On Secondary Representations of the Second

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Abstract

The most advanced optical frequency standards have surpassed the performance of the best primary caesium atomic clocks as the primary realization of the definition of the second in the International System of Units (SI) with respect to their accuracy and stability. As a consequence the International Committee of Weights and Measures (CIPM) has now recommended as secondary representations one microwave radiation in ^{87}Rb and four optical radiations in $^{199}Hg^{+}$, $^{88}Sr^{+}$ and $^{171}Yb^{+}$ and neutral ^{87}Sr atoms. This paper describes the rationale, evolution and development of criteria for acceptance of a radiation as a secondary representation of the second.

1. Introduction

In 1967 the Conference Generale des Poids et Mesures (CGPM) adopted as a new definition of the SI unit of time, the second, the transition between hyperfine levels in the ground state of caesium. This definition has proved to be a very efficient and lasting one in that aspect that on one hand it led to an increase in accuracy of the primary clocks by about one decade per decade (see Fig. 1) with the best Cs fountain clocks [1] showing a fractional uncertainty of a few parts in 10^{16}. On the other hand it resulted in the development of commercial caesium beam clocks for a wide variety of time and frequency applications such as satellite navigation.

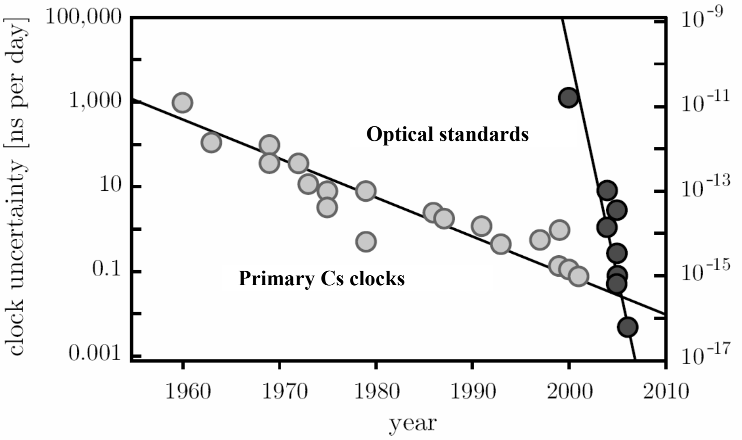

Figure 1: Evolution of the uncertainty of primary caesium clocks and optical frequency standards

It is long known that optical frequency standards [2, 3] have advantages in comparison with the microwave standards since the optical frequency is about five orders of magnitude higher as compared to the frequency of the caesium atomic clock. Given the same linewidth of a quantum transition the line quality factor Q scales with the frequency and hence is increased by this factor. In the same way any perturbing effect that leads to a constant frequency shift scales with the frequency and its fractional influence is reduced. The high frequency also has a prominent effect on the achievable stability as this property in general also scales with Q. A particular boost for optical frequency standards and optical clocks came from the invention of the optical frequency comb generator [4]. This breakthrough dramatically simplified the construction and utilization of optical clockworks and was the prerequisite for the dramatic progress of optical clocks (see Fig. 1).

2. Optical clocks

The currently most important optical clocks group themselves into two classes where the quantum absorber either consists of a single ion trapped in a radio frequency trap or of a large number of neutral atoms trapped in an optical trap which is tuned to a wavelength where the interaction of the atoms with the trapping radiation is such that the clock transition is not shifted by that interaction. To benefit from the long interaction times possible in such traps the clock transition is usually a forbidden transition which has a natural linewidth of a few hertz or below.

2.1 Single Ion Standards

The most advanced single ion frequency standards with the lowest uncertainties are the $^2S_{1/2}$ F=0 - $^2D_{5/2}$ F=2 quadrupole transition in $^{199}Hg^+$ at 282 nm [5], the $^2S_{1/2}$ - $^2D_{5/2}$ quadrupole transition in $^{88}Sr^+$ at 674 nm [6] and the $^2S_{1/2}$ F=0 - $^2D_{3/2}$ F=2 quadrupole transition in $^{171}Yb^+$ at 436 nm [7] (see Fig. 2), and more recently the $^{27}Al^+$ at 267 nm [8] .

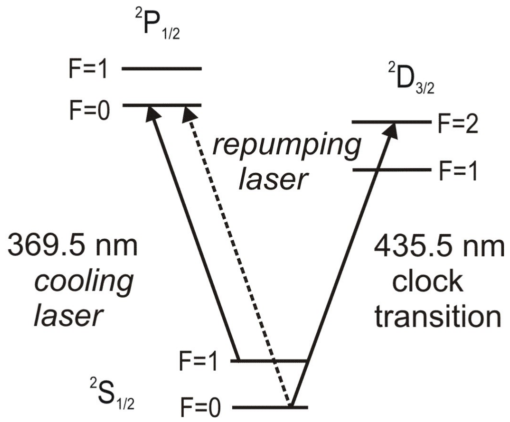

Figure 2: Excerpt from the energy level scheme of the ^{171}Yb 435.5 nm quadrupole clock. The transition at 369.5 nm is used for cooling the ion and the quadrupole transition at 435.5 nm is the clock transition**.**

The properties of the respective species, the used techniques and the results are published in the above references. Here it suffices to say that all similarly to the energy level scheme of the $^{171}Yb^+$ have a transition which is used for cooling the ion and an (almost) forbidden optical clock transition**.**

2.2 Neutral Atom Standards

One of the most promising neutral atom standards is the optical lattice clock of ^{87}Sr at 698 nm [9], Fig. 3.

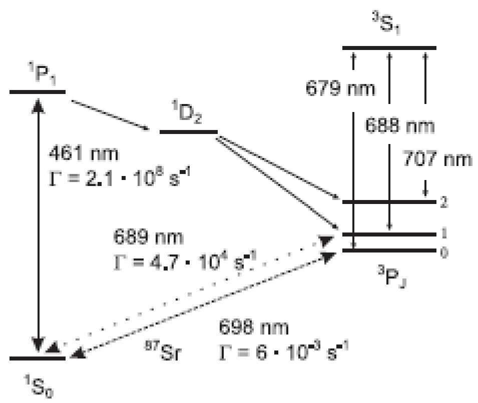

Figure 3: Excerpt from the energy level scheme of ^{87}Sr. The transitions at 461 nm and 689 nm are used for cooling the atoms. The dashed line (698 nm) is the clock transition.

Atoms are cooled on the 461 nm line to a few millikelvin and later on the intercombination transition at 689 nm to a few microkelvin before being transferred into an optical dipole trap whose wavelength is chosen such that the ac Stark shifts are the same for the $^1S_0$ ground state and the $^3P_0$ excited state. Different groups in Japan, the USA and in Europe are currently exploring the uncertainty of this clock.

3. Secondary Representations of the Second

The progress with optical frequency standards time motivated the organs of the Meter Convention in 2001 to consider the establishment of secondary representations of the second [10], where such representations, whether optical or microwave, could be used to realise the second. In general, only such candidates were evaluated whose frequency uncertainty was not worse than a factor of ten than the uncertainty of the best caesium standards of that time. It was considered that the establishment of these representations would help with the detailed evaluation of reproducibility at the highest level, and significantly aid the process of comparing different standards in the preparation of a future redefinition of the second. As a result of this process CIPM recommended in autumn 2006 four optical frequency standards (see tab. 1) that can be used as "secondary representations of the second".

Table 1: Secondary representations of the second as recommended by the CIPM 2006

Frequency / Hz	Uncertainty	Atomic species
6 834 682 610.904 324	3×10^{-15}	^{87}Rb
429 228 004 229 877	1.5×10^{-14}	^{87}Sr
444 779 044 095 484	7×10^{-15}	$^{88}Sr^+$
688 358 979 309 308	9×10^{-15}	$^{171}Yb^+$
1 064 721 609 899 145	3×10^{-15}	$^{199}Hg^+$

The phrase "secondary representations" takes into account that the frequency of such an optical frequency standard can never surpass the accuracy of the primary standard of time and frequency, the Cs clock. However, these secondary representations might be very important also for time keeping because of their outstanding stability. These values are currently included into a new list of "Recommended frequency standard values for applications including the practical realisation of the metre and secondary representations of the second" that will be published in Metrologia and on the internet and updated on a regular basis.

4. Acknowledgments

The author would like to acknowledge the significant contributions of all the members of the Joint Working groupof the Consultative Committee for Length and the Consultative Committee for Time and Frequency in the consideration of the requirements of a secondary representation list and the development of strategies to achieve this.

5. References

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