EPJ Web of Conferences **58**, 03002 (2013)
DOI: 10.1051/epjconf/20135803002

Lasers, Cold Atoms and Atomic Clocks: Realizing the Second Today

Davide Calonico[1]

[1]Istituto Nazionale di Ricerca Metrologica (INRIM), Optics Department, Strada delle Cacce 91, 10135 Torino, Italia

Abstract. The time is the physical quantity that mankind could measure with the best accuracy, thanks to the properties of the atomic physics, as the present definition of time is based on atomic energy transitions. This short review gives some basic information on the heart of the measurement of time in the contemporary world, i.e. the atomic clocks, and some trends related.

1 The atomic second

The idea to refer the units of measurements to fundamental physics and in particular to quantum physics found its first, and presently the most fruitful application in time and frequency metrology.

Considering the quantization of the atomic energy levels and the fundamental Bohr equivalence $E = h\nu$ stating that the difference of two atomic energy level E is proportional to a frequency ν by the Planck's constant h, it is straightforward to think of the atom as a possible frequency standard. The exploitation of this idea started in the Forties of last century by the researches of Rabi, Ramsey e Zacharias, then consolidated in the following decade [1]. In 1955 Essen and Parry built the first Cesium atomic beam clock at the National Physics Laboratory (England) [2], and since then in few years the new time standards outperformed in accuracy the definition of the second in the International System of Units. In 1967 the General Conference of Weights and Measurements, the decisional body of the International System, changed the definition of the unit of time, the second, from the former based on astronomical phenomena such as Earth rotation or revolution (e.g. .″*the second is the 1/86400 part of the mean solar day*″) to the present atomic definition: ″*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*.″

An atomic clock, or an atomic frequency standard (AFS) is basically a device composed of a macroscopic oscillator, hereafter Local Oscillator (LO), e.g. a quartz oscillator for a microwave clocks, or a laser for an optical clock, which frequency is directly compared to the frequency of an atomic transition taken as standard, called clock transition. The Cesium iperfine ground transition has been chosen for the definition of the second, and Cesium clocks are also called primary frequency standards. Other kind of atomic clocks exist, based on different atoms and different atomic transitions: there are clocks based on Hydrogen, Rubidium, Mercury, Ytterbium, Strontium, Indium, Aluminum…

Once compared to the atomic transition, the frequency of the LO is corrected to match as better as possible the frequency of the reference.

Therefore, the basic blocks of an atomic clock are the atomic system, the LO, the interaction phase between LO and atoms, the detection of the frequency error and its correction.

The atomic system should be prepared in a particular atomic state, and great care is required to produce atomic systems that are as unperturbed as possible. In fact, an atomic reference is physically universal, i.e. it is the same for everyone, everywhere, ever, only for unperturbed atoms. Any interaction with the outer world shifts the atomic reference frequency; aiming at universal atomic clocks it is mandatory to correct the frequency for all the perturbations of the atomic system.

The interaction between LO and atoms is an electromagnetic interaction, performed in a dedicated region following basically two type of schemes. In the first, the Rabi interaction, LO electromagnetic radiation and the atoms interact once for a fixed time τ. In the second, the Ramsey spectroscopy scheme, atoms and LO interact twice: there are two Rabi interactions separated by a time T where the atoms undergo a free, unperturbed evolution. The Ramsey spectroscopy is the basic technique for microwave atomic clocks today, i.e. Cesium clocks. The technique is of capitol relevance, recognized by the Nobel Prize to Norman Ramsey in 1989 for discovering the advantages of his technique [3].

Mainly, the Ramsey spectroscopy allows to have an interrogation time much longer than the Rabi technique. For fundamental reasons, that we can label as a wide-sense Heisenberg Principle, longer is the interaction time ΔT, lower is the frequency uncertainty $\Delta\nu$ of the spectroscopy measurement, then more accurate is the clock. This could be stated as $\Delta\nu\Delta T\sim 1$, and it has a very general and basic validity.

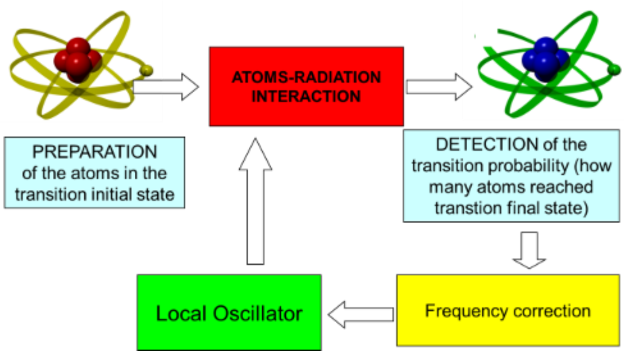

Fig. 1. The block-scheme of an atomic clock.

1.2 Accuracy and stability of an atomic clock

Primary atomic clocks are metrologically characterized by their accuracy and stability. They are very basic concepts, so it is useful to define them and then to discuss a practical example to fully clarify this issue.

The stability of atomic clocks could be defined as the capability to deliver a frequency reference stable over time. The quantitative estimation is performed by statistical methods, and the most used estimator is a particular statistical deviation, called Allan deviation [4, 5]. Allan deviation is quite the same as normal Gaussian deviation when the main statistical noise affecting the atomic clock has a white frequency noise spectrum. This is the typical situation of Cs clocks, for example, and in general of passive atomic clock as the one described in the previous paragraph. In this case, measuring the frequency for longer times means reducing the uncertainty associated to the stability. In particular, the uncertainty is reduced by the inverse of the square root of the measurement time, that is increasing 100 times the time, means reducing 10 times the uncertainty.

Other types of noise affect clocks and frequency oscillators: in all the noises but the white frequency, classical Gaussian deviation is not a proper choice to assign a statistical uncertainty to the clock, whilst Allan deviation properly estimate the data statistical dispersion.

The accuracy of a clock expresses the uncertainty associated to the frequency corrections to the atomic clock. Those corrections are necessary to take into account the external perturbations on the atom. In other words, once an atomic clock is realized, all the perturbations should be evaluated and corrected to obtain the universal frequency standard. The evaluations of the perturbation come with an uncertainty, the total uncertainty is the quantitative estimation of the accuracy.

A Cs fountain atomic clock, presently the best realization of the SI second, has a typical accuracy of few parts in 10^{-16}, in terms of relative frequency, limited by:

a). Atomic collisions. The definition of the second refers to one single atoms, a Cs fountain uses about 10.000 Cs atoms bunching among them; the collision energy shifts the atomic transition frequency, typically of about 10^{-15}, then corrected at the 10^{-16} level.

b). Zeeman effect. All Cs clocks implement the Ramsey spectroscopy using a mandatory quantization magnetic field, that in a fountain shifts the clock transition of about 10^{-14}-10^{-13},corrected to the 10^{-17} level.

c) Blackbody radiation. The atoms are not isolated from the environment: they interact with it through the heat radiation, or black body radiation. At room temperature, this effect shifts Cs transition frequency by 3×10^{-14} and is corrected with an uncertainty of parts in 10^{-16}.

d) Doppler effect. As the atoms are not at rest, Doppler shift affects the clock frequency. Cs fountains reduced this effect by laser cooling to a negligible level below 10^{-16}.

e). Gravitation. To compare two remote clocks on Earth, the effect of General Relativity has to be assessed. Within the Earth gravity potential, atomic clocks differ in frequency by 10^{-16} per meter height difference. The SI second is defined on the level of the Earth Geoid, that is a gravity equipotential surface corresponding *on average* with the sea level.

Other effects could be considered, but this was intended just as an example.

2 Laser cooling

The development of the laser cooling technique [6] for neutral atoms has been fundamental for present atomic clock. In fact, laser cooling has made available atomic samples that are sensibly less affected by Doppler shift than hot vapors, and at the same time it has allowed for longer interaction time. This two challenging issues led to improved stability and accuracy and presently they are unavoidable features for an accurate atomic clock.

The first achievement in the exploitation of laser cooling for clocks has been the realization of atomic fountains, and after that the development of optical clock, respectively the present best realization of the second and the best candidate for a redefinition of the SI second.

Considering an orthonormal space-reference, given on each direction a couple of counter propagating laser beams, with the same frequency, in the intersection region it is possible to create a dissipative medium for an atom moving around, called optical molasses. The required conditions of the laser-atom system to obtain a cooling mechanism are the following:

- The laser frequency should be slightly lower than a specific resonance of the atom (cooling transition)
- The cooling transition, must be a close two level transition, i.e. once excited to the final state of the transition, the atom will come back to the initial state. If the transition is not completely closed, i.e. there is a limited number of other levels that the atom could occupy once excited, then it is possible to implement an effective closure adding some additional lasers (repumpers) that couple the alien level to the excited state of the cooling transition.
- The cooling transition should be a very allowed one, to enhance the effectiveness of the cooling, i.e. the rate of adsorbed photons per second should be as higher as possible.

Fig. 2. The cryogenic Cs fountain at INRIM, ITCsF2.

Given those conditions, it is possible to implement a Doppler cooling mechanism, and the atom will experience a friction damping force proportional to its velocity, at least for velocities lower than a value called *capture velocity*. The force could be evaluated from a semi classical theory combining quantum mechanics and electromagnetism (Bloch equations) and Stochastic, dissipative systems dynamics (Fokker-Planck equations) [6].
A further cooling is possible adding a polarization gradient in the optical molasses (sub-Doppler or Sisyphus cooling). The sub-Doppler cooling is completely due to quantum internal properties of the atomic system, and it is described by a full-quantum theory.
Typical limits for the sub-Doppler cooling are of few micro Kelvin for atoms like Cesium or mass-equivalent atoms, that is a residual average speed of few cm/s.

3 Atomic Fountains

The idea of an atomic fountains is quite simultaneous with the realization of the very first Cesium beam clocks. In 1954, Zacharias at the MIT in Boston proposed to realize a vertical geometry for the implementation of the Ramsey technique. The idea was to launch a sample of atoms in a vertical ballistic flight, letting them to pass through an interaction region. The first Ramsey interaction should happen with the atoms going upwards, the second, after the flight apogee, with the atoms coming back downwards. This idea is known today as atomic fountain, even if Zacharias referred to as *Fallotron*. The advantages of the Zacharias proposal were twofold. First of all, the time between the two interactions could be much longer than in horizontal atomic beam configurations, improving the accuracy and the stability of the clock. Second, the two interactions should happen in the same region, avoiding some technical sources of inaccuracy such as the phase shift, that is an undesired shift occurring when the phase of the LO frequency is different in the two interaction. Having two separate interaction regions, such as in a beam clock, it is technically a challenge to maintain the same phase at a very high level.
Zacharias' proposal was unsuccessful in the Fifties. The reason was that, even with a selection of the lower speed class of the Maxwell-Boltzmann distribution for the atoms, the number of atoms coming back in the microwave region was too small to be detected. Atomic vapors were too hot for this experiment. After the development of the laser cooling techniques, the availability of very cold atomic sample, with residual speed of few cm/s, made feasible the fountain proposal. The first realizations were at the Standford University (Stephen Chu' group) and at the Paris Ecole Normale Superieure (C. Salomon group) [7, 8]. The first Cs fountain realized at a metrological level was in 1996 the Cs-FO1 at the Laboratoire Primaire du Temps et des Frequences in Paris, by Andrè Clairon and Cristophe Salomon. Then, fountains have been realized at the National Institute of Standards and

Technology (NIST, Boulder Colorado), the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany) and Istituto Nazionale Ricerca Metrologica (INRIM, Turin) [9-11].
Today, Cs fountains are also operated at the National Physical Laboratory in UK, and at the NICT and at the NMIJ in Japan. A very good summary of performances of the Cs fountain participating to the realization of the International Atomic Time of the BIPM is reported in [12].
With respect to the previous Cs atomic beam clocks, the fountain advantages are several, and the accuracy is improved from 5×10^{-14} to $2\text{-}5\times10^{-16}$.
An atomic fountain is a pulsed clock, and its time-cycle is continuously repeated. The basic operative steps are the following:
a) Cold sample production;
b) Cold atoms launch in the ballistic flight (through laser technique);
c) Selection of the initial state of the transition (combining microwave and optical methods);
d) Ramsey spectroscopy;
e) Optical detection for LO frequency error measurement.
The all cycle typically lasts about 1- 3 seconds. A picture of the Italian INRIM CsF2 fountain is reported in Fig. 2. Behind the Ultra High Vacuum vertical structure of the fountain, there is the optical table with the laser sources and all the optoelectronics to produce the radiation for cooling, launching, selecting and detecting the Cs atoms. The LO in this case is an Hydrogen Maser, filtered in the short term by a BVA quartz, which RF frequency output is multiplied to 9.191 GHz by a dedicated synthesis chain.

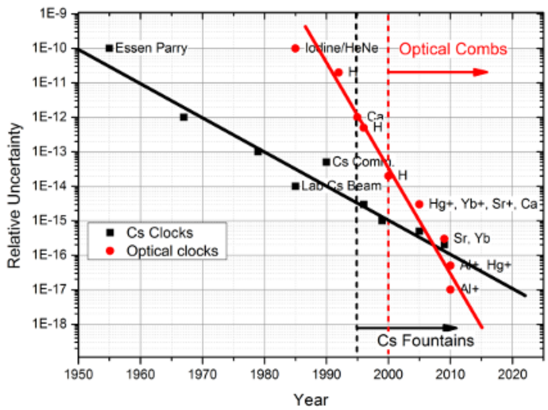

Fig. 3. The evolution in time of the uncertainty of Cs and optical clocks.

4 Lasers become a clock

Further improving the definition of the second could be obtained still keeping atomic clocks, but changing the atomic reference transition. The basic principle is always to increase the quality factor of the atomic line (Q factor), i.e. using higher frequency and lowering the linewidth. A larger Q factor is strictly related to a better stability and accuracy of the clock. The optical part of the atomic levels spectra, that is the atomic transitions with an equivalent frequency in the visible domain, offers higher frequency range than microwave (hundreds of Terahertz for the visible versus few Gigahertz for the microwave), and several transitions with excellent narrow linewidth, related to highly forbidden transitions according to quantum mechanics rules.
Moreover, the transition suitable for a clock must exhibit a sensitivity as small as possible to external perturbing fields, such as electric or magnetic fields.

The visible part of the electromagnetic spectrum is also characterized by excellent local oscillators and frequency sources, i.e. the lasers, that offer coherent radiation, tunable, stable and ultra-stable with some tricky technology.
A last ingredient for a new clock is the possibility of laser cooling for the chosen atom: indeed, after the realization of atomic fountains, an accurate clock must be laser cooled to avoid Doppler shifts and be effective as a clock. Luckily, Nature offers several atomic species that could be cooled, have a visible transition with ultra-narrow linewidth, and a relatively small sensitivity to external perturbations. These atomic species are almost all the alkaline-hearth atoms, with two electrons on the external shell, or several alkaline-heart like species. Among them, let's mention here Strontium, Ytterbium, Mercury, Aluminium. All of them offer a clock transition to realize an optical clock, that is the short name to indicate an atomic clock based on an optical transition.
The optical clock's development has got a huge boost with the advent of the optical frequency comb at the end of last millennium. We suggest to read [13] and the references therein for the description of the comb; here we just need to stress that an optical frequency comb is a pulsed laser (femtosecond pulses), capable to directly bridge the difference between GHz and THz, that is allowing a direct measurement of optical frequencies in terms of primary frequency standards in the microwave domain. The comb does not limit the uncertainty of that measurement. This was a large achievement, awarded by the Nobel prize to Ted Haensch in 2005. Previously, optical frequencies could be absolutely measured in terms of the definition of the second, only with complicated methods and large uncertainties. Today, cancelling out the measurement technique uncertainty, the comb allows to put face to face the accuracy of a Cs clock with the uncertainty of optical clocks. The improvement has been quite astonishing and nowadays optical clocks outperform Cs clocks and a redefinition of the second should be considered for discussion.
The best optical clock today could claim for an accuracy better than 50 times the Cs accuracy [14], even if strictly speaking only a primary frequency standard, based on Cs could report for accuracy. This clock is the NIST aluminium ion clock, capable of a priori uncertainty of systematic biases $<10\times^{-17}$, and his principal inventor, David Wineland, is the Nobel Prize for physics in 2012.

5 Atomic clocks and fundamental physics

Due to their high accuracy and stability, atomic clocks are useful devices for fundamental physics tests. Here, two categories of this experiments are described.

5.1 Test for General Relativity

The Equivalence Principle, one of the postulates of the General Theory of Relativity (GR), could be stated in the form so called Weak Equivalence Principle, and following the formulation of Will [15]:
A body, electrically non charged, located in the space time with given speed, has a consequent trajectory independent from its internal structure and composition.
Using a formulation closer to Newton's mechanics, this statement implies the equivalence between inertial and gravitational mass. From the Weak Postulate, the Strong Equivalence Principle is stated considering that every experiment on a free falling reference, both in presence of a gravitational field or not, has the same outcome.
In other words: given the Weak Equivalence Principle, every local experiment (i.e. not involving gravity), is independent from the speed and the space time location of the experiment itself.
For example, a comparison among atomic clock is a local experiment if the clocks are close enough that gravity corrections are negligible or if their frequency is corrected for the gravity effect.
Moreover, the proper time measured by an atomic clock depends only on the space time path, not on the atomic species considered, and this is referred to as Local Position Invariance (LPI).
One of the tests for GR is then to compare different clocks based on different atomic species while they are moving in the Earth-Sun gravitational system. The atomic clock frequency difference is constantly null for GR.

This has been verified using different atomic clocks in several laboratories [15]. The present level of accuracy confirms the statements of GR at an uncertainty level of 1×10^{-6}.

5.2 Fundamental Constants, are they constant?

The challenging theoretical problem to unify the theories of gravitation with the Standard Model of fundamental interactions has led to the development of a large class of theories, such as for example string theory, and many of them use extra-dimensions beyond the our space time ones. This kind of approach has a common feature, the violation of the stability of commonly defined fundamental constants [16].

Atomic clocks are based on the electromagnetic interaction, so the fundamental constant intrinsically related to atomic clocks is the fine structure constant $\alpha=e^2/(2\varepsilon_0 hc)$, i.e. the coupling constant in QED, the quantum field theory of electromagnetism.

In particular, the energy levels are proportional to the fine structure constant (and others, like Rydberg constant), and comparing different atomic transition over the time it is possible to have a test on the time variation of the constant itself. It could be demonstrated that considering an atomic transition frequency:

$$\delta \ln\left(\frac{\nu_{at}}{R_\infty c}\right) \cong K_\alpha^{at}\frac{\delta\alpha}{\alpha} + K_e^{at}\frac{\delta(m_e/\Lambda_{QCD})}{m_e/\Lambda_{QCD}} + K_q^{at}\frac{\delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}} \tag{1}$$

where, ν_{at} is the atomic frequency, R_∞ is the Rydberg constant, c the speed of light, α the fine structure constant, m_e and m_q the mass of the electron and of the quark, Λ the coupling constant of quantum chromo dynamics. Comparing over time two different atomic species offer a test for those constants and in particular for the fine structure constant.

Many experiments have been carried out so far, showing that alpha is not changing at the level of [17]:

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = (2\pm2)\times10^{-17}/\,year \tag{2}$$

Other test, not based on atoms, as the Oklo natural reactor in Gabon as demonstrated firstly in 1976 by Shlyakhter and then reanalyzed by Daymor and Dyson and Fujii [16], has shown no variation, while astrophysical measurement by the Webb group in Australia [17] suggested a variation of

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = (6.4\pm1.4)\times10^{-16}/\,year \tag{3}$$

6 Remote comparisons of atomic clocks

One peculiar feature of the unit of time is that it is possible to compare two remote clocks at a very high accuracy using electromagnetic waves.

The status of the art in remote clock comparison up to few years ago has been the satellite radiofrequency technique [18]. Among them, the use of the GPS constellation and the Two Way Satellite Time and Frequency Transfer (TWSTFT) technique were the best solution for remote comparison. The TWSTFT is capable to transfer a frequency with an uncertainty of 10^{-9} at 1 s, that decreases with the inverse of time, so that we have 10^{-14} at one day and 5×10^{-16} at 20 days. In this way, after 20 days of continuous operation RF techniques are suitable to exploit Cs fountains, but still not enough for the new generation of optical clocks.

In recent years, the use of a technique called coherent optical fiber link method has exploited fiber optics to transfer time and frequency [19-21], and it has been demonstrated to outperform RF satellite techniques and suitable for optical clocks comparisons. In fact, the optical fiber technique is

capable of an uncertainty of $\times 10^{-14}$ at 1 s over 900 km of fiber link, and below 10^{-17} after 1000 s of measurement.
This opens the possibility of a large integration of continental experiments, i.e. new comparisons and new more stringent fundamental test.
In Fig.4 a summary of possible uncertainties is reported, giving a sight to actual situation in remote comparison and clocks' uncertainty.

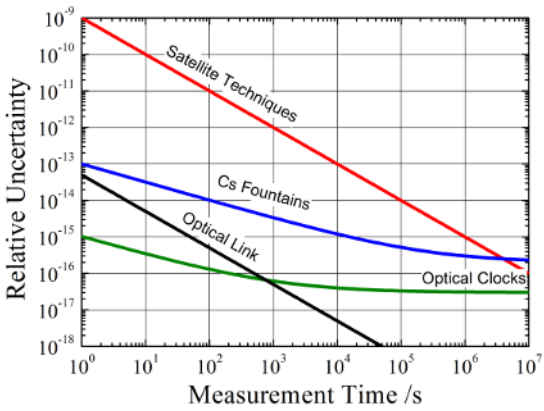

Fig. 4. Comparison of the uncertainty of remote clock comparison techniques.

The coherent fiber optic technique is based on the realization of ultrastable lasers at 1550 nm, where there is the minimum attenuation over fibers. The ultra-stable laser has a frequency stability about 10^{-15} and it is used as a transfer oscillator. Two remote laboratories, A and B, measure at the same time the frequency of the laser versus their local clock. Exchanging the measured value, Lab A and B can evaluate the difference between the respective clocks. The uncertainty of the comparison method is as low as described only if the influence of environment on the fiber is taken into account and corrected. In fact, seismic noise and temperature fluctuations act on the fiber, with the result of a fiber length noise that in turn results in a phase noise on the disseminated frequency.
In Fig. 5 a scheme of this technique is reported. To compensate for the fiber phase noise, the laser is sent from A to B, then a part of the laser radiation is sent back to Lab A. Here, the coming back signal is compared with the initial frequency of the laser: this enables for an evaluation of the fiber noise and it continuous cancellation, using an optoelectronic actuator.

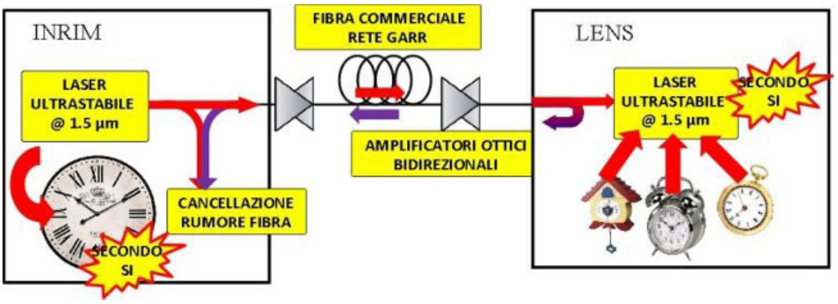

Fig. 5: Coherent optical link technique: concept scheme.

Some particular issues have to be required from the fiber infrastructure: for example, the path has to be *full-optical*: conversion optical to electric to optical typical of old generation architecture must be avoided; optical amplifiers are necessary, but they should be completely bidirectional, because the fiber should be the same going and coming back.

Several optical links are under realization worldwide, and European National Metrological Institutes are putting a lot of effort in that technique [22], as it is demonstrated by the map in Fig. 6, where it is shown also the new optical link in Italy, between Turin (INRIM), Milan, Bologna and Florence (European Laboratory for Nonlinear Spectroscopy, LENS and University of Florence) [23].

Fig. 6. Ongoing European optical links projects.

Conclusions

Today, the definition of the unit of time, the second, is based on the quantum properties of Cesium atom, but a redefinition is foreseen that will probably open to several species of atoms with transition in the optical domain. The paradigm for defining the time, in physics, will remain the atomic world and its quantum rules. Atomic clocks will still be complicated and very precise devices, using the best physics discoveries, and offering themselves as tools for metrology but also for fundamental tests for the law of nature.

Acknowledgements

The author thanks all the Optics Division at INRIM, and in particular the atomic frequency standards group.

References

1. F.G. Major, The Quantum Beat (Springer,1998)
2. W. Markowitz, R. G. Hall, L. Essen, and J. V. L. Parry, Phys. Rev. Lett. **1**, 105 (1958)
3. N.F. Ramsey, Nobel Lectures, Physics 1981-1990, Editor-in-Charge Tore Frängsmyr, Editor Gösta Ekspång, (World Scientific Publishing Co., Singapore, 1993)
4. D. Allan, Proceedings of IEEE **54** (1966)
5. E. Rubiola, Rev. Sc. Instr. **76 (**2005**)**
6. H.J. Metcalf, P. Van der Straten, Laser cooling and trapping (Springer, 1999)
7. M.A. Kasevich, E. Riis, S. Chu, and R.G. DeVoe, Phys. Rev. Lett. **63** (1989)
8. A. Clairon, C. Salomon, S. Guellati and W.D. Phillips, EPL **16 (**1991**)**
9. S. R. Jefferts et al. , *Metrologia* **39** (2002)
10. S. Weyers et al., Metrologia **38** (2001)
11. F. Levi, D. Calonico, L. Lorini and A. Godone, Metrologia **43** (2006)

12. T.E. Parker, Metrologia **47** (2010)
13. J. Ye and S.T. Cundiff, eds. *Femtosecond optical frequency comb technology* (Springer, New York, 2005)
14. C.W. Chou, D.B. Hume, J.C.J. Koelemeij, D.J. Wineland, and T. Rosenband, Phys. Rev. Lett. **104** (2010)
15. C.M. Will, Living reviews in relativity **3** (2006)
16. J.-P. Uzan, Rev. Mod. Phys. **75** (2003)
17. J.K. Webb et al. Phys. Rev. Lett. **87** (2001)
18. A. Bauch et al., *Metrologia* **43** (2006)
19. O. Lopez, et al., Opt. Expr. **18** (2010)
20. K. Predehl, Science **336** (2012)
21. W. Williams, W.C. Swann, and N.R. Newbury, J. Opt. Soc. Am. B **25** (2008)
22. http://www.ptb.de/emrp/neatft_home.html
23. D. Calonico, Proc. of the European Frequency and Time Forum (EFTF) (Gothenburg, Sweden, April 2012)