CCTF

Task Force on the Roadmap for the redefinition of the second

Subgroup B: Status of the new definition possibilities

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CONSULTATIVE COMMITTEE
FOR TIME AND FREQUENCY

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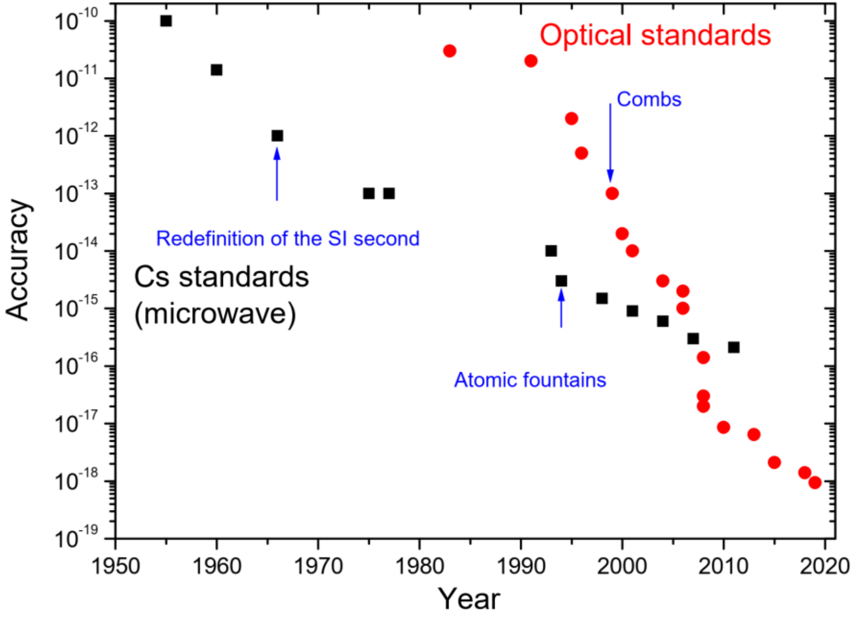
Outline

- Status and capabilities of optical frequency standards
- Secondary representations of the second and their use
- Options for a redefinition of the second
- Considering some impacts of a redefinition
- Indicators for comparing options

- Questions to CCTF members and liaisons

Status and capabilities of optical frequency standards

– Progress of optical frequency standards
  - See for instance:
    - Rev. Mod. Phys. 87, 637 (2015)
    - C.R. Physique 20, 153 (2019)



- Optical frequency standards surpass Cs standards
  - By more than 2 orders of magnitudes
- Significant improvements yet to come
  - Ultra-stable lasers, quantum metrology, better traps / environments, novel atomic transitions

Status and capabilities of optical frequency standards

- **Different levels of achievements and verifications of uncertainties**
  - Physical effects identified, understood, controlled individually
  - Given setup operating with all systematics shifts controlled at the same time
  - Comparisons of 2 or more standards based on the same transition
    - ν_A/ν'_A ratio should be 1 within stated uncertainties
    - At the same institute, between different institutes
  - Measurements of optical frequency ratios
    - Ratios of atomic frequencies are dimensionless quantities given by nature
    - Independent measurements of ν_A/ν_B made in different places can be compared
    - NB: these measurements involve and therefore test optical frequency combs
    - A particular case corresponds to absolute frequency measurements
      - i.e. ratio to the Cs hyperfine transition
      - Limited by the accuracy of Cs standards
  - Closure based on multiple frequency ratios
    - Closure with stated uncertainties can be verified

$$\frac{\nu_A}{\nu_B} \times \frac{\nu_B}{\nu_C} \times \frac{\nu_C}{\nu_A} = 1 + \Delta$$

$$\Delta = 0\ ?$$

Increasing level of verification / difficulty / maturity

Status and capabilities of optical frequency standards

based on peer-reviewed publications to date (28/10/2020)

- **Accuracy**
  - Best accuracies to date
    - 27Al+: 9.4E-19, 171Yb: 1.4E-18, 87Sr: 2E-18, 171Yb+(E3): 2.3E-18, etc.
  - Systematic shifts subject of recent studies and progress
    - Blackbody radiation, lattice light shift, background gas collisions, micro-motion, residual first-order Doppler, etc.
- **Comparisons of identical optical frequency standards**
  - Best reported uncertainties
    - 171Yb: 9.4E-19, 87Sr: 3.4E-18, 171Yb+(E3): 4.2E-18, etc.
  - Long-distance, international
    - 87Sr: 5E-17 via fibre link (1440 km)
    - 87Sr: 1.8E-16, 171Yb+(E3): 2E-16 via GNSS PPP, 2.7 – 3.5E-16 via TWSTFT (continental, Europe)
    - Note: TAI provides a permanent mean of global comparisons at the level of 1E-16

Status and capabilities of optical frequency standards

based on peer-reviewed publications to date (28/10/2020)

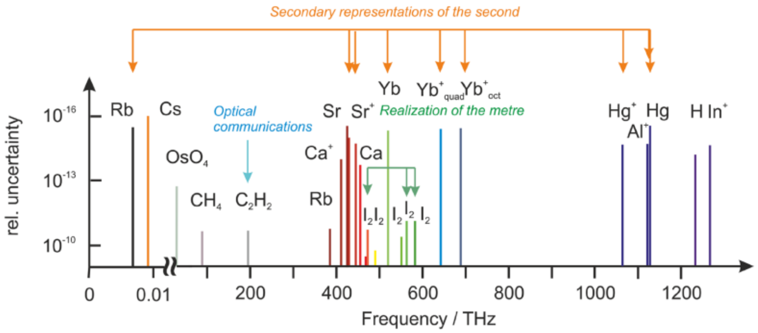
- Measurements of optical frequency ratios
  - Best reported uncertainties to date
    - 88Sr/87Sr: 2.8E-17 (no comb) and 2.3E-17 (same system)
    - 171Yb/87Sr: 4.6E-17, 27Al+/199Hg+: 5.3E-17, etc.
- Absolute frequency measurements
  - Best reported uncertainties to date
    - 87Sr: 1.5E-16, 171Yb: 2.1E-16 (vs TAI), etc.
  - 87Sr >20 measurements, several against TAI
- Work toward transportable, commercial and space clocks
  - Best reported uncertainties (prototype transportable clocks)
    - 87Sr: 5.5E-18, 88Sr: 2.0E-17, 87Sr: 7.4E-17, 40Ca+: 7.8E-17

- *Note: lists of relevant peer-reviewed references will be annexed to the roadmap document*

Secondary representations of the second

– What they are

- CIPM maintains a List of recommended standard frequencies (LoF) recommended for applications including the practical realization of the metre (MeP) and secondary representations of the second (SRS)
- Based on the work of the CCL-CCTF working group on frequency standards
- SRS were adopted by the CCTF 2001 to help assessing standards with the highest level of uncertainties and to prepare for a possible redefinition of the second
- LoF is published on the BIPM website



https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

Riehle et al., Metrologia 55, 188 (2018)

Frequency (Hz)	Fractional uncertainty	Transition
6834682610.9043126	6×10^{-16}	^{87}Rb ground state hfs
429228004229873.0	4×10^{-16}	^{87}Sr neutral atom, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$
444779044095486.5	1.5×10^{-15}	$^{88}Sr^+$ ion, $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$
518295836590863.6	5×10^{-16}	^{171}Yb neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$
642121496772645.0	6×10^{-16}	$^{171}Yb^+$ ion, $^2S_{1/2}$–$^2F_{7/2}$
688358979309308.3	6×10^{-16}	$^{171}Yb^+$ ion, $6s\ ^2S_{1/2}$–$5d\ ^2D_{3/2}$
1064721609899145.3	1.9×10^{-15}	$^{199}Hg^+$ ion, $5d^{10}6s\ ^2S_{1/2}$–$5d^9 6s^2\ ^2D_{5/2}$
1121015393207857.3	1.9×10^{-15}	$^{27}Al^+$ ion, $3s^2\ ^1S_0$–$3s3p\ ^3P_0$
1128575290808154.4	5×10^{-16}	^{199}Hg neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$

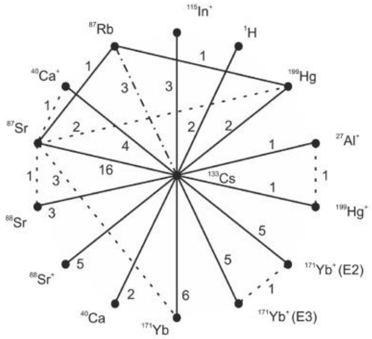
Secondary representations of the second

— A mean of assessing frequency standards

- Recommended frequencies and uncertainties established by:
  - A global least-square adjustment of a set of independent measurements of frequency ratios from peer-reviewed publications.
  - Current LoF a based on an over-determined dataset of about 70 measurements comprising 6 optical frequency ratios and 53 absolute measurements of optical frequencies.
  - Check of consistency of measurements of same quantity (e.g. many 87Sr/133Cs consistent to 3E-16, 2 199Hg/87Sr and 171Yb/87Sr consistent to <2E-16).
  - Performance indicators of the adjustment give a global consistency check of the field.

— Measurements since 2017

- >30 new measurements known, about half of them optical frequency ratios
  - >15 to be taken into account (peer-reviewed) to update the LoF.
- No new transition. >3 new optical ratios to be taken to update the LoF.
- Should bring consistency check to the mid-1E-17 or better.
- Will be reported to the 22nd CCTF in March 2021.

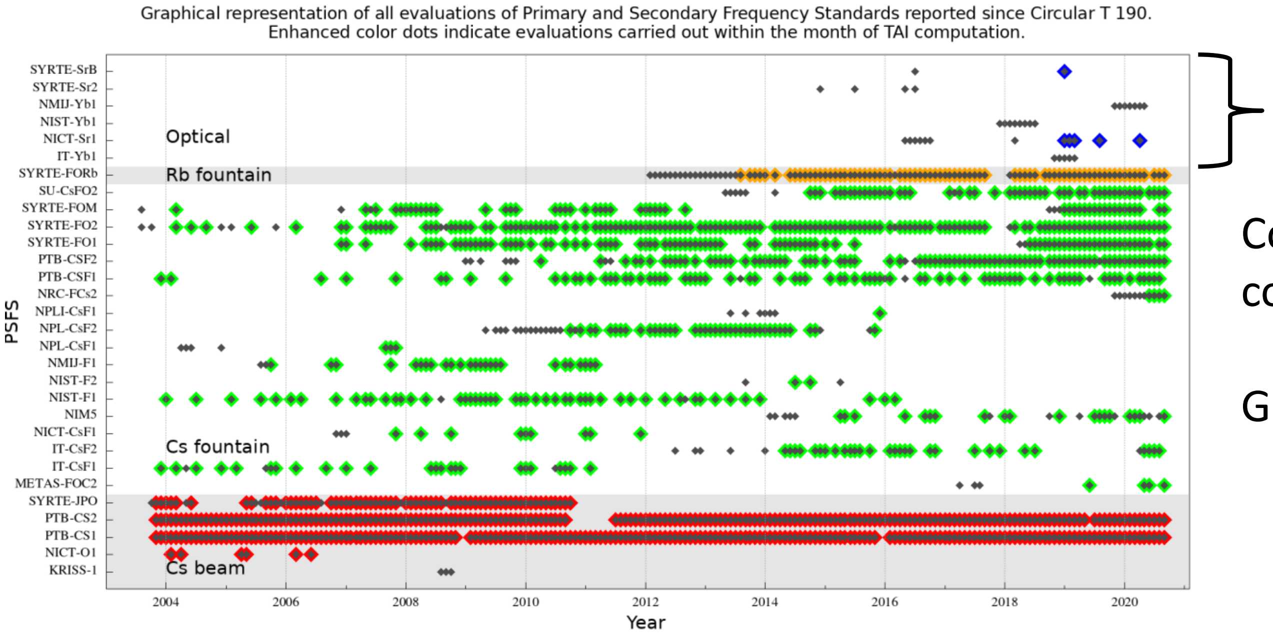


Metrologia 52, 628 (2015)
Metrologia 53, 1272 (2016)
Metrologia 55, 188 (2018)

Secondary representations of the second

– Use of SRS to calibrate TAI

- Optical frequency standards are compatible with existing architectures (thanks to combs)
- Calibrations of TAI
  - – Scarcity of contributions from optical frequency standards



Color dots: on time, actual contribution to TAI computation

Grey dots: ex post, comparison

Options for a redefinition of the second

– Single atomic transition

- Definition: fix the frequency of a single (optical) atomic transition

$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$

$$\Downarrow$$

$$\boxed{\Delta\nu_{\mathrm{Xy}} = 567\ 890\ 123\ 456\ 789.01\ \mathrm{Hz}}$$

- Realization: with frequency standards based on Xy
- Continue to maintain and update a list of SRS
- Significant role of SRS in practical realizations and dissemination, in particular in TAI
- To be redefined if major progress occurs in the uncertainty of frequency standards based on other transition(s)

Options for a redefinition of the second

- Several transitions on an even basis
  - Definition: geometric mean of an ensemble *C* of chosen transitions
    - weight inversely proportional to the squared uncertainty of best standard using transition i

$$\nu = \frac{1}{N} \prod_{i \in \mathcal{C}} \nu_i^{w_i}$$

See J. Lodewyck, Metrologia 56, 055009 (2019)

  - Realization: with frequency standards based on transitions part of *C* (*representations of the second*) using frequency ratio matrix updated by the CIPM
    - A single frequency standard i part of *C* realizes the unit
    - 133Cs can (should) be part of *C*
  - Updating the LoF will continue
    - Including transitions in ensemble *C* and transitions not part of ***C***
  - Can follow the progress of frequency standards
    - by updating the ensemble and the weights

Options for a redefinition of the second

- **Fixing the value of another fundamental constant**
  - Definition: fix the value of one more fundamental constant

$$\Delta\nu_{\mathrm{Cs}}, c, h, e, k$$
$$\Downarrow$$
$$\boxed{X, c, h, e, k}$$

  - Directly connected to the underlying fundamental framework: general relativity and the standard model of particle physics
    - see e.g. C. Bordé, C. R. Physique 20, 22 (2019)
    - Planck's natural system of units: $G, c, h, \varepsilon_0, k$, 5D optics formalism: m_e, c, h, e, k
  - *Mise en pratique* would be based on atomic transition(s) (one of 2 previously discussed options)
  - Realization: experiment(s) currently leading to the determination of constants
    - See CODATA 2018
    - Problem: poor accuracy of the practical realization

Constant	Frac. Unc.
G	2.2×10^{-5}
m_e	3.0×10^{-10}
R_∞	1.9×10^{-12}
$\mathrm{H(1S - 2S)}$	4.5×10^{-15}

    - Either of these uncertainties would apply to the realization of the entire system of units

Considering some impacts of a redefinition

- What will happen at and after redefinition
  - 133Cs will become a SRS. Initially, recommended value will be 9192631770 Hz with an uncertainty of 1 to 4E-16. May evolve (improve) if Cs standards continue to progress as well as their measurement in SI unit.
  - Commercial Cs standards will continue realizing the SI second, virtually with an unchanged uncertainty.
  - Cs fountains will continue realizing the SI second with a slightly degraded uncertainty, because the uncertainty of the Cs recommended value will have to be added.
  - Cs (and other SRS) can and will continue to calibrate TAI (probably for quite some time). TAI continues to disseminate the SI second to few 1E-16 or better
  - More and more optical frequency standards (are accepted to) contribute to TAI, gradually leading to improvement of the timescale
- Impact on SI system, on other (base) units
  - Technically: none because of the gap in uncertainties.
- Impact on CODATA
  - With special attention to the atomic physics sector
- Impact astrophysics and fundamental physics

Comparing options

- Some possible criteria for comparative analysis
  - Achieved and verified accuracy
    - Based on existing measurements, taking into account confidence (number, uncertainty) established by (same species) comparisons. Ease to repeat such measurements.
    - Potentially complemented with achieved short term stability.
  - Continuity with Cs
    - Uncertainty, number, consistency of independent measurements against Cs, number of institutes having done independent measurements at the highest level.
  - Level of dissemination
    - Based on number of existing standards / number of institutes hosting such standards.
  - Connectivity within the optical domain
    - Number and quality of measurements against other existing optical frequency standards. Ease to repeat such measurements. Number of institutes hosting standards connected by these measurements.
  - Potential for industrial and space standards
  - (Durability of definition)
  - (Understandability by a broad audience)
  - (above list not complete, not limitative)

Questions for CCTF members and liaisons

- What is your opinion on motives presented by CCTF delegates and experts for a redefinition of the second? Do you agree with them? Which different advantages are you aware of?
- Where do you see possible problems and challenges for a redefinition of the second? In general? At your NMI/organization specifically? In your country specifically?
- Are you developing optical frequency standards with the aim of becoming primary standards and/or contributing to time scales? Which ones? Based on which criteria was the selection of the type of standard made?
- Do you plan to operate optical frequency standards for the calibration of TAI? Which standards? When do you expect to report them?
- Are you working on other frequency standards (other than in the previous question). For which purpose: metrology, fundamental research, geodesy, etc.? Please specify.
- If a redefinition of the second based on optical transition(s) is adopted, will it trigger new developments of optical frequency standards or other developments? At your NMI? In your country? For which purposes?
- It is absolutely necessary that a sufficient number of high-quality frequency standards are operated regularly and report calibrations of TAI based on them, before and after a redefinition. Can your institute confirm to continue developing, maintaining and regularly operating its clock ensemble, including Cs fountain clocks?
- What is your opinion on the 3 options for the redefinition as presented to CCTF delegates and experts? What atomic species do you think are the best for the optical frequency standard(s) used in a new definition of the second? For which reason(s)?