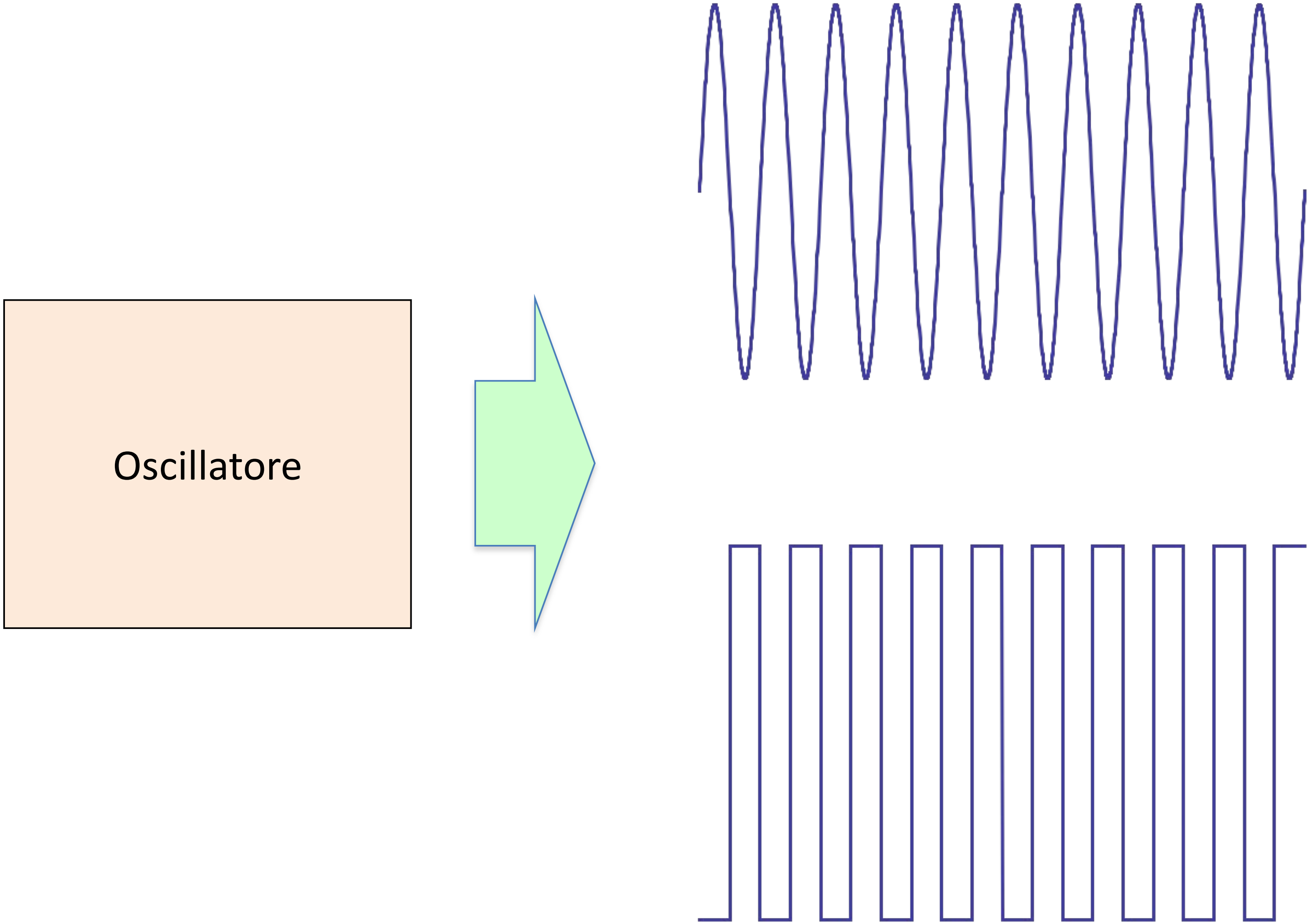
Struttura di un orologio a quarzo con display meccanico



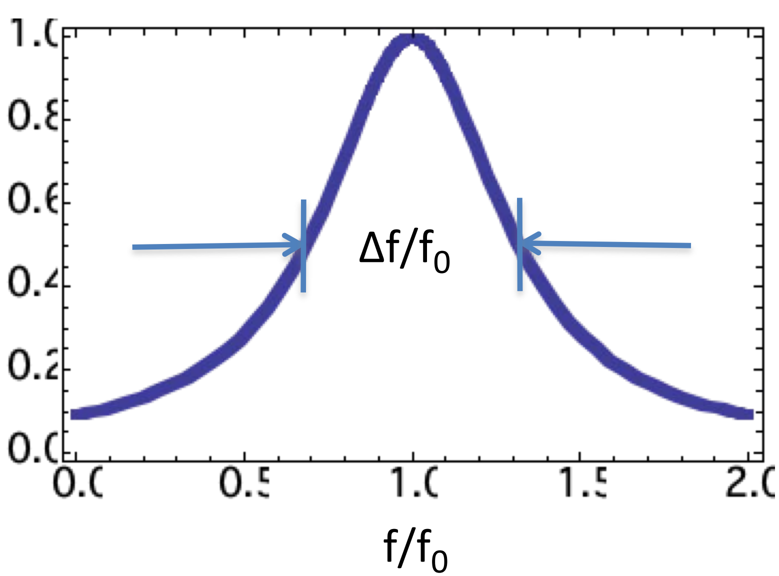
1 Batteria
2. Motore elettrico passo-passo
3. Microchip
4. Circuito stampato
5. Cristallo di quarzo
6. Vite a corona per regolare la posizione delle lancette
7. Meccanismi di demoltiplica per le lancette
8. Asse centrale

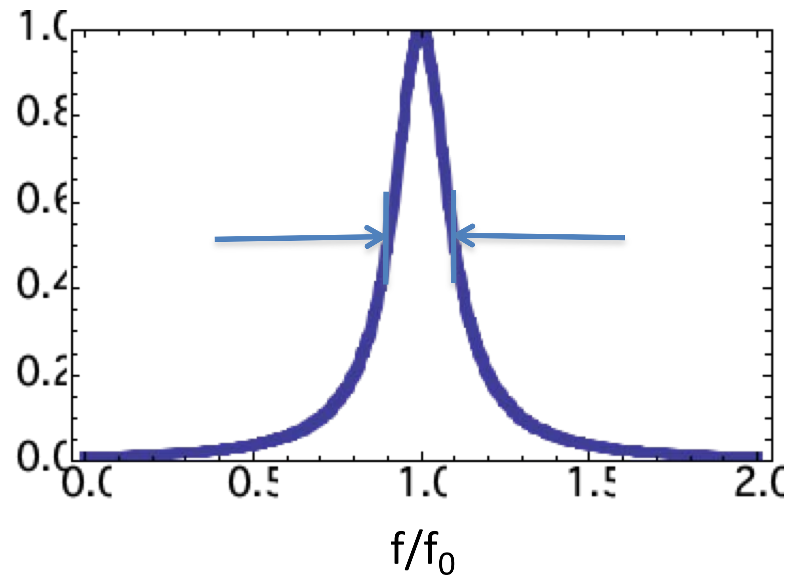
Ma com'è fatto dunque un orologio?




Oscillatore

Risonatore (stabilizzazione dell'orologio)

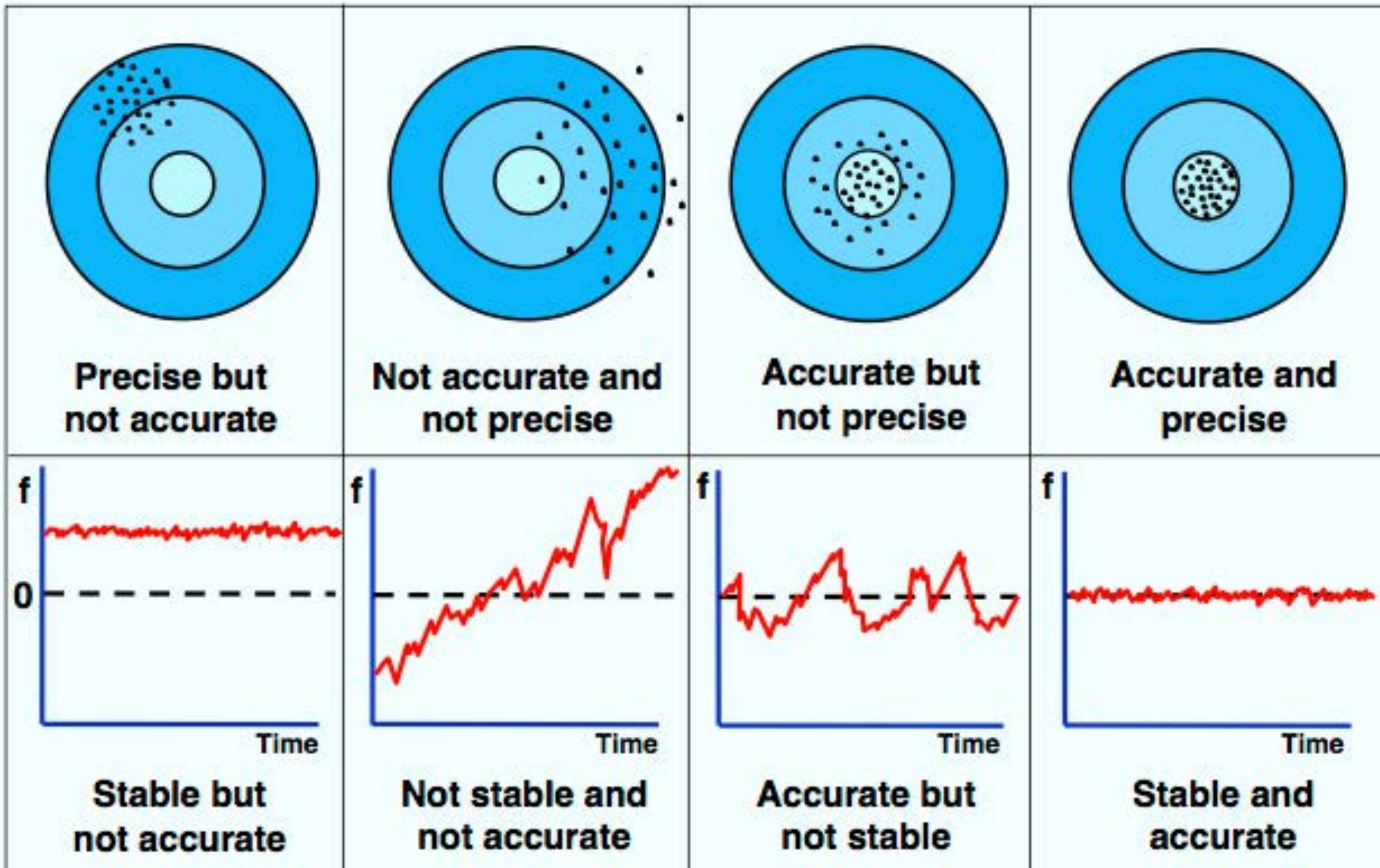




$$Q = \frac{f_0}{\Delta f}$$

Q-valore: parametro che ci dice quanto è buono un risonatore

Accuracy, Precision, and Stability



Come funziona un orologio atomico?

L'idea fondamentale è quella di utilizzare le oscillazioni delle onde elettromagnetiche emesse da atomi, invece delle oscillazioni meccaniche o elettriche di sistemi fisici macroscopici

Spettro di emissione visibile dell'azoto

Il suggerimento iniziale sul funzionamento di un orologio atomico è stato dato da dato da Isidor Rabi (premio Nobel 1944), un fisico con una grande esperienza nella produzione e studio di fasci atomici (1945)

Nella sua proposta Rabi parla di un orologio atomico a cesio...

'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

DESIGN TERMED FEASIBLE

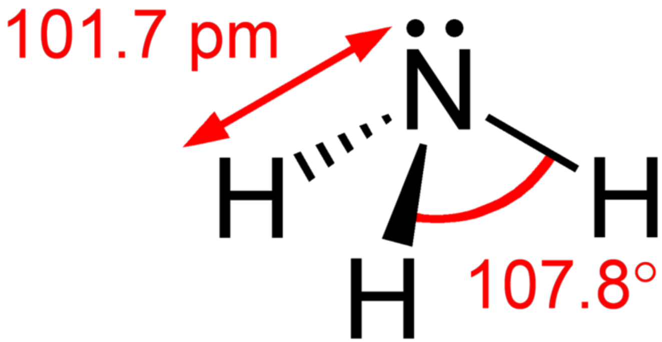
Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

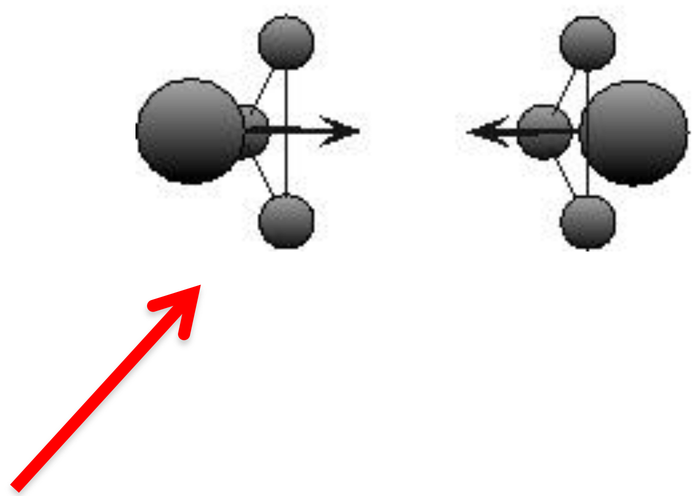
By WILLIAM L. LAURENCE

Blueprints for the most accurate clock in the universe, tuning in on radio frequencies in the hearts of atoms and thus beating in harmony with the "cosmic pendulum," were outlined yesterday at the annual New York meeting of the American Physical Society, at Columbia University, by Prof. I. I. Rabi, who delivered the Richtmyer Memorial Lecture under the auspices of the American Association of Physics Teachers.

Articoletto del 21 gennaio 1945 comparso sul New York Times

Un oscillatore nelle microonde: il maser ad ammoniaca (NH_3)





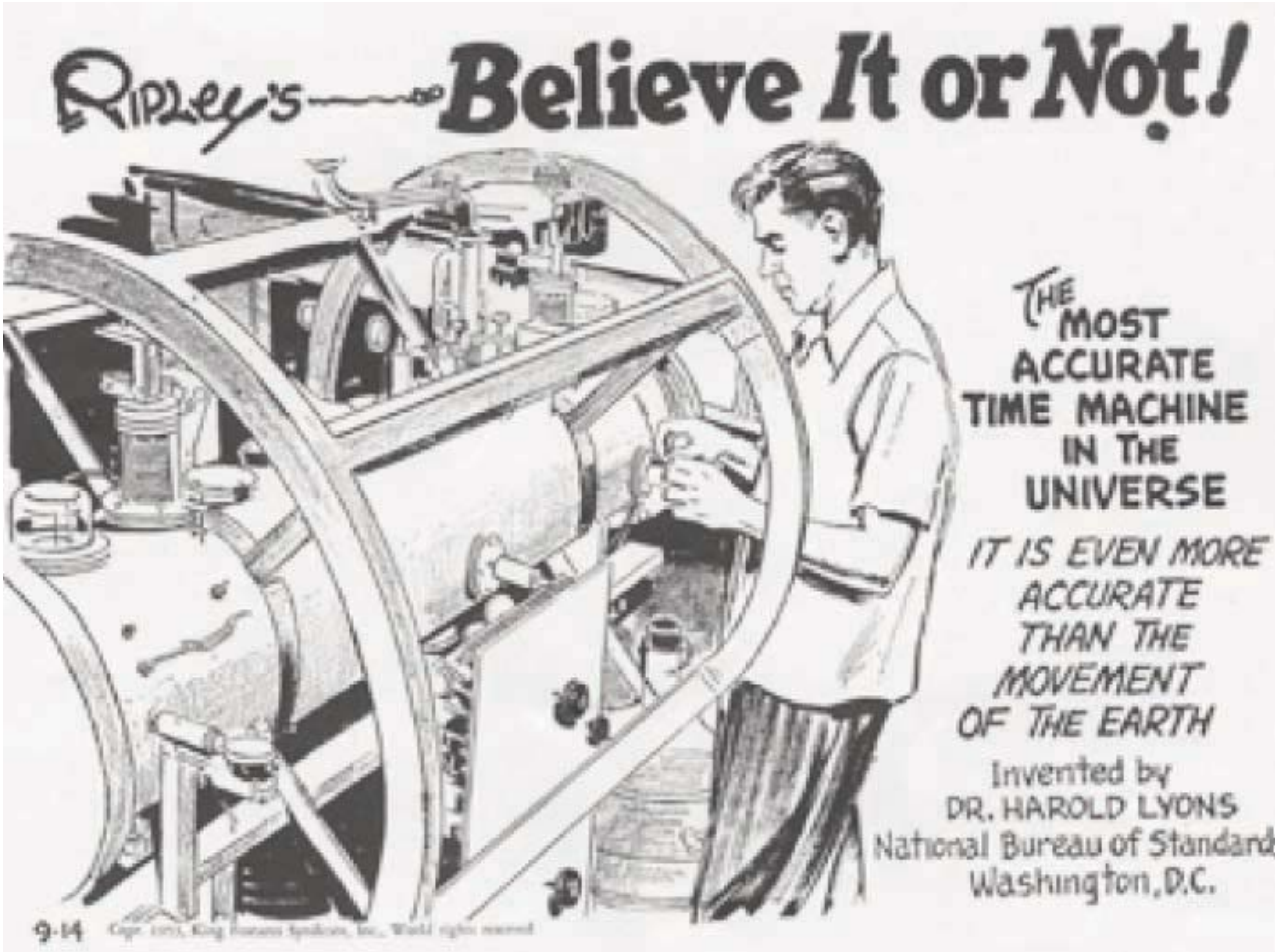
Due stati possibili, completamente simmetrici uno rispetto all’altro, MA

1. Quando vengono immersi in un campo elettrico i due stati sono un po’ diversi
2. Le diverse energie dei due stati permetto di realizzare un’azione LASER (ma nelle microonde ... quindi MASER)

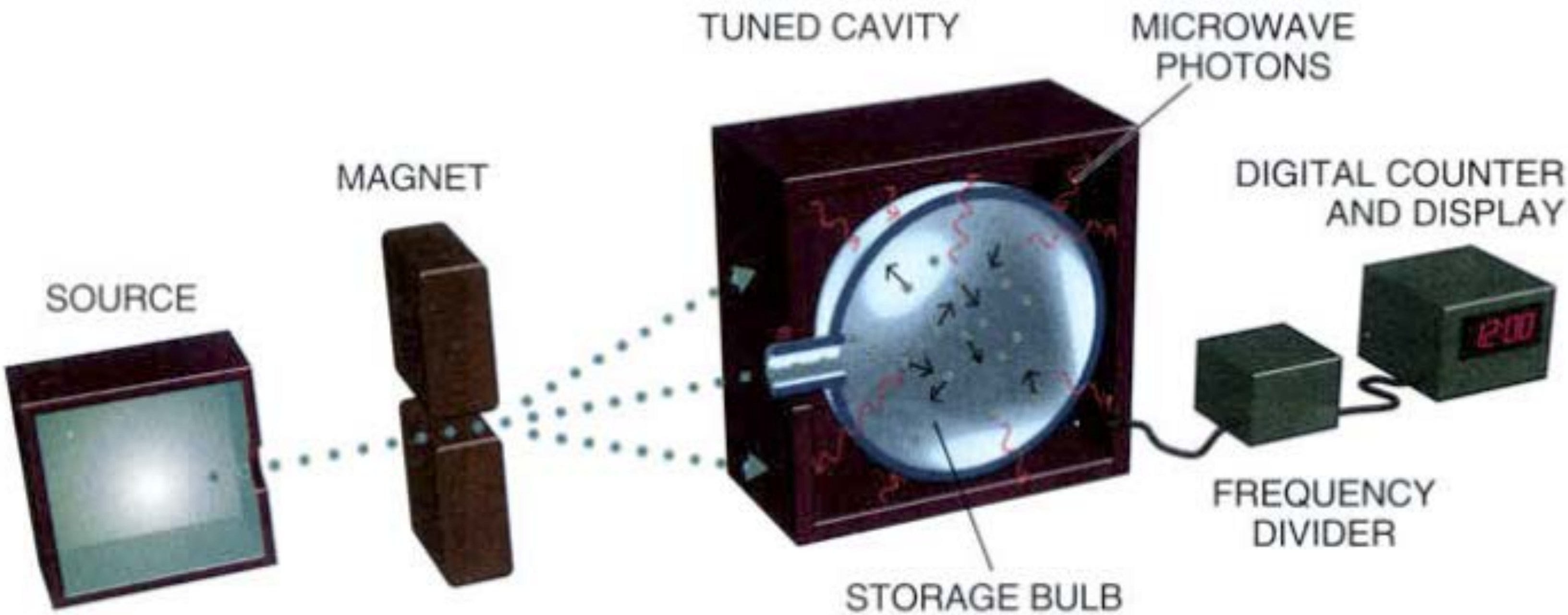
La frequenza delle microonde è molto precisa (circa 23.8 GHz) e permette di realizzare un oscillatore preciso

Nel 1949 Lyons realizza il primo “orologio atomico” ad ammoniaca presso i laboratori del National Bureau of Standards (NBS)

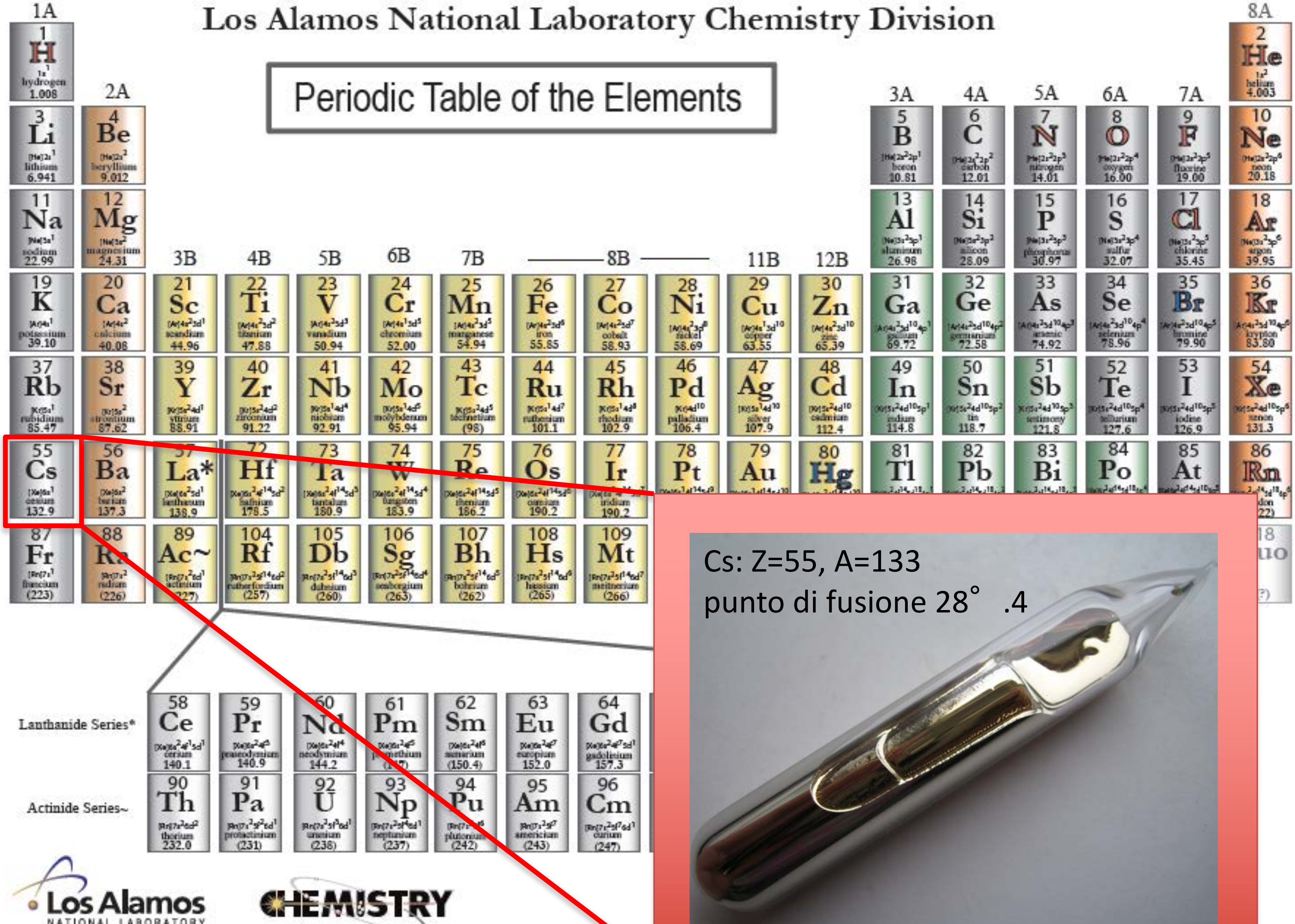
Figure 5. The first atomic frequency standard, based on the ammonia molecule (1949). Inventor Harold Lyons is on the right; Edward Condon, then the director of NBS, is on the left.

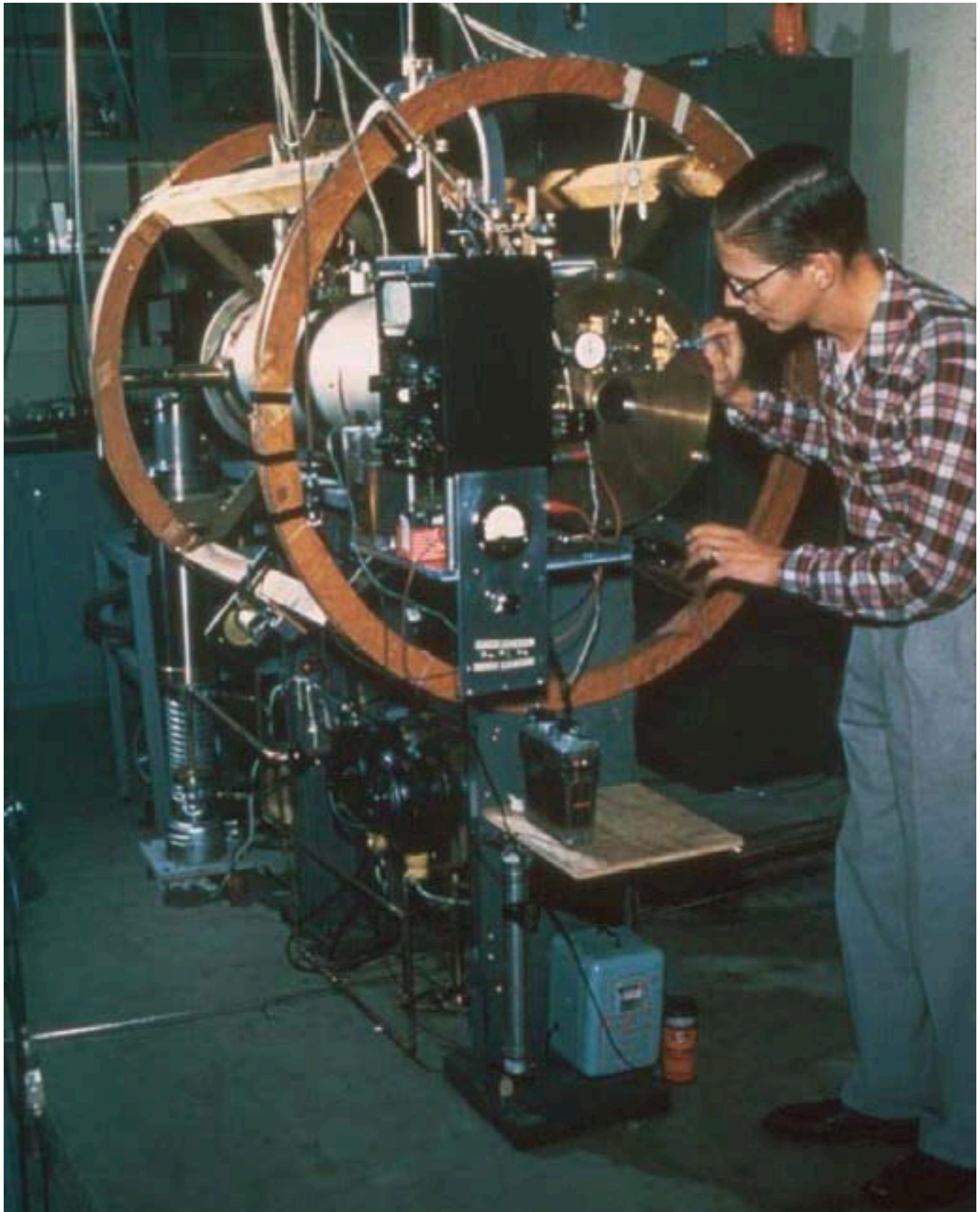

Ripley's Believe It or Not!
THE MOST ACCURATE TIME MACHINE IN THE UNIVERSE
IT IS EVEN MORE ACCURATE THAN THE MOVEMENT OF THE EARTH
Invented by DR. HAROLD LYONS National Bureau of Standard Washington, D.C.
9-14

MASER ad idrogeno atomico (Ramsey)



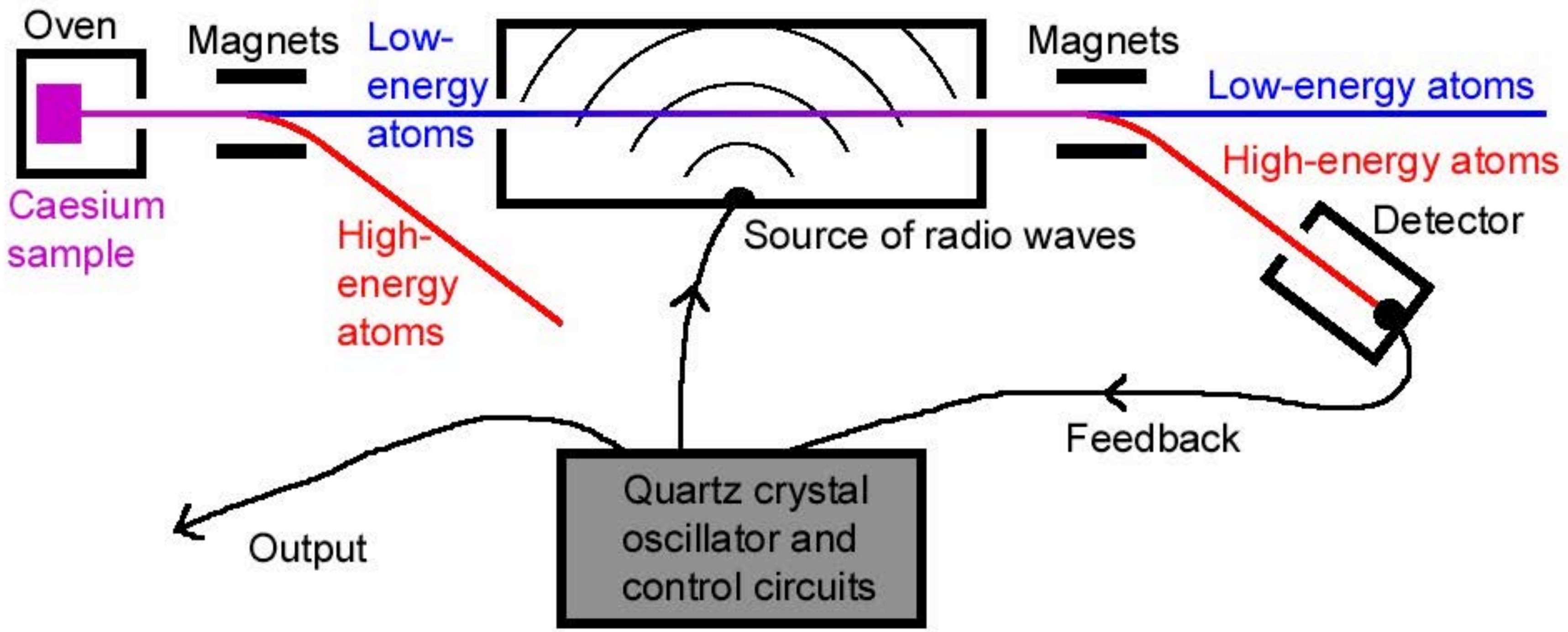
ATOMIC HYDROGEN MASER relies on a self-sustaining microwave field to serve as a frequency standard. Hydrogen atoms in the correct energy level are deflected by a magnet into a storage bulb. Some atoms will drop to a lower level, releasing a microwave photon. The photon stimulates other atoms to drop to a lower level, which produces more photons. The process quickly builds up a microwave field in the bulb. The field induces an alternating current in a wire placed in the cavity. The tuned cavity helps to redirect the photons back into the bulb to maintain the process.


Los Alamos National Laboratory Chemistry Division
Periodic Table of the Elements
Lanthanide Series*
Actinide Series~
Los Alamos
NATIONAL LABORATORY
CHEMISTRY
Cs: Z=55, A=133
punto di fusione 28° .4

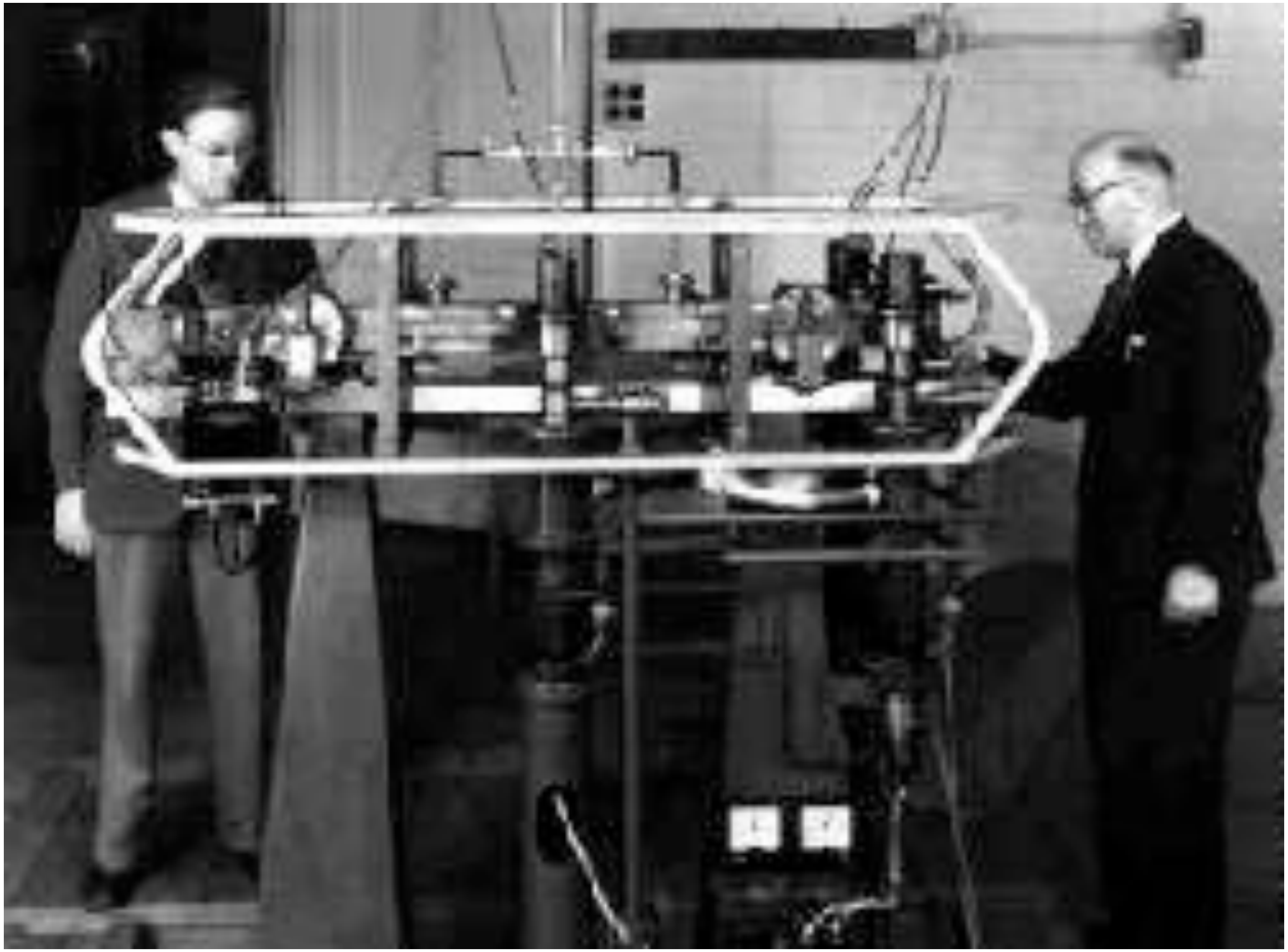


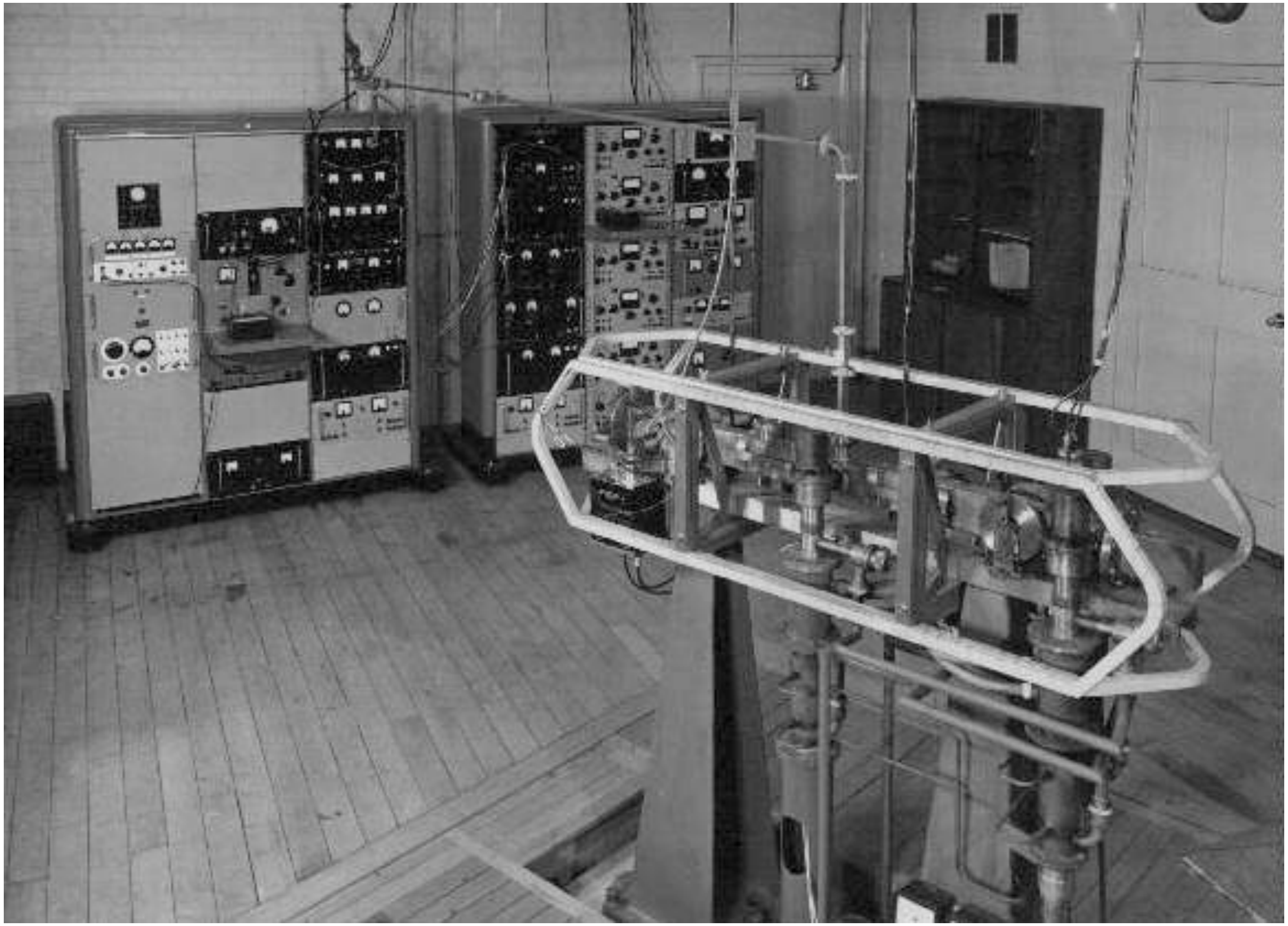
Nel 1952 il gruppo di Lyons costruisce un oscillatore a cesio (NBS-1) che però non funziona da subito, viene messo in standby per mancanza di fondi

Schema di funzionamento di un orologio atomico a cesio



Nel 1955 Essen e Parry sviluppano il primo vero orologio atomico a cesio presso l’NPL





Il laboratorio di Essen e Parry presso il National Physical Laboratory

La precisione con cui si può determinare la frequenza è limitata da diversi effetti, ad esempio:

- lunghezza limitata della cavità (quindi il tempo di attraversamento Δt pone un limite alla determinazione della frequenza Δf a causa del principio di indeterminazione)

- effetto Doppler

Norman Ramsey (Nobel 1989) e l'invenzione dei campi oscillanti separati (separated oscillatory fields)

N. F. Ramsey 557

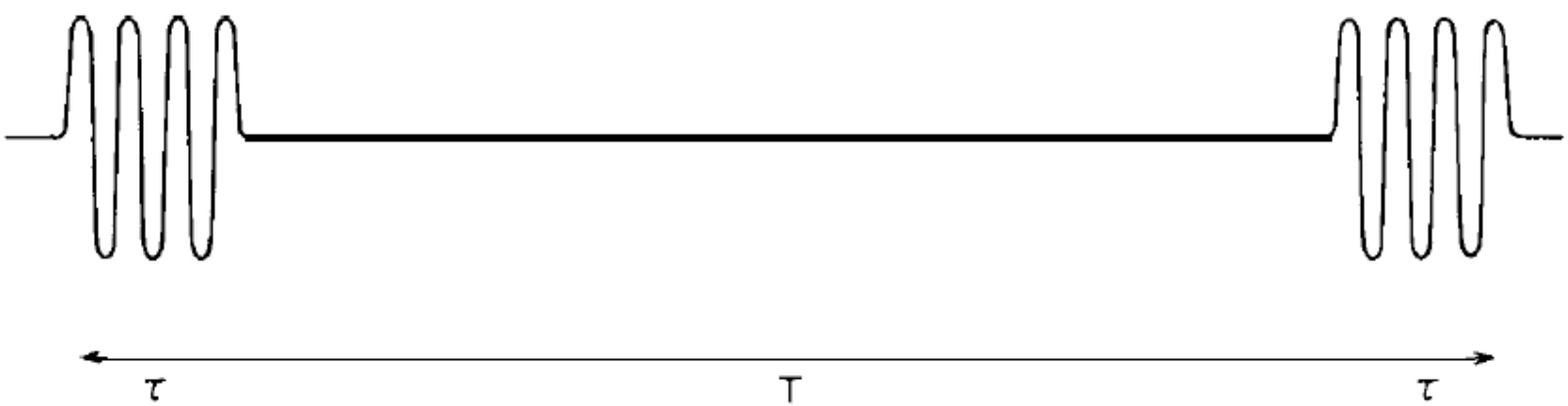
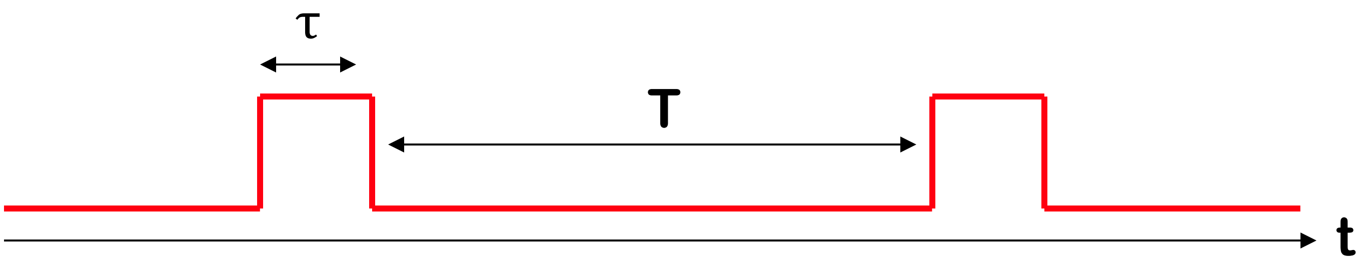


Figure 4. Two separated oscillatory fields, each acting for a time τ, with zero amplitude oscillating field acting for time T. Phase coherency is preserved between the two oscillatory fields so it is as if the oscillation continued, but with zero amplitude for time T.

Analisi approssimata del metodo dei campi separati di Ramsey



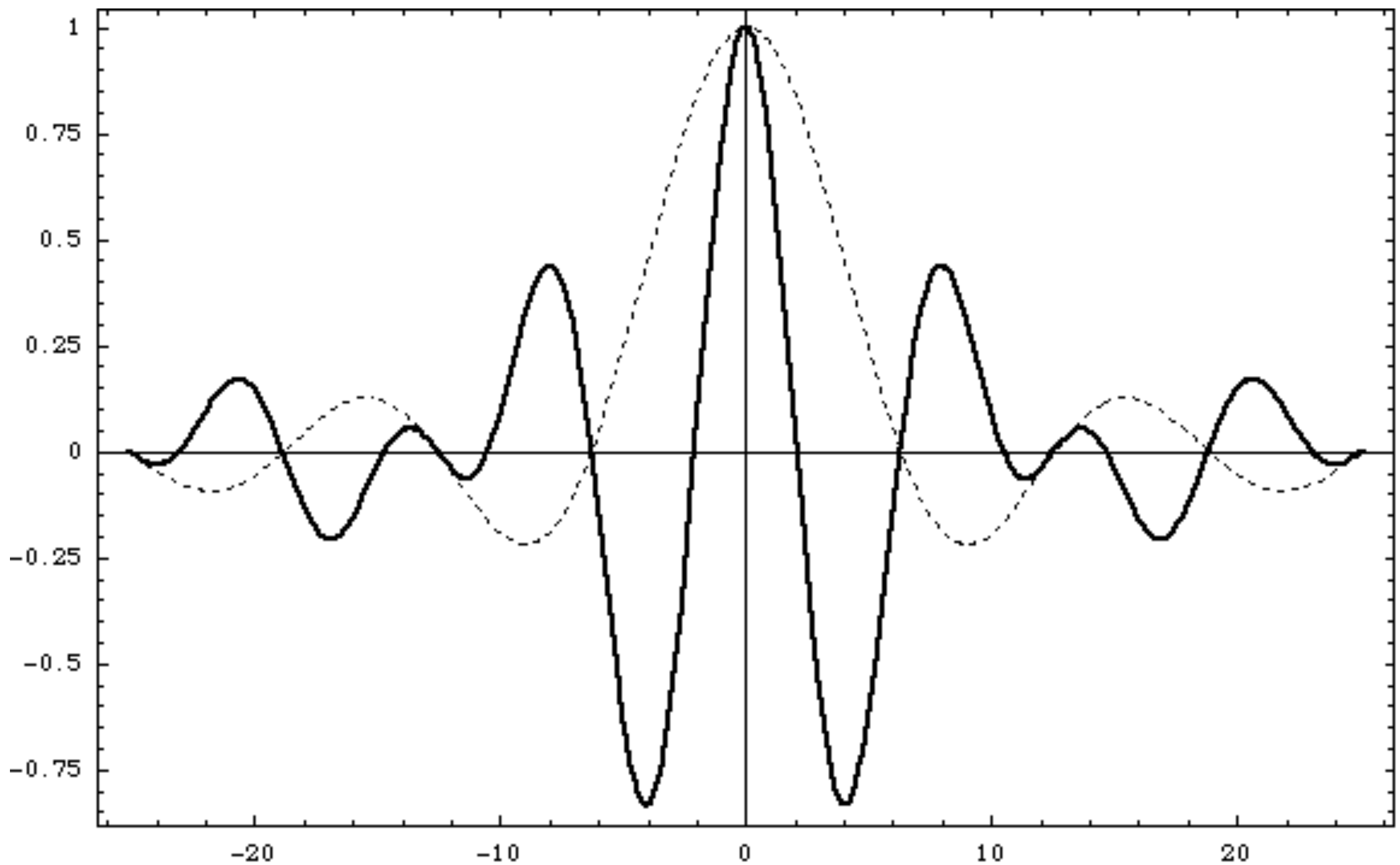
$$\int_{-\infty}^{+\infty} f(t) e^{-i\omega t} dt = \int_{-T/2-\tau}^{-T/2} e^{-i\omega t} dt + \int_{+T/2}^{+T/2+\tau} e^{-i\omega t} dt$$

$$= -\left.\frac{e^{-i\omega t}}{i\omega}\right|_{-T/2-\tau}^{-T/2} - \left.\frac{e^{-i\omega t}}{i\omega}\right|_{T/2}^{+T/2+\tau}$$

$$= -\frac{1}{i\omega}\left\{e^{i\omega T/2} - e^{i\omega T/2} e^{i\omega\tau} + e^{-i\omega T/2} e^{-i\omega\tau} - e^{-i\omega T/2}\right\}$$

$$= -\frac{2}{\omega}\sin\frac{\omega T}{2} + \frac{2}{\omega}\sin\left(\frac{\omega T}{2} + \omega\tau\right)$$

Esempio con $\tau = T/2$

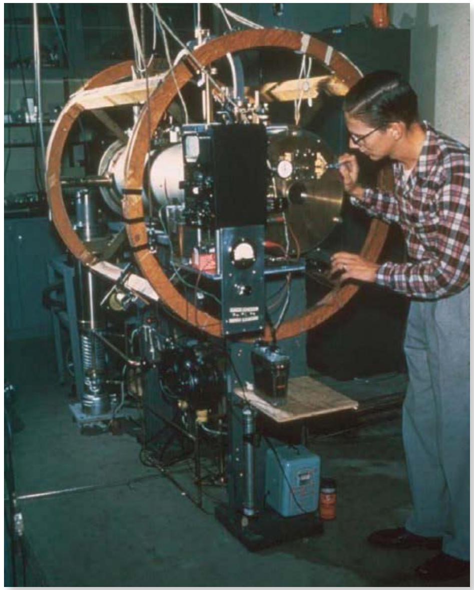


frequenza adimensionale $\omega\tau$

Vantaggi del metodo di Ramsey

- il picco centrale è più stretto rispetto al caso di un campo oscillante singolo
- le disuniformità di campo hanno un effetto ridotto
- il metodo è efficace o addirittura essenziale ad alta frequenza, quando la lunghezza d'onda è confrontabile o addirittura più piccola della regione di interazione
- l'effetto Doppler viene eliminato al primo ordine
- il metodo può essere utilizzato per studiare il comportamento dei livelli di energia in regioni altrimenti inaccessibili, per esempio si può studiare la frequenza di precessione di Larmor dei neutroni dentro un blocco di ferro magnetizzato
- se i campi oscillanti separati sono abbastanza distanti si possono studiare risonanze molto strette, anche andando al di sotto del limite del principio di indeterminazione

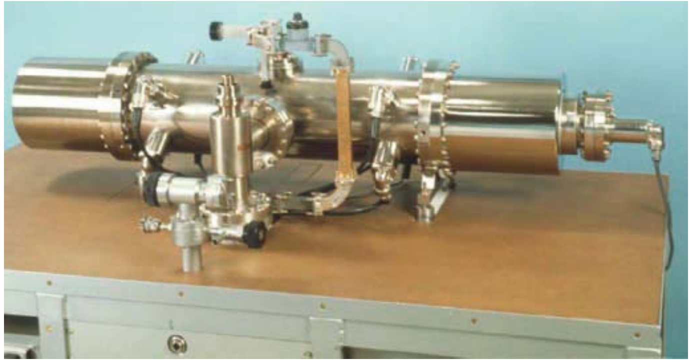
Successione di orologi sempre migliori presso l'NBS - NIST



NBS-1; accuratezza $8.5 \cdot 10^{-11}$

NBS-2; accuratezza $8 \cdot 10^{-12}$

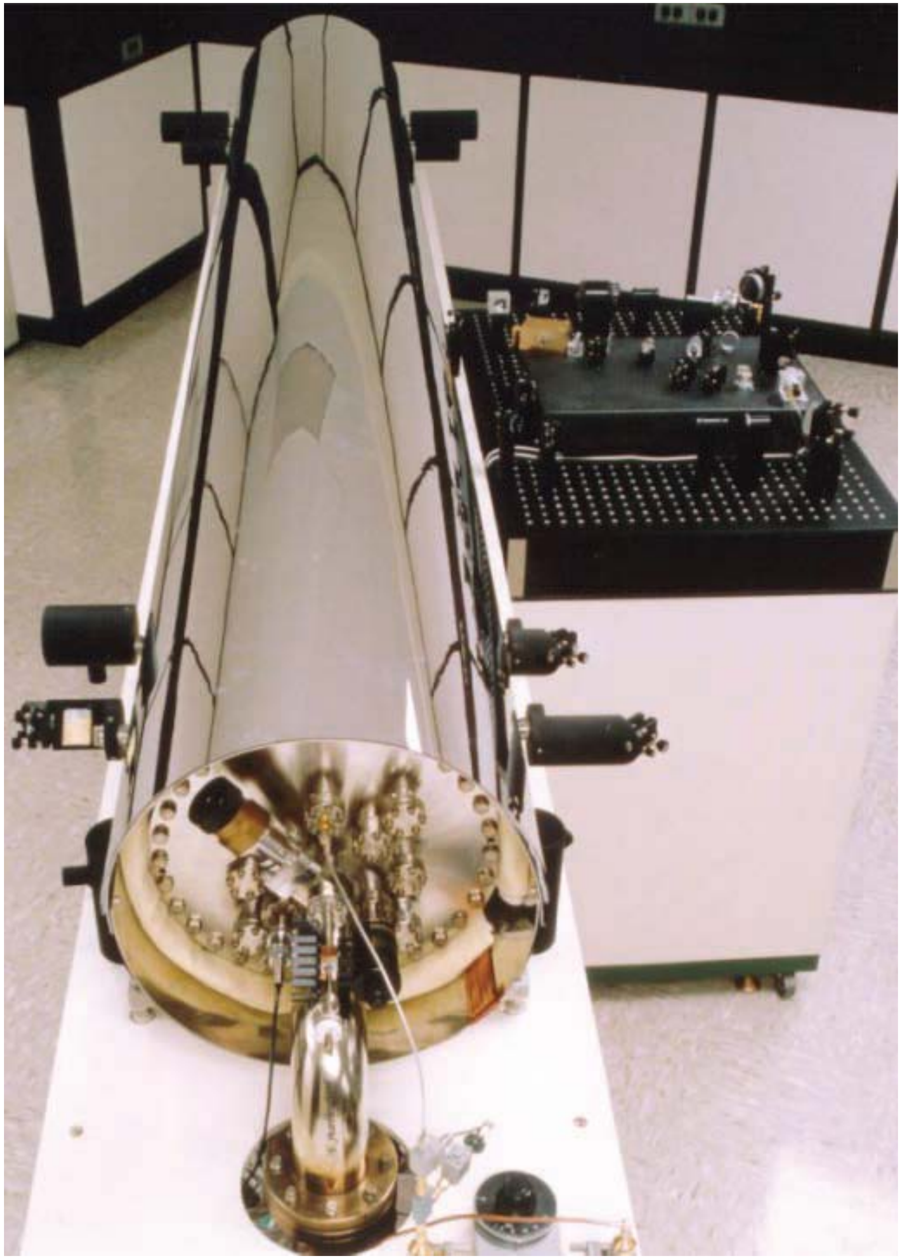
NBS-2;
accuratezza $5 \cdot 10^{-13}$



NBS-4; accuratezza $3 \cdot 10^{-13}$

NBS-5; accuratezza $1.8 \cdot 10^{-13}$

NBS-6; accuratezza $8 \cdot 10^{-14}$

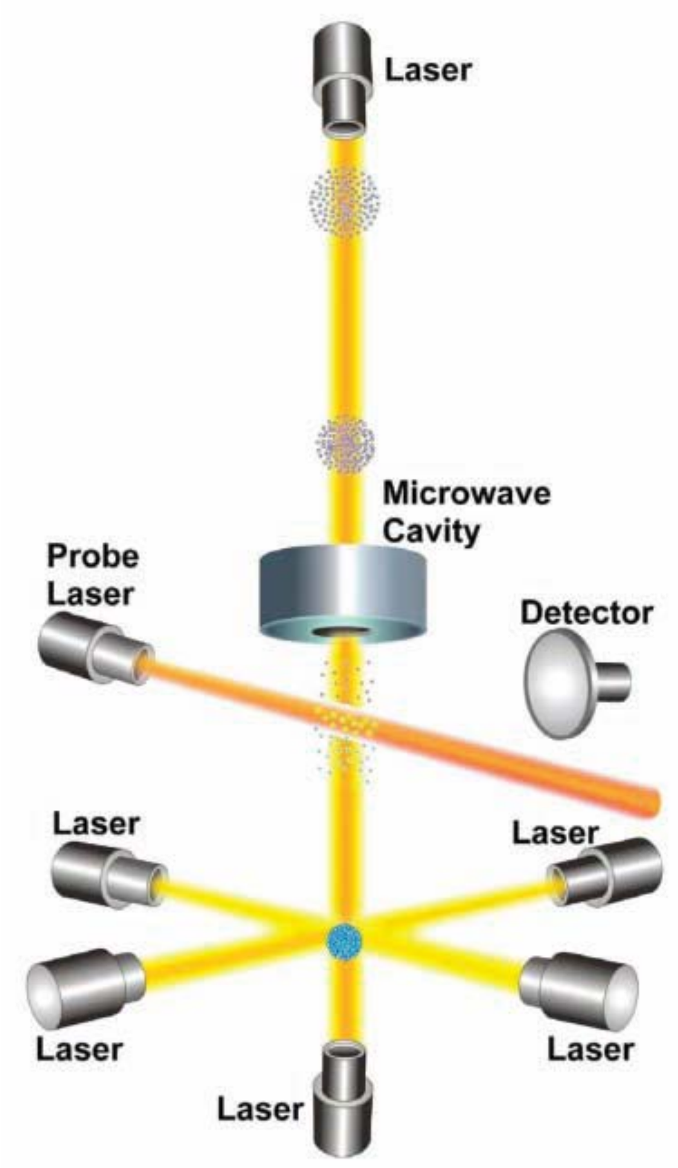


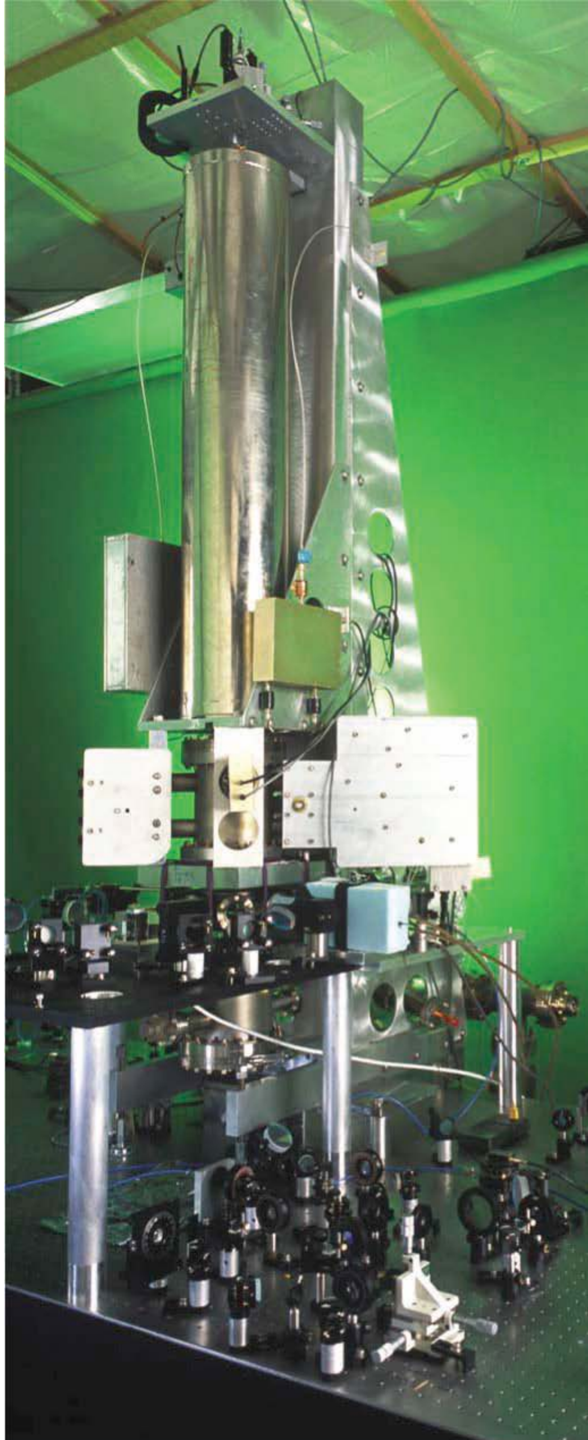
NIST-7; accuratezza $5 \cdot 10^{-15}$

NIST-7, l’ultimo oscillatore con sorgente termica di atomi di Cs

Per la prima volta si utilizza il laser invece di un campo magnetico per indurre la transizione atomica

L’orologio a fontana atomica



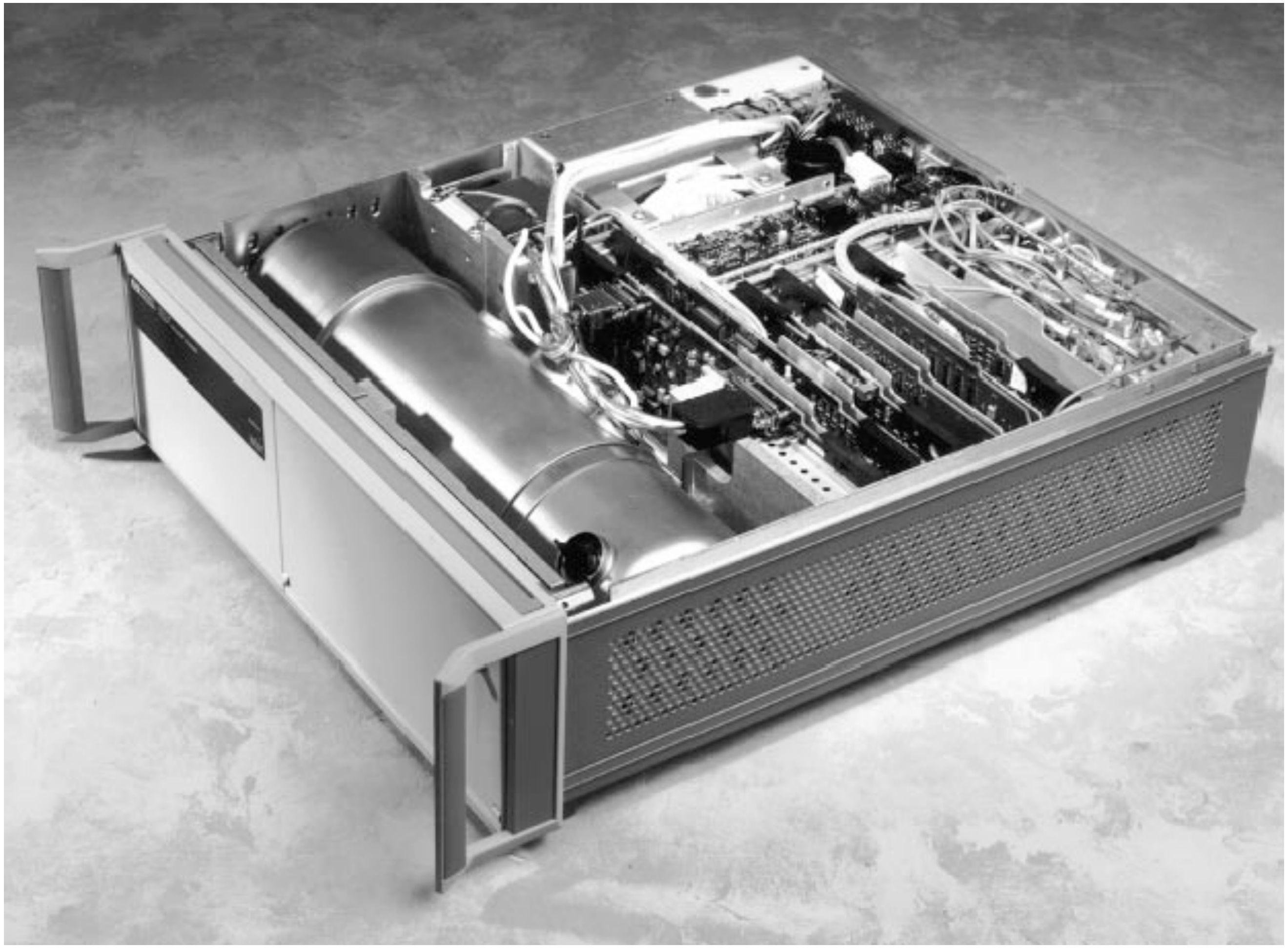


NIST-F1; accuratezza $4 \cdot 10^{-16}$

Presto vengono costruiti orologi a cesio commerciali (HP ... Agilent)

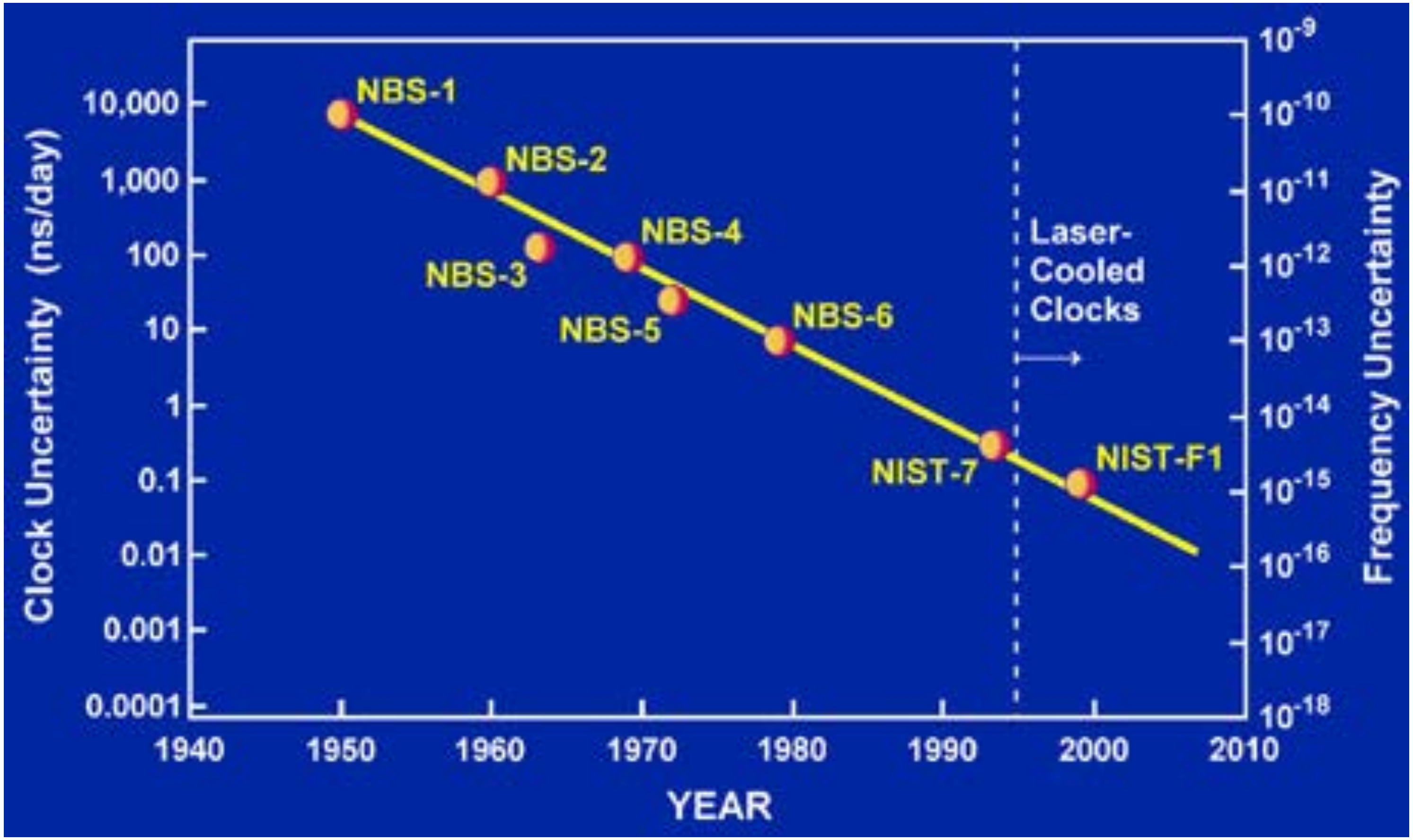
Tubo a cesio di un HP5060 (1964)

Un moderno orologio a cesio (Agilent 5071A)



Agilent 5071A ...

Miglioramento dell’accuratezza degli orologi del NIST



Ridefinizione del secondo (1967)

Vecchia definizione: 1/86400 del giorno solare medio

Nuova definizione: durata di 9 192 631 770 periodi della radiazione che corrisponde alla transizione tra due livelli iperfini dello stato fondamentale dell'atomo di cesio 133.

Orologi atomici di dimensioni sempre più ridotte !

A chip-scale atomic clock based on ^{87}Rb with improved frequency stability

S. Knappe, P.D.D. Schwindt, V. Shah[†], L. Hollberg, and J. Kitching

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knappe@boulder.nist.gov

http://www.boulder.nist.gov/timefreq/ofm/smallclock/

L. Liew and J. Moreland

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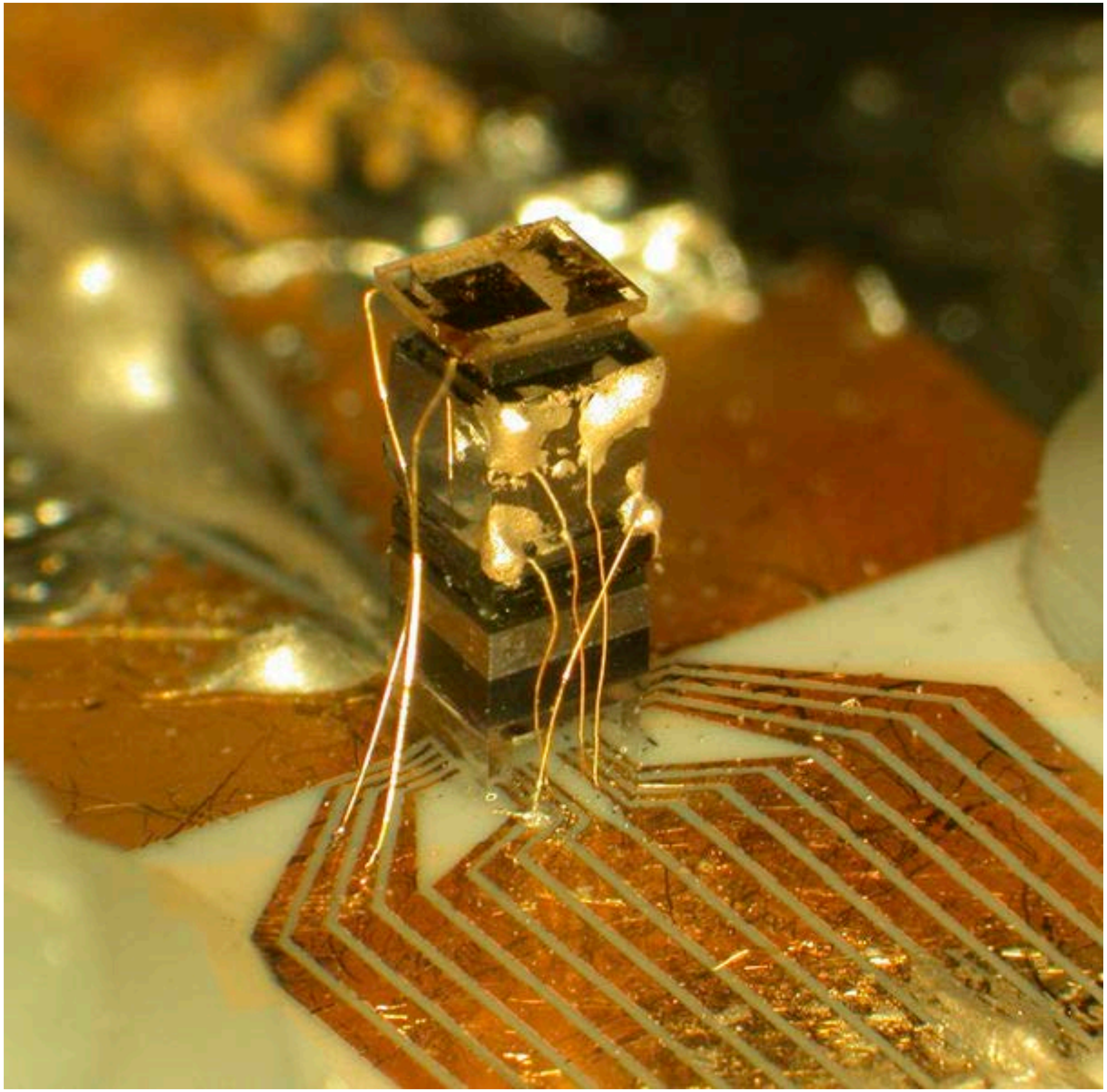
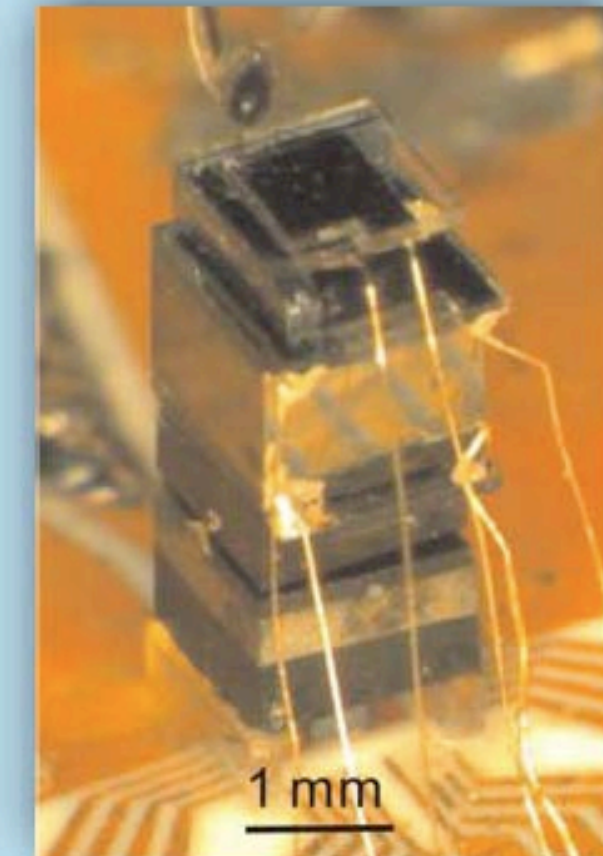
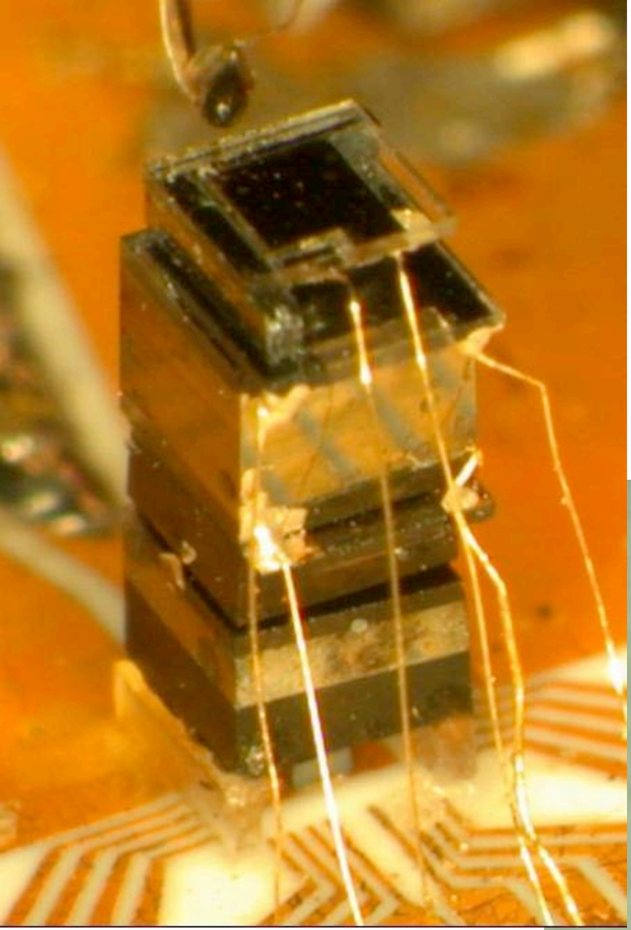
Abstract: We demonstrate a microfabricated atomic clock physics package based on coherent population trapping (CPT) on the D_1 line of ^{87}Rb atoms. The package occupies a volume of 12 mm^3 and requires 195 mW of power to operate at an ambient temperature of 200 °C. Compared to a previous microfabricated clock exciting the D_2 transition in Cs [1], this ^{87}Rb clock shows significantly improved short- and long-term stability. The instability at short times is $4 \times 10^{-11} / \tau^{1/2}$ and the improvement over the Cs device is due mainly to an increase in resonance amplitude. At longer times ($\tau > 50$ s), the improvement results from the reduction of a slow drift to -5×10^{-9} / day. The drift is most likely caused by a chemical reaction of nitrogen and barium inside the cell. When probing the atoms on the D_1 line, spin-exchange collisions between Rb atoms and optical pumping appear to have increased importance compared to the D_2 line.

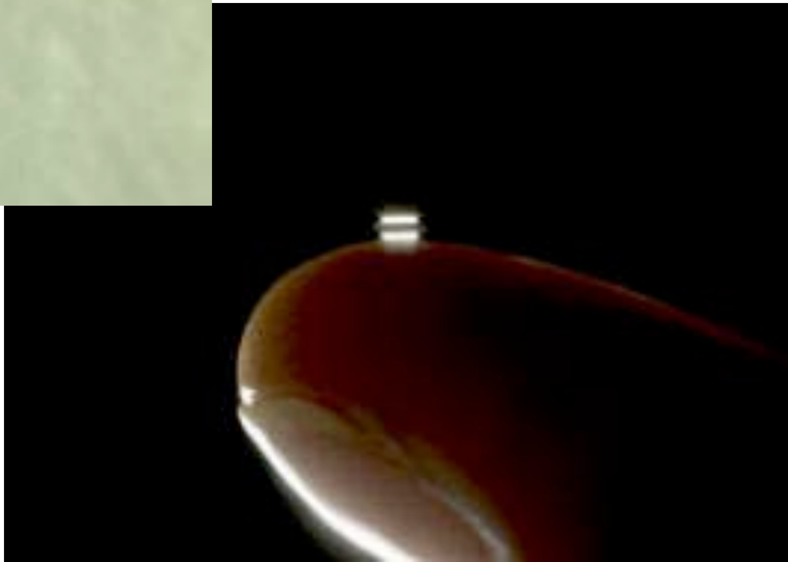
21 February 2005 / Vol. 13, No. 4 / OPTICS EXPRESS 1249



Orologio atomico miniaturizzato (Rb)


1 mm





Orologi atomici sempre più precisi !

PRL **97,** 020801 (2006) PHYSICAL REVIEW LETTERS week ending 14 JULY 2006

Single-Atom Optical Clock with High Accuracy

W. H. Oskay,* S. A. Diddams, E. A. Donley, T. M. Fortier,† T. P. Heavner, L. Hollberg, W. M. Itano, S. R. Jefferts, M. J. Delaney, K. Kim,‡ F. Levi,§ T. E. Parker, and J. C. Bergquist‖

Time and Frequency Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

(Received 7 November 2005; published 14 July 2006)

For the past 50 years, atomic standards based on the frequency of the cesium ground-state hyperfine transition have been the most accurate time pieces in the world. We now report a comparison between the cesium fountain standard NIST-F1, which has been evaluated with an inaccuracy of about 4×10^{-16}, and an optical frequency standard based on an ultraviolet transition in a single, laser-cooled mercury ion for which the fractional systematic frequency uncertainty was below 7.2×10^{-17}. The absolute frequency of the transition was measured versus cesium to be 1 064 721 609 899 144.94 (97) Hz, with a statistically limited total fractional uncertainty of 9.1×10^{-16}, the most accurate absolute measurement of an optical frequency to date.

DOI: 10.1103/PhysRevLett.97.020801 PACS numbers: 32.30.Jc, 06.30.Ft, 32.30.Bv

NIST-F1: 4×10^{-16}

Single atom mercury clock: 7.2×10^{-17}

A cosa serve misurare il tempo con precisione così elevata?

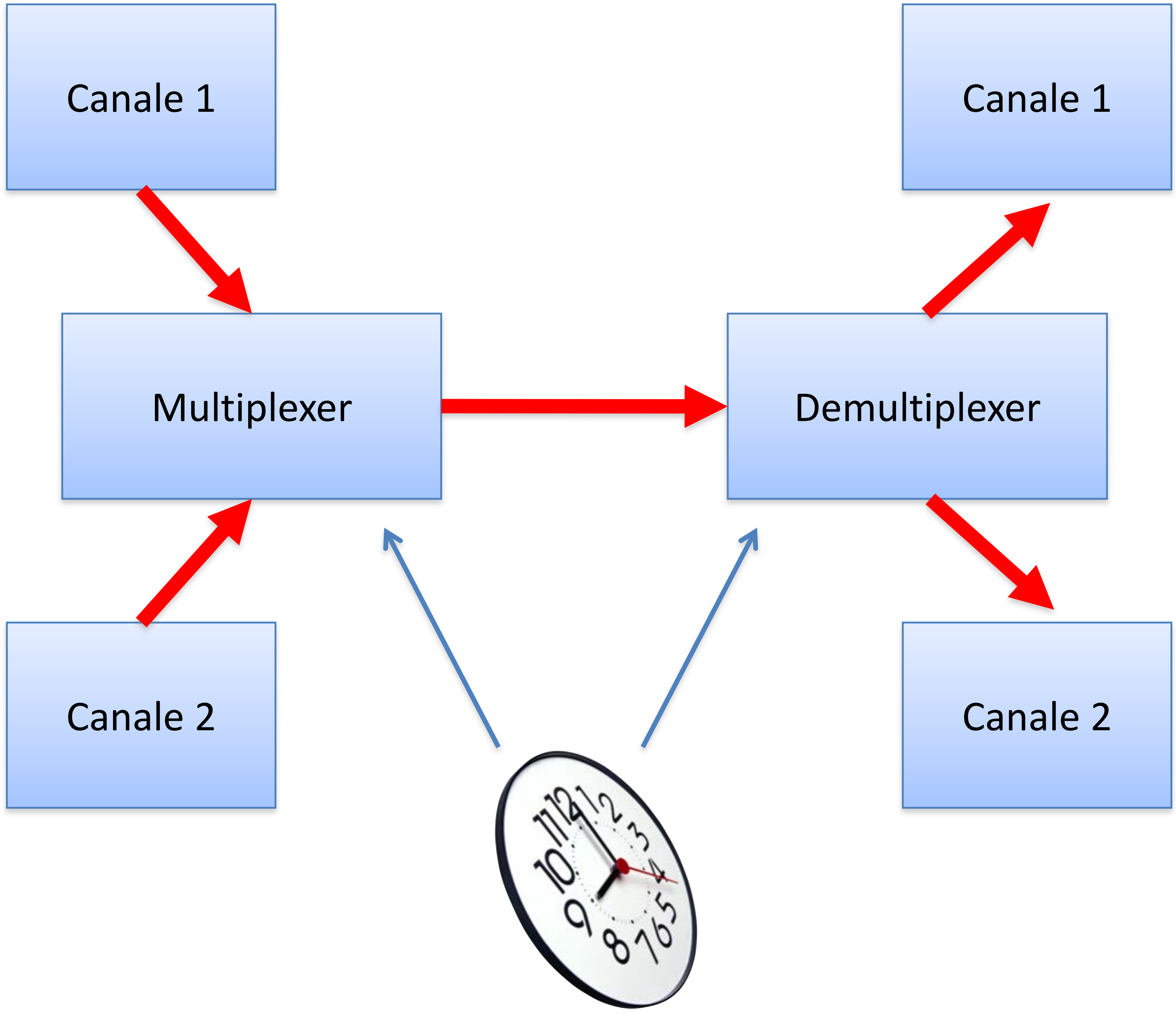
- La precisione è richiesta dalle vaste reti elettriche ed elettroniche di cui ci serviamo continuamente

- Misurare il tempo è equivalente a misurare distanze: questo rende possibili tecnologie come il GPS

- La misura precisa del tempo rende possibili esperimenti nell'ambito della fisica (fisica della gravitazione, astrofisica)

Applicazioni particolari

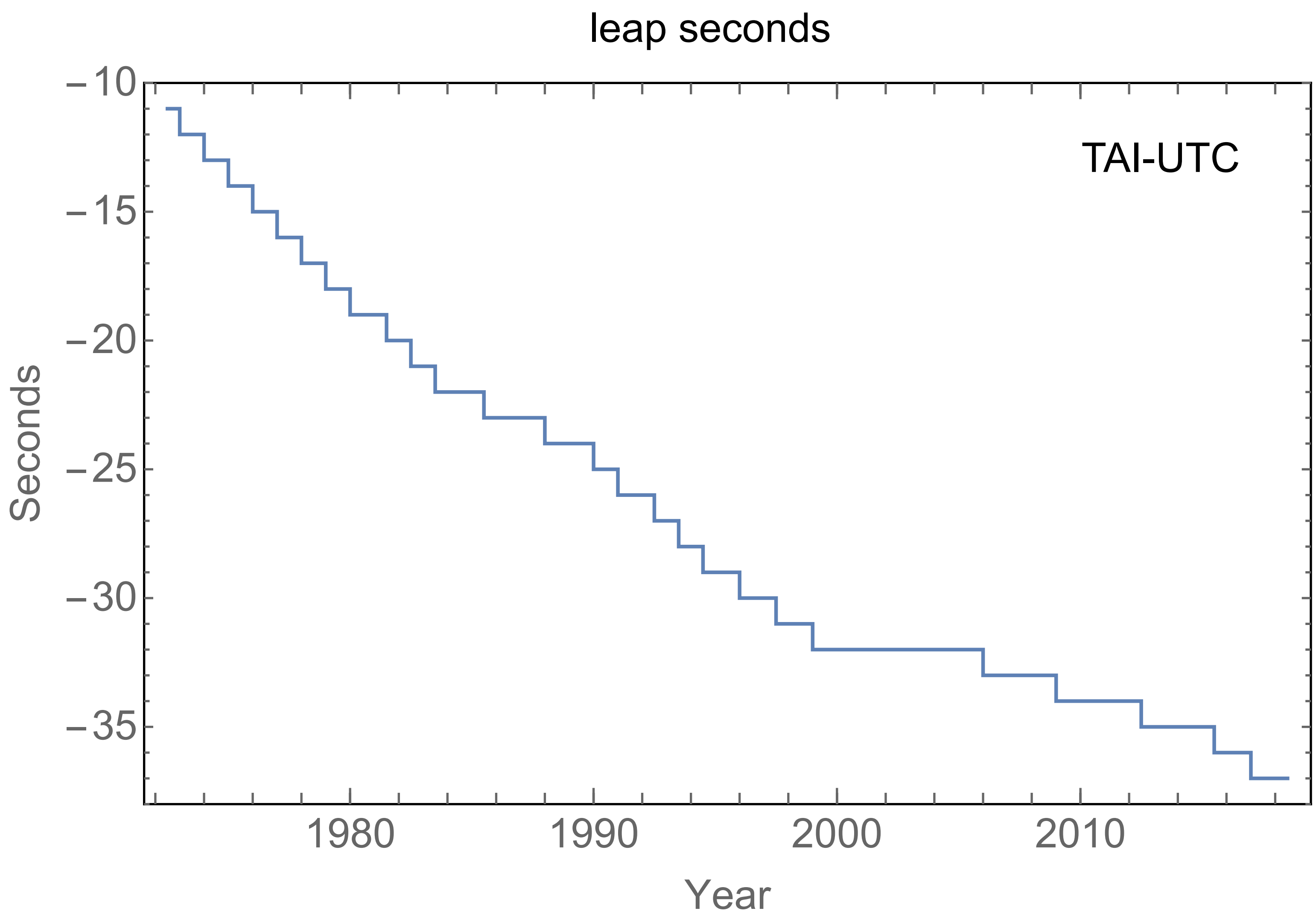
- nei sistemi di comunicazione
- nei sistemi di navigazione
- nelle reti di computer
- nei sistemi di contabilità bancaria
- nell'individuazione dei guasti nella rete elettrica
- nella ricerca ed esplorazione spaziale
- in geologia
- nella rilevazione ambientale
- nel controllo del traffico aereo
- nella sorveglianza delle flotte di trasporto
- nella guida automatica


Canale 1
Canale 1
Multiplexer
Demultiplexer
Canale 2
Canale 2

Il Tempo Atomico Internazionale (TAI)
e il Tempo Universale Coordinato (UTC)

TAI = media pesata di più di 300 orologi atomici in tutto il mondo

UTC = compatibile con UT, ma agganciato alla scala atomica. Richiede riaggiustamenti periodici.



leap seconds
TAI-UTC
−10
−15
−20
−25
−30
−35
Seconds
1980
1990
2000
2010
Year

Geographical distribution of the laboratories that contribute to TAI and time transfer equipment as of April 2013 (from https://www.bipm.org/en/bipm/tai/tai).

Optical atomic clocks?

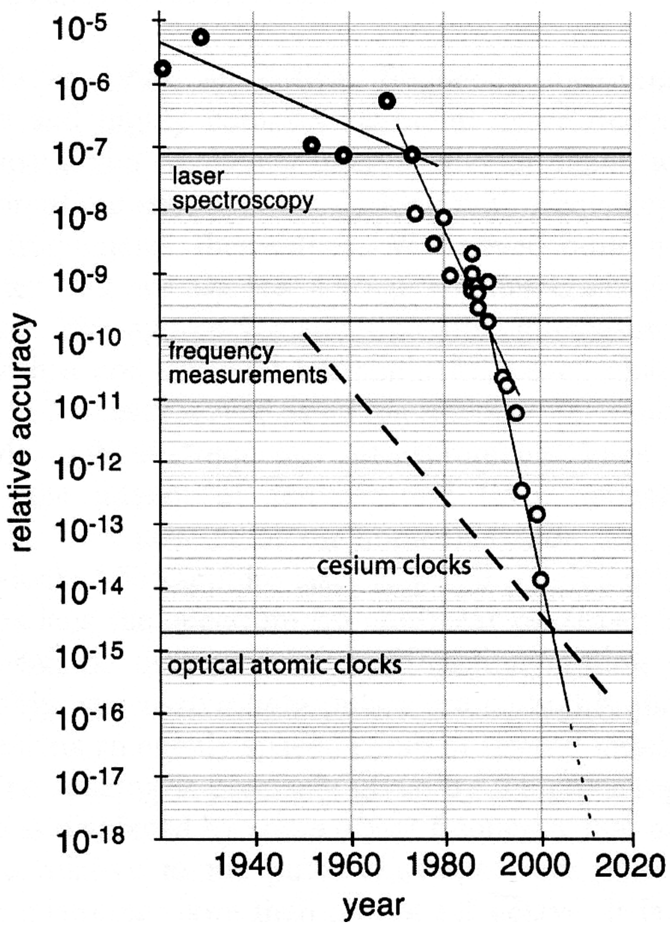
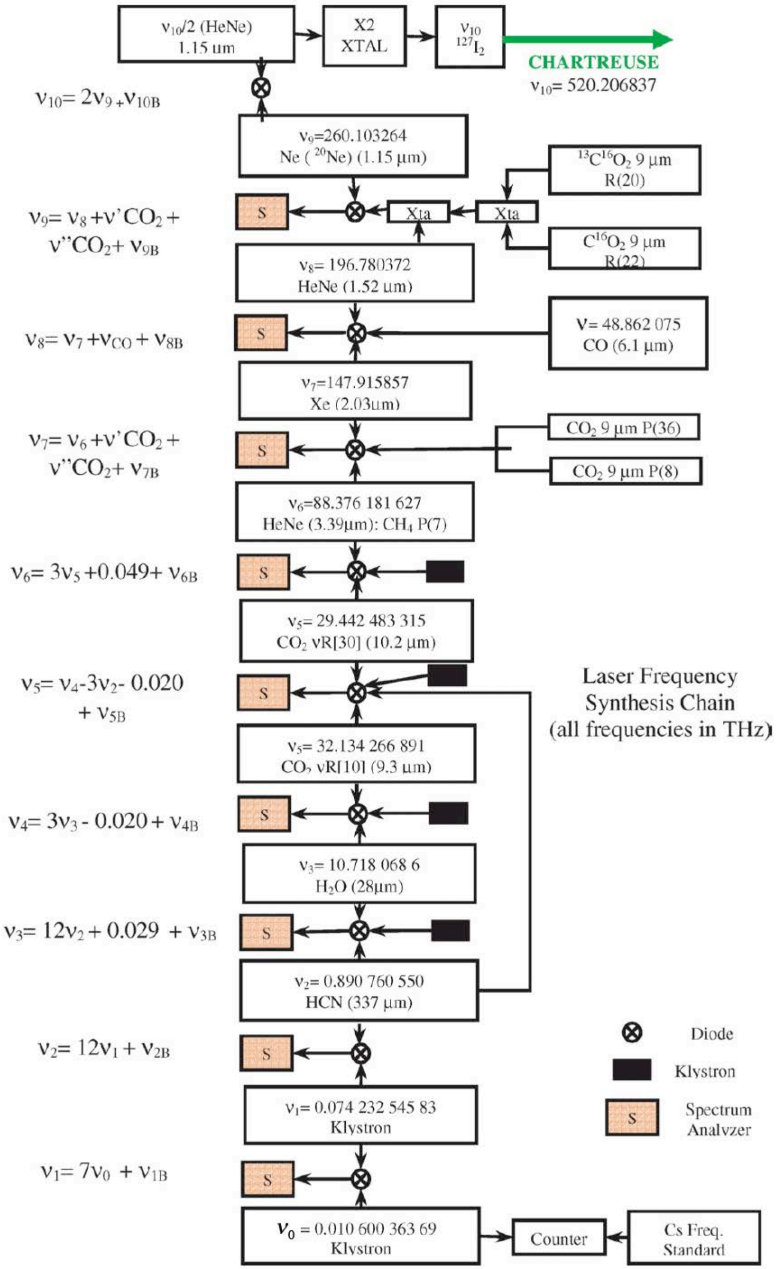


Fig. 2. Developments in relative accuracy in precision spectroscopy. The level 10^{-15} has been achieved in optical as well as microwave based systems, where the former now are taking the lead



La figura mostra una catena di sintesi di frequenza sviluppata al NIST per misurare la frequenza di un laser a colorante stabilizzato allo iodio che opera nel visibile (520 THz), relativamente ad uno standard primario di frequenza (orologio atomico al cesio)

In questa catena di sintesi di frequenza, il grande rapporto tra frequenza dell'orologio atomico che fa da standard di riferimento (circa 9.1 GHz) e quella ottica (520 THz) viene coperto in passi successivi.

In ogni passo le frequenze di due oscillatori vengono confrontate per mezzo della generazione di armoniche. Il segnale dei due oscillatori viene combinato in un componente non-lineare (un diodo) in modo da dare dei battimenti a bassa frequenza, con un periodo facilmente misurabile.

Nota: i klystron sono dei generatori di microonde

The Nobel Prize in Physics 2005

John L. Hall
Nobel Prize in Physics
2005, Prize share: 1/4

Theodor W. Hänsch
Nobel Prize in Physics
2005, Prize share: 1/4

According to quantum physics, light and other electromagnetic radiation appear in the form of quanta, packets with fixed energies, which also correspond to energy transitions in atoms. Consequently, determining the frequency of light waves provides information about the atoms' properties, benchmarks for time and length, and the possibility of determining physical constants. Around the year 2000, John Hall and Theodor Hänsch developed the frequency comb technique, in which laser light with a series of equidistant frequencies is used to measure frequencies with great precision.

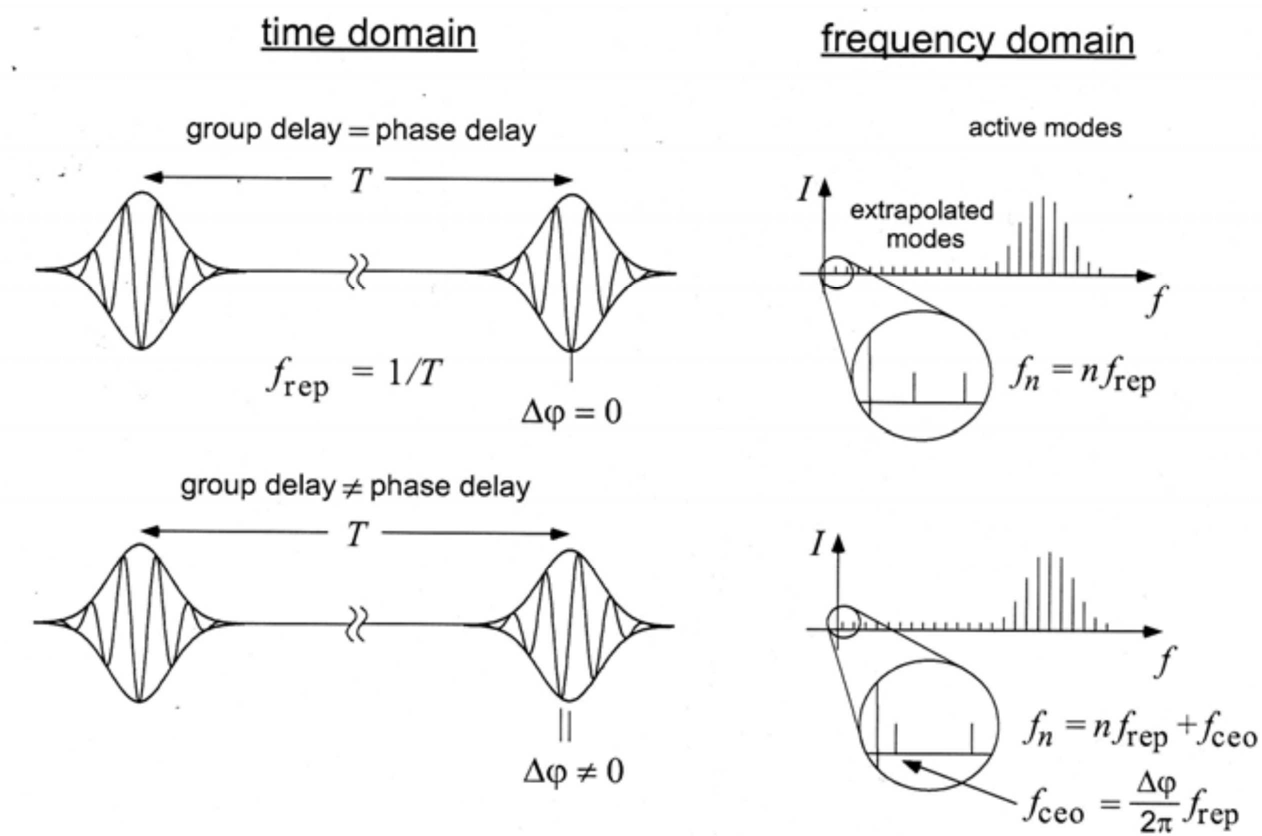


Fig. 3. Time and frequency representations of femtosecond radiation. In the general case the electrical field of the laser light moves under the pulse envelope. The frequency comb can be extrapolated down to frequency 0, and then there is generally an off-set f_{CEO}, which must be determined (From Ref. [17]).

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Architecture for the photonic integration of an optical atomic clock

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Laboratory optical atomic clocks achieve remarkable accuracy (now counted to 18 digits or more), opening possibilities for exploring fundamental physics and enabling new measurements. However, their size and the use of bulk components prevent them from being more widely adopted in applications that require precision timing. By leveraging silicon-chip photonics for integration and to reduce component size and complexity, we demonstrate a compact optical-clock architecture. Here a semiconductor laser is stabilized to an optical transition in a microfabricated rubidium vapor cell, and a pair of interlocked Kerr-microresonator frequency combs provide fully coherent optical division of the clock laser to generate an electronic 22 GHz clock signal with a fractional frequency instability of one part in 10^{13}. These results demonstrate key concepts of how to use silicon-chip devices in future portable and ultraprecise optical clocks.

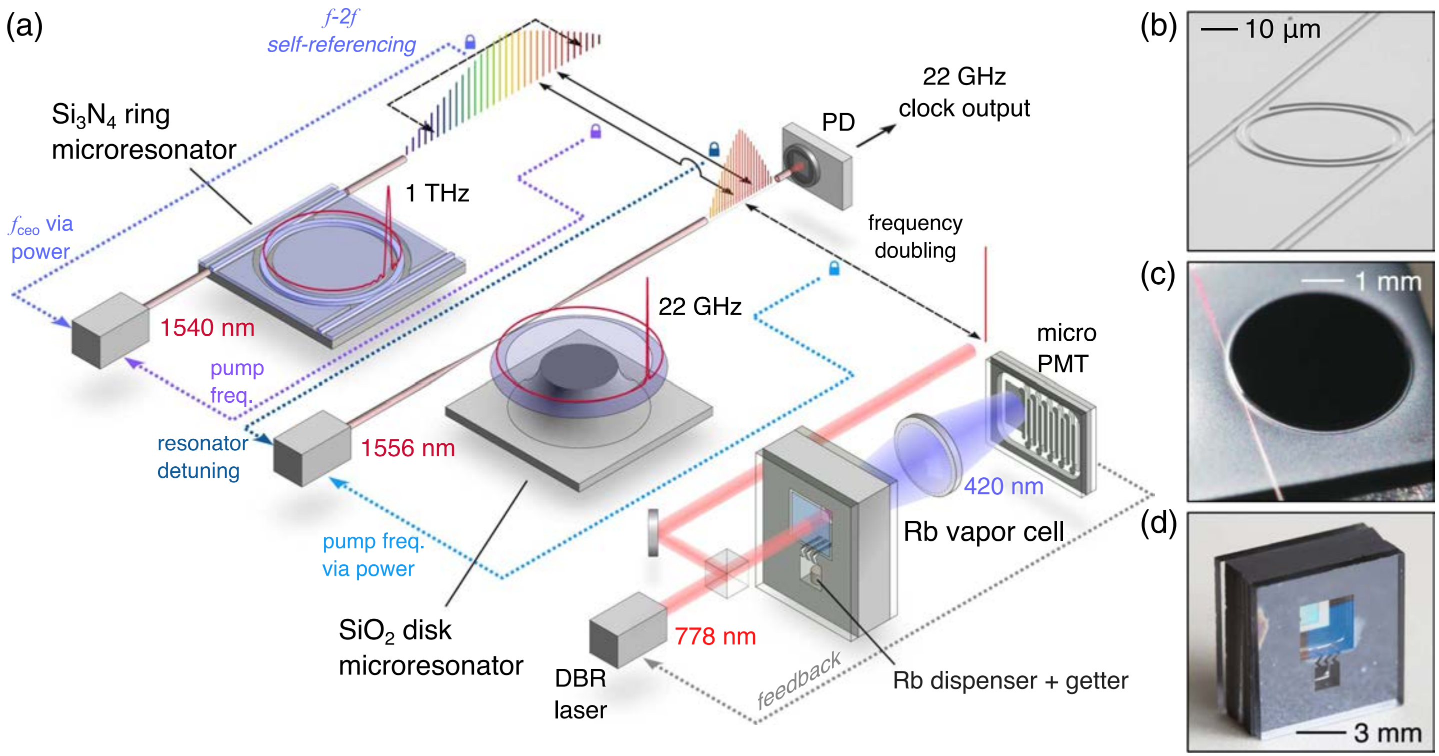

Fig. 1. Schematic of the microfabricated photonic optical atomic clock. (a) The microfabricated optical clock consists of an optical local oscillator, a microfabricated Rb vapor cell, and a pair of microresonator frequency combs, which serve as optical clockwork. Absorption of the clock laser in the cell is detected via the collection of 420 nm fluorescence using a microfabricated PMT. The optical clockwork consists of interlocked DKS combs generated using a ≈2 mm diameter, silica microresonator, and a 46 µm diameter, SiN microresonator. Stabilization of the frequency combs' output is performed via electronic feedback (indicated by dotted lines) to the pump frequency and resonator detuning of the ECDLs used to pump the microresonators. The feedback signals are generated from optical heterodyne beat notes of adjacent comb teeth, as indicated by the solid black arrows. In some cases, frequency doubling (dashed black arrows) was required to compare optical signals. For simplicity, we do not picture the frequency and intensity modulators used for feedback in the comb frequency servo loops. (b) Scanning-electron microscope image of the SiN microresonator. Photographs of (c) the silica microresonator and (d) the microfabricated Rb vapor cell.

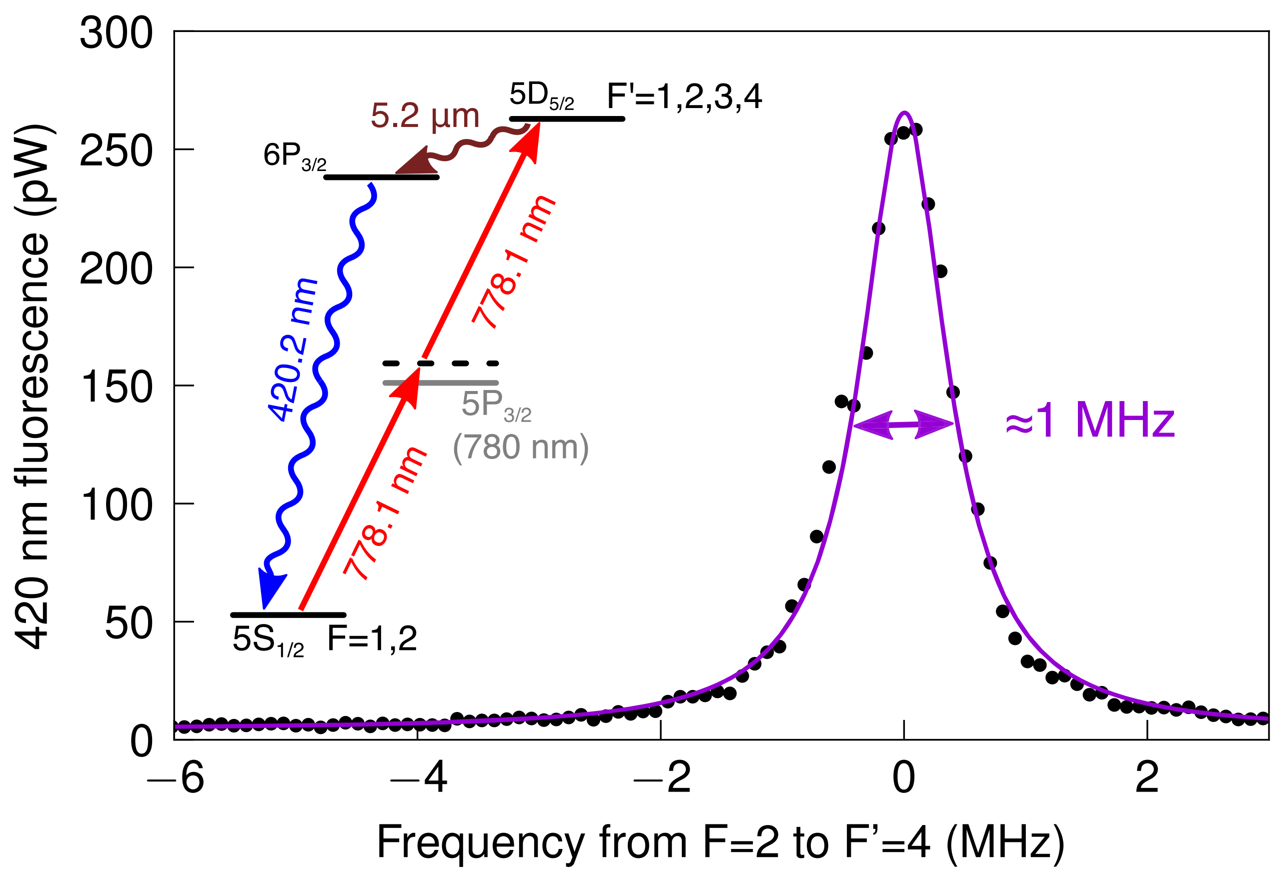

Fig. 2. Spectroscopy of optical clock transition. Doppler-free fluorescence spectroscopy of the optical clock transition between the $5S_{1/2}$, $F = 2$ to $5D_{5/2}$, $F = 4$ levels at 385.284566 THz, with a full width at half-maximum of ≈1 MHz. The atomic level structure of the ^{87}Rb two-photon transition is shown as an inset.

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Towards the optical second: verifying optical clocks at the SI limit

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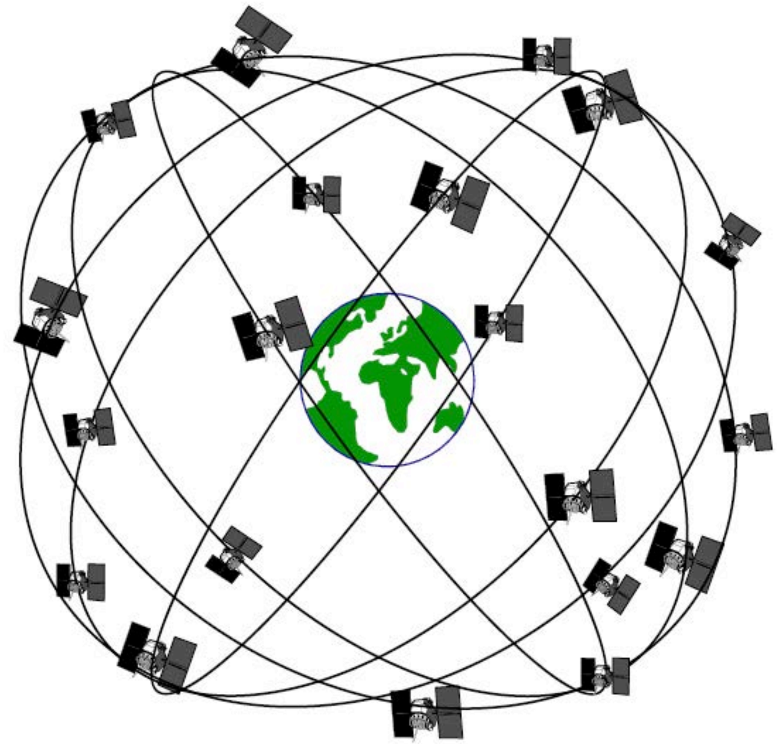
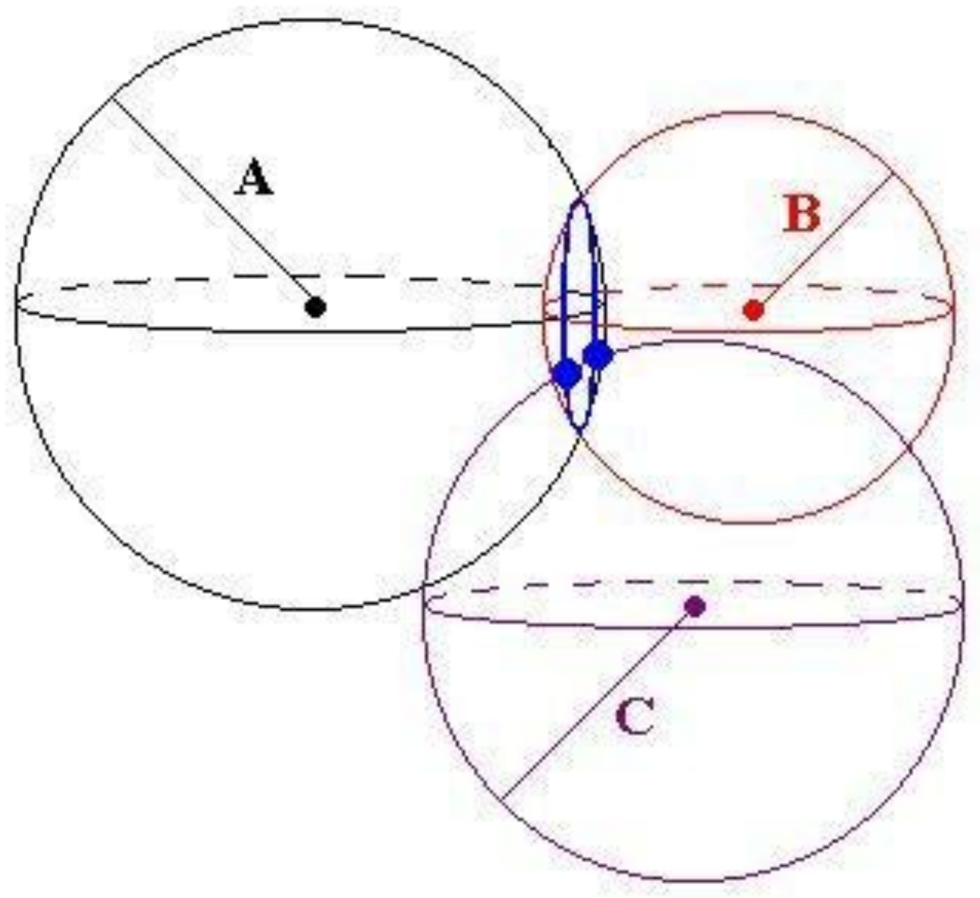
The pursuit of ever more precise measures of time and frequency motivates redefinition of the second in terms of an optical atomic transition. To ensure continuity with the current definition, based on the microwave hyperfine transition in ^{133}Cs, it is necessary to measure the absolute frequency of candidate optical standards relative to primary cesium references. Armed with independent measurements, a stringent test of optical clocks can be made by comparing ratios of absolute frequency measurements against optical frequency ratios measured via direct optical comparison. Here we measure the $^1S_0 \rightarrow {}^3P_0$ transition of ^{171}Yb using satellite time and frequency transfer to compare the clock frequency to an international collection of national primary and secondary frequency standards. Our measurements consist of 79 runs spanning eight months, yielding the absolute frequency to be 518 295 836 590 863.71(11) Hz and corresponding to a fractional uncertainty of 2.1×10^{-16}. This absolute frequency measurement, the most accurate reported for any transition, allows us to close the Cs-Yb-Sr-Cs frequency measurement loop at an uncertainty $<3 \times 10^{-16}$, limited for the first time by the current realization of the second in the International System of Units (SI). Doing so represents a key step towards an optical definition of the SI second, as well as future optical time scales and applications. Furthermore, these high accuracy measurements distributed over eight months are analyzed to tighten the constraints on variation of the electron-to-proton mass ratio, $\mu = m_e/m_p$. Taken together with past Yb and Sr absolute frequency measurements, we infer new bounds on the coupling coefficient to gravitational potential of $k_\mu = (-1.9 \pm 9.4) \times 10^{-7}$ and a drift with respect to time of $\frac{\dot{\mu}}{\mu} = (5.3 \pm 6.5) \times 10^{-17}/\mathrm{yr}$.

Un'applicazione importante: il GPS.



34 satelliti a 26600 km di altezza

- il tempo di propagazione corrisponde ad una distanza
- le superfici di "uguale tempo di propagazione" sono sfere
- in generale tre sfere si intersecano in due punti
- un quarto satellite risolve l’ambiguità e permette di correggere la densità variabile dell’atmosfera



Block	Launch period	Satellite launches				Currently in orbit and healthy
		Suc-cess	Fail-ure	In prep-aration	Plan-ned	
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	0
IIR	1997–2004	12	1	0	0	12
IIR-M	2005–2009	8	0	0	0	7
IIF	2010–2016	12	0	0	0	12
IIIA	From 2018	4	0	4	10	4
IIIF	—	0	0	0	22	0
Total		73	2	5	24	34

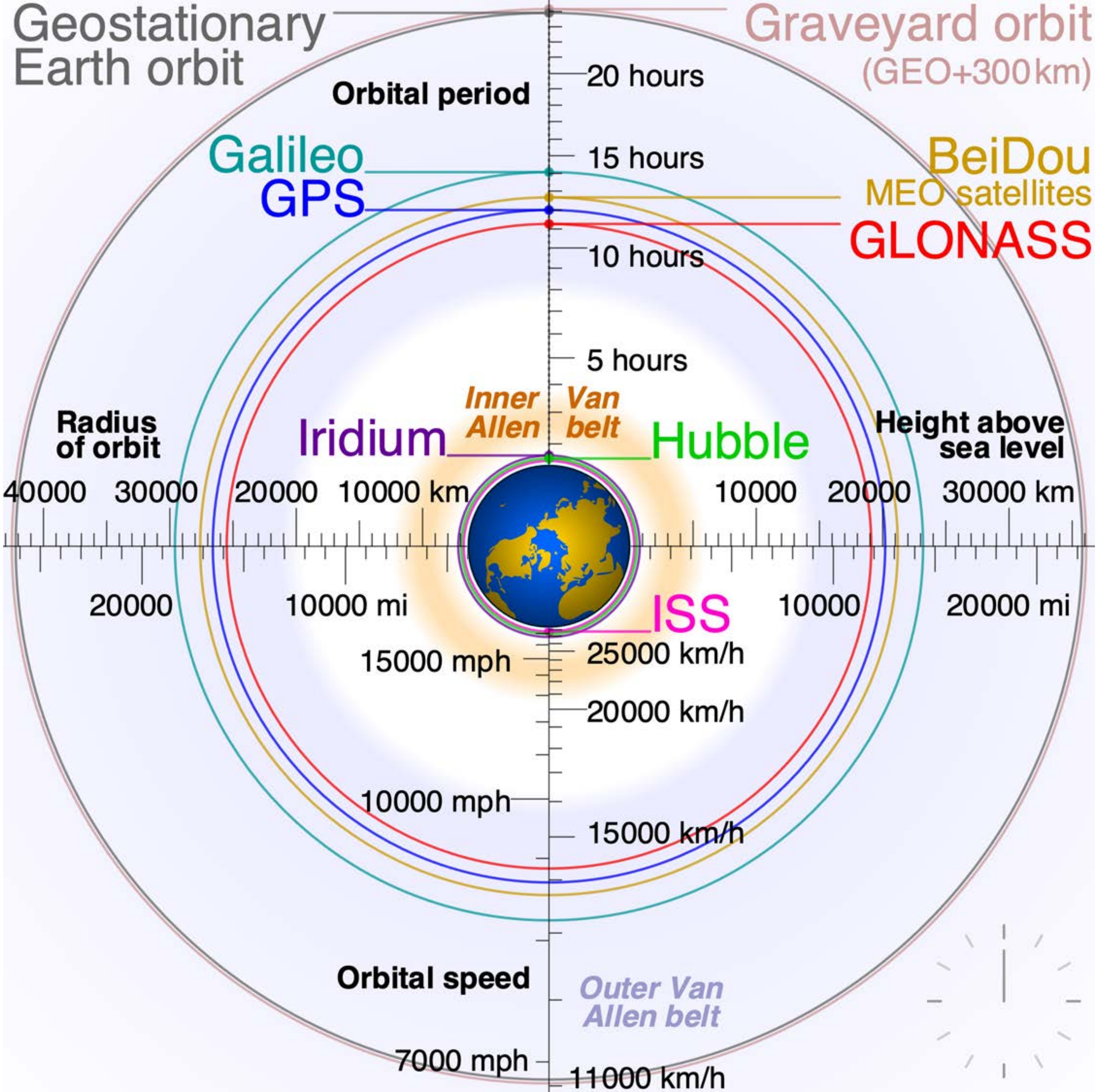
(Last update: July 12, 2020)

8 satellites from Block IIA are placed in reserve

USA-203 from Block IIR-M is unhealthy

[48] For a more complete list, see *list of GPS satellite launches*

from Wikipedia https://en.wikipedia.org/wiki/Global_Positioning_System

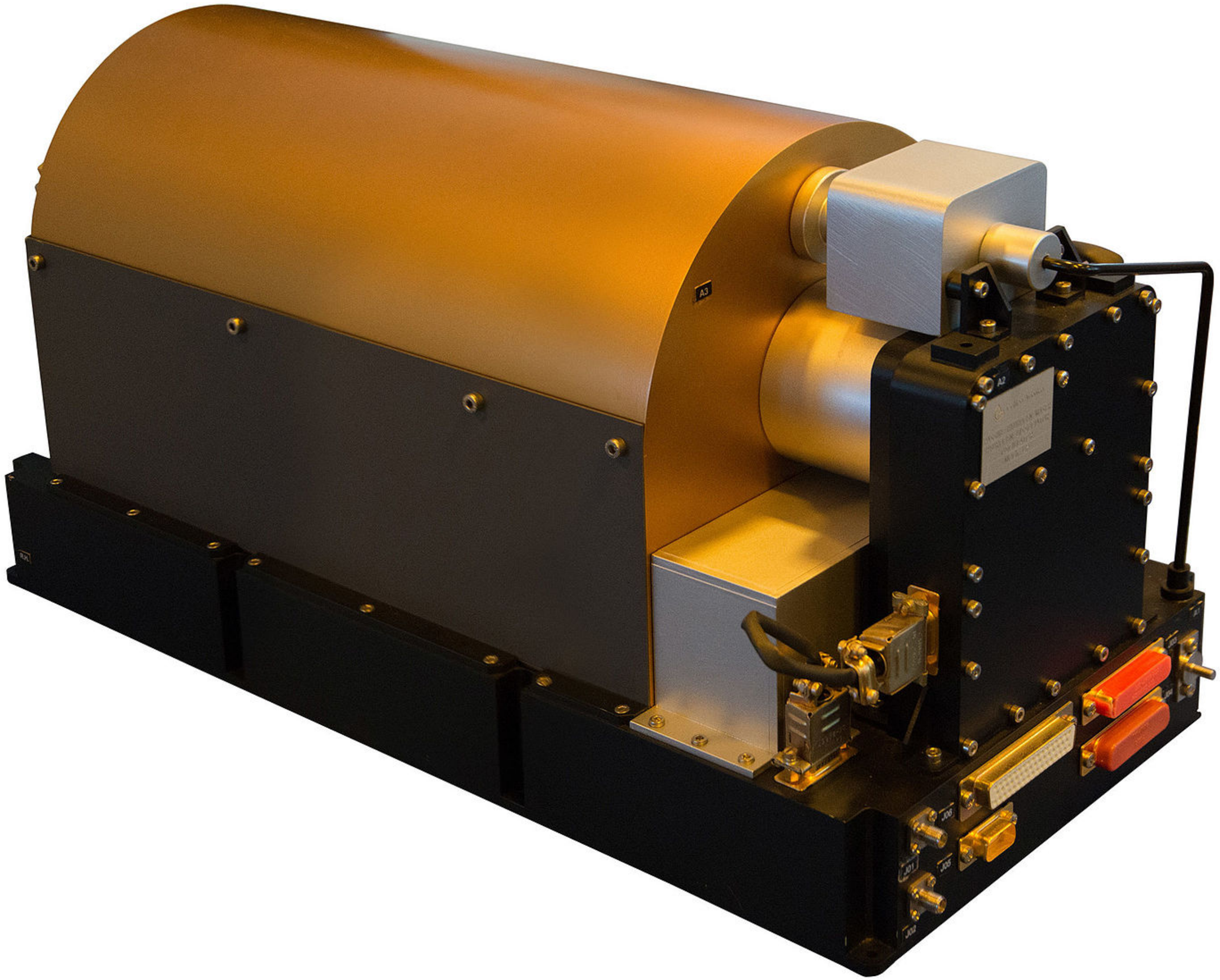


from Wikipedia (https://en.wikipedia.org/wiki/Galileo_(satellite_navigation))

progetto GALILEO

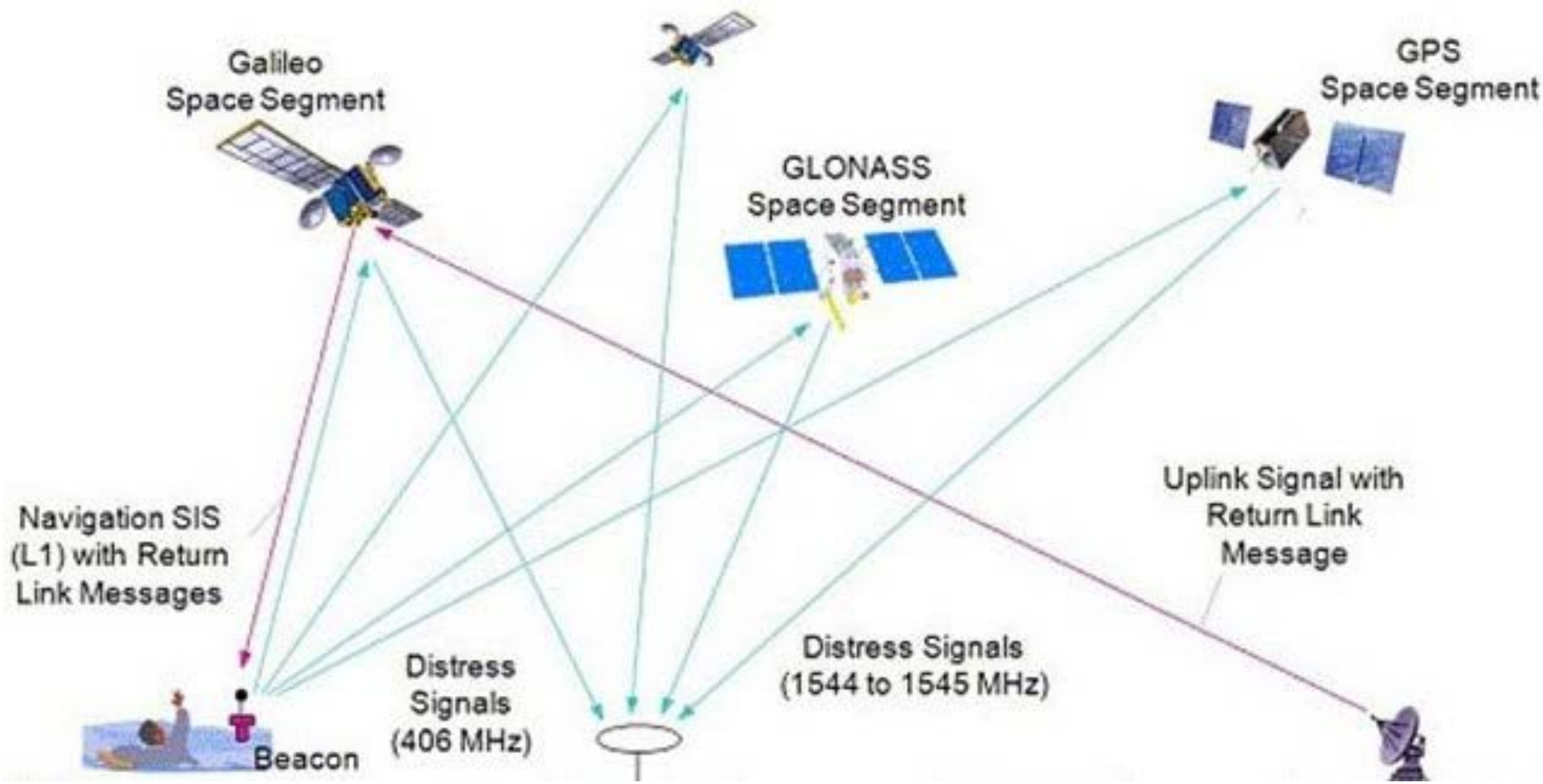
(inizio operatività nel 2014)

Europe’s Galileo satellite navigation system has entered its initial operational phase, offering positioning, velocity and timing services to suitably equipped users worldwide. It takes a minimum of four Galileo satellites to be visible in the local sky to fix a receiver’s position. This animation shows how service availability increases as the overall number of satellites in the Galileo constellation goes up.



Space Passive Hydrogen Maser used in Galileo satellites as a master clock for an onboard timing system (from Wikipedia, https://en.wikipedia.org/wiki/Galileo_(satellite_navigation))

GNSS-based Search-And-Rescue System (SAR)



Applicazioni future del sistema Galileo e della scienza dello spazio in Europa

https://gssc.esa.int/navipedia/index.php/Galileo_Future_and_Evolutions

The 'Rapid Action Coronavirus Earth observation' dashboard, also known as RACE, provides access to key environmental, economic and social indicators to measure the impact of the coronavirus lockdown and monitor post-lockdown recovery. The RACE dashboard can be accessed here: https://race.esa.int/