Towards a new definition for the second

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With contributions from Patrizia Tavella, Director of BIPM Time Department, and CCTF WG chairs

20th Meeting of the Directors of NMIs and Member State Representatives
Oct 17th, 2019

Bureau
International des
Poids et
Mesures

Definitions of the SI unit of time

The SI unit of time – the second – is defined as :

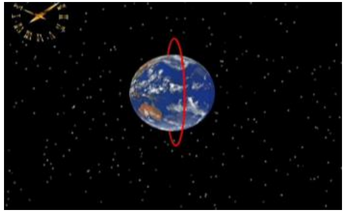
→ **until 1956 : the fraction 1/86 400 of the mean solar day**

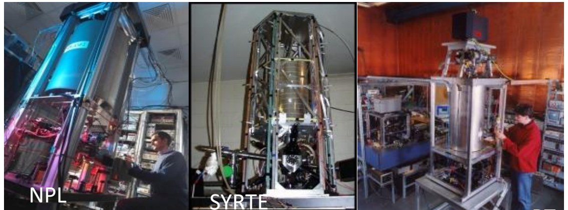
→ **1956 to 1967 : the fraction 1/31,556,925.9747 of the tropical year 1900**
1 tropical year = 365,2422 solar days = 366,2422 sideral days

« Time » approach (→ angle measurements in astronomy)

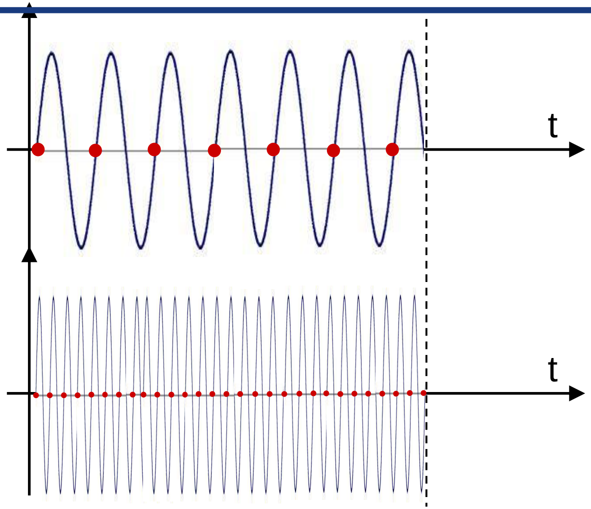
→ **since 1967 : the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom (*Added in 1999 → This definition refers to a cesium atom at rest at a temperature of 0 K*)**

« Frequency » approach

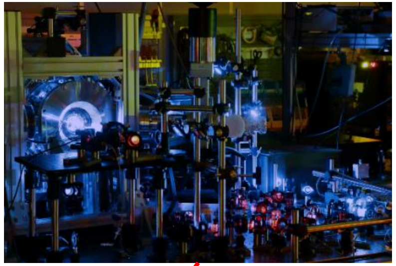




Importance of the reference frequency

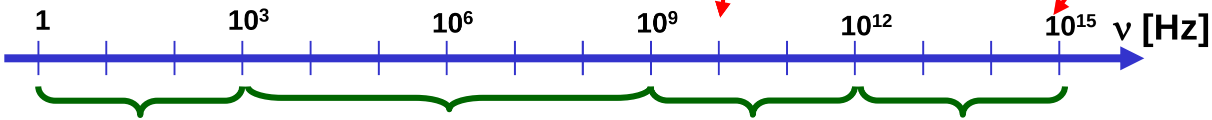


→ **The higher the frequency, the lower the measurement uncertainty**

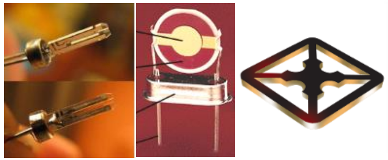


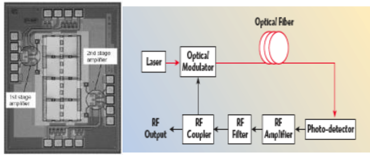
Cs clocks

Optical clocks

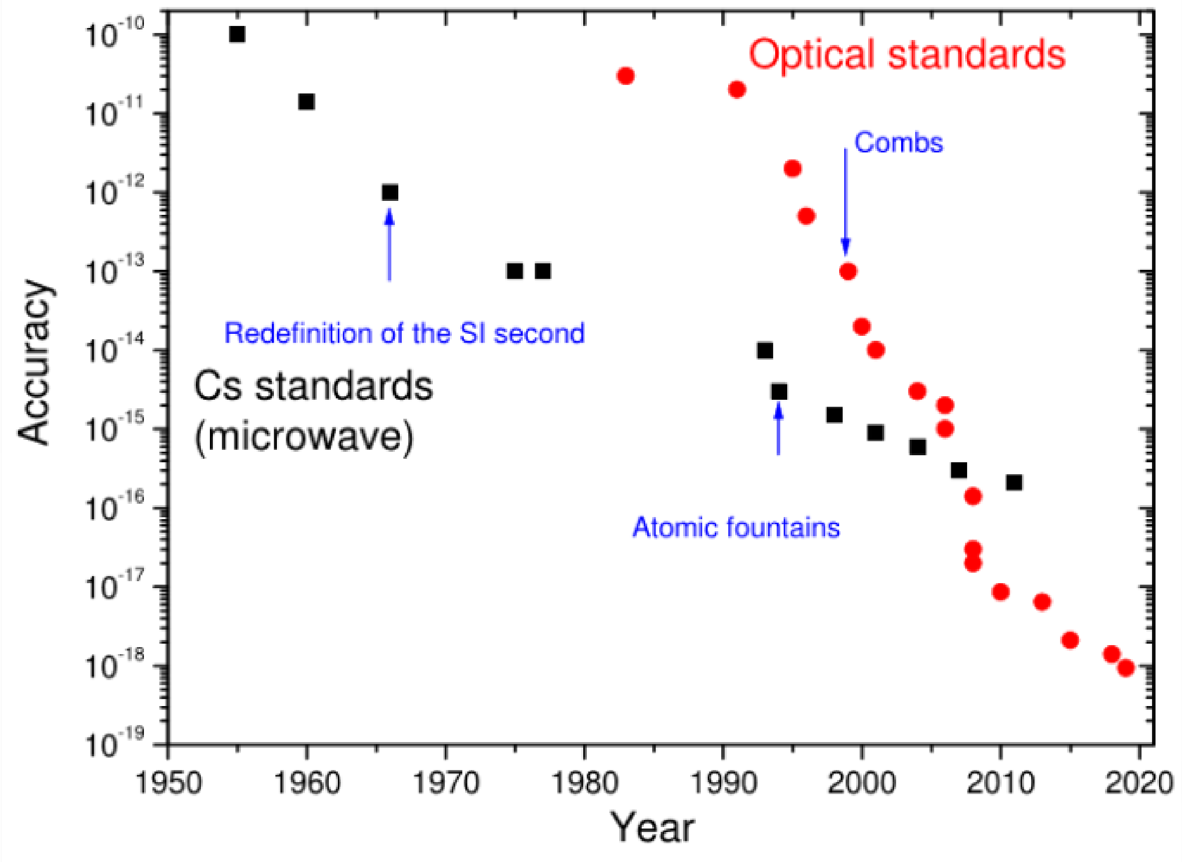


Type of oscillator → mechanical | quartz (+ MEMS) | microwave | optical





Progress of atomic frequency standards



Primary and secondary frequency standards in UTC

5-10 primary standards (Cs fountains) contributing to UTC + 6 under development

4 secondary standards have been reporting to the BIPM: 1 Rb fountain + 3 optical lattices

UTC steering also on secondary optical standards:

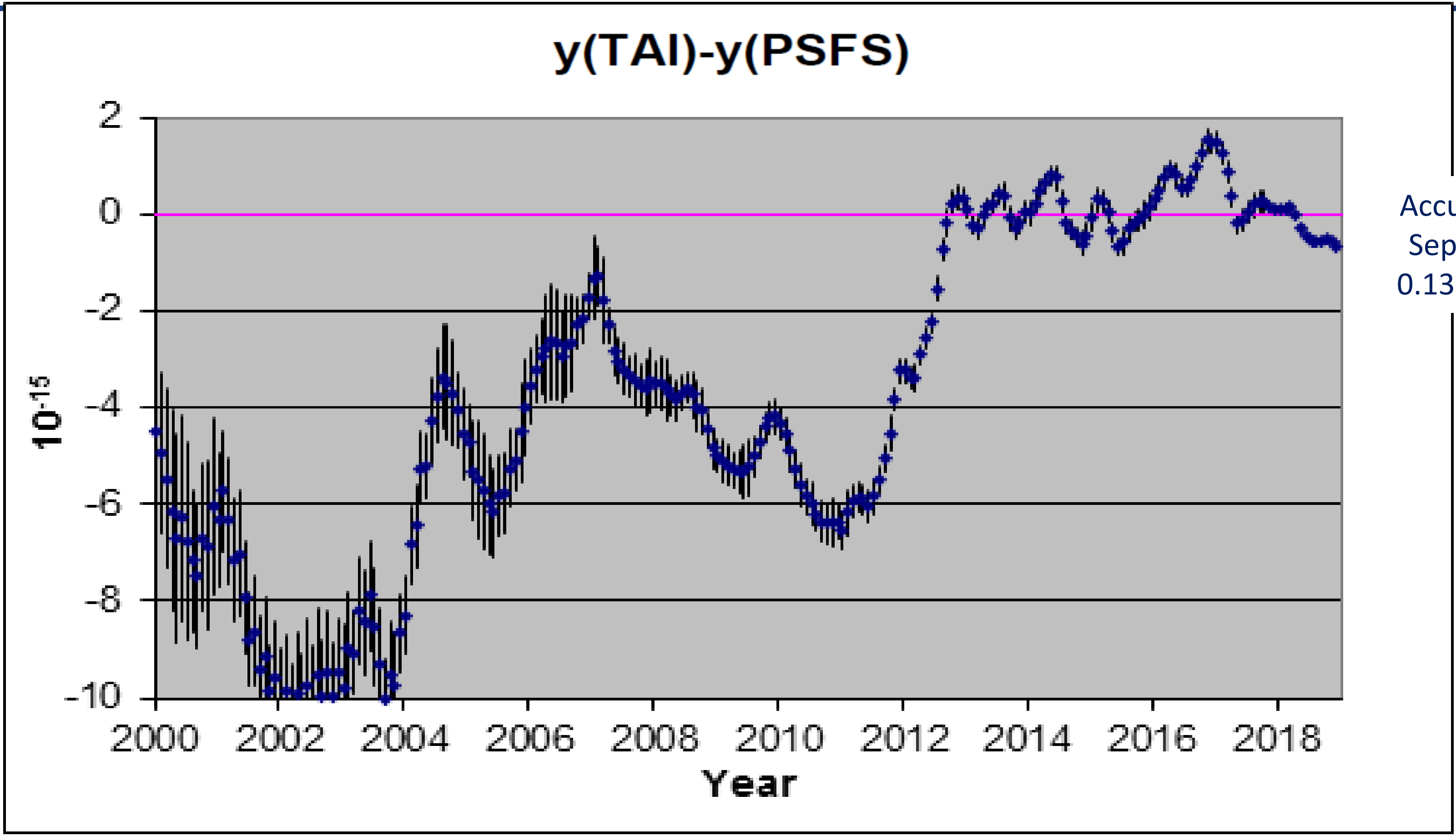
Syrte Sr (March 2017),

NICT Sr (Nov. 2018),

NIST Yb (Feb. 2019)

Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CsF2	Fountain	0.17	Discontinuous	H maser	2 / 10 d to 15 d
METAS-FOC2	Fountain	2.01	Discontinuous	H maser	3 / 15 d to 25 d
NIM5	Fountain	0.9	Discontinuous	H maser	3 / 15 d to 25 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 25 d to 35 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	12 / 25 d to 35 d
PTB-CSF1	Fountain	0.28 to 0.40	Nearly continuous	H maser	8 / 10 d to 30 d
PTB-CSF2	Fountain	0.18 to 0.21	Nearly continuous	H maser	11 / 10 d to 30 d
SU-CsFO2	Fountain	0.24	Nearly continuous	H maser	10 / 10 d to 30 d
SYRTE-FO1	Fountain	0.32 to 0.43	Nearly continuous	H maser	11 / 15 d to 35 d
SYRTE-FO2	Fountain	0.20 to 0.31	Nearly continuous	H maser	11 / 15 d to 35 d
SYRTE-FOM	Fountain	0.63 to 1.13	Discontinuous	H maser	4 / 30 d
Secondary Standard	**Type /selection**	**Type B std. Uncertainty / 10^{-15}**	**Operation**	**Comparison with**	**Number/typical duration of comp.**
SYRTE-FORb	Fountain	0.24 to 0.30	Nearly continuous	H maser	12 / 15 d to 35 d
NICT-Sr1	Lattice	0.06 to 0.08	Discontinuous	H maser	8 / 10 d to 35 d
SYRTE-SrB	Lattice	0.10	Discontinuous	H maser	1 / 10 d
NIST-Yb1	Lattice	0.031	Discontinuous	UTC(NIST)	8/ 30 d

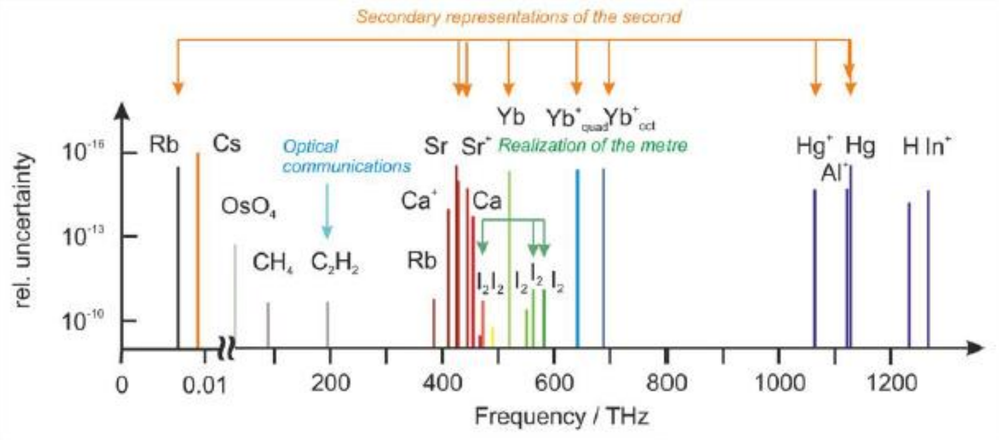
Improvement of the accuracy to TAI and UTC



Accuracy in
Sept 2019
0.13 x 10^{-15}

Secondary realizations of the second

Increasing number of secondary representations of the second (CCTF-CCL)

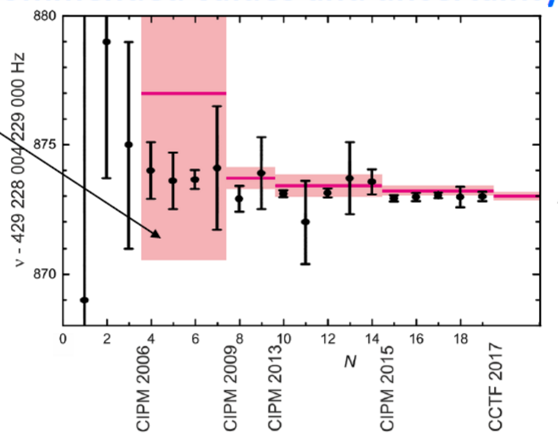


Improved quality of realizations

1.5x10^-14

4x10^-16

uncertainty for ^87Sr



Towards a redefinition of the SI second

1) Deeper analysis of the possible options for choosing a new definition and its practical realization

Possible options for a redefinition of the SI second

- **Choose a single atomic transition** similarly to what is currently done, and make use of secondary representations of the second

  Candidates: atoms (^{87}Sr,^{88}Sr,Yb,Hg,Mg,Cd,etc.) and ions (Hg+, Ca+, Sr+, Yb+, In+, etc.)

- Adopt a definition relying on an **ensemble of reference transitions**, each of them usable for the mise en pratique

- Chose a **more fundamental definition** + using reference transitions for the practical realization.

Example: Fix the value of the electron's mass which fixes the value of the De Broglie-Compton frequency of the electron, and use an ensemble of frequencies for the mise en pratique

$$\boxed{\nu_e = \frac{m_e c^2}{h}} \qquad \nu_e \sim 10^{20}\ \mathrm{Hz}$$

Note: CODATA 2018: $u(m_e) = 3.10^{-10}$, check compatibility with current SI mass definition

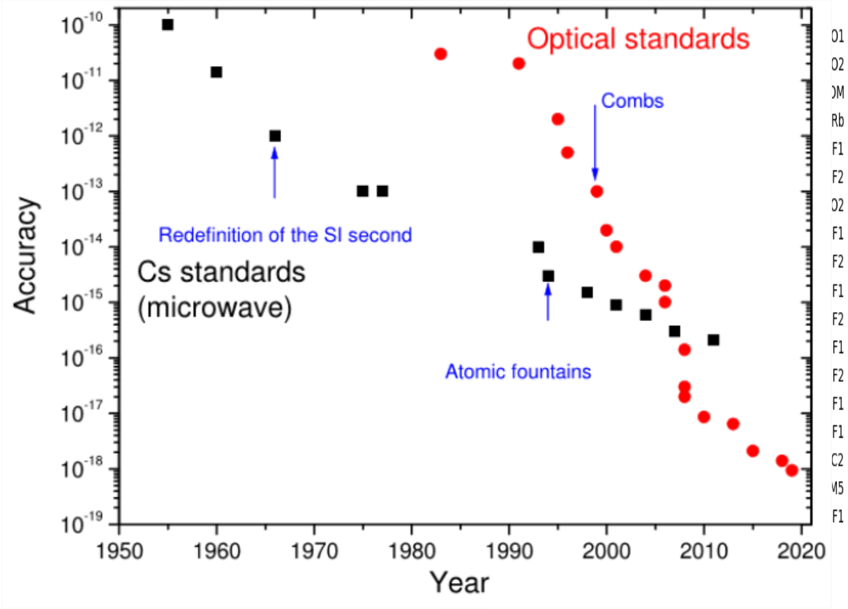
Towards a redefinition of the SI second

1) Deeper analysis of the possible options for choosing a new definition and its practical realization

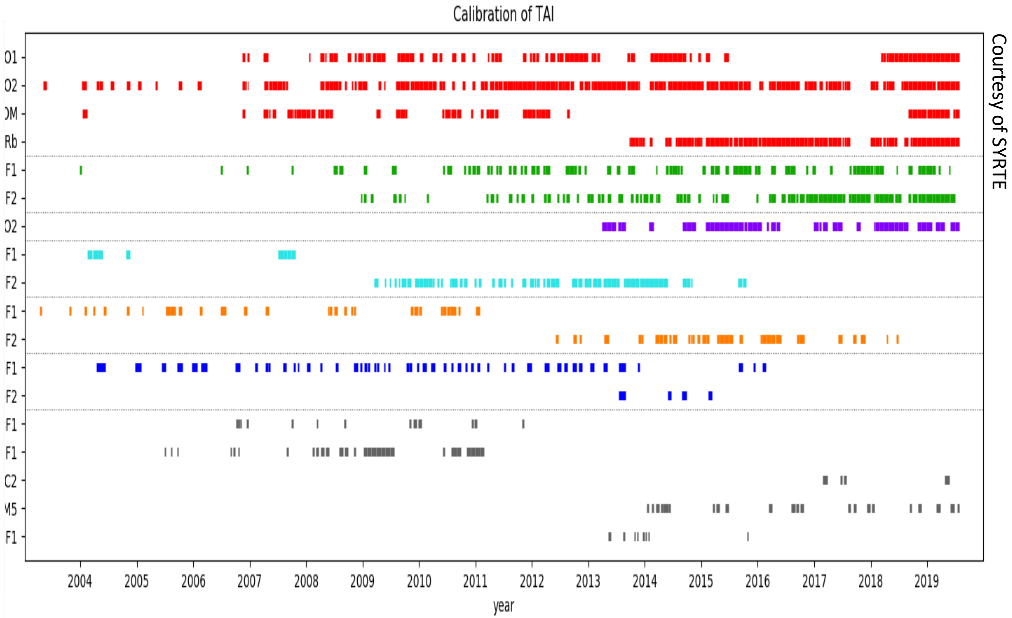
2) Ensure capability of optical frequency standards (level of performances, reliability and continuous operation, sustainable contributions to UTC)

Capability of optical frequency standards

Accuracy



Cs fountains contributions to the calibration of TAI



→ Accuracy of some optical frequency standards already demonstrated to be 100 times better than Cs, but important efforts still needed to increase the duration of continuous operation and their contributions to TAI (relies on a commitment of NMIs on long term)

Towards a redefinition of the SI second

1) Deeper analysis of the possible options for choosing a new definition and its practical realization

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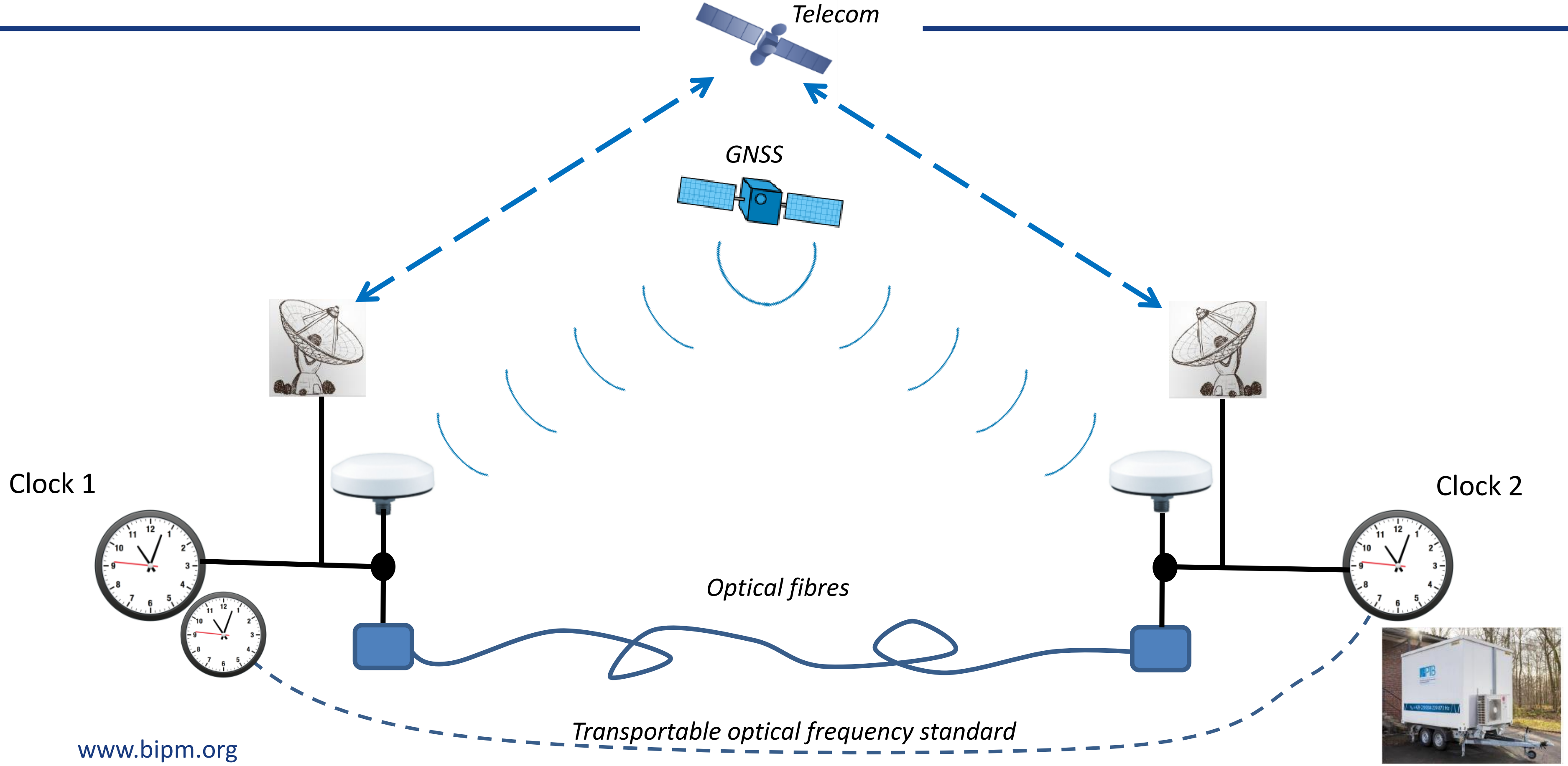
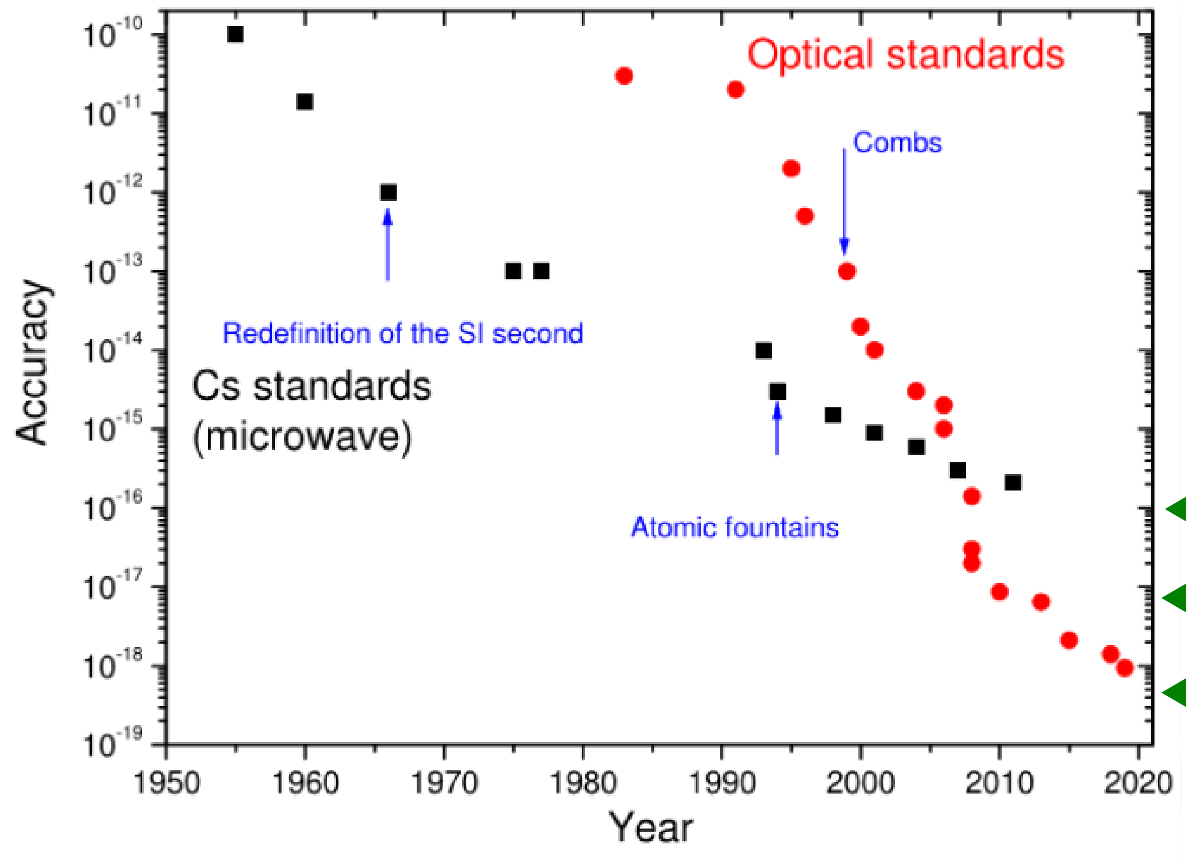
3) Ensure capability of T/F transfer techniques for frequency standards comparisons, the construction of UTC and the dissemination of the unit towards users

T/F transfer techniques



T/F comparison capability



T/F transfer limitation level:

Satellite links

Transportable clock

Fibre links

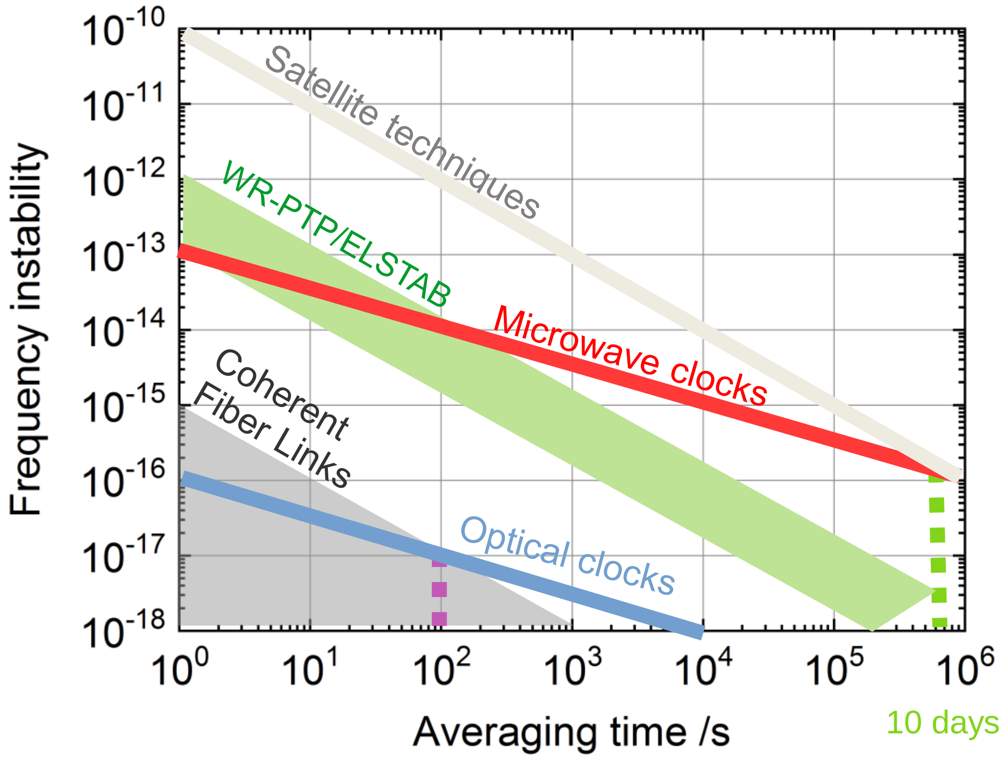
Developments of optical fibre links for T/F metrology

Fiber Link in use

Ongoing projects

But no long distance intercontinental fiber link at present time

Instability of atomic frequency standards and T/F transfer



Satellites:

>4 h for commercial Cs

>10 d for Cs fountains

>1000 d for optical FS

Fibre Links:

Cs fountains in real time

1000 s for optical FS

→ Need to know better the gravitation potential for general relativity corrections (1 cm for 10^{-18})

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Detailed criteria defined in CCTF roadmap

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(Items 2 and 3: Detailed criteria defined in CCTF roadmap)

4) Get the stakeholder and end-users point of views, better know their needs and requirements and estimate a possible impact of a redefinition of the second in their fields

Requirements according to application fields

Application fields

Society: time for appointments or use of public transport, legal time stamping, …

Socioeconomic networks: **:** global satellite positioning systems, telecommunications, energy distribution and smart grids, economy and financial sector, …

Scientific networks: solar system probe tracking, radioastronomy, Lunar / satellite laser ranging, …

Fundamental science and metrology: definition of SI second (and other SI units), atomic time scales, tests of fundamental physics, high precision spectroscopy, astronomy, geodesy & geophysics, …

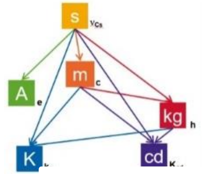
Stakeholders & end-users requirements

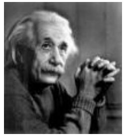
Quantity of interest: « absolute » time, time interval, absolute frequency, ratio of frequencies, phase difference, …

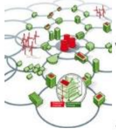
Uncertainty level: from second to “the best as possible”

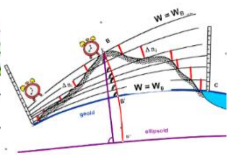
Synchronization scales: local, regional, international, on Earth or in space

Special needs: continuous / occasional synchronizations of the user clock, reliability, traceability to UTC and legal times (notaries, banks,…)









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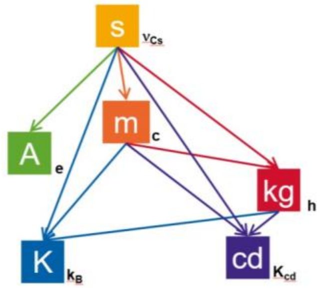
} Detailed criteria defined in CCTF roadmap

4) Get the stakeholder and end-users point of views, better know their needs and requirements and estimate a possible impact of a redefinition of the second in their fields

5) Check that a new definition has no impact on other units



Resolution 2 on the definition of time scales

26e CGPM
Versailles
13-16 novembre 2018

states that

− TAI is a continuous time scale produced by the BIPM based on the best realizations of the SI second, and is a realization of TT as defined by IAU Resolution B1.9 (2000),

− in the transformation from the proper time of a clock to TAI, the relativistic rate shift is computed with respect to the conventionally adopted equipotential $W0$ = 62636856.0 m^2s^{-2} of the Earth's gravity potential, which conforms to the constant LG defining the rate of TT,

− as stated in the IAU Resolution A4 (1991), TT - TAI = 32.184 s exactly at 1 January 1977, 0h TAI at the geocentre, in order to ensure continuity of TT with Ephemeris Time,

− UTC produced by the BIPM, based on TAI, is the only recommended time scale for international reference and the basis of civil time in most countries,

− UTC differs from TAI only by an integral number of seconds as published by the BIPM,

− users can derive the rotation angle of the Earth by applying to UTC the observed or predicted values of UT1 - UTC, as provided by the IERS,

− UTC provides a means to measure time intervals and to disseminate the standard of frequency during intervals in which leap seconds do not occur,

− traceability to UTC is obtained through local real-time realizations "UTC(*k*)" maintained by laboratories contributing data to the calculation of UTC, identified by "*k*",

…..

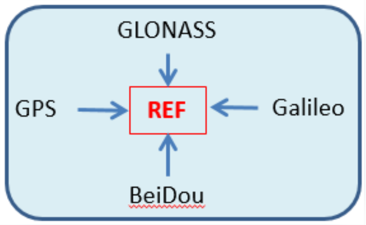
and **recommends** that

− all relevant unions and organizations consider these definitions and work together to develop a common understanding on reference time scales, their realization and dissemination with a view to consider the present limitation on the maximum magnitude of UT1 - UTC so as to meet the needs of the current and future user communities,

− all relevant unions and organizations work together to improve further the accuracy of the prediction of UT1 - UTC and the method for its dissemination to satisfy the future requirements of users.

Other important topics in T/F metrology

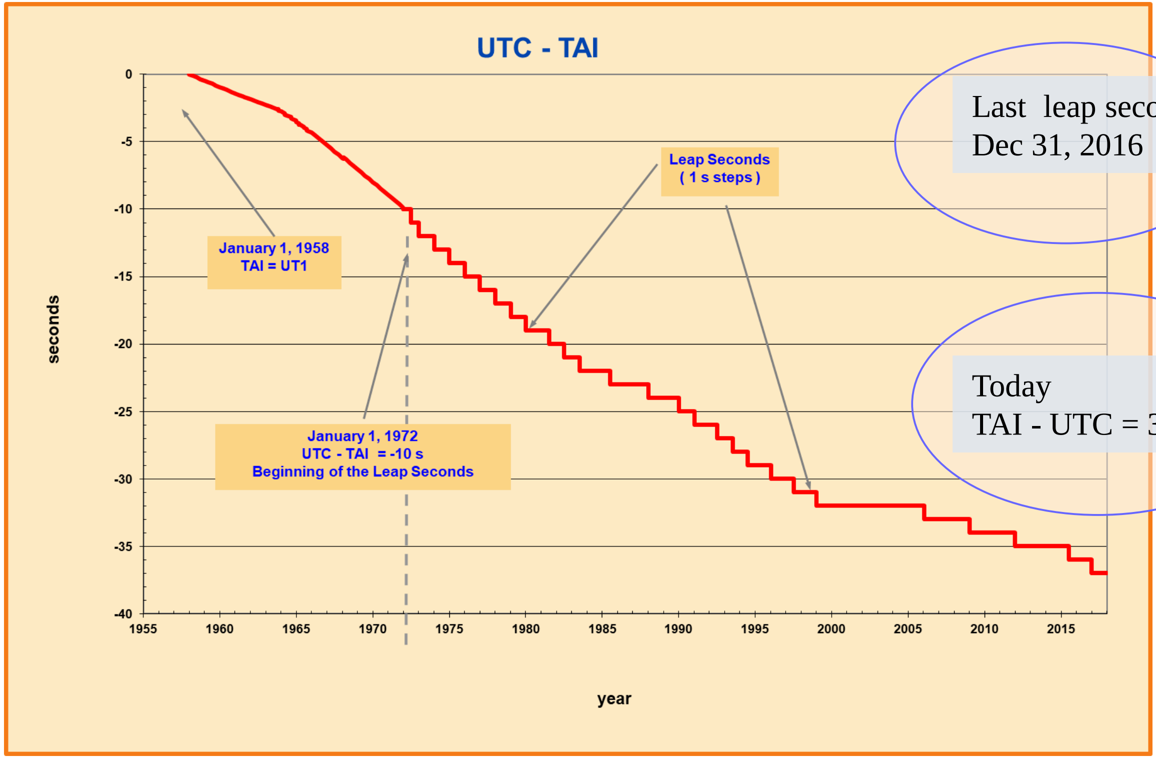
- Following Resolution 2 of 26th CGPM on the definition of time scales:
  - Promotion of the important benefits of the unique reference time UTC to the international scientific and industrial communities
  - CIPM decision to support the IGS (International GNSS Service) and the ICG (International Committee on GNSS) in exploring the capacity of GNSS providers to ensure Multi GNSS interoperability based on the reference time UTC *(and not on a new international time scale)*, with the final goal of avoiding the proliferation of international reference time scales.



Universal Coordinated Time and leap seconds

When the rotation of the Earth (UT1 time scale) reaches a one second difference with respect to atomic time TAI, one second is added to maintain the reference time scale UTC in agreement with the Earth's rotation

|UTC - UT1| < 1 second



Last leap second
Dec 31, 2016

Today
TAI - UTC = 37 s

UTC = TAI + leap seconds

UTC and the second discontinuity

Users have addressed this issue in different ways:

- GNSS systems defined their own time scale, initially synchronized with UTC and then not adding leap second (with the exception of GLONASS).
- Some users implement the leap second in various non-standard ways. As examples: the Google smear, which adjusts the frequency of the clock to add a second over a longer period such as a day; the Microsoft method, which slows the time advance by a factor of 2 during the last second of the leap second day, so that 23:59:59 advances monotonically at one-half of the normal rate; the extra second is added as the first second of the next day, so that the time 00:00:00 is repeated twice.

All of these methods can agree with UTC in the long-term, but produce non-standard time scales that have offsets from each other in time or in frequency in the vicinity of a leap second. Since the methods are not standard, they generally disagree with each other, and it is not clear to a user what time value is actually being received.

The long-term problem is that the UTC product will slowly become less relevant to a large segment of the time community.

Other important topics in T/F metrology

- Preparation of the 2023 ITU World Radio Assembly, especially on the topic of UTC-UT1 and leap seconds (CIPM task force to be further defined)

  - Actions at a « political level », with communication and pedagogical approach towards NMIs, International Unions, … and especially ITU members which will be present at 2023 ITU meeting

  - Better understanding of the origins of oppositions to the suppression of leap seconds, e.g. to have UTC-UT1 > 1 s

→ CIPM task force to be further defined for next CIPM meeting: composition, terms of reference and methodology