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)

- Barycentric system: time coordinate is TCB
  - TDB may be used
    \[ \frac{dTDB}{dTCB} = 1 - L_B \]
    \[ L_B = 1.550519768 \times 10^{-8} \]

- Geocentric system: time coordinate is TCG
  - TT is used in practice
    \[ \frac{dT}{dT} \]
    \[ L_G = 6.969290134 \times 10^{-10} \]

- TT and TDB have been introduced to have “\( \sim \) the same rate” as a clock on the geoid
Time coordinates and time transformations (2/2)

• **Barycentric system: TCB to TDB**
  \[
  \frac{dTDB}{dTCB} = 1-L_B, \quad L_B = 1.550519768 \times 10^{-8}
  \]

• **Geocentric system: TCG to TT**
  \[
  \frac{dT}{dTCG} = 1-L_G, \quad L_G = 6.969290134 \times 10^{-10}
  \]

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

\[
TCB - TCG = \frac{L_C \times (TT - T_0) + P(TT) - P(T_0)}{1 - L_B} + c^{-2} \vec{v}_e \cdot (\vec{x} - \vec{x}_e) \tag{10.5}
\]

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 \(\mu s\) 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
    \[ TT \approx TAI + 32.184s \]
  – UTC defined by the CCIR (now ITU) in 1970:
    \[ UTC = TAI - \text{leap seconds} \]
  – TT(BIPMxy) realized every year by the BIPM;
  – GPS Time;
    \[ \text{GPS Time} \approx TAI - 19s \]
  – 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 \( \rightarrow \) UTC Uncertainty in the ns range, 1 ns at best
  • UTC \( \rightarrow \) TAI Exact
  • TAI \( \rightarrow \) TT Uncertainty ~ few ns/year if TT(BIPM) is used
    Error may be large if TT = TAI+32.184 s
  • TT \( \rightarrow \) TCB Using formulas. Uncertainty ~ ns/year
• 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
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
Some clocks and orders of magnitude

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

<table>
<thead>
<tr>
<th>Commercial clocks</th>
<th>« Best » present standards</th>
<th>Future standards</th>
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<tbody>
<tr>
<td>Cs tube, H-maser</td>
<td>Cs fountains (in ~ 10 labs)</td>
<td>Lattice (e.g. Sr), trapped ions</td>
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<tr>
<td>$10^{-14}$ $\approx$ 1 ns / 1 day</td>
<td>$10^{-16}$ $\approx$ 0.1 ns / 10 days</td>
<td>$10^{-17}$ $\approx$ 1 ps / 1 day</td>
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<tr>
<td>$10^{-15}$ $\approx$ 0.1 ns / 1 day</td>
<td></td>
<td>$10^{-18}$ $\approx$ 1 ps / 10 days</td>
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</tbody>
</table>
~ 450 atomic clocks in ~ 75 laboratories

~ 13 primary frequency standards (~ 8 labs)

Measurement of Earth’s rotation (IERS)

All reported measurements of PFS

Timescales at the BIPM

EAL (Echelle Atomique Libre)
- Freq stability
  ~ 3-4 x 10^{-16} @20-40 d

TAI (Temps Atomique International)
- Freq accuracy
  ~ 2-2.5 x 10^{-16}

UTC (Universal Time Coordinated, monthly)

Circular T

UTC(k)

“average”

“steering”

“leap seconds”

TT(BIPMxy) (annual)
- Freq accuracy
  ~ 2 x 10^{-16}
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 $6-9 \times 10^{-16}$ in 1999-2000 to about $4 \times 10^{-16}$ in 2003, close to $3 \times 10^{-16}$ 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.
Final product: the Circular T

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<th>MJD</th>
<th>MAR 27</th>
<th>APR 1</th>
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</table>

- Values every 5 days
- Uncertainties

Stability
Accuracy
Total

IPTA 2017
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
  - $2.5 \times 10^{-15}$ in 1999
  - $<1 \times 10^{-15}$ since 2004
  - $<0.5 \times 10^{-15}$ since 2008
  - $\sim0.2 \times 10^{-15}$ since 2012
• 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)
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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 >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 (~3x10^{-14}) was operated continuously 1978-1995
  – PTB Cs2 (~1.5x10^{-14}) started continuous operation in 1986
  – NIST7 (~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
    • ~1x10^{-14} in the end 1980s-early 1990s
    • ~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.

- 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 $2 \times 10^{-16}$
  May be limited around $1 \times 10^{-16}$

• 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 $2 \times 10^{-18}$ [Nicholson et al. 2015]
  Several more are in the $1 \times 10^{-17}$ region or better.
Atomic timescales from the end 1990s until now

- TAI based on more clocks: 200 (2000) - 300 (2005) - 400+ (now)
- 1-month instability now at ~ $3 \times 10^{-16}$
- TAI long-term (years) instability could reach $1-2 \times 10^{-15}$ until 2012. Now it should remain well below $1 \times 10^{-15}$.

- TT(BIPM) computed each year; Prediction available until next version.
  - Accuracy / long-term instability was $6 \times 10^{-15}$ in 1993-1994
  - Reached $1 \times 10^{-15}$ in the early 2000s
  - Now about $2 \times 10^{-16}$ since 2012
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.
• Timescales: definitions and realizations
• BIPM atomic time scales: EAL-TAI-UTC, TT(BIPM)
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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)

- 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 time

- **2-3x10^{-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 1x10^{-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 1x10^{-16} (and beyond)?
  - **New generation of very stable clocks**: better reliability and wider availability needed.
  - Present time transfer techniques will reach 1x10^{-16} and below but will be ultimately limited….=> new time transfer technology needed
  - Start to study alternative algorithms for TAI in a sub-1x10^{-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