Atomic time scales TAI and TT(BIPM): present performances and prospects

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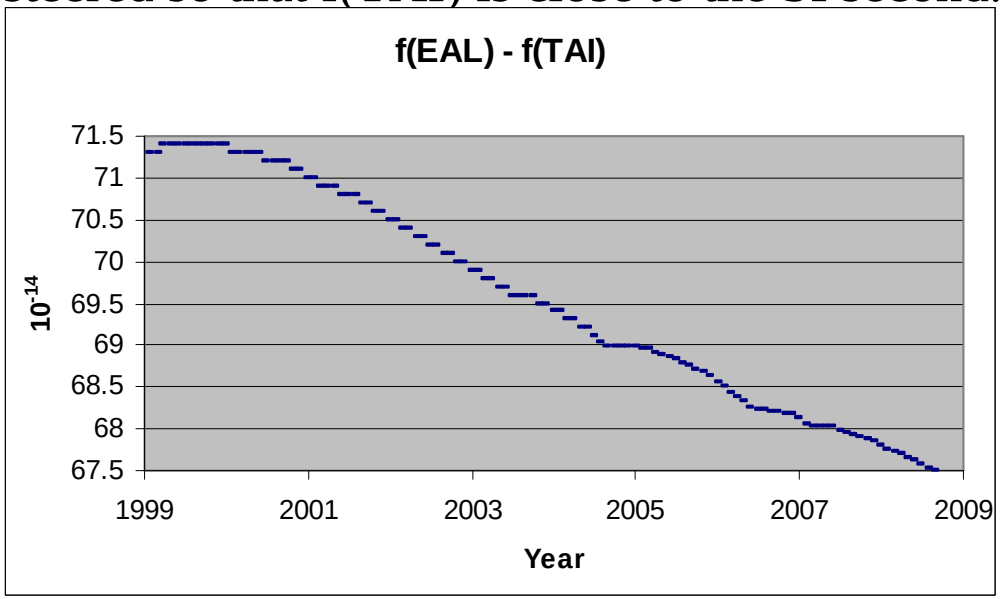
Résumé

- Time scales: EAL-TAI-TT(BIPM)
- Already achieving sub-10^{-15}
- TT(BIPM): accuracy, consistency of primary frequency standards
- Towards 10^{-16} and below?
- Contributions of frequency standards to TAI

EAL and TAI

- TAI calculation is done each month (i.e. in “real time”)
- The BIPM computes a free atomic scale, EAL, from some 350 atomic clocks worldwide, aiming at optimal 1-month stability.
  - An average of N identical clocks should be √N more stable than each one.
  - Clocks in different laboratories have to be compared by time transfer techniques: presently GPS and Two-way; the goal is that time transfer noise is negligible.
  - f(EAL) is stable but it can have any value (with respect to the SI second).
- Each month, primary frequency standards (PFS) are used to estimate f(EAL).
  - PFS are expected to represent the SI second.
- The frequency of TAI is then steered so that f(TAI) is close to the SI second.



TT(BIPMxx)

- As TAI is computed in real time and is not updated if an error is discovered, it is not optimal.
- Therefore the BIPM computes a post-processed time scale TT(BIPM)
- Each new version TT(BIPMxx) updates and replaces the previous one.
- 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(BIPM08), released in January 2009.

- Significant and time-varying frequency difference between TAI and TT(BIPM) integrates to (up to) 100 ns/yr, and even more before 2003: TAI should NOT been used as a long-term reference e.g. for pulsar analysis.

Achieving sub-10^{-15} stability/accuracy

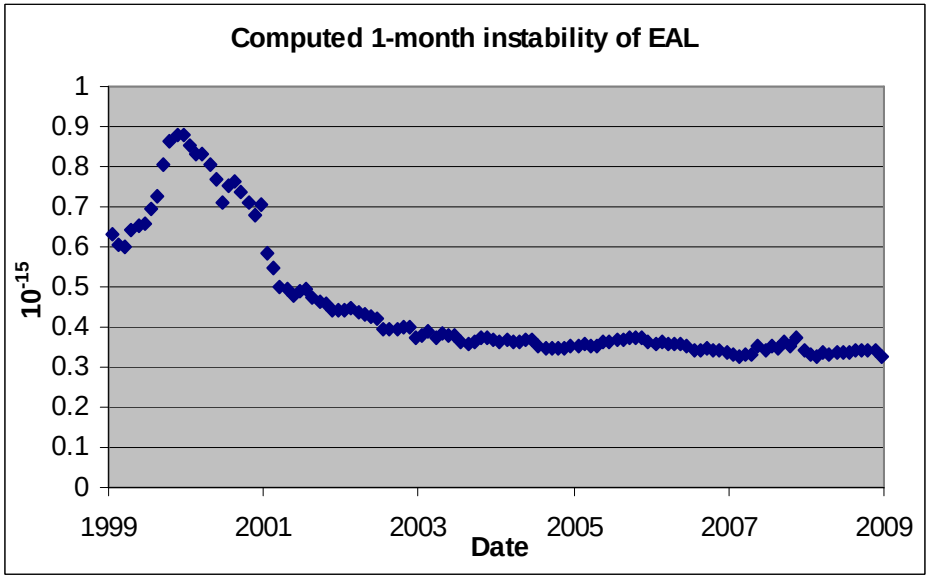
- **Time scale**
  - Stability of ensemble time scale assessed by statistical analysis
  - Accuracy depends on PFS performance

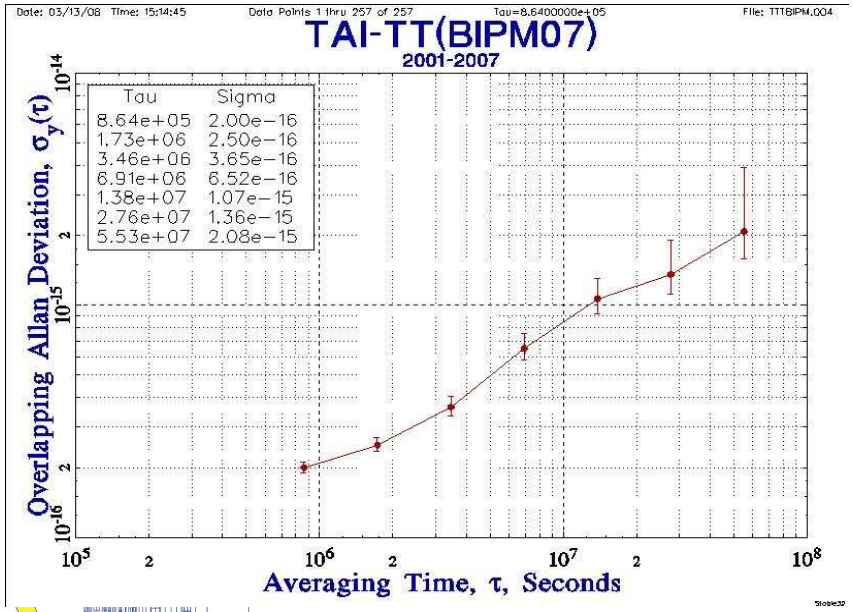
- **Time transfer**
  - Performance assessed by comparison of independent techniques
  - Also by the ability to compare ultra-stable clocks

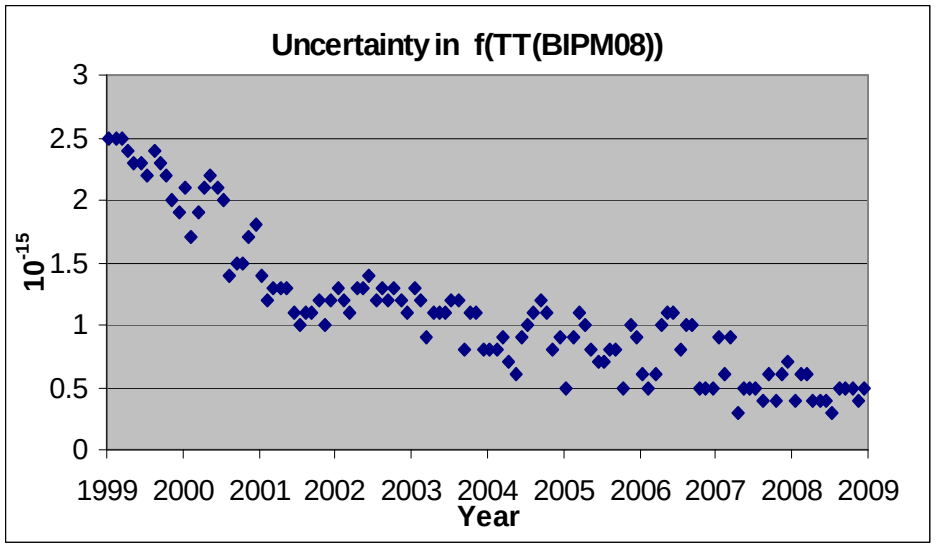
- **Frequency standards**
  - Numerous Cs fountains claim to achieve this level
  - Other transitions also available, some have been named "secondary representations of the second"

Time scales: achieving 10^{-15} and below

- 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.

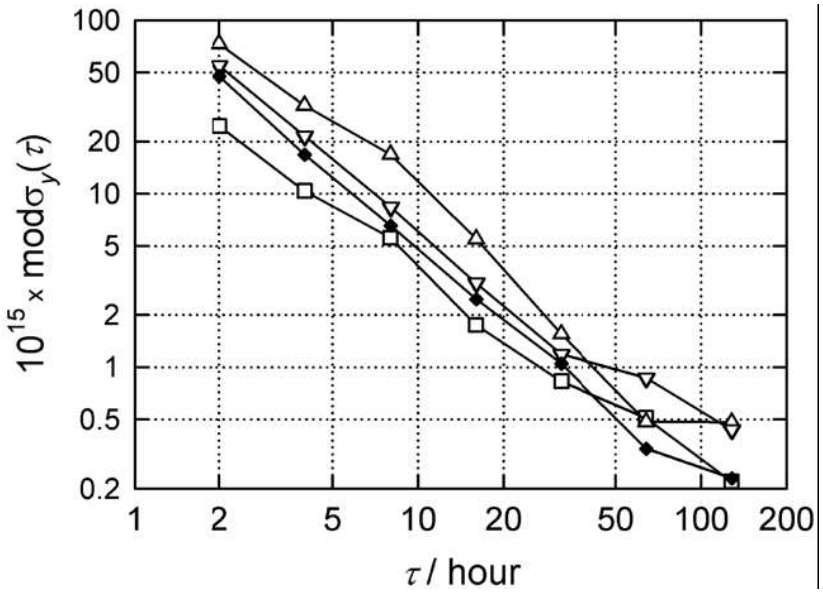


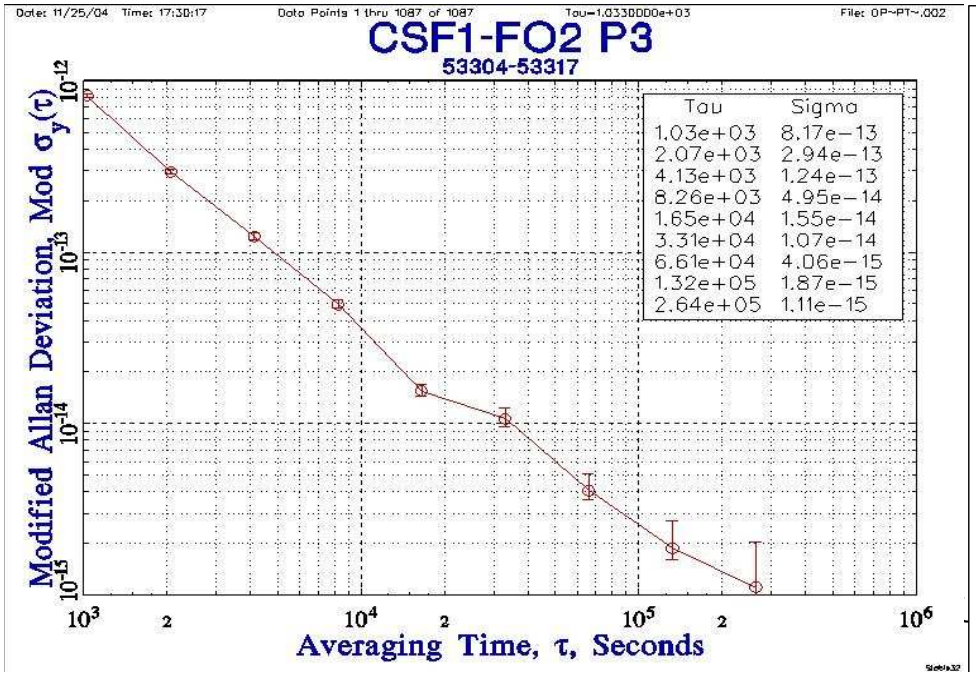


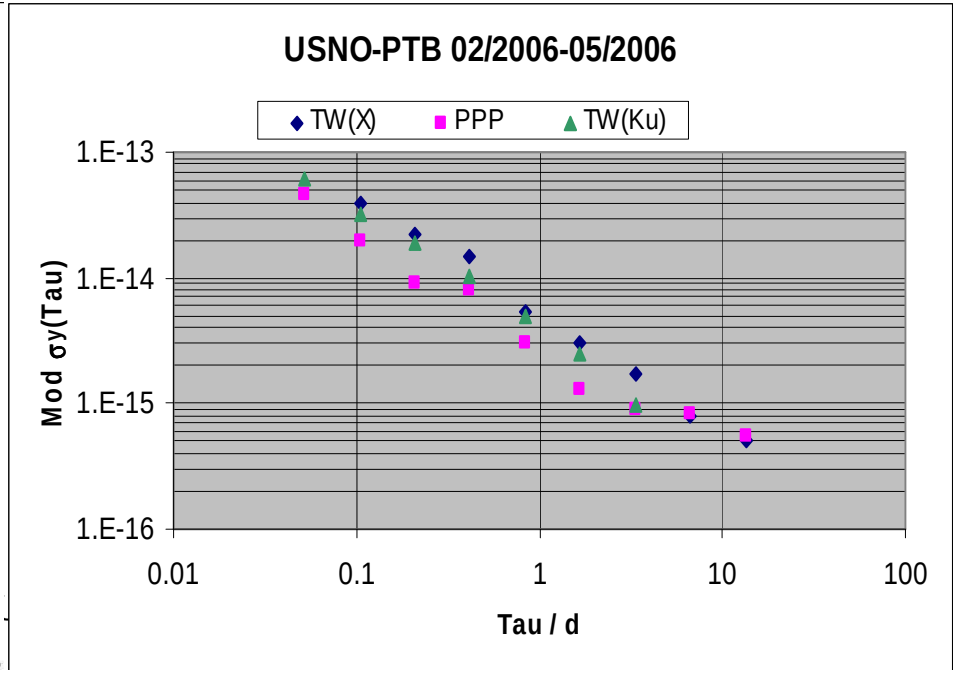


Time transfer: achieving 10^{-15} and below

- Present best: GPS CP and Two Way
- TW−GPS-CP for four links (Bauch et al. 2006) show both techniques cross 1.10^{-15} @ 1 day.
- TW needs 24 pts/day and same transponder to achieve this.
- Performance of GPS CP is about independent on the distance => PPP to be used in TAI
- GPS-code only, as well as TW with two transponders are slightly less stable 1.10^{-15} @ 2-3 day







Accuracy of frequency standards: achieving 10^{-15} and below

Primary Standard	Type /selection	Type B std. Uncertainty	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	$(0.5 \text{ to } 0.7)\times10^{-15}$	Discontinuous	H maser	6 / 10 to 20 d
NICT-CSF1	Fountain	$(0.8 \text{ to } 1.5)\times10^{-15}$	Discontinuous	UTC(NICT)	2 / 10-15 d
NIST-F1	Fountain	0.3×10^{-15}	Discontinuous	H maser	5 / 15 to 25 d
NMIJ-F1	Fountain	4×10^{-15}	Discontinuous	H maser	7 / 15 to 25 d
PTB-CS1	Beam /Mag.	8×10^{-15}	Continuous	TAI	10 / 30 d
PTB-CS2	Beam /Mag.	12×10^{-15}	Continuous	TAI	12 / 30 d
PTB-CSF1	Fountain	0.9×10^{-15}	Discontinuous	H maser	2 / 15 d
SYRTE-FO1	Fountain	$(0.4 \text{ to } 0.6)\times10^{-15}$	Discontinuous	H maser	8 / 10 to 30 d
SYRTE-FO2	Fountain	$(0.4 \text{ to } 0.6)\times10^{-15}$	Discontinuous	H maser	9 / 10 to 30 d
SYRTE-FOM	Fountain	$(0.7 \text{ to } 0.9)\times10^{-15}$	Discontinuous	H maser	6 / 10 to 30 d
SYRTE-JPO	Beam /Opt.	6×10^{-15}	Discontinuous	H maser	12 / 10 to 30 d

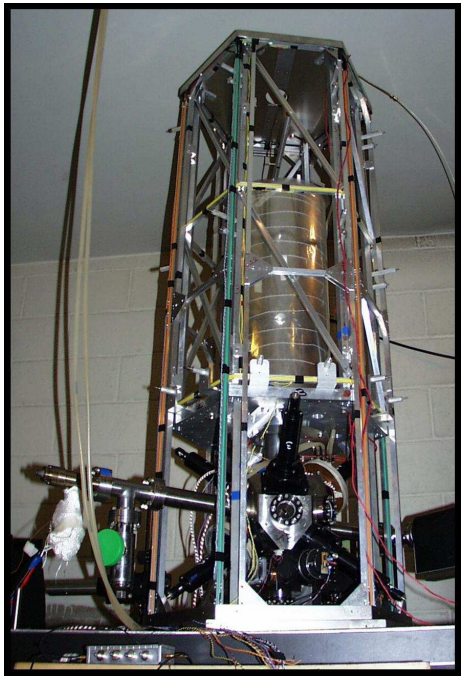
Primary standards reported to the BIPM in 2008 (8 fountains and 3 beams)

Accuracy of frequency standards: achieving 10^{-15} and below

Type B standard uncertainty ($\times 10^{16}$)		
Fountain	FO1	FO2
Physical origin	Uncertainty	Uncertainty
2nd order Zeeman	0.3	0.2
Blackbody Radiation	0.6	0.6
Cold Collisions + cavity pulling	2.4	2.9
First Doppler	<3.2	3
Synchronous phase fluctuations	<0.6	
Microwave Leaks, spectral purity	<0.7	0.5
Background gas collisions	<0.3	<1
Microwave recoil	<1.4	<1.4
Ramsey & Rabi pulling	<1	<1
Second order Doppler	<0.1	<0.1
Red shift	1	1
Total uncertainty	**4.7**	**4.8**

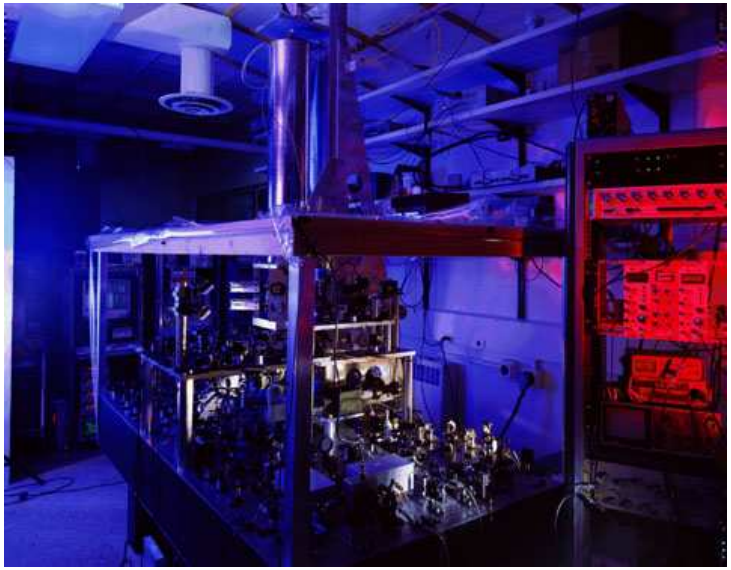
(Units are fractional frequency $\times 10^{-15}$)

SYRTE FO1/FO2



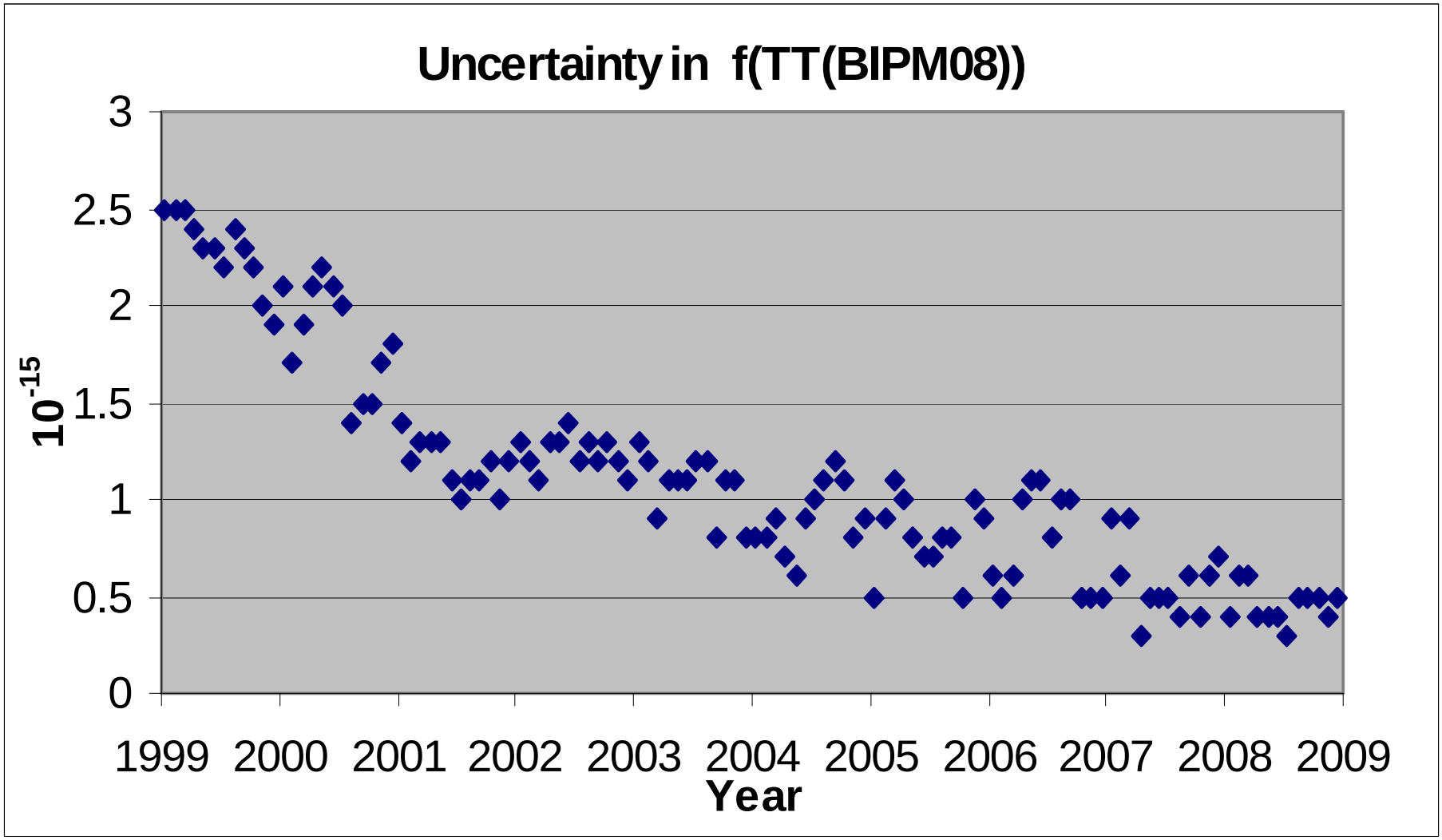
Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+181.10	0.013
Blackbody	-22.84	0.28
Microwave Amplitude Shift	-0.026	0.12
Spin Exchange (low density)	(-0.33)*	(0.11)*
AC Zeeman (heaters)	0.05	0.05
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Cavity Phase (distributed)	0.02	0.02
Second-Order Doppler	0.02	0.02
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	3×10^{-3}	3×10^{-3}
Integrator offset	0	0.01
Total Type B Standard Uncertainty		0.31

NIST-F1



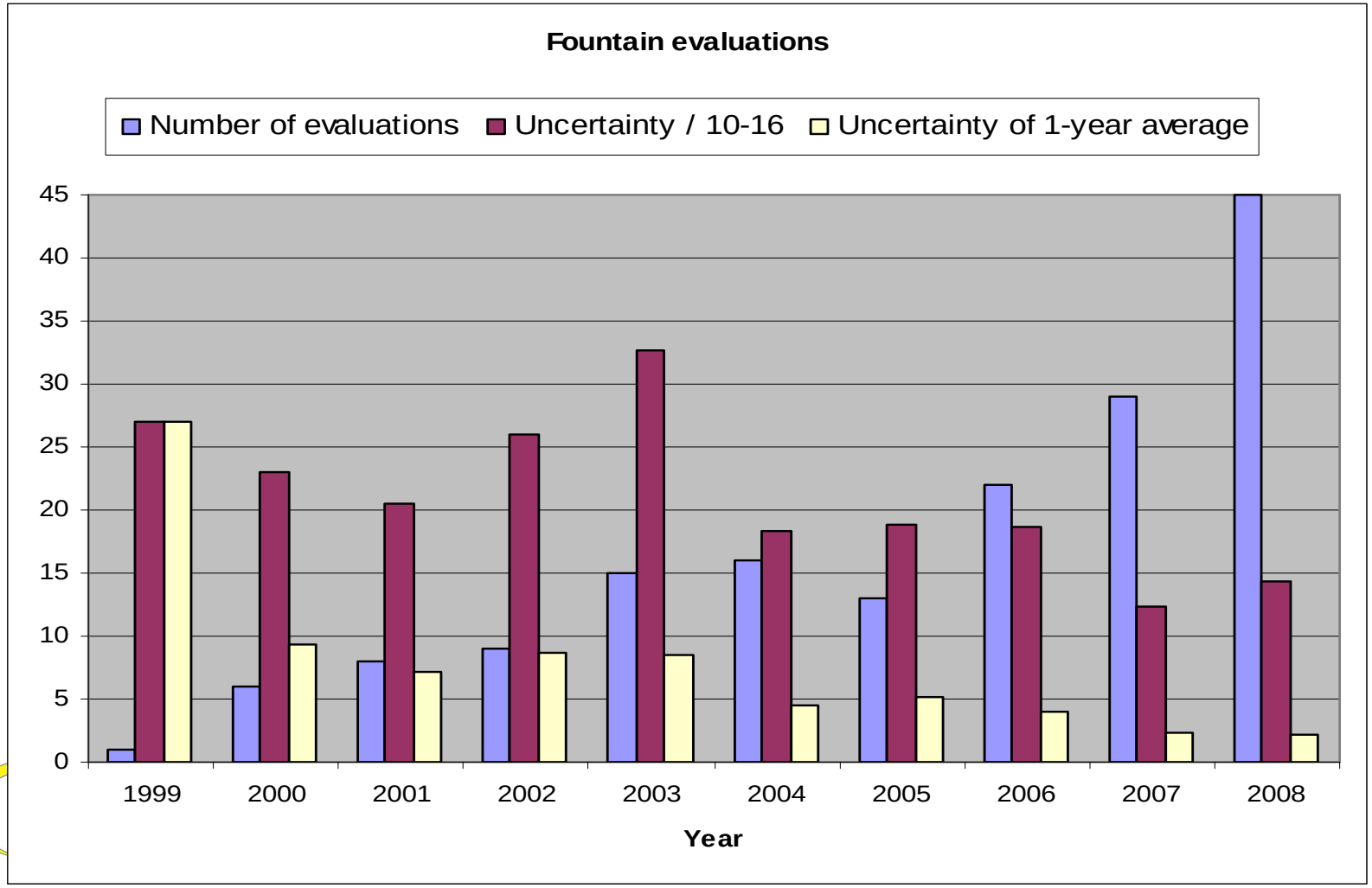
TT(BIPM): the latest realization TT(BIPM08)

- Post-processed in January 2009 using all primary frequency standards data until December 2008.
- Frequency accuracy over the period: decreases from 2.5×10^{-15} in 1999 to $<1 \times 10^{-15}$ since 2004, $<0.5 \times 10^{-15}$ in 2008.



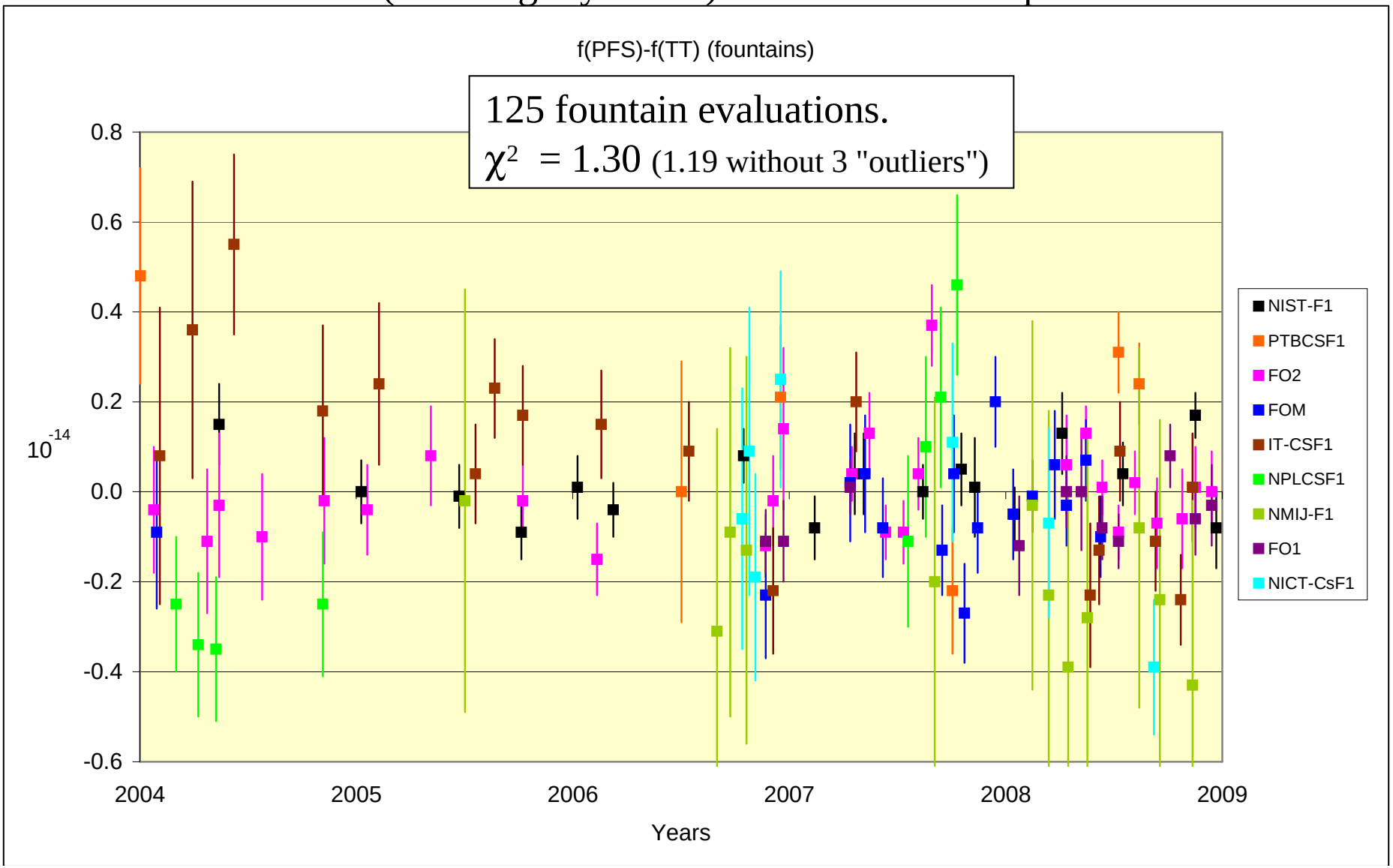
Contributions to TT(BIPM)

- TT(BIPM) performances due to increasing number of Cs fountains
- A rough statistical estimate would put TT(BIPM) accuracy in the low 10^{-16}, but time transfer and instability of EAL limit this.



Fountains vs. TT over 2004-2008

- Results globally coherent, but $\chi 2$ slightly too large
- Situation similar (even slightly worse) in the most recent period



Estimation of systematic effects in Cs fountains

- Because the accuracy of TAI/TT(BIPM) depends on that of the PFS, we want to check for the existence of systematic effects in Cs fountains.
- When one Cs fountain has enough evaluations, we compare its results with an ensemble average of the other PFS: **Tp(Rest_of_the_world)**
  - Computation equivalent to TT(BIPM) but using all primary standards **except** the one under study
- This estimation has been done (until end 2006) for four fountains with largest number of evaluations (13 to 19).
- Results show
  - Good self coherence of the four studied PFS.
  - But some systematic differences: none of the four studied PFS agree with the "rest of the world" within the uncertainties. This may be due to
    - Systematic effects: Estimated accuracy of PFS may be (slightly) optimistic.
    - Uncertainty in frequency transfer: may also be (slightly) optimistic.

Aiming at 10^{-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).
  - See e.g. Proc. of 7th Symposium on frequency standards and metrology, 2008

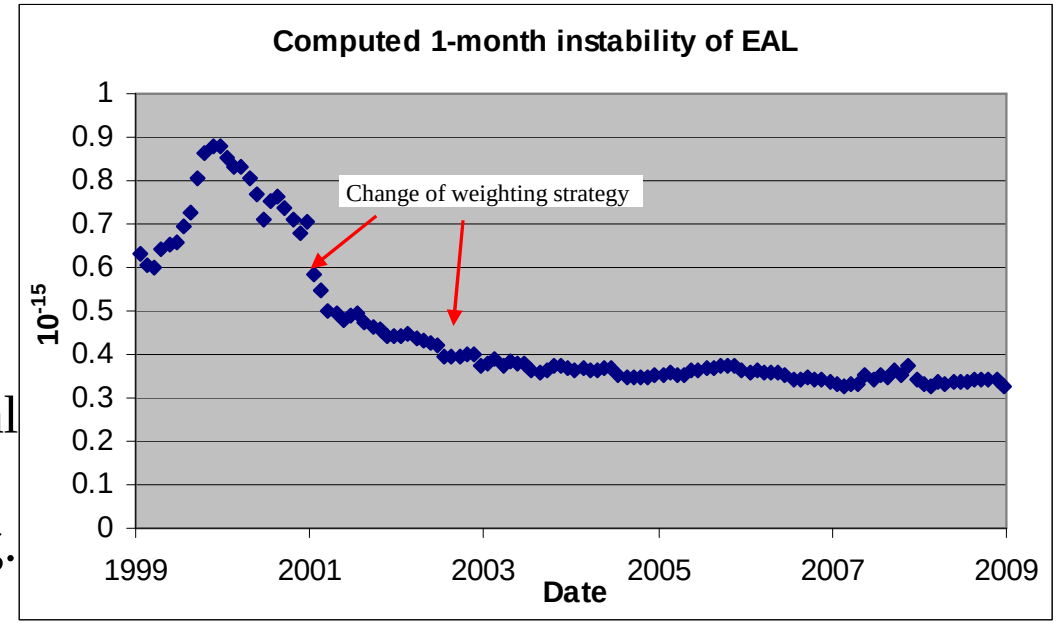
Ensemble time scale: aiming at 10^{-16} and beyond

- With present technologies, a 10-fold increase in clock number would be needed to reach 1.10^{-16} .
  - Back of the envelope calculation (for the present situation): 100-200 clocks, each with $\approx 5.10^{-15}$ stability @ 1 month provide 3-4.10^{-16} for the ensemble time scale.

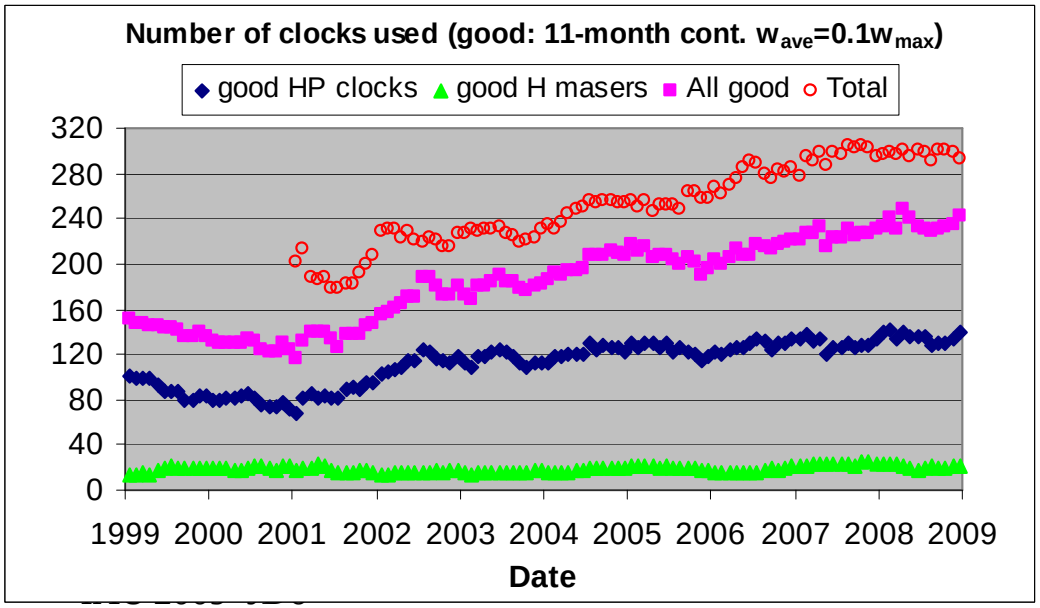
- Reaching 1.10^{-16} and beyond on the long term (1 month and above) will depend on the availability of new clock technologies.

Limits to long-term stability of EAL

- Has decreased from about 6-9.10^{-16} in 1999-2000 to about 4.10^{-16} in 2003.
- But more or less constant since 2003. Total number of clocks still increasing, but total number of good continuous clocks only slightly increasing.

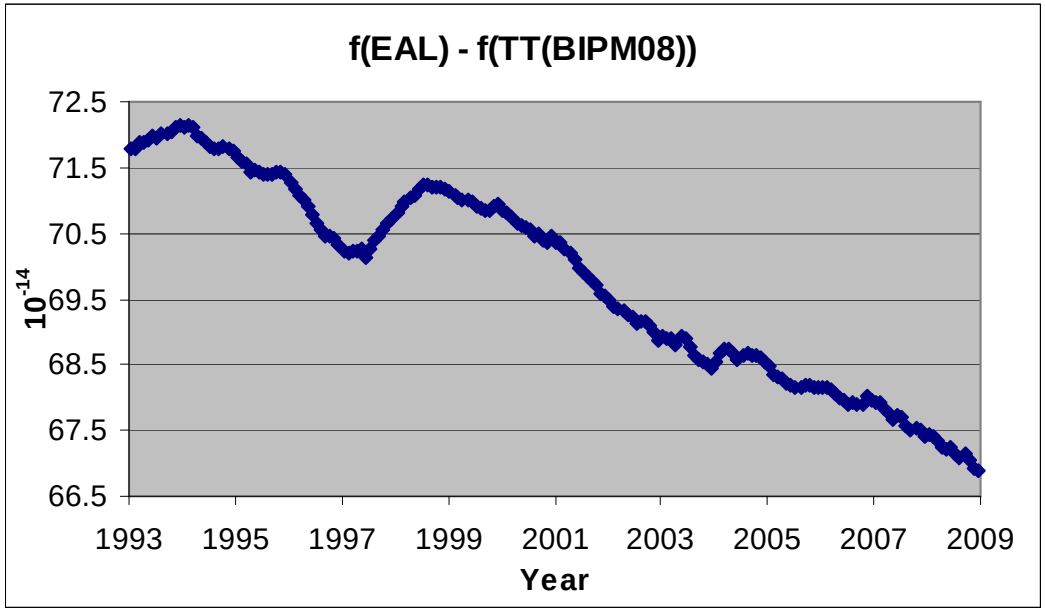


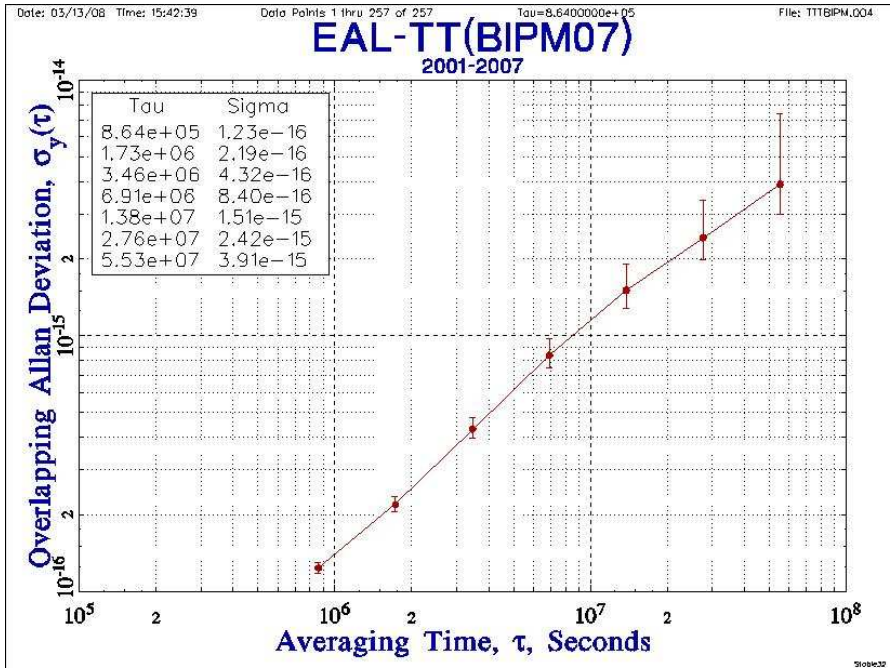
- Some marginal improvements still possible.
- But gaining e.g. one order of magnitude does not seem possible without new clocks.



Limits to the long-term stability of EAL

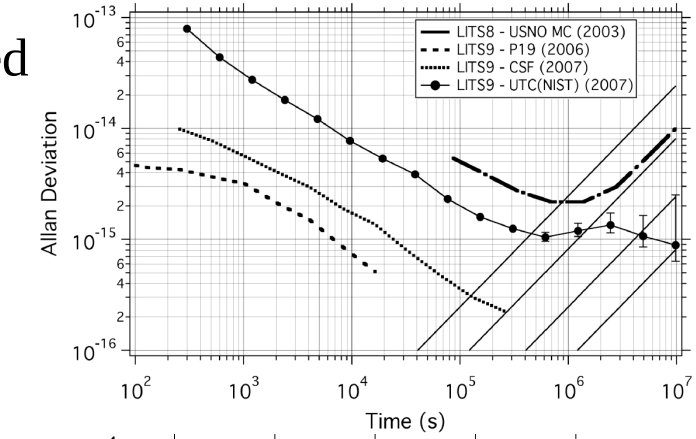
- f(EAL) is compared to TT(BIPM): Some systematic frequency trends persist for many years
- Systematic drift is only partly due to H-masers.
- Long-term (1 year) stability of EAL is presently limited
- TAI not too affected if the number of PFS evaluations is large enough, but life would be easier without EAL drift.

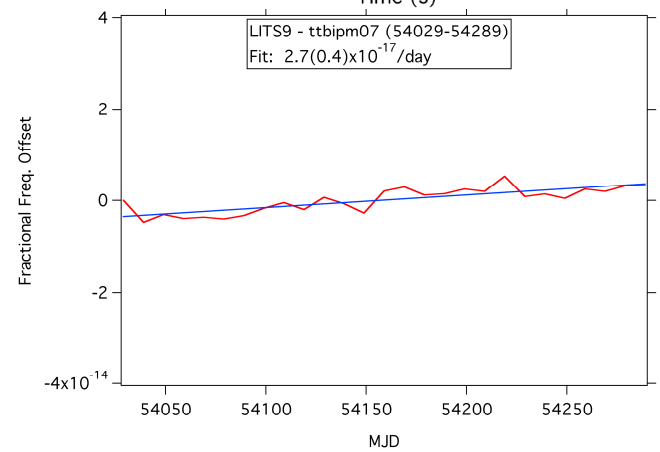




New clock technology

- LITS $^{199}Hg^{+}$ (Burt et al. 2008) : 9-month uninterrupted operation at JPL.
  - $5x10^{-14}/\tau^{1/2}$ (estimated from maser comparison)
  - floor of less than $2x10^{-16}$ (from comparison to Cs fountain)
  - drift < $2.7x10^{-17}$/day (from comparison to TT(BIPM07)





- Rb fountain (Ekstrom et al. 2008)
  - $1.5x10^{-13}/\tau^{1/2}$
  - floor at about $3x10^{-16}$

- Your favorite clock…

Frequency transfer: limits to the current techniques

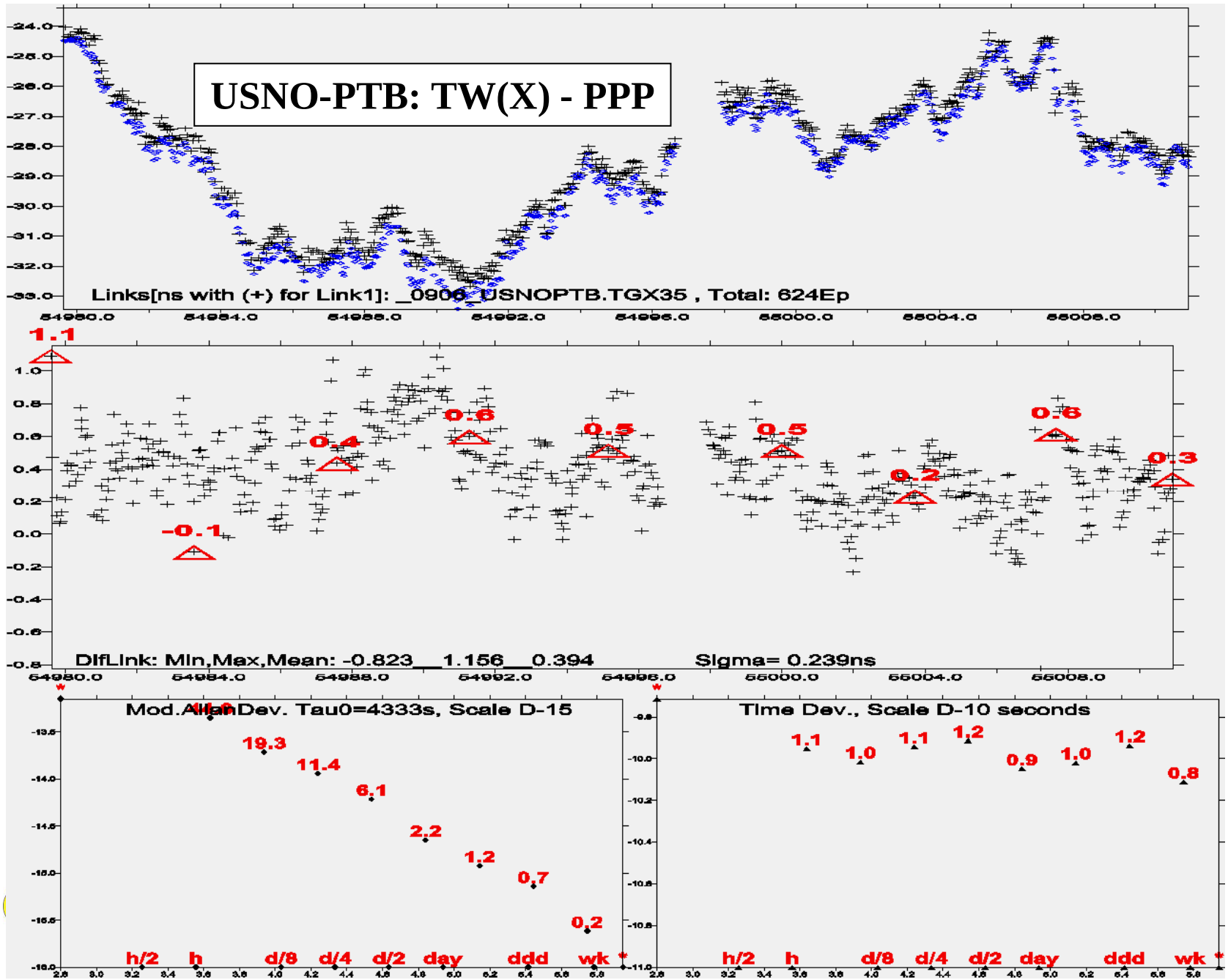
- The current techniques may still be (slightly) improved
- GPS/GNSS:
  - More systems, more satellites, more frequencies, different codes
  - Best performance presently is with GPS dual frequency phase and code (such as PPP)
- TW:
  - More bandwidth, more time (both very expensive), use phase

- Comparisons of techniques in ftp://tai.bipm.org/TimeLink/LkC/yymm
  - Typical values of RMS of (TW-PPP) over one month: 0.2 to 0.6 ns
  - All techniques stable to 100-300 ps up to 10-day averaging

- TW and PPP can provide 10^{-16} frequency accuracy, but only averaging > 10-15-20 days.

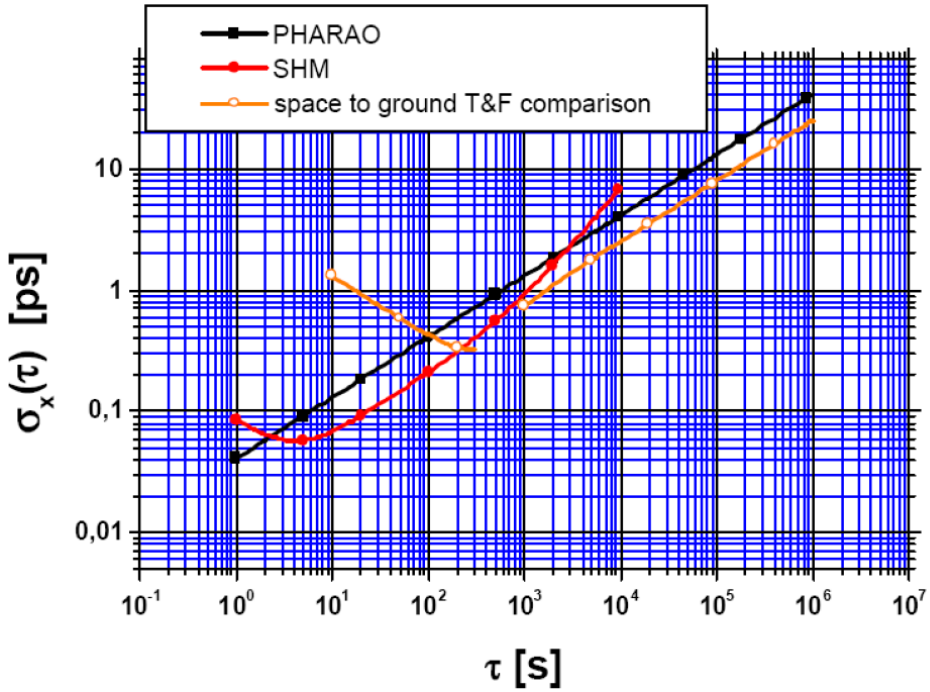
- But TW and PPP cannot presently reach that level at 1-day averaging: New techniques needed

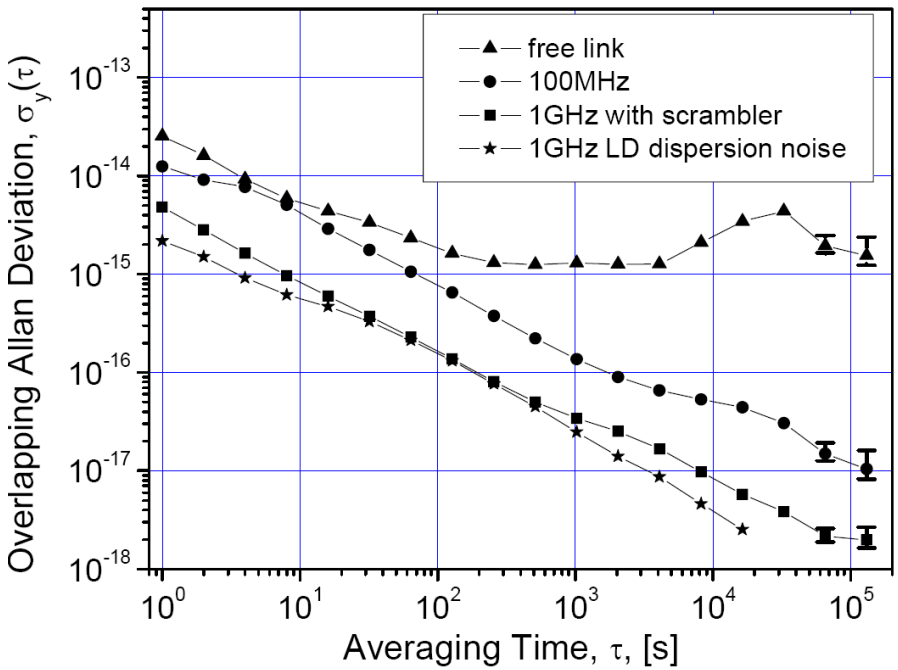
ftp://tai.bipm.org/TimeLink/LkC/0906

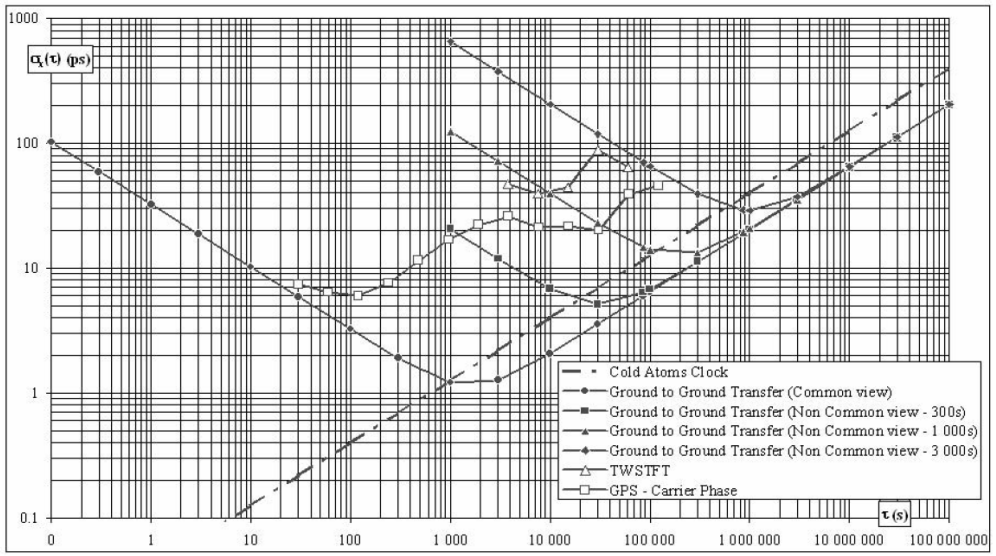


Frequency transfer: aiming at 10^{-16} and beyond

- ACES Microwave link (from Salomon et al 2007)
- T2L2 (from Guillemot et al. 2006)
- Optical fiber (from Lopez et al. 2007)







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,

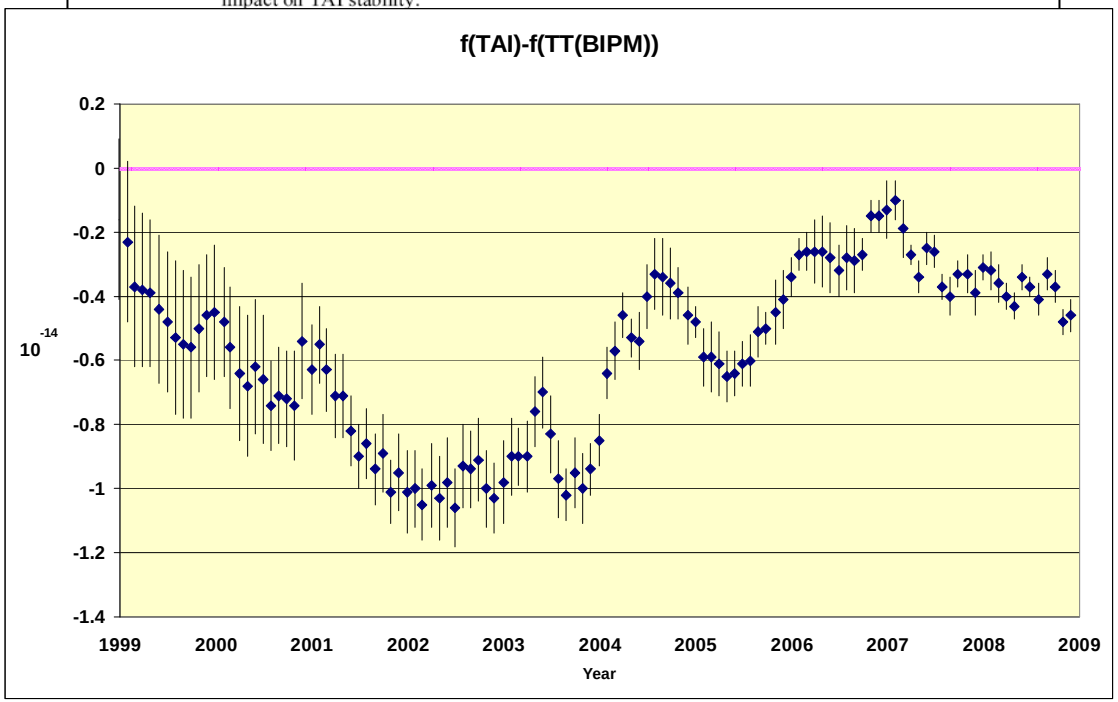
considering that

- 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 is generally not achieved except end 2006-early 2007



Contributions of frequency standards to TAI

- Evaluations of PFS always needed.
- Presently (2009), nearly 4 fountain evaluations per month. Quite good in regard to the number of available fountains.
- New FS encouraged
  - PFS
  - "Secondary representations of the second" are also expected to provide evaluations, in order for us to get experience with their use.

RECOMMENDATION CCTF 3 (2006)
Concerning the use of measurements of the International Atomic Time (TAI) scale unit

The Consultative Committee for Time and Frequency (CCTF),

considering that

- the number of primary frequency standards (PFS) reporting measurements of the TAI scale unit has significantly increased and is expected to continue doing so,
- in the future, secondary representations of the SI second are also expected to report measurements of the TAI scale unit,
- Recommendation CCTF 2 (2004) provides guidelines for reporting such measurements, and recommends that the Working Group on the Expression of Uncertainties in Primary Frequency Standards (at present the Working Group on Primary Frequency Standards) reviews the use of all reported evaluations of PFS,
- the first measurements from a new PFS might exhibit excessive frequency excursions that tend to disappear as more experience with the standard and the frequency transfer process is gathered,
- PFS sometimes undergo modifications leading to significantly changed characteristics and corresponding uncertainties;

recommends that

- the BIPM circulates to the Working Group on Primary Frequency Standards first reports of measurements from new standards, as well as those from frequency standards whose uncertainties have changed appreciably,
- the use and subsequent publication of those reports in *Circular T* be delayed to allow comments from the WG on PFS, following which, publication should be subject to a mutual decision by the concerned laboratory and the BIPM, and
- the long-term frequency stability of a new PFS relative to TAI should be evaluated over several months prior to the submission of a first report, and such data should be included in this report.

Conclusions

- Sub-10^{-15} level is proven for all components of time scale formation:
  - Ensemble time scale stability
  - Time transfer
  - Primary frequency standards
  - More studies to check for systematic effects
- How to reach $1x10^{-16}$ (and beyond)?
  - Very stable clocks already exist. Better reliability and wider availability are needed for time scale formation.
  - Present time transfer techniques may reach this level for long averaging time (10 days). New techniques needed to reach it at short averaging time, and go beyond.
- In the mean time, more (P)FS data needed (more regularly)
- Start to study alternative algorithms for
  - minimizing long term instability, drift, in EAL
  - TAI steering
  - TT(BIPM) computation.

Stability of EAL and TAI vs. TT(BIPM)

- TT(BIPM) is correlated to EAL at 1-few month averaging. The 1-month stability of EAL is estimated at 3-4x10^{-16} over the past years.
- EAL: the long-term behavior indicates that a drift is present.
- TAI: the long term stability has been much improved due to better steering (because better PFS are available).