Introduction to reference time scales

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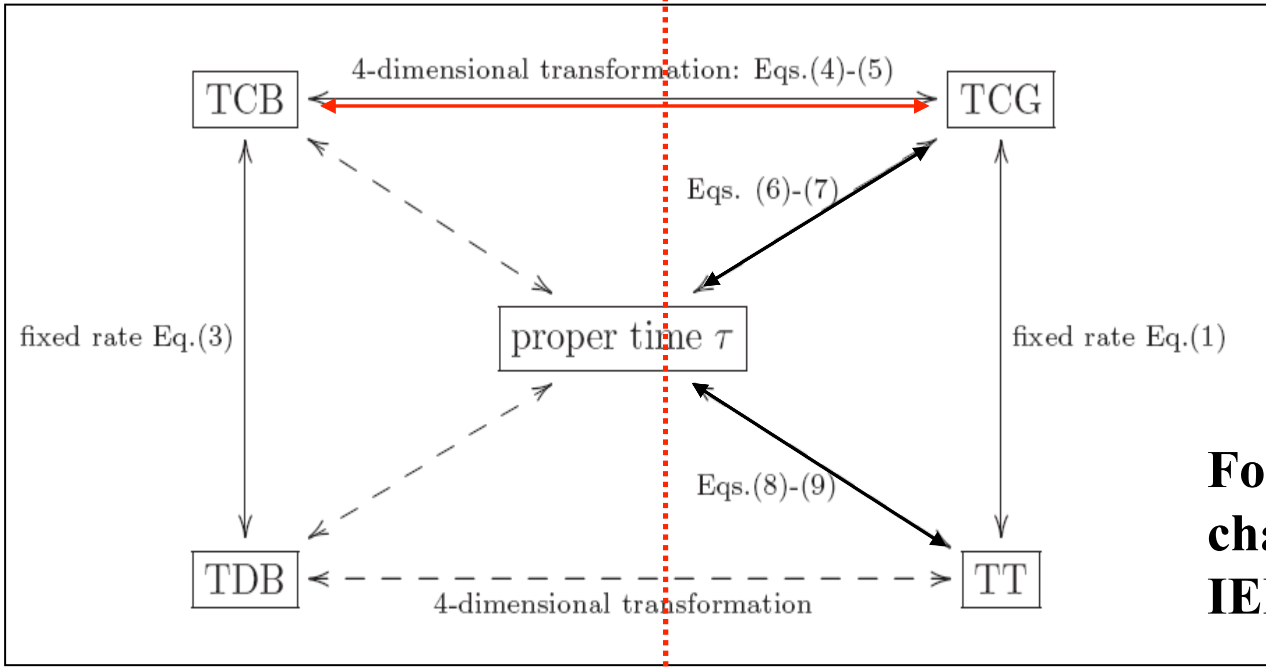
Résumé

- **Timescales: definitions and realizations**
- BIPM atomic time scales: EAL-TAI-UTC, TT(BIPM)
- Primary standards, TAI and TT(BIPM) between the end 1980s and now
- Pulsars and TAI / TT(BIPM)
- Conclusions

Time coordinates and time transformations (1/2)



For more info, see chapter 10 of the IERS Conventions

- Barycentric system: time coordinate is TCB
  - TDB may be used

dTDB/dTCB = $1-L_B$, L_B= 1:550519768x10^{-8}

- **Geocentric system: time coordinate is TCG**
  - **TT is used in practice**

dTT/dTCG = $1-L_G$, L_G= 6.969290134x10^{-10}

- **TT and TDB have been introduced to have "~ the same rate" as a clock on the geoid**

Time coordinates and time transformations (2/2)

- **Barycentric system: TCB to TDB**

  $dTDB/dTCB = 1-L_B$, $L_B= 1.550519768 \times 10^{-8}$

- **Geocentric system: TCG to TT**

  $dTT/dTCG = 1-L_G$, $L_G= 6.969290134 \times 10^{-10}$

- **Between the barycentric and the geocentric systems, all coordinate transformations are 4-dimensional**

$$\mathrm{TCB} - \mathrm{TCG} = \frac{L_C \times (TT - T_0) + P(TT) - P(T_0)}{1 - L_B} + c^{-2}\vec{v_e} \cdot (\vec{x} - \vec{x}_e) \quad (10.5)$$

where the values of L_C and L_B may be found in Chapter 1 Table 1.1. Non-linear terms denoted by $P(TT)$ have a maximum amplitude of around 1.6 ms.

Various formulas exist to estimate P(TT) or the full transformation, see IERS Conventions (2010) chapter 10.

Location-dependent terms are of order µs on Earth.

Coordinate times for pulsar analysis

- **All "usual" timescales provide realizations** of TT (possibly with an a priori offset), therefore are **coordinate times**. They make use of coordinate synchronization.
- These **realized** timescales are
  - **TAI** defined by the CIPM in 1970 — TT ≈ TAI + 32.184s
  - **UTC** defined by the CCIR (now ITU) in 1970: — UTC = TAI – leap seconds
  - **TT(BIPMxy)** realized every year by the BIPM;
  - **GPS Time**; — GPS Time ≈ TAI – 19 s
  - all timescales aiming at realizing UTC like UTC(k), GLONASS Time…

- Pulsar analysis is done in the barycentric frame, but timing is in the local scale

• Local scale	→ UTC	Uncertainty in the ns range, 1 ns at best
• UTC	→ TAI	Exact
• TAI	→ TT	Uncertainty ~ few ns/year if TT(BIPM) is used
		Error may be large if TT = TAI+32.184 s
• TT	→ TCB	Using formulas. Uncertainty ~ ns/year

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- **BIPM atomic time scales: EAL-TAI-UTC, TT(BIPM)**
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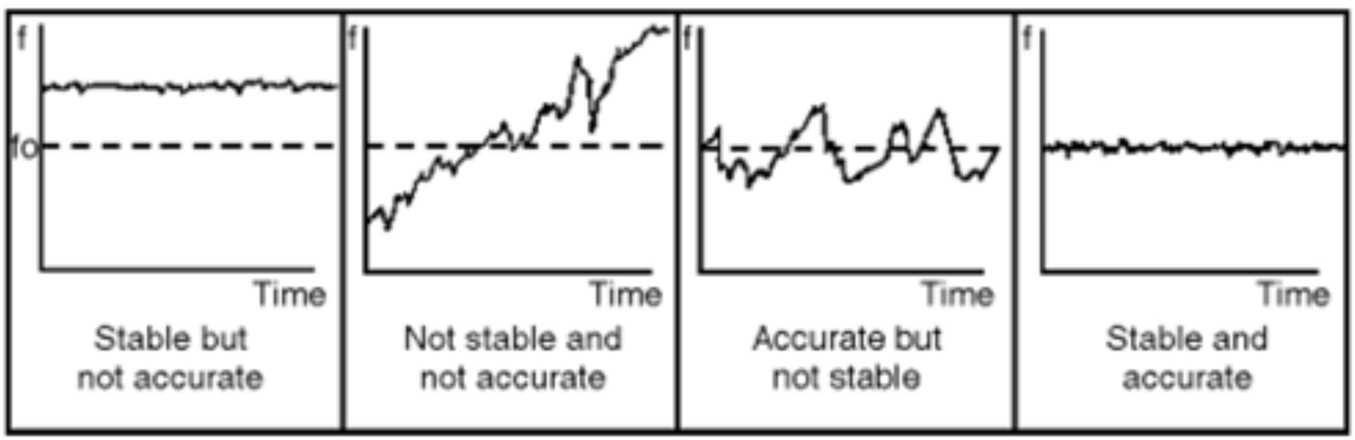
Ingredients and properties of an atomic time scale

- Based on atomic clocks
- Ensemble of clocks to provide stability, reliability
  - Weighting algorithm to make best use of best clocks
  - Prediction algorithm to deal with known changes
- Also use Primary Frequency Standards (PFS) to provide accuracy
- Time transfer techniques, if clocks are in remote sites
- The performance of a timescale depends on all the ingredients
  - Clocks, time transfer, PFS



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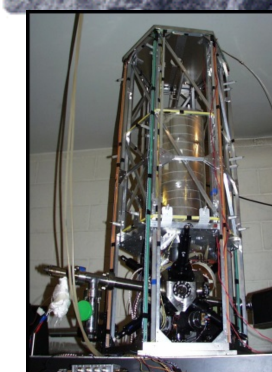
Some clocks and orders of magnitude

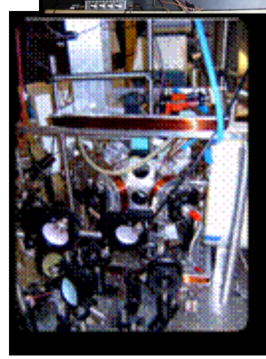
- Clocks aim at running continuously
- Frequency standards aim at generating the same frequency whenever they run.

Commercial clocks
Cs tube, H-maser
10^{-14} ≈ 1 ns / 1 day
10^{-15} ≈ 0.1 ns / 1 day

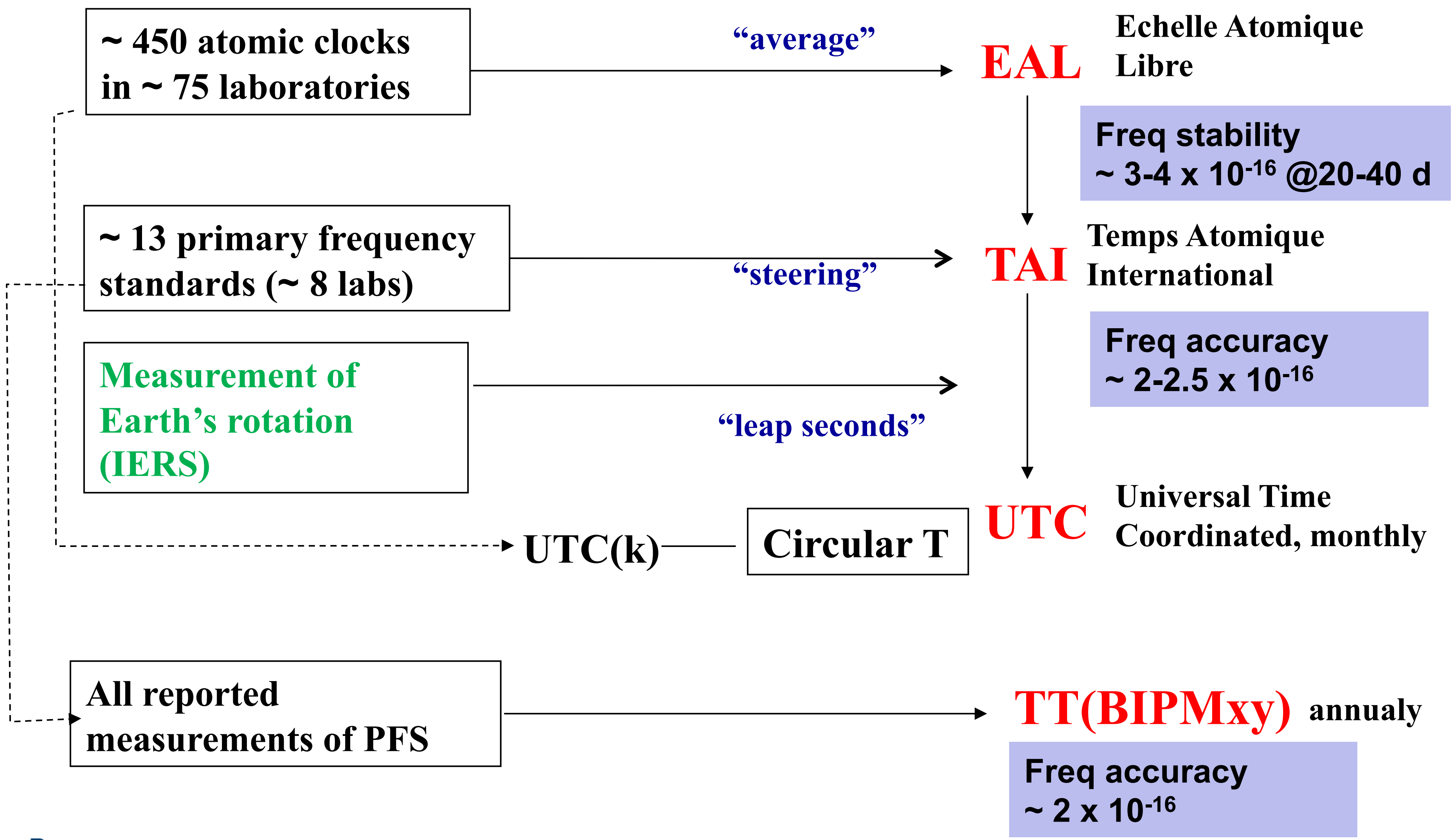

« Best » present standards
Cs fountains (in ~ 10 labs)
10^{-16} ≈ 0.1 ns / 10 days
10 ps / 1 day




Future standards
Lattice (e.g. Sr), trapped ions
10^{-17} ≈ 1 ps / 1 day
10^{-18} ≈ 1 ps / 10 days




Timescales at the BIPM



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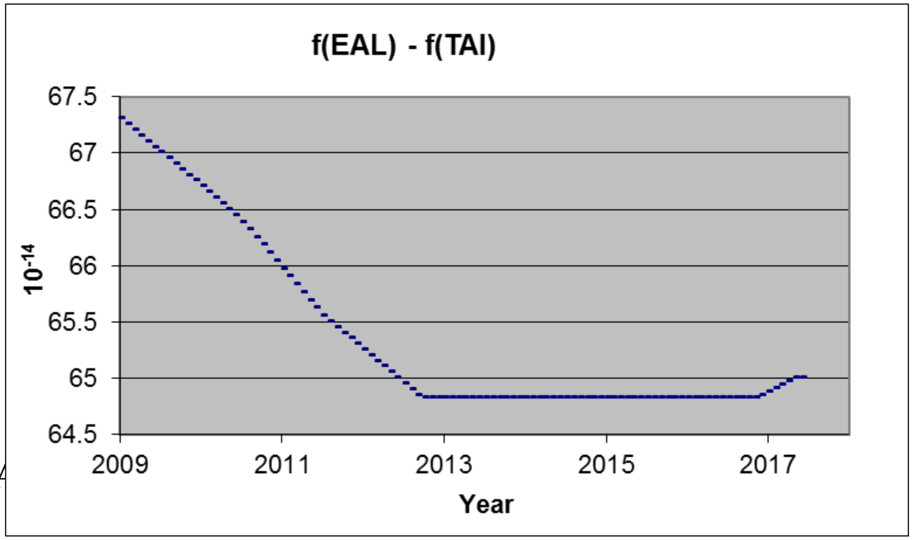
Generation of TAI (and UTC)

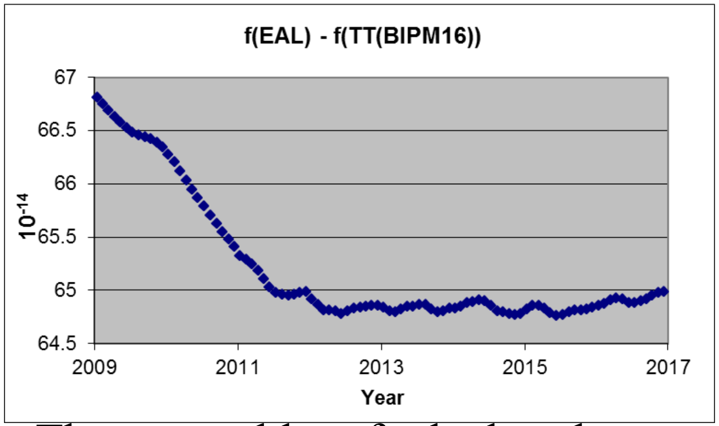
Each month (~real time), a 2-step process

1. the BIPM computes a free atomic scale, **EAL**, from more than 450 atomic clocks worldwide (as of 2015-2017).
   - Ensemble time scale computed on 1-month intervals using a **prediction** of the clock frequency where each clock receives an individual **weight** (may be 0);
   - Algorithm ALGOS for clock **prediction** and clock **weighting**
     - Revised in 2011 (prediction part) and 2014 (weighting part)
2. primary and secondary frequency standards estimate f(EAL).
   - Using an estimation procedure that takes into account all PFS/SFS available, even past data (although with less weight)
   - The frequency is then steered: **TAI** = EAL + steering

- However, with the 2011 prediction algorithm, EAL is not “truly free”, and from end-2012 to end-2016, no steering needed!
- Finally **UTC** = TAI – leap seconds



EAL prediction and weighting algorithms



UTC is calculated with > 450 clocks of which:

- Caesium clocks 5071 (high performance tube): ~ 270
- H-masers: ~130
- 4 Rb fountains

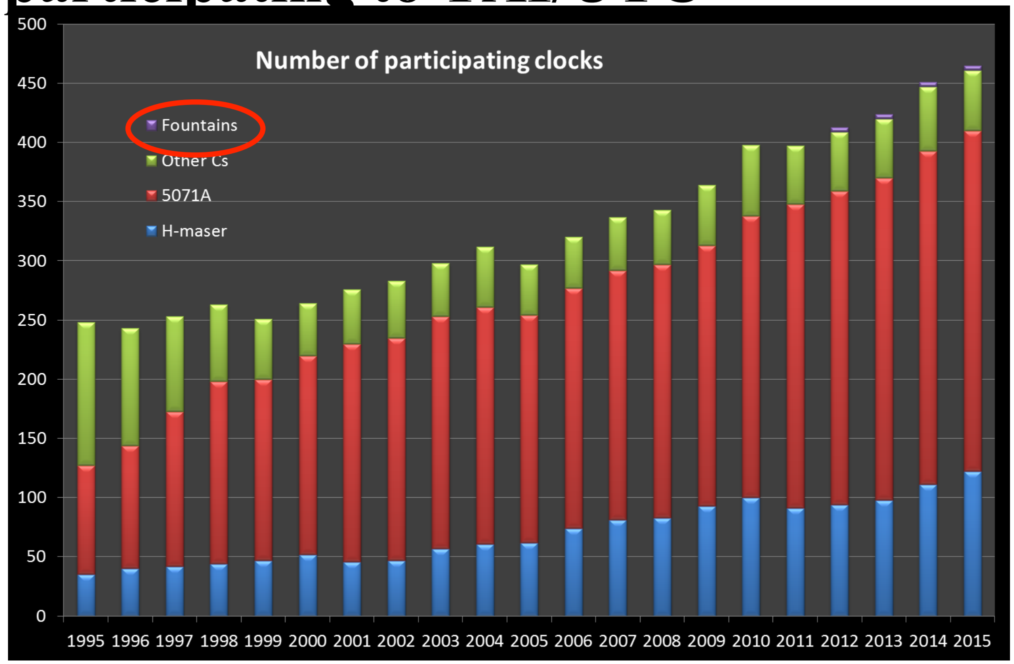
Prediction algorithm

- Until July 2011 a linear prediction had been used. The ensemble of clocks shows deterministic signatures (frequency drift or aging), so does EAL
- Since August 2011 a quadratic prediction with respect to TT(BIPM) is used to describe the clock behaviour. The systematic frequency drift of EAL has disappeared

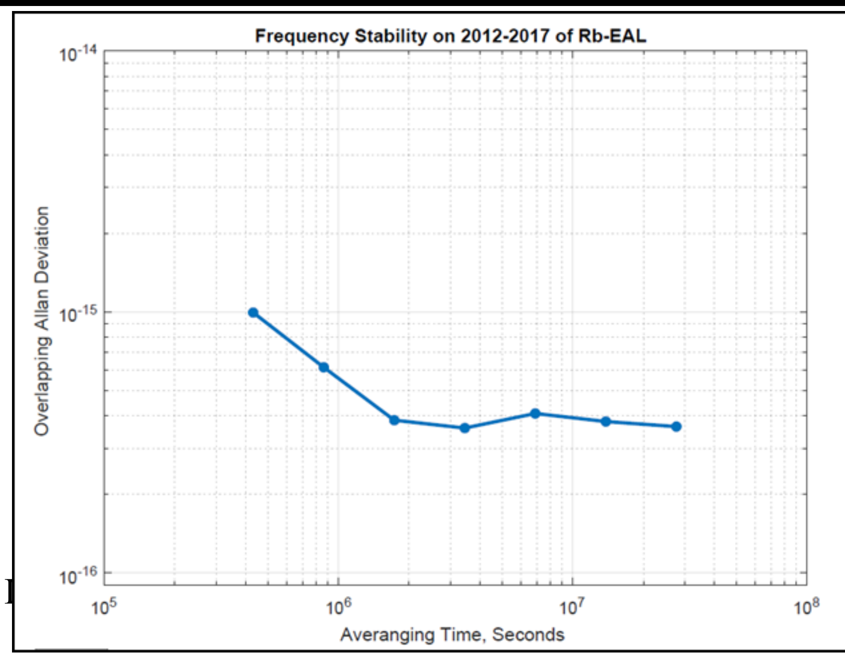
Weighting algorithm

- Until 2014: weight based on the stability, drifting clocks have little or no weight.
- Starting 2014: weight represents the predictability of the clock's frequency, regularly drifting clocks (H-masers) will gain weight. It makes the weighting algorithm consistent with the prediction algorithm.
- A maximum weight (~1%) prevents one (a few) clock(s) to become predominant.

Statistics on clocks participating to TAI/UTC



- TAI instability has decreased from about 6-9x10^{-16} in 1999-2000 to about 4x10^{-16} in 2003, close to 3x10^{-16} since 2012.
- Performance more or less constant since 2003, only improving with the number of good continuous clocks.
- Some "marginal" improvements still possible, e.g. with new (2014) weighting algorithm
- Major steps needed to gain something e.g. new types of clocks: 4 Rb "fountains" in 2012



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Final product: the Circular T

CIRCULAR T 352 ISSN 1143-1393
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The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BI
available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

Values every 5 days

Uncertainties

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

Date 2017 0h UTC	MAR 27	APR 1	APR 6	APR 11	APR 16	APR 21	APR 26	Uncertainty/ns			Notes
MJD	57839	57844	57849	57854	57859	57864	57869	uA	uB	u	
Laboratory k				[UTC-UTC(k)]/ns							
AOS (Borowiec)	-3.7	-1.9	0.8	1.7	1.4	-0.3	-2.9	0.4	3.3	3.3	
APL (Laurel)	2.1	2.6	3.1	3.8	1.4	1.0	0.9	0.3	10.9	10.9	
AUS (Sydney)	715.3	667.8	658.4	659.7	654.7	643.4	614.0	0.4	5.9	5.9	
BEV (Wien)	-1.7	-6.9	-1.0	1.5	0.8	0.6	12.4	0.4	2.7	2.7	
BIM (Sofiya)	5779.9	5857.5	5889.2	5927.9	5963.1	5988.1	6019.1	0.7	2.7	2.8	
BIRM (Beijing)	-5.7	-5.8	-5.3	-4.7	-5.4	-5.9	-7.1	0.4	20.0	20.0	
BOM (Skopje)	-809.1	-808.4	-808.7	-812.1	-811.7	-810.8	-816.7	0.4	2.7	2.7	
BY (Minsk)	-4.0	-5.7	-3.2	-3.2	-5.0	-4.2	-6.0	1.5	9.2	9.4	
CAO (Cagliari)	-19520.7	-19631.3	-19727.8	-19832.3	-19942.0	-20046.8	-20150.3	8.0	20.0	21.6	
CH (Bern-Wabern)	3.9	5.1	1.5	4.2	3.5	1.3	-5.2	0.5	1.7	1.8	
CNES (Toulouse)	-12.6	-12.4	-15.0	-18.9	-16.6	-14.1	-11.6	0.4	4.1	4.1	
CNM (Queretaro)	8.3	12.0	2.6	-5.2	-3.4	-3.1	-3.3	2.5	11.2	11.5	
CNMP (Panama)	-32.8	-22.8	-16.9	-31.3	-38.0	-24.0	0.1	0.5	7.2	7.2	
DFNT (Tunis)	13971.7	14173.4	14339.3	14529.9	14694.9	14878.7	15085.2	0.7	20.0	20.0	
DLR (Oberpfaffenhofen)	7.5	-17.5	-20.1	-30.7	-9.4	-4.3	-3.8	0.7	2.7	2.8	
DMDM (Belgrade)	8.3	17.8	22.4	32.8	8.6	-1.0	-7.7	0.4	7.4	7.4	
DTAG (Frankfurt/M)	108.1	97.1	86.8	82.8	84.8	86.4	88.7	0.4	7.6	7.6	
EIM (Thessaloniki)	8.9	8.7	3.3	1.9	9.2	7.5	1.6	4.0	7.9	8.8	
ESTC (Noordwijk)	-5.8	-4.3	-3.2	-2.8	-3.1	-4.0	-5.4	0.4	5.5	5.5	
HKO (Hong Kong)	800.8	801.9	809.2	810.3	819.9	826.7	835.6	0.4	7.3	7.4	

Stability → uA
Accuracy → uB
Total → u

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.
  - –Starting 2013, secondary standards are used in the computation of TT(BIPM)
  - –Post processing algorithm; each version is a new complete run.
- TT(BIPM) is updated every year, latest is TT(BIPM16) in January 2017.
  - –A prediction of TT(BIPM) is obtained from TAI

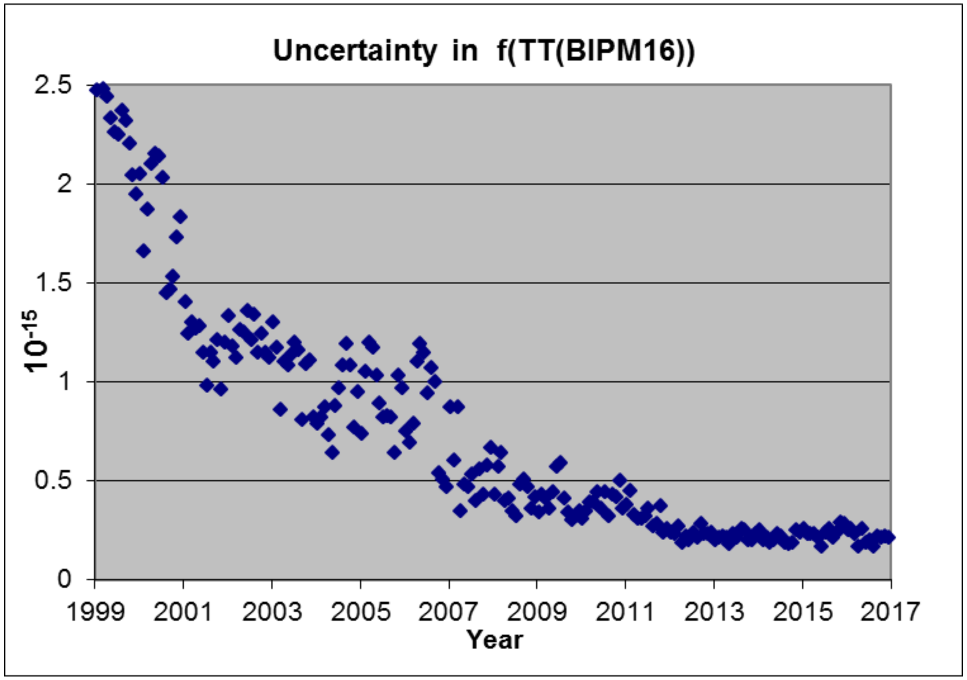
•We consider TT(BIPM) our best frequency reference to evaluate the performance of EAL, TAI and all the primary and secondary standards: Frequency accuracy improves

– 2.5×10^{-15} in 1999

– $<1 \times 10^{-15}$ since 2004

– $<0.5 \times 10^{-15}$ since 2008

– $\sim 0.2 \times 10^{-15}$ since 2012



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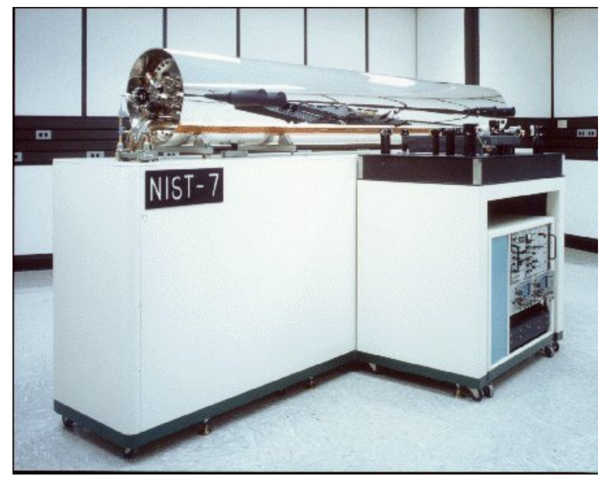
Atomic clocks and timescales from the 1980s to the end 1990s

- Atomic time TAI, published every month
  - End 1980s – early 1990s: Stability from 150-170 clocks, and instability $>1\text{x}10^{-14}$ possible over several months to years;
  - MAJOR FEATURE: First HP5071A appeared in 1993, a factor of 2-3 improvement in stability over previous clocks;
  - End 1990s: Stability from more than 200 clocks; 1-2 year instability ~few $\text{x}10^{-15}$.

- Laboratory Cs standards attain $1\text{x}10^{-14}$ accuracy at the end of the 1980s / early 1990s
  - PTB Cs1 ($\sim 3\text{x}10^{-14}$) was operated continuously 1978-1995
  - PTB Cs2 ($\sim 1.5\text{x}10^{-14}$) started continuous operation in 1986
  - NIST7 ($\sim 1\text{x}10^{-14}$) started (discontinuous) in 1995.
  - A few other standards are also available (CRL, NIST, NRC, SU).

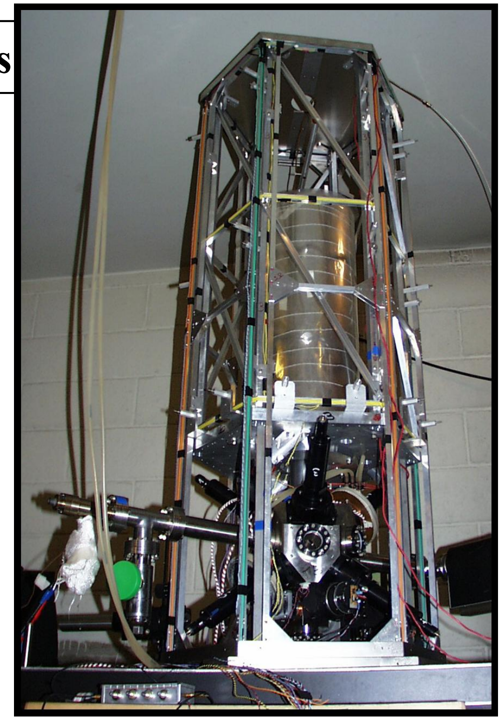


- Post-processed time scale TT(BIPM):
  - First computed in 1988 as TT(BIPM87), yearly after 1992
  - Accuracy / instability over a few years
    - $\sim 1\text{x}10^{-14}$ in the end 1980s-early 1990s
    - $\sim 3\text{x}10^{-15}$ in the end 1990s

Clocks and frequency standards from the end 1990s until now

- Industrial clocks not « very much » changed over the last twenty years.

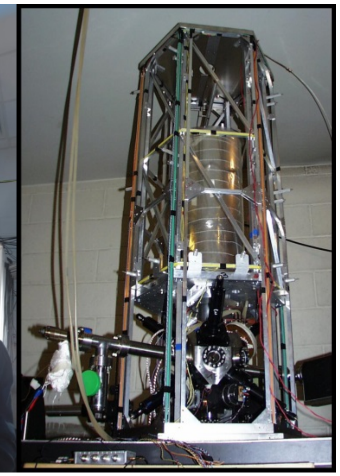
SYRTE Paris



- Cs fountains now reach 1-2x10^{-16} accuracy
  - SYRTE: FO1 (back in 2006), FO2 and FOM (since 2002)
  - NIST: F1 (since end 1999), F2 (since 2014)
  - PTB: CsF1 (since 2000), CsF2 (since end 2008)
  - IT: CsF1 (since 2003), CsF2 (since 2014)
  - NPL:CsF1 (since 2004), CsF2 (since end 2009)
  - SU: CsF2 (since 2014)
  - NICT, NIM, NMIJ, NPLI,…
  - Some now operating ~ continuously
- Many new frequency standards
  - Operational reporting: Rb fountain at SYRTE since 2013
    Sr lattice at SYRTE since 2017
  - Many more, more or less operational, and not reporting yet (some claim ~10^{-17})

Primary and secondary frequency standards

- Frequency standards aim at generating the same frequency whenever they run.
- Primary frequency standards: Cs fountains



Cs fountains (~ 10 laboratories)

Present best slightly below 2×10^{-16}

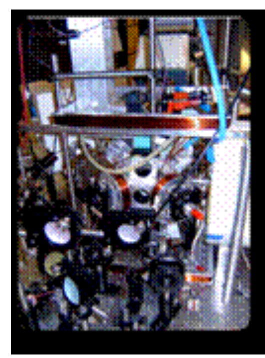
May be limited around 1×10^{-16}

- Secondary frequency standards: from a list of recommended transitions
- Some day, one secondary representation will become primary

Future standards: Lattice (e.g. Sr), trapped ions

Best uncertainty of systematic effects for optical lattice clock: Sr atoms at 2×10^{-18} [Nicholson et al. 2015]

Several more are in the 1×10^{-17} region or better.



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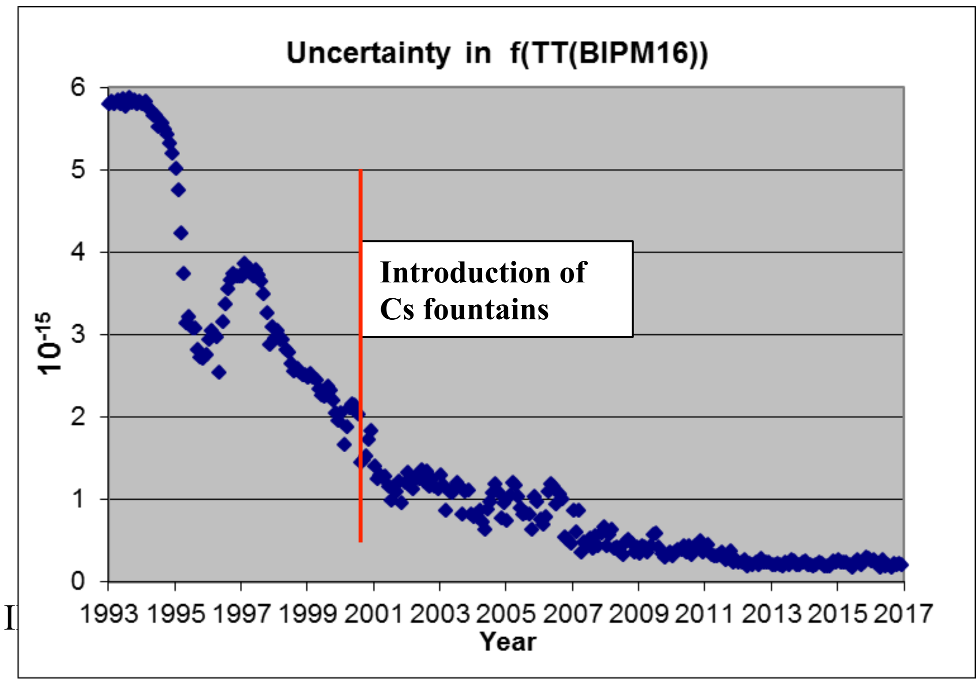
Atomic timescales from the end 1990s until now

- TAI based on more clocks: 200 (2000) - 300 (2005) - 400+ (now)
- Algorithm improved: weighting scheme (2001,2003), prediction of drift (2011), new weighting scheme (2014)
- 1-month instability now at ~ $3x10^{-16}$
- TAI long-term (years) instability could reach $1\text{-}2x10^{-15}$ until 2012. Now it should remain well below $1x10^{-15}$.

- TT(BIPM) computed each year; Prediction available until next version.
  - Accuracy / long-term instability was $6x10^{-15}$ in 1993-1994
  - Reached $1x10^{-15}$ in the early 2000s
  - Now about $2x10^{-16}$ since 2012



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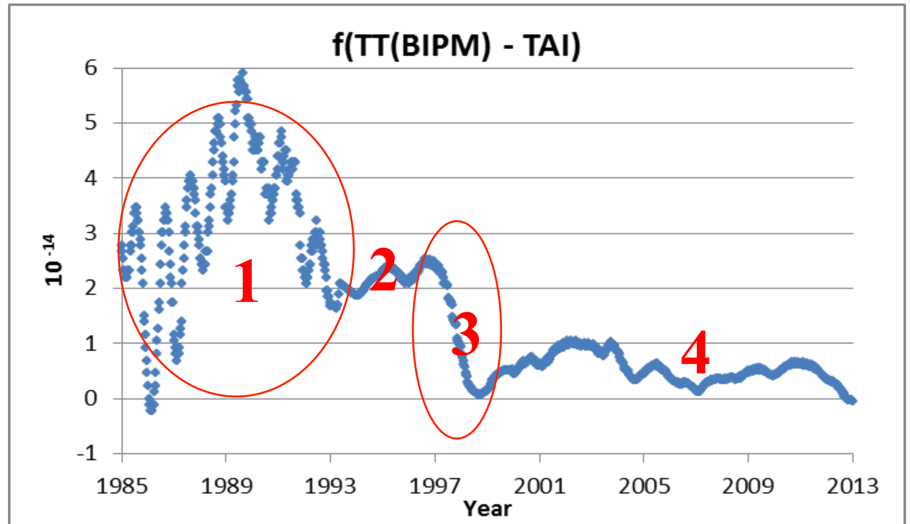
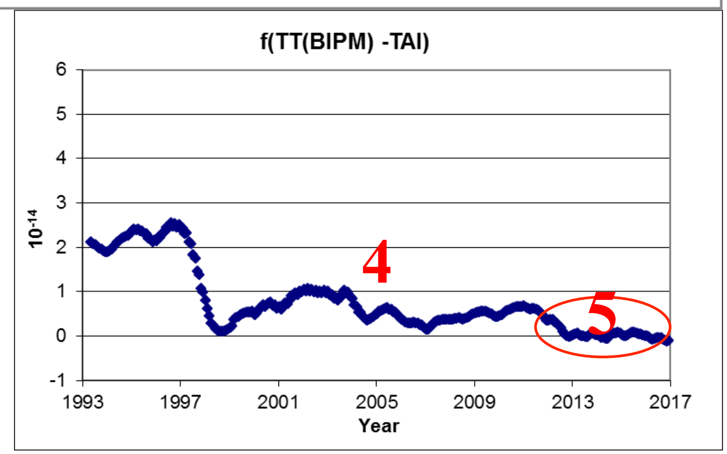
Long term comparison of TAI vs. TT(BIPM)

1. Before 1993: Poor stability due to the clocks/time transfer.
2. After 1993: Stability improves with the number of HP5071A (+GPS links).
3. 1996-1998: Intentional frequency change of ~2.10^{-14} to implement new realization of the second (BBR shift).
4. 1999-2012: More or less "random walk" behavior, but bounded. Instability of order 2.10^{-15} @ years.
5. 2013-…..: EAL drift removed => Same kind of RW behavior for TAI, but reduced instability expected.





TAI is not as accurate / stable as TT(BIPM).
TT(BIPM) should be used.

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PSR analysis to solve for the reference timescale (1/2)

- Long pulsar analysis can discriminate between TAI and TT(BIPM)
  - Difference TAI-TT(BIPM): several 10^{-15} (after 1999) to several 10^{-14} (before 1998)
  - Using TT(BIPM) should improve any long fit of pulsar data
- **TT(BIPM) should be used (the most recent one in principle)**

- **(Hobbs et al. 2012) solve for a "pulsar-based timescale" TT(PPTA11) using 19 pulsars over 1994-2011**
- **Claim that TT(PPTA11) "follows" the 1996-1998 TAI frequency change**
- **Find "marginally significant differences between TT(PPTA11) and TT(BIPM11).**

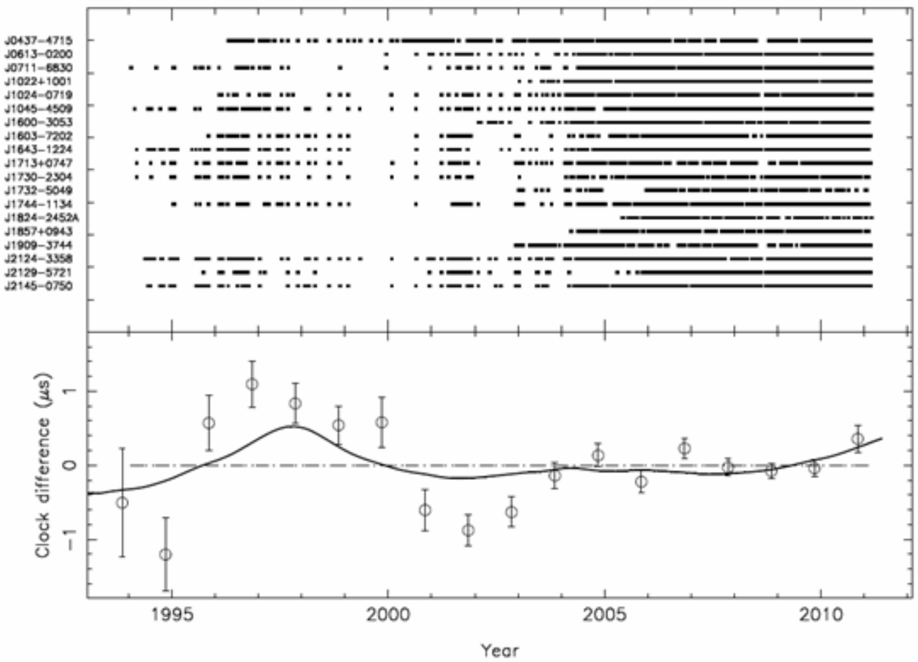

Figure 6. The top panel shows the sampling for the 19 pulsars in our sample. The lower panel shows the difference between TT(BIPM11) and TT(TAI) as the solid line. The data points indicate the difference between TT(PPTA11) and TT(TAI).

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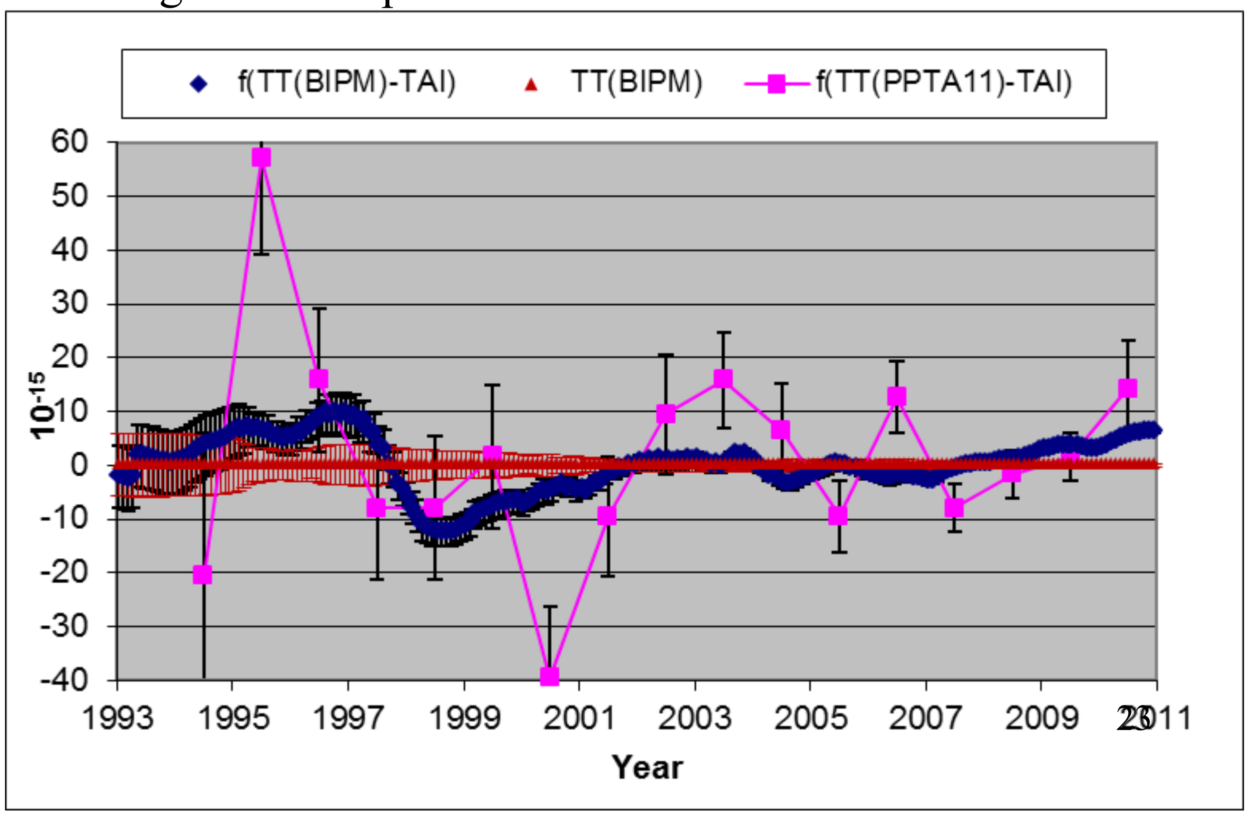
PSR analysis to solve for the reference timescale (2/2)

- TT(PPTA11) does seem to be closer to TT(BIPM) than to TAI.
- However solving for "one parameter per year" yields results and uncertainties which are many times higher than the uncertainty of the atomic time scale.
- Thus differences between TT(PPTA11) and TT(BIPM11) are more likely to be due to TT(PPTA11) than to TT(BIPM11).
- TT(PPTAxx) analysis may provide results which are significant with respect to timescale uncertainties if solving for fewer parameters.



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Conclusions: Atomic time

- **$2\text{-}3\times10^{-16}$ level** is proven for all components of time scale formation (ensemble time scale, time transfer, primary frequency standards).

- New frequency standards now reach or promise 1×10^{-16} (and beyond)
  - We have started integrating Secondary Frequency Standards in TAI
  - More and different SFS needed, ultimately yielding new definition of the second

- How to reach 1×10^{-16} (and beyond)?
  - New generation of very stable clocks: better reliability and wider availability needed.
  - Present time transfer techniques will reach 1×10^{-16} and below but will be ultimately limited….=> new time transfer technology needed
  - Start to study alternative algorithms for TAI in a sub-1×10^{-16} era

Conclusions: Pulsars and atomic time

- Atomic timescales have gained one order of magnitude in long-term stability and accuracy every ~12 years, and this trend should continue for another order of magnitude.
- Thus the observed long-term rotation stability of pulsars is unlikely to supersede that of the best atomic time scales.
- “Pulsar-based” timescales have to overcome several noise sources:
  - "intrinsic“: long-term noise from the pulsar, observation noise
  - observation gaps, hardware changes …
  - DM variations
- However, pulsars may be used as flywheels to transfer the current accuracy of atomic time to the past (or to the future).
- Use TT(BIPM) as a time reference in your pulsar analysis

- Thanks to my BIPM colleagues F. Arias, G. Panfilo, A. Harmegnies for contributing material
- Note:
  - Metrologia special issue

    48(4) August 2011

    Modern applications of timescales
  - Comptes Rendus de Physique

    16 (5) June 2015

    La mesure du temps