Bureau International des Poids et Mesures

Long-term stability of atomic time scales

Gérard Petit

Elisa Felicitas Arias

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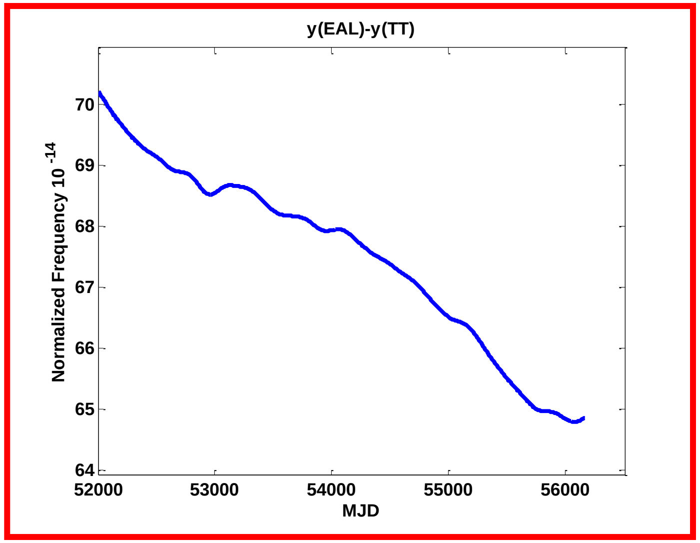
Résumé

- Time scales (EAL-TAI-UTC-TT(BIPM))
- Already achieving low-10^{-16}
- TT(BIPM): accuracy and comparison of PFS
- Towards 1×10^{-16} and below?

BIPM

EAL, TAI and TT(BIPMxx)

- EAL, TAI calculation ("real time")
  - Each month, the BIPM computes a free atomic scale, EAL, from some 400 atomic clocks worldwide.
  - Each month, primary frequency standards (PFS) are used to estimate f(EAL).
  - The frequency of TAI is then steered.



- TT(BIPMxx) calculation
  - Post-processed using all available PFS data, as of year 20xx.
  - Complete re-processing starting 1993, possibly with change of algorithm.
  - f(EAL) is estimated each month using available PFS. Monthly estimates are smoothed and integrated to obtain TT(BIPMxx).
  - Last realization: TT(BIPM11), released in January 2012.

BIPM

Achieving low-10^{-16} stability/accuracy

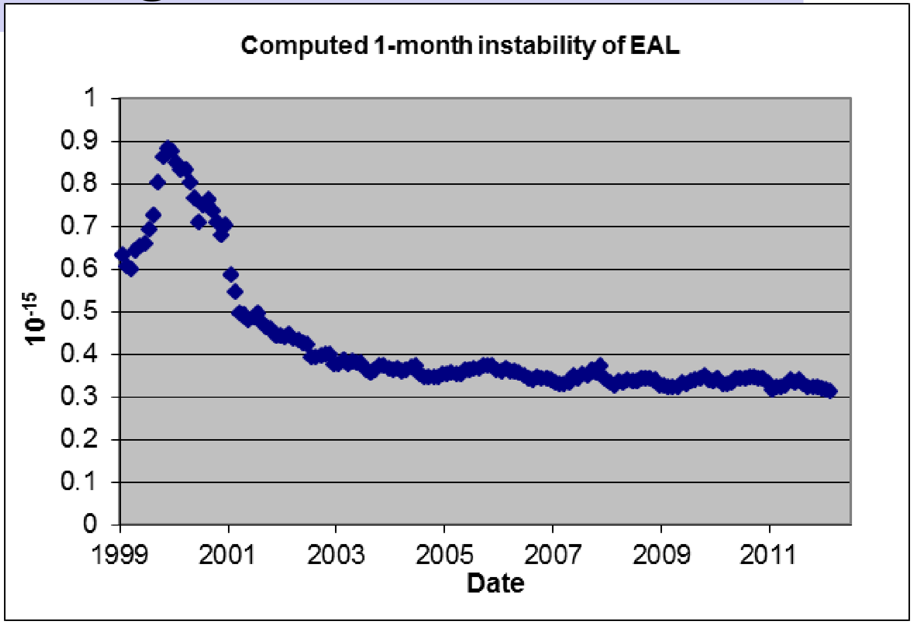
- **Time scale**
  - Stability of ensemble time scale assessed by statistical analysis
  - Accuracy depends on PFS performance

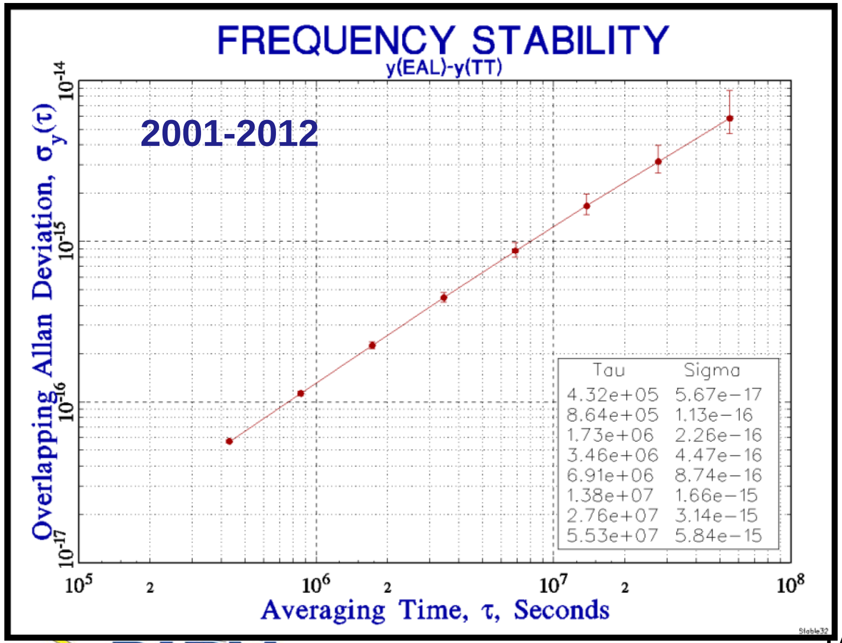
- **Time transfer**
  - Assessed by comparison of independent techniques
  - Also by comparison of clocks with low-10^{-16} stability

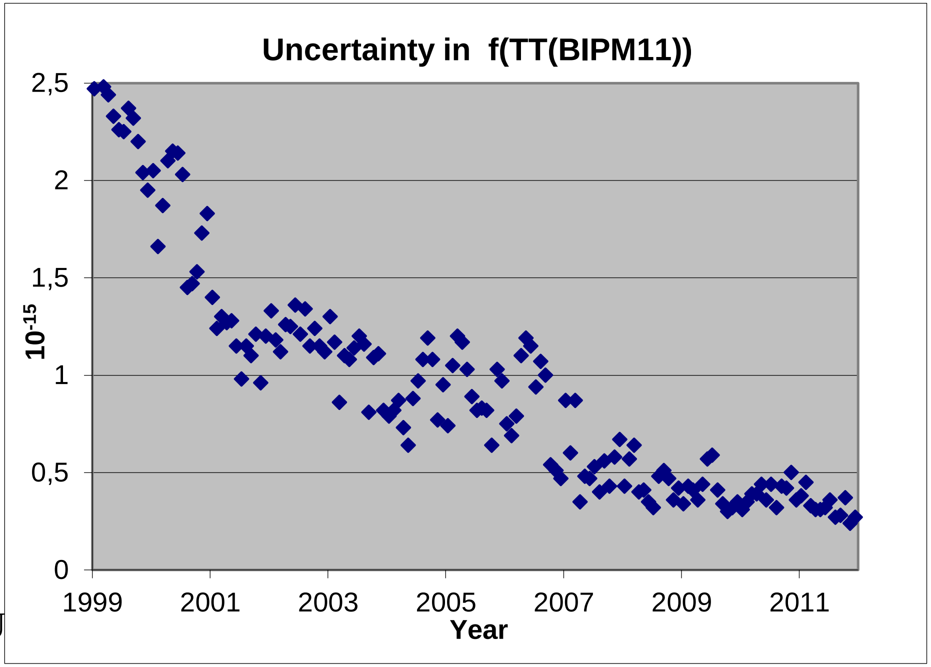
- **Frequency standards**
  - Numerous Cs fountains claim to achieve this level
  - Other transitions also available, some have been recommended for "secondary representations of the second"

Time scales: achieving low 10^{-16}

- EAL: < 4.10^{-16} @ 1 month since 2003, from the stability of participating clocks.
- TT(BIPM): < 1.10^{-15} @ any averaging since 2003, from statistical treatment of PFS uncertainty.
- TAI: In between. Close to EAL @ 1 month, < 2.10^{-15} @ years.







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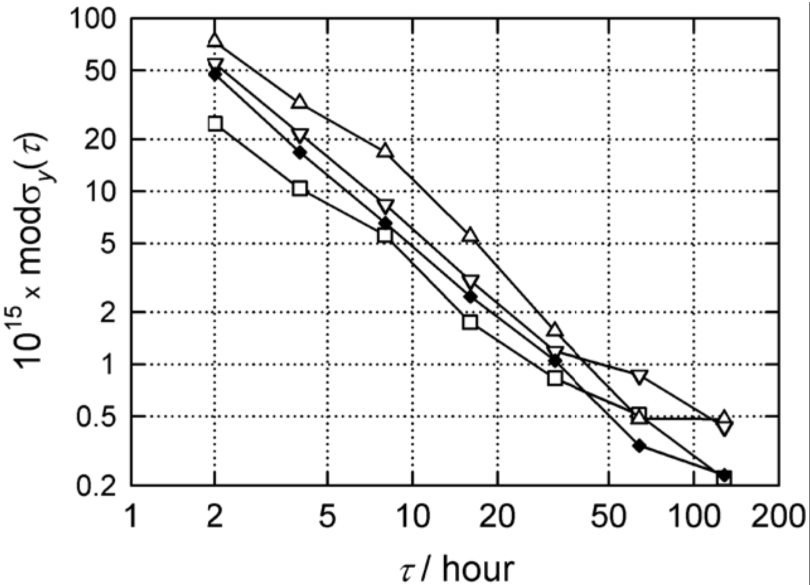
Time transfer: achieving 10^{-16}



- TW−GPS-CP for four links (Bauch et al. 2006) show both techniques cross 1.10^{-15} @ 1 day
- Performance of GPS CP is about independent on the distance => PPP provides 43% of the time links used in TAI (mid-2012)
- GPS-code only, as well as TW are slightly less stable 1.10^{-15} @ 2-3 day
- TW needs 24 pts/day and same transponder to achieve PPP performance

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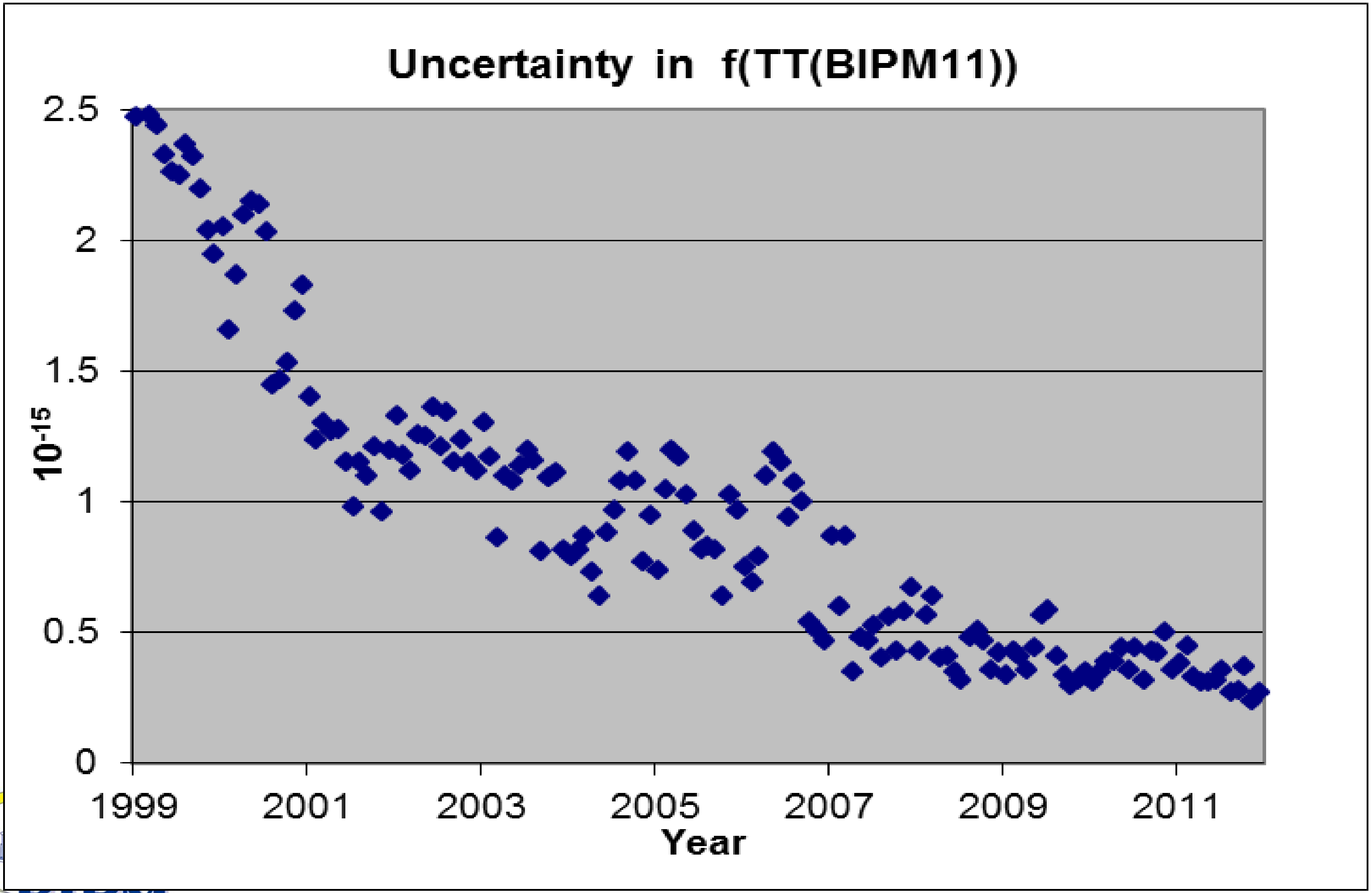
TT(BIPM): the latest realization TT(BIPM11)

- Post-processed in January 2012 using all primary frequency standards data until December 2011.
- Frequency accuracy: decreases from 2.5×10^{-15} in 1999 to $<1 \times 10^{-15}$ since 2004, $<0.5 \times 10^{-15}$ in 2008, 0.3×10^{-15} in 2012.



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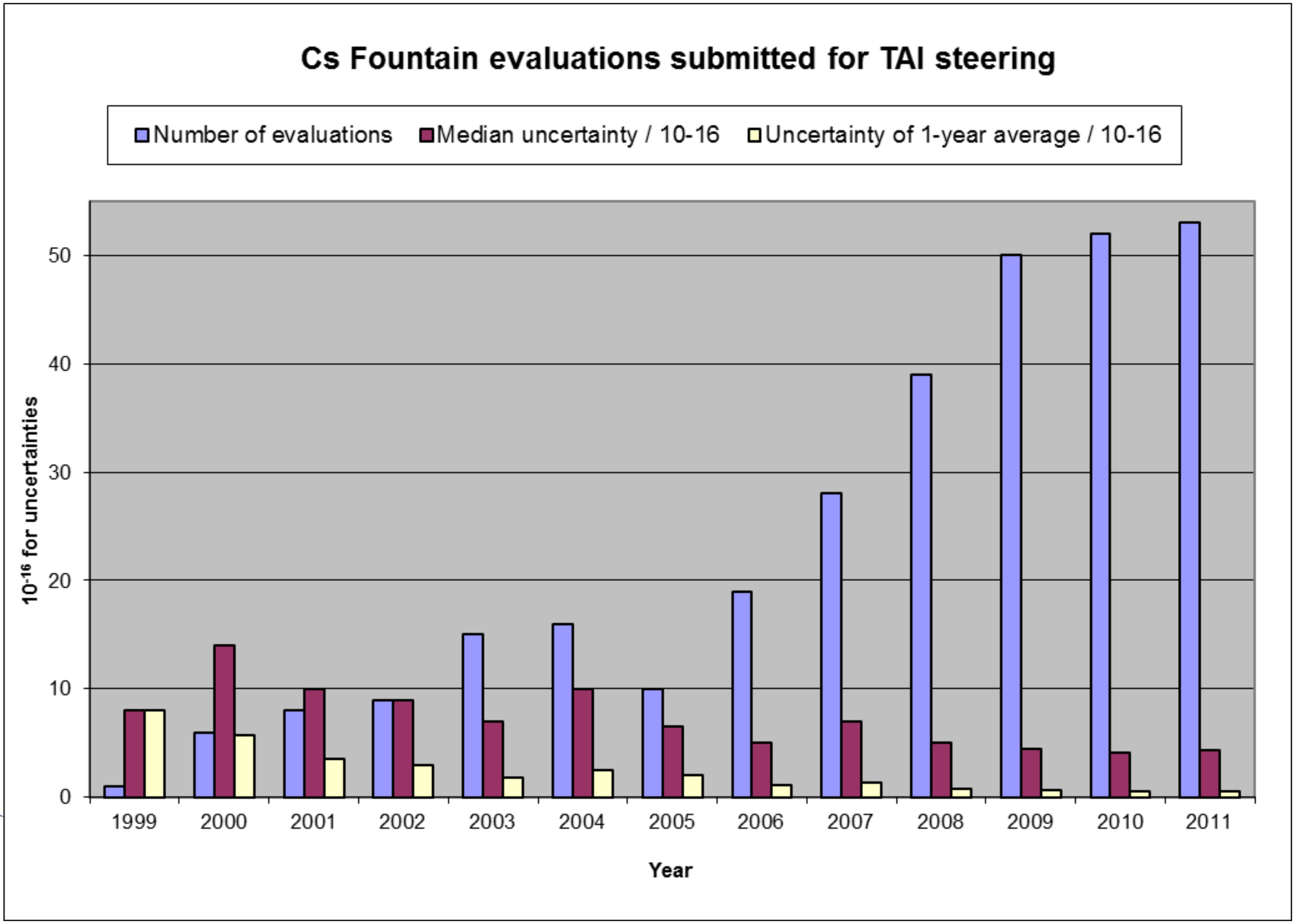
Contributions of frequency standards to TAI and TT(BIPM) (1)

- Evaluations of PFS are continuously needed to ensure accuracy of TAI and of TT(BIPM).
  - Accuracy of TT(BIPM) (~3×10^{-16} in 2012) directly depends on the stated uncertainties of PFS
- Since 2009, more than 4 fountain evaluations are reported each month. Quite good in regard to the number of available fountains.
- New FS encouraged (see CCTF meetings 2004-2006-2009)
  - New Cs fountains (several currently under development)
  - "Secondary representations of the second" are also expected to provide evaluations, in order for BIPM to get experience with their use. Evaluations from the Rb fountain of LNE-SYRTE are reported January 2012.
- Eventually, one of the secondary representations may become the primary in the future.

Contributions of frequency standards to TAI and TT(BIPM) (2)

- TT(BIPM) performances improve due to increasing number of Cs fountains and to improvements in each fountain.
- Averaging assuming white noise would put TT(BIPM) accuracy close to $1x10^{-16}$, but systematics, time transfer and instability of EAL may limit this.



Contributions of frequency standards to TAI

- CCTF 3 (2004) recommends that TAI scale unit be conform to its definition to within 3 σ.

RECOMMENDATION CCTF 3 (2004):
Concerning the steering of International Atomic Time (TAI)

The Consultative Committee for Time and Frequency,

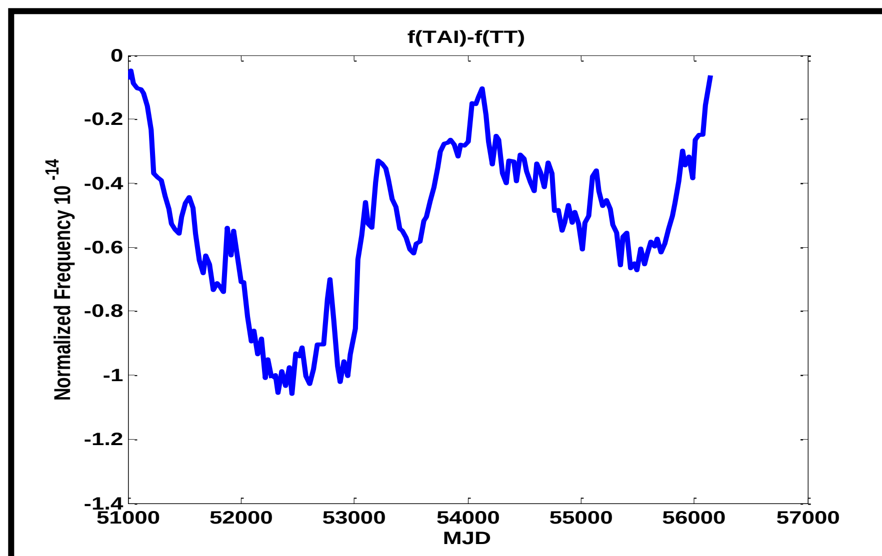
considering that

- TAI was defined by the General Conference on Weights and Measures in 1971, complemented by the Consultative Committee for the Definition of the Second in 1980,
- TAI is a realization of Terrestrial Time (TT) as defined, most recently, in Resolution B1.9 (2000) of the International Astronomical Union,
- the scale unit of TAI has significantly deviated from its definition over the past years,
- new primary frequency standards permit the determination of this deviation with adequate uncertainty,
- it is advantageous that TAI provides direct traceability to the SI second,

recommends that

- the procedure of TAI frequency steering be adapted with the aim of ensuring that the estimation of the TAI scale unit conforms to its definition within 3 σ uncertainty,
- this procedure be designed, in collaboration with the Working Group on TAI, to minimize the impact on TAI stability.

- This has generally not been achieved except end 2006-early 2007.
- But should be achieved in the next months!!



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Primary frequency standards in 2011: low 10^{-16}

Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	0.7	Discontinuous	H maser	1 / 25 d
NICT-CSF1	Fountain	(1.0 to 1.2)	Discontinuous	UTC(NICT)	2 / 10-20 d
NIST-F1	Fountain	0.31	Discontinuous	H maser	5 / 15-30 d
NMIJ-F1	Fountain	3.9	Discontinuous	H maser	2 / 30 d
NPL-CSF2	Fountain	0.40 then 0.23	Discontinuous	H maser	7 / 15-25 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 30 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	7 / 30 d
PTB-CSF1	Fountain	(0.74 to 0.79)	Nearly continuous	H maser	10 / 15-25 d
PTB-CSF2	Fountain	(0.36 to 0.56)	Discontinuous	H maser	6 / 15-25 d
SYRTE-FO1	Fountain	(0.42 to 0.49)	Discontinuous	H maser	6 / 10 to 25 d
SYRTE-FO2	Fountain	(026 to 0.39)	Nearly continuous	H maser	12 / 15 to 35 d
SYRTE-FOM	Fountain	(0.82 to 0.92)	Discontinuous	H maser	6 / 20 to 30 d

Primary standards reported to the BIPM in 2011 (10 fountains and 2 beams)

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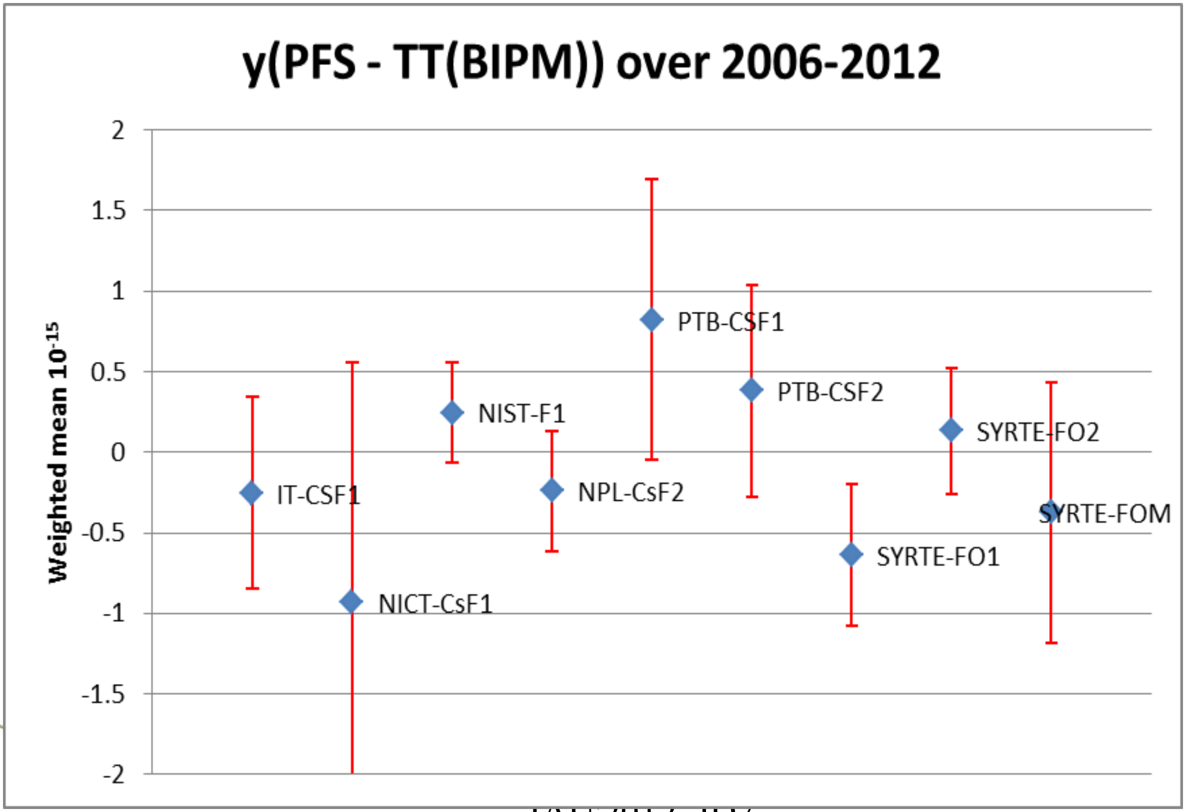
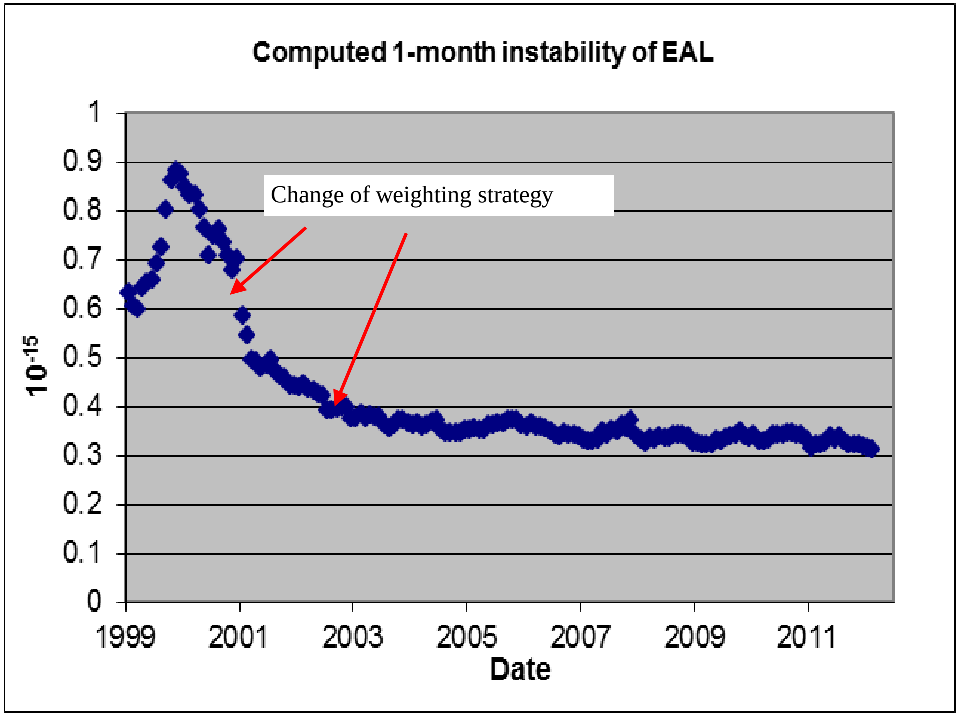
Comparison of PFS to TT(BIPM): The ensemble of PFSs

- The mean frequency bias computed for each fountain vs. TT(BIPM) is plotted with the mean uncertainty u_B of the fountain
- The Birge ratio of this series is 0.86: No indication of underestimation of u_B or of any significant systematic shift: Most significant shift is SYRTE-FO1 = -1.45 u_B
- This confirms the estimations given for the accuracy of TT(BIPM)
- If it made sense to average all 9 values, the uncertainty of the mean would be 1.7×10^{-16}



Limits to long-term stability of EAL

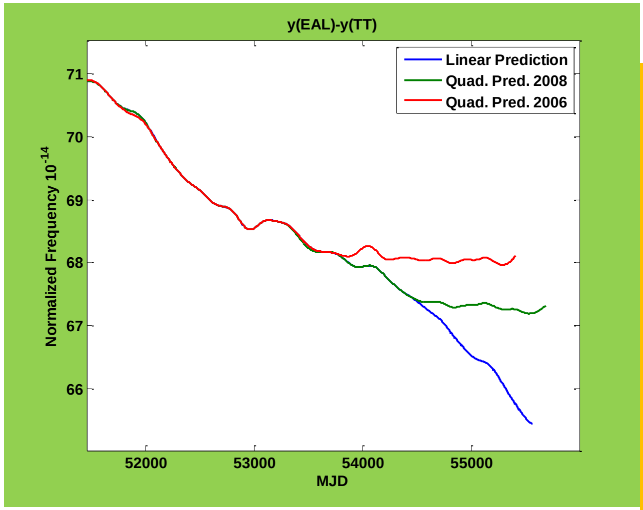
- Has decreased from about 6-9x10^{-16} in 1999-2000 to about 4x10^{-16} in 2003, 3x10^{-16} in 2012.
- But more or less constant since 2003. Total number of clocks still increasing, but total number of good continuous clocks only slightly increasing.

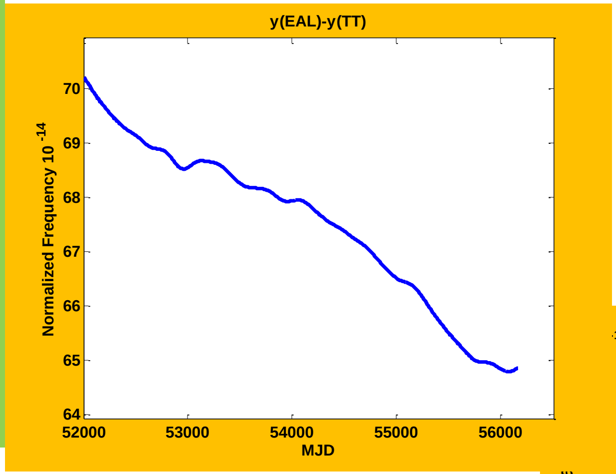


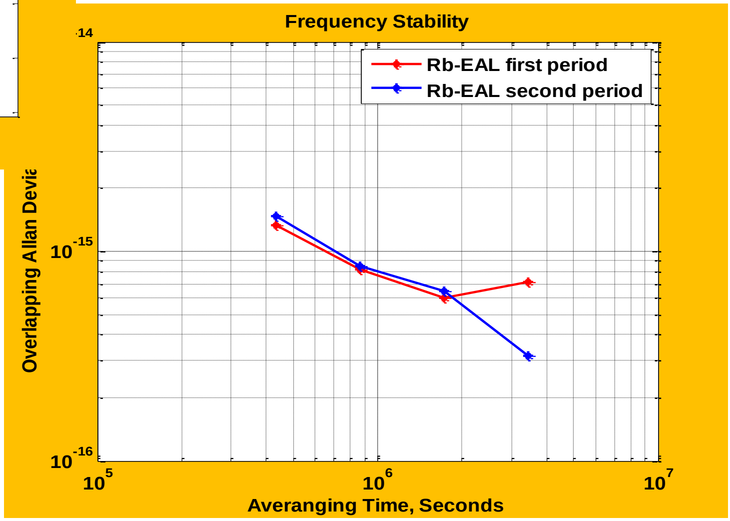
- Some marginal improvements still possible.
- But new clocks needed to gain e.g. one order of magnitude.
- Four Rb fountains (Ekstrom et al. 2008) now in EAL ensemble
  - 1.5x$10^{-13}/\tau^{1/2}$; floor at or below 3x10^{-16}

Limits to the long-term stability of EAL

- f(EAL)-f(TT(BIPM)): Systematic frequency trends were removed with new clock frequency prediction model (since August 2011)
  - Systematic drift was due to H-masers and aging of cesiums.
- Long-term (1 year) stability of EAL was limited by the drift

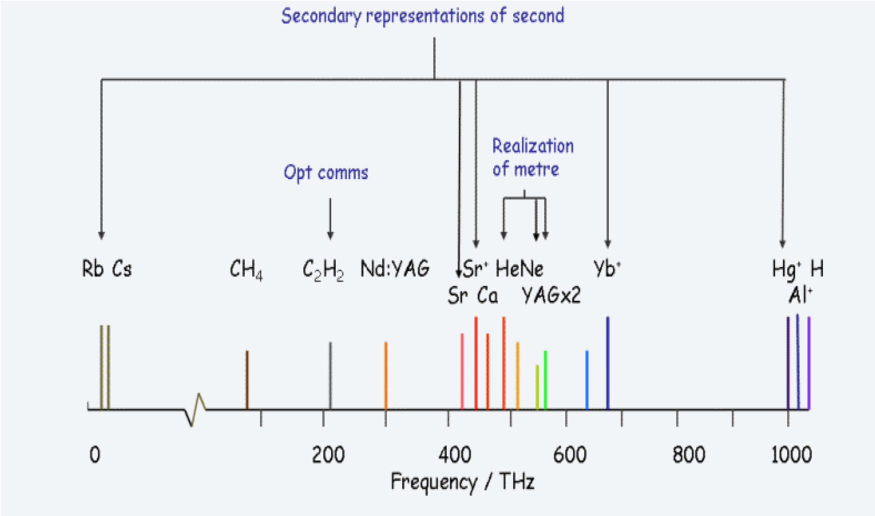






Secondary representations of the second

- CCL-CCTF Frequency Standards WG: producing and maintaining a single list of *Recommended frequency standard values for applications including the practical realization of the metre and secondary representations of the second*.



CIPM-2006 / 2009:

Unperturbed optical transition $5s^2\ ^1S_0 - 5s\ 5p\ ^3P_0$ of ^{87}Sr: 1×10^{-15}

Unperturbed ground-state hyperfine transition of ^{87}Rb: 3×10^{-15}

Unperturbed optical $5d^{10}\ 6s\ ^2S_{1/2}$ ($F = 0$) – $5d^9\ 6s^2\ ^2D_{5/2}$ ($F = 2$) transition of $^{199}Hg^+$: 3×10^{-15}

Unperturbed optical $5s\ ^2S_{1/2} - 4d\ ^2D_{5/2}$ transition of $^{88}Sr^+$: 7×10^{-15}

Unperturbed optical $6s\ ^2S_{1/2}$ ($F = 0$) – $5d\ ^2D_{3/2}$ ($F = 2$) transition of $^{171}Yb^+$: 9×10^{-15}

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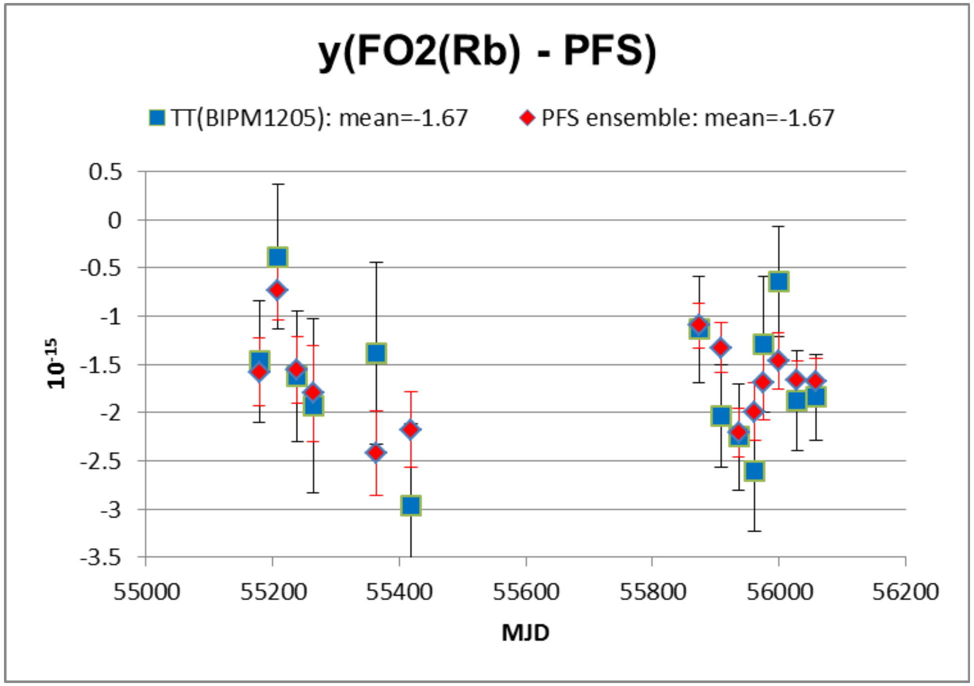
First use of a secondary standard: SYRTE-FO2(Rb)

- Submitted in 01/2012 by SYRTE, reviewed by the WG on PFS
- Allows determining a correction to the reference frequency of ^{87}Rb
  - SYRTE evaluation by local comparison to SYRTE PFS: -1.48×10^{-15} based on data over 1998-2012
  - Comparison to TT(BIPM11): -1.67×10^{-15}. based on data over 2010-2012, communicated by SYRTE to the BIPM



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Aiming at $1x10^{-16}$ and beyond

- **Ensemble time scale**
  - May be limited by the clocks available
- **Time transfer**
  - Will depend on technology developments.
  - Always improved by longer averaging
- **Frequency standards**
  - This is already achieved both for the stability and for the capacity to evaluate systematic effects.
  - Practical application will depend on the achievable continuous operation time (i.e. possible averaging time).

Conclusions

- Low-10^{-16} level is proven for all components of time scale formation (ensemble time scale, time transfer, primary frequency standards);
- The PFS reported uncertainties are globally consistent with the data,
  - Implies that TT(BIPM) accuracy is ~3×10^{-16} in 2012
- New frequency standards now reach or promise 1×10^{-16} (and beyond)
  - We have started integrating Secondary Frequency Standards in TAI
  - This work should be expanded (more and different SFS needed)
- How to reach 1×10^{-16} (and beyond)?
  - Very stable clocks already exist. Better reliability and wider availability are needed for time scale formation.
  - Present time transfer techniques need to be improved, but this is less a limitation for long-term.
  - More (P)FS data needed (more regularly)
- Start to study alternative algorithms for
  - » EAL formation
  - » TAI steering
  - » TT(BIPM) computation.

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