Toward a redefinition of the SI second with optical clocks: an overview of recent progress

Sébastien BIZE
SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE

Consultative Committee on Units
October 09th 2019
BIPM, Sèvres, France
Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions
Progress of frequency standards over time

- Optical frequency standards surpass Cs standards
  - By more than 2 orders of magnitudes
- Points toward a redefinition of the SI second
  - Once readiness of optical frequency standards is proven
- Status of optical frequency standards
Optical frequency standards

- **Current primary frequency standards**
  - Cs hyperfine transition in laser-cooled atomic fountains
  - Accuracy: $2-3 \times 10^{-16}$, stability: $<2 \times 10^{-14}$ at 1s

- **Optical frequency standards**
  - Atomic transition frequency near $10^{15}$ Hz
  - The fundamental output is the ultra-stable oscillation of electromagnetic fields of laser light
  - Importance of ultra-stable lasers

\[ h\omega = h\nu = E_e - E_f \]
Lamb-Dicke spectroscopy

- Need to deal with the effect of external motion
  - Limitation of probe time, Doppler shift, recoil shift, relativistic time dilation
  - Laser-cooled atoms: $v \sim 1 \text{ cm/s}$, $v/c \sim 3 \times 10^{-11}$!

- Laser cooling & tight confinement
  - Quantized states of motion
  - Lamb-Dicke / resolved sideband regime
  - Effects of motion in sidebands. Carrier essentially unaffected.

- Need to care for effects of trapping fields

Campbell et al. Science 358, 90 (2017)
Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions
(Single) Ion optical clocks

- **Paul trap**
  - Electric field acting on ion charge

- **Mitigation of trapping effects**
  - Laser-cooling
  - Single ion at trap center where $<E> = 0$

- **Detection by electron shelving**
  - Observation of quantum jumps

- **Disadvantage**
  - Low signal-to-noise (quantum projection noise for $N=1$)

- **Advantage**
  - Ion kept cycle-to-cycle
  - No collision shift
(Single) ion optical clocks

- **Candidates**
  - Hg+, Ca+, Sr+, Yb+(E2), Yb+(E3), In+, etc.

- **Quantum logic clocks**
  - Al+, assisted by Be+, Mg+, Ca+

- **Examples**
  - Yb+(E3) at PTB: $3.2 \times 10^{-18}$
    - Huntemann et al. PRL 116, 063001 (2016)
  - Al+ at NIST: $9.4 \times 10^{-19}$
Optical lattice clocks

- **Dipole lattice trap**
  - By an intense standing-wave laser field

- **Mitigation of trapping effects**
  - Laser cooling
  - Lattice trap at magic wavelength

- **Detection**
  - Fluorescence

- **Disadvantage**
  - Atom-atom interactions

- **Advantage**
  - High signal-to-noise: $N=10^4-10^5$
  - Possibility of non-destructive detection

Optical lattice clocks

- **Candidates**
  - $^{87}\text{Sr}$, $^{88}\text{Sr}$, Yb, Hg, Mg, Cd, etc.

- **Examples**
  - Sr at JILA: $2.0 \times 10^{-18}$
    - Nicholson et al., Nat. Com. 6, 6896 (2015)
    - Bothwell et al (2019)
    - Metrologia in press
  - Sr at UT/RIKEN: $4.8 \times 10^{-18}$
  - Yb at NIST: $1.4 \times 10^{-18}$
Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions
How to assess optical frequency standards?

- Operate with all systematic shifts controlled at the same time
  - Required but not enough

- Comparisons of standards based on the same atom/ion
  - Built a second system and check the agreement between them
  - $\nu_A / \nu'_A$ should 1 within stated uncertainties

- Frequency ratios
  - Ratios of atomic frequencies are dimensionless quantities given by nature
  - Independent measurements in different places can be compared
  - A particular case corresponds to absolute frequency measurements
    - i.e. ratio to the Cs hfs
    - Limited by the accuracy of Cs standard

- Closure based on multiple frequency ratios
  - Closure within stated uncertainties can be verified
    $$\frac{\nu_A}{\nu_B} \times \frac{\nu_B}{\nu_C} \times \frac{\nu_C}{\nu_A} = 1 + \Delta$$
Same standard comparisons

- **Same clock comparisons**
  - Le Targat et al., Sr (2013)
  - Bloom et al., Sr (2013)
  - Ushijima et al., Sr (2015)
  - McGrew et al., Yb (2018)

\[-7\pm(5)_{\text{stat}}\pm(8)_{\text{sys}}\] \times 10^{-19}

- **Example**
  - Comparison of 2 cryogenic Sr clocks at RIKEN
    Ushijima et al., Nat. Photon. 9, 185 (2015)
  - Uncertainty: \(4.4\times10^{-18}\)
  - Note: a synchronized comparison

- **Some terms can be common mode**
  - And therefore not well tested in comparisons
  - e.g. atomic coefficient if fields are similar
Absolute frequency measurements

- **CCTF 2017**: 13 optical transitions measured with uncertainties <10^{-14}
- **^{87}Sr 1S0-3P0 at 698 nm** by far the most frequently measured (16x)
  - Agreement. Limited by the accuracy of Cs fountain
  - Measurements since CCTF 2017
    - Yb via TAI, 2.1E-16, NIST, McGrew et al., Optica 6, 448 (2019)


Lowest uncertainty of individual measurement: 2.6x10^{-16}
Optical frequency ratios (CCTF 2017)

- 7 optical ratios measured
  - lowest uncertainty: $4.6 \times 10^{-17}$
  - $2.3 \times 10^{-17}$ for $^{87}\text{Sr}/^{88}\text{Sr}$ in the same setup

- Only 2 ratios measured independently in 2 institutes
  - Sr/Yb, Sr/Hg

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Value</th>
<th>Fractional uncertainty</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}\text{Sr}/^{87}\text{Sr}$</td>
<td>1,00000001448836827727</td>
<td>2.30E-17</td>
<td>Takamoto2017</td>
</tr>
<tr>
<td>Hg/Sr</td>
<td>2,62931420989890915</td>
<td>1.80E-16</td>
<td>Tyumenev2016</td>
</tr>
<tr>
<td>Hg/Sr</td>
<td>2,62931420989890960</td>
<td>8.40E-17</td>
<td>Yamanaka2015</td>
</tr>
<tr>
<td>Yb/Sr</td>
<td>1,207507039343337749</td>
<td>4.60E-17</td>
<td>Nemitz2016</td>
</tr>
<tr>
<td>Yb/Sr</td>
<td>1,20750703934333776</td>
<td>2.40E-16</td>
<td>Takamoto2015</td>
</tr>
<tr>
<td>Yb/Sr</td>
<td>1,20750703934333412</td>
<td>1.40E-15</td>
<td>Akamatsu2014</td>
</tr>
<tr>
<td>Hg/Yb</td>
<td>2,17747319413456507</td>
<td>2.50E-16</td>
<td>Takamoto2015</td>
</tr>
<tr>
<td>Yb(E2)/Yb(E3)</td>
<td>1,07200737363420630</td>
<td>3.40E-16</td>
<td>Godun2014</td>
</tr>
<tr>
<td>Sr/Ca+</td>
<td>1,0442433345296416</td>
<td>2.40E-15</td>
<td>Matsubara2012</td>
</tr>
<tr>
<td>Al+/Hg+</td>
<td>1,052871833148990438</td>
<td>5.30E-17</td>
<td>Rosenband2008</td>
</tr>
</tbody>
</table>

- Since CCTF 2017: 2 new measurements
  - $^{87}\text{Sr}/^{88}\text{Sr}$, 3E-17, independent apparatus, Phys. Rev. A 98, 053443 (2018)
  - $^{171}\text{Yb}/^{87}\text{Sr}$, 2.8E-16, Nat. Phys. 14, 437 (2018)
Remote optical clock comparisons

- **With optical frequency transfer by fiber**
  - Takano et al., Nat. Photon. 10, 662 (2016)

- **International comparison over 1450 km**
  - Sr(SYRTE)/Sr(PTB) comparison: \((4\pm5)\times10^{-17}\)
  - Link compatible with \(10^{-18}\) comparison at \(10^4\) s

- **Transportable optical frequency standards**
Development of optical fiber links

- A few more comparison campaigns
  - ~1 month long, with holes
  - LNE-SYRTE, PTB, NPL

- Maturity of coherent optical fiber links
  - New 680 km cascaded link deployed by industry
  - State-of-the-art performance

Other cases, methods and applications
- e.g. INRIM: link to VLBI & laser ranging stations
- → WG ATFT workshop tomorrow

Chronometric geodesy

- **Einstein’s gravitational redshift**
  - Space-time is modified in the vicinity of masses
  - Magnitude near the surface of the Earth
    - $10^{-16} \text{ m}^{-1} \rightarrow 10^{-18} \Leftrightarrow 1 \text{ cm}$

- **Chronometric geodesy**
  - Remote frequency standard comparisons to measure gravity potential differences

- **Present and future impact on TAI**
  - General relativity already taken into account in definition and elaboration of TAI. See Resolution 2 of the 2018 CGPM on the definition of timescale.
  - Irregularities and variations may limit time coordinate with frequency standards on the Earth surface to few $10^{-18}$.
  - Tides amount to up to $10^{-16}$ (1 m).
  - Started to be considered by IAG/IUGG, by the BIPM time department, etc.
Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions
Toward a redefinition: work of the CIPM/CCTF

- **CIPM/CCTF 2001**
  - Expected optical and other microwave standards to surpass primary Cs standards in reproducibility, stability and uncertainty
  - Such systems could be used to realize the second provided their accuracy is close to that of Cs standards
  - Adoption of such *secondary representations of the second* (SRS) would help assessing these standards at the highest level
  - This activity is likely to aid the process of evaluating standards in preparation for a possible redefinition of second

- **CIPM/CCTF documents**
  - Several recommendations
  - CCTF strategic plan
  - Work of several working groups and of the time department of the BIPM
CCL-CCTF frequency standard working group

- Terms of reference - The objectives of the CCL-CCTF WGFS are:
  - To make recommendations to the CCL for radiations to be used for the realization of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second;
  - 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 metre and secondary representations of the second;
  - To take responsibility for key comparisons of standard frequencies such as CCL-K11;
  - To respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.

CCL-CCTF WGFS in particular and practically:

- Monitors the status of optical and microwave standards based on existing peer-reviewed publications
- Proposes updates to the CIPM List of recommended standard frequencies (LoF) recommended for applications including the practical realization of the metre (MeP) and secondary representations of the second (SRS).

Recent description CCL-CCTF WGFS activity in Metrologia

Frequency ratios considered by the CCTF 2017

- Overview of measurements
  - About 70 measurements
  - 6 optical frequency ratios
  - An over-determined dataset

- Procedure for consistency check
  - Measurements expressed in a matrix of frequency ratios
  - Least-square adjustment
  - 3 independent implementations by H. Margolis, L. Robertsson, C. Oates

- For the LoF, the CCL-CCTF WGFS takes into account
  - Inconsistencies, scarcity of measurements, etc.
Overview of the 2017 LoF

- References
  - LoF on BIPM website

- List of recommended standard frequencies (CCTF 2017)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Fractional uncertainty</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>6834682610.9043126</td>
<td>$6 \times 10^{-16}$</td>
<td>$^{87}\text{Rb}$ ground state hfs</td>
</tr>
<tr>
<td>429228004229873.0</td>
<td>$4 \times 10^{-16}$</td>
<td>$^{87}\text{Sr}$ neutral atom, $5s^21S_0–5s5p,^3P_0$</td>
</tr>
<tr>
<td>444779044095486.5</td>
<td>$1.5 \times 10^{-15}$</td>
<td>$^{88}\text{Sr}^+\text{ion,}$ $5s,^2S_{1/2}–4d,^2D_{5/2}$</td>
</tr>
<tr>
<td>518295836590863.6</td>
<td>$5 \times 10^{-16}$</td>
<td>$^{171}\text{Yb}$ neutral atom, $6s^21S_0–6s6p,^3P_0$</td>
</tr>
<tr>
<td>642121496772645.0</td>
<td>$6 \times 10^{-16}$</td>
<td>$^{171}\text{Yb}^+\text{ion,}$ $2S_{1/2}–2F_{7/2}$</td>
</tr>
<tr>
<td>688358979309308.3</td>
<td>$6 \times 10^{-16}$</td>
<td>$^{171}\text{Yb}^+\text{ion,}$ $6s,^2S_{1/2}–5d,^2D_{3/2}$</td>
</tr>
<tr>
<td>1064721609899145.3</td>
<td>$1.9 \times 10^{-15}$</td>
<td>$^{199}\text{Hg}^+\text{ion,}$ $5d^{10}6s,^2S_{1/2}–5d^96s^2,^2D_{5/2}$</td>
</tr>
<tr>
<td>1121015393207857.3</td>
<td>$1.9 \times 10^{-15}$</td>
<td>$^{27}\text{Al}^+\text{ion,}$ $3s^21S_0–3s3p,^3P_0$</td>
</tr>
<tr>
<td>1128575290808154.4</td>
<td>$5 \times 10^{-16}$</td>
<td>$^{199}\text{Hg}$ neutral atom, $6s^21S_0–6s6p,^3P_0$</td>
</tr>
</tbody>
</table>
A dynamical process

- Successive recommended values and uncertainty for $^{87}\text{Sr}$
  - $1.5 \times 10^{-14}$
  - $4 \times 10^{-16}$

- Normal given the fast evolution of optical frequency metrology
Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions
Impact of precise time and frequency references

- **Cs definition serves well industry’s needs**
- **Precise time is important in global scale applications & services**
  - Elaboration/dissemination of TAI/UTC
  - Determination of Earth orientation parameters
  - Global navigation satellite systems
  - Networks (telecommunication, transport, electrical power, etc.)
- **Precise, consistent time and frequency references are important for science**
  - VLBI, deep space navigation, pulsar timing, test of fundamental theories, fundamental constants, etc.
- **Progress of optical frequency standards continues**
  - No definite argument for a given atom or ion
Important considerations for a redefinition

- New definition must last long

- Continuity between old and new definition must be ensured

- Effectiveness of dissemination must be guarantied
  - In particular in the elaboration of TAI

- Optical frequency standards must have validated uncertainties
  - At a level much better than Cs standards (e.g. 2 orders of magnitudes)
Possible milestones towards a new definition

See CCTF strategy document and Metrologia 55, 188 (2018)

- New definition should not take place before...

  - ... the progress with the different optical frequency standards slows down
    Alternatively: .. when at least three different (either in different laboratories, or of different species) optical clocks have validated uncertainties two orders of magnitude better than the best Cs atomic clocks. (To increase the probability that the new definition will last long)

  - ... there are three independent measurements of the optical frequency standards listed in item 1 limited essentially by the uncertainty of the best Cs fountain clocks (e.g. $\Delta \nu/\nu < 3 \times 10^{-16}$). (To allow for continuity between the old and new definition)

  - ... three or more optical clocks with the same atomic species were compared in different institutes (e.g. $\Delta \nu/\nu < 5 \times 10^{-18}$) (either by transportable clocks, fiber links, or frequency ratio closure) (To validate item 1)

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

  - ... optical frequency ratios between a few (at least 5) other optical frequency standards have been performed; each ratio measured at least twice by independent labs and agreement (with e.g. $\Delta \nu/\nu < 5 \times 10^{-18}$) (To allow closures and links between the different optical standards)
Possible roadmap

See CCTF strategy document and Metrologia 55, 188 (2018)

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

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

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

Regular contribut. 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
Possible roadmap completed

3 clocks
\[ \Delta v_i/v_i \sim 10^{-18} \]

3 comparisons
\[ \Delta (v_i/v_i) < 5 \times 10^{-18} \]

3 clocks
\[ \Delta v/v < 3 \times 10^{-16} \]

Regular contrib. to TAI
permanent, continuous, sustainable contributions

2 comp. betw. 5 clocks
\[ \Delta (v_i/v_k) / (v_i/v_k) < 5 \times 10^{-18} \]

Validation and decision for optical standard
CGPM
Sustainable contribution to TAI

Calibration with fountains

- See Circular T. Note: Cs beams not shown.

So far, very few contributions from optical frequency standards
- LNE-SYRTE (Sr), NICT (Sr), NIST (Yb). Only 2 or 3 given in “real-time”.
- Note: comb generate a microwave frequency tied to the optical transition that readily connect to existing architectures.

Need of strong commitment from NMIs

Suggest to update strategy document accordingly
- And (stronger) recommendation at the 2020 CCTF
Options for a redefinition of the SI second

- **Choose a single atomic transition similarly to what is currently done**
  - And make use of secondary representations of the second
  - Change again once major progress is observed

- **Adopt a definition using several transitions at the same time**
  - See J. Lodewyck, Metrologia 56, 055009 (2019)
  - Realization using frequency ratio matrix from CIPM
  - Update the ensemble and weights, with rules yet to be agreed upon

- **Fix the value of the electron’s mass**
  - Which fixes the value of the De Broglie-Compton frequency of the electron
    \[ \nu_e = \frac{m_e c^2}{\hbar} \]
    \[ \nu_e \sim 10^{20} \text{ Hz} \]
    - And use one of the above as *mise en pratique*
    - Note: CODATA 2018: \( u(m_e) = 3.0 \times 10^{-10} \), \( u(c R_\infty) = 1.9 \times 10^{-12} \)
    - While: \( u(H(1S-2S)) = 4.5 \times 10^{-15} \) (proton size)

- **Fix the value of \( G \) which fixes Planck’s mass**
  \[ m_P = \sqrt{\frac{\hbar c}{G}} \]
After a new definition

- **Cs will be a secondary representation of the second**
  - with first the same frequency as before: 9 192 631 770 Hz
  - If Cs standard improve and new measurements are made, a new recommended values be defined which will deviate from 9 192 631 770 Hz

- **Processes for the elaboration of TAI will remain the same**
  - Cs (and other SRS) can and will continue to calibrate TAI (probably for quite some time)
  - More and more optical frequency standards are accepted to contribute to TAI, gradually leading to improvement of the timescale

- **Deeper impact of optical frequency standards on timekeeping**
  - With improved remote time and frequency comparisons
  - With improved (optical) local oscillators

- **Impact of the redefinition on other units**
  - Insignificant because of the gap in uncertainties