Optical clocks as secondary frequency standards and re-definition of the second

Gérard Petit
BIPM Time Department

ISSI Workshop “Spacetime metrology, clocks and relativistic geodesy”
19-23 March 2018
Optical frequency standards

- Two main types of optical frequency standards
  - (Single) ion in an EM trap
    - Low SNR
    - Lots of studied ions
  - (Many) neutral atoms trapped in a lattice
    - High SNR
    - Reduce shifts / interactions between atoms

*From F. Riehle*
Outline

- Frequency standards: progresses in the CCTF working groups
- Techniques for the comparison of frequency standards
- Computation of the relativistic shift
- Issues for the CCTF and the CGPM
Frequency standards in the CCTF

1. **WG on Frequency Standards**: A WG of the Consultative Committee for Time and Frequency (joint with the CC for Length) examines all transitions and their realizations. It decides which are recognized as SRS and what are the recommended values of the transitions wrt Cs.

2. **WG on PSFS**: A CCTF WG advises the BIPM in using PSFS for TAI. TAI monthly steering is based on the most recent PSFS, and depends on timely submission. The yearly recomputation TT(BIPMxx) intends to make optimal use of all submitted PSFS evaluations.

3. **WG on ATFT**: A CCTF WG advises the BIPM on Advanced Time and Frequency Transfer techniques. As required to compare PSFS at a distance.
Mission (Terms of Reference)
a) to make recommendations to the CCL for radiations to be used for the realization of the definition of the meter and to make recommendations to the CCTF for radiations to be used as secondary representations of the second,
b) to maintain, together with the BIPM, the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the meter and secondary representations of the second,
c) to take responsibility for key comparisons of standard frequencies such as CCL-K11,
d) to respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.
For the secondary representations of the second, typically revises the list of transitions and recommended values for each session of the CCTF (every 2-3 years)

www.bipm.org
The available data set in 2017

- Number of measurements of absolute frequency and of frequency ratios (Margolis, 2017)
- Numbers in red refer to measurements known but yet unpublished (in the end not used)
Redundant measurements of absolute frequencies and of frequency ratios drove the development of new tools

- Robertsson L, On the evaluation of ultra-high-precision frequency ratio measurements: examining closed loops in a graph theory framework, Metrologia 53 (2016) 1272–1280

The two techniques (+ another implementation of least squares) were verified to provide identical results

- 2017 situation
  - 14 frequencies to determine
  - 59 absolute measurements
  - 11 ratios

Results presented to the CCTF in June 2017
Result of 2017 adjustment

- The adjustment procedure provides a self-consistent set of recommended values of the transition frequencies

- Stated uncertainties are estimated by the working group “by consensus”

- Methods of the working group described in Riehle, F., Gill, P., Arias, F., Robertsson, L.: Recommended frequency standard values for applications including the practical realisation of the metre and secondary representations of the second; Metrologia 2018
Example: the case of $^{87}$Sr

Figure 4.
Frequency measurements of the unperturbed $^{87}$Sr transition in an optical lattice (points) and associated uncertainties for $N$ measurements together with the frequency values (purple bars) recommended by the CIPM and the associated uncertainty bands (pink bands).

Riehle et al. 2018
Laboratories having contributed data to the WG FS

<table>
<thead>
<tr>
<th>Labo</th>
<th>Transitions</th>
</tr>
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<tbody>
<tr>
<td>JILA</td>
<td>Sr</td>
</tr>
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</tr>
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<td>Sr+</td>
</tr>
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<td>H</td>
</tr>
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<td>U. Innsbruck</td>
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</tr>
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<td>U. Tokyo</td>
<td>Sr</td>
</tr>
<tr>
<td>RIKEN</td>
<td>Sr, Hg, Yb</td>
</tr>
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Contributing frequency standards
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- Sixteen laboratories over more than 10 years (many more existing or in development)
- Three main geographical areas
- Intercomparisons between laboratories only starting
- Frequency standards: progresses in the CCTF working groups

- Techniques for the comparison of frequency standards

- Computation of the relativistic shift

- Issues for the CCTF and the CGPM
Frequency transfer 1: Present satellite techniques

- **Standard techniques**
  
  ’Classical’ GNSS and Two Way time/frequency transfer limited to ~few $10^{-16}$ after several days averaging.

- **Advanced techniques**
  
  Using phase measurements improves much over standard code techniques, but requires phase continuity:
  
  - **GPS IPPP** (integer ambiguities) provides $1 \times 10^{-16}$ at 3 days, low $10^{-17}$ at 20 days. Checked vs. 420 km fiber link.
  
  - **TWCP** should be even better but phase continuity may be more difficult to ensure.
Better than $10^{-18}$ within hours.

- 1500 km link demonstrated on public telecom network.
- Requires hardware installation (bi-directional amplifiers, multiplexers, regenerating stations) and a lot of negotiations with operators.
- Continental networks are emerging.

From A. Amy-Klein

www.bipm.org
Frequency transfer 3: Future ACES time link

- Atomic Clock Ensemble in Space mission
  - PHARAO Cs clock and H maser
  - Microwave link (2+1 ways)
  - Laser link

- To fly 2020 (?) on board the ISS for 18 months to 3 years

From Ch. Salomon
Performance of ACES frequency transfer

MWL: Ground Clock comparisons@ 10^{-17} achieved over 1 day in Common view, over 4-5 days in non common view

But limited
- to the duration of the mission
- to the few ground terminals available
Frequency transfer 4: Ground-space optical links

- **Time transfer by Laser Link (T2L2)**
  - On board Jason 2 since 2008
  - $1 \times 10^{-15} @ 1000 \text{ s}$
  - Actual measurements very discontinuous
  - Mostly an accurate system (100 ps)

- **ELT / ISOC**

- **Two-way ground-satellite coherent optical links**
  - Same dependence to weather
  - Turbulence, see e.g. Robert et al, 2016 J. Phys.: Conf. Ser.
What needs to be achieved to compare clocks at a distance?
In terms of frequency accuracy \(\equiv\) time stability

**« Commercial » clocks**
Cs tube, H-maser
- \(10^{-14} \approx 1\) ns / 1 day
- \(10^{-15} \approx 0.1\) ns / 1 day

**« Best » present standards**
Cs fountains (in ~ 10 labs)
- \(10^{-16} \approx 0.1\) ns / 10 days
- 10 ps / 1 day

**« Future » standards**
Lattice (e.g. Sr), trapped ions
- \(10^{-17} \approx 1\) ps / 1 day
- \(10^{-18} \approx 1\) ps / 10 days

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ISSI 19-23 March 2018
Clock transport?

- Allows placing an accurate clock in any location.
- Allows cross-checking the uncertainty budget (accuracy) of distant clocks.
- But does not allow frequency comparisons as needed for relativistic geodesy.

From C. Lisdat

Grotti et al., (2017)
- Frequency standards: progresses in the CCTF working groups
- Techniques for the comparison of frequency standards
- Computation of the relativistic shift
- Issues for the CCTF and the CGPM
\[
\frac{d\tau_A}{d\tau_B} \approx 1 + \frac{(W_B - W_A)}{c^2}
\]

- 1st option to compare two clocks:
  If the two clocks are close enough, one can compute \(\Delta W = -\int g \cdot dH\) by integration
  Or use a regional geopotential model (without considering the absolute value of \(W\))

- General case: compute the absolute value of the geopotential at each clock, then form \(W_B - W_A\)
Obtain the gravity potential $W$ at a marker close to the clock.

Three solutions:

1. Use a **Global Geopotential model** (marker position is obtained by GPS) (**GG**)
   - But poor resolution
2. Use a **Regional Geoid** (**RG**)
   - How is set $W$(RG reference)?
3. Use a **Levelling Network** (**LN**) + reference value
   - How is set $W$(LN reference)?

Then go from the marker to the atoms:

– Standard levelling OK at short distance
– Don't forget to account for the motion of atoms (if any)
The situation for 2016 primary standards

- A purely bibliographic study of the refereed publications for some of the best primary frequency standards (Cs fountains) presently operating: estimations of the uncertainty of the relativistic rate shift range from very conservative to may be somewhat optimistic.

- In general it is not possible to find all details in such a simple bibliographic study (except for NIST and IT).

<table>
<thead>
<tr>
<th>Standard</th>
<th>$u_b$ unc/10^{-16}</th>
<th>$u_b$(Rel)/10^{-16}</th>
<th>Method</th>
<th>Ref($u_b$)</th>
<th>Ref(Relat shift)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYRTE-F02</td>
<td>2.5 to 2.9</td>
<td>1.</td>
<td>LN</td>
<td>Guena et al IEEE Trans 2012</td>
<td>TBC</td>
</tr>
<tr>
<td>NIST-F2</td>
<td>1.5</td>
<td>0.3</td>
<td>GG, RG, LN</td>
<td>Heavner et al Metrologia 2014</td>
<td>Pavlis and Weiss, Metrologia, 2003</td>
</tr>
<tr>
<td>NFL-CSF2</td>
<td>2.0 to 2.7</td>
<td>0.5</td>
<td>LN</td>
<td>Szymaniec et al Metrologia 2010</td>
<td>Riedel B 2005 priv. comm.</td>
</tr>
<tr>
<td>IT-CsF2</td>
<td>1.7 to 2.5</td>
<td>0.1</td>
<td>RG</td>
<td>Levi et al Metrologia 2014</td>
<td>Calonico et al Metrologia 2007</td>
</tr>
<tr>
<td>PTB-CSF2 2015</td>
<td>2.8 to 3.5</td>
<td>0.06</td>
<td>RG (EGG97)</td>
<td>Weyers et al Metrologia 2012</td>
<td>TBC (shift=85.67x10^{-16})</td>
</tr>
<tr>
<td>PTB-CSF2 2016</td>
<td>2.0</td>
<td>0.3</td>
<td>RG (TBC)</td>
<td>idem</td>
<td>ITOC (shift=85.45x10^{-16})</td>
</tr>
<tr>
<td>SU-CsFO2</td>
<td>2.5</td>
<td>0.5</td>
<td>LN (Baltic)</td>
<td>Domnin et al. Meas. Tech. 2013</td>
<td>TBC</td>
</tr>
</tbody>
</table>
More recent work

- NIST: Pavlis and Weiss (Metrologia, 2003) stated $3 \times 10^{-17}$ (≈ 30 cm), now (Metrologia, 2017) states $0.6 \times 10^{-17}$

- All three methods envisioned, some weighted average chosen.
  - **GG**: EGM2008 + GPS; **RG**: USGG2009/2012 referenced to EGM2008
  - **LN**: NAVD88 levelling + estimation of $W$ (levelling reference) to EGM2008

  Overall uncertainty estimated to be $0.6 \times 10^{-17}$

- Denker et al. 2017 for SYRTE, PTB, LUH, MPQ
  - **RG**: EGG2015 states $0.2 \times 10^{-17}$ uncertainty.
Location of sites on a global geoid map

Clock sites are not all in smooth geopotential. Can formal uncertainties of a few $10^{-18}$ be obtained everywhere?
- Frequency standards: progresses in the CCTF working groups
- Techniques for the comparison of frequency standards
- Computation of the relativistic shift
- Issues for the CCTF and the CGPM
Path towards the re-definition of the second

CCTF 21st meeting
June 2017

RECOMMENDATION CCTF 1 (2017)

Recommendations for operating, comparing and reporting frequency standards as secondary representations of the second in preparation for a redefinition of the second by optical transitions

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017, considering that

- a list of secondary representations of the second (SRS) has been maintained following the recommendations of the CIPM,
- different optical SRS have estimated fractional frequency uncertainties nearly two orders of magnitude lower than those of the best caesium primary standards,
- improvements in uncertainty associated with optical frequency standards are ongoing,
- a roadmap for a future redefinition of the second using optical frequency standards has been agreed by the CCTF;

recommends that

- the institutes put effort into operating their frequency standards to realize SRS in such a way that they routinely contribute to TAI via reporting to the BIPM,
- the optical standards be compared with uncertainties that are comparable to the estimated uncertainties of the standards themselves,
- the institutes measure the frequencies of the realizations of their SRS with respect to the best primary caesium standards as a necessary requirement for a possible future redefinition of the second in terms of optical transitions,
- the relevant CCTF working groups finalize the milestones for a redefinition and regularly inform the CIPM about the progress towards meeting these milestones.
A roadmap towards the redefinition of the second

The Consultative Committee for Time and Frequency adopted in 2017 a roadmap towards the redefinition of the second (Riehle 2016):

1. ... at least three different optical clocks (......) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks at that time.

2. ... at least three independent measurements of at least one optical clock were compared in different institutes (e.g. $\Delta \nu/\nu < 5 \times 10^{-18}$) ... by transportable clocks, advanced links, ....

3. ... there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, ... limited essentially by the uncertainty of these Cs fountain clocks (e.g. $\Delta \nu/\nu < 3 \times 10^{-16}$).

4. ... optical clocks (secondary representations of the second) contribute regularly to TAI.

5. ... optical frequency ratios between a few (at least 5) other optical frequency standards have been performed (......) at least twice by independent laboratories and agreement was found e.g. $\Delta \nu/\nu < 5 \times 10^{-18}$.
1. ... at least three different optical clocks (……) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks at that time.

- Well under way: For some of the transitions studied by the WGFS, the uncertainty on the estimation of systematic shifts is much lower than for Cs.

<table>
<thead>
<tr>
<th>Atom / ion</th>
<th>Clock type</th>
<th>Clock $\nu$ THz</th>
<th>Clock $\lambda$ nm</th>
<th>Lowest published clock systematic uncertainty</th>
<th>Uncertainty of CIPM $\nu$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{87}$Sr</td>
<td>Lattice</td>
<td>429</td>
<td>698</td>
<td>$2.1 \times 10^{-18}$</td>
<td>$5 \times 10^{-16}$</td>
</tr>
<tr>
<td>$^{171}$Yb</td>
<td>Ion octopole</td>
<td>642</td>
<td>467</td>
<td>$3.2 \times 10^{-18}$</td>
<td>$6 \times 10^{-16}$</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>Ion, quantum logic</td>
<td>1121</td>
<td>267</td>
<td>$8.6 \times 10^{-18}$</td>
<td>$1.9 \times 10^{-15}$</td>
</tr>
<tr>
<td>$^{88}$Sr</td>
<td>Ion quadrupole</td>
<td>445</td>
<td>674</td>
<td></td>
<td>$1.6 \times 10^{-15}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>Ion quadrupole</td>
<td>1065</td>
<td>282</td>
<td></td>
<td>$1.9 \times 10^{-15}$</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>Ion quadrupole</td>
<td>411</td>
<td>729</td>
<td></td>
<td>$1.2 \times 10^{-14}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>Lattice</td>
<td>1129</td>
<td>266</td>
<td></td>
<td>$6 \times 10^{-16}$</td>
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<td>$^{171}$Yb</td>
<td>Ion quadrupole</td>
<td>688</td>
<td>436</td>
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<td>$6 \times 10^{-16}$</td>
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<tr>
<td>$^{171}$Yb</td>
<td>Lattice</td>
<td>518</td>
<td>578</td>
<td></td>
<td>$3.4 \times 10^{-16}$</td>
</tr>
<tr>
<td>H</td>
<td>Cryogenic beam</td>
<td>1233</td>
<td>243</td>
<td></td>
<td>$9 \times 10^{-15}$</td>
</tr>
</tbody>
</table>

From Gill (2017)
Milestone 2

2. ... at least three independent measurements of at least one optical clock were compared in different institutes (e.g. $\Delta \nu / \nu < 5 \times 10^{-18}$) ... by transportable clocks, advanced links, ....

- Not yet done at this level but potentially OK, cf. ITOC campaigns involving comparisons by fiber links between SYRTE, PTB, NPL
  - See talk by Helen Margolis

- Potential question: How will the T/F community react as long as this level of performance cannot be achieved on intercontinental links?
3. ... there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, ... limited essentially by the uncertainty of these Cs fountain clocks (e.g. $\Delta \nu/\nu < 3 \times 10^{-16}$).

- In the 2017 list of frequencies, six transitions have uncertainties with respect to Cs that are in the $10^{-16}$ region:
  - $\nu (^{87}\text{Sr})$ $4\times10^{-16}$
  - $\nu (^{171}\text{Yb})$ $5\times10^{-16}$
  - $\nu (^{199}\text{Hg})$ $5\times10^{-16}$
  - $\nu (^{88}\text{Sr}^+)$ $6\times10^{-16}$
  - $\nu (^{171}\text{Yb}^+ \text{ qu})$ $6\times10^{-16}$
  - $\nu (^{171}\text{Yb}^+ \text{ oc})$ $6\times10^{-16}$

- Uncertainty will go to $<3\times10^{-16}$ with larger number of comparisons, and longer operation of the optical clocks.
Milestone 4

4. ... optical clocks (secondary representations of the second) contribute regularly to TAI.

- In February 2017 were published the first contributions to TAI by optical clocks: Four evaluations by SYRTE Sr2, one by SYRTE SrB

- That’s it for the moment....
Some frequency ratios are being measured with much smaller uncertainty than Cs e.g.

- $\nu (^{27}\text{Al}^+) / \nu (^{199}\text{Hg}^+) \approx 5.5 \times 10^{-17}$
  (Rosenband et al. 2008)
- $\nu (^{171}\text{Yb}) / \nu (^{87}\text{Sr}) \approx 5.5 \times 10^{-17}$
  (Nemitz et al. 2016)
- $\nu (^{88}\text{Sr}) / \nu (^{87}\text{Sr}) \approx 2.3 \times 10^{-17}$
  (Takano et al. 2017)
- A few more + others in preparation

These are mostly in same lab but it is OK for this milestone
Possible roadmap (Riehle, 2016)

- 3 clocks
  $\Delta \nu / \nu \sim 10^{-18}$

- 3 comparisons
  $\Delta (\nu_i / \nu_j) < 5 \times 10^{-18}$

- 3 clocks
  $\Delta \nu / \nu < 3 \times 10^{-16}$

- Regular contrib. to TAI

- 2 comp. betw. 5 clocks
  $\Delta (\nu_i / \nu_k) / (\nu_i / \nu_k) < 5 \times 10^{-18}$

- Validation and decision for optical standard

- CGPM

- 2017
- 2020
- 2025
- 2030
Rec CCTF-3 (2017) Definitions of timescales TAI and UTC

- Remove ambiguity between TAI and TT that has been present since the IAU redefined TT in 2000.
- Should be adopted by the CGPM in November 2018

states that

- TAI is a continuous time scale produced by the BIPM based on the best realizations of the SI second, and is a realization of TT as defined by IAU Resolution B1.9 (2000),
- in the transformation from the proper time of a clock to TAI, the relativistic rate shift is computed with respect to the conventionally adopted equipotential $W_0 = 62636856.0 \text{ m}^2\text{s}^{-2}$ of the Earth’s gravity potential, which conforms to the constant $L_G$ defining the rate of TT,

decides

1- International Atomic Time (TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000),
2- Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds,
Main conclusions

- The work of the WG on Frequency Standards paves the way for a redefinition of the second.

- New better long distance frequency transfer techniques are needed.
  - In the meantime, do the best with existing satellite techniques

- This work goes exactly in parallel to the needs of relativistic geodesy.

Please note: Meeting of the IAG WG on relativistic geodesy planned at the BIPM early October 2018 (dates to be fixed)
THANK YOU

Thanks to CCL-CCTF WG on Frequency Standards (ex) co-chairs F. Riehle and P. Gill and (ex) co-secretaries F. Arias and L. Robertsson.