2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

The SI second: present realization and path to a redefinition

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On 13 October 1967, the 13th General Conference on Weights and Measures (CGPM) adopted a new definition of the unit of time, the second, based on an atomic transition in its Resolution 1 reading "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom". Progresses of laboratory devices realizing the SI second, i.e. primary frequency standards (PFS), have been continuous since that time. The first generation of thermal atomic beam devices progressed by about two orders of magnitude until reaching the accuracy level of $1x10^{-14}$ around year 2000, and some of these standards are still operating today. This improvement prompted a clarification to the 1967 definition as stated at the meeting of the Consultative Committee for Time and Frequency (CCTF) in 1999. The second generation of devices, the Cs fountains, started at the end of the 1990s with accuracy in the 10^{-15} range and has now reached accuracy of $1\text{-}2x10^{-16}$ in the best cases.

Less well known is Resolution 2 of the 13th CGPM (1967), which considered that there were good perspectives for realizing other frequency standards of better quality than the caesium to define the second, and invited organizations and laboratories to pursue studies in this direction. Organizations and laboratories have just done this and these efforts have resulted in large progresses in accuracy over fifty years. New standards have been developed using transitions in the optical frequency domain, some of which have already been recommended by the International Committee for weights and Measures as secondary representations of the second (SRS) [1]. The best optical standards today are about 2 orders of magnitude better than the best Cs standards.

Primary frequency standards provide accuracy to the timescales generated by the BIPM: International Atomic Time (TAI) which is basis of the world's time reference UTC, and the post-processed timescale TT(BIPM). In addition to PFS, secondary frequency standards which realize one of the transitions that are listed as secondary representations of the second have recently been contributing to the accuracy estimation of TAI and to the generation of TT(BIPM). The presentation will review the frequency standards currently provided to the BIPM, and the resulting accuracy of TAI and of TT(BIPM).

Progresses in optical clocks and in the methods to compare them at a distance led the CCTF to start considering a redefinition of the second in terms of an optical transition. Several conditions must be met, as emphasized by the working group on frequency standards, see e.g. [1]. These conditions can be summarized as: At least three transitions have uncertainties two orders of magnitude better than Cs and have been measured independently with respect to Cs; For the same transition, several optical clocks have been compared in different laboratories; Optical frequency rations between transitions have been independently measured and found to be in agreement; And optical clocks regularly contribute to TAI. The working group on strategic planning of the CCTF has prepared a roadmap for the redefinition based on these conditions, and tentatively indicates that the new definition could be established as early as 2026.

In this aim, a crucial need is the ability to compare new optical clocks at a distance with a frequency transfer uncertainty consistent with the clocks' accuracy. Fiber links easily achieve this over distance up to ~1000 km and potentially on any continental link. Satellite-based techniques which have worldwide extension have recently reached the 10^{-17} accuracy range when averaging a few days [2,3], but new technical developments may be needed to reach the 10^{-18} range. It is also necessary to compute the relativistic frequency shift of the clocks to the same 10^{-18} level worldwide, which may be difficult in a few places. Such challenges in comparing standards should not prevent changing the definition.

1. F. Riehle, P. Gill, F. Arias, L. Robertsson, The CIPM list of recommended frequency standard values: guidelines and procedures, Metrologia, accepted, 2018.
2. G. Petit et al., Sub 10^{-16} frequency transfer with IPPP: Recent results, Proc. Joint EFTF/IFCS, 784-787, 2017.
3. M. Fujieda et al., Advanced satellite-based frequency transfer at the 10^{-16} level, IEEE Trans. UFFC, accepted.