Time scales

P. Tavella

With the support of all
the BIPM Time Dept

Gressoney, September 2018

**Bureau
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Mesures**

What time it is?

What is the Universal Time Coordinated?

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Time scale: the 4th coordinate of a space-time system

From the observation of a position,
based on Newtonian dynamics

Dynamic Time Scale

to the time coordinate

From the integrated accumulation
of time units, defining an origin

Integrated Time Scale

to a proper time scale

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Dynamic Time Scale

Time is the parameter of a mathematical equation describing the dynamics of an observable system

For any configuration of the dynamical system a unique (or distinguishable) time instant is associated

Example: Keplero law gives a relation between observed positions of the Earth and particular time instants

Measuring time means measuring position

A coordinating organisation is needed, time unit is not directly accessible

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Error of the Dynamic Time Scale

Observation errors

−

- Decrease as technology improves

Definition errors

+

- in the mathematical equations
- in the knowledge of initial conditions
- imperfect knowledge of influencing factors

Integrated Time Scale

Let's take a physical system that presents repetitively two identifiable different states. If the time interval between the two states is constant

we can define a unit of time

Choosing arbitrarily an origin and summing up successive time units (without dead time)

we build up a time scale.

Any time interval is easily measured as difference between final and initial dates, the time unit is easily accessible

Error of the Integrated Time Scale

Definition errors

−

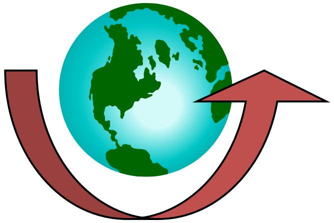
- the origin has not a unique definition

Realisation errors

+

- difficult to reproduce the time unit always in same conditions
- if the time unit realisation differs from the definition, the error accumulates and the realised time scale diverges from the definition

For centuries



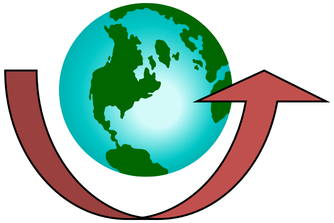
The time was given by the rotating Earth

on which we set the clock

From 1967

The time is given by atomic clock

used to study Earth rotation



Along centuries...

Universal Time

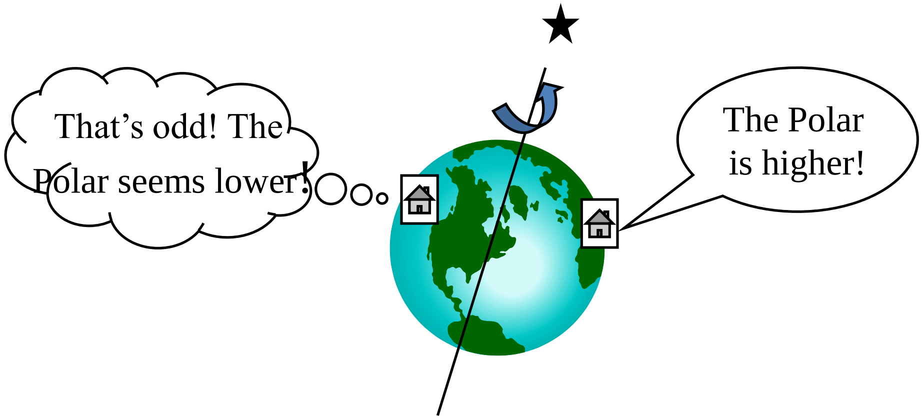
- day and night are the “natural” time unit
- it was observed that during the year the length of day changes but the “Mean Solar Day” was deemed constant and Universal
- Universal Second = 1/86400 of rotational day (Mean Solar Time)
- 1884 Greenwich reference meridian
- 1925 International Astronomical Union fixes the beginning of the mean solar day at h. 00 and defines the Universal Time

Universal Time

the rotation rate is constant?

Polar motion

Suspected around 1850 from astronomers



Polar motion can be measured but is not predictable

Polar motion
Solid line : mean pole displacement,

About
10 m

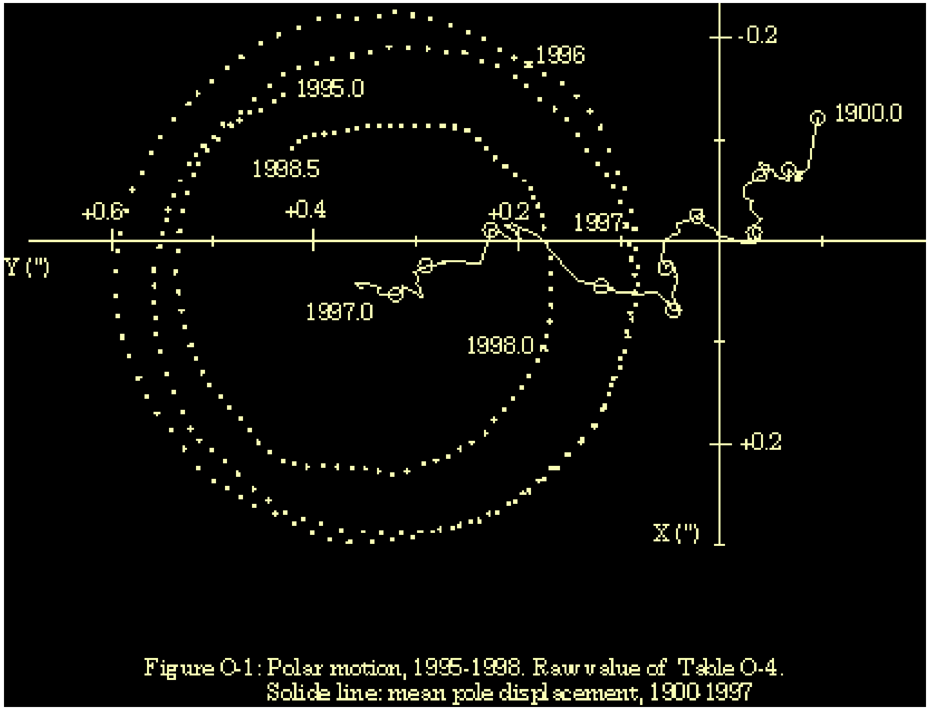
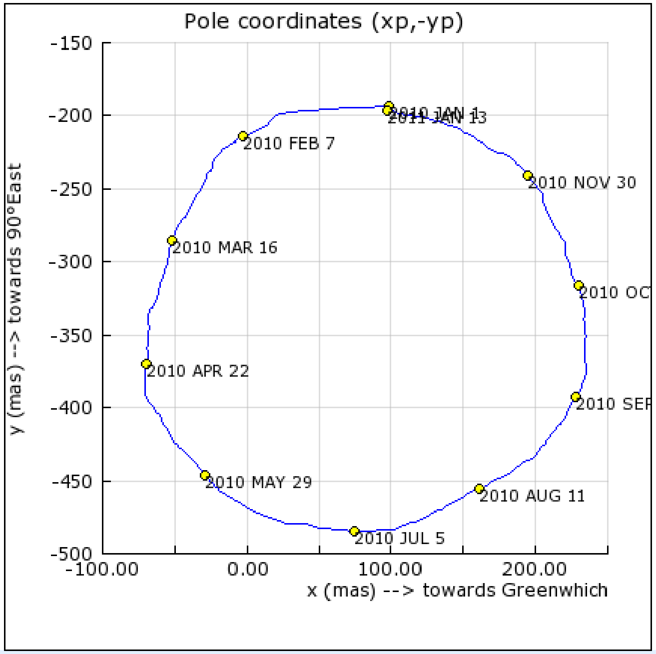


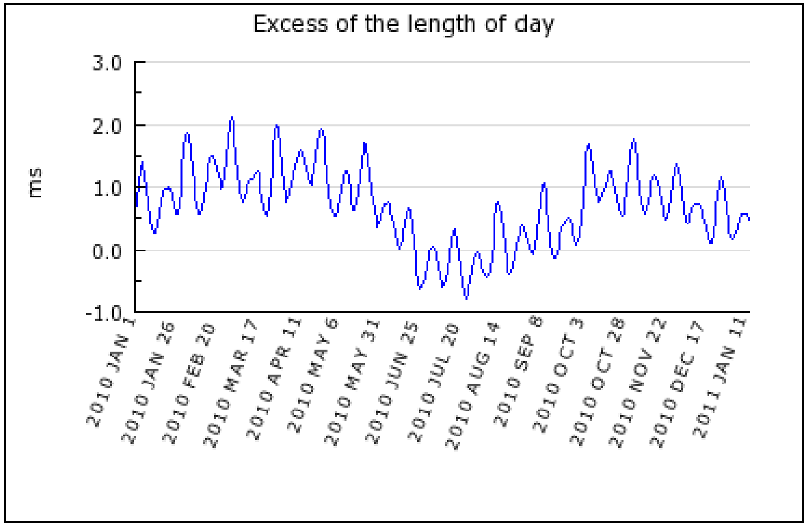
Figure O-1: Polar motion, 1995-1998. Raw value of Table O-4.
Solide line: mean pole displacement, 1900 1997

http://www.iers.org *International Earth Rotation and Reference Systems Service* http://www.iers.org



About
10 m

Polar motion over recent year



Atmospheric excitation in 2010

Units and conversion of units

1 astronomical unit	UA	149 597 870.691(6)	km	0.00004	numerical IERS Standards
From milliarcseconds (mas) to radians	1 mas =4.8481(1) 10^{-9} rad				
What represents an arc of 1mas from the center of the Earth at distance equal to the polar radius (6 356 755 m)?	**3.1(1) cm**				
Conversion of arc units in hour, minute, second to arc units in degree, arcminute, arcsecond	24 h = 360° 1 h = 15° 1 min = 15' 1 s = 15" 1 ms = 15 mas				

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Seasonal variation: in summer we spin faster

- A. Scheibe, 1936 in Berlin
- N. Stoyko, 1936 in Paris (BIH)

with crystal clock the day was measured shorter of about 1.2 ms

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Variations in the duration of the day

http://www.iers.org

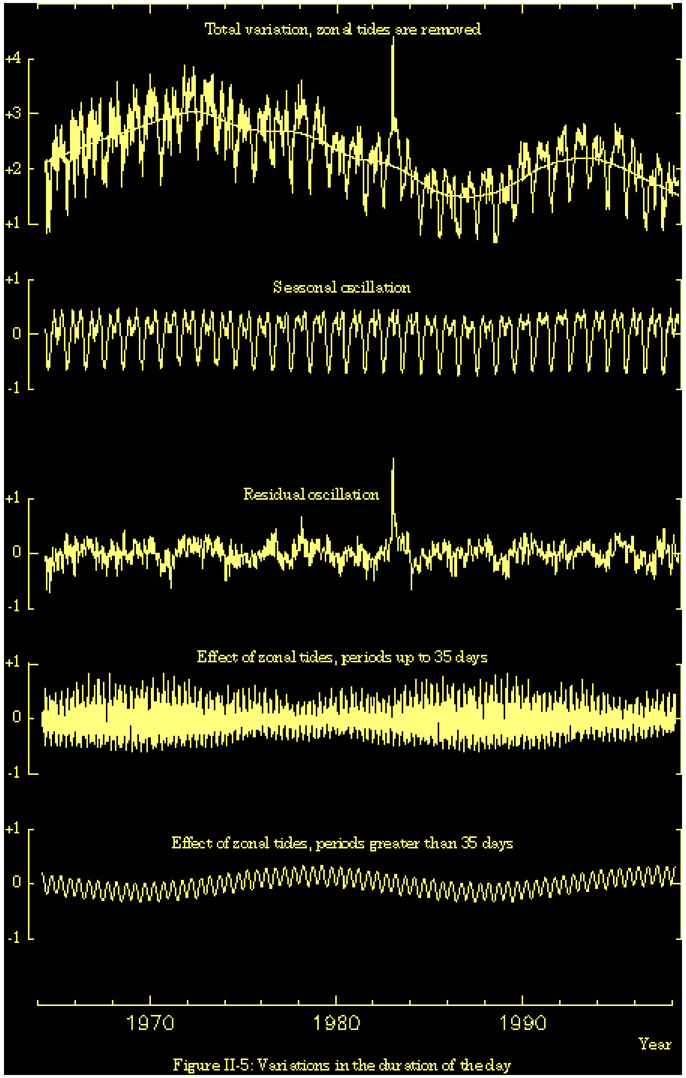
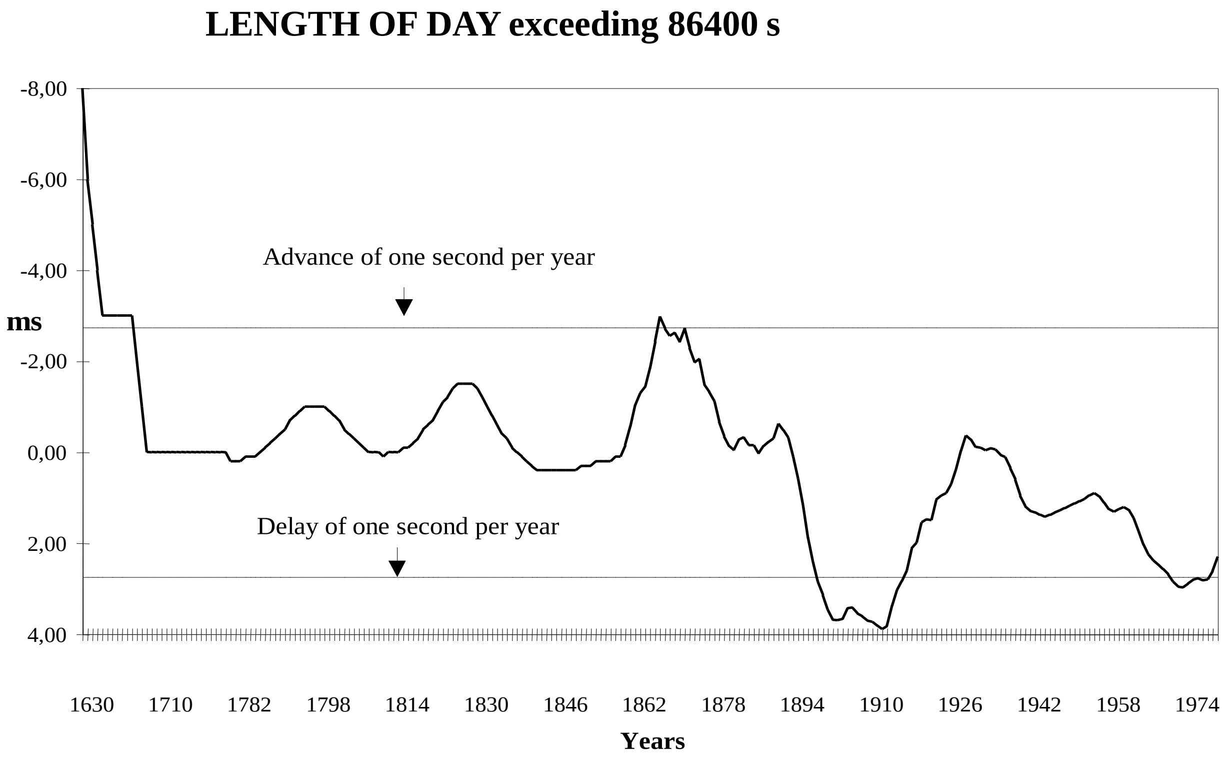


Figure II-5: Variations in the duration of the day

Secular slowing down



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The Universal Time was improved

UT = Universal Time scale

UT1 = Universal Time corrected by polar motion

UT2 = Universal Time scale corrected by seasonal variations

…. (UT not GMT!)

…in 1960

Ephemeris Time

- the "revolution" of the Earth around the Sun is constant.

- Measuring the longitude of the Sun and using the equation of the apparent Sun orbit

- The new time scale: Ephemeris Time starts from h. 0 UT of January 1st, 1900.

- Time unit is the Ephemeris Second = 1/31 556 925.9747 of the tropical year on day **January 0, 1900**

that duration!

- any new definition of the Second has to be in agreement with the previous one. For continuity with UT, this is the duration of the second in 1900

in 1960 this duration was already shorter than 1/86400 of the Mean Solar Day

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…in 1967

Atomic Time

- Atomic Second = 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Cs 133 atom

- First comes the second, then the time scale: in 1971: Temps Atomique International TAI, International Atomic Time

- TAI starts from h. 0 UT of January 1st, 1958.

- The length of the atomic second is in agreement with the Ephemeris second

therefore shorter than 1/86400 of the Mean Solar Day

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So far we have learnt that the Atomic Second is, by definition, shorter than the **current** Rotational Second (Universal Time)

because it was defined in agreement with
the duration of the Rotational Second in 1900 and
the Earth is (slowly!) slowing down

In a relativistic frame

Any clock realises a proper local time

The average of many different proper times may be a coordinate time
(as the International Atomic Time)

The International Astronomical Union recommends time scales and reference frames for the different applications in Geocentric or Solar System Barycentric frames. On the Earth or in the vicinity (50000 km) the reference time scale (1991) is the

Terrestrial Time

The Terrestrial Time is a coordinate time scale defined in a geocentric reference frame (centered at the centre of the Earth), with scale unit the SI second as realised on the rotating geoid, i.e. differing by a constant rate with respect to a geocentric clock.

The SI second *as realised on the* ***rotating geoid***

The **geoid** is an empirical surface known with relative uncertainty of about 10^{-17} . In addition, the **rotating** velocity impacts at 10^{-19} level.

The definition of the Terrestrial Time was updated (IAU 2000) as:

> The Terrestrial Time is a coordinate time scale defined in a geocentric reference frame (centered at the centre of the Earth), with scale unit the SI second differing by a constant rate $L_G = 6.969290134 \times 10^{-10}$ with respect to a geocentric clock.

L_G equals U_G/c^2 where U_G is the geopotential at the geoid

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The International Atomic Time

is the best realisation of the Terrestrial Time

But which is **now** the angular position of the EARTH?

Some users need to know the relationship between the Universal Time UT1 (rotational) and the Atomic Time

in 1975

Coordinated

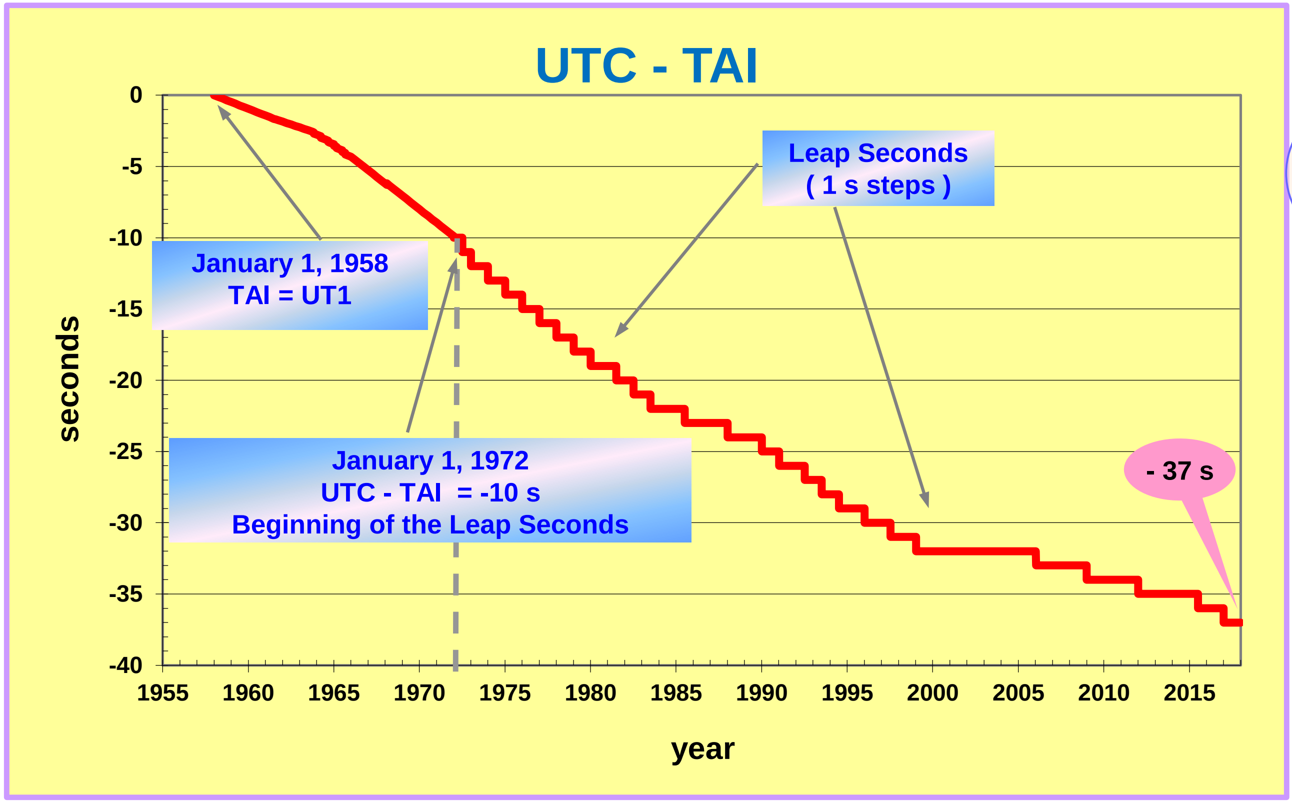
The Universal Coordinated Time (UTC) is a trade-off defined with the same time unit as TAI but with insertion of additional leap second

$\mathrm{TAI}-\mathrm{UTC} = n$ seconds $\qquad n = 0, \pm 1, \pm 2, \ldots$

$|\mathrm{UT1}-\mathrm{UTC}| < 0.9$ s

Universal Time UT0, UT1, UT2,….

Universal Coordinated Time and leap seconds



Last leap
second
Dec 31, 2016

Today
TAI - UTC
= 37 s

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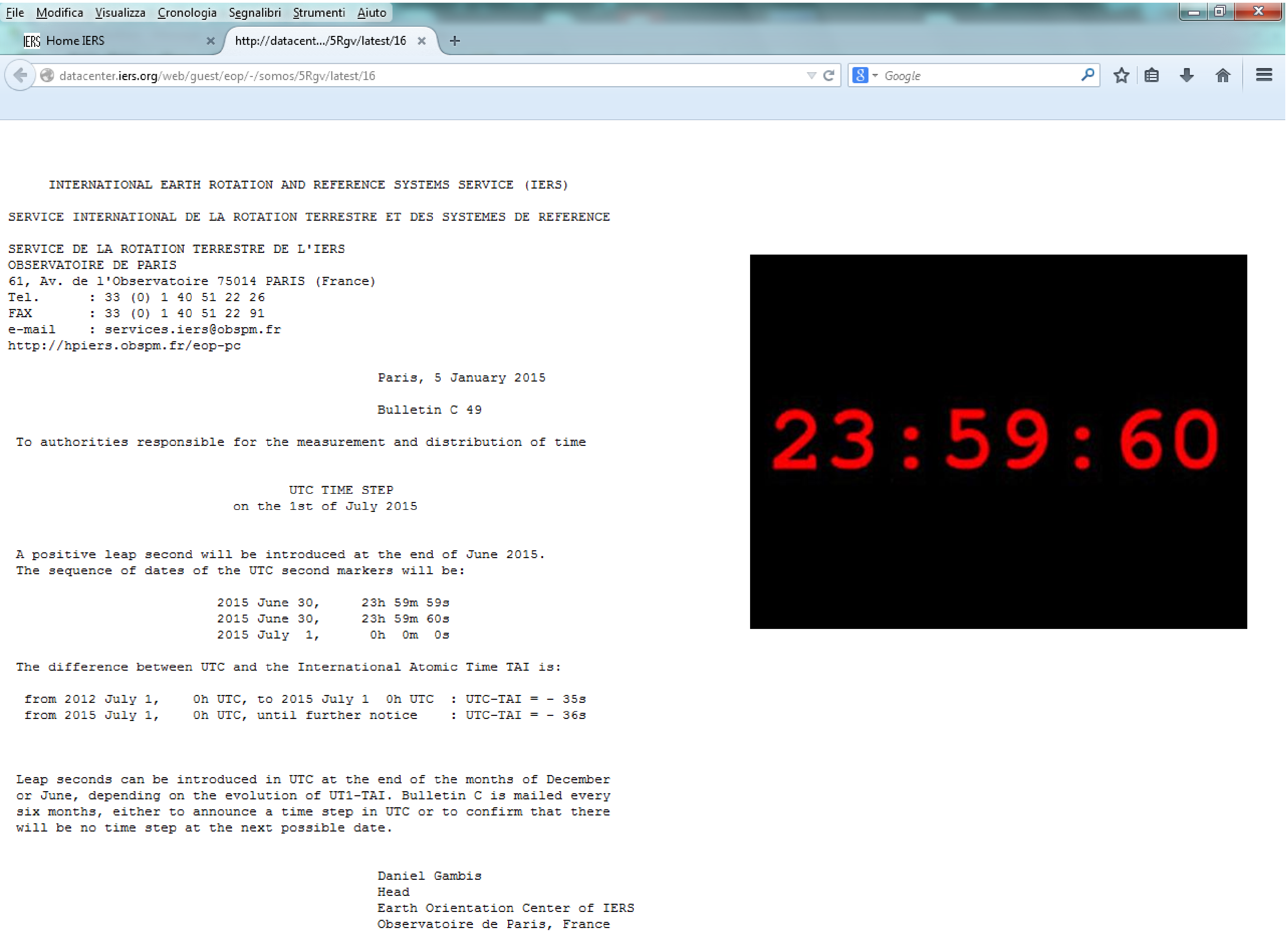

```
     INTERNATIONAL EARTH ROTATION AND REFERENCE SYSTEMS SERVICE (IERS)

SERVICE INTERNATIONAL DE LA ROTATION TERRESTRE ET DES SYSTEMES DE REFERENCE

SERVICE DE LA ROTATION TERRESTRE DE L'IERS
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http://hpiers.obspm.fr/eop-pc

                                              Paris, 5 January 2015

                                              Bulletin C 49

 To authorities responsible for the measurement and distribution of time


                                   UTC TIME STEP
                            on the 1st of July 2015


 A positive leap second will be introduced at the end of June 2015.
 The sequence of dates of the UTC second markers will be:

                          2015 June 30,     23h 59m 59s
                          2015 June 30,     23h 59m 60s
                          2015 July  1,      0h  0m  0s

 The difference between UTC and the International Atomic Time TAI is:

  from 2012 July 1,    0h UTC, to 2015 July 1  0h UTC  : UTC-TAI = - 35s
  from 2015 July 1,    0h UTC, until further notice    : UTC-TAI = - 36s



 Leap seconds can be introduced in UTC at the end of the months of December
 or June, depending on the evolution of UT1-TAI. Bulletin C is mailed every
 six months, either to announce a time step in UTC or to confirm that there
 will be no time step at the next possible date.


                                              Daniel Gambis
                                              Head
                                              Earth Orientation Center of IERS
                                              Observatoire de Paris, France
```

Leap seconds are useful or annoying?

- Idea first raised in public in 1999

INNOVATION

GPS and Leap Seconds

Time to Change?

Dennis D. McCarthy, U.S. Naval Observatory
William J. Klepczynski, Innovative Solutions International

Since ancient times, we have used the Earth's rotation to regulate our daily activities. By noticing the approximate position of the sun in the sky, we knew how much time was left for the day's hunting or farming, or when we should stop work to eat or pray. First sundials, water clocks, and then mechanical clocks were invented to tell time more precisely by essentially interpolating from noon to noon.

As mechanical clocks became increasingly accurate, we discovered that the Earth does not

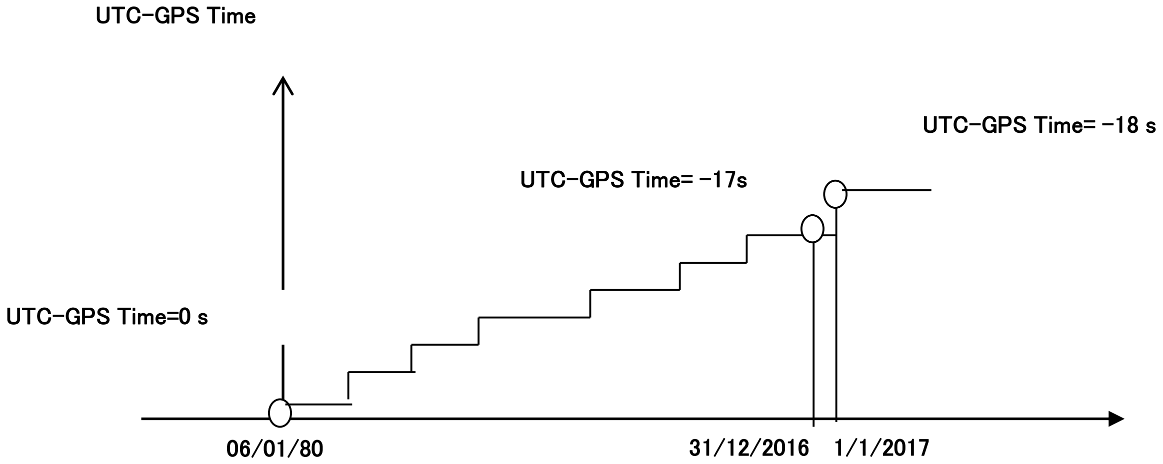
Just as leap years keep our calendar approximately synchronized with the Earth's orbit about the Sun, leap seconds keep precise clocks in synchronization with the rotating Earth, the traditional "clock" that humans have used to determine time. Coordinated Universal Time (UTC), created by adjusting International Atomic Time (TAI) by the appropriate number of leap seconds, is the uniform time scale that is the basis of most civil timekeeping in the world. The concept of a leap second was

seconds. While resetting the GLONASS clocks, the system is unavailable for navigation service because the clocks are not synchronized. If worldwide reliance on satellite navigation for air transportation increases in the future, depending on a systems that may not be operational during some critical areas of flight could be a difficulty. Recognizing this problem, GLONASS developers plan to significantly reduce

Source:
GPS World
Nov 1999

Global Positioning System: navigation and timing services

GPS time was set in agreement with UTC on h. 00 Jan 6, 1980



The accumulate time difference between UTC and GPS time is now of 18 seconds. GPS time is ahead 18 s

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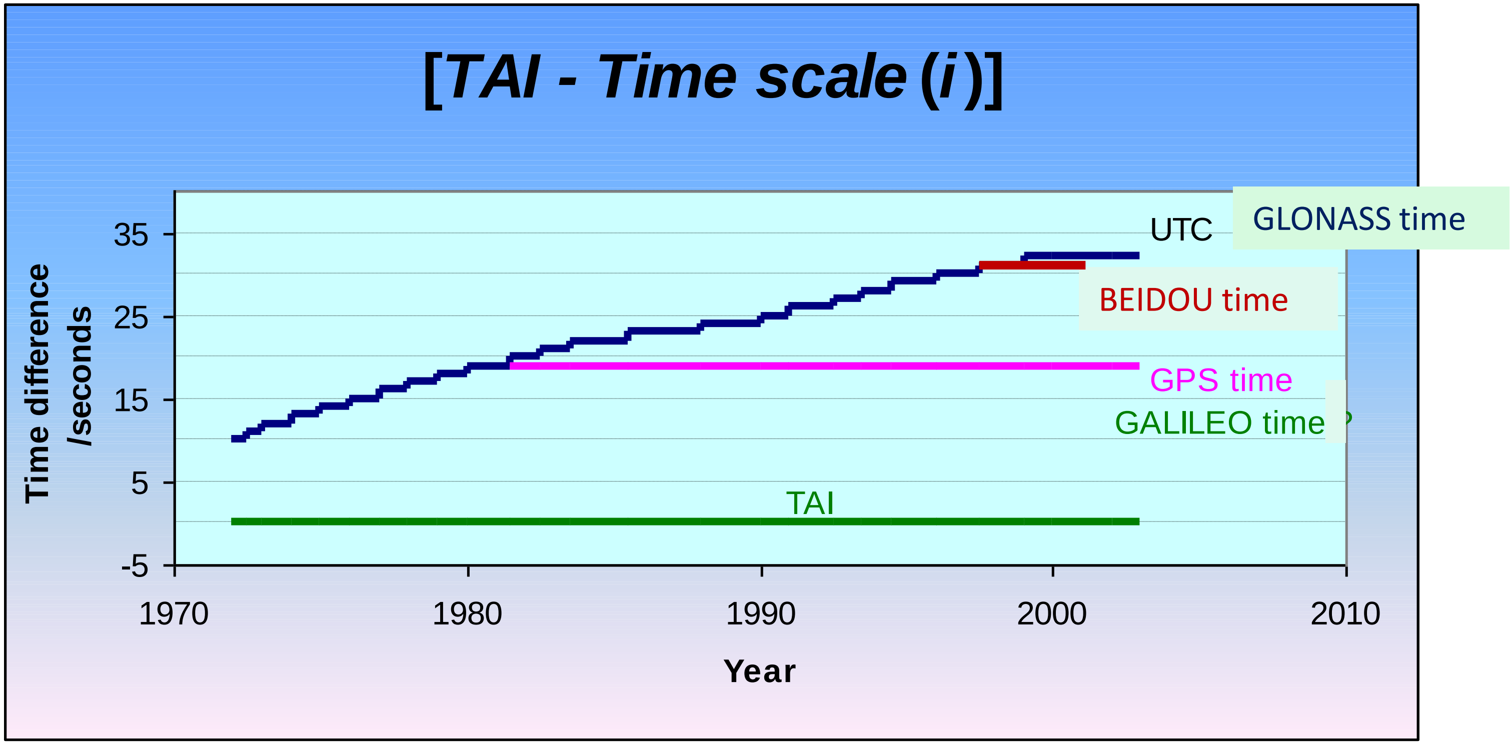
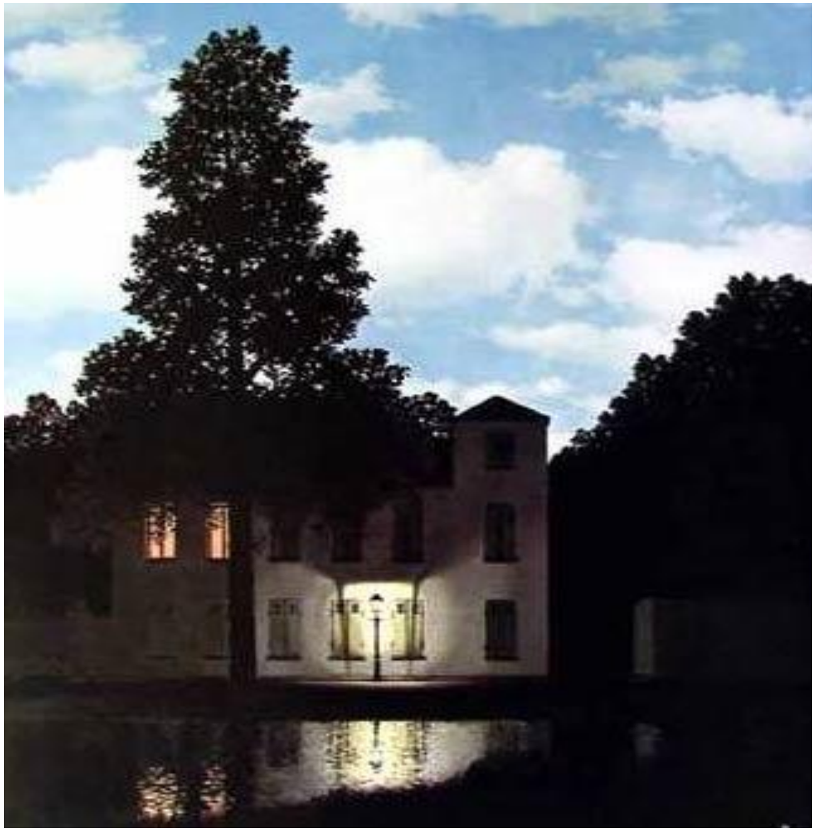
Leap seconds in Global Navigation Satellite System time scales

GNSSs prefer not to apply leap seconds (except GLONASS), their time scale is easily available all over the world inside the navigation message, reference time scales differ from seconds, source of CONFUSION!!!



Should we abandon leap second?



<u>BIPM press release 13 October 2011</u>
The proposed redefinition of Coordinated Universal Time, UTC

Today, leap seconds keep UTC, a time scale based on atomic clocks, in phase with the slightly variable rotation of the Earth.
The possibility of dropping the leap seconds in UTC has created misconceptions in the popular press as to what is at stake.
There are an increasing number of users of precise timing for whom the leap second causes serious technical problems.

Leap seconds are useful or annoying? The current proliferation of time scales is generating confusion and possible danger

INTERNATIONAL TELECOMMUNICATION UNION

RADIOCOMMUNICATION STUDY GROUPS

Special Rapporteur Group 7A
(SRG 7A) on the
Future of the UTC Time Scale

Colloquium on the UTC Timescale
Torino, 28-29 May 2003

Several international organisations created working groups to evaluate this issue. **In November 2015 ITU General Assembly** decided not do change till 2022. ITU would continue to be responsible for the dissemination of time signals via radiocommunication and BIPM for establishing and maintaining the second of the International System of Units (SI) and its dissemination through the reference time scale.
Rendez-vous in 2023 at the next ITU World Assembly

Coordinated Universal Time (UTC)

- UTC is the reference time scale for world wide time coordination.
- It serves as the basis of legal times in the different countries.
- UTC is calculated at the BIPM on the basis of readings of clocks in the national laboratories.
- Local realizations of UTC named UTC(k) are broadcast by time signals.

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

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The International Atomic Time and the Universal Time Coordinated are the ultimate time reference but available

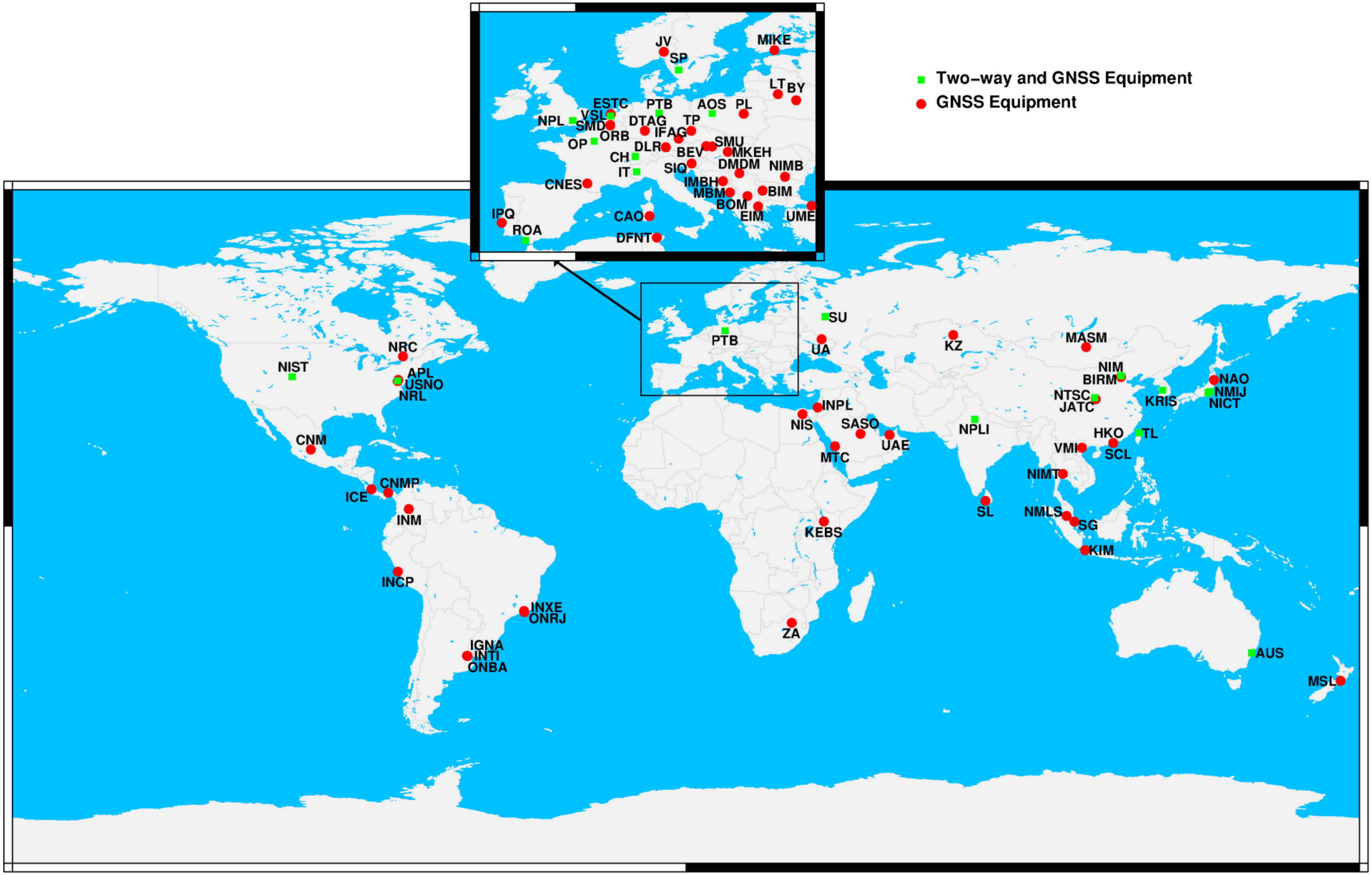
in deferred time

Local time scale UTC(k) are realised by national laboratories

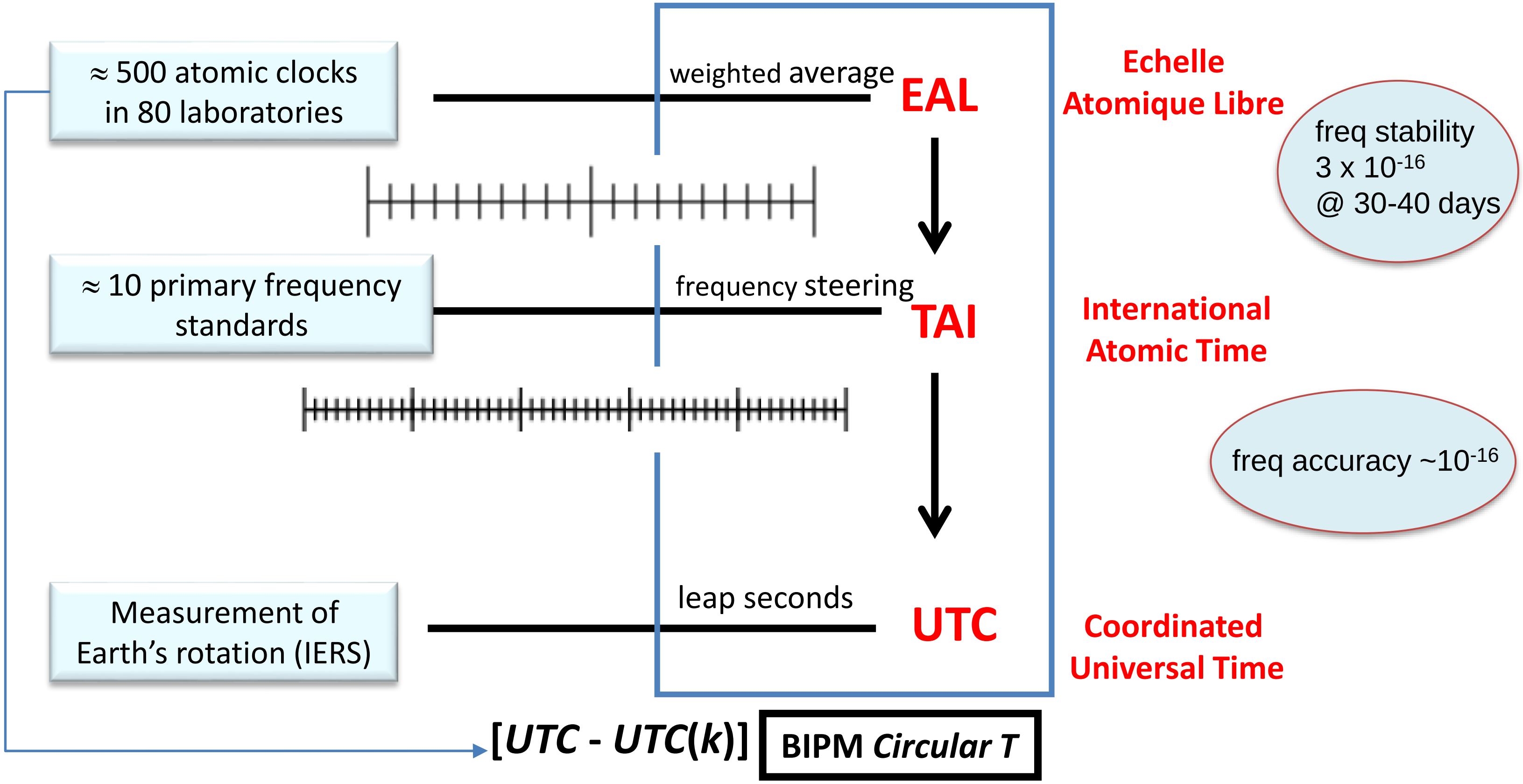
in real-time

The UTC computation is international, the local time scale UTC(k) are based on similar principles (see T.Ido tomorrow)

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



Computation of UTC (monthly) at the BIPM



≈ 500 atomic clocks in 80 laboratories

≈ 10 primary frequency standards

Measurement of Earth's rotation (IERS)

weighted average

EAL

Echelle Atomique Libre

freq stability 3 x 10^{-16} @ 30-40 days

frequency steering

TAI

International Atomic Time

freq accuracy ~10^{-16}

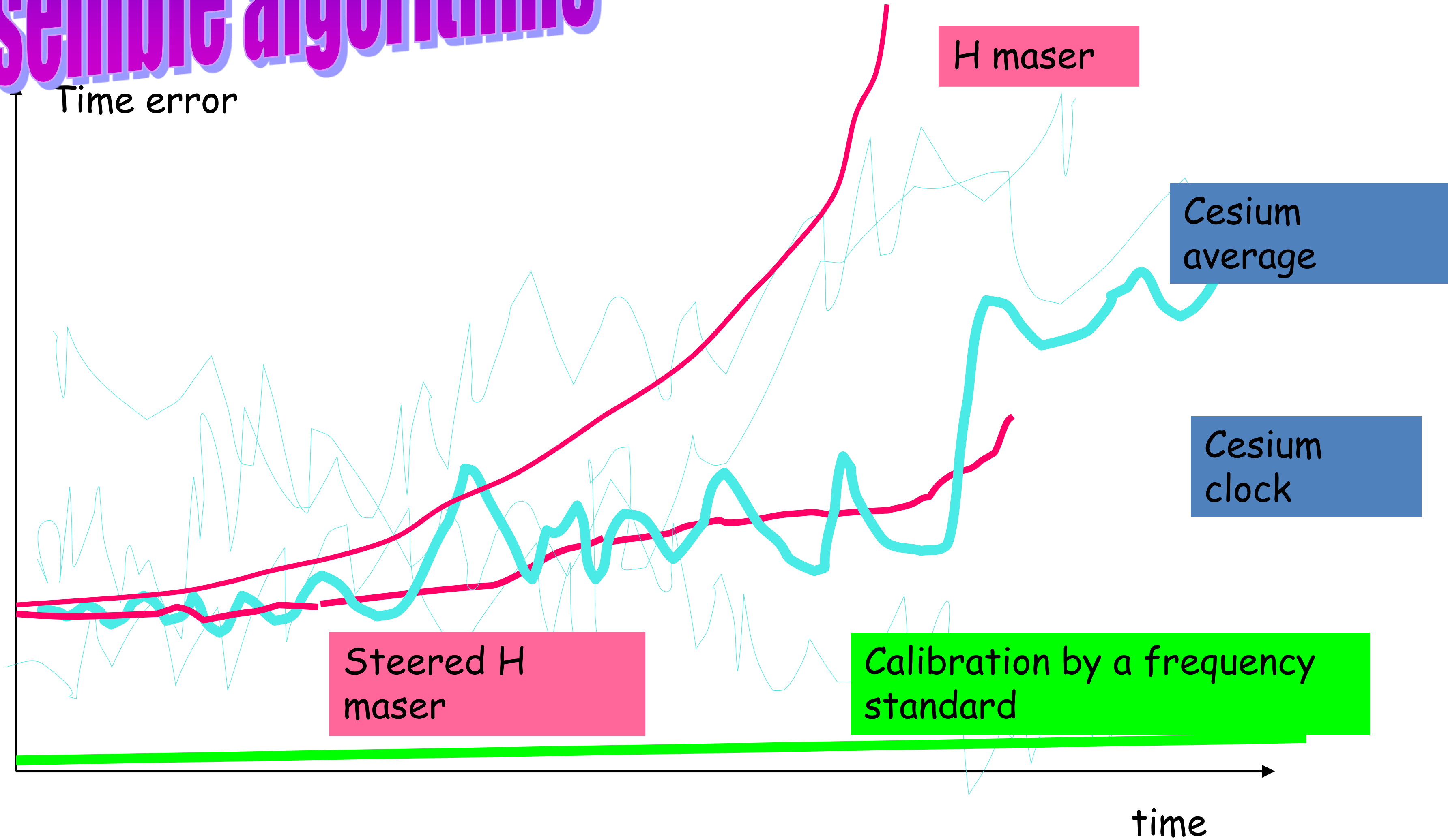
leap seconds

UTC

Coordinated Universal Time

[*UTC* - *UTC*(*k*)] **BIPM *Circular T***

Ensemble algorithms



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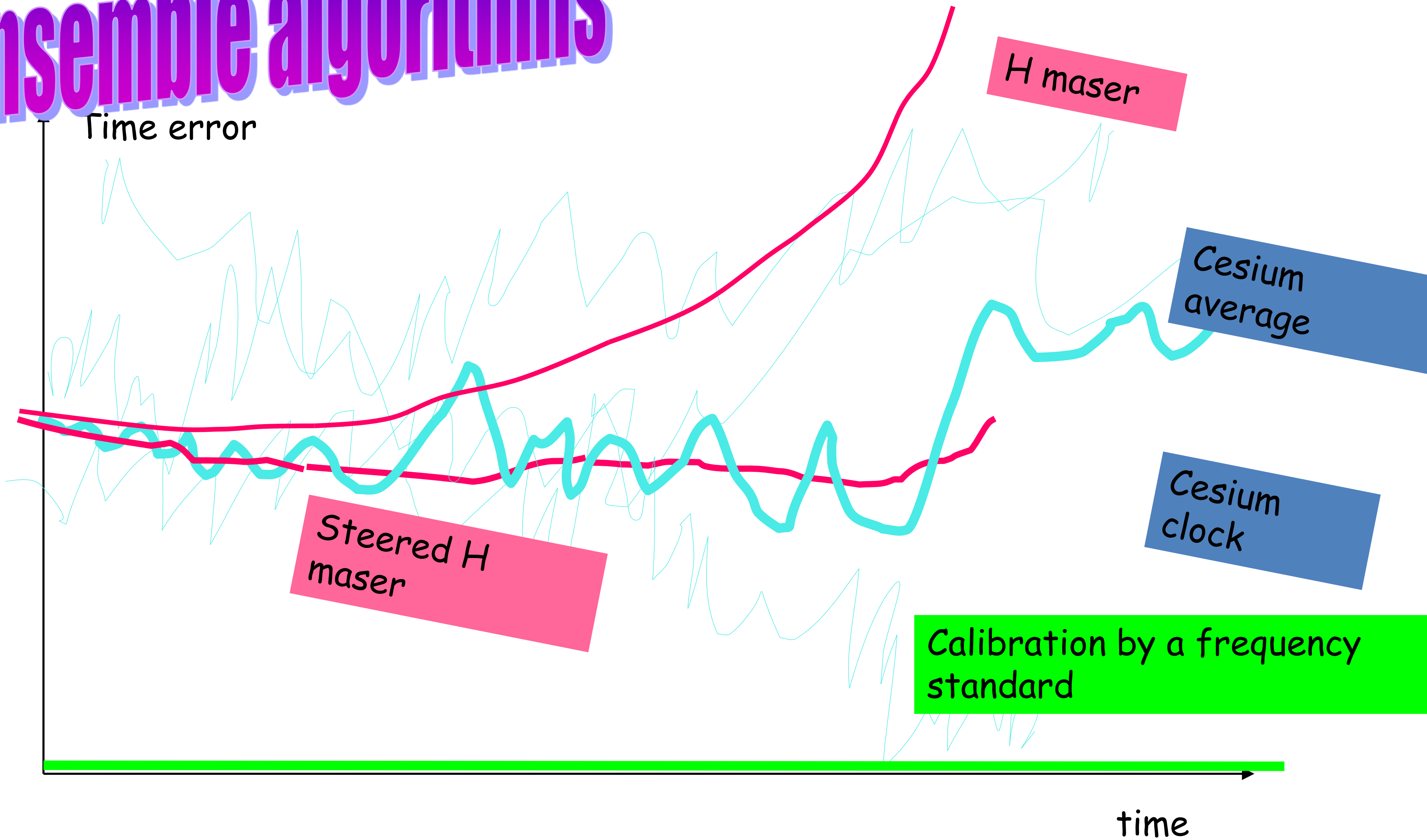
Ensemble algorithms

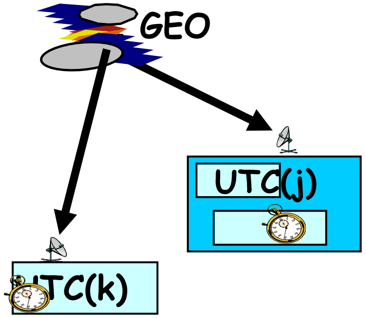


About 500 Clocks participating in TAI

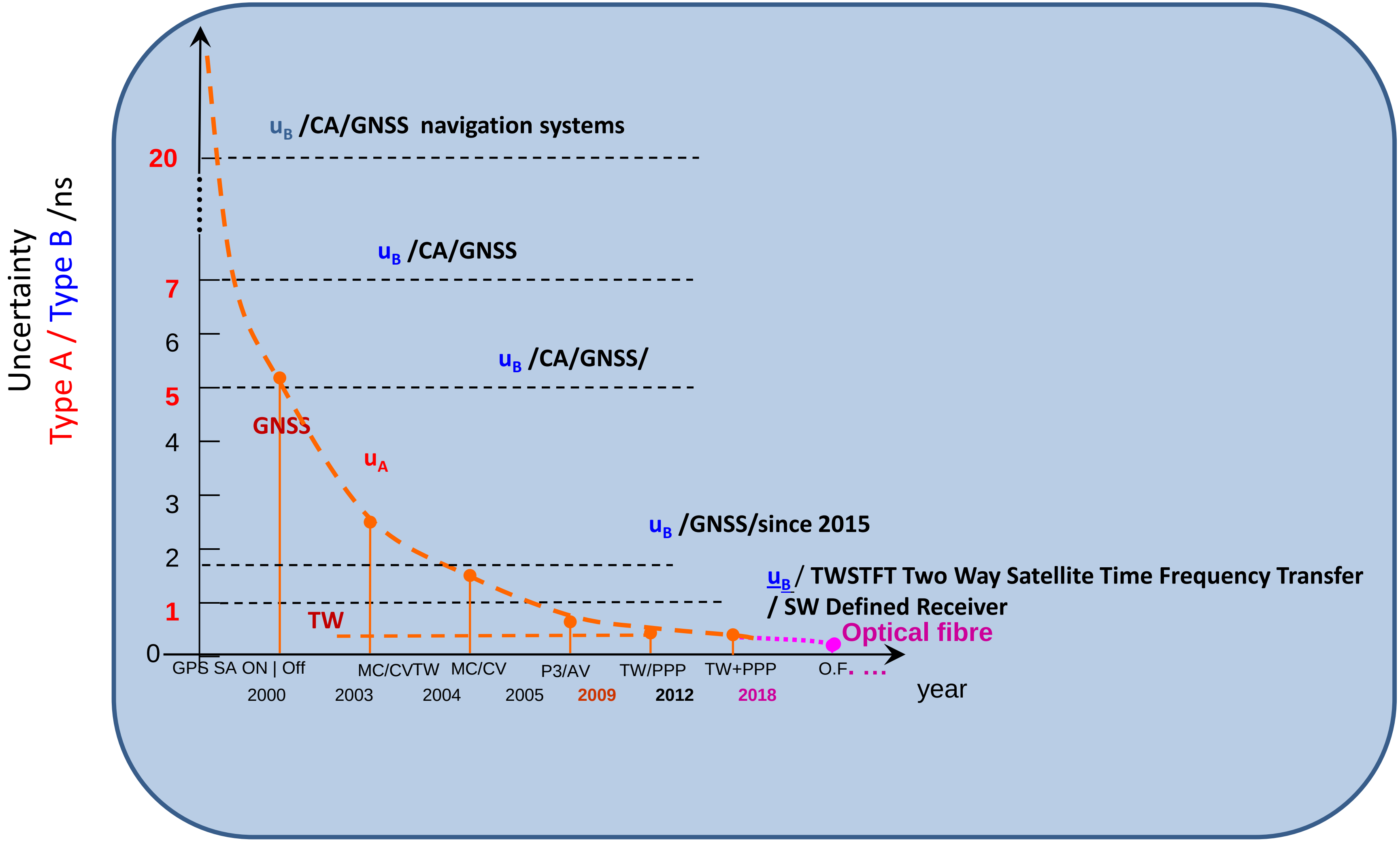
• Cesium clocks	60%
• Hydrogen masers	35%
• Others	5%

PTB-CS1
PTB-CS2

Remote clock comparison



Evolution of time links and uncertainties since 2000



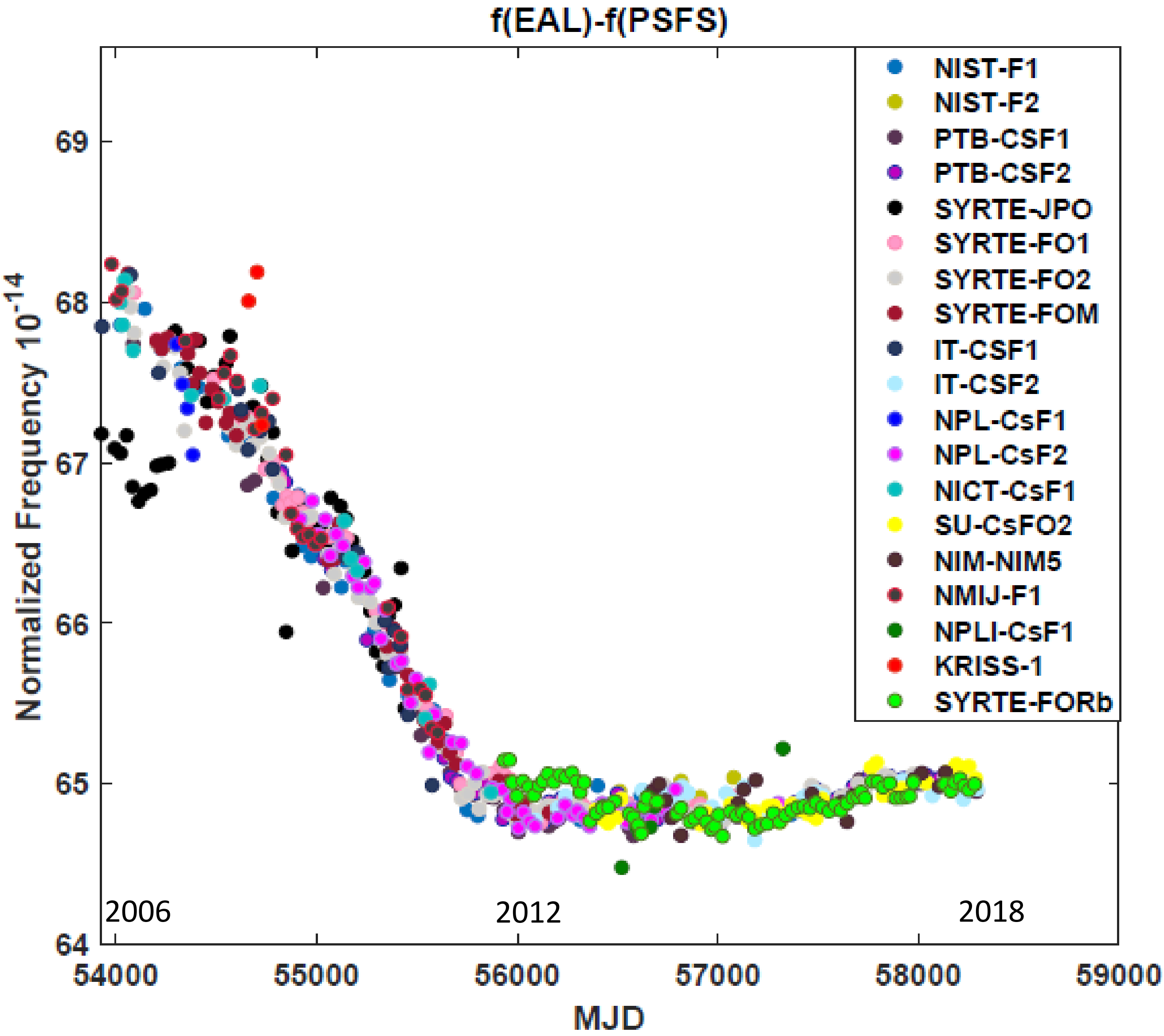
Primary and secondary frequency standards

- Primary and secondary standards reported to the BIPM
  - 2016: 56 reports from 8 fountains (the best is slightly below 2x10^{-16})
  - 2017: 45 reports from 7 fountains + 2 optical lattices

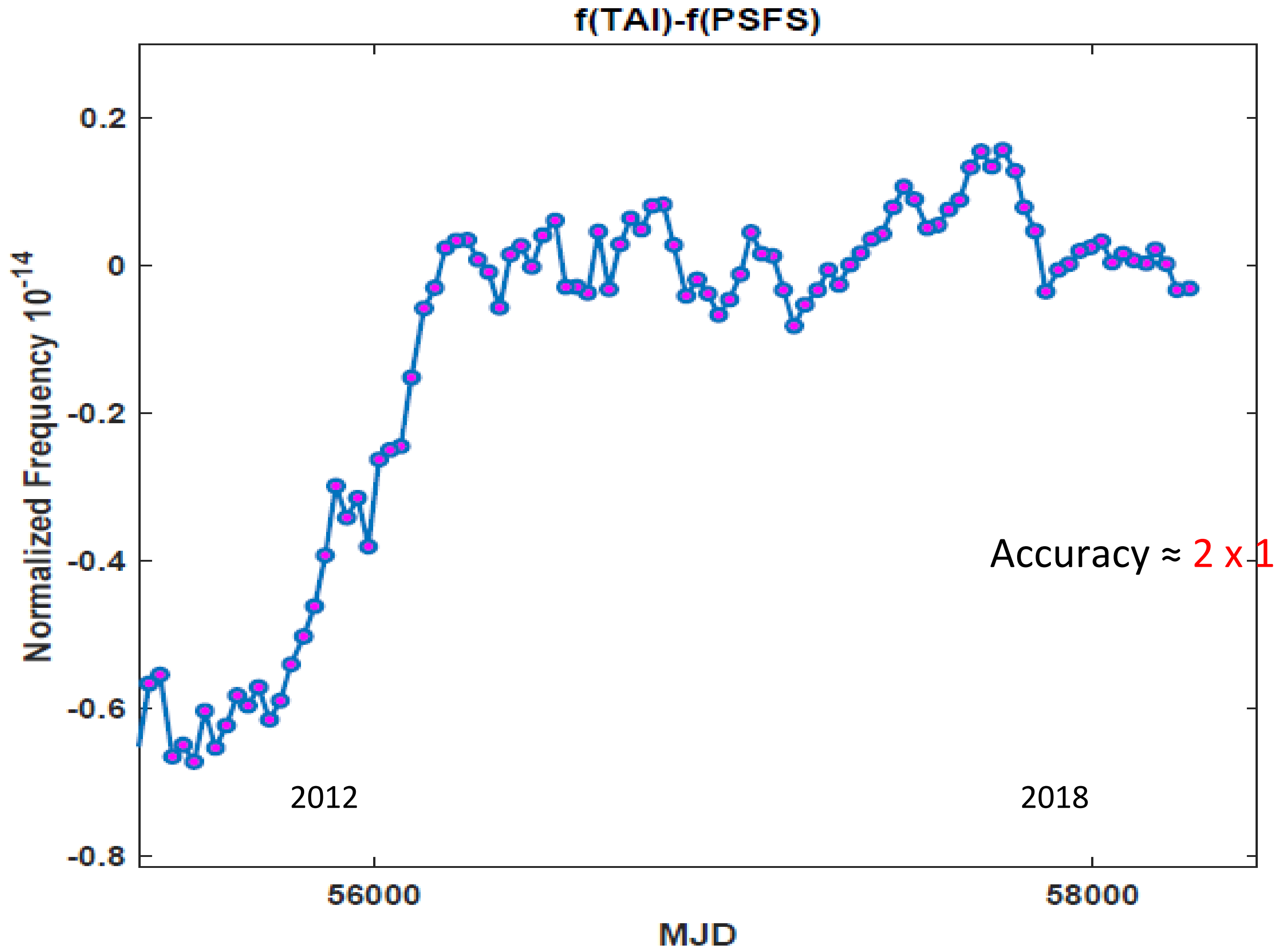
Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CsF2	Fountain	0.17	Discontinuous	H maser	3 / 20 d to 30 d
NIM5	Fountain	1.4, then 0.9	Discontinuous	H maser	3 / 15 d to 20 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 25 d to 35 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	12 / 25 d to 35 d
PTB-CSF1	Fountain	0.35 to 0.40	Nearly continuous	H maser	7 / 15 d to 30 d
PTB-CSF2	Fountain	0.20 to 0.24	Nearly continuous	H maser	12 / 20 d to 35 d
SU-CsFO2	Fountain	0.24	Nearly continuous	H maser	6 / 15 d to 35 d
SYRTE-FO2	Fountain	0.24 to 0.37	Nearly continuous	H maser	9 / 10 d to 35 d
Secondary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
SYRTE-FORb	Fountain	0.28 to 0.30	Nearly continuous	H maser	9 / 10 d to 35 d
SYRTE-Sr2	Lattice	0.04 or 0.20	Discontinuous	H maser	4 / 10 d to 20 d
SYRTE-SrB	Lattice	0.05	Discontinuous	H maser	1 / 15 d

- Development of new standards is encouraged
  - Cs fountains (~6-7 currently under development)
  - Secondary Frequency Standards are strongly expected to contribute

Primary standards calibrate the frequency of the Echelle Atomique Libre EAL



From EAL to TAI with the PFS steering

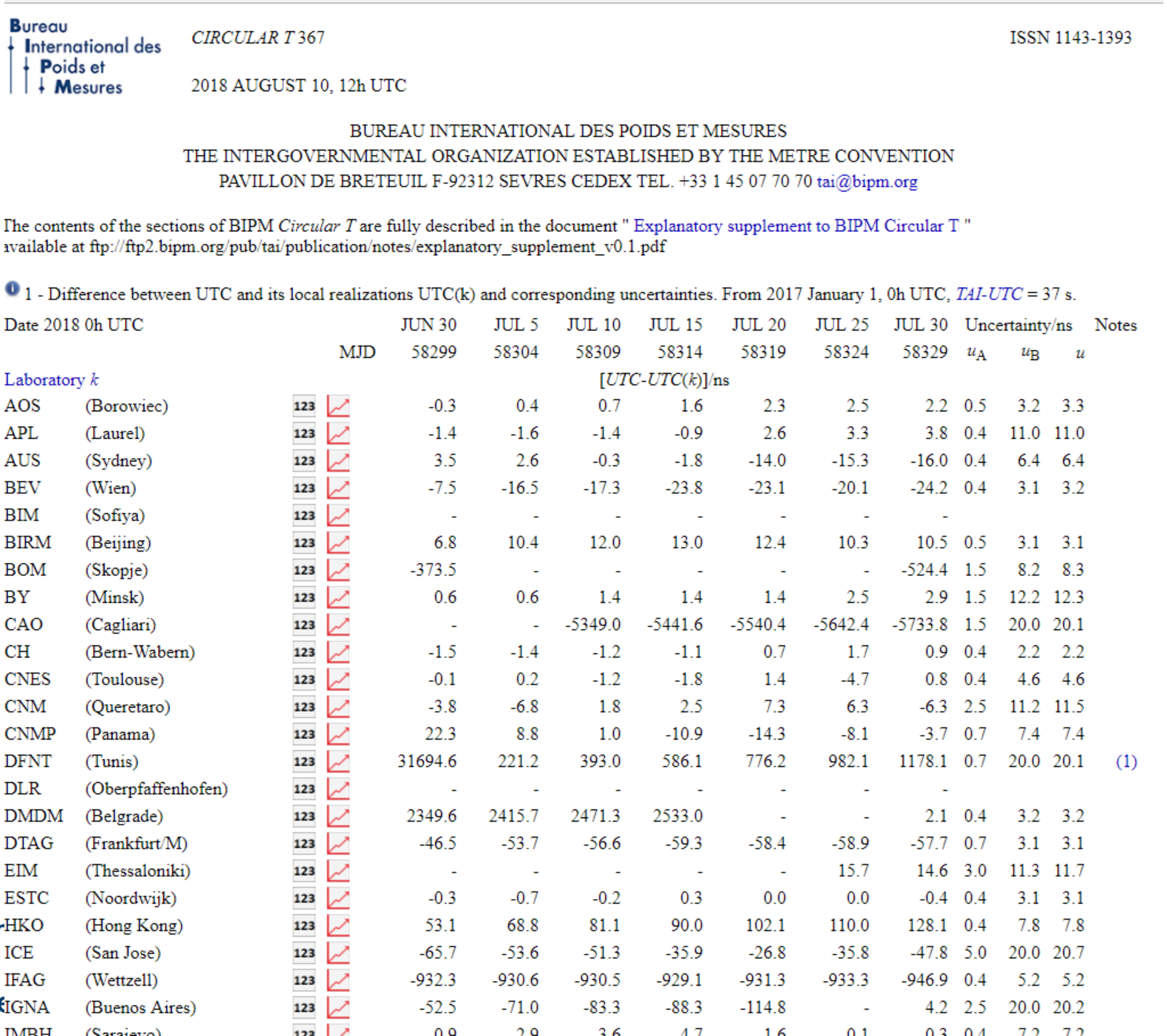


Accuracy ≈ 2 x 10^{-16} since 2012

Period of estimation	*d departure of TAI unit from the SI second*	*u*	
58299-58329	0.63×10^{-15}	0.25×10^{-15}	(2018 JUN 30 - 2018 JUL 30)

ftp://ftp2.bipm.org/pub/tai//Circular-T/cirthtm/cirt.367.html

UTC - UTC(lab) in BIPM Circular T



CIRCULAR T 367

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2018 AUGUST 10, 12h 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_v0.1.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 2018 0h UTC				JUN 30	JUL 5	JUL 10	JUL 15	JUL 20	JUL 25	JUL 30	Uncertainty/ns			Notes
			MJD	58299	58304	58309	58314	58319	58324	58329	u_A	u_B	u	
Laboratory *k*						[*UTC-UTC*(*k*)]/ns								
AOS	(Borowiec)	123	📈	-0.3	0.4	0.7	1.6	2.3	2.5	2.2	0.5	3.2	3.3	
APL	(Laurel)	123	📈	-1.4	-1.6	-1.4	-0.9	2.6	3.3	3.8	0.4	11.0	11.0	
AUS	(Sydney)	123	📈	3.5	2.6	-0.3	-1.8	-14.0	-15.3	-16.0	0.4	6.4	6.4	
BEV	(Wien)	123	📈	-7.5	-16.5	-17.3	-23.8	-23.1	-20.1	-24.2	0.4	3.1	3.2	
BIM	(Sofiya)	123	📈	-	-	-	-	-	-	-				
BIRM	(Beijing)	123	📈	6.8	10.4	12.0	13.0	12.4	10.3	10.5	0.5	3.1	3.1	
BOM	(Skopje)	123	📈	-373.5	-	-	-	-	-	-524.4	1.5	8.2	8.3	
BY	(Minsk)	123	📈	0.6	0.6	1.4	1.4	1.4	2.5	2.9	1.5	12.2	12.3	
CAO	(Cagliari)	123	📈	-	-	-5349.0	-5441.6	-5540.4	-5642.4	-5733.8	1.5	20.0	20.1	
CH	(Bern-Wabern)	123	📈	-1.5	-1.4	-1.2	-1.1	0.7	1.7	0.9	0.4	2.2	2.2	
CNES	(Toulouse)	123	📈	-0.1	0.2	-1.2	-1.8	1.4	-4.7	0.8	0.4	4.6	4.6	
CNM	(Queretaro)	123	📈	-3.8	-6.8	1.8	2.5	7.3	6.3	-6.3	2.5	11.2	11.5	
CNMP	(Panama)	123	📈	22.3	8.8	1.0	-10.9	-14.3	-8.1	-3.7	0.7	7.4	7.4	
DFNT	(Tunis)	123	📈	31694.6	221.2	393.0	586.1	776.2	982.1	1178.1	0.7	20.0	20.1	(1)
DLR	(Oberpfaffenhofen)	123	📈	-	-	-	-	-	-	-				
DMDM	(Belgrade)	123	📈	2349.6	2415.7	2471.3	2533.0	-	-	2.1	0.4	3.2	3.2	
DTAG	(Frankfurt/M)	123	📈	-46.5	-53.7	-56.6	-59.3	-58.4	-58.9	-57.7	0.7	3.1	3.1	
EIM	(Thessaloniki)	123	📈	-	-	-	-	-	15.7	14.6	3.0	11.3	11.7	
ESTC	(Noordwijk)	123	📈	-0.3	-0.7	-0.2	0.3	0.0	0.0	-0.4	0.4	3.1	3.1	
HKO	(Hong Kong)	123	📈	53.1	68.8	81.1	90.0	102.1	110.0	128.1	0.4	7.8	7.8	
ICE	(San Jose)	123	📈	-65.7	-53.6	-51.3	-35.9	-26.8	-35.8	-47.8	5.0	20.0	20.7	
IFAG	(Wettzell)	123	📈	-932.3	-930.6	-930.5	-929.1	-931.3	-933.3	-946.9	0.4	5.2	5.2	
IGNA	(Buenos Aires)	123	📈	-52.5	-71.0	-83.3	-88.3	-114.8	-	4.2	2.5	20.0	20.2	
IMBH	(Sarajevo)	123	📈	0.9	2.9	3.6	4.7	1.6	0.1	0.3	0.4	7.2	7.2	

Since 2013 a rapid evaluation of UTC is available

every week,
on Wednesdays

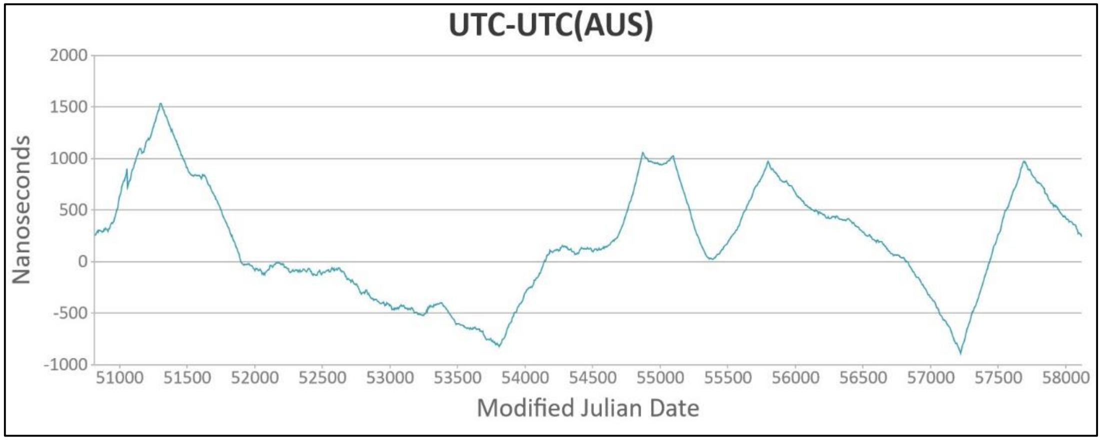
the results are

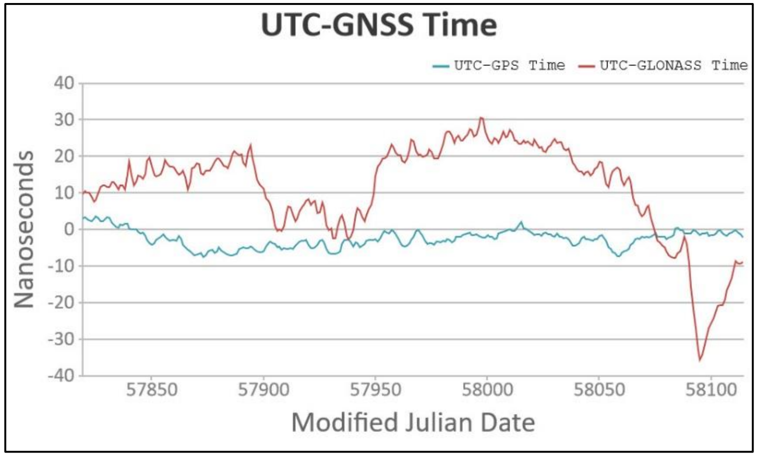
UTCr - UTC (k)

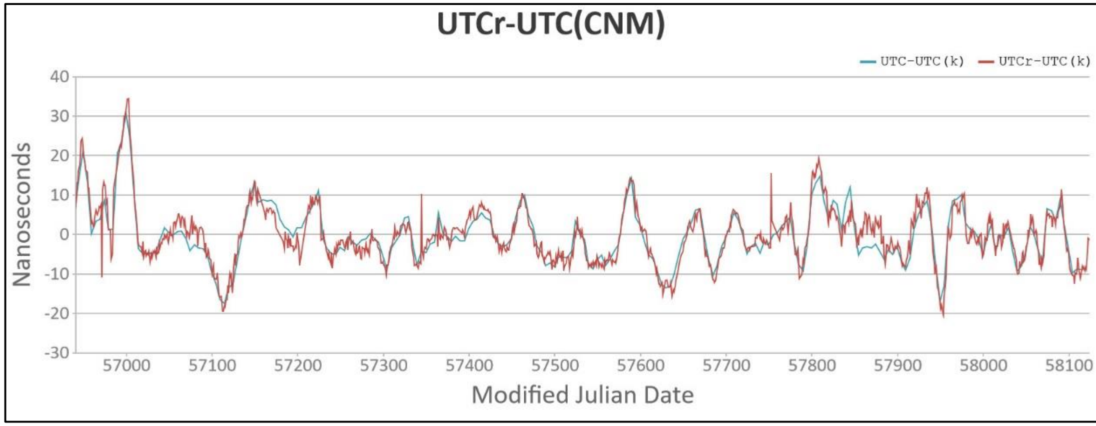
in the previous week (Monday-Sunday)

Results are available in the data base *http://webtai.bipm.org/database/* *and https://www.bipm.org/en/bipm-services/timescales/time-ftp*

- Allows to generate dynamic plots using Time Department products :
  - UTC-UTC(k)
  - UTCr-UTC(k)
  - UTC-GNSS Times







ftp://ftp2.bipm.org/pub/tai/other-products/etoile/et18.07

```
--- Fractionnal frequency of EAL for CirT.367 TAI367
```

```
                 Measurements               in 10**-13
  Code   Standard         Start   End      f(EAL)-f(st.) Unc.A     Unc.B      Coef.       Residual    Norm.Res
 1920001 PTB CS1        57934. 57964.   6.53409  0.06001  0.08000   0.000003   0.03940   0.39401
 1920002 PTB CS2        57934. 57964.   6.55145  0.03003  0.12000   0.000002   0.05676   0.45888
 1920803 OP  FO2        57934. 57944.   6.49370  0.00930  0.00240   0.000333  -0.00099  -0.10269
 1920803 OP  FO2        57949. 57964.   6.50082  0.00552  0.00240   0.000700   0.00613   1.01903
 1920502 PTB CSF2       57934. 57954.   6.50325  0.00275  0.00240   0.001964   0.00856   2.34622
 1930803 OP  FORb       57934. 57944.   6.49550  0.00775  0.00662   0.000296   0.00082   0.08027
 1930803 OP  FORb       57949. 57964.   6.49592  0.00597  0.00662   0.000319   0.00124   0.13889
 1920001 PTB CS1        57964. 57994.   6.57614  0.06002  0.08000   0.000002   0.08145   0.81444
 1920002 PTB CS2        57964. 57994.   6.50245  0.03005  0.12000   0.000001   0.00776   0.06276
 1924801 NIM NIM5       57969. 57989.   6.50262  0.00913  0.01400   0.000056   0.00793   0.47468
 1920803 OP  FO2        57964. 57984.   6.50575  0.00467  0.00260   0.000710   0.01106   2.06992
```

```
# Estimate of d by individual PSFS measurements and corresponding uncertainties.
#-------------------------------------------------------------------------------------------------------
 SU-CsFO2   56684 56714  -0.50   0.29   0.50  0.10   0.33    0.67   PFS/NA     [3]    0.50     Y         1403
 SU-CsFO2   56899 56929   0.85   0.24   0.25  0.10   0.33    0.49   PFS/NA    T315     0.48     Y        1409
 SU-CsFO2   56929 56959   0.13   0.22   0.25  0.11   0.33    0.48   PFS/NA    T315    0.50     Y        1410
 SU-CsFO2   56959 56989   0.53   0.23   0.25  0.11   0.33    0.48   PFS/NA    T315    0.50     Y        1411
```

How secondary frequency standard

can contribute to UTC ?

They are already contributing

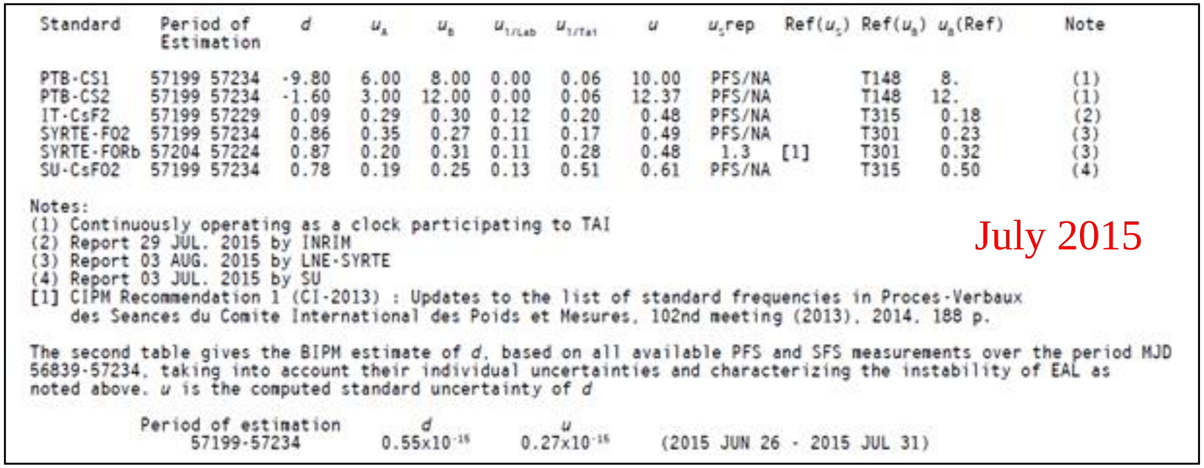
In Circular T there are the PFS evaluations

In July 2015 we can see the SYRTE – Rb fountain

in March 2017 the SYRTE Strontium standards

Secondary Standards contribute to the steering of TAI since July 2013, if deemed not detrimental.

=> new column introduced.



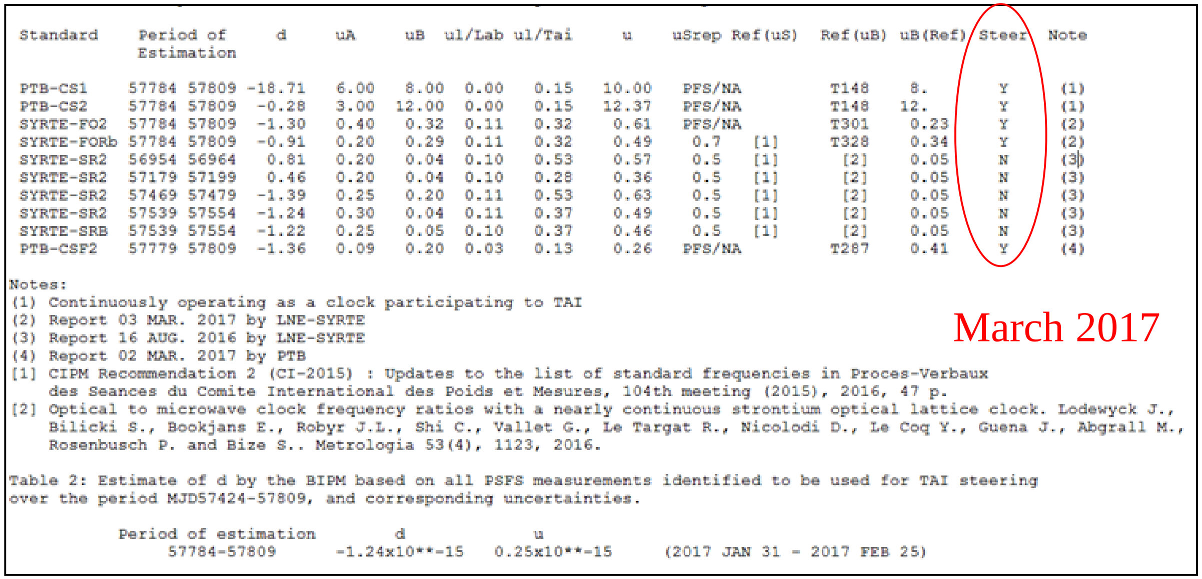
Standard	Period of Estimation	d	u_A	u_B	$u_{l/Lab}$	$u_{l/Tai}$	u	$u_S$rep	Ref(u_S)	Ref(u_B)	u_B(Ref)	Note
PTB-CS1	57199 57234	-9.80	6.00	8.00	0.00	0.06	10.00	PFS/NA		T148	8.	(1)
PTB-CS2	57199 57234	-1.60	3.00	12.00	0.00	0.06	12.37	PFS/NA		T148	12.	(1)
IT-CsF2	57199 57229	0.09	0.29	0.30	0.12	0.20	0.48	PFS/NA		T315	0.18	(2)
SYRTE-FO2	57199 57234	0.86	0.35	0.27	0.11	0.17	0.49	PFS/NA		T301	0.23	(3)
SYRTE-FORb	57204 57224	0.87	0.20	0.31	0.11	0.28	0.48	1.3	[1]	T301	0.32	(3)
SU-CsF02	57199 57234	0.78	0.19	0.25	0.13	0.51	0.61	PFS/NA		T315	0.50	(4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 29 JUL. 2015 by INRIM
(3) Report 03 AUG. 2015 by LNE-SYRTE
(4) Report 03 JUL. 2015 by SU
[1] CIPM Recommendation 1 (CI-2013) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 102nd meeting (2013), 2014, 188 p.

The second table gives the BIPM estimate of *d*, based on all available PFS and SFS measurements over the period MJD 56839-57234, taking into account their individual uncertainties and characterizing the instability of EAL as noted above. *u* is the computed standard uncertainty of *d*

Period of estimation	d	u	
57199-57234	0.55×10^{-15}	0.27×10^{-15}	(2015 JUN 26 - 2015 JUL 31)

July 2015



Standard	Period of Estimation	d	uA	uB	ul/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Steer	Note
PTB-CS1	57784 57809	-18.71	6.00	8.00	0.00	0.15	10.00	PFS/NA		T148	8.	Y	(1)
PTB-CS2	57784 57809	-0.28	3.00	12.00	0.00	0.15	12.37	PFS/NA		T148	12.	Y	(1)
SYRTE-FO2	57784 57809	-1.30	0.40	0.32	0.11	0.32	0.61	PFS/NA		T301	0.23	Y	(2)
SYRTE-FORb	57784 57809	-0.91	0.20	0.29	0.11	0.32	0.49	0.7	[1]	T328	0.34	Y	(2)
SYRTE-SR2	56954 56964	0.81	0.20	0.04	0.10	0.53	0.57	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57179 57199	0.46	0.20	0.04	0.10	0.28	0.36	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57469 57479	-1.39	0.25	0.20	0.11	0.53	0.63	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57539 57554	-1.24	0.30	0.04	0.11	0.37	0.49	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SRB	57539 57554	-1.22	0.25	0.05	0.10	0.37	0.46	0.5	[1]	[2]	0.05	N	(3)
PTB-CSF2	57779 57809	-1.36	0.09	0.20	0.03	0.13	0.26	PFS/NA		T287	0.41	Y	(4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 03 MAR. 2017 by LNE-SYRTE
(3) Report 16 AUG. 2016 by LNE-SYRTE
(4) Report 02 MAR. 2017 by PTB
[1] CIPM Recommendation 2 (CI-2015) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 104th meeting (2015), 2016, 47 p.
[2] Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. Lodewyck J., Bilicki S., Bookjans E., Robyr J.L., Shi C., Vallet G., Le Targat R., Nicolodi D., Le Coq Y., Guena J., Abgrall M., Rosenbusch P. and Bize S.. Metrologia 53(4), 1123, 2016.

Table 2: Estimate of d by the BIPM based on all PSFS measurements identified to be used for TAI steering over the period MJD57424-57809, and corresponding uncertainties.

Period of estimation	d	u	
57784-57809	-1.24x10**-15	0.25x10**-15	(2017 JAN 31 - 2017 FEB 25)

March 2017

13th CGPM (1967)

Resolution 1

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.

Resolution 2

Considering that the cesium frequency standard is still perfectible and current experiments allow the hope of producing other standards with even better qualities to define the second,

invites …. laboratories in the field of atomic frequency standards to actively pursue their studies.

Metrologia **55** (2018) 188 F Riehle *et al*

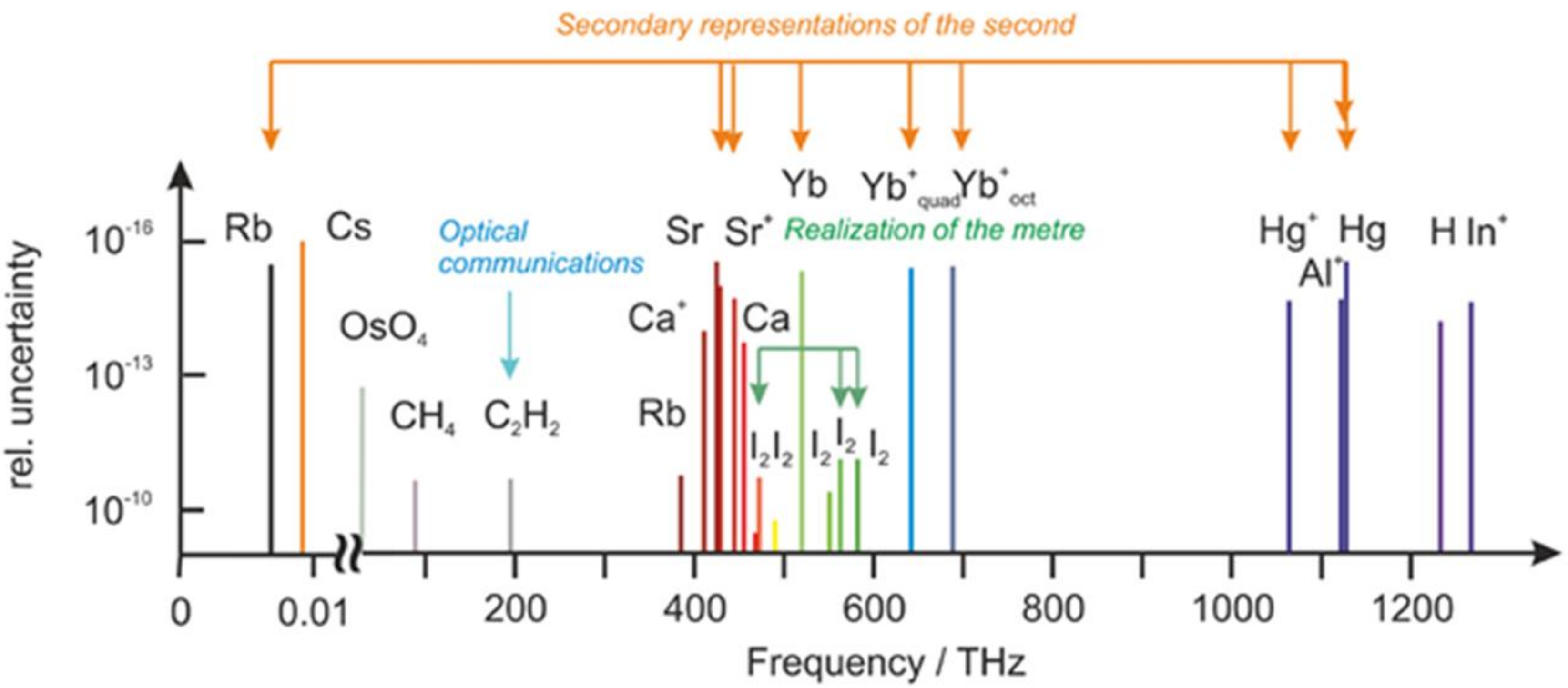


Figure 3. Graphical summary of the recommended frequency standard values (as of 2017) and their specific use for optical communications, for the realization of the metre, or for SRS.

See https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

How a Secondary Frequency Standard can be evaluated with respect to the SI second?

- By comparing against a primary freq standard, like a CS fountain, connected by a short cable or a long fibre
- By measuring SFS with respect to a UTC(k) time scale or an individual clock entering in UTC
  - Using Circular T monthly estimation of d_{TAI}
  - Comparison to the best estimate of an ensemble of PFS (a d_{TAI} estimation on demand)

If the SFS is in Lab, not producing a UTC(k) time scale and not part of UTC?

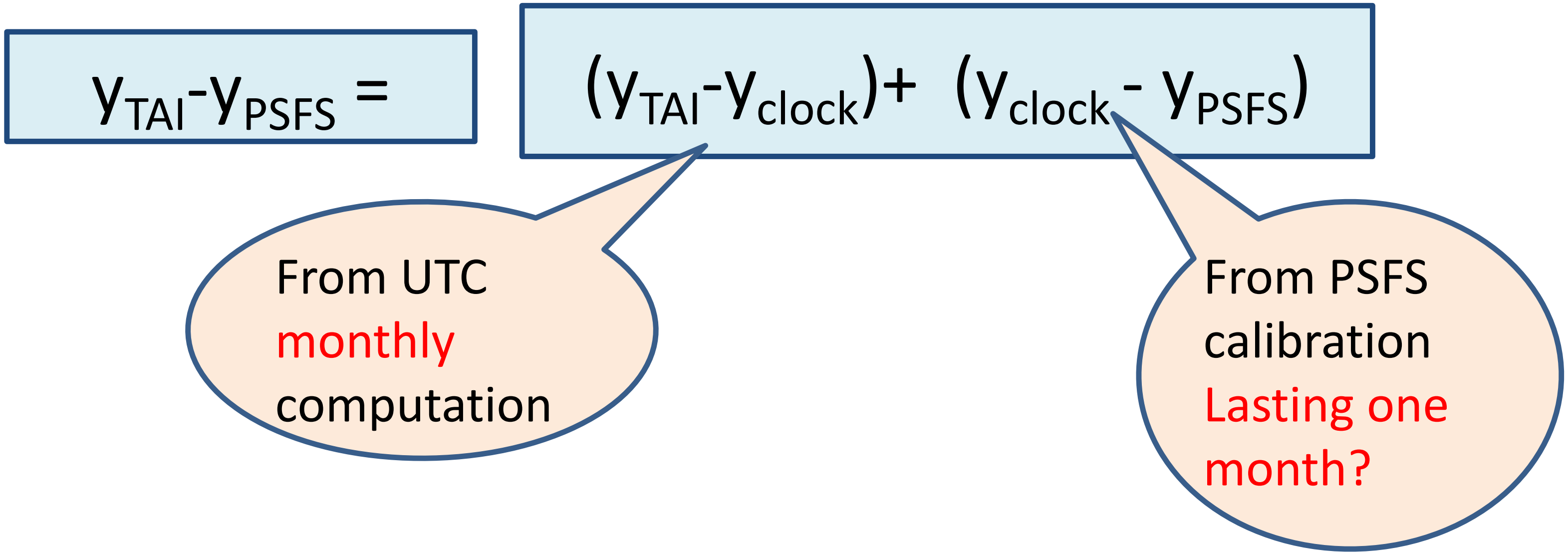
- Any laboratory can be considered as a virtual “additional laboratory” that can be included in BIPM computation if it is equipped for example with a GNSS (Global Navigation Satellite System) receiver.
  - This evaluation will be limited by frequency transfer uncertainty, the TAI deadtime (if the measurement is shorter than 1 month), and by the accuracy of PFS/SFS, as for a UTC laboratory.

See G.Petit, G.Panfilo, “Optimal traceability to the SI second through TAI” Proceedings of the EFTF 2018 and T. Ido tomorrow

How primary and secondary frequency standard PSFS can better enter in UTC?

UTC is a weighted average of clock reading based on clock time comparison

The PSFS are frequency calibrations usually of a « clock » participating to UTC



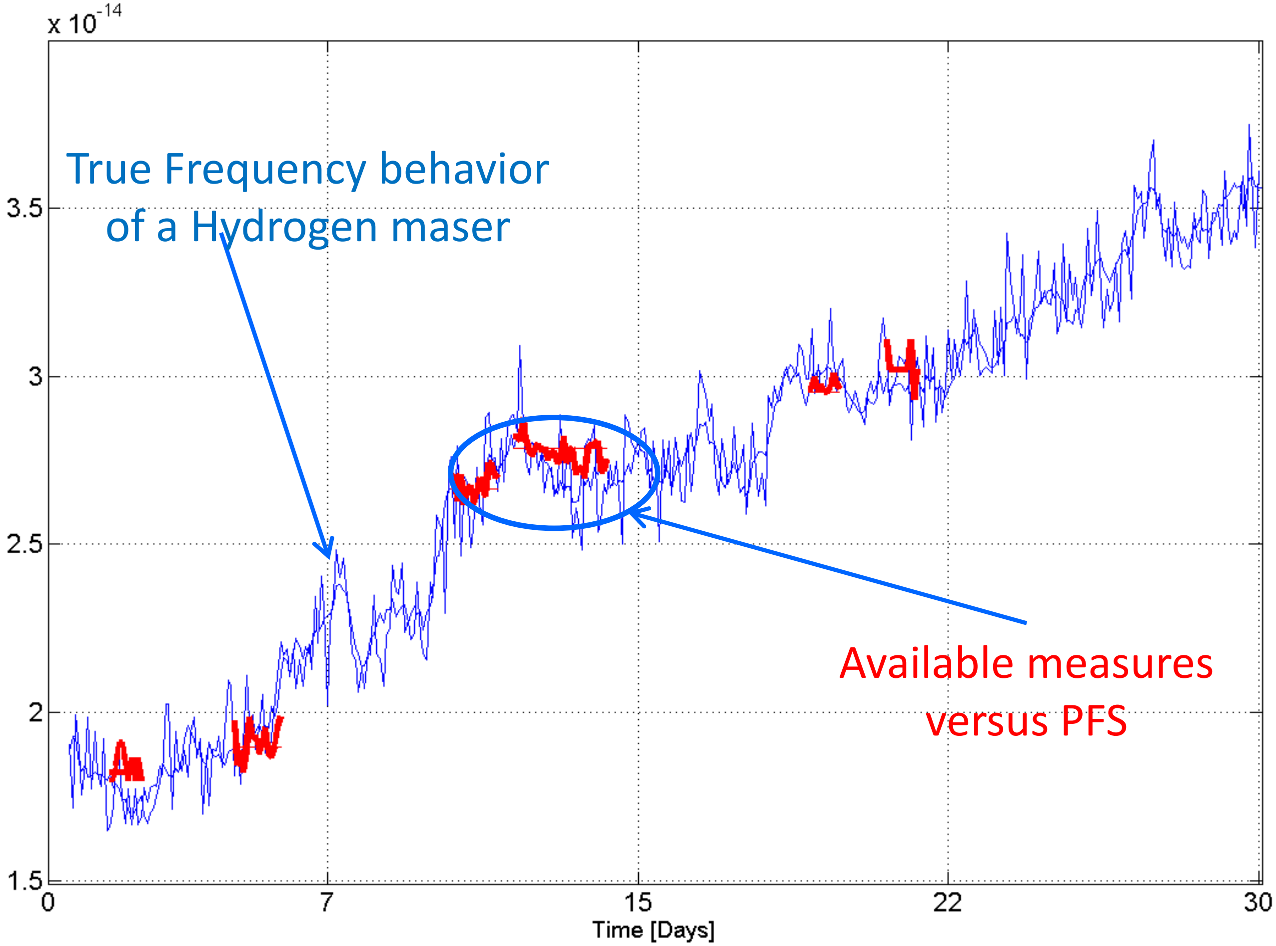
$$y_{TAI}-y_{PSFS} = (y_{TAI}-y_{clock})+ (y_{clock}- y_{PSFS})$$

From UTC
monthly
computation

From PSFS
calibration
Lasting one
month?

How deadtime can affect the estimation?

Study case: a PSFS is used as reference to measure the frequency of a H maser, whose frequency deviation evolution can be modeled as a straight line affected by *white frequency noise*. PSFS measures are available only a few days during the month



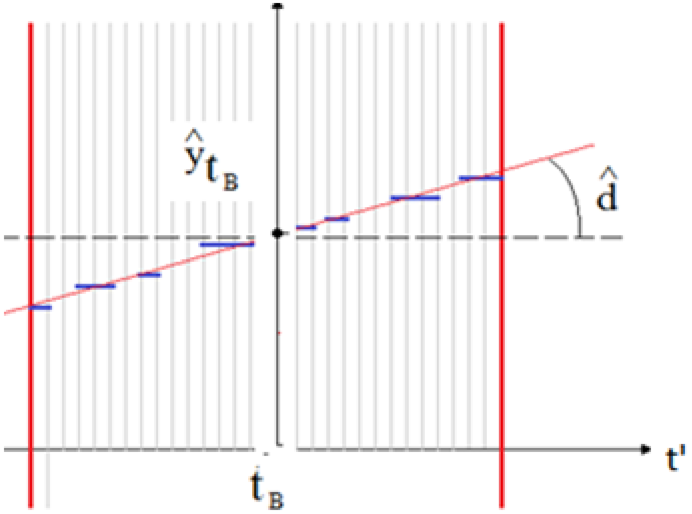
True Frequency behavior of a Hydrogen maser

Available measures versus PFS

Deadtime on a Least Square linear fit

We estimate the effect of deadtime on the least square estimation of a straight line

For easy visualization we use a *barycentre coordinate* → the origin of the new time coordinate is placed in the center of the available measures epochs



$$y(t) = y_{tb} - d(t - t_B)$$

$$t'_i = t_i - t_B$$

$$\sum_{i=1}^{N} t'_i = 0$$

Least Square approach

$$y(t) = y_{tb} - d(t - t_B)$$

$$t_i' = t_i - t_B$$

Estimate of the mean frequency

Estimate of the linear drift

$$\hat{X} = \begin{vmatrix} \widehat{y_b} \\ \hat{d} \end{vmatrix} = \begin{bmatrix} \dfrac{\sum_{i=1}^{N} y_i}{N} \\ \dfrac{\left(\sum_{i=1}^{N} t_i' y_i\right)}{\sum_{i=1}^{N} {t_i'}^2} \end{bmatrix}$$

$$\boxed{\Sigma_{\widehat{y_b}} = \frac{\sigma^2}{N}}$$

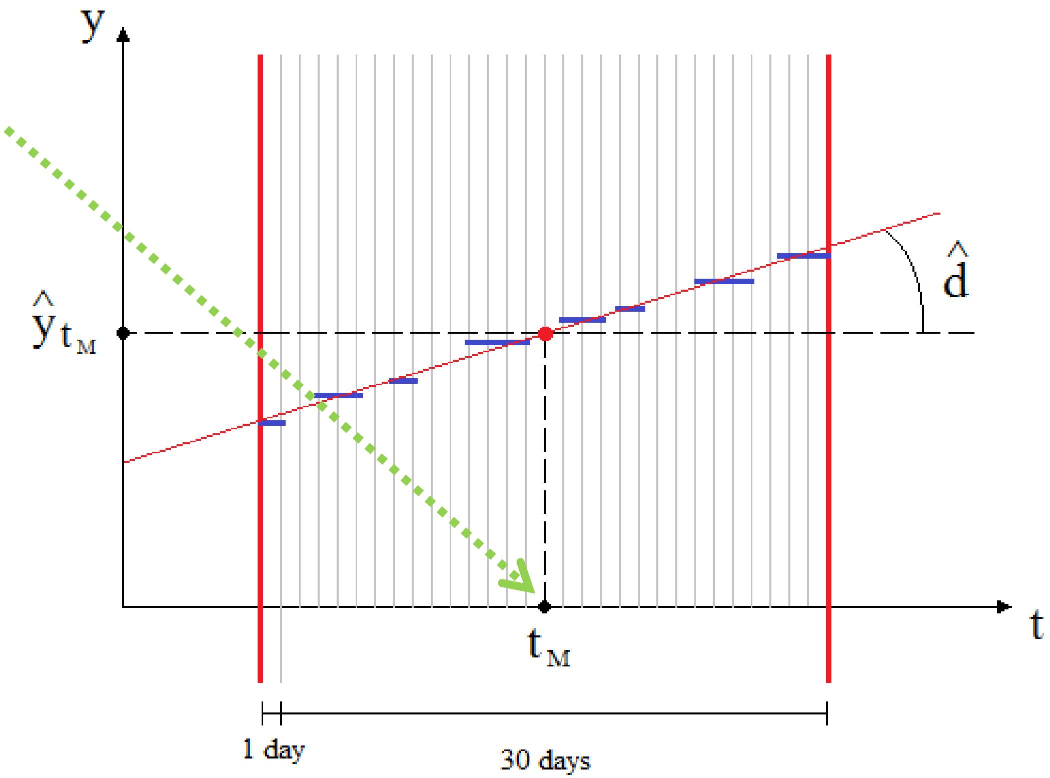
$$\boxed{\Sigma_{\hat{d}} = \frac{\sigma^2}{\sum_{i=1}^{N} {t_i'}^2}}$$

$\Sigma_{\widehat{y_b}}$ depends only on the number of measures and the uncertainty of each of them

$\Sigma_{\hat{d}}$ depends on the uncertainty σ of the measures and on the sum of the distance between all measurement epoch t_i and the baricentre time t_B

Study case: H maser participating to UTC measured versus PSFS

We want to estimate the
mean frequency of the H Maser vs PSFS
in t_M the center of the previous month



In presence of dead time
the estimation time t_M could be
different from the barycentre $t_M \neq t_B$.

$$\hat{y}_{t_M} = \widehat{y_b} + \hat{d}(t_B - t_M)$$

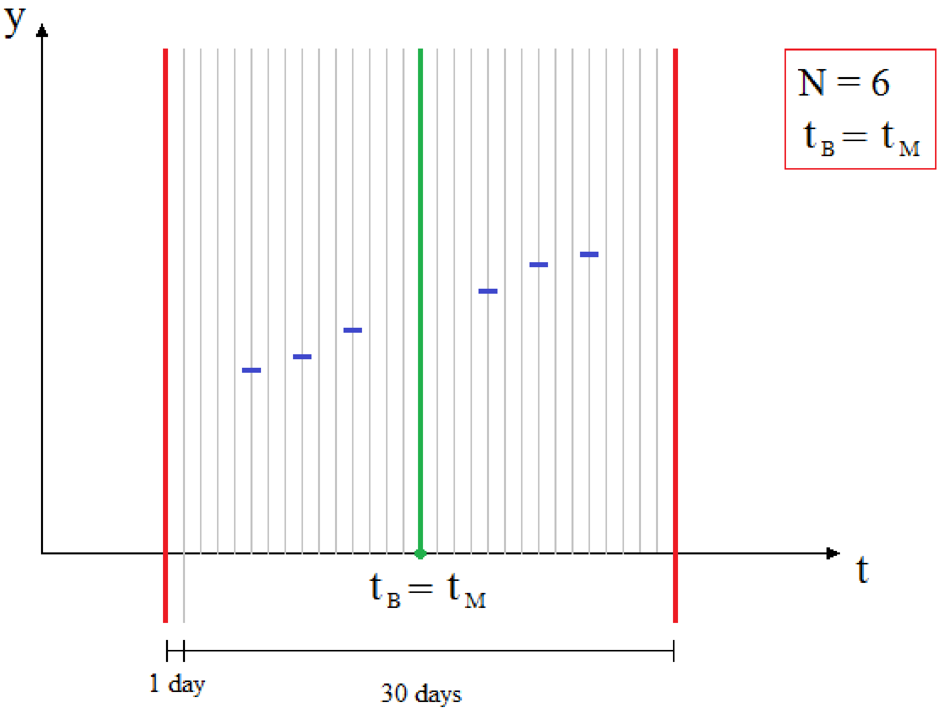
$$u^2_{\hat{y}_{t_M}} = u^2_{\hat{y}_b} + u^2_{\hat{d}}\,(t_B - t_M)$$

H maser participating to UTC measured versus PSFS

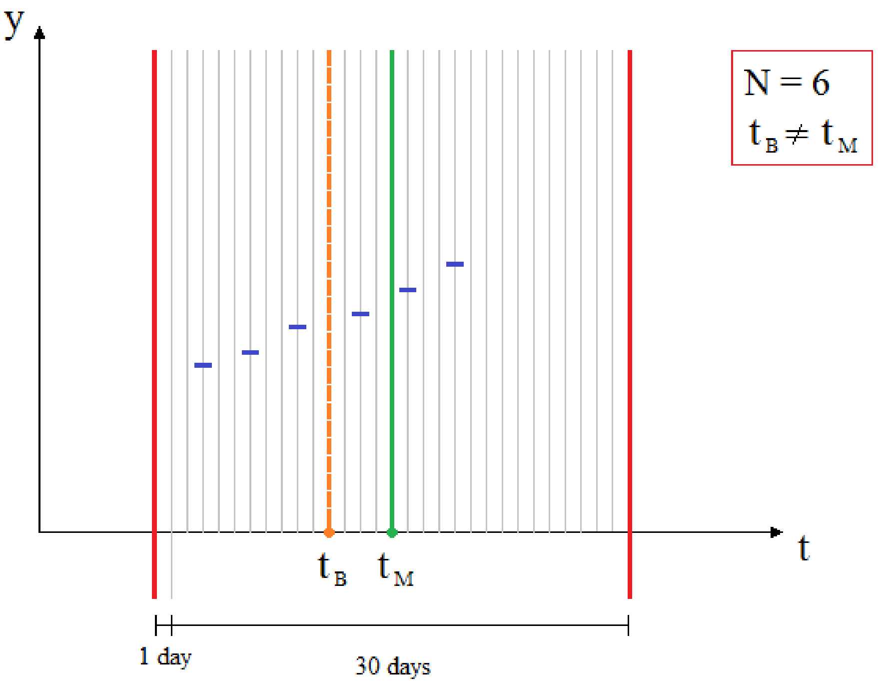
Estimate of $\hat{y}_{t_M}$ *is always good*

$$\begin{cases} y_{t_M} = \dfrac{\sum_{i=1}^{N} y_i}{N} + \dfrac{\sum_{i=1}^{N} t_i' y_i}{\sum_{i=1}^{N} t_i'^2}(t_B - t_M) \\ u^2_{y_{t_M}} = \dfrac{\sigma^2}{N} + \boxed{\dfrac{\sigma^2}{\sum_{i=1}^{N} t_i'^2}(t_B - t_M)^2} \end{cases}$$

the best case with lower uncertainty on the estimate of $\hat{y}_{t_M}$ corresponds to the case $t_B = t_M$,



the worst case is when t_B is very distant from t_M and the measures are very close to each other

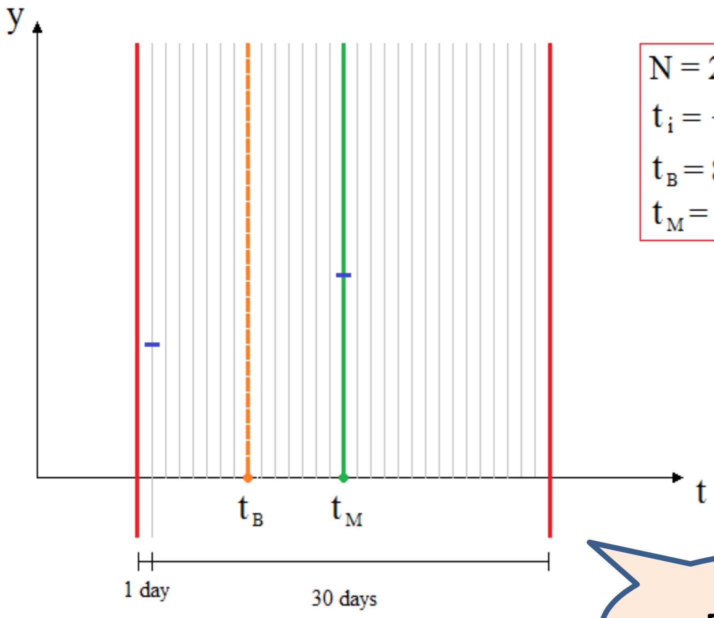


H maser participating to UTC measured versus PSFS

When $t_B \neq t_M$ the uncertainty depends on the distance among the measures and between t_B and t_M

CASE A

Distant Measures

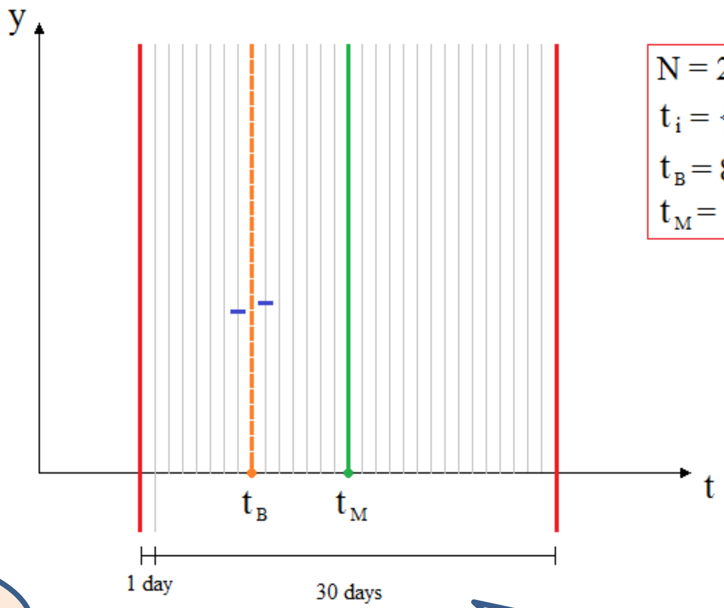


$N = 2$
$t_i = \{1 , 15\}$
$t_B = 8$
$t_M = 15$

Best case

CASE B

Contiguous Measures



$N = 2$
$t_i = \{7 , 9\}$
$t_B = 8$
$t_M = 15$

Worst case

H maser participating to UTC measured versus PSFS

- The estimate of the frequency offset does not depends on dead times and it is always correct (under these assumptions)
- Minimum uncertainty is obtained when the measures are symmetric with respect to the center of the month
- Measures not symmetric and very close to each other leads to the worst case

How primary and secondary frequency standard PSFS can better enter in UTC?

Which are the affecting noises and are them stationary?

Time and Frequency spectral analysis
is a useful tool

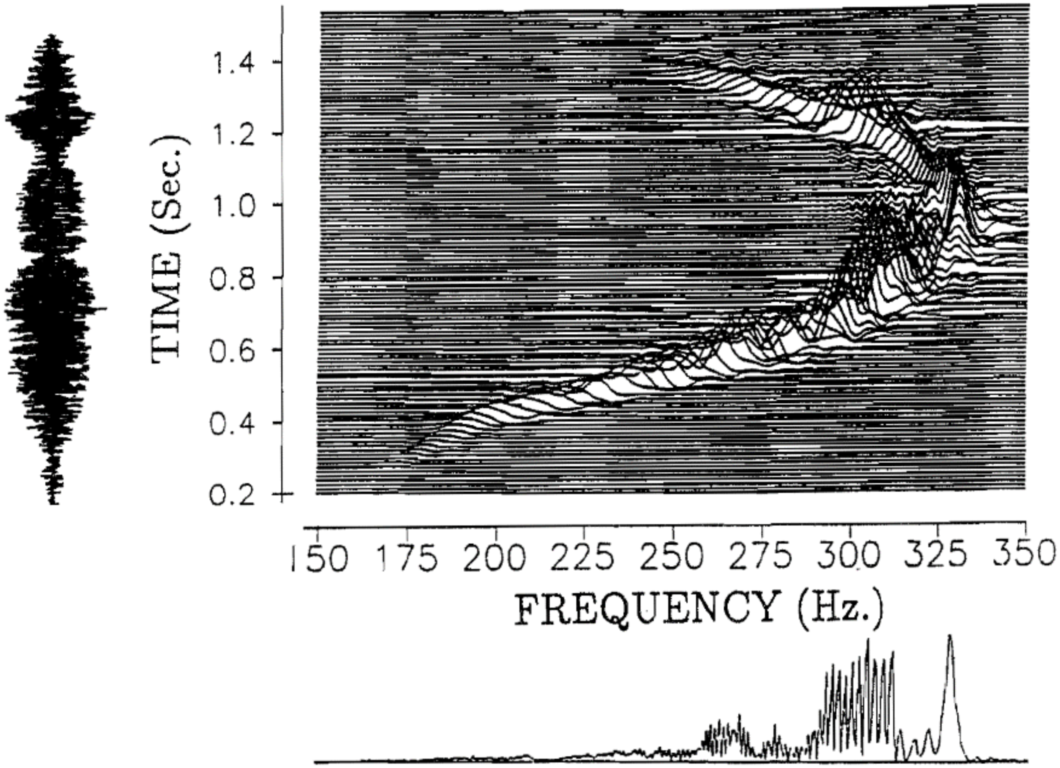
Not only estimating which frequencies existed

But also estimating when they existed

Time-frequency analysis

It describes how the frequencies of a signal change with time

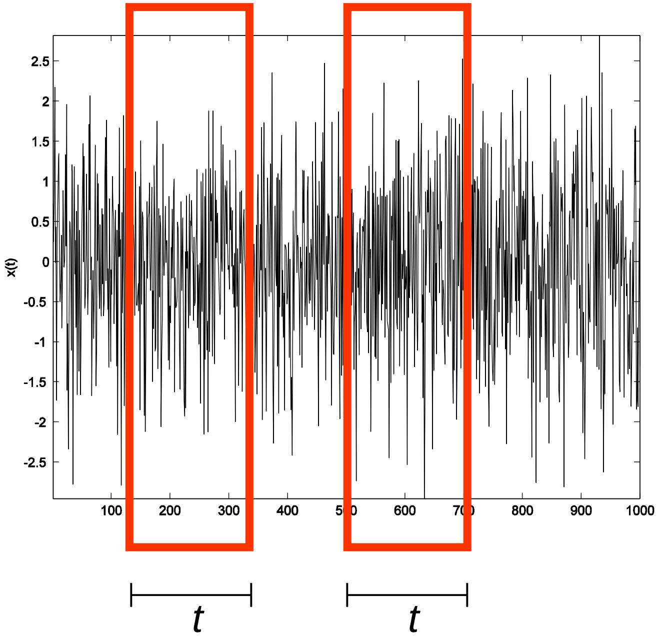
Bowhead whale



L. Cohen, *Time-frequency analysis*, Prentice-Hall, 1995

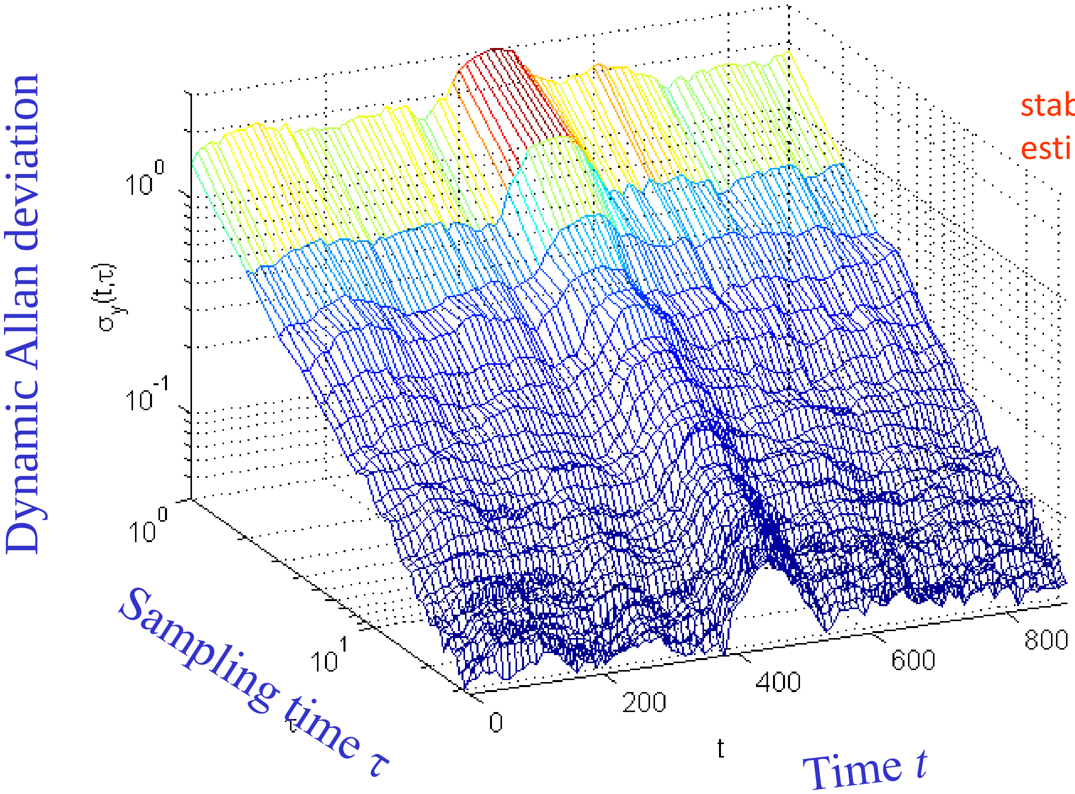
A Dynamic Allan variance

sliding the Allan variance estimator on the data



$$\sigma_y(t_1,\tau) \quad \sigma_y(t_2,\tau) \quad \cdots \Rightarrow \sigma_y(t,\tau)$$

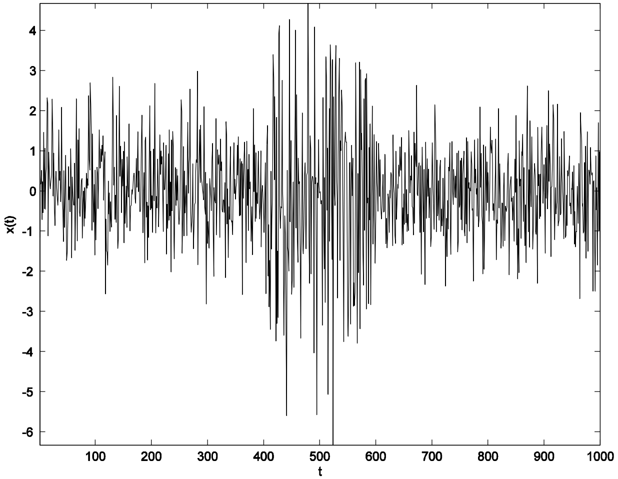
stability may vary with time



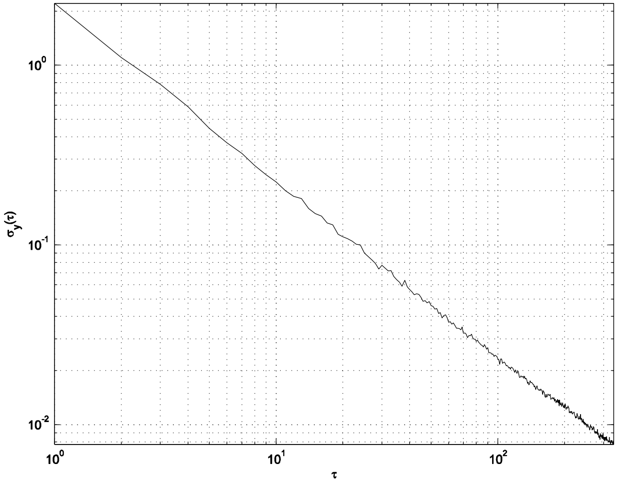
stability sliding estimator

L. Galleani, P. Tavella, "Dynamic Allan variance" , IEEE Trans UFFC, vol. 56, no. 3, March 2009, pp450-464

Simulation results : Bump

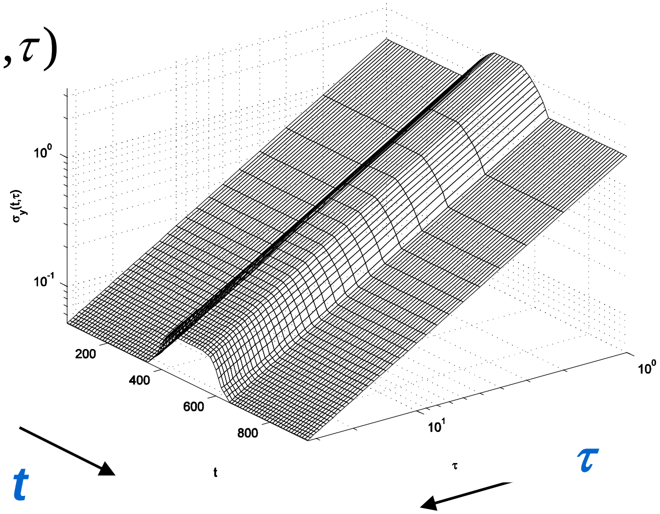


t

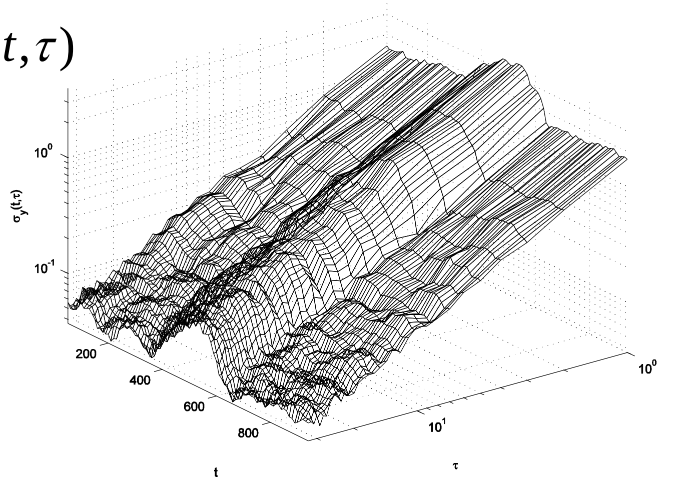


τ

$\sigma_y(t,\tau)$



$\hat{\sigma}_y(t,\tau)$



The Dynamic Allan variance

Discrete time formulation from the phase samples *x*[*n*]

$$\sigma^2{}_y[n,k] = \frac{1}{2k^2\tau_0{}^2}\,\frac{1}{Nw-2k}\sum_{m=n-Nw/2+k}^{n+Nw/2-k-1} E\left[\left(x_N[m+k]-2x_N[m]+x_N[m-k]\right)^2\right]$$

where:

- *Nw* is the window length
- x_N is the phase signal in the window *Nw*
- τ_0 is the sampling time

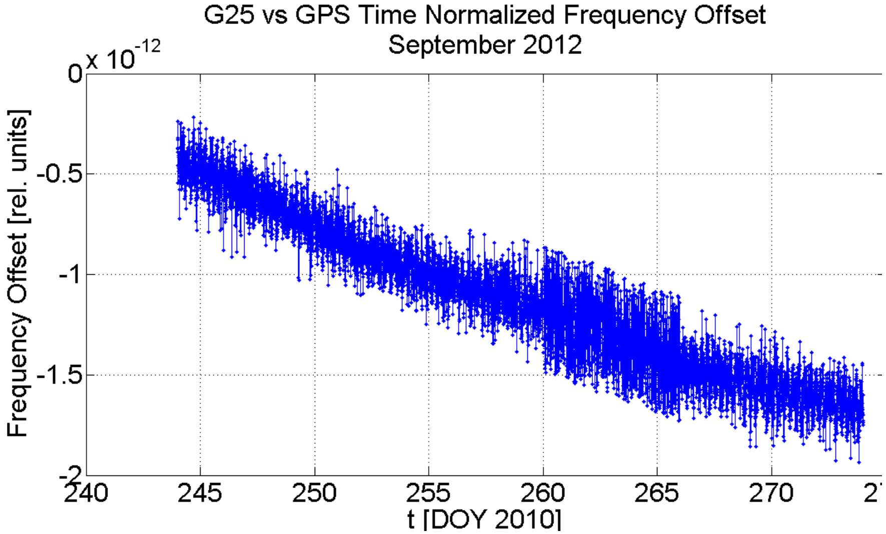
the DAVAR estimator

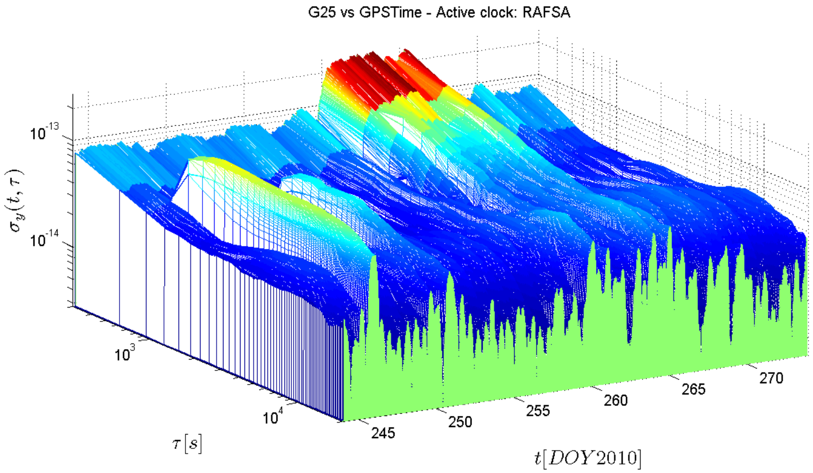
has no expectation value *E* because we have one realization only

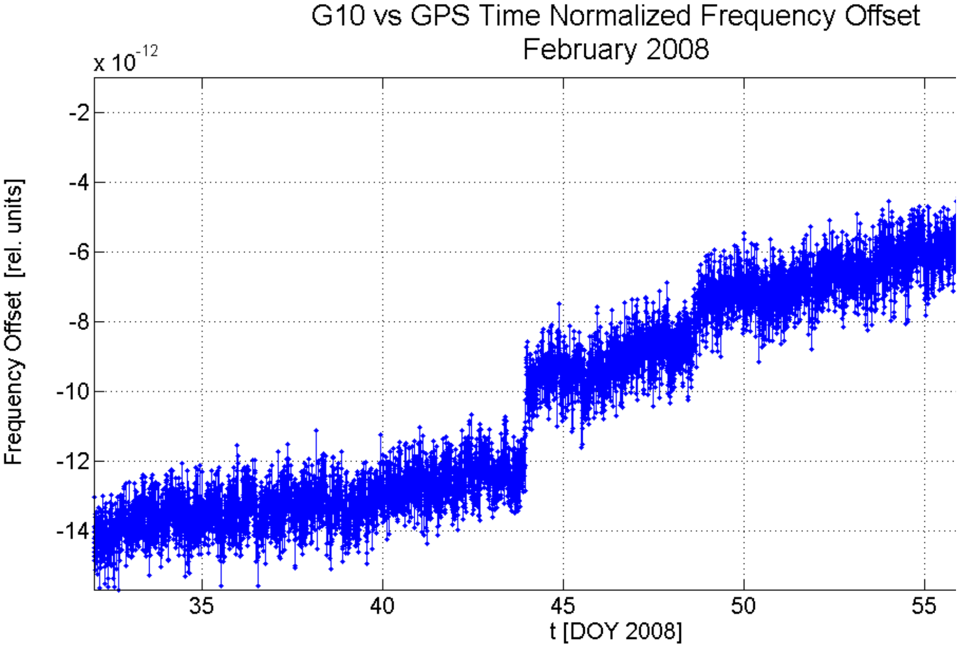
Bureau
International des
Poids et
Mesures

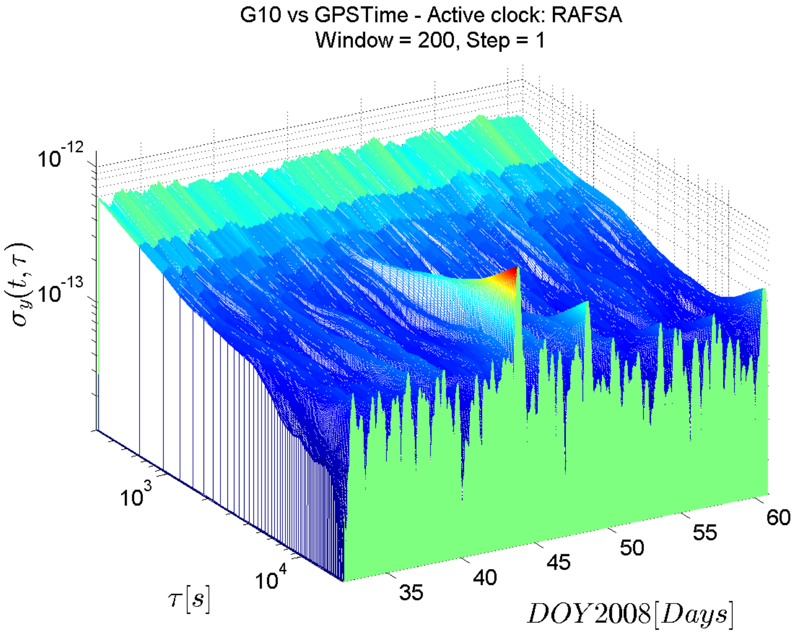
L. Galleani, P. Tavella, “Dynamic Allan variance” , IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC, vol. 56, no. 3, March 2009, pp450-464

L. Galleani, P. Tavella, “The Dynamic Allan Variance V: Recent Advances in Dynamic Stability Analysis”, EEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 63, No. 4, Pag 624 - 635, April 2016


G25 vs GPS Time Normalized Frequency Offset
September 2012


G25 vs GPSTime - Active clock: RAFSA


G10 vs GPS Time Normalized Frequency Offset
February 2008


G10 vs GPSTime - Active clock: RAFSA
Window = 200, Step = 1

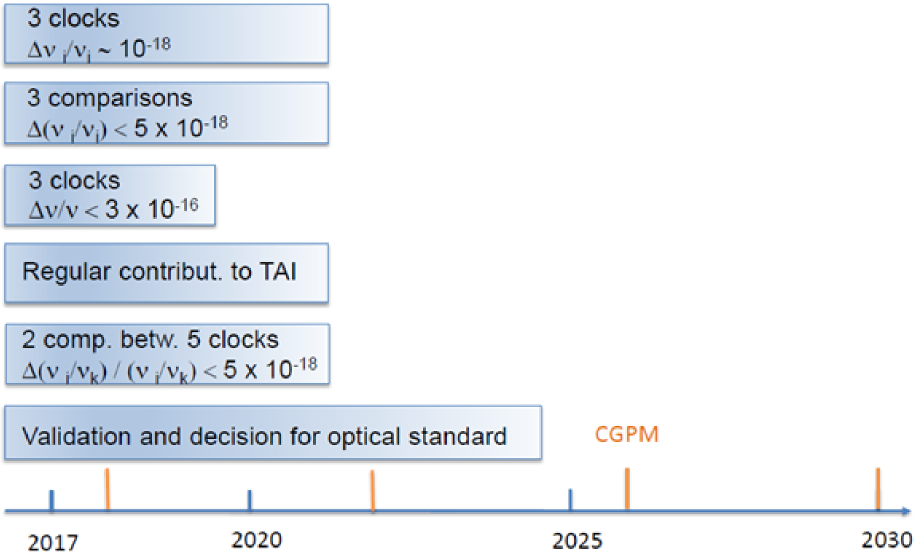
CANVAS by NRL @ **https://goby.nrl.navy.mil/canvas/download/**

STABLE 32 version 1.5

Coming back to optical clock

When are we ready for an optical definition of the second?

1. ... at least three different optical clocks (either in different laboratories, or of different species) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks at that time
2. 2. … at least three independent measurements of at least one optical clock of milestone 1 were compared in different institutes (e.g. $\Delta\nu/\nu$ < 5 x 10 -18) either by transportable clocks, advanced links, or frequency ratio closures.
3. … there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, where the measurements are limited essentially by the uncertainty of these Cs fountain clocks (e.g. $\Delta\nu/\nu$ < 3 x 10 -16).
4. … optical clocks (secondary representations of the second) contribute regularly to TAI.
5. … optical frequency ratios between a few (at least 5) other optical frequency standards have been performed; each ratio measured at least twice by independent laboratories and agreement was found (with e.g. $\Delta\nu/\nu$ < 5x10 -18).



3 clocks
$\Delta\nu_i/\nu_j \sim 10^{-18}$

3 comparisons
$\Delta(\nu_i/\nu_j) < 5 \times 10^{-18}$

3 clocks
$\Delta\nu/\nu < 3 \times 10^{-16}$

Regular contribut. to TAI

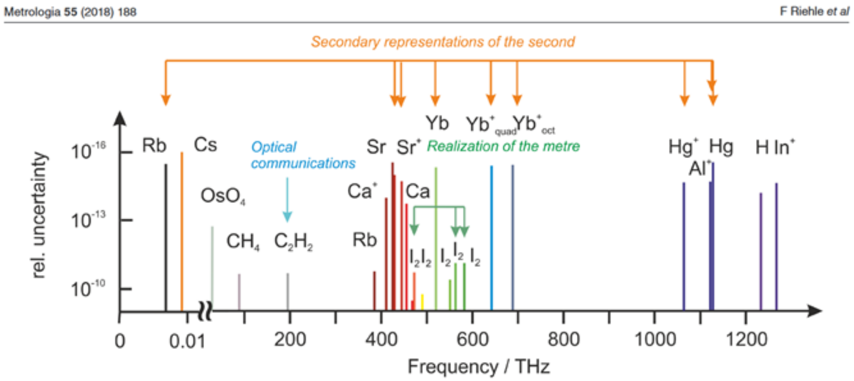
2 comp. betw. 5 clocks
$\Delta(\nu_i/\nu_k) / (\nu_i/\nu_k) < 5 \times 10^{-18}$

Validation and decision for optical standard

Roadmap to a redefinition (CCTF 2017)
https://www.bipm.org/utils/en/pdf/CCTF-strategy-document.pdf

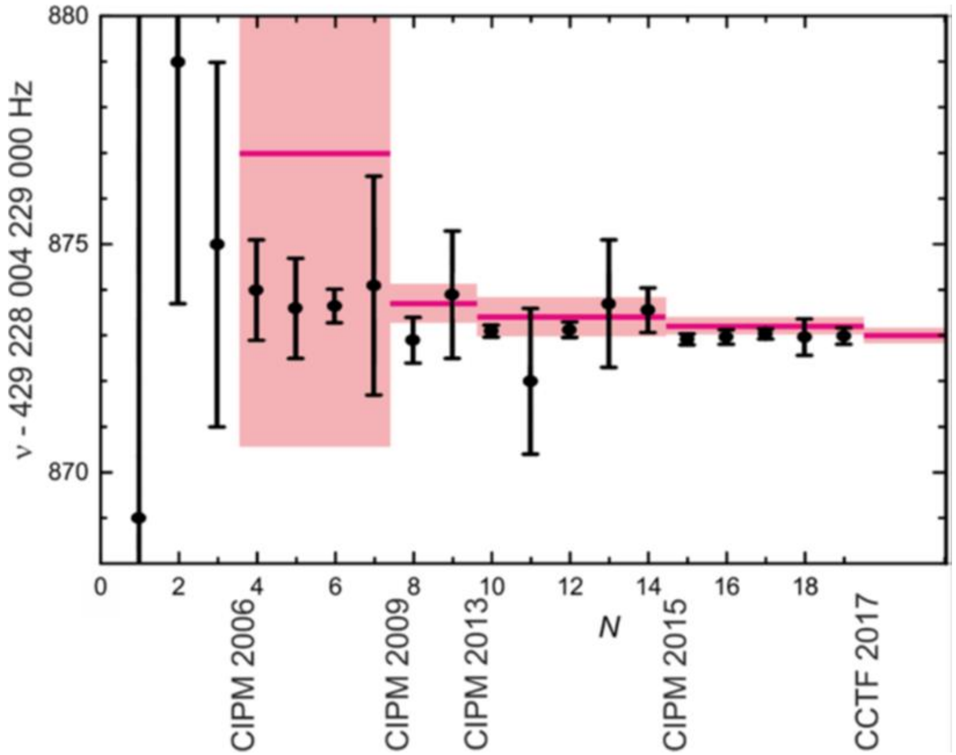
Are we ready for an optical definition of the second?

- The WGFS typically revises the list of transitions and recommended values for each session of the CCTF (every 2-3 years)



https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

- Example of the ^{87}Sr transition
  - Value and uncertainty revised 5 times since 2006
  - Conventional uncertainty now at 4×10^{-16} limited by Cs uncertainty.



F. Riehle, P. Gill, F. Arias & L. Robertsson, Metrologia 55, 188 (2018)

How to compare optical clocks at distance?

- At the 10^{-18} accuracy level

Only fiber links can make it within hours

Presently limited to (sub) continental links

- At the 10^{-17} accuracy level

Several techniques can provide such performance

GPS IntegerPPP

< 1×10^{-16} after several days

Readily available, no constraint

Two way Carrier Phase

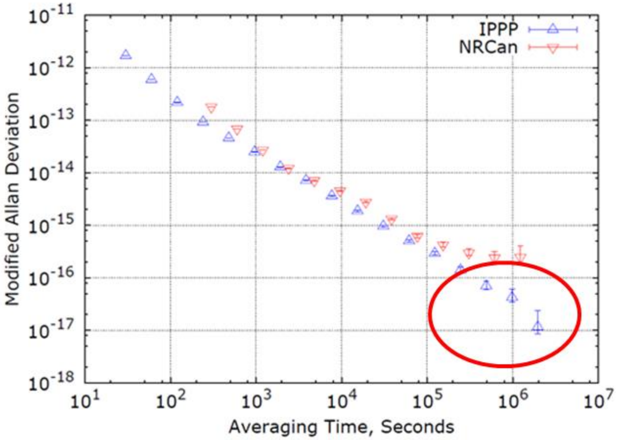
< 1×10^{-16} after one day?

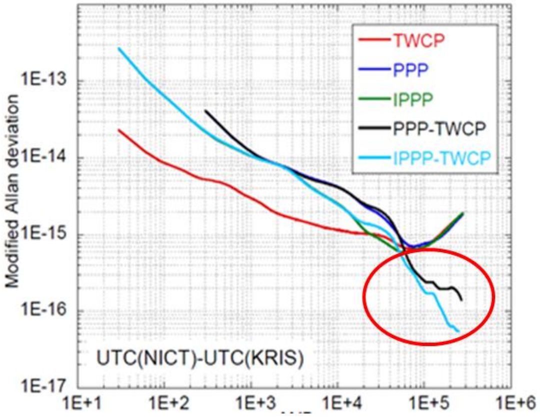
Available, with constraints

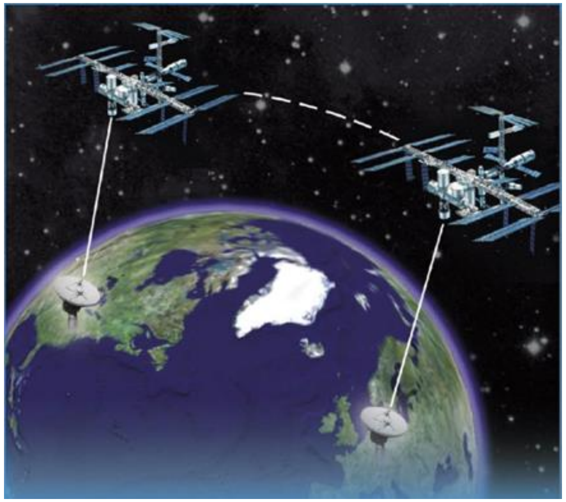
ACES MWL

1×10^{-17} after one/several days?

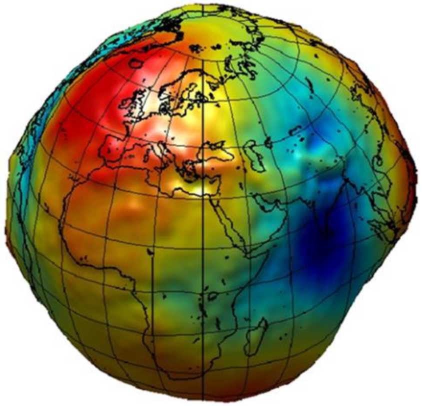
To be launched > 2020







Relativistic geodesy



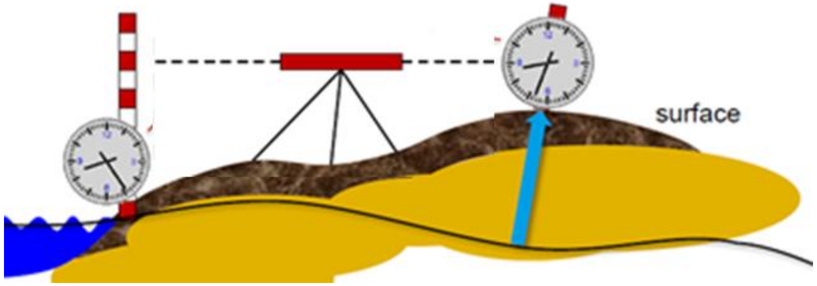
To compare two clocks at a distance, one has to account for their relativistic frequency shift

$d\tau_A / d\tau_B \approx 1 + (W_B - W_A)/c^2$ where W is the gravity potential

- At the 10^{-18} accuracy level one needs to know the clocks height with 1 cm accuracy

Conversely one can directly measure the geopotential (height) difference between any two clocks (1 cm $\approx 1 \times 10^{-18}$) if

- The clocks are accurate to 10^{-18}
- Their frequency difference can be measured to 10^{-18}

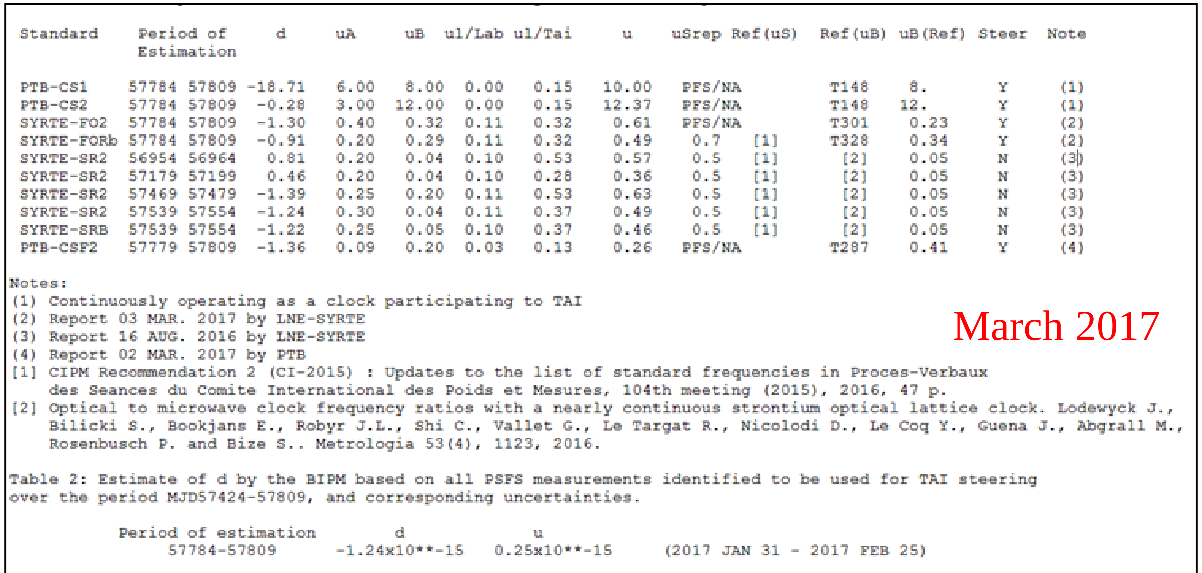


The clock is measuring the geopotential or the knowledge of the geopotential is used to correct the clock? Shall we define time scale in space?

… optical clocks (secondary representations of the second) contribute regularly to TAI

We look forward to your evaluations of secondary standards

- to gain experience and promote their use
- to determine / check their reference frequency
- to prepare for future changes



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 Standard     Period of      d       uA      uB   ul/Lab ul/Tai      u     uSrep Ref(uS)  Ref(uB) uB(Ref) Steer  Note
              Estimation

 PTB-CS1     57784 57809 -18.71    6.00    8.00   0.00   0.15    10.00    PFS/NA          T148    8.        Y     (1)
 PTB-CS2     57784 57809  -0.28    3.00   12.00   0.00   0.15    12.37    PFS/NA          T148   12.        Y     (1)
 SYRTE-FO2   57784 57809  -1.30    0.40    0.32   0.11   0.32     0.61    PFS/NA          T301    0.23      Y     (2)
 SYRTE-FORb  57784 57809  -0.91    0.20    0.29   0.11   0.32     0.49     0.7    [1]     T328    0.34      Y     (2)
 SYRTE-SR2   56954 56964   0.81    0.20    0.04   0.10   0.53     0.57     0.5    [1]      [2]    0.05      N     (3)
 SYRTE-SR2   57179 57199   0.46    0.20    0.04   0.10   0.28     0.36     0.5    [1]      [2]    0.05      N     (3)
 SYRTE-SR2   57469 57479  -1.39    0.25    0.20   0.11   0.53     0.63     0.5    [1]      [2]    0.05      N     (3)
 SYRTE-SR2   57539 57554  -1.24    0.30    0.04   0.11   0.37     0.49     0.5    [1]      [2]    0.05      N     (3)
 SYRTE-SRB   57539 57554  -1.22    0.25    0.05   0.10   0.37     0.46     0.5    [1]      [2]    0.05      N     (3)
 PTB-CSF2    57779 57809  -1.36    0.09    0.20   0.03   0.13     0.26    PFS/NA          T287    0.41      Y     (4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 03 MAR. 2017 by LNE-SYRTE
(3) Report 16 AUG. 2016 by LNE-SYRTE
(4) Report 02 MAR. 2017 by PTB
[1] CIPM Recommendation 2 (CI-2015) : Updates to the list of standard frequencies in Proces-Verbaux
    des Seances du Comite International des Poids et Mesures, 104th meeting (2015), 2016, 47 p.
[2] Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. Lodewyck J.,
    Bilicki S., Bookjans E., Robyr J.L., Shi C., Vallet G., Le Targat R., Nicolodi D., Le Coq Y., Guena J., Abgrall M.,
    Rosenbusch P. and Bize S.. Metrologia 53(4), 1123, 2016.

Table 2: Estimate of d by the BIPM based on all PSFS measurements identified to be used for TAI steering
over the period MJD57424-57809, and corresponding uncertainties.

           Period of estimation         d              u
               57784-57809       -1.24x10**-15   0.25x10**-15     (2017 JAN 31 - 2017 FEB 25)
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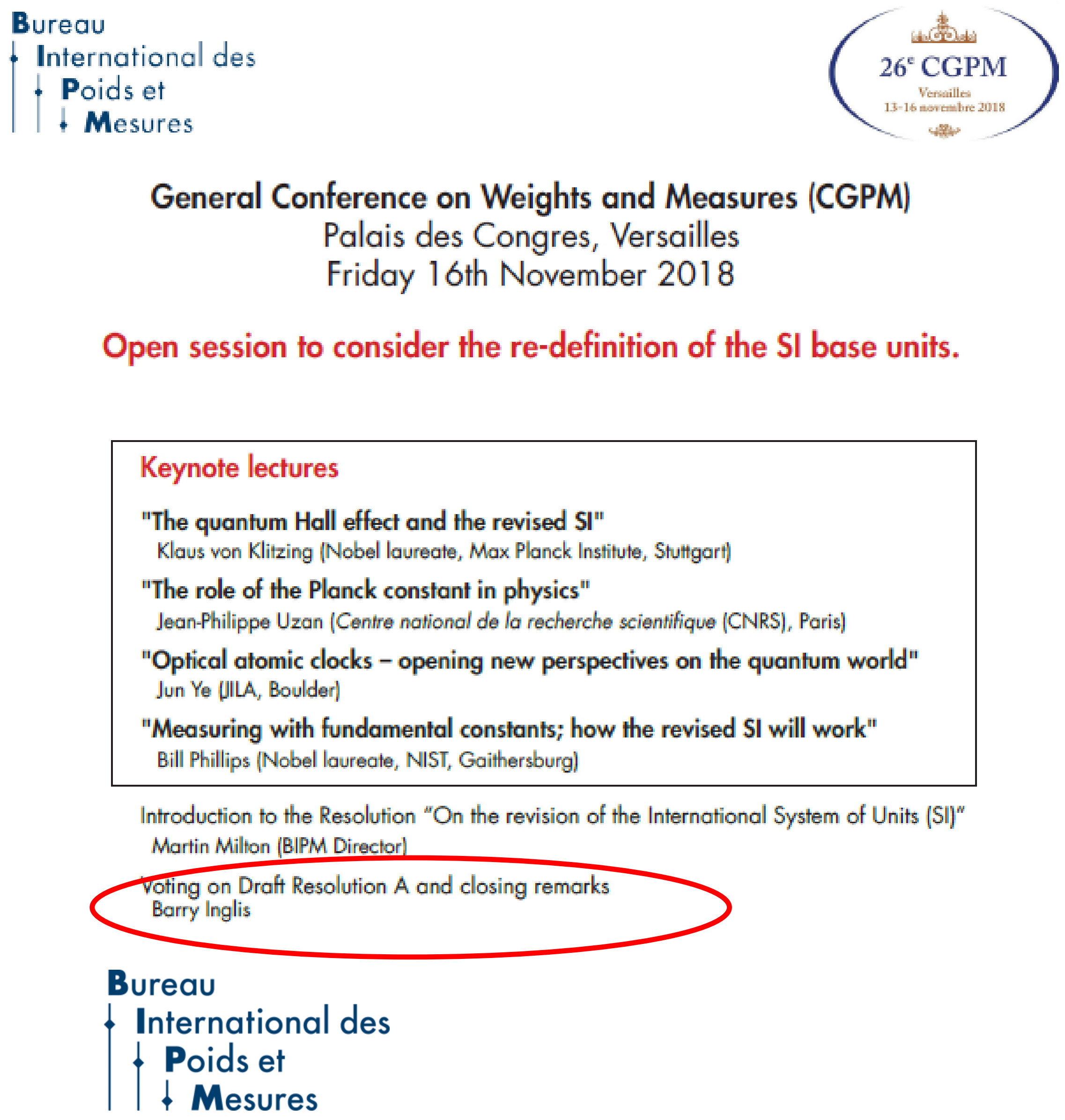
March 2017

ADVERTISEMENT: CGPM 2018 is expected to change SI



Bureau
International des
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26e CGPM
Versailles
13-16 novembre 2018

General Conference on Weights and Measures (CGPM)
Palais des Congres, Versailles
Friday 16th November 2018

Open session to consider the re-definition of the SI base units.

Keynote lectures

"The quantum Hall effect and the revised SI"
Klaus von Klitzing (Nobel laureate, Max Planck Institute, Stuttgart)

"The role of the Planck constant in physics"
Jean-Philippe Uzan (*Centre national de la recherche scientifique* (CNRS), Paris)

"Optical atomic clocks – opening new perspectives on the quantum world"
Jun Ye (JILA, Boulder)

"Measuring with fundamental constants; how the revised SI will work"
Bill Phillips (Nobel laureate, NIST, Gaithersburg)

Introduction to the Resolution "On the revision of the International System of Units (SI)"
Martin Milton (BIPM Director)

Voting on Draft Resolution A and closing remarks
Barry Inglis

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CGPM open session
on Friday Nov 16th morning

available in streaming

https://www.bipm.org/utils/en/pdf/26th-CGPM-open-session.pdf

THANK YOU

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