

INRIM: its role as NMI and in the generation of the Italian Standard Time

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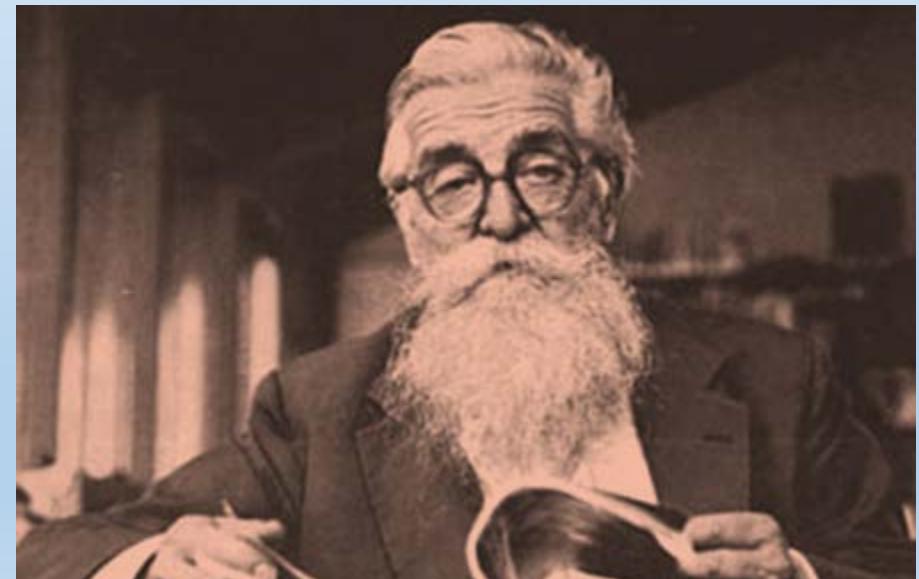
INRiM History

Born in 2006 merging

IEN Istituto Elettrotecnico
Nazionale Galileo Ferraris (1934)



Istituto di Metrologia Gustavo Colonnelli
(1968)

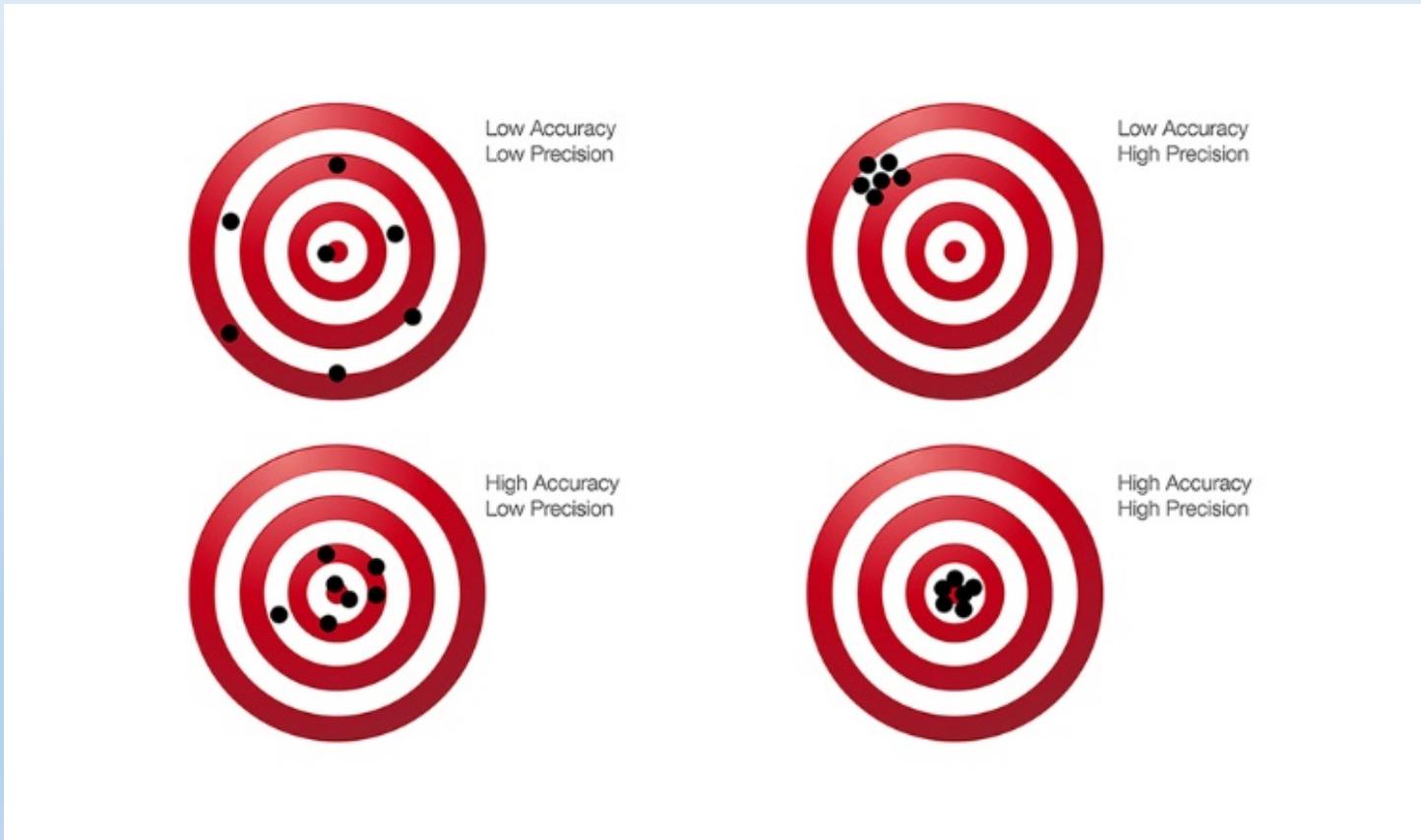


INRiM role

Italian NMI National Metrology Institute

- Realize and maintain the basic and derived units of the International System of units (SI) also through their international comparison with the standards of other countries.
- Provide the national measurements traceability to the SI through instruments calibration against the primary power standards.
- Represent Italy in international metrological organisms.
- Collaborate for the accreditation of the calibration laboratories in Italy

Why calibration is important?



The international system of units SI

Born in 1961 after a process started during the French Revolution

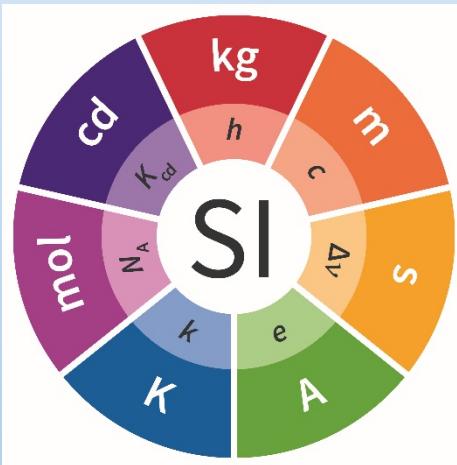


7 base units:

1. **metre**: unit of length
2. **kilogram**: unit of mass
3. **second**: unit of time
4. **Ampere**: unit of electric current
5. **Kelvin**: unit of thermodynamic temperature
6. **mole**: unit of amount of substance
7. **candela**: unit of luminous intensity

A change of paradigm: the SI revision

26th CGPM Versailles 13-16 november 2018
Resolution 1



decides that, effective from 20 May 2019, 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,



How units definitions change

The metre is the length of the path travelled by light in vacuum during a time interval of $1/299\,792\,458$ of a second.

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol".

When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be $299\,792\,458$ when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{Cs}$.

The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \times 10^{-34}$ when expressed in the unit J s, which is equal to $\text{kg m}^2 \text{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\,649 \times 10^{-23}$ when expressed in the unit J K $^{-1}$, which is equal to $\text{kg m}^2 \text{s}^{-2} \text{K}^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{Cs}$.

The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\,140\,76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A , when expressed in the unit mol $^{-1}$ and is called the Avogadro number.

The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd} , to be 683 when expressed in the unit lm W $^{-1}$, which is equal to cd sr W $^{-1}$, or cd sr kg $^{-1}$ m $^{-2}$ s $^{-3}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{Cs}$.

The definition of the second - 1



Before 1960 second was based on the axial rotation of the earth as the fraction 1/86400 of the mean solar day.



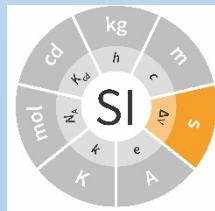
From 1960 to 1967 time was based on the orbit of the earth around the sun, one ephemeris second being $1/31556925.9747$ of the tropical year 1900

The definition of the second - 2

From 1967 to 2019

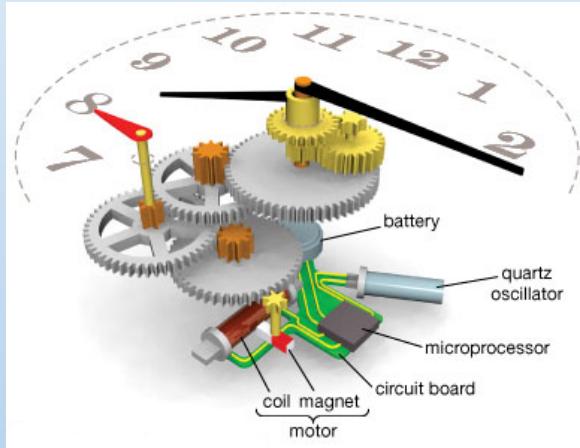
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

From 20th may 2019



The second, symbol s , is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} .

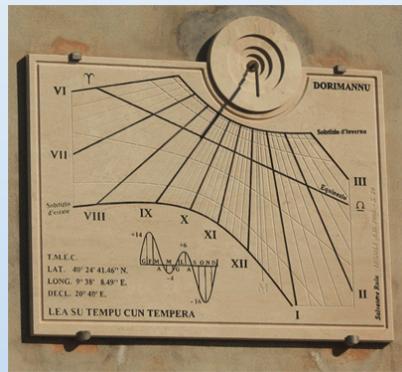
What is a clock?



A clock is composed by:

- An oscillator: the heart of the clock that generates periodic events
- A counter that counts the number of periodic events
- A display that shows the results of the counter
- An energy storage

History of clocks – very ancient clocks



Sundials



Hourglass
clepsydra (water clock)



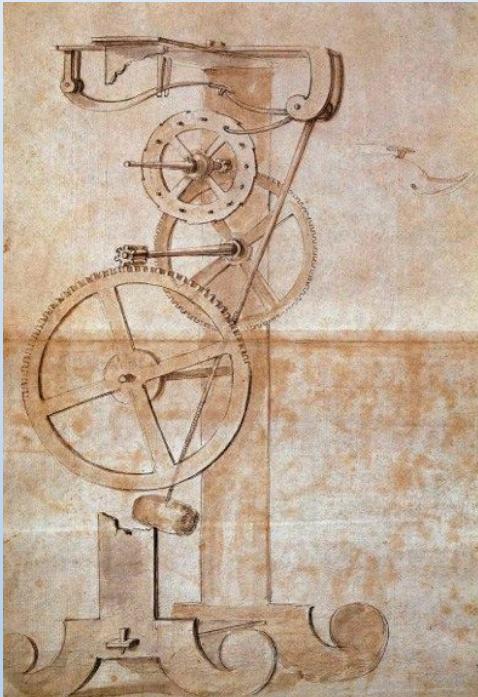
Candle clocks

History of clocks – medieval clocks

«Monks clocks» («Svegliarino monastico»)
around 1300
Verge escapement



History of clocks – the pendulum – 1650



Galileo's project

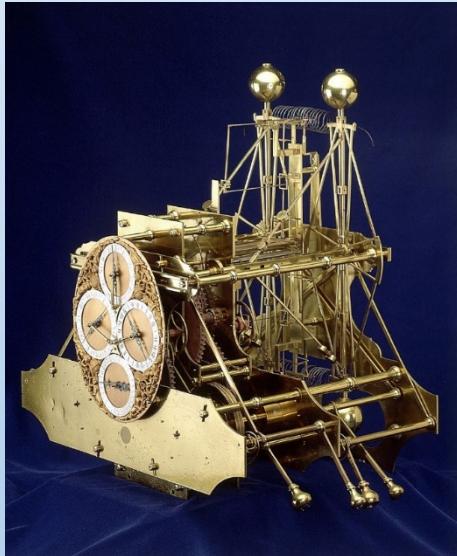


A modern realization

History of clocks

Harrison's marine chronometer

John Harrison (1693-1776)



Harrison's H1 - 1735



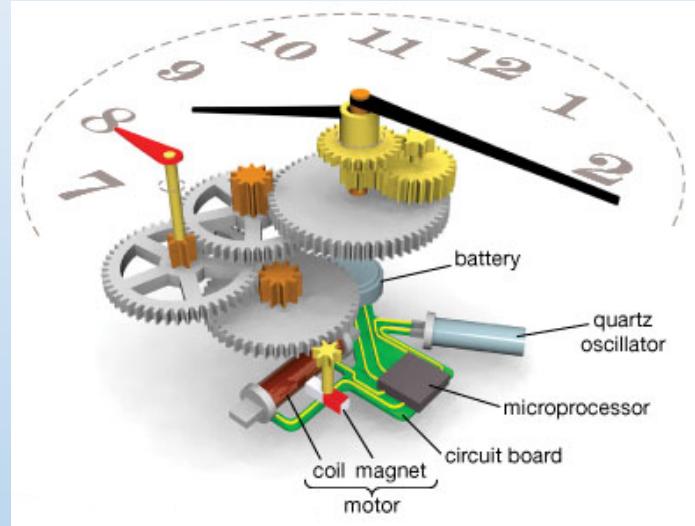
Harrison's H4 - 1759

Modern clocks

Balance wheel mechanism

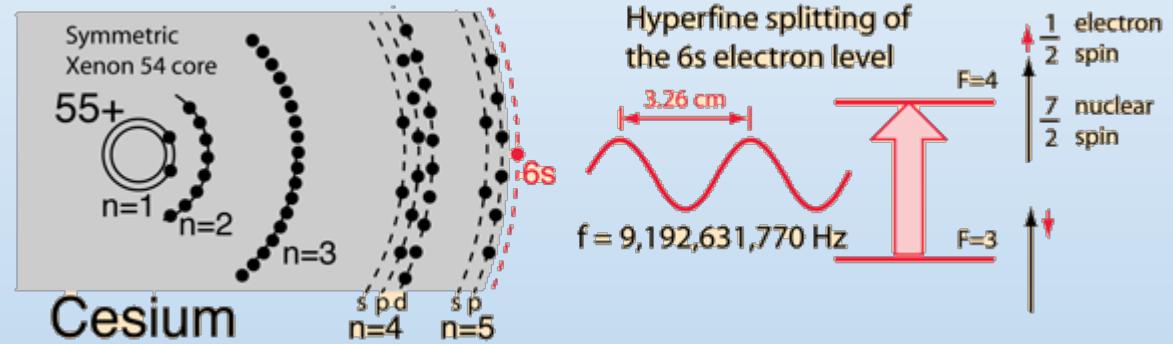
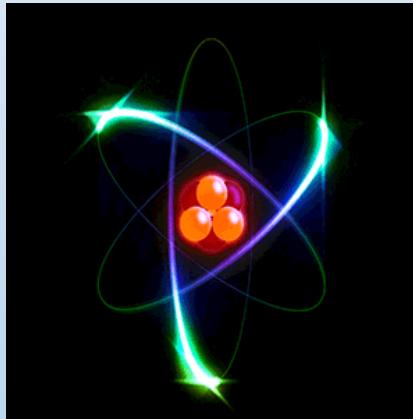


Quartz oscillator



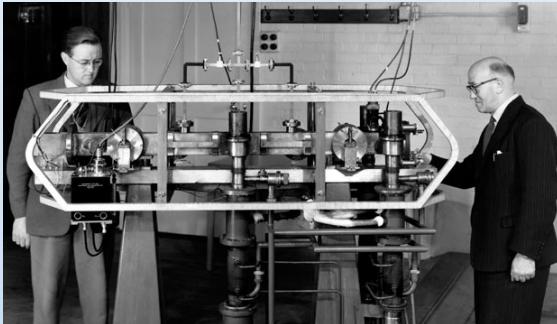
Piezoelectric effect

Atomic clocks



Atomic transition generates a radiation used as the «beating heart» of the clock

Caesium clocks



Louis Essen (right) and Jack Parry (left) - 1955



Modern commercial caesium standard

Caesium fountain standard

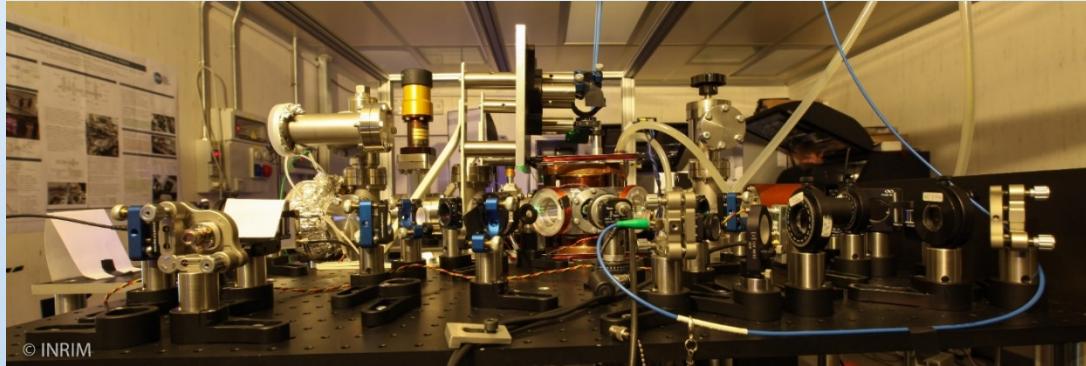
Primary frequency standard

7 laboratories in the world



INRIM IT-CsF2

Towards the future: optical clocks



INRIM Yb optical clock



In an ytterbium optical clock, the frequency of an ultra-stable laser is locked to a particular transition of ytterbium prepared in an ultra-cold atom sample

A bit of math: the clock equation

Phase offset

$$x(t) = x(t_0) + y(t_0)$$

Relative frequency offset

$$\cdot (t - t_0) + \frac{1}{2} d_0 (t - t_0)^2 + \varepsilon(t)$$

Noise

Phase offset at t_0

Frequency drift

Evolution of clocks



Optical clocks – $r = \text{few ps/d}$



Caesium fountain – $r = 10 \text{ ps/d}$



Maser clock – $r = 80 \text{ ns/d}$



Caesium clock – $r = 5 \text{ ns/d}$



Rubidium oscillator – $r = \text{some } \mu\text{s/d}$



Quartz oscillator – 1950 – $r = 40 \text{ ms/d}$



Harrison's chronograph – 1760 – $r = 0.3 \text{ s/d}$



Pendulum – 1650 – $r = \text{tenths of seconds/d}$

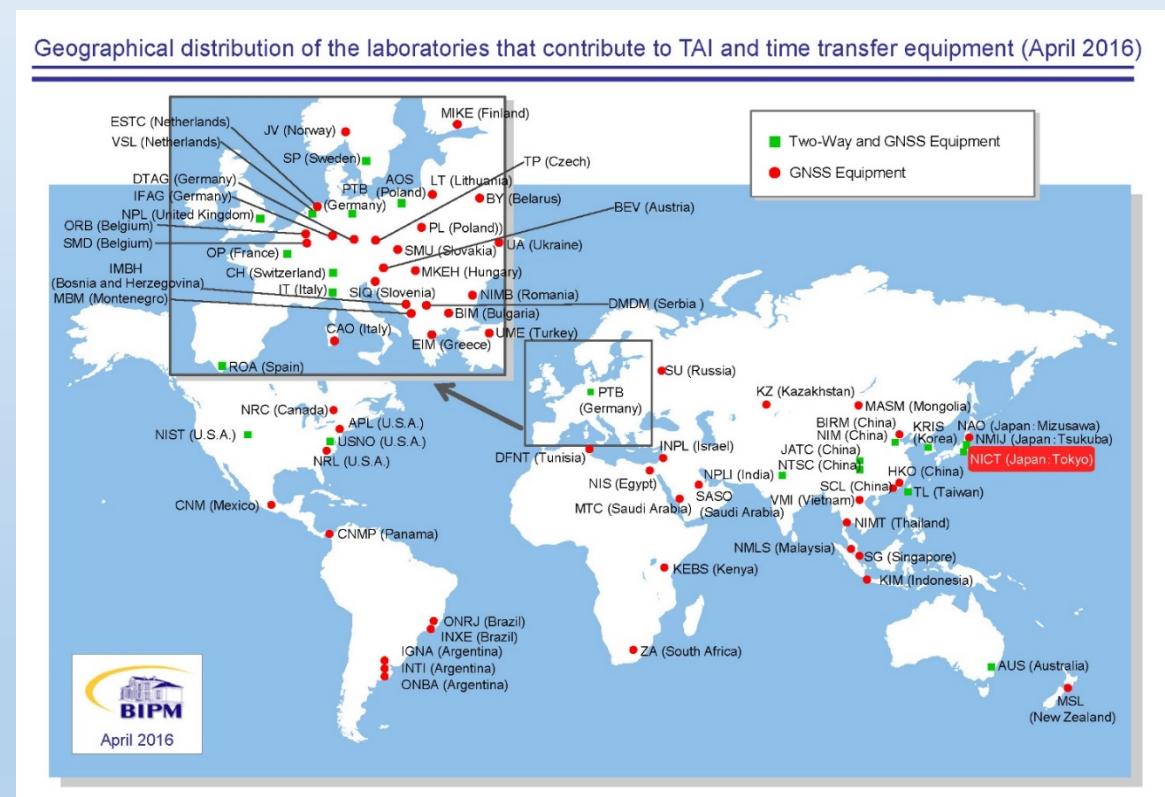


Verge escapement – 1300 – $r = \text{tenths of minutes/d}$

Time scale definitions – EAL and TAI

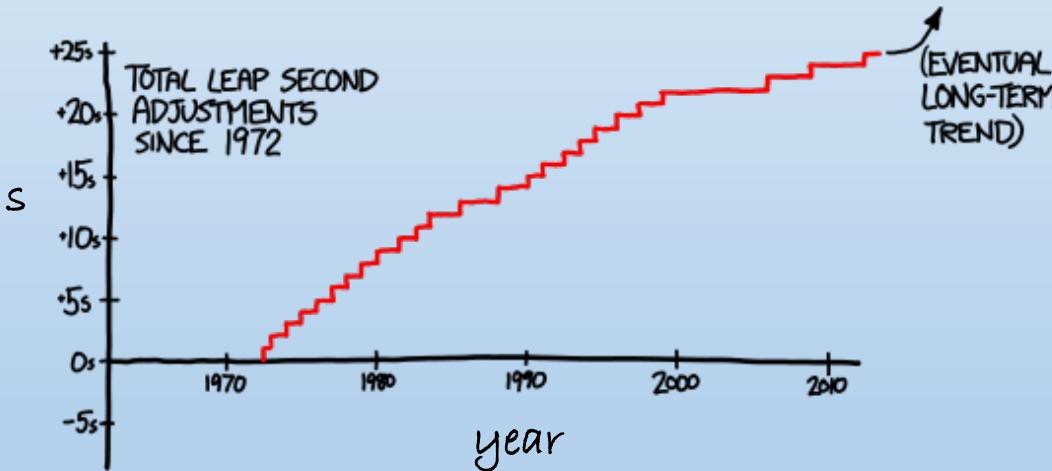
Laboratories participating communicate clocks data to BIPM that computes a weighted mean called EAL: Free Atomic Scale (*Echelle Atomique Libre*)

EAL is calibrated using the primary standard (Cs fountains) to generate TAI (International Atomic Time - temps atomique international). TAI is a paper scale, stable but not related to Earth rotation.



Time scale definitions - UTC

- UTC is the Universal Time Coordinated obtained by correcting TAI in order to keep it below 0.9 s from UT1, by adding leap seconds when needed. Paper scale.
- UT1 is the Universal Time based on the Earth's rotation defined by astronomers.

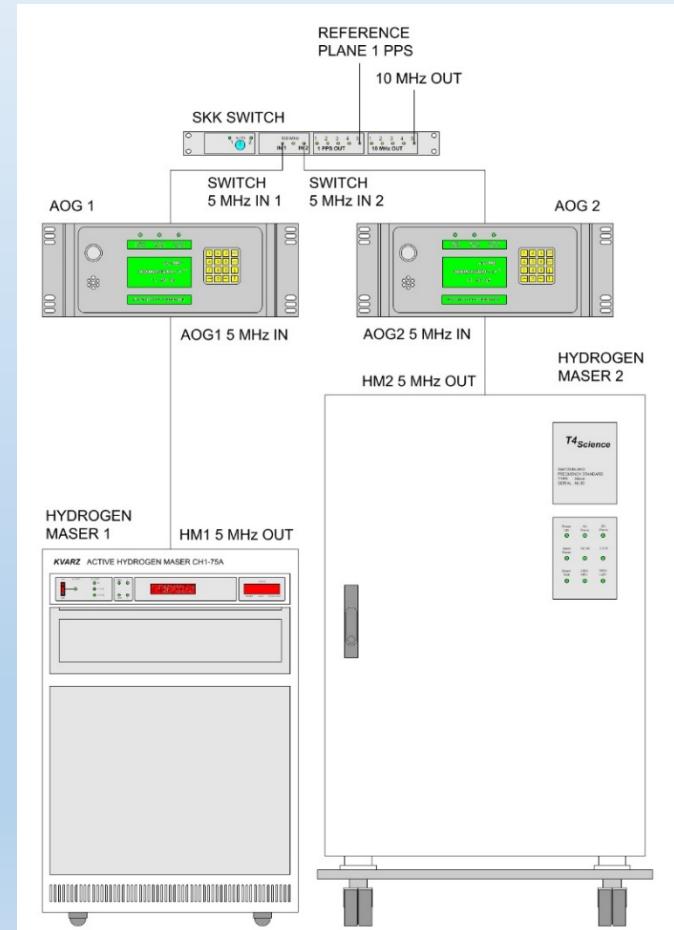


Each laboratory generates a local scale called UTC(k):

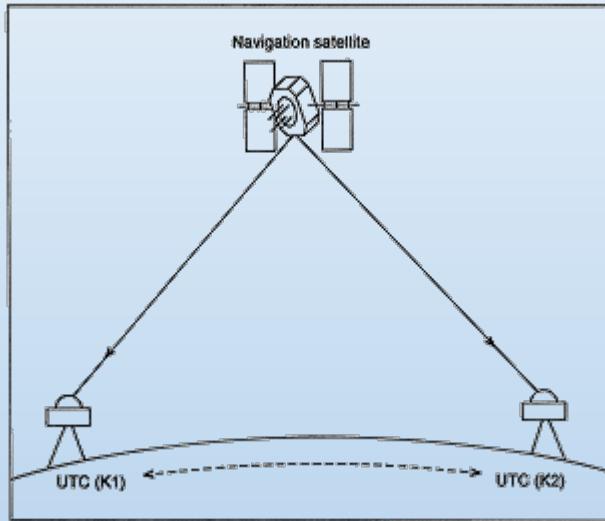
- UTC(IT) for Italy
- UTC (PTB) for Germany
- UTC(OP) for France
- UTC(USNO) for USA available via GPS
- UTC (NIST) for USA

The Italian Time Scale UTC(IT)

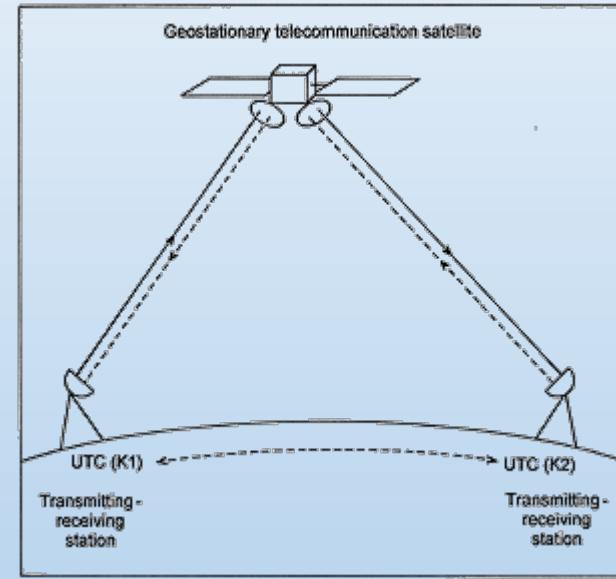
The active hydrogen maser relative frequency offset and drift are corrected by means of an AOG (Auxiliary Output Generator). Two independent scales are connected to a special switch to assure redundancy.



Time scales comparison



GPS (Global Positioning System): satellites UTC(K) compared independently with GPS Time.



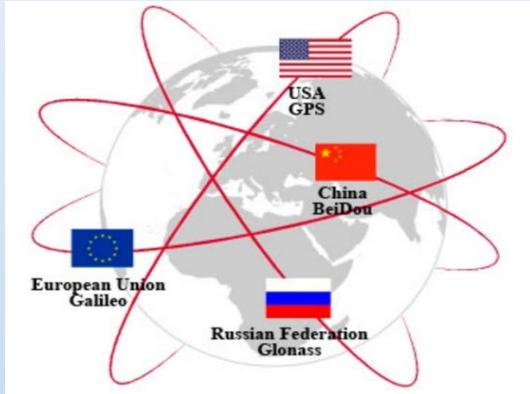
TWSTFT (Two-Way Satellite Time and Frequency Transfer) UTC(K1) and UTC(K2) directly compared with a transmitting-receiving station.

Time dissemination examples

- NTP – Network time protocol - ntp1.inrim.it uncertainty hundreds of milliseconds
- SRC – Segnale Rai Codificato – 1979-2016 uncertainty hundreds of milliseconds
- DCF77 – radiofrequency signal – uncertainty tenths of milliseconds
- Optical fibers – uncertainty (sub)nanoseconds

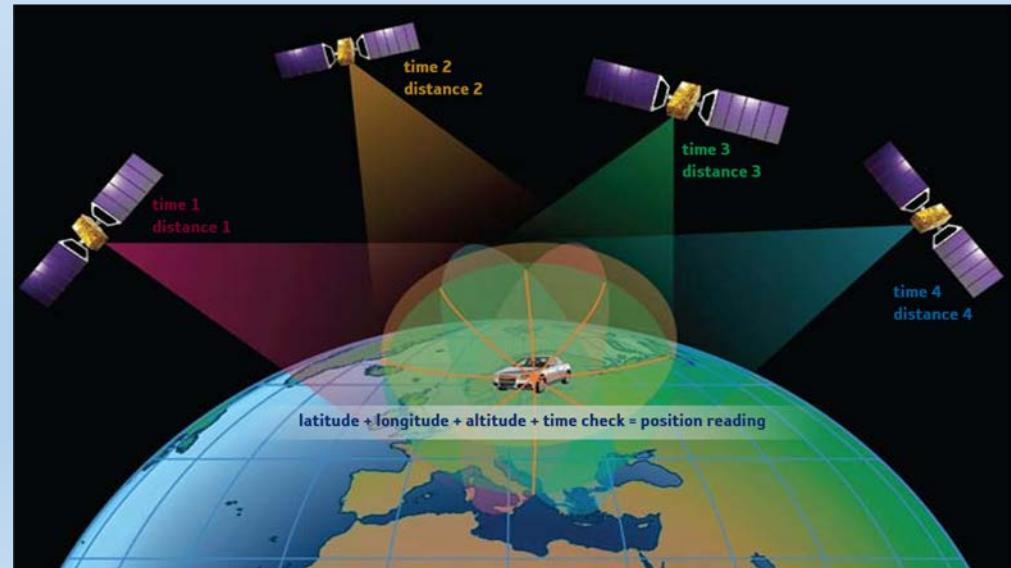


GNSS: Global Navigation Satellite Systems



Each constellation: 24-30 satellites
Period \approx 12 hours
Height \approx 22000 km
5-12 satellites always available
4 atomic clocks on board

- GPS
- GLONASS
- BEIDOU
- GALILEO



Galileo – European radionavigation system



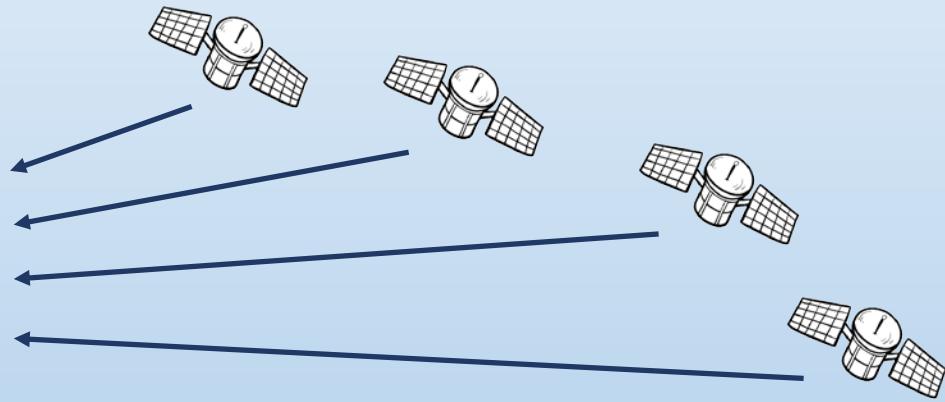
Collaboration between:
ESA – European Space Agency
European Research Centers
European companies

- 24-30 satellites
- around 23 000 km
- Technical, scientific, commercial and users services

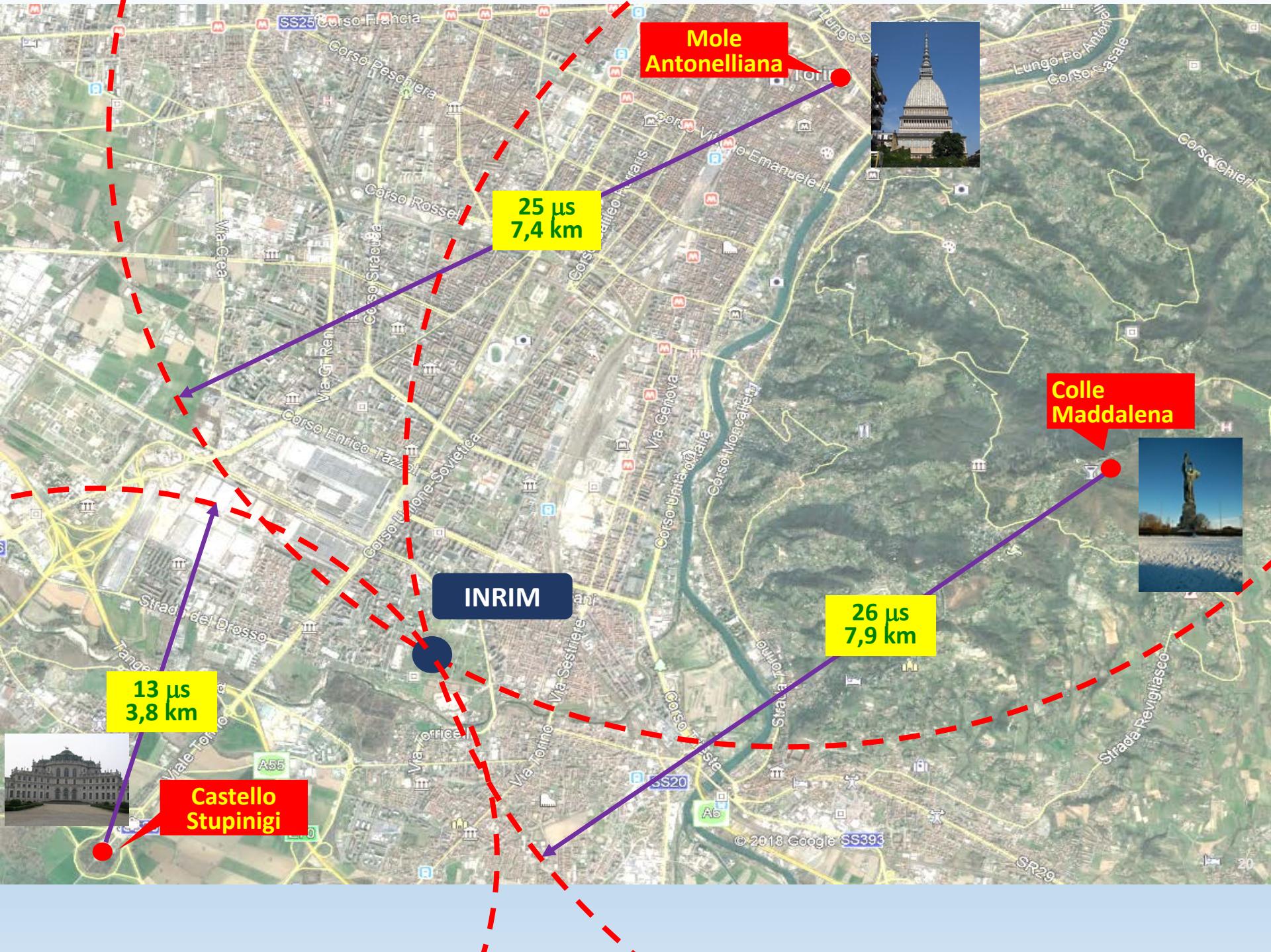
How a GNSS works

4 satellites in view

Solve 4 non-linear equations
to get position and time



Distance measurements through the time of flight of a signal sent by a transmitter on the satellite.
Error of 3 ns on the time leads to an error of 90 cm in position.



Bibliography

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