Atomic timescales

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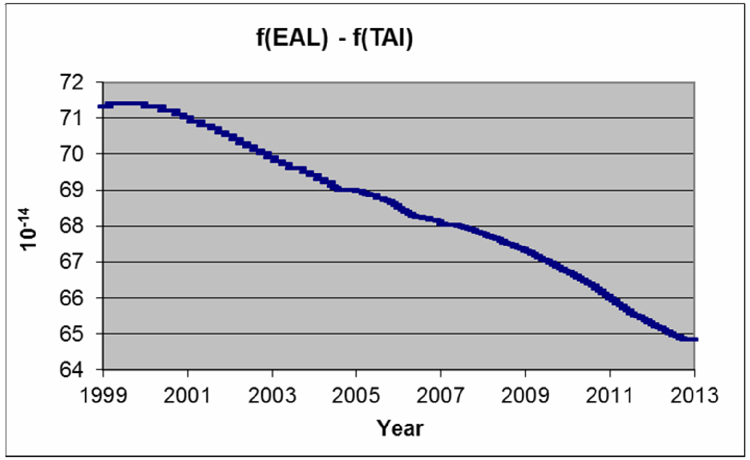
Résumé

- BIPM atomic time scales
- Atomic time and primary standards between the end 1980s and now
- TAI vs. TT(BIPM)
- What pulsars may say on TAI / TT(BIPM)
- Conclusions

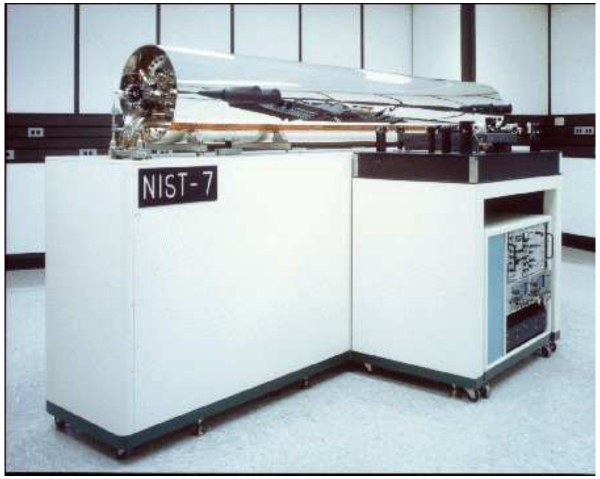
EAL, TAI and TT(BIPMxx)

- 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).
  - Latest realization: TT(BIPM12), released in January 2013.

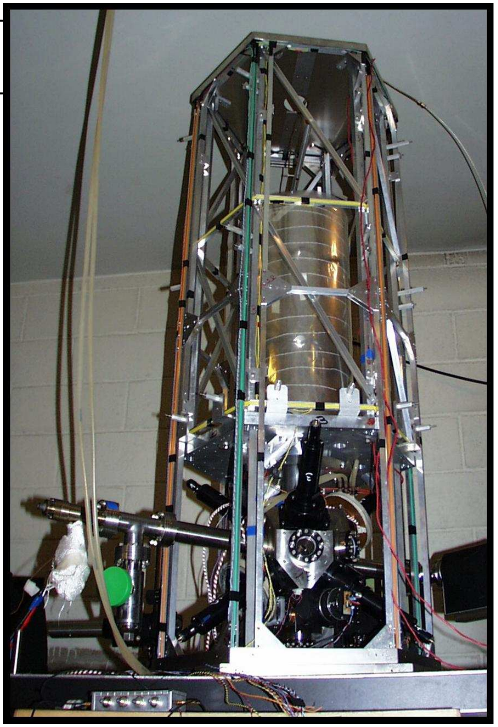
Atomic clocks and timescales from the 1980s to the end 1990s



- Atomic time TAI, published every month
  - End 1980s – early 1990s: Stability from 150-170 clocks, and instability $>1x10^{-14}$ 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 at ~few $x10^{-15}$.
- Laboratory Cs standards attain $1x10^{-14}$ accuracy at the end of the 1980s / early 1990s
  - PTB Cs1 ($\sim 3x10^{-14}$) was operated continuously 1978-1995
  - PTB Cs2 ($\sim 1.5x10^{-14}$) started continuous operation in 1986
  - NIST7 ($\sim 1x10^{-14}$) 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
    - $\sim 1x10^{-14}$ in the end 1980s-early 1990s
    - $\sim 3x10^{-15}$ 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

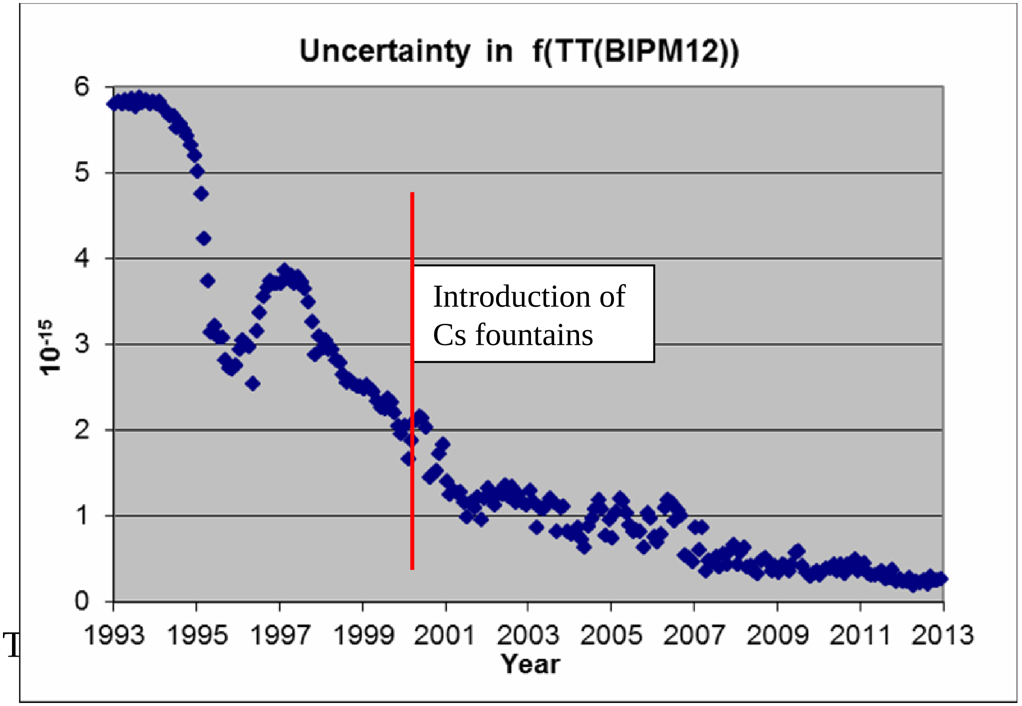
- Cs fountains reach 2-3x10^{-16} accuracy
  - SYRTE: FO1 (back in 2006), FO2 and FOM (since 2002)
  - NIST: F1 (since end 1999)
  - PTB: CsF1 (since 2000), CsF2 (since end 2008)
  - IT: CsF1 (since 2003)
  - NPL:CsF1 (since 2004), CsF2 (since end 2009)
  - NMIJ: F1 (since 2005)
  - NICT: CsF1 (since 2006)
  - more coming
  - Some now operating ~ continuously

- Many new frequency standards
  - Operational and reporting: Rb fountain at SYRTE
  - Many more, more or less operational, and not reporting yet (some claim ~10^{-17} e.g. Al^+ ion)

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 ~ $3\text{-}4 \times 10^{-16}$
- Long-term (years) instability could reach $1\text{-}2 \times 10^{-15}$ until 2012. Now it should remain well below 1×10^{-15}.

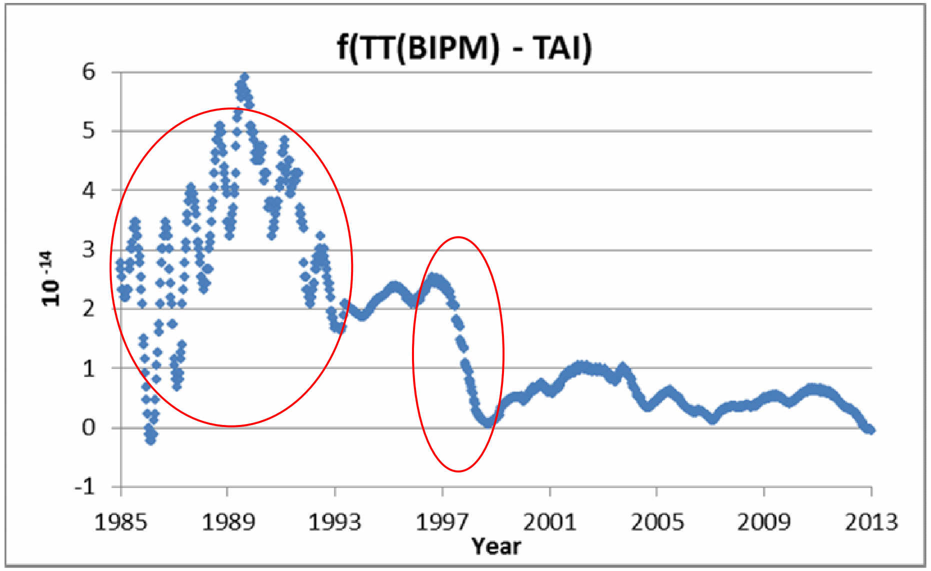
- TT(BIPM) computed each year. Monthly update since 2009.
  - Accuracy / long-term instability was 6×10^{-15} in 1993-1994
  - Reached 1×10^{-15} in the early 2000s
  - Now about $2\text{-}3 \times 10^{-16}$ since 2011



Introduction of Cs fountains

Long term comparison of TAI vs. TT(BIPM)

- Before 1993: Poor stability due to the clocks/time transfer.
- After 1993: Stability improves with the number of HP5071A (+GPS links).
- 1996-1998: Intentional frequency change of ~2.10^{-14} to implement new realization of the second (BBR shift).
- 1999-2012: More or less “random walk” behavior, but bounded. Instability of order 2.10^{-15} @ years.
- 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.

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).

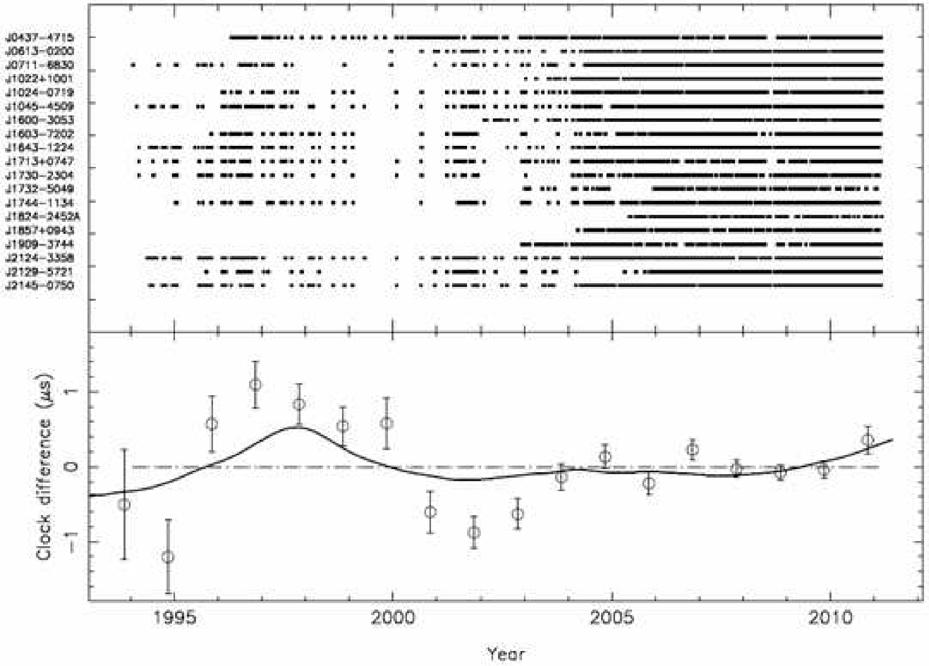
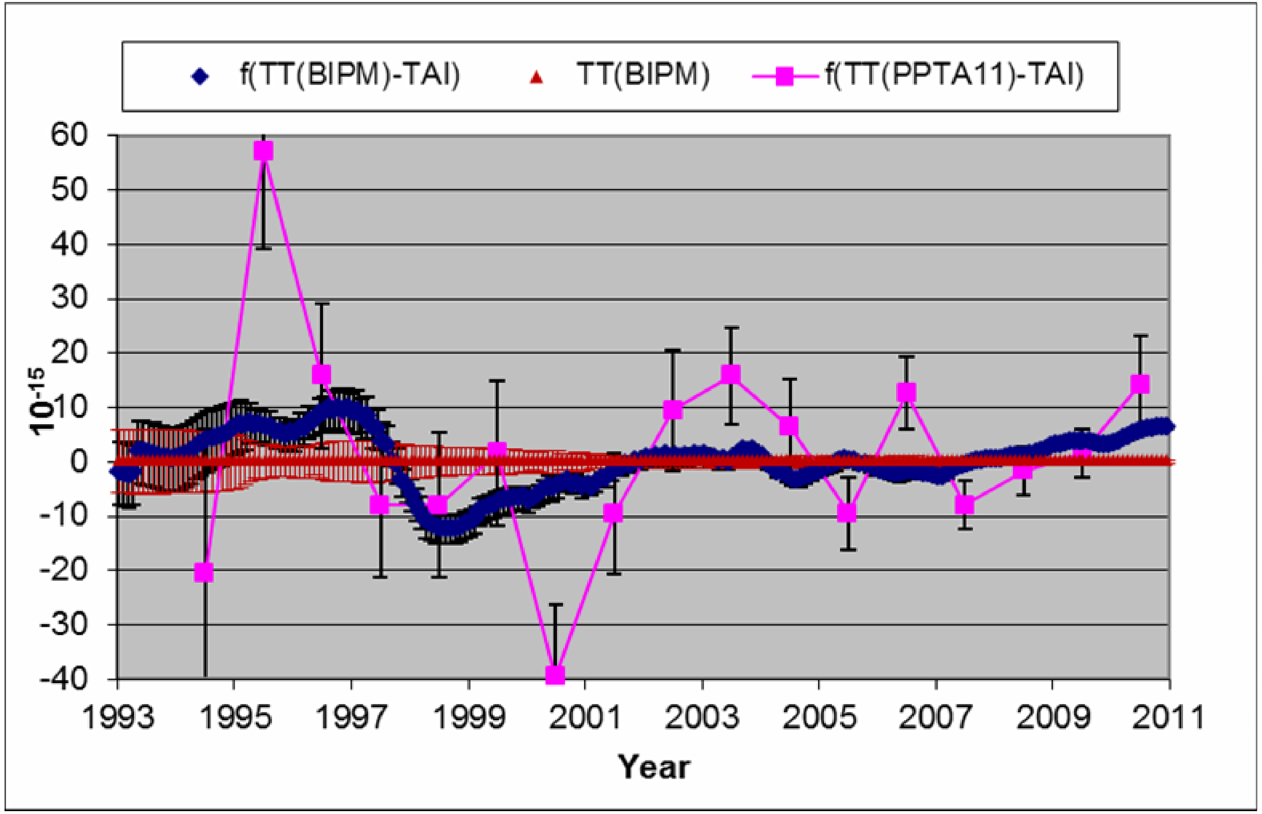


Figure 6. The top panel shows the sampling for the 19 pulsars in our sample. The lower panel shows the difference between TT(BIPM11) and TT(TAI) as the solid line. The data points indicate the difference between TT(PPTA11) and TT(TAI).

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.



Conclusions

- 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.
- Sources of uncertainty that “pulsar-based” timescales have to overcome:
  - "intrinsic“: long-term noise from the pulsar, observation noise
  - observation gaps, hardware changes …
  - DM variations
- Nevertheless 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