Optical clocks and fiber links

J. Lodewyck
LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 61 avenue de l'Observatoire 75014 Paris, France

Optical clocks are now the most stable and accurate frequency standards, with performances in the low 10^{-18}, outperforming by two orders of magnitude the best microwave primary standards based on cesium. This opens the question of a possible redefinition of the SI (Système International) second with an optical transition. However, several operational steps have to be demonstrated before such a redefinition can be effective: reliable and interconnected clocks are necessary to realize the definition. Here, we report on several experimental advents in this direction, including the remote comparison of optical lattice clocks via phase compensated optical fiber links between different metrology institutes across Europe.

1 Introduction

The primary microwave cesium clock, the cold atom fountain being its most accurate implementation, are currently realizing the SI and are used to build international timescales such as TAI (Temps Atomique International) and its derivative UTC (Universal Time Coordinated). The widespread usage of fountain clocks for these application relies on four pillars. First, the availability in several metrology institutes of highly reliable atomic fountains makes possible a continuous operation. Second, these remote clocks are interconnected by satellite-based microwave links, in oder to compare them. Third, repeated measurement of frequency ratios between cesium clocks and between cesium and rubidium clocks have confirmed their accuracy budget, evaluated at a few parts in 10^{16}. Finally, regular calibrations of TAI reported to the Bureau International des Poids et Mesures (BIPM) make them key players in building accurate time scales [1].

More recently, optical clocks, whose frequency is referenced to a narrow optical atomic transition in ions or neutral atoms instead of a microwave hyperfine transition, have progressed fast down to a control of systematic effect of a few parts in 10^{18} [2,3,4]. The frequency stability of optical clocks using neutral atoms confined in an optical lattice have reach a few 10^{-16} for an integration time of 1 s, effectively reaching a the statistical resolution of a few 10^{-18} in a mere hour of measurement [5,6,2]. The performances of optical clocks thus outperform the performances of microwave primary standards by two orders of magnitude, opening the way to a redefinition of the SI second using an optical transition.

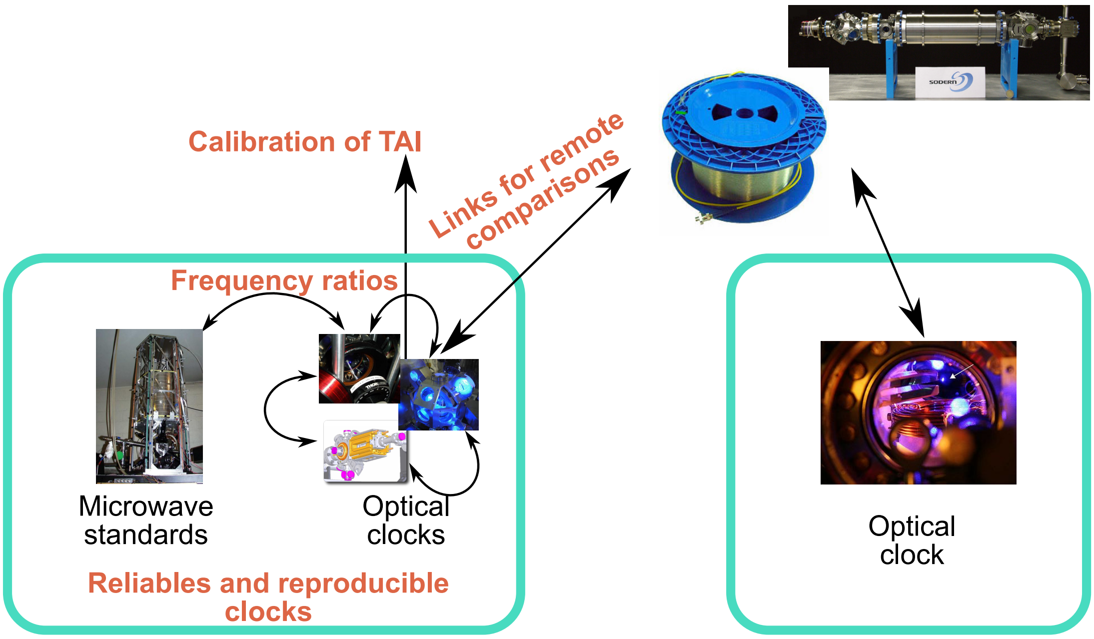


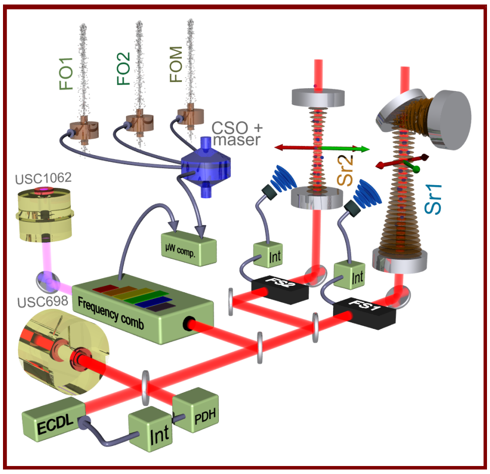
Figure 1 – Optical clock architecture proposed in this paper. It includes all four components (text in red) that integrate optical clocks into a network of clocks whose implementation is necessary to envision a SI second based on an optical transition.

However, before optical clocks can replace the operational microwave clocks, a full network of optical clocks implementing the four pillars listed above has to be realized, as depicted in figure 1. In this paper, we report on several experimental advents that, together, are a first demonstration that optical clocks are in the process of fully reproducing the current clock architecture based on microwave clocks. First, the experimental demonstration of reliable optical lattice clocks, able to operate almost continuously over extended periods of several weeks, shows that optical clocks are now suitable for applications such as calibrating timescales. Second, reproducible measurements of frequency ratios between optical and optical clocks confirm the excellent control of systematic effects advertised for these clocks, while frequency ratio measurements between optical and microwave clocks bridge the two frequency domains. Third, linking optical clocks together enable the comparison of completely independent remote clocks located at different metrology institutes. To fully benefit from the statistical resolution of optical clocks, these comparisons are now conducted by fiber links, as the satellite comparisons methods feature a limited frequency stability. Finally, we report on the first contribution to TAI with an optical frequency standard, complementing the regular contributions of cesium and rubidium microwave standards.

2 Optical clocks

Optical clocks take advantage of the high quality factor offered by narrow electronic transitions in the optical spectrum, probed by a pre-stabilized narrow linewidth laser. Optical lattice clocks are therefore composed of two elements: a laser locked on an ultra-stable Fabry Perot resonator with relative length fluctuations on the order of 10^{-16}, and a set of ultra-cold atoms confined in an optical lattice for a Doppler-free spectroscopy. LNE-SYRTE has built a set of two optical lattice clocks with strontium atoms with frequency instability of 10^{-15} at 1 s and an accuracy of 4.1×10^{-17}. They are connected, via a frequency comb to an optical lattice clock with mercury atoms, an ultra-stable laser injected in fiber links (section 4), and a set of three microwave standards (figure 2).

The strontium optical clocks have been demonstrated to be operable over several weeks with minimal human intervention, and a time coverage ranging from 67% to 92%. This shows that optical lattice clocks are suitable for calibrating time scale for which long term operation is necessary. It also makes possible to measurement of optical-to-microwave frequency ratio, which, because of the limited frequency stability of microwave standards, require long integration times [7].



Effect	Correction	Uncertainty
Black-body radiation shift	5208	20
Quadratic Zeeman shift	1317	12
Lattice light-shift	−30	20
Lattice spectrum	0	1
Density shift	0	8
Line Pulling	0	20
Probe light-shift	0.4	0.4
AOM phase chirp	−8	8
Servo error	0	3
Static charges	0	1.5
Black-body radiation oven	0	10
Background collisions	0	8
Total	6487.4	41

Figure 2 – Left: clock architecture at LNE-SYRTE, showing two Sr clocks, ultra-stable cavities, and the frequency comb linking these clocks to the Cs and Rb atomic fountains. Right: accuracy budget of the two strontium clocks. It is dominated by the uncertainty on the black-body radiation shift arising from temperature inhomogeneities in the vacuum environment of the atoms.

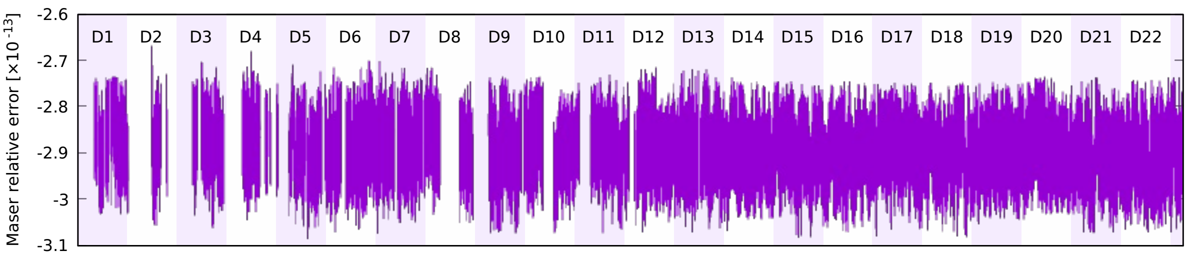


Figure 3 – 3 week operation of the two Sr optical lattice clocks at LNE-SYRTE. This graph shows the relative frequency error of SYRTE's master maser with respect to the strontium clock transition. These data are directly used to calibrate international timescales. the second half of the experiments, the Sr clock was operated unattended without failure.

3 Optical to optical and optical to microwave frequency ratios

Comparing two clocks using the same atomic species enables to confirm the accuracy budget of the clocks. We have conducted comparisons between our two strontium clocks (Sr2 and SrB) over extended periods, and found an agreement compatible with the total uncertainty:

$$\frac{\nu_{\mathrm{Sr}_2} - \nu_{\mathrm{Sr}_B}}{\nu_{\mathrm{Sr}}} = (2.3 \pm 7.1) \times 10^{-17}. \quad (1)$$

This result improves on the first comparison between two optical lattice clocks with an uncertainty beyond the best realization of the SI second [8], conducted at SYRTE.

High resolution interspecies optical-to-optical comparisons enable many applications of optical clocks, such as test of fundamental physics, by verifying that the measured frequency ratio stays constant over time. Indeed, many theories beyond the standard model predict that the constants of nature may vary with time, hence frequency ratios between clocks, whose frequency depends on these constants. At LNE-SYRTE, we measured the frequency ratio between strontium and mercury lattice clocks with a total uncertainty of 1.7×10^{16} [9]. This ratio is in agreement with a completely independent measurement at RIKEN, Japan [10]. This quantity is thus one of the best frequency ratio measurement reproduced in different laboratories. It confirms that optical clocks can be reproduced with uncertainties better than the best realization of the SI second.

Frequency ratios between optical and microwave clocks, although they do not reach an uncertainty as low as optical to optical comparisons, bring several advantages. First, measuring the stability of these ratios tests different physical theories, owing to the different nature of the atomic transitions involved (the frequency of optical clocks is mainly determined by the electron orbit, while the frequency of microwave hyperfine transitions is mainly determined by the properties of the nucleus). Second, they are able to bridge the microwave domain and the optical domain, which is a necessary condition for a redefinition of the SI second.

At SYRTE, we conducted extensive measurements of the frequency ratio between Sr lattice clocks and Cs and Rb microwave clocks [7]. This frequency ratio has been extensively measured by different laboratories worldwide, leading to a very good agreement. Figure 4 shows the recent history of the Sr/Cs measurements.

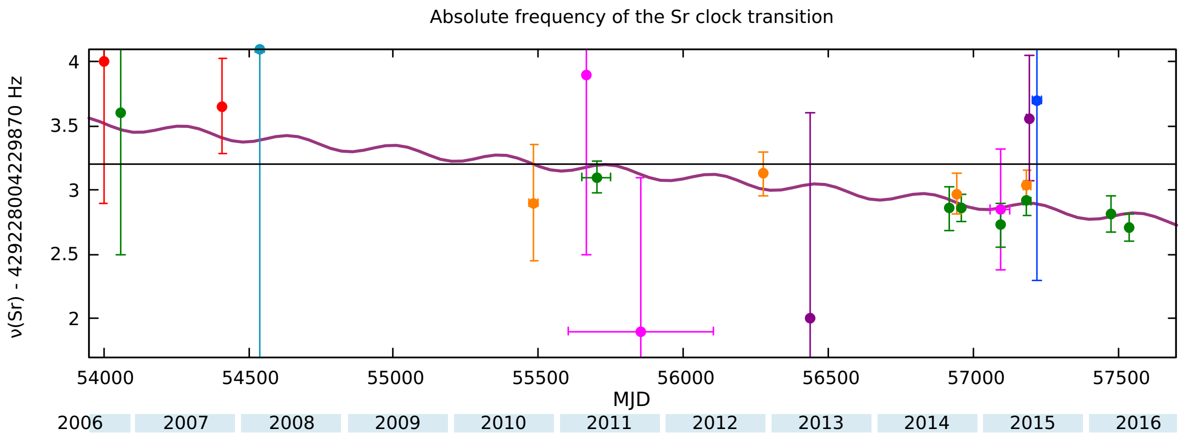


Figure 4 – International agreement of the frequency ratio between Sr optical lattice clocks and the Cs primary standard: green •: LNE-SYRTE, red •: JILA, light blue •: Tokyo University, orange •: PTB, pink •: NICT, purple •: NMIJ, blue •: NIM. The graph also shows a fit of these data points by a linear drift of the fundamental constants, as well as a fit with a possible coupling to the Sun's gravitational potential, with a yearly signature. Although no effect is resolved yet, the Sr/Cs data bring a decisive contribution to constraints on these effects.

4 Comparisons between remote optical clocks with fiber links

Remote clock comparison can provide many more application with respect to local comparisons. First, it extends the possibilities of clock comparisons by making more clock pairs available, also enabling to directly compare completely independent clocks built by different teams. But it also makes new applications possible, one of the most prominent being a mapping of the gravitational potential at long distances by comparing the rates of clocks located at different positions in the gravitational potential of the Earth, via the gravitational redshift. Geodetic models can predict this redshift with an uncertainty of several 10^{-18}, *i.e.* several centimeters on the clocks' positions with respect to a common reference geoid. When laboratories are able to compare remote clocks with uncertainties in the low 10^{-18}, these comparisons will therefore contribute previously unknown information to geophysicists [11].

Satellite comparisons methods are limited to a resolution around 10^{-16}, reached after several weeks of integration. Applications of remote optical clocks comparisons therefore require new comparison methods. For this purpose, optical fiber links are being deployed at continental scale between laboratories, especially in Europe where several of these links are being operated. These links make use of an infrared laser as a transfer laser, sent back and forth in the link in order to measure and actively cancel the phase fluctuations in the fibers, by comparing the phase of the laser sent into the fiber with the phase of the laser coming back from the fiber. Repeater and regeneration stations are necessary to overcome the problem of the large attenuation in the fibers, and to overcome the limitation on the bandwidth of the active compensation of phase fluctuations set by the round-trip delay in the fiber.

A link between LNE-SYRTE and PTB has been used for the first time in 2015 to compare remote strontium optical lattice clocks [12]. The statistical resolution reached a few 10^{-17} after a mere hour of measurements, that is to say one order of magnitude better than satellite methods, and two orders of magnitude faster. This comparison enabled to evaluate the frequency difference to:

$$\frac{\nu_{\mathrm{Sr_{PTB}}} - \nu_{\mathrm{Sr_2}}}{\nu_{\mathrm{Sr}}} = (4.7 \pm 5.0) \times 10^{-17} \qquad (2)$$

To reach this agreement, a correction of the gravitational redshift of $(-247.4 \pm 0.4) \times 10^{-17}$ was applied, independently determined by geodetic models. This comparison was the first all-optical international agreement between two optical clocks. Along with a similar comparison between SYRTE and NPL, this comparison already contributed to a first test of special relativity with optical fiber links [13]

5 Contributing to international time scales with optical clocks

The last component of the clock architecture proposed in this paper is the first contribution of an optical frequency standard to TAI. While cesium clocks routinely contribute to TAI, calibration reports from the rubidium fountain clock at SYRTE has been the only contribution so far with a secondary representation of the SI second. Before the SI second can be redefined, it is however necessary that optical standards used in practice for the calibration of TAI. However, such calibrations are challenging, as calibration intervals are composed of multiple of five continuous days. SYRTE has reported five calibration reports spanning from 2014 to 2016, with calibration intervals ranging from 10 to 20 days. This first calibration has been accepted by the BIPM, as a non steering contribution. It shows that optical clocks are closer to supersede microwave clocks.

Acknowledgments

This paper gathers several experimental achievements conducted by many contributors at SYRTE, LPL, PTB and NPL. These authors are listed in the relevant publications [7,12,9,13].

References

1. M. Abgrall, B. Chupin, L. De Sarlo, J. Guéna, P. Laurent, Y. Le Coq, R. Le Targat, J. Lodewyck, M. Lours, P. Rosenbusch, G. D. Rovera, and S. Bize. Atomic fountains and optical clocks at SYRTE: Status and perspectives. *Comptes Rendus Physique*, 16(5):461 – 470, 2015.
2. T.L. Nicholson, S.L. Campbell, R.B. Hutson, G.E. Marti, B.J. Bloom, R.L. McNally, W. Zhang, M.D. Barrett, M.S. Safronova, G.F. Strouse, et al. Systematic evaluation of an atomic clock at 2×10^{-18} total uncertainty. *Nature communications*, 6:6896, 2015.
3. Ichiro Ushijima, Masao Takamoto, Manoj Das, Takuya Ohkubo, and Hidetoshi Katori. Cryogenic optical lattice clocks. *Nature Photonics*, 9(3):185–189, 2015.
4. N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, and E. Peik. Single-ion atomic clock with 3×10^{-18} systematic uncertainty. *Phys. Rev. Lett.*, 116:063001, Feb 2016.

5. M Schioppo, RC Brown, WF McGrew, N Hinkley, RJ Fasano, K Beloy, TH Yoon, Gianmaria Milani, D Nicolodi, JA Sherman, et al. Ultrastable optical clock with two cold-atom ensembles. *Nature Photonics*, 11:48, 2017.
6. Sebastian Häfner, Stephan Falke, Christian Grebing, Stefan Vogt, Thomas Legero, Mikko Merimaa, Christian Lisdat, and Uwe Sterr. 8×10^{-17} fractional laser frequency instability with a long room-temperature cavity. *Opt. Lett.*, 40(9):2112–2115, 2015.
7. J. Lodewyck, S. Bilicki, E. Bookjans, J.-L. Robyr, C. Shi, Vallet G., R. Le Targat, D. Nicolodi, Y. Le Coq, J. Guéna, Abgrall M., P. Rosenbusch, and S. Bize. Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. *Metrologia*, 53(4):1123, 2016.
8. R. Le Targat, L. Lorini, Y. Le Coq, M. Zawada, J. Guéna, M. Abgrall, M. Gurov, P. Rosenbusch, D. G. Rovera, B. Nagórny, R. Gartman, P. G. Westergaard, M. E. Tobar, M. Lours, G. Santarelli, A. Clairon, S. Bize, P. Laurent, P. Lemonde, and J. Lodewyck. Experimental realization of an optical second with strontium lattice clocks. *Nature Communications*, 4:2109, 2013.
9. R Tyumenev, M Favier, S Bilicki, E Bookjans, R Le Targat, J Lodewyck, D Nicolodi, Y Le Coq, M Abgrall, J Guéna, L De Sarlo, and S Bize. Comparing a mercury optical lattice clock with microwave and optical frequency standards. *New Journal of Physics*, 18(11):113002, 2016.
10. Kazuhiro Yamanaka, Noriaki Ohmae, Ichiro Ushijima, Masao Takamoto, and Hidetoshi Katori. Frequency ratio of ^{199}Hg and ^{87}Sr optical lattice clocks beyond the si limit. *Phys. Rev. Lett.*, 114:230801, Jun 2015.
11. P. Delva and J. Lodewyck. Atomic clocks: new prospects in metrology and geodesy. *Acta Futura*, 7:67, 2013.
12. C Lisdat, G Grosche, N Quintin, C Shi, SMF Raupach, C Grebing, D Nicolodi, F Stefani, A Al-Masoudi, S Dörscher, et al. A clock network for geodesy and fundamental science. *Nature Communications*, 7:12443, 2016.
13. P. Delva, J. Lodewyck, S. Bilicki, E. Bookjans, G. Vallet, R. Le Targat, P.-E. Pottie, C. Guerlin, F. Meynadier, C. Le Poncin-Lafitte, O. Lopez, A. Amy-Klein, W.-K. Lee, N. Quintin, C. Lisdat, A. Al-Masoudi, S. Dörscher, C. Grebing, G. Grosche, A. Kuhl, S. Raupach, U. Sterr, I. R. Hill, R. Hobson, W. Bowden, J. Kronjäger, G. Marra, A. Rolland, F. N. Baynes, H. S. Margolis, and P. Gill. Test of special relativity using a fiber network of optical clocks. *Phys. Rev. Lett.*, 118:221102, Jun 2017.