Long-term stability of atomic time scales

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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\times10^{-16} and below?
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.
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.
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
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 $2.5 \times 10^{-15}$ in 1999 to $<1 \times 10^{-15}$ since 2004, $<0.5 \times 10^{-15}$ in 2008, $0.3 \times 10^{-15}$ in 2012.
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) (~3x10^{-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 $1 \times 10^{-16}$, 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 $\sigma$.

- This has generally not been achieved except end 2006-early 2007.

- But should be achieved in the next months!!
### Primary frequency standards in 2011: low 10^{-16}

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

Primary standards reported to the BIPM in 2011 (10 fountains and 2 beams)
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 $1.7 \times 10^{-16}$. 

![Graph showing the comparison of PFS to TT(BIPM) over 2006-2012](image-url)
Limits to long-term stability of EAL

- Has decreased from about $6-9 \times 10^{-16}$ in 1999-2000 to about $4 \times 10^{-16}$ in 2003, $3 \times 10^{-16}$ 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
  - $1.5 \times 10^{-13}/\tau^{1/2}$; floor at or below $3 \times 10^{-16}$
Limits to the long-term stability of EAL

- $f(\text{EAL}) - f(\text{TT(BIPM)})$: 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 \(^{87}\text{Sr}\): \(1 \times 10^{-15}\)
- Unperturbed ground-state hyperfine transition of \(^{87}\text{Rb}\): \(3 \times 10^{-15}\)
- Unperturbed optical \(5d^{10} \, 6s \, ^2S_{1/2} \, (F = 0) - 5d^9 \, 6s^2 \, ^2D_{5/2} \, (F = 2)\) transition of \(^{199}\text{Hg}^+\): \(3 \times 10^{-15}\)
- Unperturbed optical \(5s \, ^2S_{1/2} - 4d \, ^2D_{5/2}\) transition of \(^{88}\text{Sr}^+\): \(7 \times 10^{-15}\)
- Unperturbed optical \(6s \, ^2S_{1/2} \, (F = 0) - 5d \, ^2D_{3/2} \, (F = 2)\) transition of \(^{171}\text{Yb}^+\): \(9 \times 10^{-15}\)

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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 $^{87}\text{Rb}$
  - SYRTE evaluation by local comparison to SYRTE PFS: $-1.48 \times 10^{-15}$ based on data over 1998-2012
  - Comparison to TT(BIPM11): $-1.67 \times 10^{-15}$. based on data over 2010-2012, communicated by SYRTE to the BIPM
Aiming at $1 \times 10^{-16}$ 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).
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 $\sim3\times10^{-16}$ in 2012
- New frequency standards now reach or promise $1\times10^{-16}$ (and beyond)
  - We have started integrating Secondary Frequency Standards in TAI
  - This work should be expanded (more and different SFS needed)
- How to reach $1\times10^{-16}$ (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.