Frequency standards
Work in the Consultative Committee for Time and Frequency

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Frequency standards: primary and secondary (PSFS)

1. Primary standards realize the SI second (^{133}Cs)

   About 10 Cs fountains in operation

2. Secondary standards realize a Secondary Realization of the Second : a list of transitions adopted as SRS or that could become SRS in due time.

   For some of these transitions, the uncertainty on the estimation of systematic shifts is much lower than for Cs.

Atom / ion	Clock type	Clock ν THz	Clock λ nm	Lowest published clock systematic uncertainty	Uncertainty of CIPM ν value
^{87}Sr	Lattice	429	698	2.1×10^{-18} [6]	5×10^{-16}
$^{171}Yb^{+}$	Ion octopole	642	467	3.2×10^{-18} [8]	6×10^{-16}
$^{27}Al^{+}$	Ion, quantum logic	1121	267	8.6×10^{-18} [9]	1.9×10^{-15}
$^{88}Sr^{+}$	Ion quadrupole	445	674	1.2×10^{-17} [10]	1.6×10^{-15}
$^{199}Hg^{+}$	Ion quadrupole	1065	282	1.9×10^{-17} [11]	1.9×10^{-15}
$^{40}Ca^{+}$	Ion quadrupole	411	729	3.4×10^{-17} [12]	1.2×10^{-14}
^{199}Hg	Lattice	1129	266	7.2×10^{-17} [13]	6×10^{-16}
$^{171}Yb^{+}$	Ion quadrupole	688	436	1.1×10^{-16} [14]	6×10^{-16}
^{171}Yb	Lattice	518	578	3.4×10^{-16} [15]	2×10^{-15}
^{1}H	Cryogenic beam	1233	243	4.2×10^{-15} [16]*	9×10^{-15}

Frequency standards in the CCTF

1. WG on Frequency Standards: A WG of the Consultative Committe for Time and Frequency (joint with the CC for Length)

   examines all transitions and their realizations

   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 most recent PSFS, 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

CCL-CCTF WG on FS

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.

- Typically revises the list of transitions and recommended values for each session of the CCTF (every 2-3 years)

CCTF WG on Primary and Secondary Frequency Standards

Mission (Terms of Reference)
a) to develop and propose standards for the documentation of frequency biases and uncertainties, operational details, and frequency transfer uncertainties for primary and secondary frequency standards (PFS and SFS). Develop and propose standards for the reporting of the results of a PFS/SFS evaluation to the BIPM,
b) to provide a forum to evaluate and discuss the consistency among primary and secondary frequency standards,
c) to provide a forum to discuss and assess the overall knowledge of the accuracy of the SI second for use in establishing the frequencies of secondary standards (microwave and optical) and possibly an eventual redefinition of the second,
d) to interact with the BIPM on issues related to PFS and SRS contributions to the accuracy of TAI, particularly in the process of integration of the first reports of a standard,
e) to encourage and facilitate direct comparisons between primary and secondary frequency standards,
f) to encourage and support laboratories with new standards under construction.

- Typically examines a few new (or rebuilt) devices each year, at the request of the BIPM.

CCTF WG on Advanced Time and Frequency Transfer techniques

Mission (Terms of Reference)
a) to review the status and projected evolution of the characteristics of frequency standards, time scales and time and frequency transfer techniques,
b) to follow and assess the evolution of microwave links in current use, based on GNSS signals and TWSTFT,
c) to follow and assess other technical possibilities, including optical fibre links, optical satellite links, and transportable optical frequency standards, which could be used for comparison of high performance frequency standards,
d) to establish the relevant connections and facilitate consultations with other relevant bodies, such as IGS, IUGG, IVS, ITU, etc.
e) together with the BIPM, to foster the spread of information on technical achievements by suitable means, e.g. workshops, and multiple techniques (such as GNSS, TWSTFT, ACES microwave link, T2L2, optical fibre links).

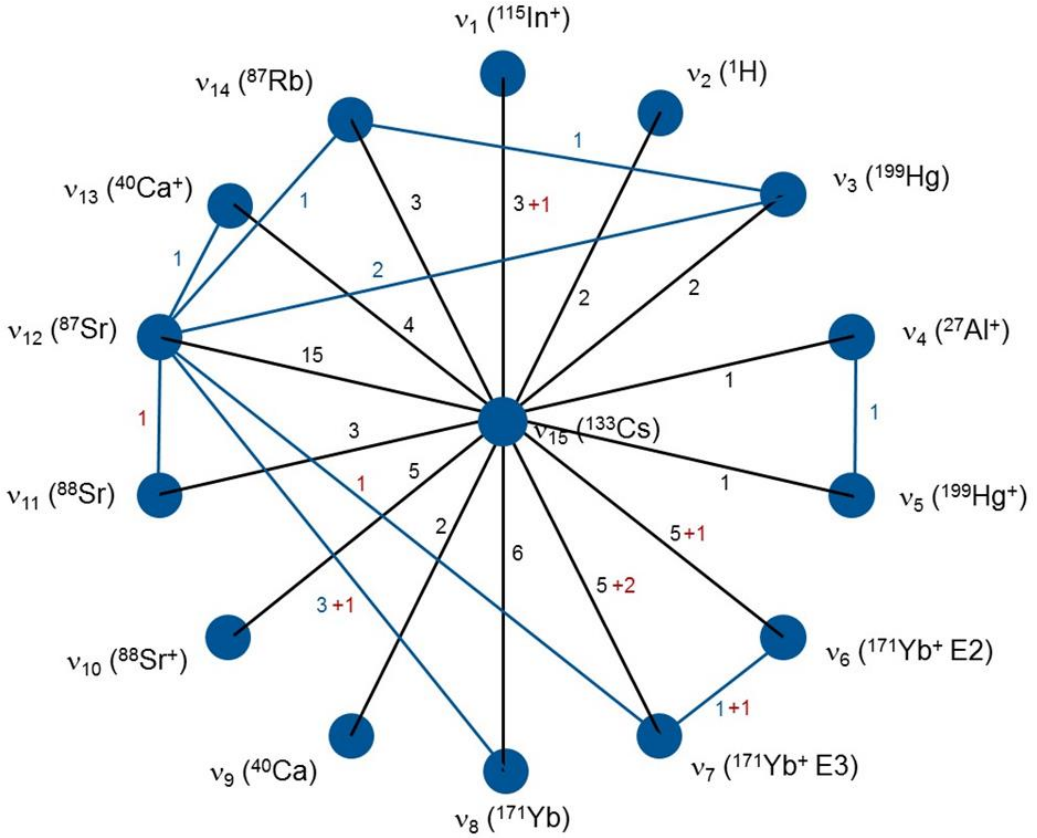
- A forum to discuss new techniques and foster cooperation

CCL-CCTF WG on FS: 2017 work

- Absolute frequency measurements are limited by uncertainty in Cs realization (low 10^{-16})

- Frequency ratios may be measured with much smaller uncertainty e.g.
  - ν (^{27}Al$^+$) / ν (^{199}Hg$^+$) 5.5x10^{-17} (Rosenband et al. 2008)
  - ν (^{171}Yb) / ν (^{87}Sr) 5.5x10^{-17} (Nemitz et al. 2016)
  - ν (^{88}Sr) / ν (^{87}Sr) 2.3x10^{-17} (Takano et al. 2017)
  - A few more in preparation

Number of measurements of absolute frequency and of frequency ratios (Margolis, 2017)
Numbers in red refer to measurements known but yet unpublished (not used)



CCL-CCTF WG on FS: 2017 work

- Redundant measurements of absolute frequencies and of frequency ratios drove the development of new tools
  - Margolis H S and Gill P, Least-squares analysis of clock frequency comparison data to deduce the optimized frequency and frequency ratio values, Metrologia 52 (2015) 628–34.
  - 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
- Present situation
  - 14 frequencies to determine
  - 59 absolute measurements
  - 11 ratios
- Results presented to the CCTF in June 2017

A roadmap for the redefinition of the second (Riehle 2016)
The milestones….

1. … at least three different optical clocks (either in different laboratories, or of different species) 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 of milestone 1 **were compared in different institutes (e.g. $\Delta\nu/\nu < 5 \times 10^{-18}$) either by transportable clocks, advanced links,** or frequency ratio closures.
3. … there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, where the measurements are 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; each ratio measured at least twice by independent laboratories and agreement was found (with e.g. $\Delta\nu/\nu < 5\text{x}10^{-18}$).

Conclusions

- WG on Frequency Standards examines 14 different transitions (13 optical)
- 8 transitions (7 optical) already adopted as secondary representations of the second, with (probably) more to come.

- CCTF is defining a roadmap for the redefinition of the second
- What happens for the redefinition of the second will be a Pilot phase for relativistic geodesy