Bureau International des Poids et Mesures

Realization and maintenance of UTC

Elisa Felicitas Arias

Radiocommunication development in light of WRC-12 decision

St. Petersburg, 6-8 JUNE 2012.

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Timescales maintained at the BIPM

International Atomic Time (TAI)	✓ Continuous ✓ Interval unit is the SI second ✓ Calculated monthly at BIPM ✓ No clock representation, no broadcast
Coordinated Universal Time (UTC)	✓ 1-second discontinuities ✓ Interval unit is the SI second ✓ Calculated monthly at BIPM, derived from TAI ✓ Clock representations UTC(k), broadcast
Terrestrial Time (TT(BIPM))	✓ Continuous ✓ Interval unit is the SI second ✓ Calculated annually at BIPM ✓ Monthly predictions ✓ No clock representation, no broadcast

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UTC

Coordinated	Universal	Time

Coordinated → Coordinated broadcast of time signals (ITU-R)

Universal → Related to the Earth's rotation; Universal Time (UT) was the name of the time scale derived from the apparent daily motion of the Sun

TAI differs from UTC in an integral number of seconds

Leap second announcement is the responsibility of the IERS

- GMT (Greenwich Mean Time) was replaced by UT in 1948 (IAU)
- UT was replaced by UTC in 1972 (CGPM)

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Each month: → 68 participants → ftp server

~400 clocks, one measurement / 5 days, t&f corr. monthly	13 primary freq. standard data monthly	~180 time transfer files daily, weekly, monthly

Data submission deadline 4/mm/yy/

Datation is in « Modified Julian Date », a contiuous count of days since an arbitrary origin

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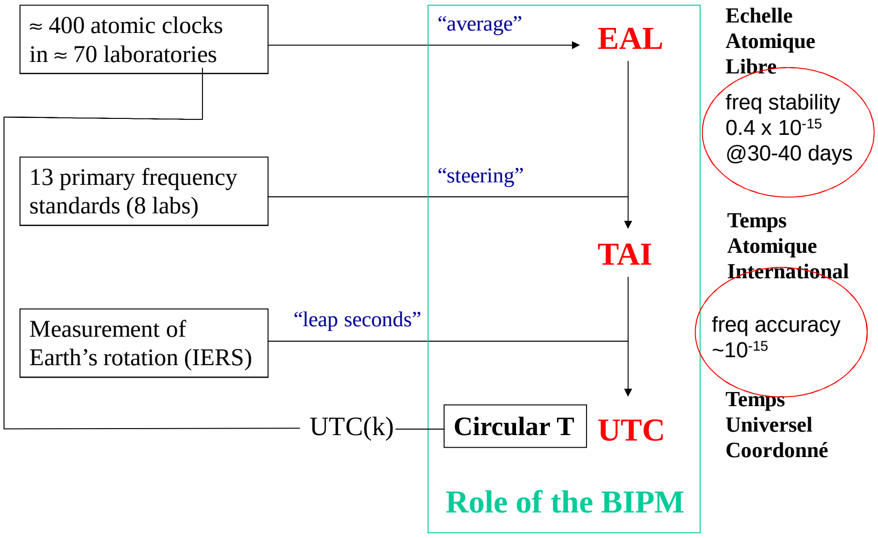
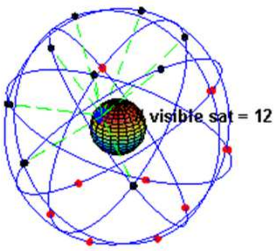
Elaboration of TAI and UTC - ALGOS



First step: from clock readings to clock differences

- Remote clock comparison by time transfer techniques
  - Global Navigation Satellite Systems
    - GPS (currently)
    - GLONASS (currently)
    - Galileo, BeiDou (future)



  - Two-way satellite time and frequency transfer

Measure with each clock a common external signal: GNSS

Each station measures

- (Local clock – Satellite clock)

Then two solutions

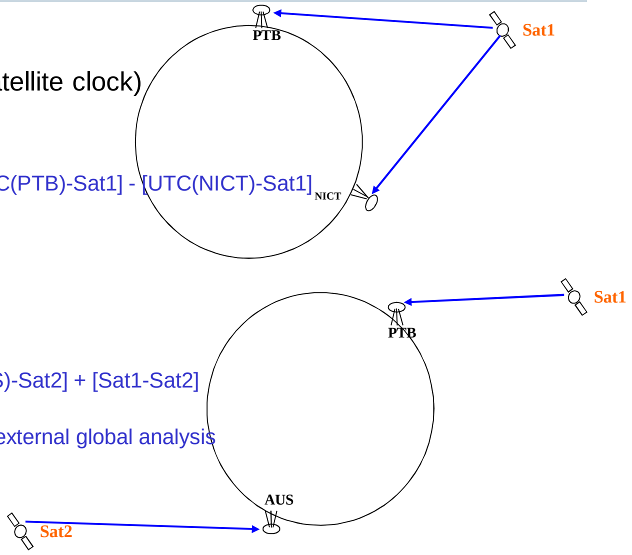
- Common-view

UTC(PTB)-UTC(NICT) = [UTC(PTB)-Sat1] - [UTC(NICT)-Sat1]

- All-in-view

UTC(PTB)-UTC(AUS) =
[UTC(PTB)-Sat1] - [UTC(AUS)-Sat2] + [Sat1-Sat2]

with [Sat1-Sat2] provided by external global analysis



GNSS time transfer

- Calibrated receivers
- Common-views / all-in-view
- Corrections for the orbital motion of the satellite
- Signal propagation delays
  - Ionosphere
  - Troposphere
- Quasi continuous observations
- Environmental conditions limit the performance of multi-channel receivers

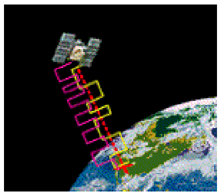
single-channel, single frequency

multi-channel, single frequency

multi-channel, dual frequency

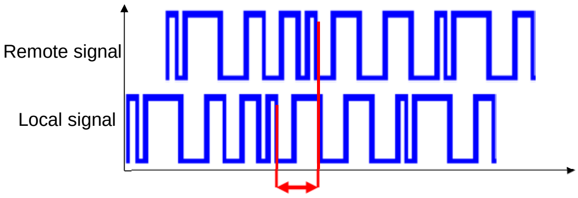
Uncertainty improves

Time comparisons by correlation: example of GNSS code

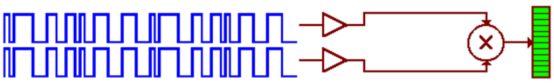


Typical uncertainty

- $\sigma_C \approx k/(B/SNR)$ where B is the transmitted bandwidth i.e. 1/B is the chip length
- GPS: B = 1/10 MHz => $\sigma_C \approx$ 10/1 ns



GPS/GLONASS SC, MC, P3

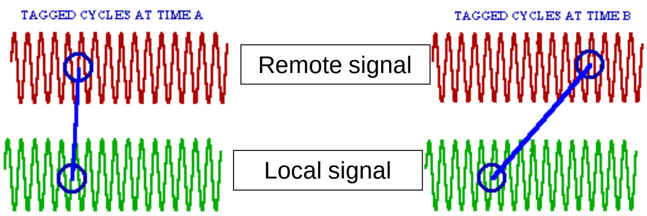


Frequency comparisons: example of GNSS phase

Continuous mixing of remote signal vs. local signal

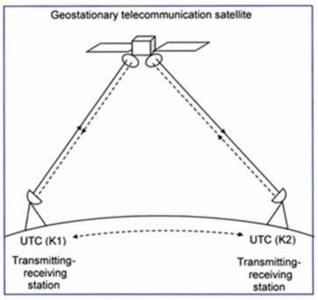
- Uncertainty on phase $\sigma_\phi \approx 1/(f/SNR)$ where f is the transmitted frequency
- GPS: f = 1.5 GHz => $\sigma_\phi \approx$ 1 ps

GPS PPP



TWSTFT

- simply computation of clock offsets
- direct link of clocks
- no models necessary
- clock effects can be separated from others
- Calibrated receiving/emitting stations
- Telecommunications satellite
  - No clock on board used
  - Geostationary



TWSTFT, TWPPP

A measurement technique used to compare two clocks or oscillators at remote locations.

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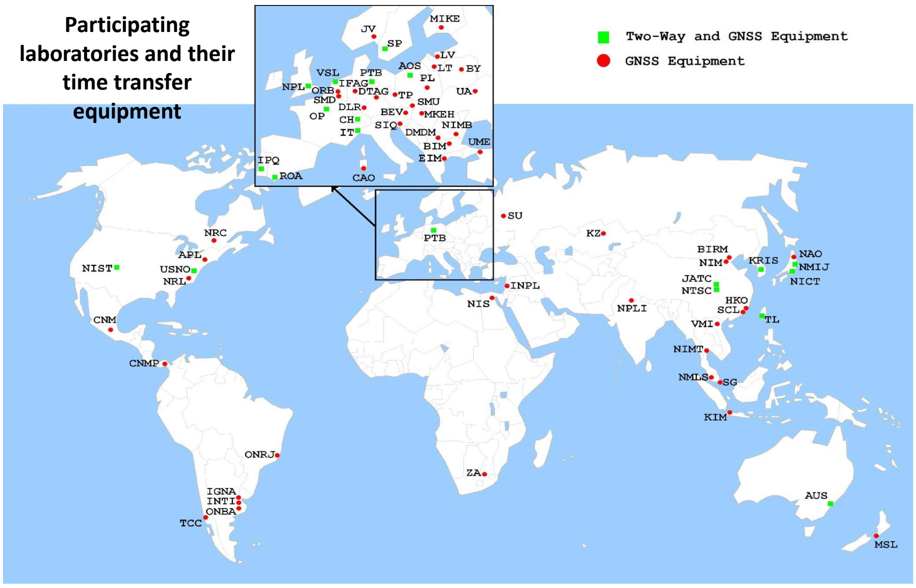
Participating laboratories and their time transfer equipment



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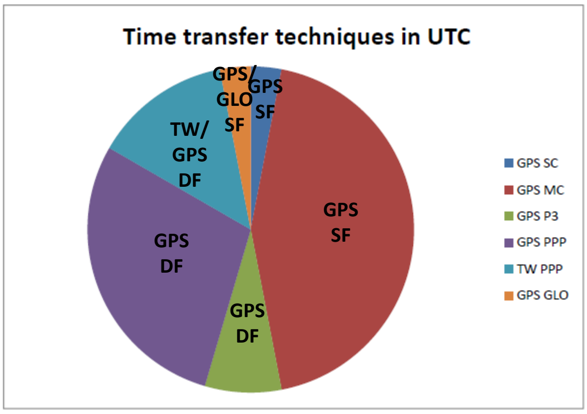
Time transfer techniques in UTC (October 2011)



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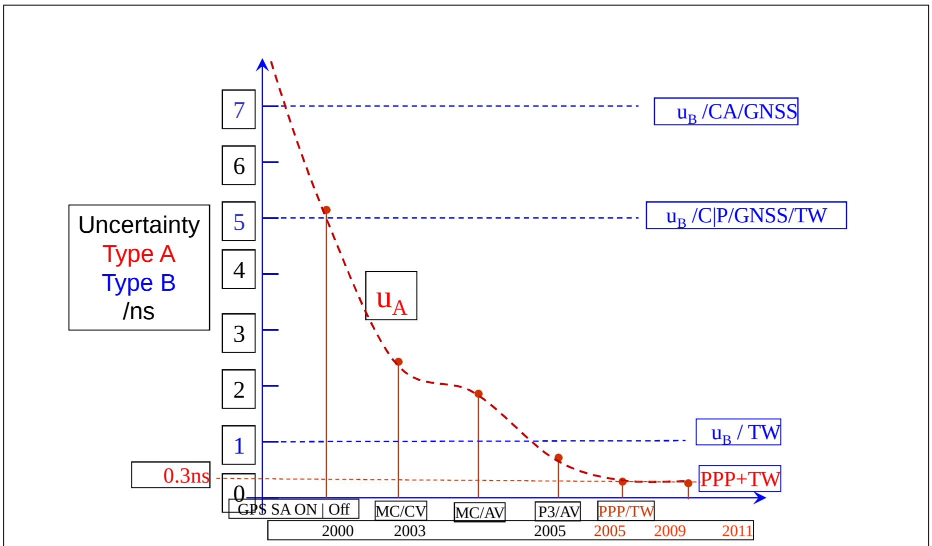
Uncertainty of time transfer in UTC



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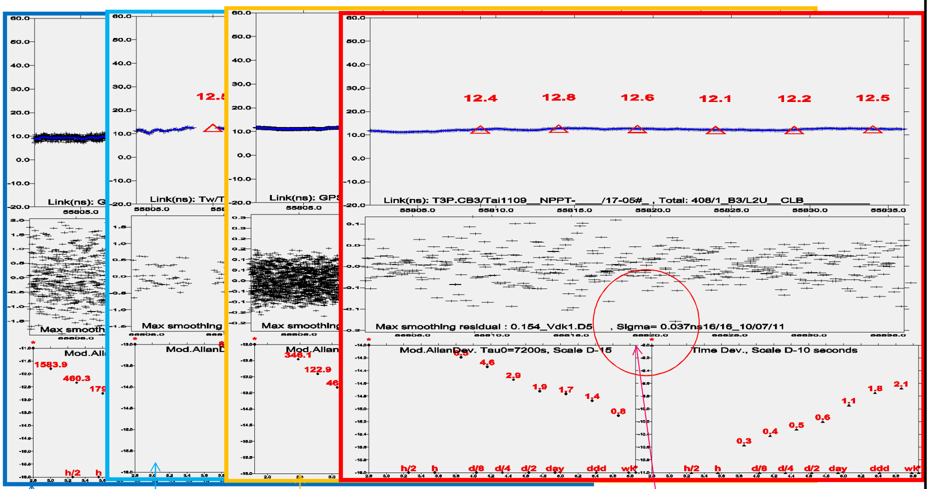


σ= 0.84 ns GPS P3

σ= 0.43 ns TWSTFT

σ= 0.06 ns GPS PPP

σ= 0.04 ns TW PPP

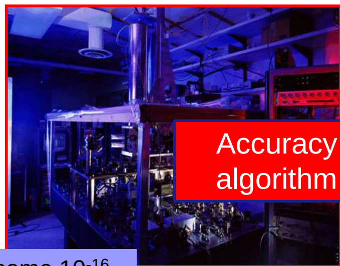
Clocks in UTC

Stability 7×10^{-16} (1 day)

Stability algorithm

Stability 1×10^{-14} (1 day)

Accuracy 5×10^{-13}



Accuracy algorithm

Accuracy some 10^{-16}

Stability algorithm

In an ideal situation,

- Simultaneous clock readings x_i,
- Fix set of contributing clocks,
- Continuously participating clocks

So, EAL (t) = $\{x_i\}$ (t) (weighted average)

In the real situation,

- Weights change,
- Clocks are interrupted, clock frequencies suffer changes
- New clocks arrive

So, EAL (t) = $\{x_i\}$ (t) + A + B(t-t_0)

EAL: Weighting Algorithm

The weight attributed to a clock reflects its long-term stability, since the objective is to obtain a weighted average that is more stable in the long term than any of the contributing elements.

In the time scale algorithms clock weights are generally chosen as the reciprocals of a statistical quantity which characterizes their frequency stability, such as a frequency variance (classical variance, Allan variance....)

EAL: Prediction Algorithm

In the generation of a time scale, the prediction of the atomic clock behavior plays an important role;

The prediction is useful to avoid or minimize the frequency jumps of the time scale when a clock is added or removed from the ensemble or when its weight changes.

......EAL (cont.)

The system solved by ALGOS:

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

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

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

$$\sum_{i=1}^{N} w_i = 1$$

The solution is:

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

Weigth

Prediction

.........Weighting Algorithm

The weight attributed to clock H_i is the reciprocal of the individual classical variance σ_i^2

$$\omega_i = \frac{1/\sigma_i^2}{\sum_{i=1}^{N} 1/\sigma_i^2}$$

$$\text{Upper Limit} \Rightarrow \omega_{MAX} = \frac{A}{N}$$

A=2.5 empirical constant

$$\sum_{i=1}^{N} w_i = 1$$

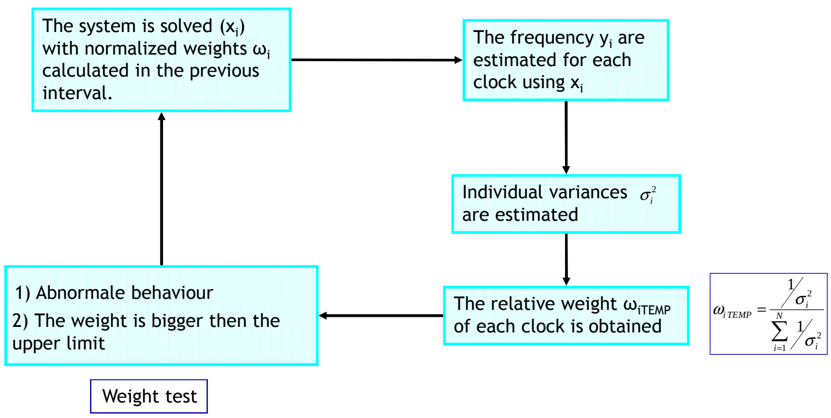
Two particular situations are checked:

1. Clock H_i shows abnormal behaviour
2. The weight is bigger then the upper limit fixed to avoid that a clock has a predominant role.

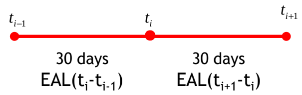
The weight attributed to clock H_i is computed from the frequencies of the clock, relative to EAL, estimated over the corrent 30 day interval and over the past five consecutive 30 days period. The weight determination thus uses clock measurement covering **one year**.

Weighting procedure for EAL

An iterative process, including 4 iterations, is used in ALGOS:

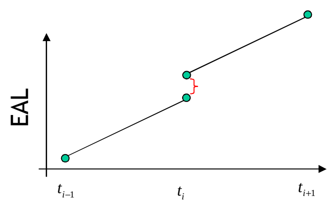


.....Prediction Algorithm

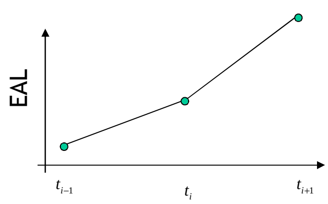


In two different intervals the clock ensemble can change

The consequences:



Time step



Frequency step

Clock behaviour

The atomic clocks are caracterized by different behaviour:

1) Deterministic behaviour
   - Linear - cesium clocks
   - Quadratic - Hmaser clocks

2) Stochastic behaviour

A statistical method used to determine instabilities given by the stochastic component is the:

Allan Variance

Prediction Algorithm on EAL

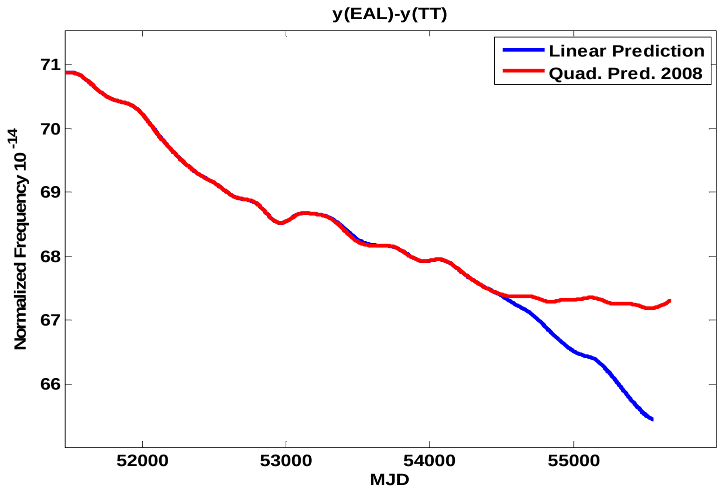
The correction term $h_i'(t)$ for clock H_i is :

Time correction — frequency

$$h_i'(t) = a_i(t_i) + B_{ip}(t)(t - t_i)$$

- $a_i(t_i)$ is the estimation of the time correction relative to EAL of clock H_i at date t_i
- $B_{ip}(t)$ is the estimation of the frequency of clock H_i, relative to EAL, predicted for the period [t_i, t]
- $C_{ip}(t)$ is the estimation of the frequency drift of clock H_i, relative to a frequency reference, predicted for the period [t_i, t]

EAL was affected by a drift relative to TT(BIPM) of about 4 x 10^{-16}/month.
The new frequency prediction model is stopping the drift and improves the stability of EAL.



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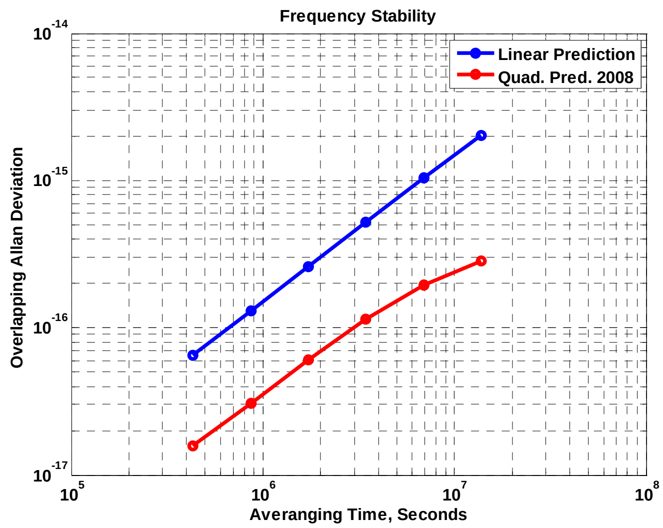
Improvement of the frequency stability of EAL with the new clock frequency prediction model (since July 2011)



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From EAL to TAI

EAL is a free-running atomic time scale optimized to be a time scale stable a long term.

We evaluate the EAL frequency (f(EAL)) by means the primary frequency standards (PFS).

TAI is expected to be stable (from EAL) and accurate (from PFS).

Accuracy is obtained by frequency steering:

f(TAI) = f(EAL) + steering frequency

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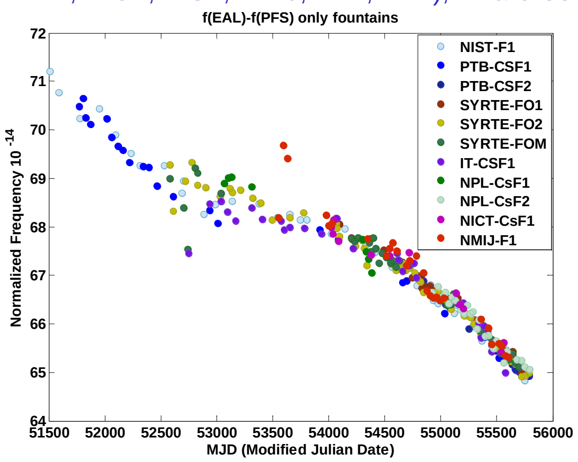
Primary frequency standards

Primary frequency standards – 13 in the last five years (KRISS, INRIM, LNE-SYRTE, NICT, NIST, NMIJ, NPL, PTB), 11 are Cs fountains



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TT(BIPM)

The BIPM computes in deferred time TT(BIPM), which is based on a weighted average of the evaluations of TAI frequency by the PFS.

TT(BIPM) is computed in deferred time and updated every year.

Predictions of TT(BIPM) are computed monthly.

It is the same algorithm used to evaluate f(EAL) but in post processing.

We consider TT(BIPM) the frequency reference to evaluate:

1. f(EAL) performance
2. f(TAI) performance
3. PFS performance

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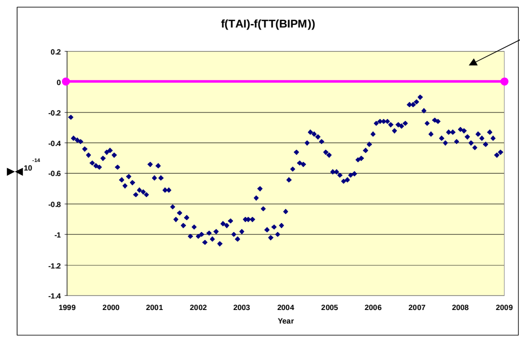
f(TAI) - f(TT(BIPM))

The goal!



TAI is close to its definition (< 5×10^{-15} over last 2 years), but still off

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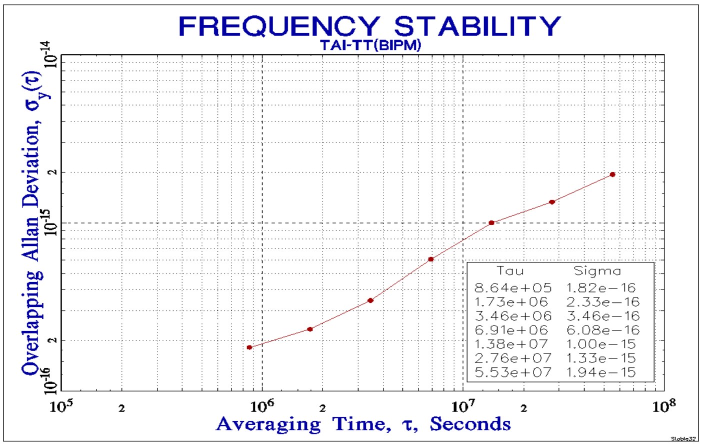
Stability of TAI respect to TT(BIPM)



The long-term instability of TAI is between 1×10^{-15} and 2×10^{-15}, a factor two or three worse than the value for TT(BIPM).

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Traceability of UTC(k) to UTC

CIRCULAR T 285 ISSN 1143-1393
2011 OCTOBER 10, 15h UTC

BUREAU INTERNATIONAL DES POIDS ET MESURES
ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 FAX. +33 1 45 34 20 21 tai@bipm.org

1 - Coordinated Universal Time UTC and its local realizations UTC(k). Computed values of [*UTC-UTC(k)*] and uncertainties valid for the period of this Circular. From 2009 January 1, 0h UTC, *TAI-UTC* = 34 s.

Date 2011 0h UTC	AUG 31	SEP 5	SEP 10	SEP 15	SEP 20	SEP 25	SEP 30	Uncertainty/ns			Notes
MJD	55804	55809	55814	55819	55824	55829	55834	u_A	u_B	u	
Laboratory *k*	[*UTC-UTC(k)*]/ns										
AOS (Borowiec)	3.6	5.6	5.5	8.2	8.4	6.7	5.4	0.4	5.2	5.2	
APL (Laurel)	10.0	13.2	14.7	2.7	-2.5	-2.9	-5.6	1.5	5.1	5.3	
AUS (Sydney)	944.8	923.8	910.9	897.1	901.4	898.8	889.5	0.4	5.2	5.2	
BEV (Wien)	15.3	-0.5	0.2	5.5	8.2	6.5	5.4	1.5	3.3	3.6	
BIM (Sofiya)	-5861.2	-5863.7	-5846.7	-5853.3	-5846.0	-5844.3	-5821.4	2.0	7.1	7.4	
BIRM (Beijing)	-2408.8	-2470.8	-2682.8	-	-2405.1	-2379.0	-2335.6	2.0	20.1	20.2	
BY (Minsk)	57.1	1.1	7.9	16.3	28.5	34.6	40.1	2.0	7.1	7.4	(1)
CAO (Cagliari)	-5726.2	-5730.3	-5736.2	-5760.2	-5792.2	-5805.9	-5825.4	1.5	7.1	7.3	
CH (Bern)	8.4	5.4	3.1	2.4	-0.2	1.0	-0.5	0.4	1.8	1.8	
CNM (Queretaro)	-1.4	-6.1	-9.4	-11.4	-0.3	-14.7	-14.3	2.5	5.2	5.8	
CNMP (Panama)	-16.8	-1.7	21.8	16.3	12.9	21.2	15.1	3.0	5.2	6.0	
DLR (Oberpfaffenhofen)	31.4	11.2	9.9	14.0	12.3	3.0	-2.0	0.4	5.2	5.2	
DMDM (Belgrade)	-17.3	2.4	-6.1	-18.7	-18.4	-22.0	-16.2	2.0	7.1	7.4	
DTAG (Frankfurt/M)	-24.2	-21.3	-19.0	-24.1	-14.8	-11.4	-11.4	0.4	10.1	10.1	
EIM (Thessaloniki)	6.1	9.1	6.7	8.3	7.8	6.0	-	5.0	5.2	7.2	
HKO (Hong Kong)	42.9	41.9	44.4	41.5	40.2	40.0	51.4	2.5	5.2	5.7	
IFAG (Wettzell)	-424.5	-437.7	-440.2	-445.6	-447.6	-452.6	-459.5	0.4	5.1	5.1	
IGNA (Buenos Aires)	4121.1	4188.5	4260.6	4326.3	4391.9	4463.9	4530.7	2.5	5.2	5.8	
INPL (Jerusalem)	-255.7	-265.1	-269.5	-272.4	-276.6	-283.4	-291.8	1.5	20.0	20.1	
INTI (Buenos Aires)	41.5	49.8	63.0	39.3	34.8	17.6	5.9	4.0	20.1	20.4	

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Improving UTC for the 21st century applications

- ✓ Better clocks (in labs)
- ✓ New pfs (in labs)
  - ✓ Optical frequency standards (in labs)
    - –Accurate time and frequency transfer (labs, BIPM)
- ✓ Improved clock comparisons by refining time transfer (labs, BIPM)
- ✓ Improved algorithms (labs for UTC(k), BIPM for UTC)
- ✓ Providing UTC more frequently (BIPM Rapid UTC project)
  - ✓ Impact on UTC(k)
  - ✓ Impact on steering GNSS times to a representation of UTC
- ✓ Rendering UTC continuous (ITU)
  - ✓ Benefits displayed at this meeting

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Many thanks for your attention!

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