How Primary and Secondary Frequency Standards contribute to international time scale performances

G. Panfilo
BIPM
gpanfilo@bipm.org

Bureau
International des
Poids et
Mesures

Summary

- The calculation of UTC, TT(BIPM), UTCr
  - Time links, clocks and algorithms
- TT(BIPM) algorithm will be introduced, and the latest calculation (2022) presented.
- The role of Primary and Secondary Frequency Standards (PSFS) in international time scale calculation, focusing on how they guarantee the long-term stability and accuracy of UTC.

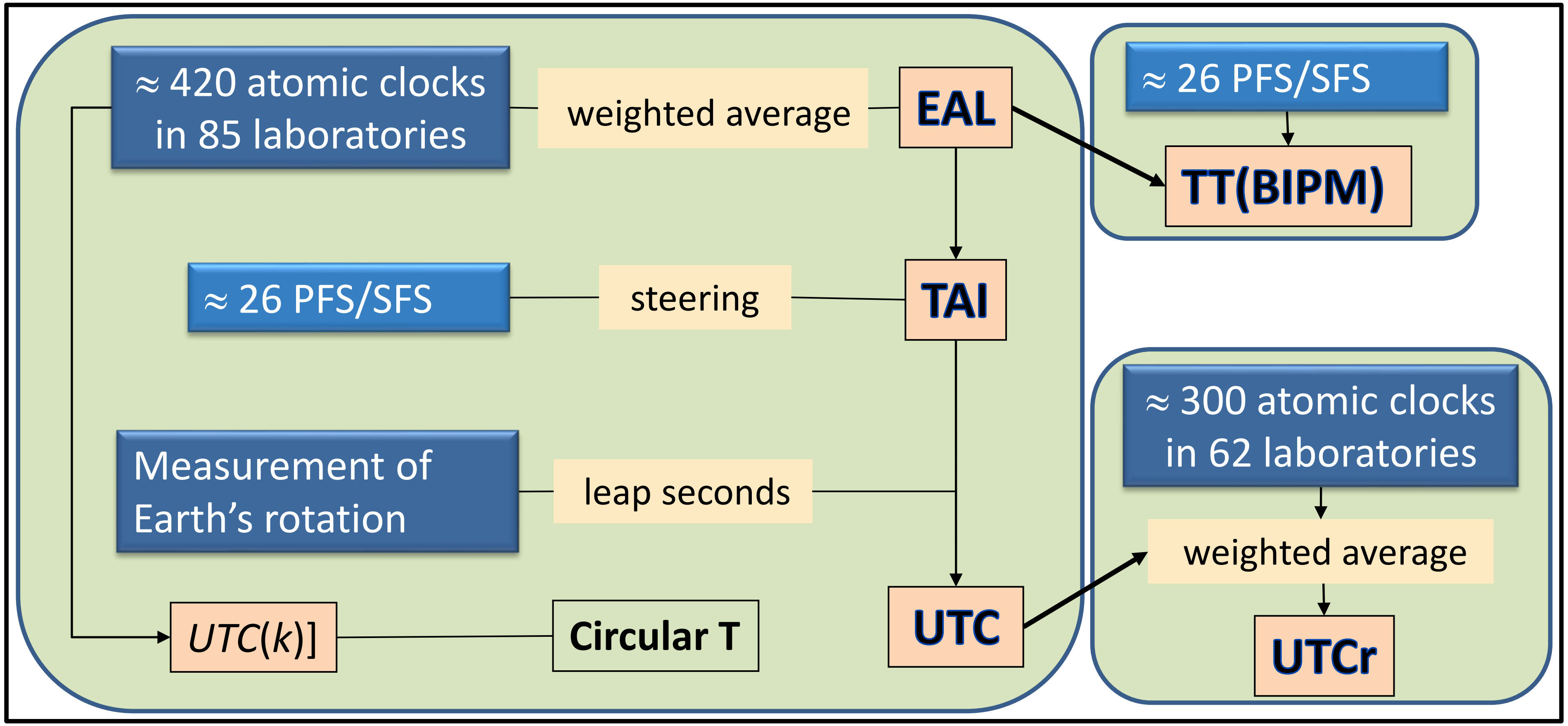
The role of the BIPM

- The BIPM is the international organization responsible for:
  - the calculation and the publication of the Coordinated Universal Time (UTC)
  - its rapid solution, UTCr
  - the realization of Terrestrial Time TT(BIPM).
- UTC is calculated each month
- UTCr each week
- TT(BIPM) each year (each month for internal use)

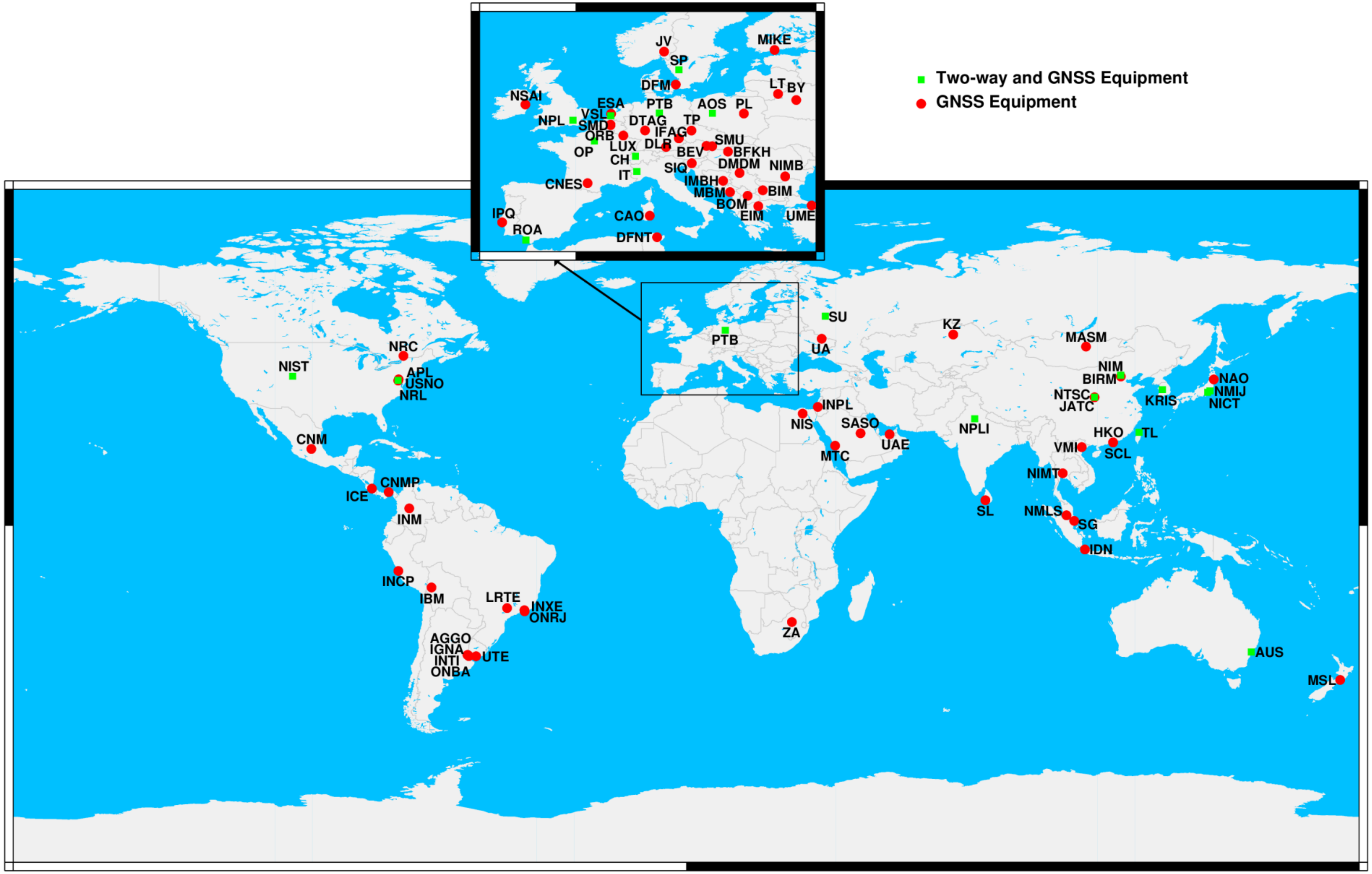
All the results are published in the BIPM website
https://www.bipm.org/en/time-metrology

Bureau International des Poids et Mesures

UTC, UTCr and TT(BIPM)

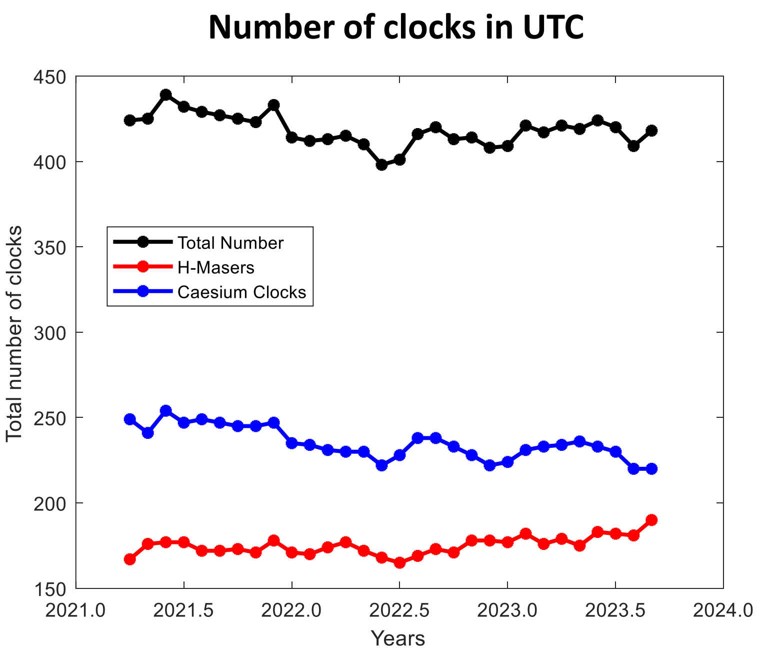


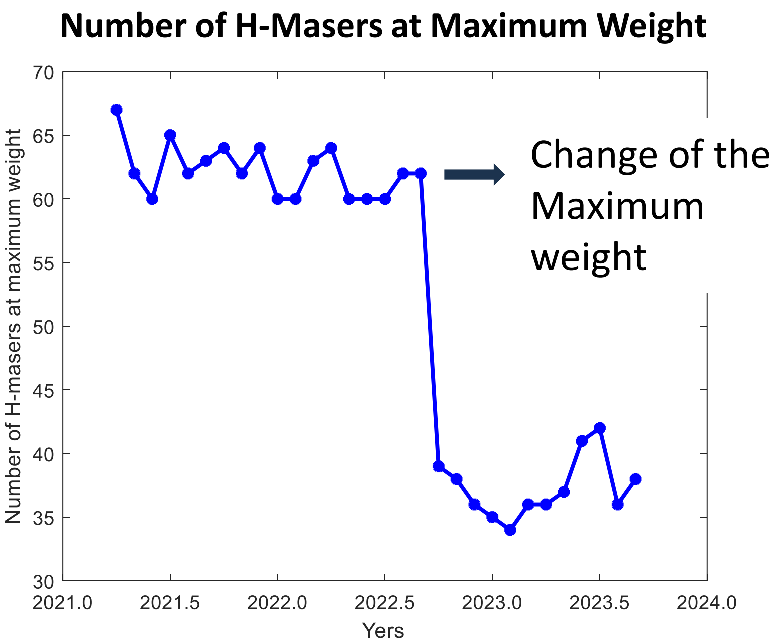
Geographical distribution of the laboratories that contribute to TAI and time transfer equipment (2023)

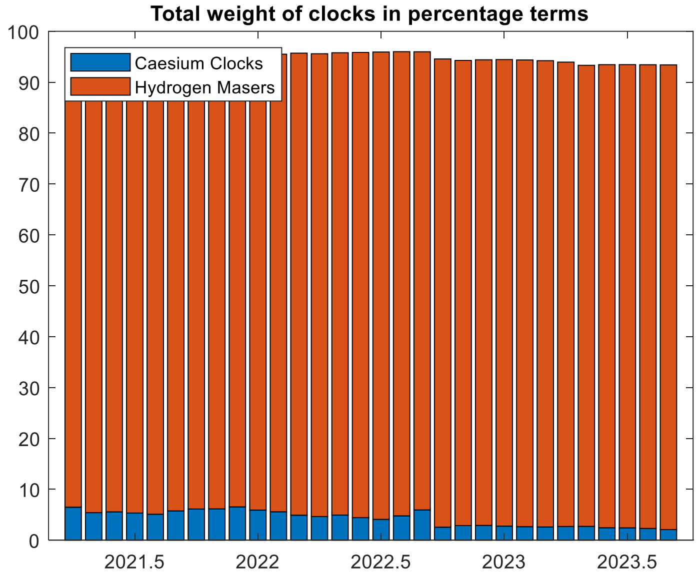


Bureau International des Poids et Mesures

Atomic clocks in UTC

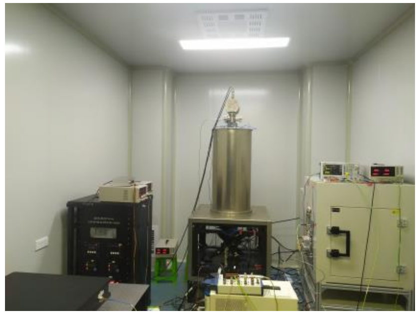






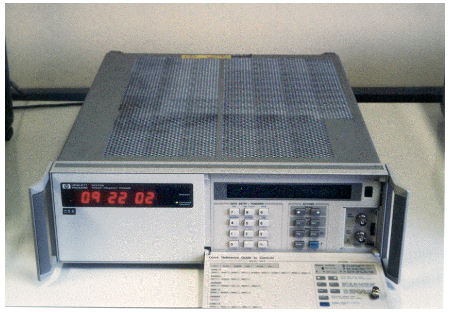
5 Rubidium Fountains in UTC

NTSC Rubidium Fountain



Credit: NTSC

Caesium Clock



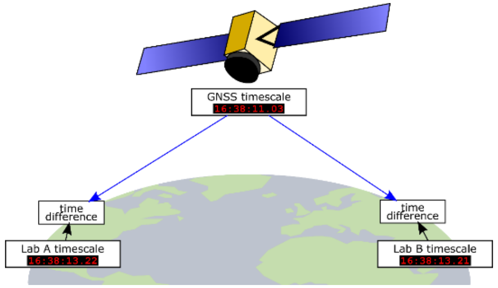
Hydrogen Masers

Bureau International des Poids et Mesures

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

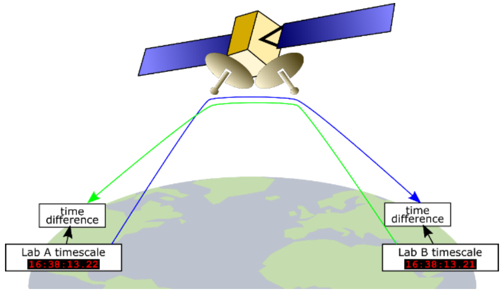
Global Navigation Satellite Systems (GNSS)

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. Typical algorithms are All in View, Common View, and Precise Point Positioning



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.



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

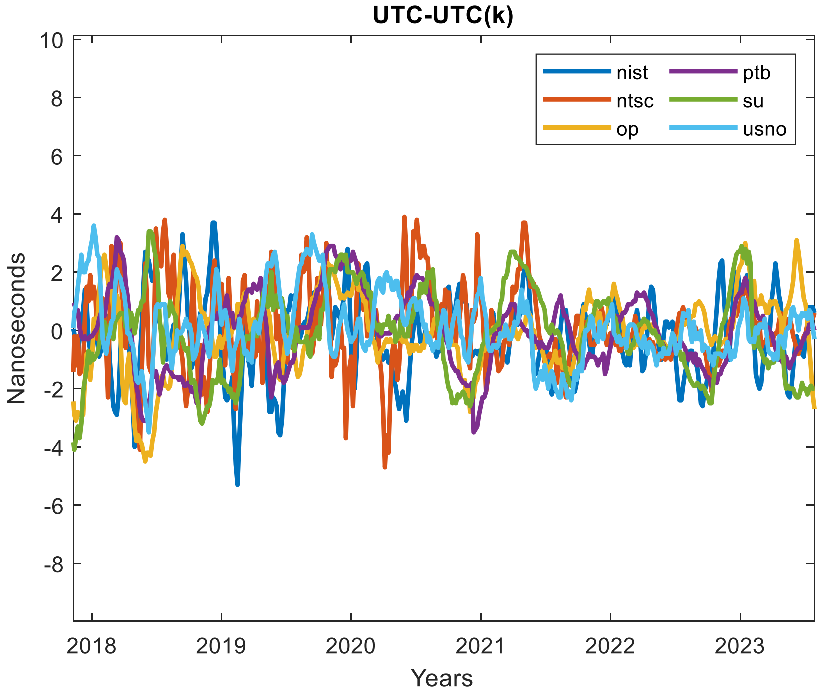
In development : Optical Fiber links

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.

Bureau International des Poids et Mesures

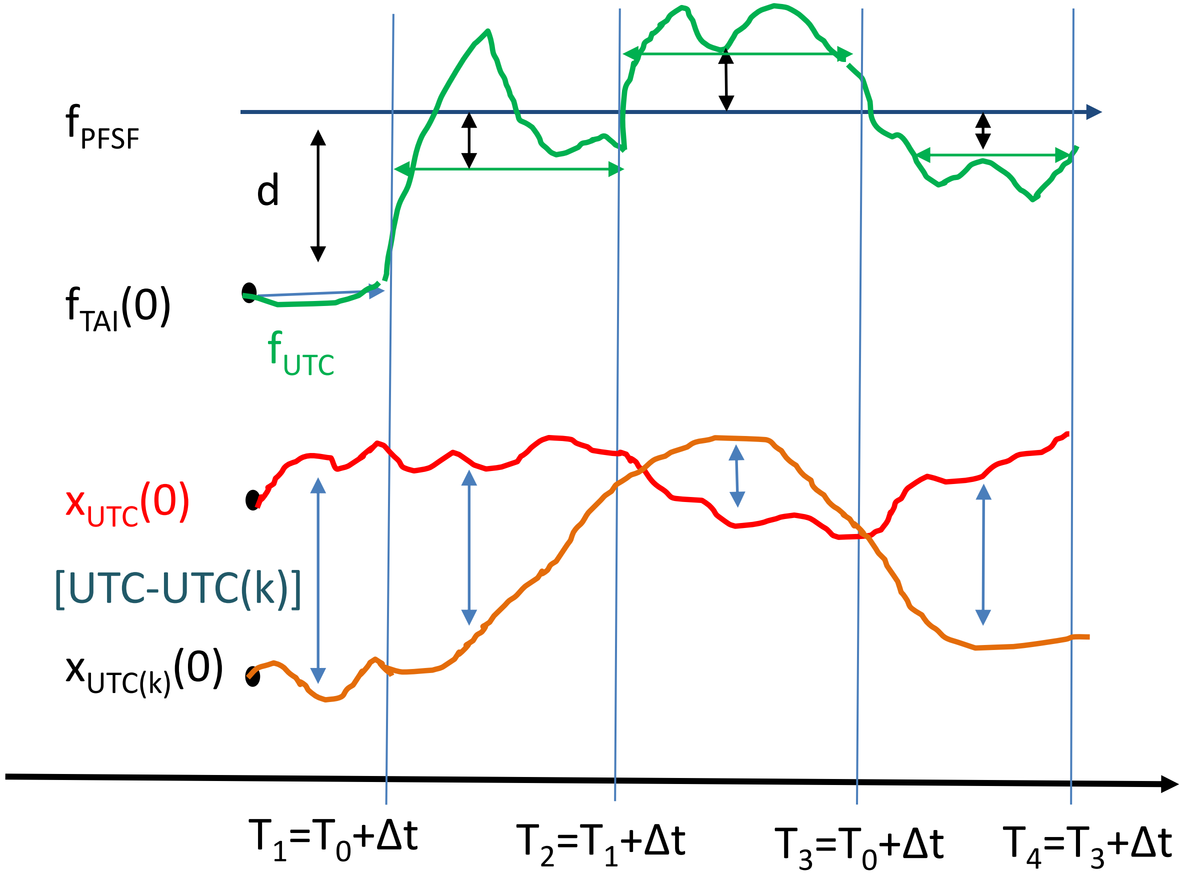
UTC, UTC(*k*) and [UTC-UTC(*k*)]

UTC	Stability based on the **atomic clocks** (420) (and PSFS) Steering procedure based on PSFS availability
UTC(k)	Stability based on the **laboratory equipment** Steering procedure to be close to UTC
[UTC-UTC(k)]	UTC, UTC(k) and time links used to compare clocks



Bureau International des Poids et Mesures

Difference between UTC and UTC(*k*)

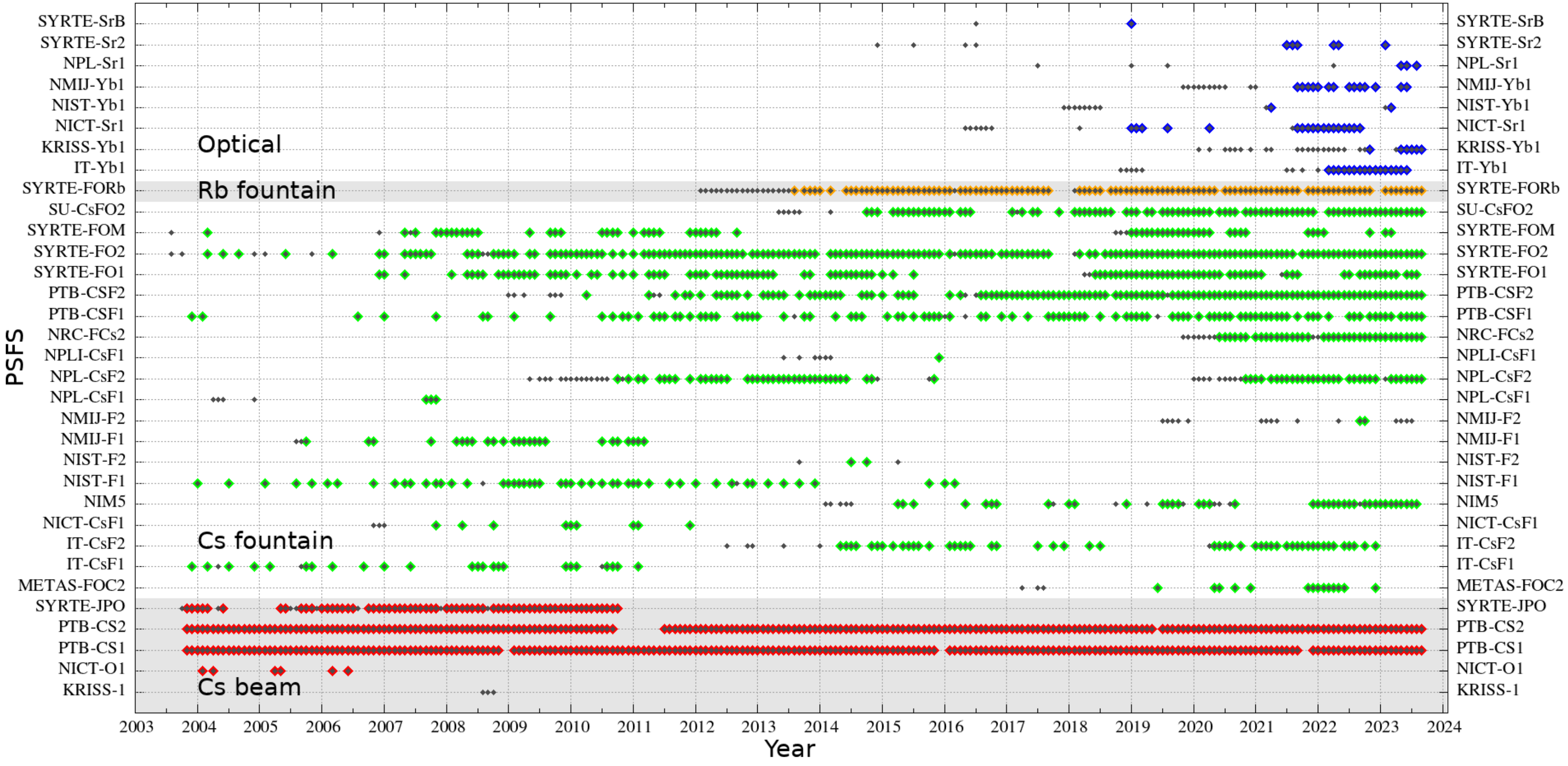


- UTC a time scale optimized to be stable in frequency at very long term. EAL provides the stability
- UTC unit is the SI second
- UTC is steered in **FREQUENCY** to be close to the frequency of PFSF (d published monthly in CirT)
- UTC(k) is generally steered in **FREQUENCY** and in **TIME** to be close to UTC

Bureau International des Poids et Mesures

Primary and Secondary standards contributing to UTC

Graphical representation of all evaluations of Primary and Secondary Frequency Standards reported since Circular T 190.
Enhanced color dots indicate evaluations carried out within the month of TAI computation.



https://webtai.bipm.org/database/show_psfs.html

Bureau International des Poids et Mesures

The role of PSFS in UTC

- In this presentation I'll highlight the role of PSFS in ensuring the log-term stability of UTC and its accuracy.
- It will be discussed:
  - the algorithm used to evaluate EAL (prediction and weight) (stability).
  - the algorithm to calculate TT(BIPM).
  - the algorithm to evaluate the difference between TAI and PSFS (accuracy).

First step: EAL - 1

Weighting algorithm

Prediction algorithm

$$EAL(t) = \sum_{i=1}^{N} w_i \left[h_i(t) + h_i'(t) \right]$$

- ***N*** is the number of atomic clocks
- $\boldsymbol{w_i}$ the relative weight of the clock H_i.
- $\boldsymbol{h_i(t)}$ is the reading of clock H_i at time t
- $\boldsymbol{h_i'(t)}$ is the prediction of the reading of clock H_i

The weights of the clocks obey the relation: $\sum_{i=1}^{N} w_i = 1$

Bureau International des Poids et Mesures

First step: EAL - 2

The system solved by the algorithm:

$$\begin{cases} \sum_{i=1}^{N} w_i x_i(t) = \sum_{i=1}^{N} w_i h_i'(t) \\ x_i(t) - x_j(t) = x_{i,j}(t) \end{cases}$$

where $x_i(t) = EAL(t) - h_i(t)$

The solution is:

Weigth

$$\boxed{x_j(t) = EAL - h_j = \sum_{i=1}^{N} w_i \left[h_i'(t) - x_{i,j}(t) \right]}$$

Prediction

The main algorithms used are:

- the **prediction algorithm** (quadratic model)
- the weighting algorithm (each clock is weighted wrt to their stability/predictability)

Bureau International des Poids et Mesures

The prediction algorithm

- The prediction algorithm has the scope to avoid/minimize any time and frequency steps to UTC when a clock is added or eliminated from the ensemble.
- Any deterministic signatures (x_0, y_0 and frequency drift) are estimated and eliminated by the clocks to avoid affecting UTC.
- The quadratic prediction for the interval (t_k, t_{k+1}) is used:

$$\widehat{h_i'}(t) = \widehat{x_0}(t_k) + \widehat{y_0}(t - t_k) + \frac{1}{2}\hat{d}(t - t_k)^2$$

EAL-h_i at date t_k

Frequency of h_i relative to **EAL** predicted over the period [t_k ,t]

Frequency drift of h_i relative to a **frequency reference** predicted over the period [t_k ,t]

Bureau International des Poids et Mesures

The estimation of the frequency drift

- It is a key issue for using at the best the hydrogen masers
- The reference used to estimate the frequency drift is the most important point; EAL and TAI are not enough stable to estimate the drift.
- The BIPM realization of TT, called TT(BIPM) is used to evaluate monthly the frequency drift of the hydrogen masers.
- The main components of TT(BIPM) are EAL and the PSFS.

Long-term stability of EAL

- EAL is currently free from frequency drifts affecting H-Masers even if they are contributing with a global weight of 90%.
- This result is obtained because of the availability of PSFS allowing us to generate TT(BIPM) each month.
- We can conclude, as some extent, that PSFS allow to the BIPM:
  - To use at the best the Hydrogen Masers
  - To ensure a long-term stability to EAL

TT(BIPM)

- As TAI is computed in real time and never corrected in retrospect, it is not optimal. Therefore, the BIPM computes a post-processed time scale TT(BIPM).
- Each new version TT(BIPM) updates and replaces the previous one.
- TT(BIPM) calculation
  - Post-processed using all available PFS data, as of year 20xx.
  - f(EAL) is estimated each month using available PFS. Monthly estimates are smoothed and integrated to obtain TT(BIPMxx).
  - Last realization: TT(BIPM22), released in March 2023.

Bureau International des Poids et Mesures

Algorithm used for estimating f(EAL)

- We want to estimate the frequency of EAL, over an estimation interval T from N PFS evaluations,

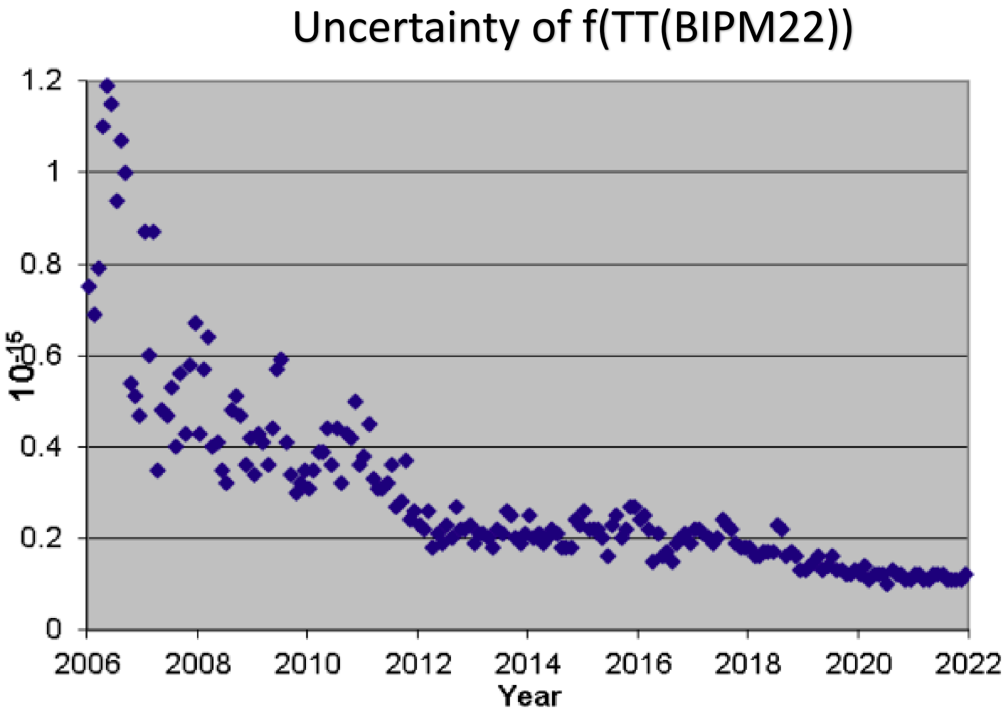
$$y = \sum_{j=1}^{N} a_j \, W_j$$

where:

- W_j is the rate difference between EAL and a PFS on a given interval T_j
- The filter coefficients a_j, are normalized and depend on
  - The uncertainty of the evaluation *j*. It is fully characterized by its components u_A, u_B. u_A is the combined uncertainty from that originated in the instability of the PFS, that of the link between the PFS and the clock participating to TAI (dead time included), and that of the link to EAL. u_B is the combined uncertainty from systematic effects
  - The distance between T_j and T
  - The instability of EAL, which transfers the evaluation from T_j to T

Uncertainty of f(TT(BIPM2022))

- We consider TT(BIPM) our best frequency reference to evaluate the performance of EAL, TAI and all the primary and secondary standards. Frequency accuracy improves with the standards:
  - < 1x10-15 since 2007
  - < 0.5x10-15 since 2009
  - ≤ 0.3x10-15 since 2012
  - ≤ 0.15x10-15 since 2020



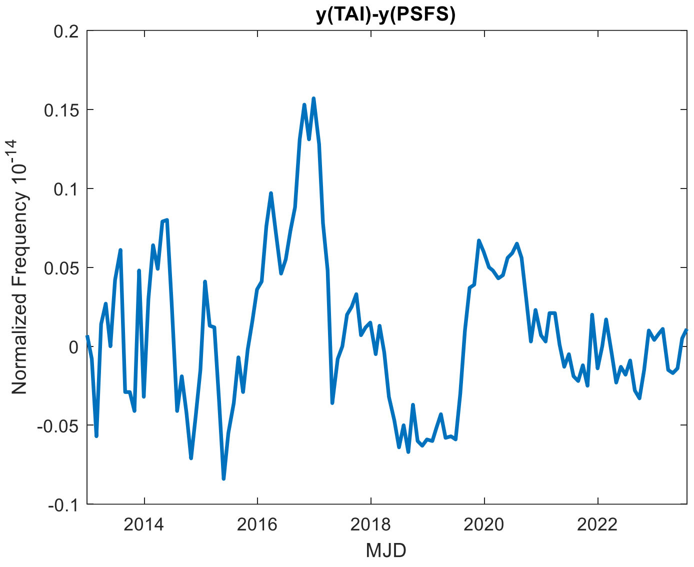
Frequency standards reported for TAI over 10 years

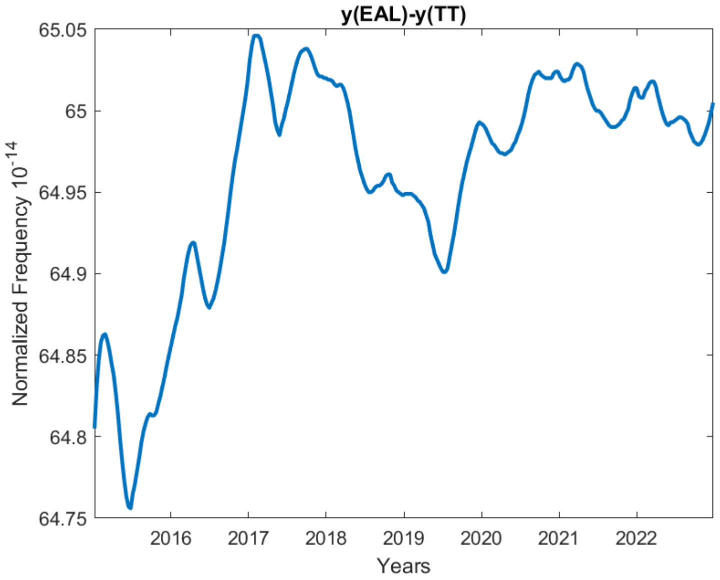
- Primary and secondary standards reported to the BIPM

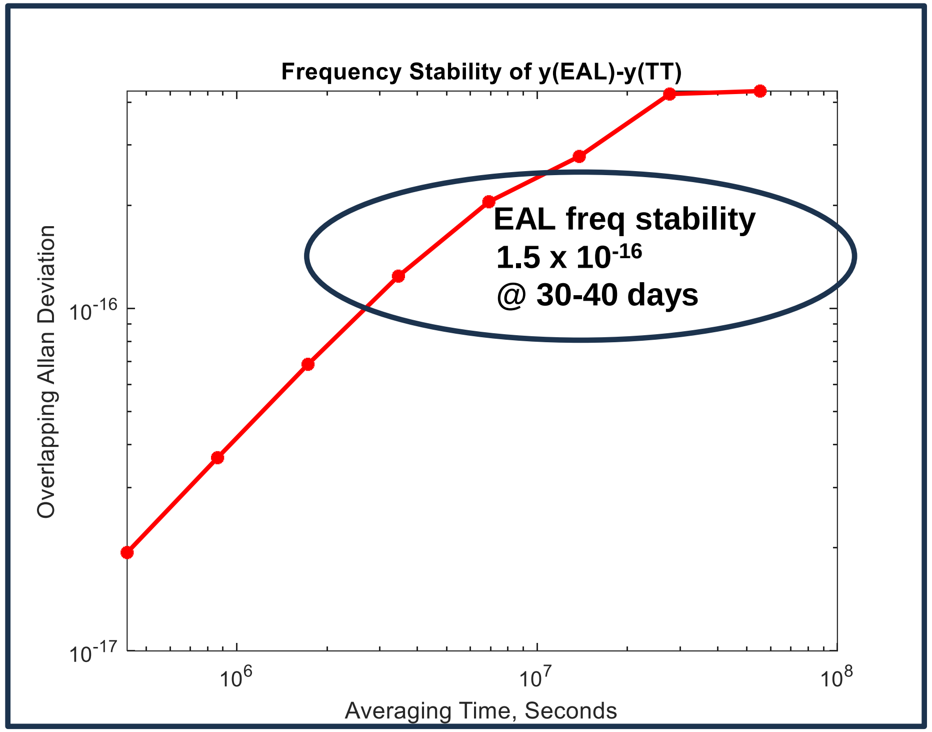
  - 2011 to 2016: 50-60 reports by ~10 fountains
  - 2017/2018: 54/84 reports by 8/10 fountains + 2 optical lattices
  - 2020: 114 reports by 11 Cs fountains+12 by SYRTE-FORb + 13 by 2 optical lattices
  - 2021: 92 reports by 11 Cs fountains + 11 by SYRTE-FORb + 22 by 5 optical lattices
  - 2022: 109 reports by 12 Cs fountains+10 by SYRTE-FORb + 50 by 6 optical lattices

EAL and TAI wrt TT(BIPM2022)

By using TT(BIPM) we can estimate the long-term stability of EAL.



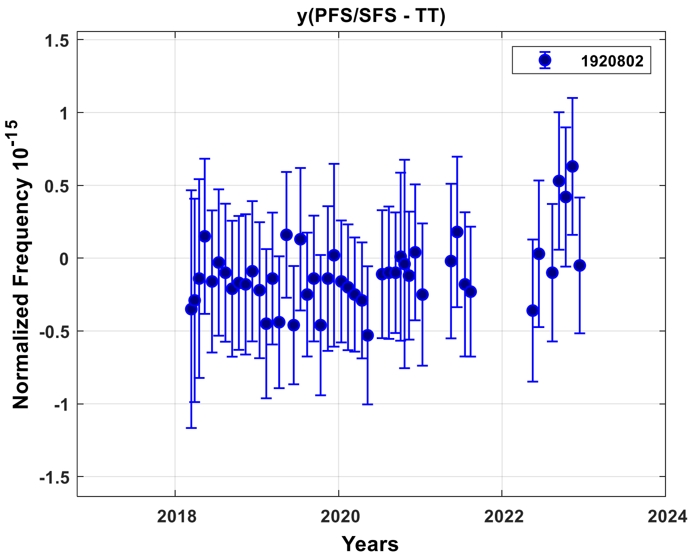


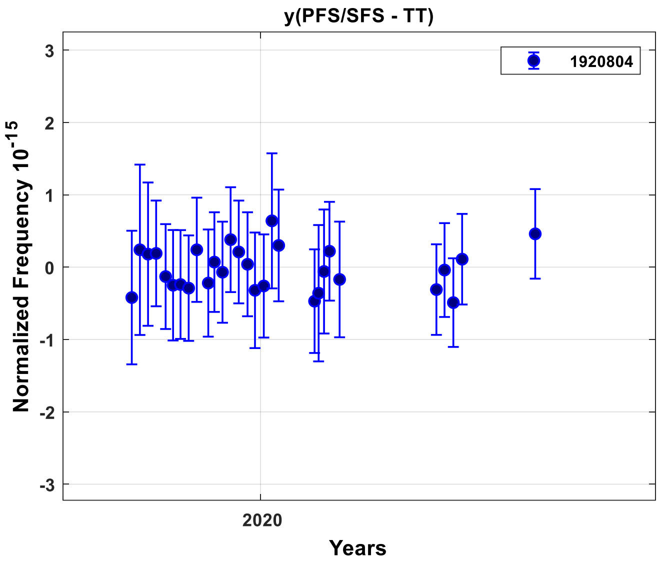


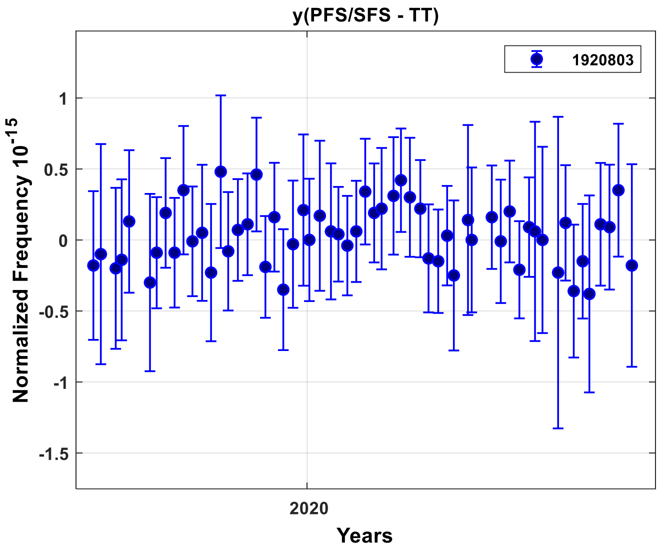
If the short term of the Allan Variance is not useful because EAL and TT are strictly correlated at the short term, we can evaluate the long-term performances of EAL by analyzing it.

Bureau International des Poids et Mesures

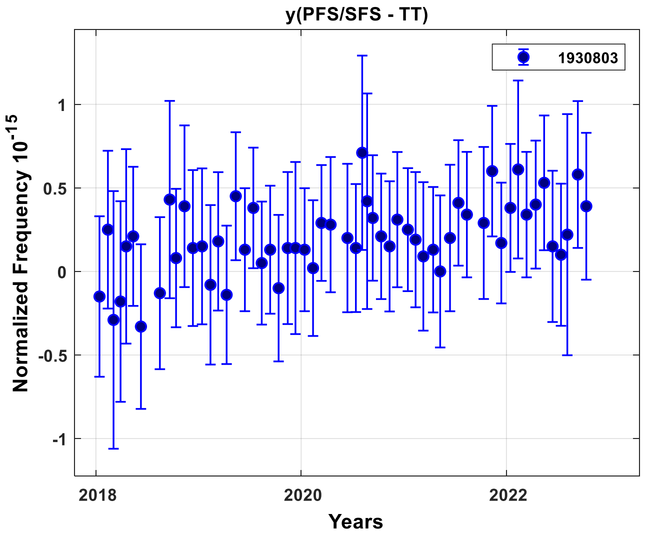
SYRTE - PSF/SFS wrt TT(BIPM)

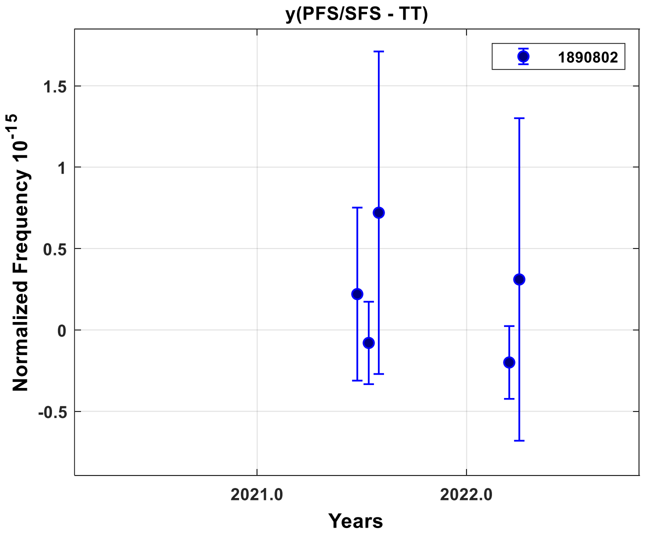






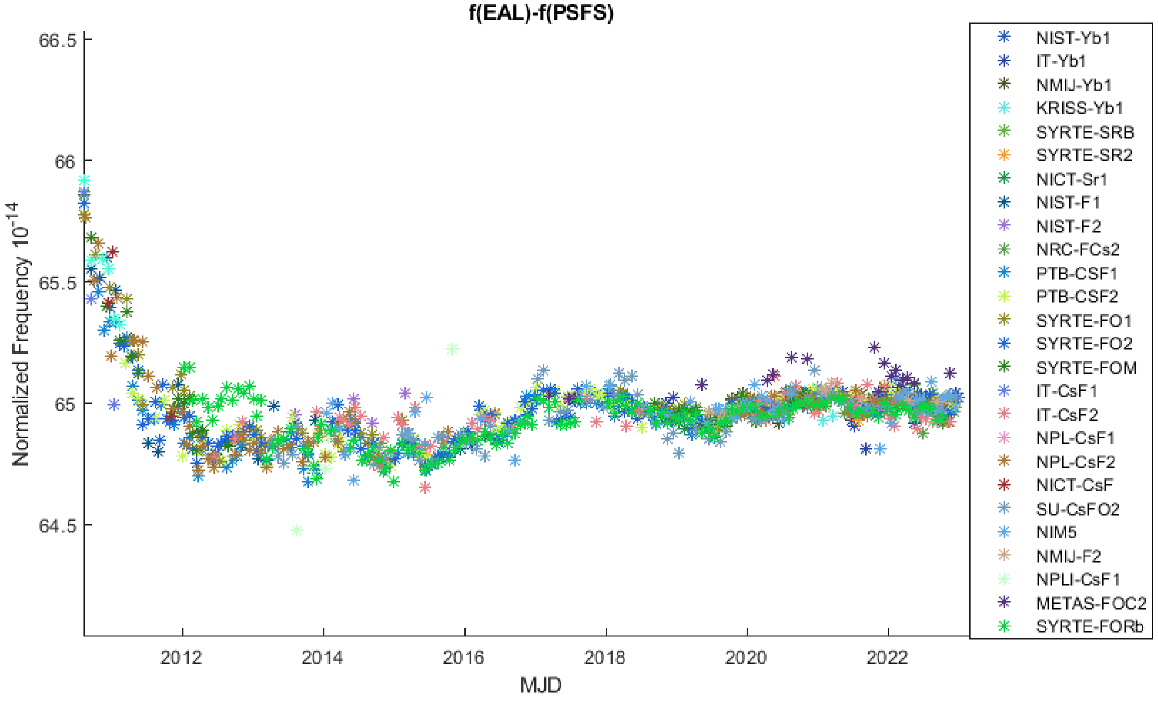
SYRTE-FO1	1920802
SYRTE-FO2	1920803
SYRTE-FOM	1920804
SYRTE-FORb	1930803
SYRTE-SR2	1890802

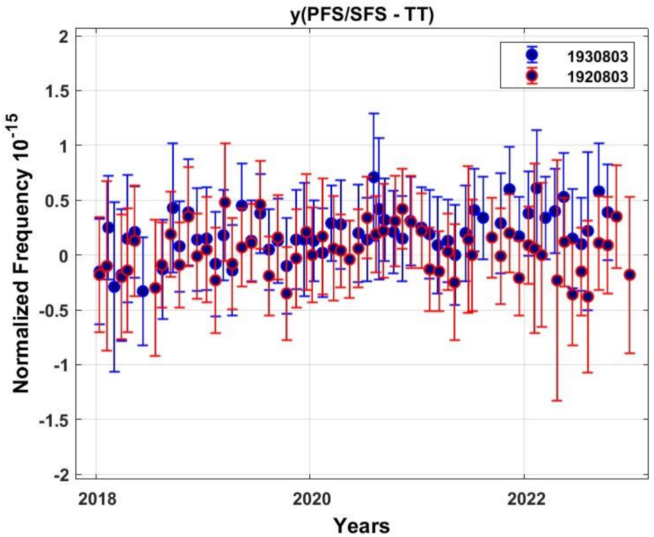




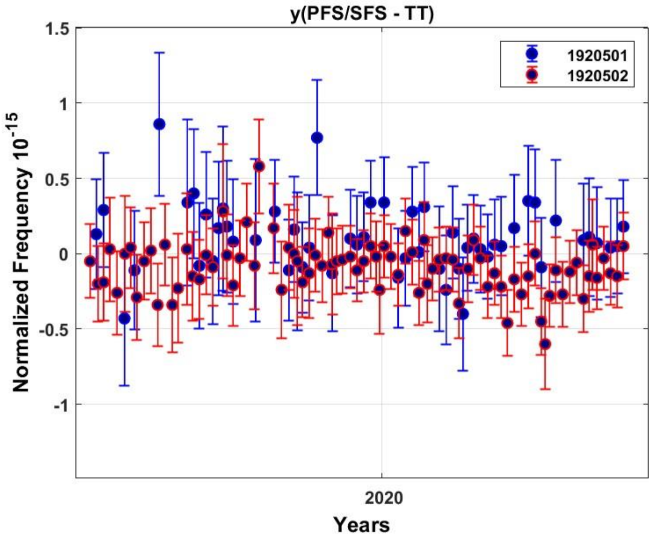
Bureau International des Poids et Mesures

Other results





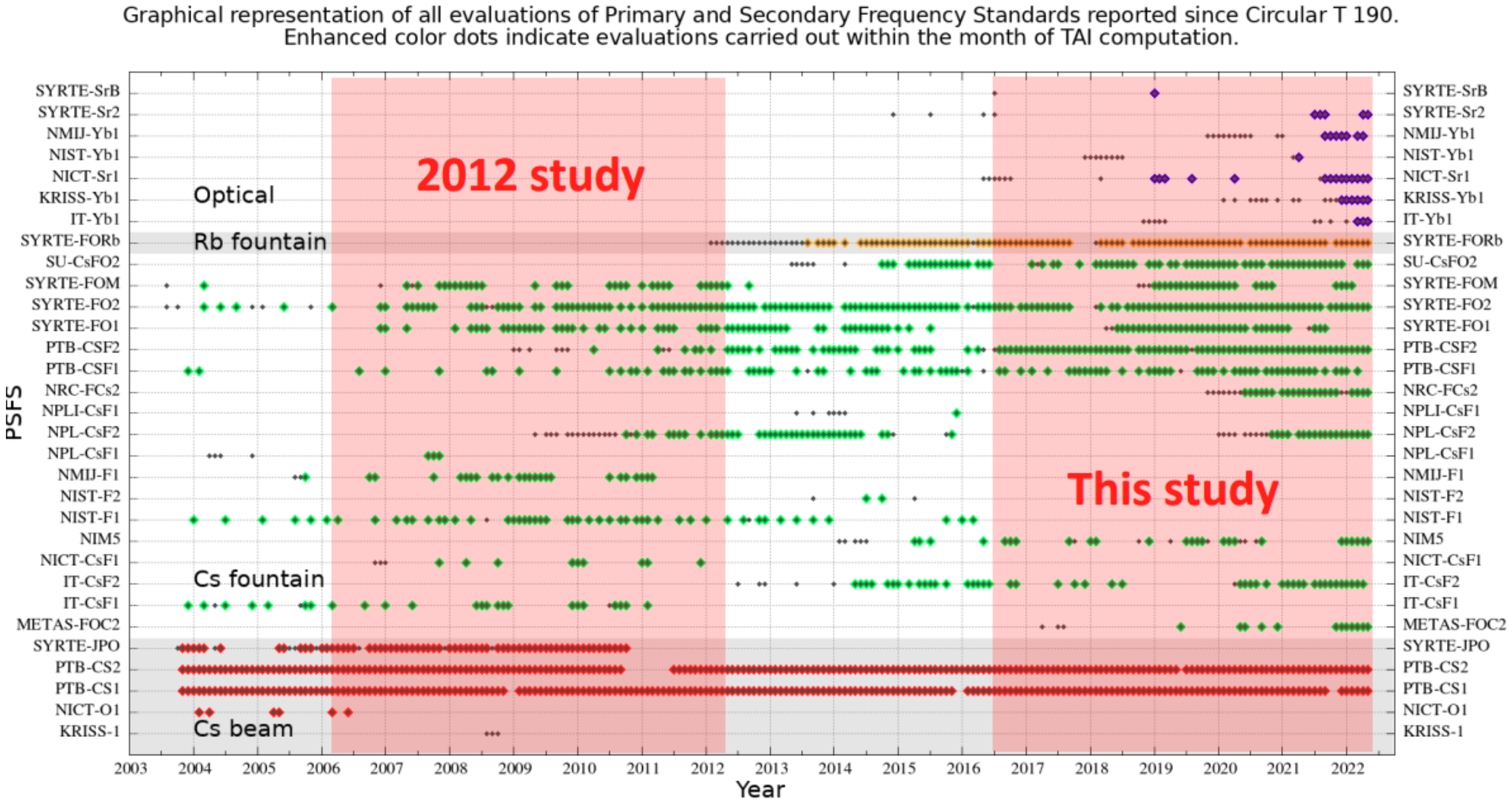
Comparison between SYRTE-FO2 and SYRTE-FORb



Comparison between PTB-CSF1 and PTB-CSF2

Comparison of primary and secondary frequency standards used for TAI

- Two studies (2012 and 2022) have been conducted in collaboration with G. Petit to analyze the level of agreement between the PSFSs compared with their stated uncertainty using TT(BIPM).



Bureau International des Poids et Mesures

Comparisons using TT(BIPM)

1. Study each PFS/SFS by comparison to TT(BIPM)
   - **Estimate one frequency bias Y_i = <y($PSFS_i$ –TT(BIPM))> for each $PSFS_i$**, weighting each evaluation y($PSFS_i$ –TT(BIPM)) using either the total uncertainty u
   - **Estimate goodness of fit for each $PSFS_i$** (Reduced Chi square χ^2, **Birge ratio R_{Bi}**)
2. Study the ensemble of PSFS:
   - Estimate if the distribution of frequency biases Y_i is consistent with the uncertainties u_{Bi} => **Birge ratio of the series of frequency biases**

Bureau International des Poids et Mesures

Evaluation of PSFS performance: detailed formulas

From the series $y_i = y(PFS(t_i) - TT(BIPM))$, estimate one frequency bias

- $\overline{Y} = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i}$ where w_i is $1/\, u_i^2$

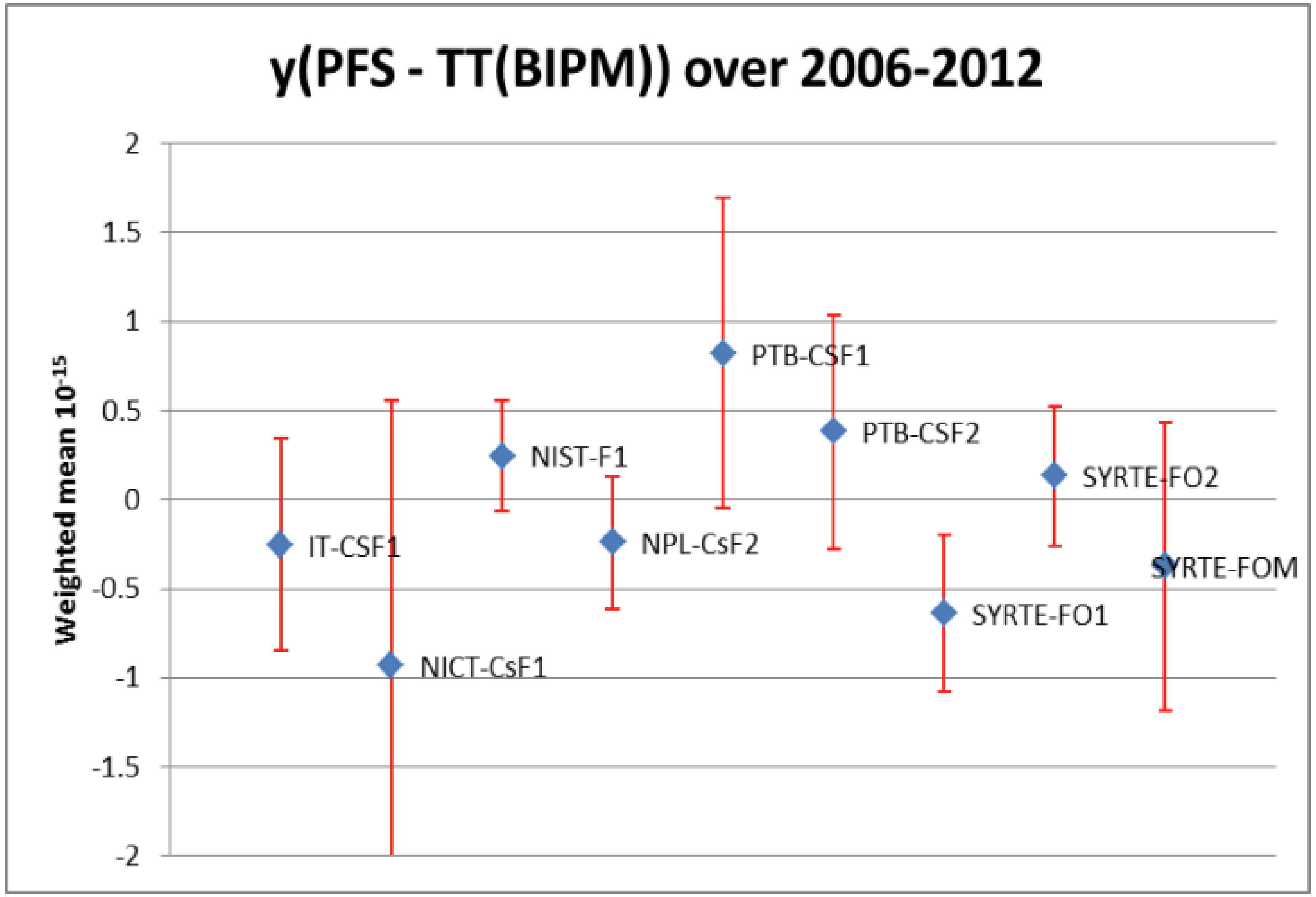
Test the consistency of values y_i and uncertainties: Birge ratio $R_B = \sqrt{\frac{\sum_{i=1}^{n} \frac{(y_i - \overline{Y})^2}{u_i^2}}{(n-1)}}$

- R_B : with the total uncertainty including
  - u_A originating in the instability of the PFS
  - $u_{l/lab}$ uncertainty in the link between the PFS and the TAI clock
  - $u_{l/TAI}$ is the uncertainty in the link to TAI
  - u_B is the combined uncertainty from systematic effects

- $R_B > 1 \equiv$ uncertainties are underestimated
- $R_B < 1 \equiv$ uncertainties are overestimated or the measurements are correlated

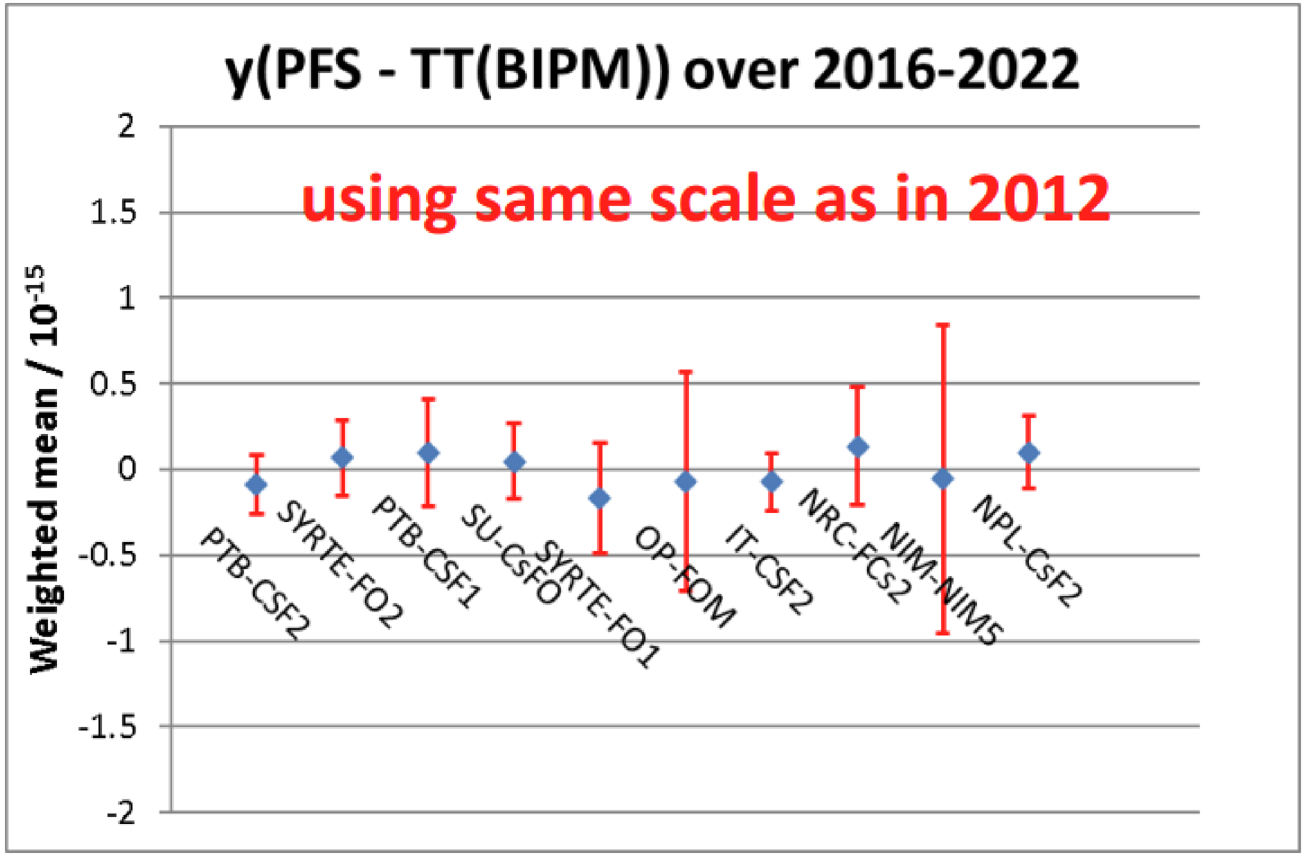
Comparison of PFS to TT(BIPM) over 2006-2012

Standard	$\overline{Y}/10^{-15}$	R_B
IT-CSF1	-0.25	**1.60**
NICT-CSF1	-0.93	0.93
NIST-F1	0.25	**1.43**
NPL-CSF2	-0.24	1.28
PTB-CSF1	0.82	1.10
PTB-CSF2	0.38	1.22
SYRTE-FO1	-0.64	1.01
SYRTE-FO2	0.13	1.27
SYRTE-FOM	-0.37	0.87



PFS vs TT(BIPM) over 2016-2022

Standard	Number	$\overline{Y}_i/10^{-15}$	R_{Bi}
PTB-CSF2	69	-0.09	0.62
SYRTE-FO2	61	0.07	0.50
PTB-CSF1	48	0.10	0.63
SU-CsFO	48	0.04	0.87
SYRTE-FO1	40	-0.17	0.36
OP-FOM	27	-0.07	0.36
IT-CSF2	27	-0.07	0.84
NRC-FCs2	26	0.14	0.65
NIM-NIM5	25	-0.06	0.51
NPL-CsF2	23	0.10	0.78



Global improvement by a factor 3, reflected in the TT(BIPM) uncertainty
Peak-to peak of fountain mean offset Y_i to TT is 3×10^{-16} vs. 1.8×10^{-15} 10 years ago

Accuracy of UTC – Calculation of *d*

- Several laboratories in the world contribute to the accuracy of UTC providing the evaluations of PSFS to the BIPM.
- In Sec. 3 of Circular T:
  - The PSFS are evaluated singularly with respect to TAI
  - The algorithm used to calculate the Terrestrial Time (TT) is used to evaluate the frequency deviation of TAI (d = -y(TAI)) with respect to the ensemble of PSFS.

$$f(TAI - PSFS) = \underbrace{\boxed{f(EAL - clock) - f(EAL - TAI)}}_{\text{BIPM calculation}} - \underbrace{\boxed{f(PSFS - clock)}}_{\text{Laboratory contribution}}$$

Labo	PFS	PfsCode	FreqRef	MJD1	MJD2	[Ref-PFS]	uA	uB	uA_Lab	uB_Lab	Uptime	Ref(uB)	uB(Ref)
						10E-15	10E-15	10E-15	10E-15	10E-15	%		10E-15
xxxx	xxxxxxxxxx	xxxxxxx	xxxxxxx	xxxxx	xxxxx	xxxxxxxxxxxx	xxxxxx	xxxxxx	xxxxxx	xxxxxx	xxxxxx	xxxxxx	xxxxxx
OP	SYRTE-FO2	1920803	1400810	60154	60184	-166.20	0.20	0.30	0.05	0.00	91.7	T301	0.23

```
ADDITIONAL INFORMATION :
Reported by           : LNE-SYRTE
Date of report        : 04 09 2023
Name of the reporter  : B. Chupin
```

Bureau International des Poids et Mesures

Section 3 of Circular T

	Interval of validity	f(EAL)-f(TAI)	
Steering correction	60154 - 60184	6.498x10**-13	(2023 JUL 29 - 2023 AUG 28)
New correction	60184 - 60214	6.498x10**-13	(2023 AUG 28 - 2023 SEP 27)
New correction foreseen	60214 - 60244	6.498x10**-13	(2023 SEP 27 - 2023 OCT 27)

Applied and foreseen steerings

3 - Duration of the TAI scale interval d.

Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainty.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

Standard	Period of Estimation	d	uA	uB	uA/Lab	uB/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Uptime %	LastRep	Nrep3y	Steer	Note
PTB-CS1	60154 60184	-4.46	8.00	8.00	0.00	0.00	0.07	11.31	PFS/NA		T148	8.00	100.0	T427	34	Y	(1)
PTB-CS2	60154 60184	-1.41	5.00	12.00	0.00	0.00	0.07	13.00	PFS/NA		T148	12.00	100.0	T427	36	Y	(1)
KRISS-Yb1	60154 60184	-0.37	0.00	0.04	0.11	0.07	0.20	0.24	0.19	[1]	T405	0.03	37.5	T427	27	Y	(2)
NPL-CsF2	60154 60169	0.27	0.12	0.23	0.10	0.05	0.37	0.46	PFS/NA		T284	0.23	91.1	T427	40	Y	(3)
NRC-FCs2	60154 60184	-0.65	0.13	0.22	0.11	0.00	0.20	0.34	PFS/NA		T389	0.23	89.9	T427	37	Y	(4)
SYRTE-FO2	60154 60184	0.49	0.20	0.30	0.05	0.00	0.20	0.41	PFS/NA		T301	0.23	91.7	T427	35	Y	(5)
SYRTE-FORb	60154 60184	0.11	0.20	0.31	0.05	0.00	0.20	0.42	0.34	[1]	T328	0.34	90.3	T427	34	Y	(5)
PTB-CSF1	60154 60184	0.09	0.09	0.47	0.01	0.00	0.07	0.48	PFS/NA		T371	0.27	96.9	T427	29	Y	(6)
PTB-CSF2	60134 60154	-0.47	0.14	0.17	0.01	0.00	0.09	0.24	PFS/NA		T370	0.17	98.3	T427	40	Y	(6)
PTB-CSF2	60154 60184	-0.11	0.10	0.17	0.02	0.00	0.07	0.21	PFS/NA		T370	0.17	95.9	T427	40	Y	(6)
SU-CsFO2	60154 60184	0.51	1.10	0.22	0.14	0.00	0.20	1.15	PFS/NA		T315	0.50	66.4	T427	33	Y	(7)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report dated 08 AUG. 2023 by KRISS
(3) Report dated 30 AUG. 2023 by NPL
(4) Report dated 31 AUG. 2023 by NRC
(5) Report dated 04 SEP. 2023 by LNE-SYRTE
(6) Report dated 01 SEP. 2023 by PTB
(7) Report dated 04 SEP. 2023 by SU
[1] CCTF Recommendation PSFS-2 (2021),22nd meeting (session II online),
available at https://www.bipm.org/en/committees/cc/cctf/22-_2-2021

Table 2: Estimate of d by the BIPM based on all PSFS measurements identified to be used for TAI steering over the period MJD 59794-60184, and corresponding uncertainties.

Period of estimation	d	u	
60154-60184	-0.11x10**-15	0.12x10**-15	(2023 JUL 29 - 2023 AUG 28)

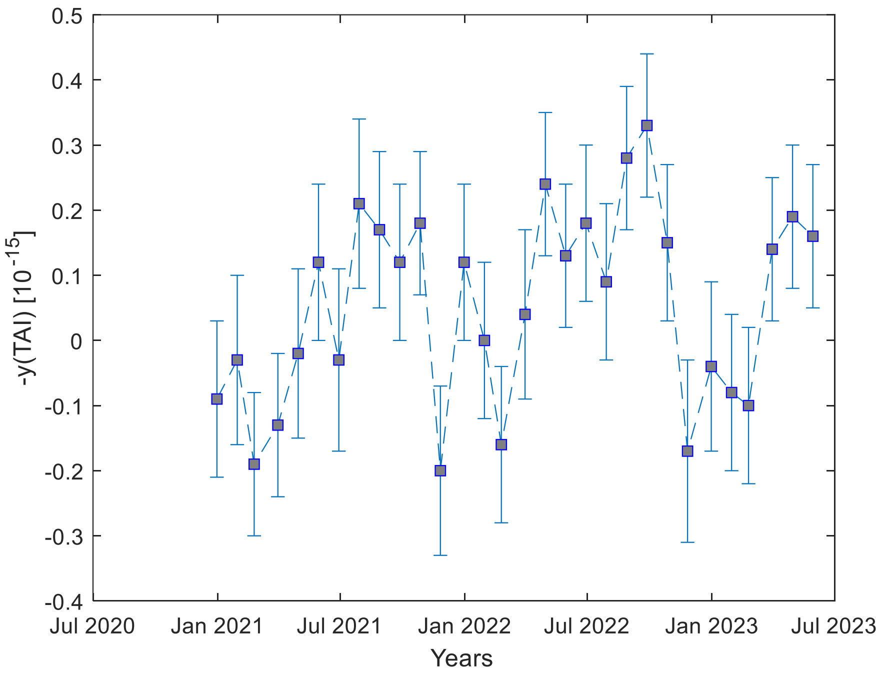
-y(TAI) and uncertainty

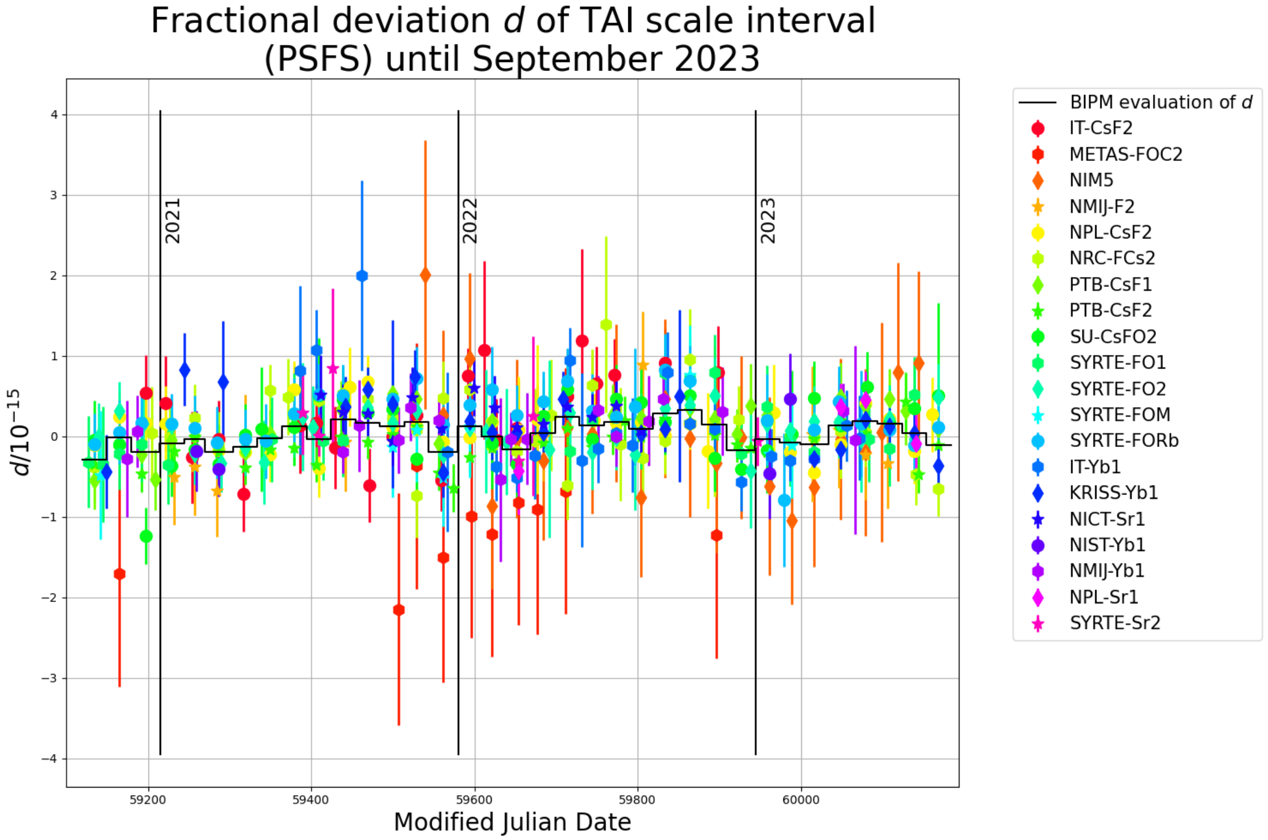
If |d|>= 1 x 10^{-15} a correction of about 0.2 x 10^{-15} is applied two months later.

The frequency accuracy of TAI is estimated at the level of ~10^{-16}

Bureau International des Poids et Mesures

d values





https://webtai.bipm.org/database/d_plot.html

Bureau International des Poids et Mesures

UTCr – the rapid realization of UTC

Since 2013 a rapid evaluation of UTC is available, UTCr.

The data are on daily batches and published each week, the Wednesday.

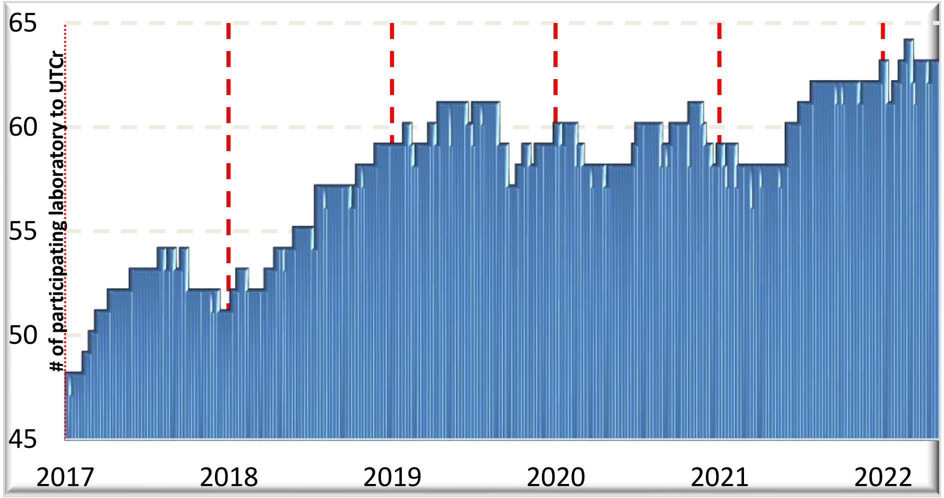
The number of participating laboratories is slightly increased in the last years.

UTCr_2336
2023 SEPTEMBER 12, 13h 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

Computed values of [UTCr-UTC(k)]

Date 2023 0h UTC	SEP 4	SEP 5	SEP 6	SEP 7	SEP 8	SEP 9	SEP 10
MJD	60191	60192	60193	60194	60195	60196	60197
Laboratory k	[UTCr-UTC(k)]/ns						
AOS (Borowiec)	-3.3	-3.2	-3.1	-3.3	-3.5	-3.4	-3.6
AUS (Sydney)	-446.2	-447.5	-444.2	-441.5	-436.8	-438.5	-438.6
BEV (Wien)	-16.0	-17.6	-19.5	-22.6	-27.6	-30.4	-30.6
BIRM (Beijing)	1.6	2.4	3.5	5.3	4.6	5.6	6.5
CH (Bern-Wabern)	-1.1	-1.3	-1.4	-1.6	-1.5	-1.5	-1.9
CNM (Queretaro)	-4.8	-	-	-	-	-	-
CNMP (Panama)	-5.9	2.6	5.1	5.1	4.8	0.4	6.1
DMDM (Belgrade)	-7.6	-16.4	-17.9	-22.5	-24.7	-28.9	-32.0
DTAG (Frankfurt/M)	-26.2	-27.0	-25.2	-25.3	-26.4	-27.6	-28.6
ESA (Noordwijk)	-0.2	-0.1	0.0	-0.1	0.2	0.4	0.0
HKO (Hong Kong)	547.2	549.8	550.4	551.9	555.4	554.5	556.2
ICE (San Jose)	-31.9	-51.5	-49.1	-38.5	-60.3	-51.0	-60.9
IFAG (Wettzell)	-780.2	-782.3	-780.3	-780.7	-779.0	-778.5	-776.2
IGNA (Buenos Aires)	-4292.4	-4305.6	-4326.8	-4343.4	-4355.2	-4371.1	-4382.7
IMBH (Sarajevo)	0.4	0.4	0.4	0.0	0.2	0.3	0.3
INTI (Buenos Aires)	275.0	279.5	279.7	279.2	268.3	270.6	274.2
INXE (Rio de Janeiro)	-12.7	-13.2	-8.8	-5.9	-1.7	1.3	5.6
IPQ (Caparica)	923.5	924.8	925.1	929.9	930.8	931.3	935.9
IT (Torino)	-0.1	-0.5	-1.0	-1.3	-1.5	-1.5	-1.7
JV (Kjeller)	1.6	1.4	1.6	0.9	0.2	0.7	0.5
KRIS (Daejeon)	-2.8	-2.9	-2.8	-2.5	-2.3	-2.5	-2.7
KZ (Astana)	1.4	1.3	1.2	0.9	0.0	-1.0	-1.1
LRTE (Sao Carlos)	1.8	0.7	2.4	2.3	3.3	4.9	3.9
LUX (Belvaux)	0.5	-3.2	-4.4	-2.7	-5.7	-5.4	-4.8
MASM (Bayanzurkh)	-543.4	-556.9	-565.9	-571.3	-578.7	-591.6	-600.3
MIKE (Espoo)	2.9	2.0	2.5	1.8	1.1	0.7	0.4
MSL (Lower Hutt)	83.6	87.1	82.3	82.1	85.8	86.5	87.6
MTC (Makkah)	-3770.0	-3768.3	-3772.5	-3775.3	-3777.8	-3782.0	-3786.4
NAO (Mizusawa)	451.2	452.4	456.7	461.1	465.5	467.2	469.1
NICT (Tokyo)	-1.6	-1.3	-1.6	-1.4	-1.6	-1.5	-1.5
NIM (Beijing)	-1.7	-1.9	-1.9	-1.8	-2.5	-2.1	-1.5
NIMB (Bucharest)	88.1	87.6	87.8	83.2	81.0	81.1	80.6

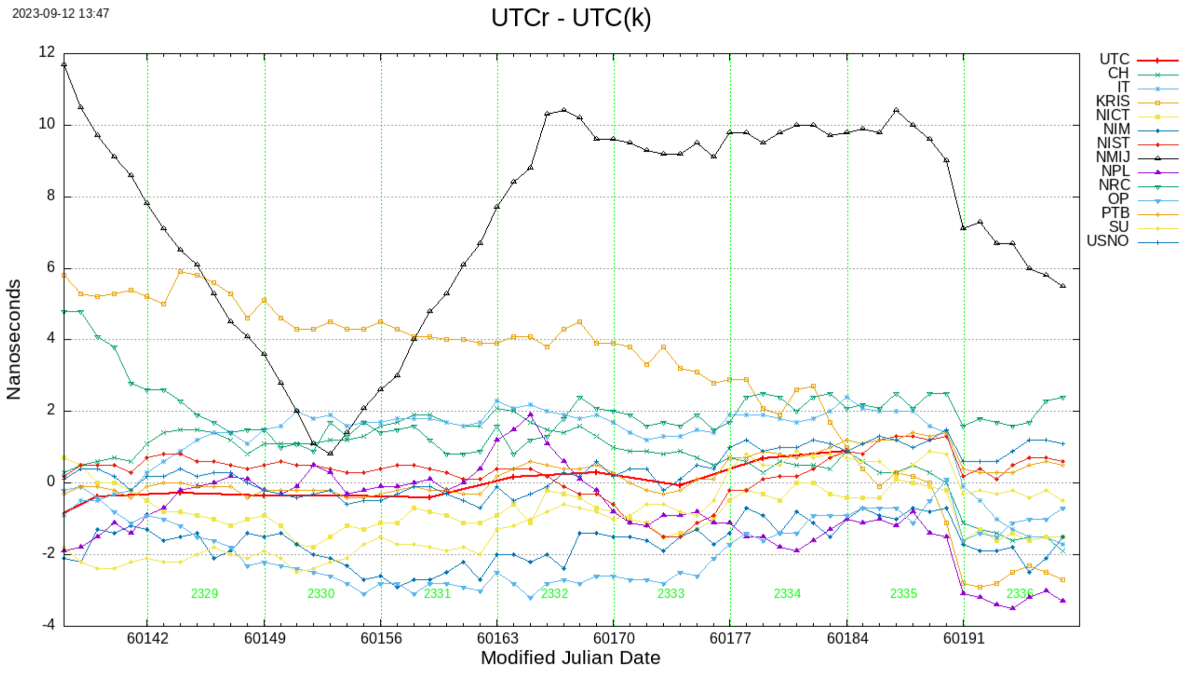


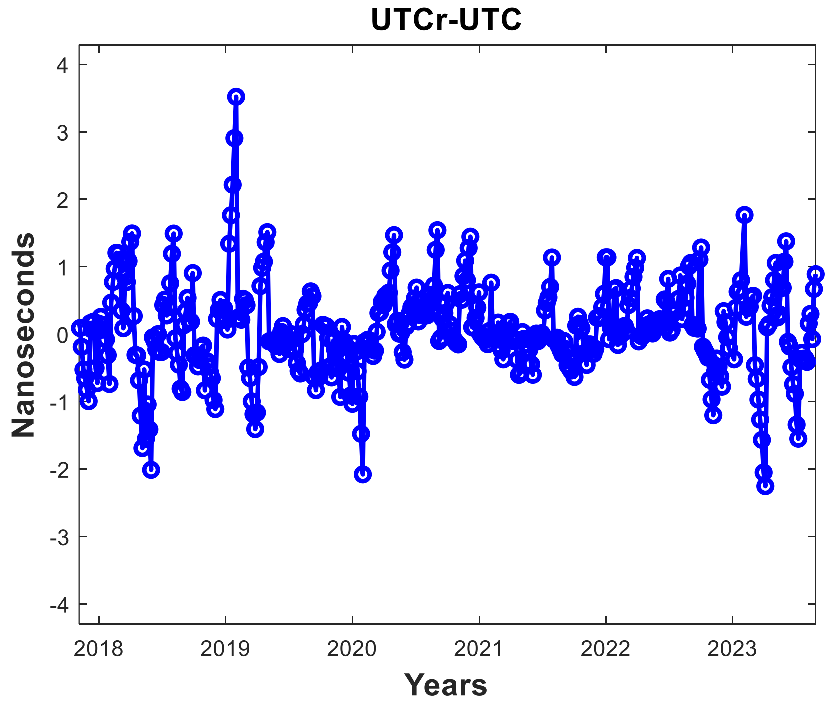
Bureau International des Poids et Mesures

UTCr versus UTC

For the week 2336 for example we had 62 participating laboratories with 260 atomic clocks.
Concerning the time links, we apply the following politics:

- if in UTC the combination of TW and GPS PPP is used ⇒ in UTCr the TW
- If in UTC we use GPS PPP ⇒ in UTCr GPS P3





Bureau International des Poids et Mesures

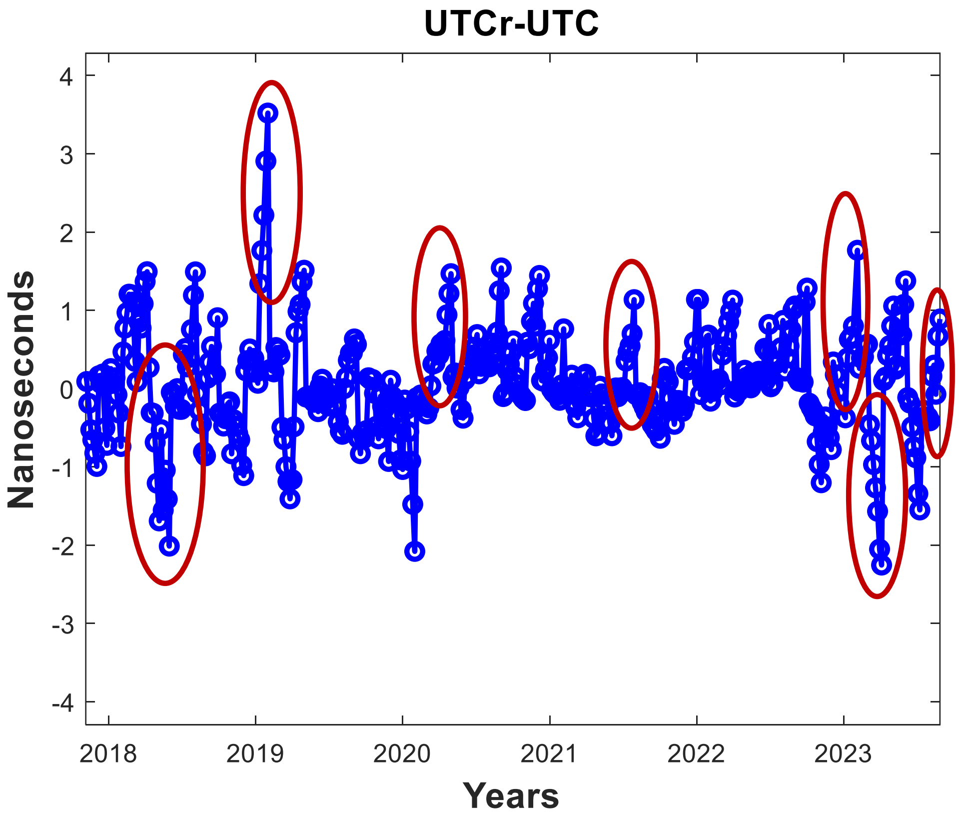
Stability of UTCr

- UTCr was not conceived to have a very good long-term stability (major difference from UTC) but to give access to UTC with a short latency to the participating laboratories .
- The goal for UTCr is to be as close as possible to UTC $(\pm 2\ ns)$
- The algorithm used for the stability is like UTC algorithm
  - quadratic prediction
  - weight algorithm attributing to the clocks a weight based on the predictability/stability

Bureau International des Poids et Mesures

Accuracy of UTCr

- The accuracy for UTCr means that UTCr must be as close as possible to UTC.
- No frequency steering is applied
- Steering in time is applied each month after the publication of Circular T.



Applied corrections

Bureau International des Poids et Mesures

Conclusions

- The contribution of PSFS to UTC is crucial to ensure:
  - The use of the clocks (hydrogen Masers) at the best of their capabilities
  - The constant improvement of long-term stability and accuracy of UTC
- The contribution to UTC of SFS is also a requirement for the possible redefinition of the second
- The BIPM thanks all the laboratories and the SYRTE in particular for their strong engagement in providing regularly PSFS data to the BIPM.

Thank you very much for your attention

Bureau International des Poids et Mesures