CCU session on the SI second

Oct 9th ,2019

Basic concepts – From the definition to the end users

Noël Dimarcq, CNRS-OCA, CCTF president

Realization of UTC/TAI at the BIPM

Patrizia Tavella, Gérard Petit, BIPM

Toward a redefinition of the SI second with optical clocks

Sébastien Bize, LNE-SYRTE

Conclusions

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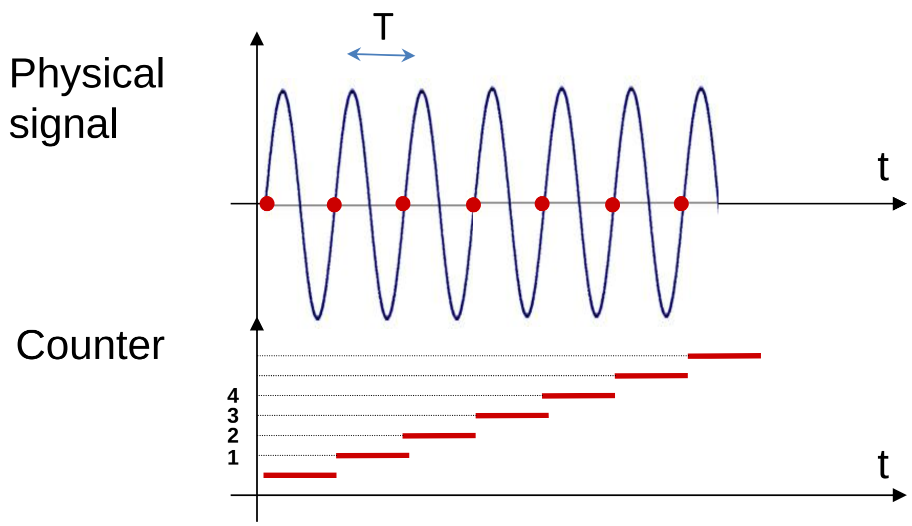
Basic concept: measuring « time » with a periodic process

Oscillator (frequency ν) = temporal ruler

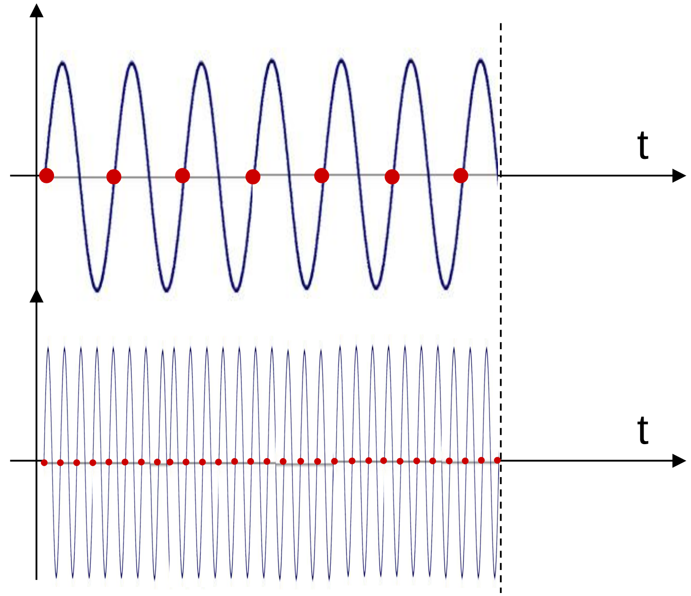
Period T = elementary temporal graduation

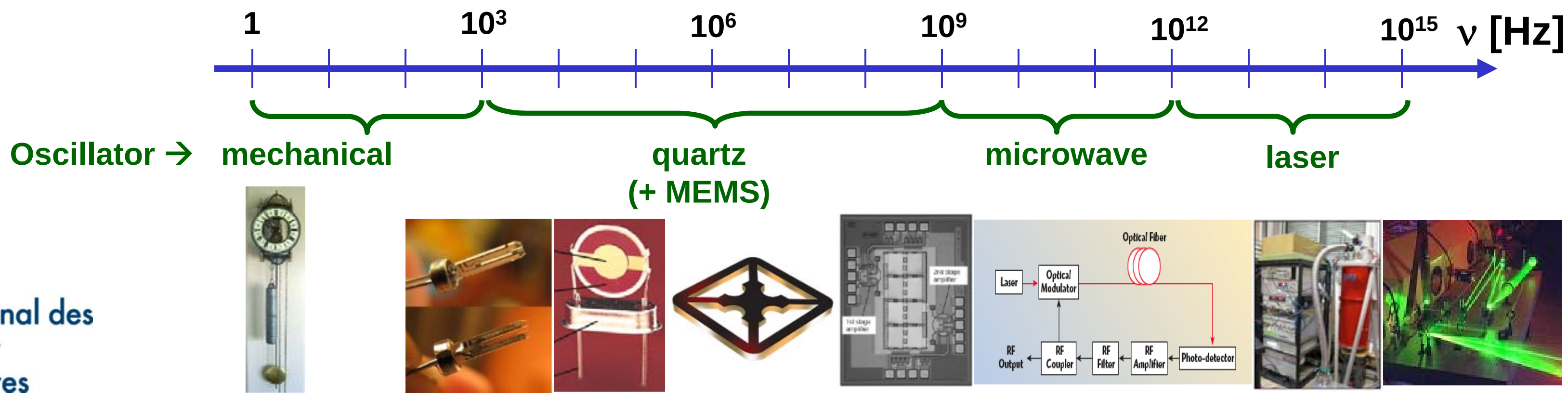
→ Measuring time interval with an oscillator: « count the oscillations » between the start and the end



Importance of the oscillator frequency

→ **The smaller the period (= the higher the frequency), the lower the measurement uncertainty**





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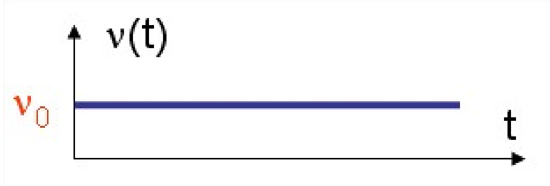
Frequency, phase and time: ideal case

$$Signal = A.\cos\left(2\pi.\upsilon(t).t\right) = A.\cos\left(\varphi(t)\right) = A.\cos\left(2\pi.\upsilon_0.T(t)\right)$$

Frequency: $\upsilon(t) = \upsilon_0$

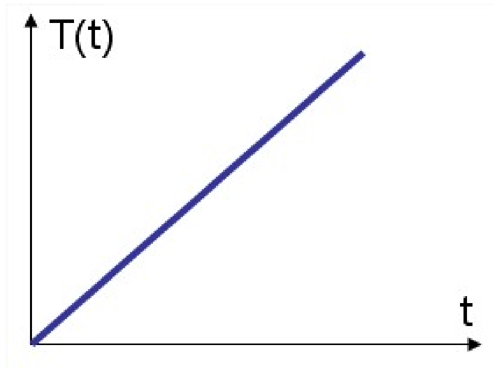


Phase: $\varphi(t) = 2\pi\int_0^t \upsilon(t')dt' = 2\pi.\nu_0.t$

Number of counted oscillations

Period

Time: $T(t) = \dfrac{\varphi(t)}{2\pi.\upsilon_0} = \dfrac{\varphi(t)}{2\pi}.\dfrac{1}{\upsilon_0} = t$

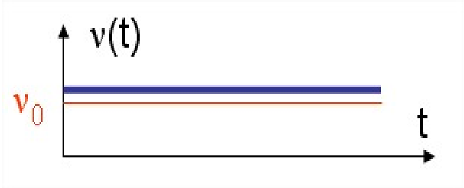


Frequency, phase and time: ideal case + bias

$$Signal = A.\cos\left(2\pi.\upsilon(t).t\right) = A.\cos\left(\varphi(t)\right) = A.\cos\left(2\pi.\upsilon_0.T(t)\right)$$

Frequency:

$$\upsilon(t) = \upsilon_0 \times \left(1+\varepsilon\right)$$

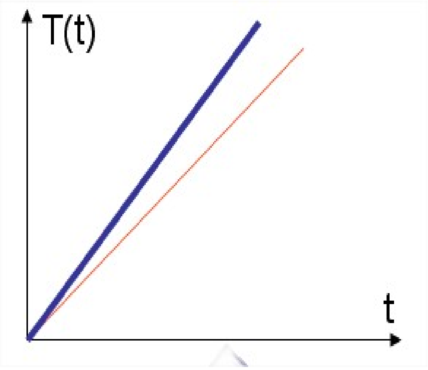


Phase:

$$\varphi(t) = 2\pi\int_0^t \upsilon(t')dt' = 2\pi.\nu_0.\left(1+\varepsilon\right).t$$

Time:

$$T(t) = \frac{\varphi(t)}{2\pi.\upsilon_0} = \frac{\varphi(t)}{2\pi}.\frac{1}{\upsilon_0} = \left(1+\varepsilon\right).t$$



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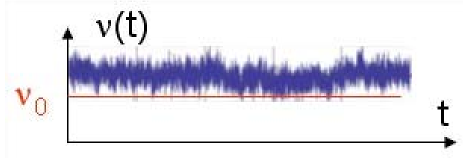
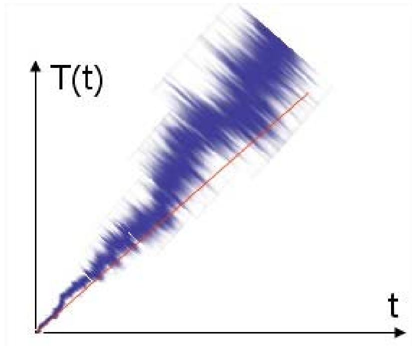
Frequency, phase and time: ideal case + bias + noise

$$Signal = A.\cos\left(2\pi.\upsilon(t).t\right) = A.\cos\left(\varphi(t)\right) = A.\cos\left(2\pi.\upsilon_0.T(t)\right)$$

Frequency: $\upsilon(t) = \upsilon_0 \times \left(1 + \varepsilon + y(t)\right)$



Phase: $\varphi(t) = 2\pi \int_0^t \upsilon(t')dt' = 2\pi.\nu_0 \left[\left(1+\varepsilon\right).t + \int_0^t y(t')dt' \right]$



Time: $T(t) = \dfrac{\varphi(t)}{2\pi.\upsilon_0} = \dfrac{\varphi(t)}{2\pi}.\dfrac{1}{\upsilon_0} = \left(1+\varepsilon\right).t + x(t)$

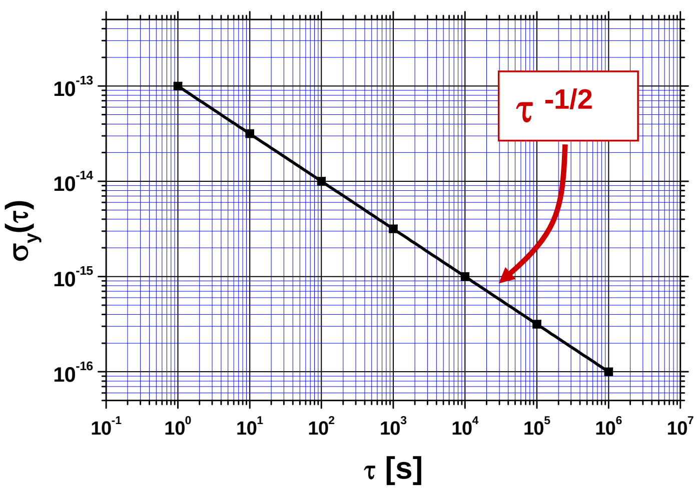
with $y(t) = \dfrac{dx(t)}{dt} \Leftrightarrow x(t) = \int_0^t y(t')dt'$

Standard deviation in frequency and time domains

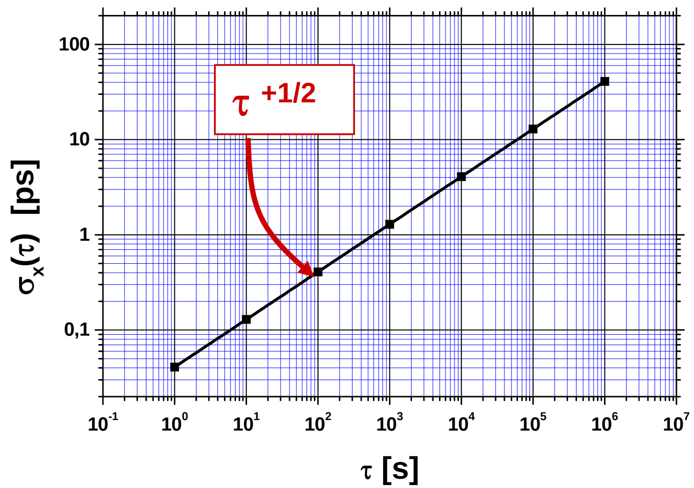
Example for white frequency noise

$$y(t) = \frac{dx(t)}{dt} \Leftrightarrow x(t) = \int_0^t y(t')dt'$$

Standard deviation in frequency domain



Standard deviation in time domain



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8

Definitions of the SI unit of time

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

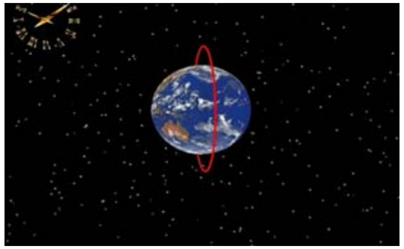
→ **until 1956 : the fraction 1/86 400 of the mean solar day**

→ **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



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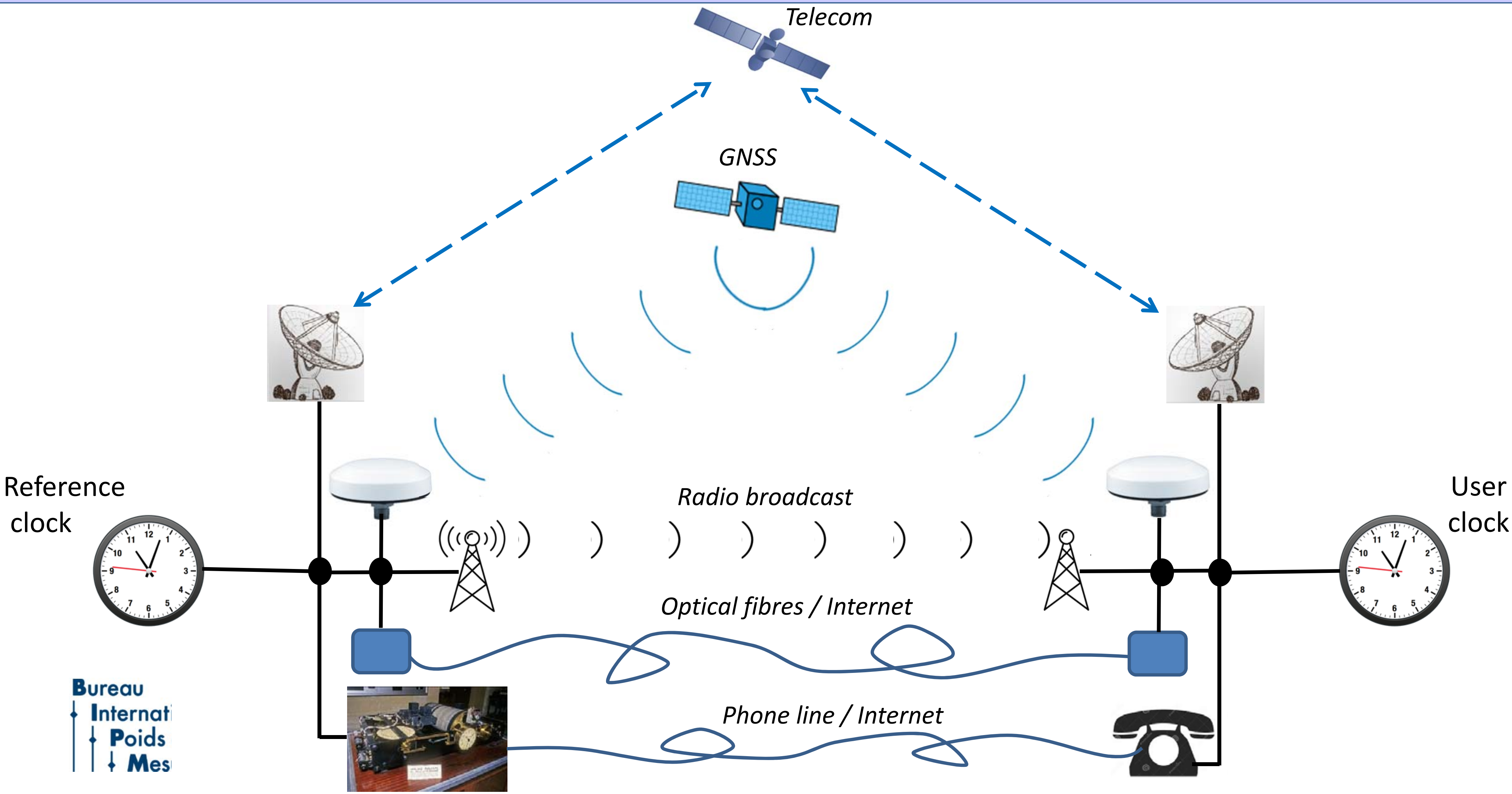
Dissemination towards end-users



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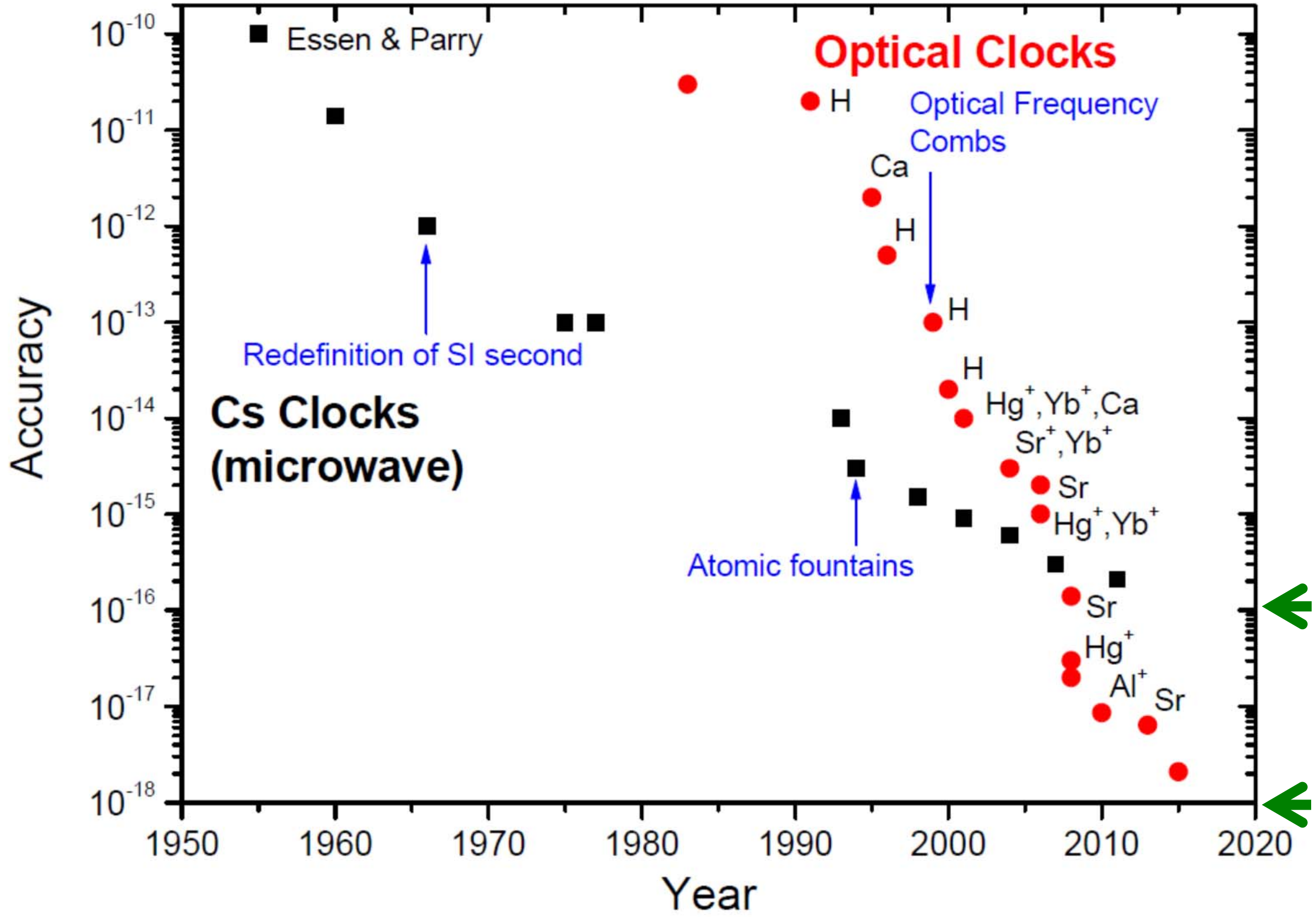
Synchronization limitations

- **Knowledge of the propagation time and mitigation of its fluctuations**
  - « Quality » of the synchronization: from 50 ms to ~ 1 nanosecond for intercontinental synchronization with satellite techniques
  - Expected improvements with upgraded satellite and fibre techniques, < 10^{-19} already demonstrated with dedicated fiber techniques for frequency comparisons over ~ 1000 km

- **Correction of relativistic effects**
  - General relativity induces frequency / time shifts in the comparisons between remote clocks: 2^{nd} order Doppler effect (10^{-10} for km/s satellites), gravitational shift (10^{-16} per meter on ground), Sagnac effect, …
  - These effects must be corrected, even for industrial applications (if not, error of 40 000 nanoseconds after 1 day for GNSS satellites = 12 km error for positioning !)
  - General relativity is today a correct framework for T/F Metrology (→ see statement from CCTF to CCU)

Clock accuracy and T/F transfer capability



T/F transfer noise level:

Satellite link

Coherent fibre link

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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, …

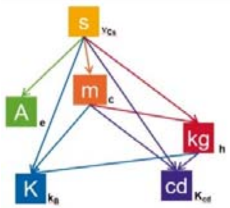
Stakeholders & end-users requirements

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

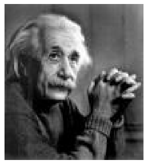
Uncertainty level: from second to “the best as possible”

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, …)

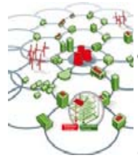
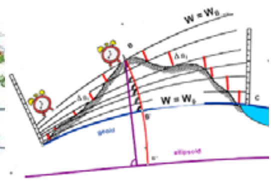






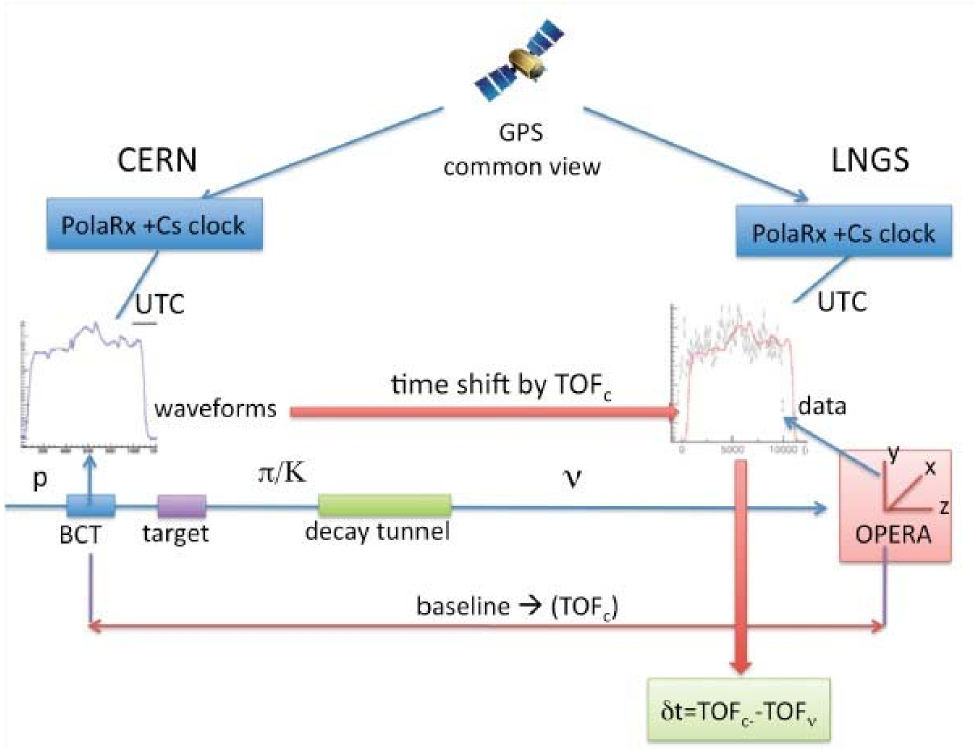


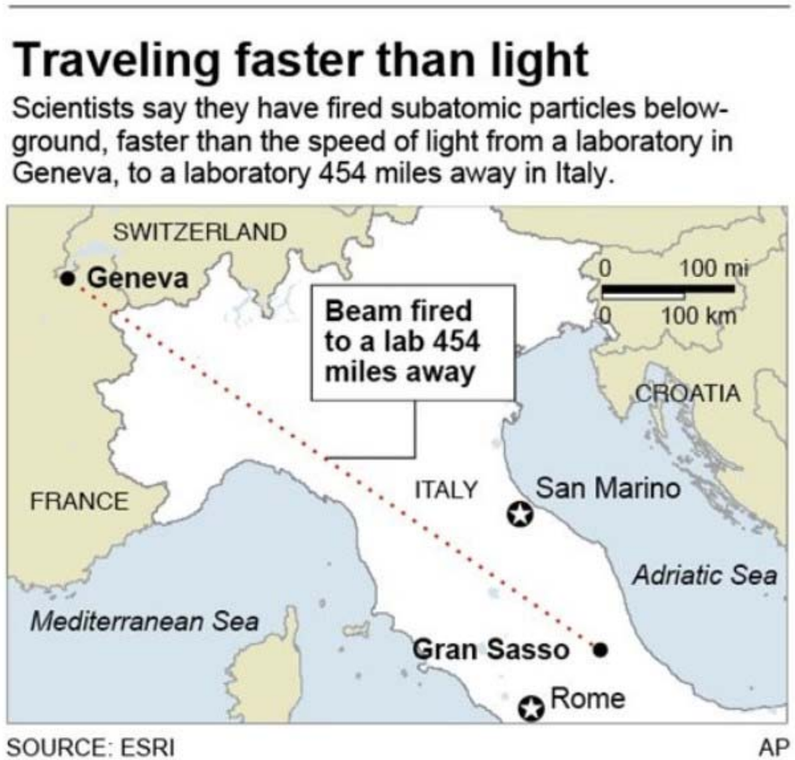


Example in science: Faster-than-light neutrino anomaly

(2011)

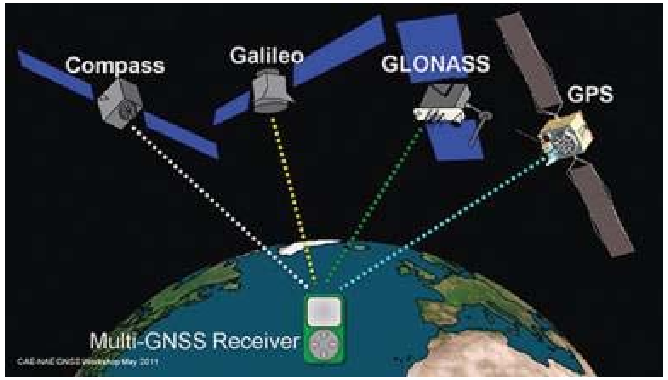




Observation of an unexpected effect: arrival of neutrinos before light (20 meters = 60 nanoseconds)

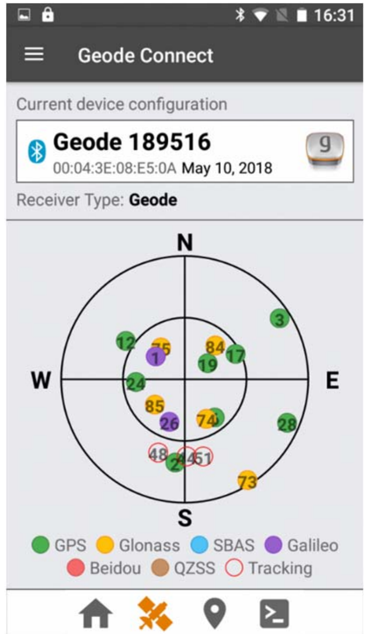
→ Not a scientific revolution (unfortunately) but a mistake in an instrument synchronisation

Example for the synchronization of networks: Global Navigation Satellite Systems (GNSS)

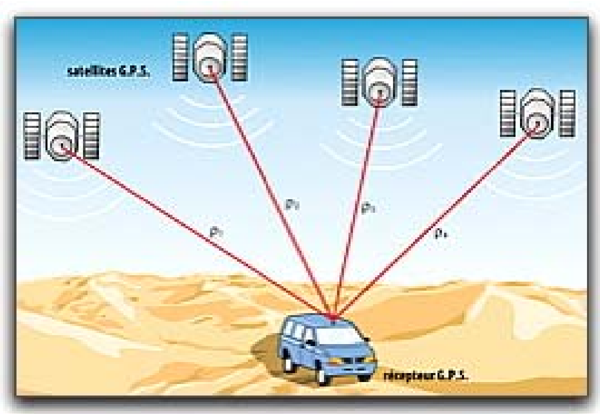


- Need to have synchronized clocks in satellites to provide the user localization in space and in time

1 nanosecond time error = 30 cm position error



- Need to synchronize GNSS time scales (GPS, GALILEO, GLONASS, Beidou, …) to the same reference time scale (UTC) to ensure the interoperability of these systems and to provide a non ambiguous reference time scale to the users



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Example in the financial sector: Worldwide high frequency trading

- Need to have fast response trading systems to minimize latency
- Have to be sure that operations and orders are correctly time stamped, to avoid mistakes or volunteer misconducts in the treatment of trade orders
- The different regulation bodies in the world are now asking a precise and traceable time tagging to UTC to avoid fictitious delays

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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.

How does the BIPM produce the Universal Coordinated Time and the International Atomic Time ?

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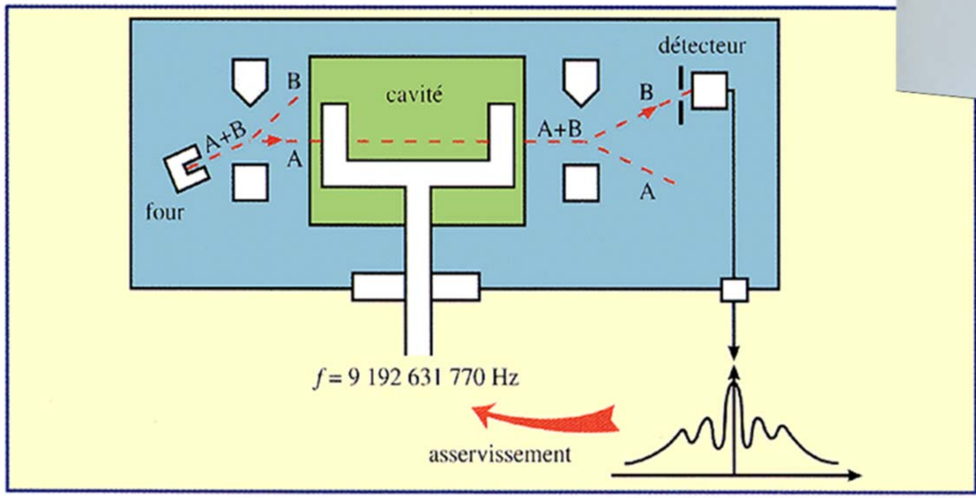
Atomic clocks realize the SI second

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 (CGPM 1967).

Any device able to generate the caesium reference signal is a frequency standard.



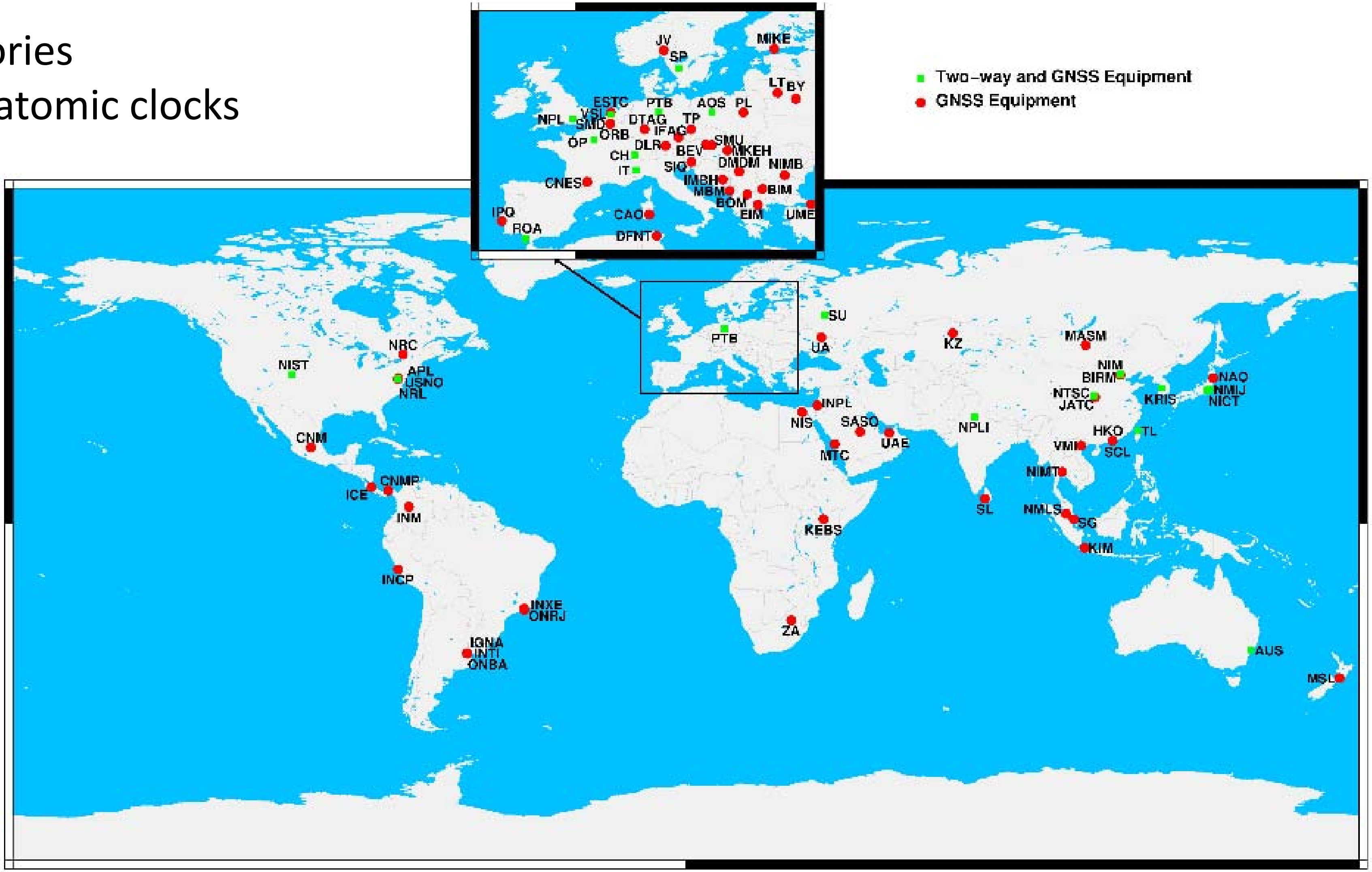
Devices can fail, **the use of an ensemble of clocks and frequency standards** helps to ensure reliability, robustness, accuracy, and continuity of a time scale.

The uncertainty of a Caesium commercial clock is about 10^{-14}

300 nanoseconds accumulated in one year

International network of time laboratories

80 laboratories
about 450 atomic clocks

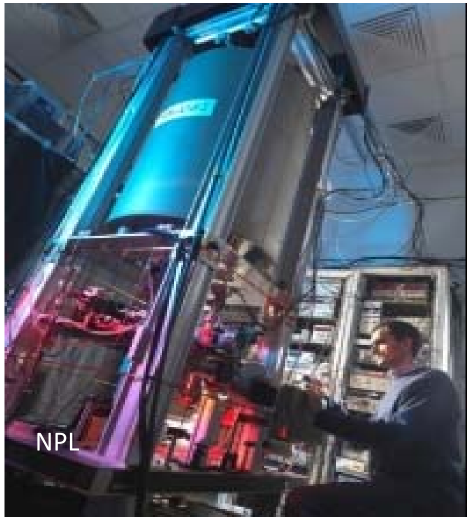


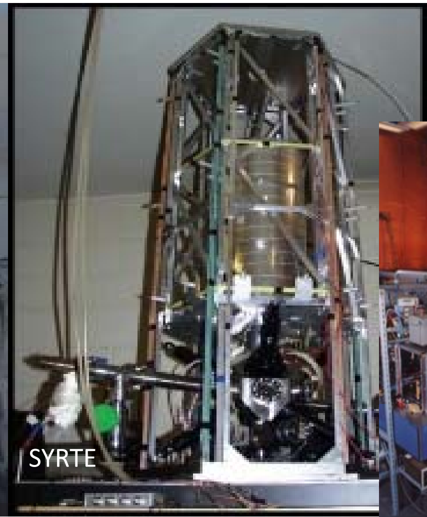
Primary frequency standards

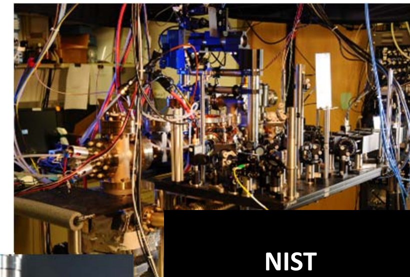
The uncertainty of Caesium primary fountains can reach 10^{-16}

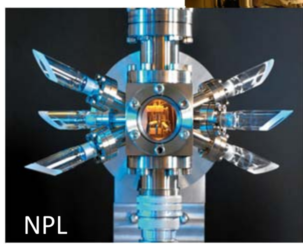
3 nanoseconds accumulated in ~~one~~ year
100

Some 10 laboratories operate primary frequency standards. Their uncertainty can be evaluated by examining the different effects perturbing the Cesium atom









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Progress in the construction of optical clocks represents a potential approach to 10^{-18} accuracy in a few years

Primary and secondary frequency standards in UTC

- Primary and secondary standards reported to the BIPM
  - 2017: 54 reports from 7 fountains + 2 optical lattices
  - 2018: 84 reports from 10 fountains + 2 optical lattices
  - 2019 so far: 66 reports from 10 fountains + 1 opt lattice




UTC steering also on secondary standards:

- In March 2017 the SYRTE Sr standard
- In Dec 2018 the NICT Sr standards
- In Feb 2019 the NIST Yb standard

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

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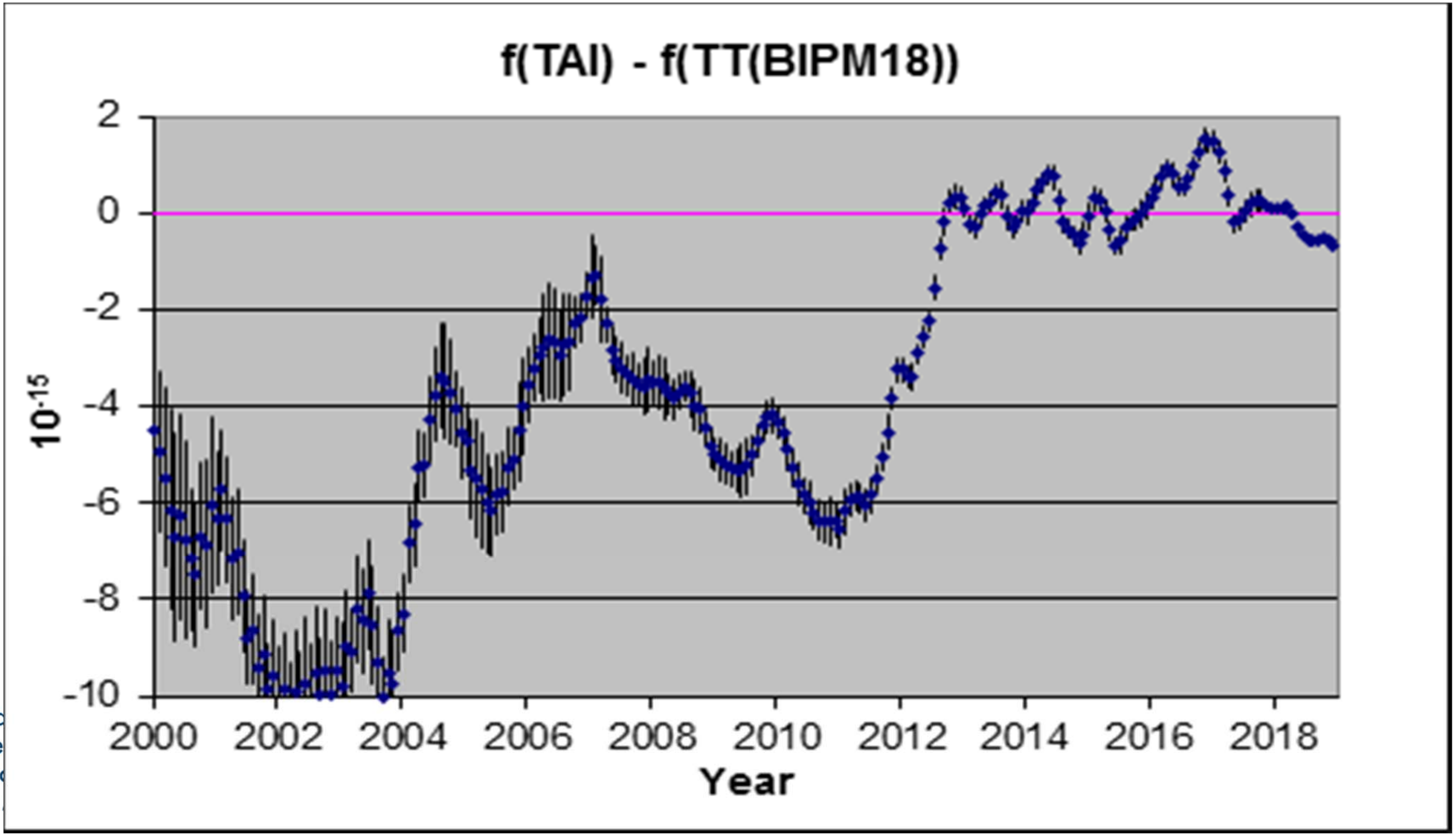
PSFS provide accuracy to TAI and TT(BIPM)



Local measurement system

High resolution
High accuracy
High stability

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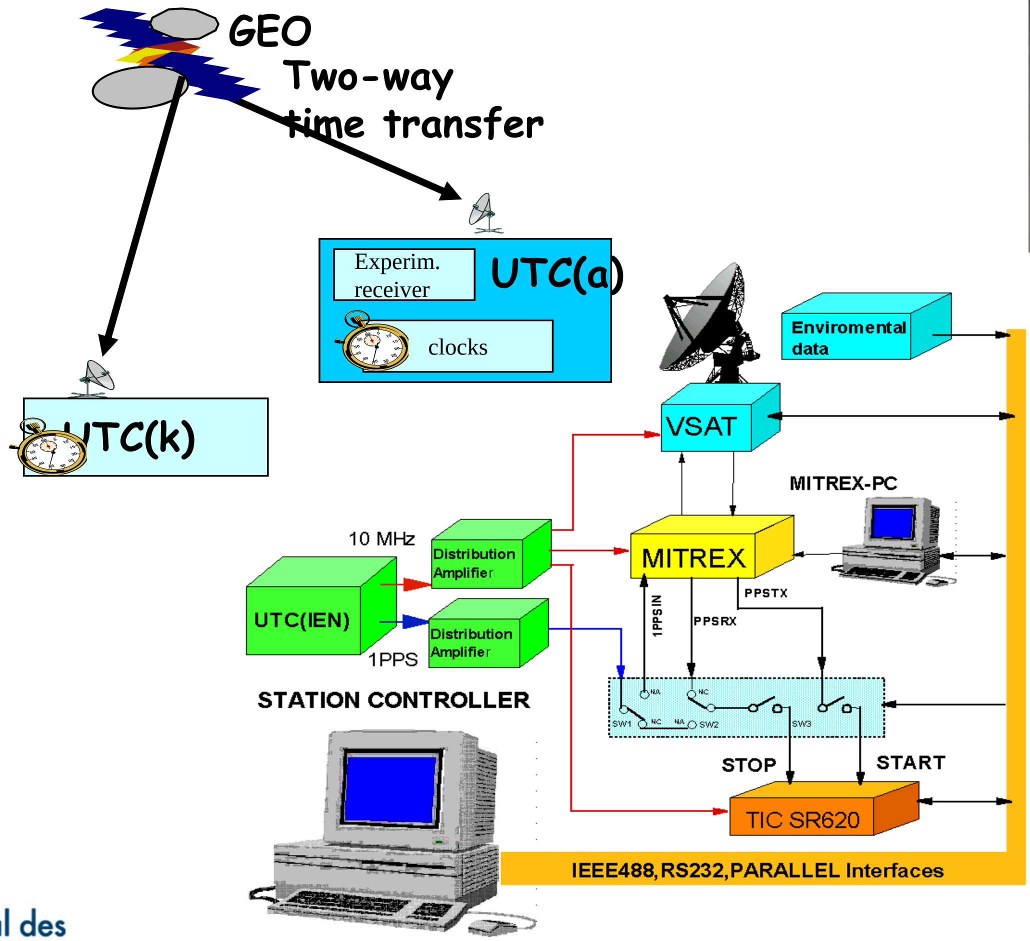
25

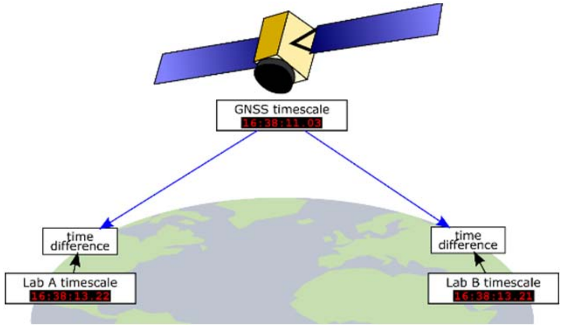
Remote measurement system



Clocks in different laboratories are compared by suitable **time and frequency transfer techniques**

Global Navigation Satellite Systems (GNSS)

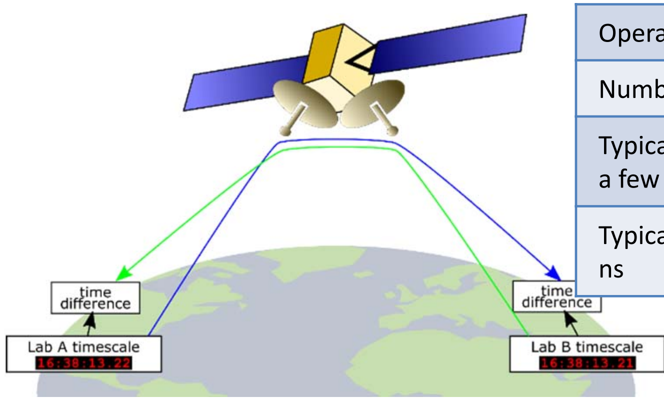
GNSS are based on time broadcasting from satellites to ground receivers (one-way time transfer). Distant labs equipped with GNSS receivers periodically compare their clocks to the broadcasted time and send the result to the BIPM.



Operational since ~ 1980
Number of links : all contributing laboratories
Typical freq. transfer accuracy @1d : a few 10^{-15}
Typical time transfer accuracy : a few ns

Two-Way Satellite Time & Freq. Transfer (TWSTFT)

dedicated ground terminals simultaneously receive and transmit time transfer signals (two-way time transfer) on geostationary telecom satellites.
Two-way method cancels out (at first order) the propagation time of the signal.



Operational since ~2000
Number of links : 18
Typical freq. transfer accuracy @1d : a few 10-15
Typical time transfer accuracy : ≳ 1 ns

Progress in GNSS measures

GPS+ GLONASS + Beidou + Galileo
IPPP : Precise Point Positioning with integer ambiguity resolution

Progress in TWSTFT

Software Designed Radio and TWSTFT Carrier Phase

In development : Optical Fiber links

A growing number of UTC laboratories are gaining access to fiber links dedicated to time and frequency. Although few of them are currently interconnected by operational, high-duty cycle links, this number is expected to grow quickly during the next decade.

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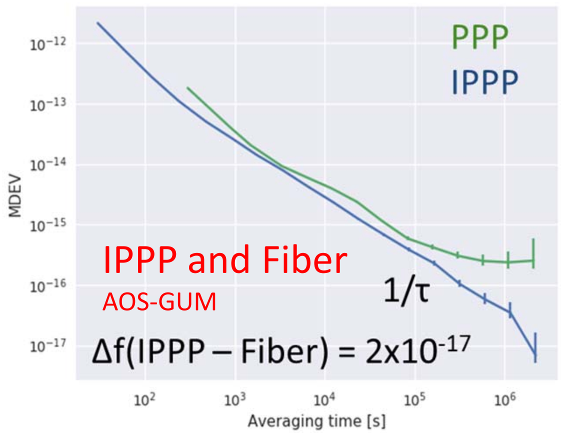
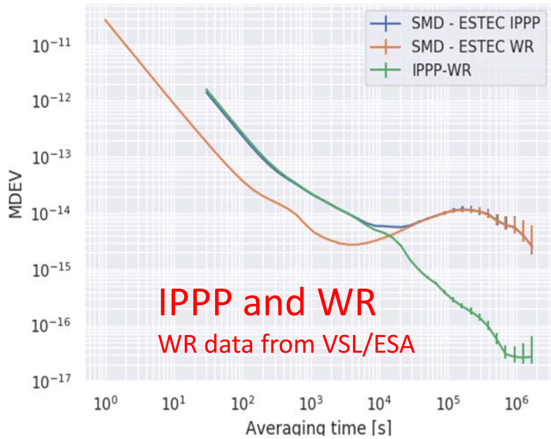
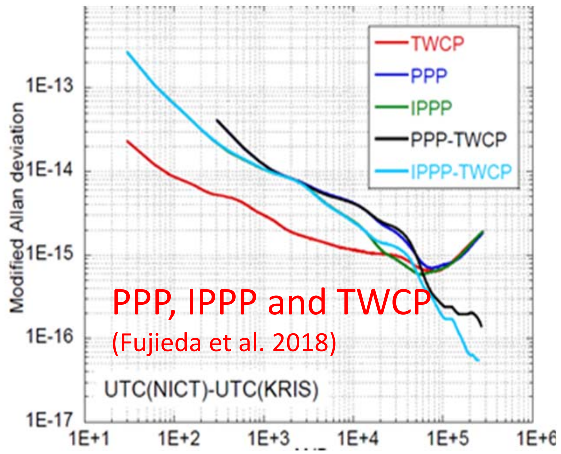
IPPP vs. Fiber, White Rabbit, TWSTFT Carrier Phase: Summary of achieved stabilities







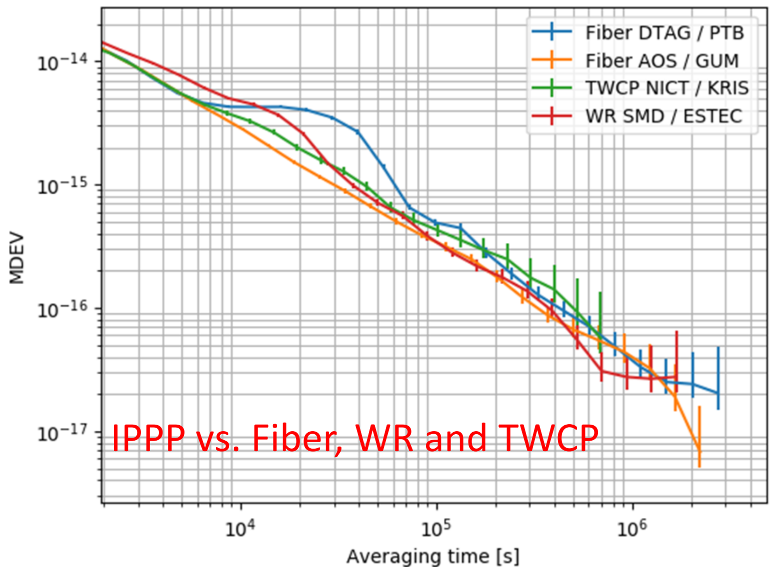
- TWSTFT CP, Fiber, WR better @ < 1 day
- Long term difficult to assess for each
- IPPP (assuming fiber is better)

  ~5-7x10^{-16} at ~ 1 day

  1x10^{-16} at ~ 5-7 days

  low 10^{-17} at 20 days

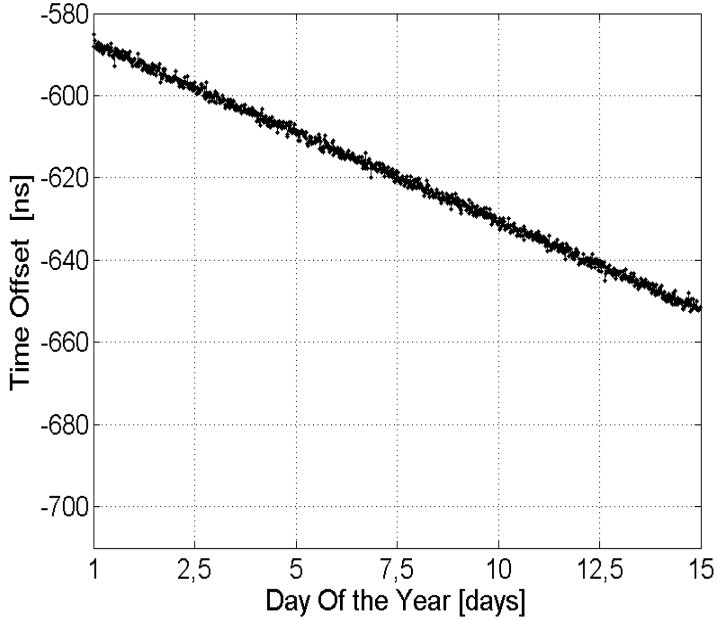
  τ^{-1} behavior until n days



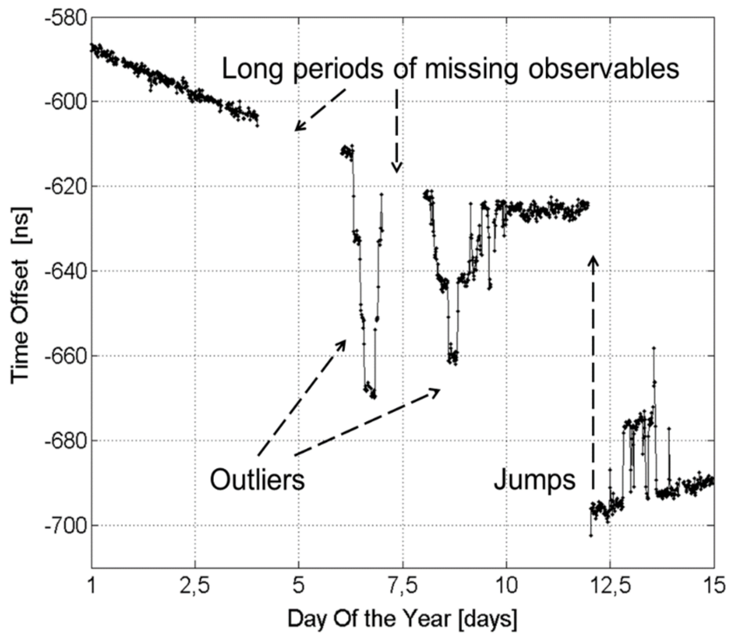
Data preprocessing, filtering and smoothing

and time scale algorithms

Ideal

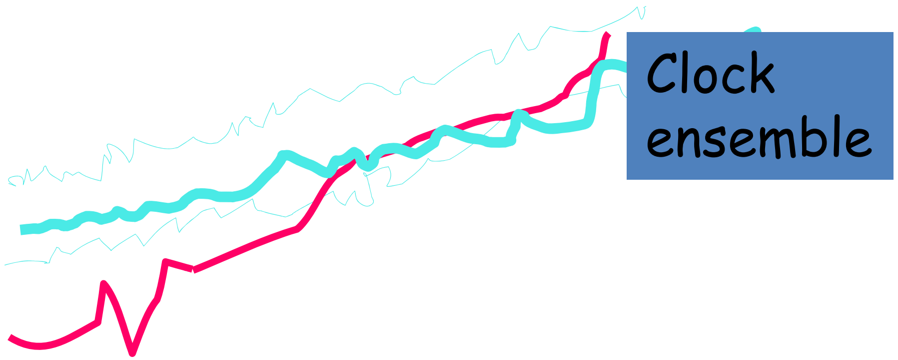


and real clock measures

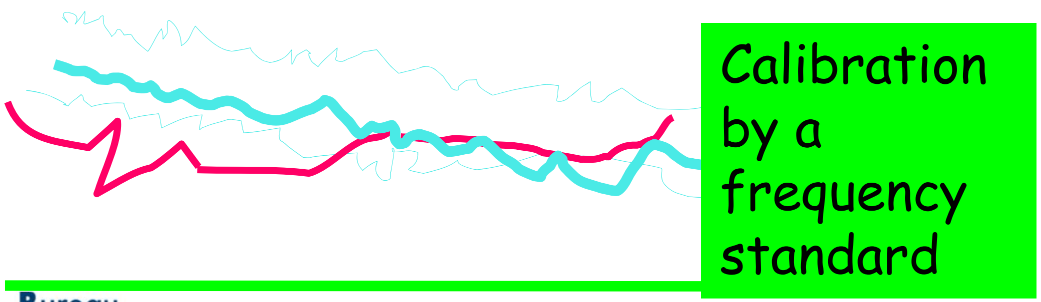


- to optimize the contribution of each clock,
- to avoid instabilities when new clocks arrive or old clocks exit
- to detect anomalies,

Ensembling algorithm

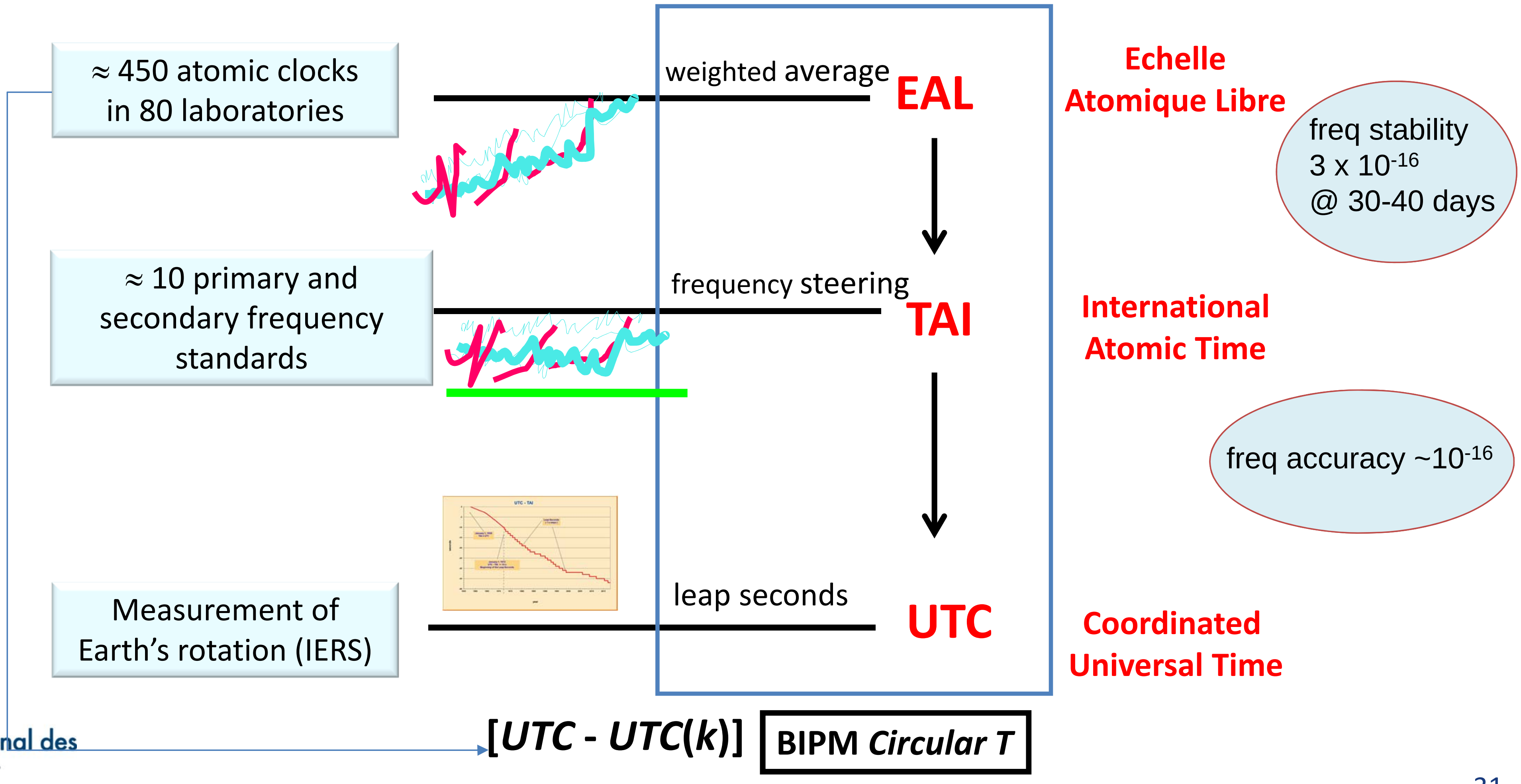


The ensemble average is usually optimized in stability



Accuracy is obtained by the steering toward the most accurate realization of the SI second

Computation of UTC (monthly) at the BIPM



Bureau International des Poids et Mesures

CIRCULAR T 374 ISSN 1143-1393

2019 MARCH 08, 10h UTC

BUREAU INTERNATIONAL DES POIDS ET MESURES
THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 tai@bipm.org

The contents of the sections of BIPM *Circular T* are fully described in the document " Explanatory supplement to BIPM Circular T " available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.2.pdf

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties. From 2017 January 1, 0h UTC, *TAI-UTC* = 37 s.

Date 2019 0h UTC		JAN 31	FEB 5	FEB 10	FEB 15	FEB 20	FEB 25	Uncertainty/ns			Notes
	MJD	58514	58519	58524	58529	58534	58539	u_A	u_B	u	
Laboratory *k*				[*UTC-UTC*(*k*)]/ns							
AOS	(Borowiec)	2.5	2.1	1.7	0.7	0.0	-1.3	0.4	4.2	4.2	
APL	(Laurel)	4.5	2.6	2.3	-3.1	-3.8	-29.9	0.4	10.9	11.0	
AUS	(Sydney)	-50.3	-39.1	-46.7	-48.6	-62.7	-77.9	0.4	6.5	6.5	
BEV	(Wien)	12.9	5.1	13.0	11.0	14.0	27.7	0.4	3.3	3.3	
BIM	(Sofi										
BIRM	(Beij										
BOM	(Sko										
BY	(Min										
CAO	(Cag										
CH	(Ber										
CNES	(Tou										
CNM	(Que										
CNMP	(Pan										
DFNT	(Tun										
DLR	(Obe										
DMDM	(Belg										
DTAG	(Frankfurt/M)	-210.1	-206.6	-209.0	-212.1	-211.3	-212.4	0.4	3.0	3.1	
EIM	(Thessaloniki)	2.0	1.2	-2.9	1.4	6.6	-0.1	3.0	11.3	11.7	
ESTC	(Noordwijk)	-1.5	-4.3	-6.4	-6.4	-3.0	-0.4	0.4	3.2	3.2	
HKO	(Hong Kong)	881.5	894.7	926.6	944.7	957.5	980.4	0.4	7.9	7.9	
ICE	(San Jose)	85.3	86.3	87.8	81.9	72.2	79.5	5.0	20.0	20.6	
IFAG	(Wettzell)	-998.1	-1009.8	-1023.6	-1027.0	-1027.7	-1020.0	0.4	5.2	5.2	
IGNA	(Buenos Aires)	6.3	-	-	-	-	-	2.5	20.0	20.2	

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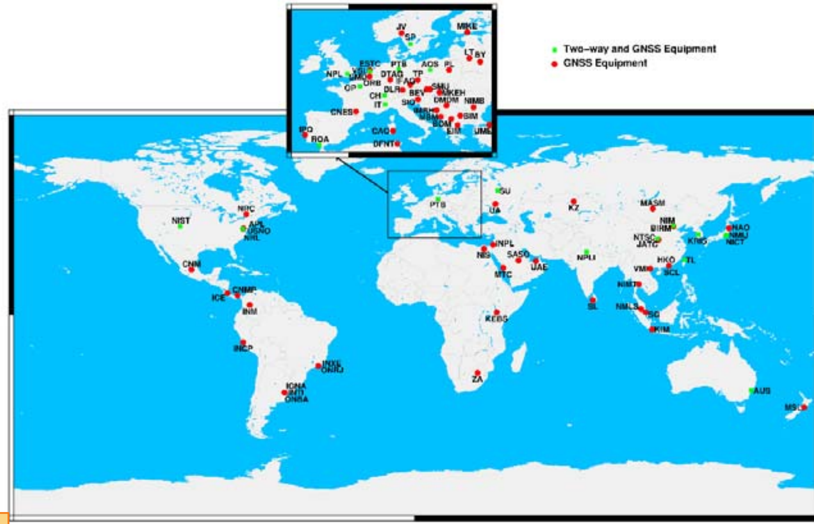
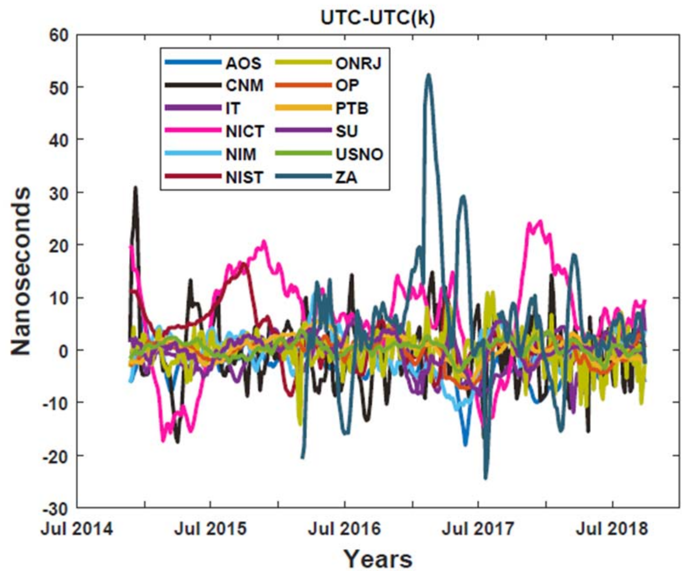
An approximation called Rapid UTC (UTCr) is calculated weekly and published each Wednesday by the BIPM.

All data and products are available on http://webtai.bipm.org/database/ and https://www.bipm.org/en/bipm-services/timescales/time-ftp

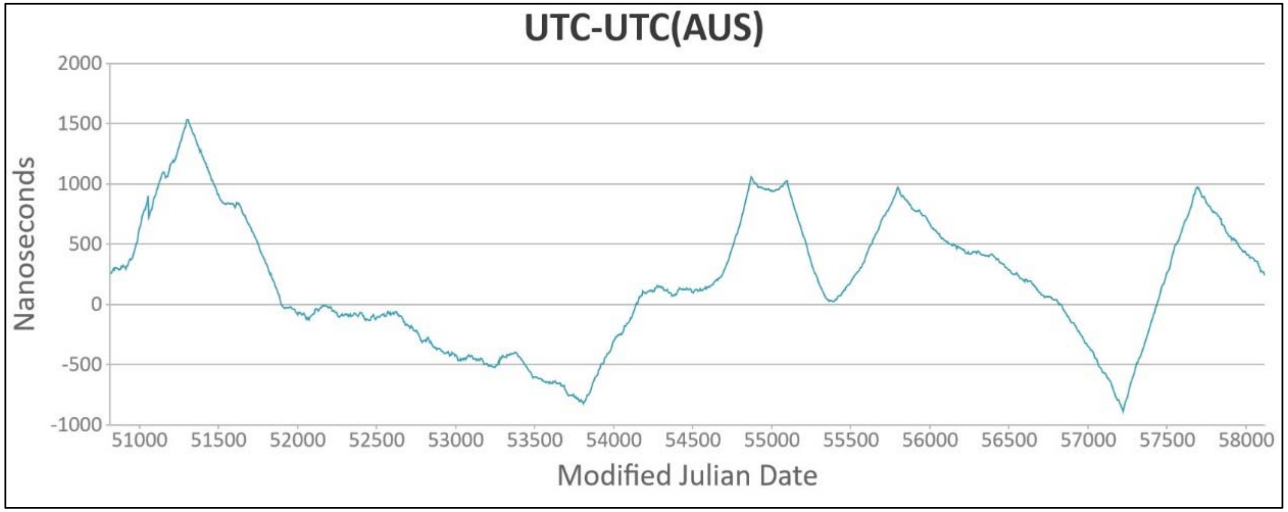
Geographical distribution of the laboratories that contribute to UTC and time transfer equipment (2018)

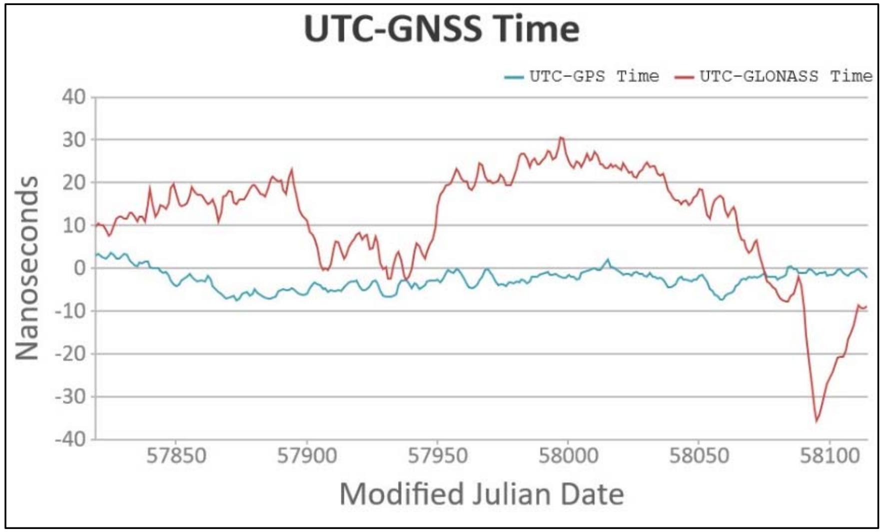


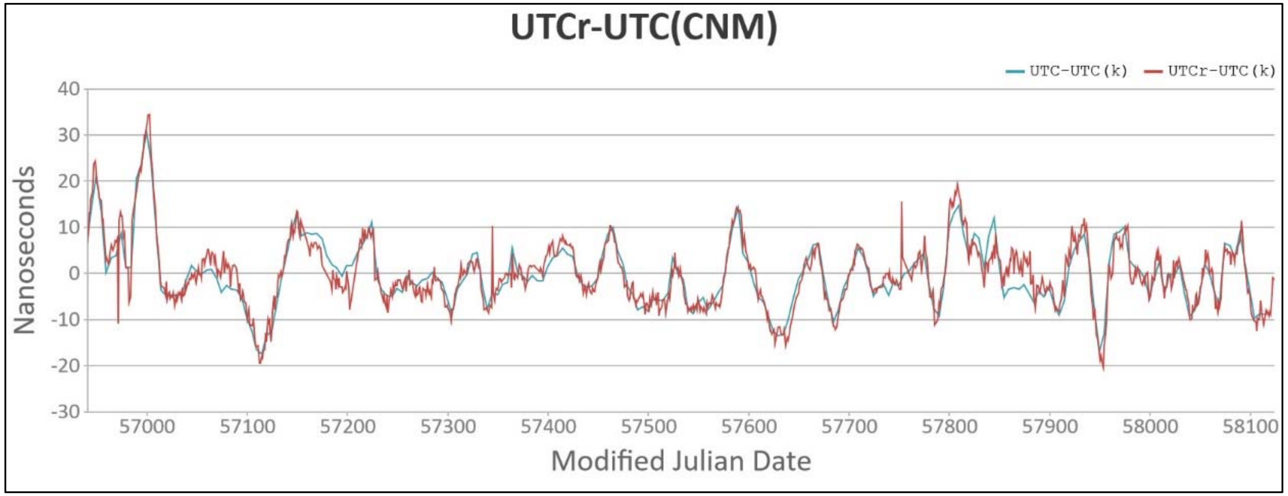


Results are available in the data base *http://webtai.bipm.org/database/*

- Allows to generate dynamic plots
- Checking the clock weights, rate, drift
- See the last calibration results



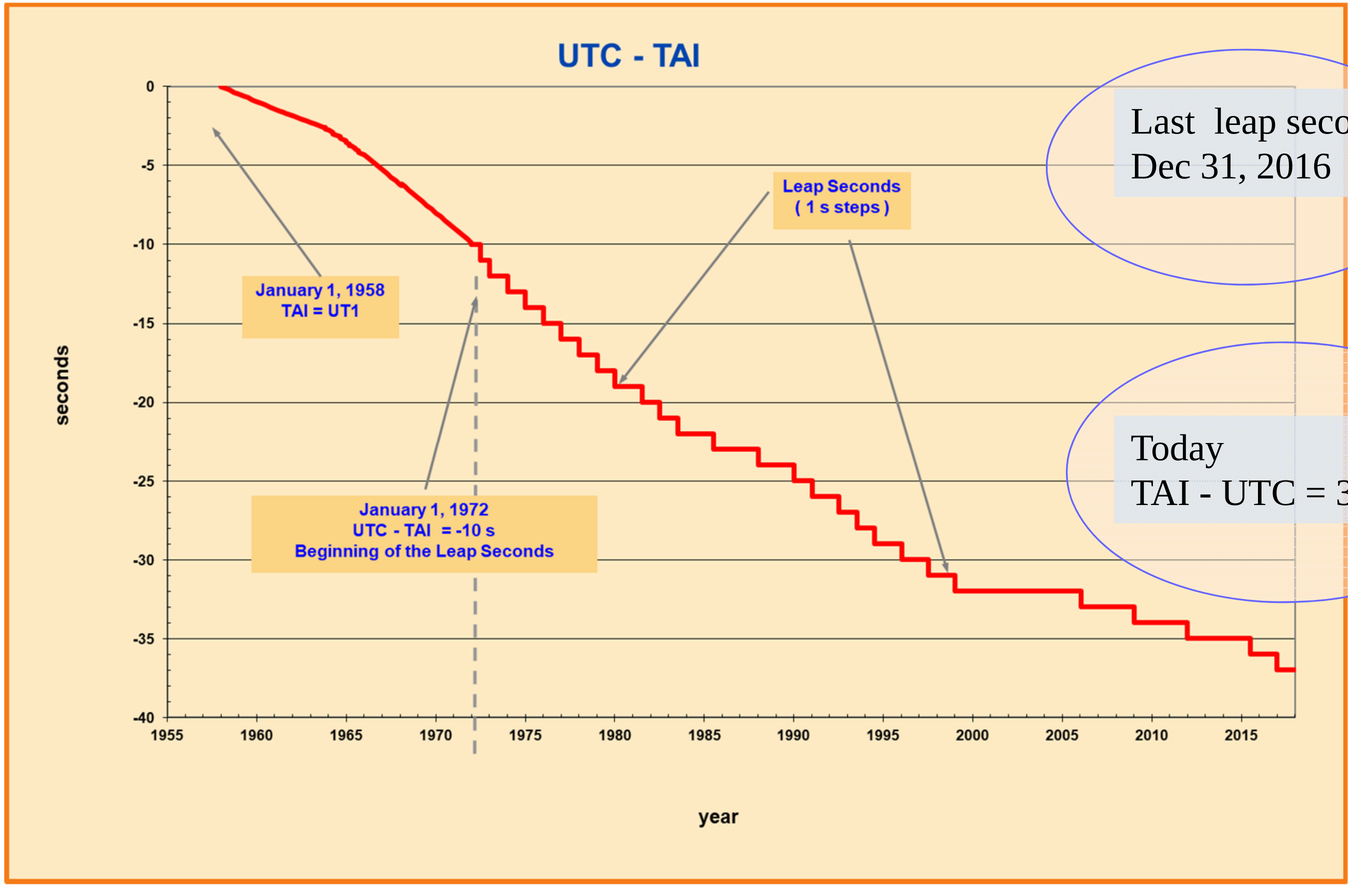




Universal Coordinated Time and leap seconds

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



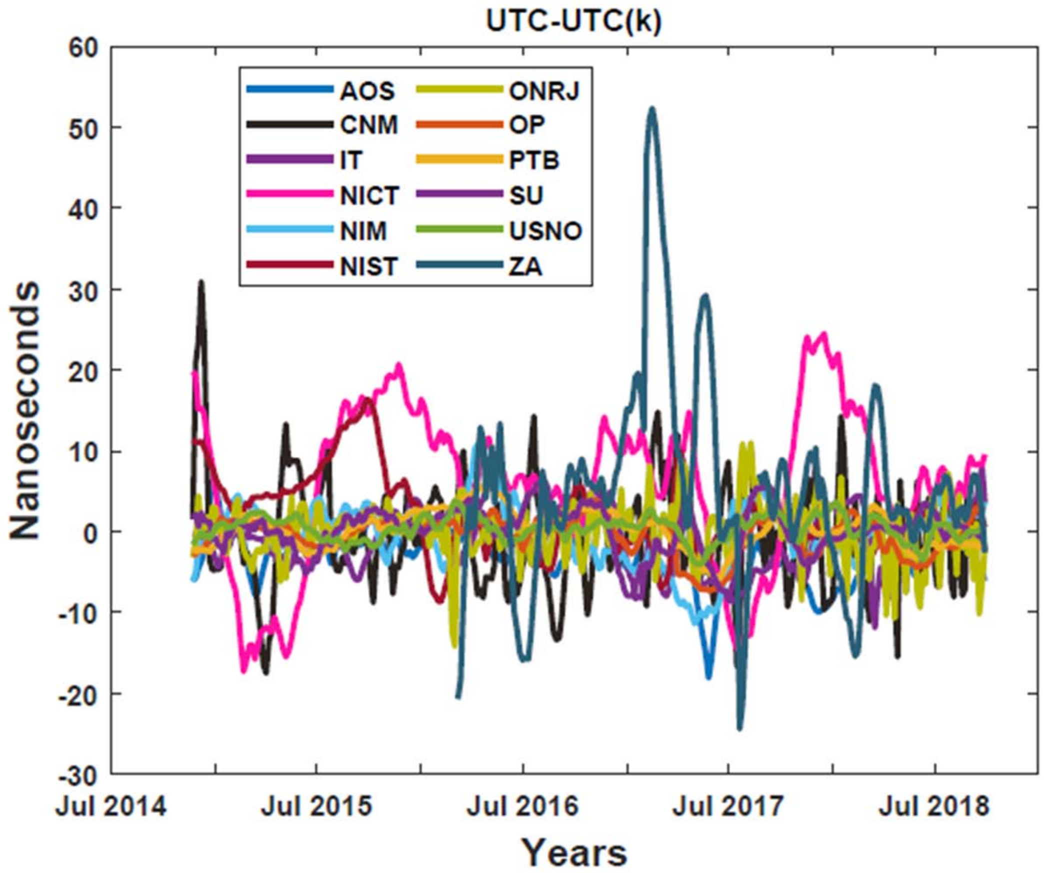
UTC = TAI + leap seconds

The Universal Time Coordinated is the ultimate time reference available **in deferred time**

Local time scales UTC(k) are realised by national laboratories
in real-time

A posteriori, they are verified versus UTC.

The BIPM Circular T and data published in the Key Comparison Data Base ensure traceability



KCDB

Bureau International des Poids et Mesures

CCU session on the SI second
Oct 9th ,2019

Basic concepts – From the definition to the end users

Noël Dimarcq, CNRS-OCA, CCTF president

Realization of UTC/TAI at the BIPM

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Conclusions

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Conclusions

Construction of TAI by BIPM with frequency stability 3 x 10^{-16} @ 30-40 days and frequency accuracy ~ 10^{-16} thanks to calibration by 10 cesium fountains

Accuracy of best optical clocks (~ 10^{-18}) surpassing microwave fountains (~ 10^{-16}), with continuous operation over few weeks;

Increasing number of optical frequency standards contributing to UTC as secondary standards

Development and deployment of long distance upgraded T/F transfer techniques (coherent fiber links) allowing non-degraded comparisons of optical clocks

Stakeholders and end-users in a large spectrum of application fields, with a variety of needs (absolute time, time interval, absolute frequency, ratio of frequencies) and requirements (stability, accuracy, continuous accessibility, traceability to international reference or legal times, …)

Conclusions

Noticeable work to be done before proposing a redefinition of the second:

- Confirm the accuracy budgets of optical clocks and ensure their reliability and their availability for the construction of time scales
- Analyze and compare the different options for the redefinition (single atomic transition, ensemble of transitions, fix the value of the electron's mass, …)
- Improve the capability of long distance comparisons at 10^{-18} uncertainty level + wider deployment; required to ensure both the best contribution of optical clocks to atomic time scales and the dissemination towards users
- Study and understand more deeply the stakeholders and users needs, and how the users will be able to fully benefit of a new definition (the current realization of the SI second is not today a limitation for the users)
- Study possibles impact of a redefinition of the second on the other SI units