The unit of time: present and future directions

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Abstract
Some 50 years ago, physicists, and after them the entire world, started to found their time reference on atomic properties instead of motions of the Earth that have been in use since the origin. Far from being an arrival point, this decision marked the beginning of an adventure characterized by a 6 orders of magnitude improvement in the uncertainty of realization of atomic frequency and time references. Ever progressing atomic frequency standards and time references derived from them are key resources for science and for society. We will describe how the unit of time is realized with a fractional accuracy approaching $10^{-16}$ and how it is delivered to users via the elaboration of the international atomic time. We will describe the tremendous progress of optical frequency metrology over the last 20 years which led to a novel generation of optical frequency standards with fractional uncertainties of $10^{-18}$. We will describe work toward a possible redefinition of the SI second based on such standards. We will describe existing and emerging applications of atomic frequency standards in science.

Keywords: time and frequency metrology, atomic fountain, timescale, optical frequency standard, quantum metrology, fundamental physics test, chronometric geodesy, redefinition of the SI second

1. The unit of time

In 1967, the 13th General Conference on Weights and Measures (CGPM) defined the SI second as “the duration of $9 192 631 770$ periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom”. Atoms have quantized energy levels. To any pair of quantized levels of energy $E_g$ and $E_e$, a frequency $\nu$ is associated via Planck-Einstein’s relation: $h\nu = E_e - E_g$. One fundamental idea behind the definition is that these atomic frequencies are perfectly stable and universal. Observations support this idea. Atoms can be regarded as “perfect” frequency standards given by nature. The immutability of atomic frequencies is integrated into fundamental theories underpinning physics: general relativity and the standard model of particle physics.

Accessing the atomic frequency and transferring its qualities to a macroscopic usable signal requires a device called atomic frequency standard. The
The output frequency $\nu(t)$ does not coincide with the atomic frequency $\nu_{at}$. It is perturbed by noises and biases of both technical and fundamental nature. These noises and biases determine two main characteristics of a given atomic frequency standard. Noises limit the uncertainty with which a frequency measurement can be made with this standard in a given duration. It is characterized by the fractional frequency instability $\sigma_y(\tau)$ which is a function of the measurement duration $\tau$. Biases offset the mean output frequency with respect to the unperturbed atomic frequency $\nu_{at}$. If known and stable, a bias can be taken into account. What really matters is the uncertainty to which biases are known. This uncertainty, often reported in fractional terms, defines the level to which the standard actually gives access to the unperturbed atomic frequency. It summarizes the capability of the standard to realize the SI second (for $^{133}$Cs primary standards), to be used for fundamental physics and for other applications.

In practice, only well-chosen atomic transitions are suitable to realize standards with lowest stability and uncertainty. Levels must have long lifetimes to enable high atomic quality factor $Q_{at} = \nu_{at}/\Delta\nu$ (see fig. 1). Transition must have low sensitivity to external fields (electric, magnetic, thermal radiation, etc.). Atomic structure must be compatible with methods needed to manipulate and detect atoms. It is also essential to consider practical criteria such as reliability, operability, possibility to generate and use the interrogation field at the transition frequency. Given the state of knowledge and technology at the time of the 13th CGPM, a frequency standard based on the $^{133}$Cs ground state hyperfine transition was one of the best possibilities, almost 2 decades after the first observation of the transition [2]. It had shown sufficient maturity and had been accurately measured with respect to the ephemeris time [3][4]. Since then, fundamental
and technological breakthroughs in many areas lead to major changes in ways to realize and use highly accurate atomic frequency standards. Their uncertainty improved by 6 orders of magnitudes. References [5] and [6] provide an overview of these developments.

In November 2018, the 26th CGPM adopted a major redefinition of the international system of units. The redefinition concerns the units of mass, of temperature, of electrical current and of amount of substance. The new system is defined by adopting conventional values for Planck’s constant $h$, for Boltzmann’s constant $k_B$, for the elementary charge $e$ and for Avogadro’s constant $N_A$, similarly to what is already done since 1983 [7] with the speed of light $c$ to define the unit of length. In essence, the definition of the second remains unchanged. The form of the definition however is modified to resemble those of other units, i.e. “the International System of Units, the SI, is the system of units in which: the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta \nu_{\text{Cs}}$ is 9 192 631 770 Hz, […]” [8].

2. Research on highly accurate atomic frequency standards

Previous section [1] gave fundamental concepts behind atomic time and atomic frequency standards. These concepts are amazingly simple and used for more than 5 decades. Still, they continue being at the basis of an active field of research in the following ways.

Search for advancing atomic frequency standards with extremely low uncertainties goes hand in hand with exploration of atomic systems interacting with electromagnetic fields. Progress in atomic frequency standards reveals new phenomena and provides means of investigating them. And vice versa, progress in other areas (e.g. laser-cooling of atoms, physics of collisions and interactions, quantum entanglement,...) enables improvement of atomic frequency standards.

These devices with extremely low uncertainties are tools of choice to probe the structure of space-time and to test fundamental laws of nature. They provide experimental inputs to the quest for a unified theory of gravitation and quantum mechanics [2][10][11] and to the search for dark matter [12][13] and to other applications.

On the applied side, atomic frequency standards are key to major applications of utmost importance in modern science and society. The practical realization of the unit of time of the SI system is one of them, in particular via the elaboration of the international atomic time and of the universal coordinate time (TAI/UTC). Another example is global navigation satellite systems (GNSS) such as GPS, GALILEO, etc. In turn, these realizations are key for telecommunications, transports, finance, digital economy, etc.

Search for ultra-low uncertainties in atomic frequency standards is a steady driver for innovation in multiple technological areas such as lasers, low noise electronics, ultra-stable oscillators. Also, it creates knowledge necessary to define trade-offs between performance and other requirements for industrial frequency standards or space clocks. This knowledge is often applicable not only to novel
frequency standards but also to other types of atom-based instruments like, for example, accelerometers and gyroscopes based on matter wave interferometry or magnetometers.

Progress in reducing the uncertainty of atomic frequency standards leads to novel applications. For instance, because of its much lower uncertainty, the new generation of optical frequency standards enable chronometric geodesy, i.e. the determination Earth gravitational potential differences via the measurement of Einstein’s gravitational red shift.

3. Primary frequency standards based on atomic fountains

The first generation of $^{133}$Cs primary frequency standards, which led to the adoption of the atomic time, was based on the thermal atomic beam technology and the separated oscillatory fields method \[14\][15]. The development of laser cooling of atoms in the 1980’s \[16\][17][18] enables a second generation called atomic fountain standards \[19\][20][21]. Atomic samples laser-cooled to temperature near 1 µK enable atomic quality factors higher than $10^{10}$, a factor 100 higher than in atomic beam standards. Figure 2 displays a schematic of an atomic fountain. When an ultra-low noise microwave source is used to interrogate the atomic transition the quantum projection noise limit is reached \[22\]. This limit is the fundamental limit set by the quantum measurement process for un-entangled particles. This yields short term fractional frequency instabilities as low as $1.6 \times 10^{-14}$ at 1 s \[22\]. Nowadays, the accuracy of best atomic fountains ranges between 1 and 3 parts in $10^{16}$. This is the result of refining models of the interrogation and detection processes, and of stringently testing these models with experiments. Such experiments typically require many frequency measurements with statistical uncertainties near $10^{-16}$, which is reached, in the very best case, after several full days of measurement duration. In other words, fountains have reached the situation where the stability imposes a practical limit to studying systematic shifts and improving the accuracy. Example of effects whose modelling improved significantly includes effects of phase gradients in the interrogation microwave cavity \[24][25], effects of cold collisions \[26][27][28], effects of collisions with background gases \[22][30] and effects of the microwave field on external atomic motion (“microwave lensing”) \[31][32][33]. Implementation of fountains with cryogenic interrogation environment enabled a new direct measurement of effects of thermal radiation shift (“blackbody radiation shift”) \[34][35][36][37]. Recently, a complete accuracy budget was published for continuous fountain at the level of $1.99 \times 10^{-15}$ \[38\]. More details on atomic fountains can be found for instance in \[39\], \[23\] and \[40\].

The $^{87}$Rb ground state hyperfine transition is also used to realise atomic fountain frequency standards. LNE-SYRTE developed a dual fountain using Rb and Cs which truly realizes two state-of-the-art microwave standards in a single setup \[41][42\]. The Rb part of this fountain has an uncertainty of $3.2 \times 10^{-16}$ similar to the one of best cesium fountains. This dual fountain enables highly accurate comparisons of the $^{87}$Rb and $^{133}$Cs hyperfine frequencies. These comparisons find many applications (see sections 6 and 7 below). In particular,
they led to the adoption of this transition has a secondary representation of the SI second [43] [42].

Agreement between fountains is well tested by the means of specific remote comparisons by satellite methods [44] and recently by optical links between LNE-SYRTE and PTB [45]. Also, the elaboration of TAI provides a vehicle to compare fountain frequency standards (see section 4 below).

Figure 2: On the left: Schematic of an atomic fountain frequency standard. A cloud of cold atoms is captured at the crossing of 3 pairs of counter-propagating laser beams. It is launched upwards at a typical speed of 4 m.s\(^{-1}\) and with temperature of \(\sim 1\) µK. During the ballistic flight, atoms are state-selected with a first microwave interaction and a push laser beam. Then, they pass upward and downward through a microwave cavity where they interact with the signal from the interrogation oscillator. They continue falling through two laser beam sheets in the detection region. On the right: Top: Energy levels of \(^{133}\)Cs showing the ground-state hyperfine transition defining the SI second. In red, transitions used for laser-cooling and detection. Bottom: Spectroscopy of the cesium hyperfine transition in an atomic fountain showing Ramsey fringes with a width < 1 Hz and an atomic quality factor \(Q_{at}\) of \(10^{10}\). Each point is a single measurement of the transition probability at a rate of \(\sim 1\) per second with a typical noise \(\sigma_{\delta P} \sim 2 \times 10^{-4}\).
4. Elaboration of TAI: accuracy of atomic fountains delivered to users

One essential outcome of time and frequency metrology is the construction of the international atomic time (TAI) and of the universal coordinate time (UTC). It is worth noting here that the 26th CGPM adopted a resolution on the definition of time scales [8], which corrects for the lack so far of a self-contained definition of TAI. We remind that a meaningful definition and realization of a time scale valid globally in the vicinity of the Earth requires the framework of general relativity, in particular to properly account for Einstein’s gravitational redshift which is about $10^{-16}$ per meter of elevation at the surface of the Earth. A description of elaboration of TAI by the BIPM can be found for example in [46] and references therein. By means of satellite-based comparisons, data from about 450 continuously operated commercial clocks are used to compute the free atomic time scale (EAL). The large number of devices and locations ensure the permanence of EAL. Data from a much smaller number of primary and secondary frequency standards (about 20) in an even more limited number of institutes are used to calibrate the frequency of EAL against the $^{133}\text{Cs}$ hyperfine transition, according to the definition of the second, and to steer EAL to realize TAI. UTC is derived from TAI by inserting leap seconds that maintain agreement with universal time (UT1) and the observed rotation of the Earth. The result of this process is published by the BIPM in its monthly Circular T [47]. This information, in turn, is used by national metrology institutes and other participants to steer their local physical representation of UTC from which disseminations in society start by various means.

Circular T and calculations done at the BIPM also yield an estimation of the performance of TAI and provide a vehicle to compare frequency standards worldwide. Differences between frequency standards observed by this means are consistent with uncertainties [48][49]. The accuracy to which the scale interval is determined with respect to $^{133}\text{Cs}$ hyperfine transition now reaches $2 \times 10^{-16}$ [46]. In other words, performance of frequency standards is transferred to the time scale and thereby to users. The $2 \times 10^{-16}$ fractional frequency uncertainty translates into an error of less than 10 ns after one year. This improvement by a factor of 10 since 2000 is the result of the commitment of a few metrology institutes to provide regular calibrations of TAI. Nowadays, about 4 or 5 calibrations by fountains are typically available each month, as can be seen in section 3 of Circular T [47]. Over the last 15 years, LNE-SYRTE made 40% of all worldwide calibrations with fountains. The adoption of secondary representations of the SI second (see [43] and section 7 below) led to the possibility to calibrate TAI with other atomic transitions than the $^{133}\text{Cs}$ hyperfine transition. This was done for the first time with the $^{87}\text{Rb}$ hyperfine transition by LNE-SYRTE which provided close to 100 calibrations by this mean [42]. LNE-SYRTE also pioneered providing calibrations based on an optical transition. This was done with the $^{87}\text{Sr} \, ^{1}\text{S}_0-^{3}\text{P}_0$ transition at 698 nm. Regular calibrations of TAI by optical frequency standards are an important prerequisite for a possible redefinition of the second based on optical transition(s) [50]. The transfer of long term stability and accuracy of primary frequency standards to TAI enables highly accurate
SI-traceable frequency measurements without a local primary frequency [51][52] and fundamental physics tests [53][54].

Progress in the reliability of atomic fountains made possible for a few institutes to steer their local realizations of UTC with fountain data [55][56][57]. Local realization of UTC by institute k is denoted UTC(k). Figure 3 shows time differences between such timescales and UTC. They are realized using hydrogen masers whose frequency is calibrated and steered with atomic fountains, and for the long term, with the time difference UTC(k)-UTC provided every month in Circular T. They typically deviate from UTC and from each others by no more than a few nanoseconds. It is worth noting another significant evolution in timekeeping, namely the rapid realization of UTC by the BIPM [58]. UTCr implements faster exchange of data than Circular T does between participating laboratories and the BIPM. It improves the level to which a given laboratory can verify the synchronization of its UTC(k) to UTC. This is of particular interest and significance for laboratories where resources allocated to the local timescale are limited (i.e. limited to a few commercial Cs beam standards).

5. A new generation of optical atomic frequency standards

Optical frequency metrology is advancing at high pace, in particular since the introduction of optical frequency combs [59][60]. Optical frequency standards
refer to atomic standards relying on transitions whose frequency corresponds to the optical domain of the electromagnetic spectrum. Their frequency is $10^4$ to $10^5$ higher than the $^{133}\text{Cs}$ hyperfine frequency and their potential atomic quality factor can exceed $10^{16}$ instead of $10^{10}$ for atomic fountain standards. To date, both neutral atoms and ions are studied with the aim to obtain the lowest possible uncertainties. Figure 4 explains the principle of operation of these two types of standards. Optical frequency standards achieve fractional frequency uncertainties close to $10^{-18}$ \[61\] \[62\] \[63\] \[64\] \[65\] \[66\] \[67\] \[68\]. For example, reference \[61\] reports an uncertainty of $1.4 \times 10^{-18}$ for a $^{171}\text{Yb}$ optical lattice standard. References \[64\] and \[62\] report uncertainties of $2.1 \times 10^{-18}$ and $4.8 \times 10^{-18}$ respectively for $^{87}\text{Sr}$ optical lattice standards. Reference \[63\] reports an uncertainty of $3.2 \times 10^{-18}$ for a $^{171}\text{Yb}^+$ ion standard. Many physical effects had to be understood and controlled at an even lower level individually. Some notable ones are frequency shifts due to blackbody radiation \[69\] \[70\] \[64\] \[66\] \[65\] \[67\] \[68\] \[71\] and to electric fields \[72\], shifts induced by the lattice light \[73\] \[74\], shifts induced by interactions \[75\], light-shifts induced by probe light \[76\]. This list of example must not be considered as complete either in terms of effects or in terms of references. Comparisons between optical frequency standards using the same transition were performed with improving uncertainties \[77\] \[78\] \[79\] \[65\] \[80\], down to below $10^{-18}$ for the most recent work \[61\]. A recent and more complete account on optical frequency standards can be found in \[81\]. Figure 5 shows a recent measurement of the stability of a $^{87}\text{Sr}$ optical lattice frequency standard from LNE-SYRTE.

Evaluation of uncertainties and comparisons at the $10^{-18}$ level are made possible by the excellent short term stabilities reached by optical frequency standards \[88\] \[89\] \[90\] \[91\] \[92\]. Stabilities as low as $1.6 \times 10^{-16}$ at 1 s can be observed for a single optical lattice frequency standard and even lower between two regions of the same atomic cloud \[92\]. Ion-based optical frequency standards show significantly worse stabilities because they are so far using a single ion instead of several hundreds of atoms or more in neutral atom standards. Synchronized and correlated interrogation of 2 ion-based standard enables comparison with stability in the mid-$10^{-16}$ at 1 s \[94\]. Such stabilities became possible only with the progress of ultra-stable lasers which remain the subject of active developments. Classical ultra-stable lasers based on Fabry-Perot prove being limited by thermal brownian noise in dielectric mirror coatings \[95\]. Several approaches were and are still investigated to mitigate this limit. Extending cavity length can already give significant improvement \[96\] \[89\] \[97\]. Crystalline silicon cavity at cryogenic temperatures showed exquisite laser instability and laser linewidth ($4 \times 10^{-17}$ and $<10$ mHz respectively) \[98\] \[99\]. Another promising method could be to use crystalline coatings that exhibit lower thermal noise \[100\]. Other approaches shift away from Fabry-Perot cavity. Prospects exist to use spectral hole burning in rare-earth doped ions in crystalline matrices at cryogenic temperatures \[101\] \[102\] \[103\]. Lasers using ultra-narrow atomic transitions are another proposed alternative \[104\] \[105\] \[106\].

Interest in quantum technologies increased considerably in the last years because they promise major breakthroughs in computation, communication and
Figure 4: On the left: Schematic of single ion optical frequency standard. The ion is confined in a Paul trap made of electrodes with oscillating electric potentials. The ion is laser-cooled and probed with ultra-stable laser light. Center: Schematic of optical lattice neutral atom frequency standard. An ensemble of atoms is confined in a corrugated potential formed by an intense standing laser field (blue). Atoms are probed with ultra-stable light aligned with the trap axis (red). On the right: Spectroscopy of the $^{87}\text{Sr}$ reference transition at 429 THz in a optical lattice. The spectrum is typical of Lamb-Dicke regime used in optical frequency standards. Because of confinement, the external motion of atoms has quantized vibrational levels. The spectrum exhibits resolved sidebands with frequency offsets corresponding to the trap vibrational frequency. The central “carrier” resonance corresponds to excitations that do not change the external atomic state. It is essentially unaffected by the first order Doppler effect and by the recoil effect $Q_{\text{at}}$. This resonance can be as narrow as few 100 mHz corresponding to atomic quality factors $Q_{\text{at}}$ of several $10^{15}$, at the origin of the superior performance of optical frequency standards. The counterpart of using confined particles is the need to care about effects of the trapping fields. Fundamentally, the ion is held thanks to its electric charge without strong perturbation of its internal structure. It is nevertheless necessary to care about effects of micro-motions induced by the oscillating electric field $[83][84]$. Trapping of neutral atoms relies on polarizing them with the intense lattice light and thereby on perturbing their internal structure. In optical frequency standards, the lattice trap can be non-perturbing if the trap wavelength has a specific wavelength called magic wavelength where the polarizability is the same for the two levels of the reference transition $[85][86][87]$. Research in optical frequency standards already gave striking examples of quantum enhanced metrology. Operation of the single Al$^+$ ion frequency standard relies on a quantum gate between Al$^+$ and a companion ion used for state readout $[77][109][110]$. To date, there is still a large potential for optical frequency standards to further exploit quantum metrology. Tailored quantum superposition of internal states can reduce sensitivity to external field perturbations $[111]$. Entangled states of several ions can improve the stability below the quantum projection noise limit $[112]$. In parallel, progress were made in designing traps that can support multiple-ion chains while maintaining low uncertainty due to motional effects $[113]$. A challenge for future ion-based standards will be to merge all methods in a single device. Neutral atom standards already use samples that comprise hundreds or thousands of atoms. Quantum non-destructive measurements performed on such samples can generate entangled states $[114]$ which are metrologically useful like, for example, spin-squeezed states $[115]$. Proof-of-principle experiments using hyperfine transitions are reported in $[116][117]$ and in $[118]$ where a specular 10-fold reduction (20 dB
squeezing) below the quantum projection limit is obtained. Non-destructive
detection by optical phase shift measurement in $^{87}$Sr optical lattice frequency
standard is developed at LNE-SYRTE [119][120]. A promising sensitivity level
of a few atoms only is achieved and the path toward quantum non-destructive
regime is clarified. Optical lattice frequency standards constitute an excellent
platform to harvest the benefit of both classical and quantum non-destructive
detection. Classical non-destructive detection could help reducing dead times in
the probing sequence and thereby limit the negative influence of laser frequency
noise on stability. Atomic phase lock method [121][122] could be used to extend
the interrogation duration beyond the probe laser coherence time. Quantum
non-destructive detection could be used to beat the quantum projection noise
limit. These schemes promise stabilities at $10^{-17}$ at 1 s or below. It will re-
main to investigate to which extent the non-destructive detection introduces
additional sources of uncertainty. Many other schemes to generate entangled
states do exist which are potentially interesting to improve frequency standards,
like for instance [123][124][125]. The present account must not be considered
complete.

![Figure 5: Stability of optical frequency standard and coherent optical fiber links. In black:
fraction frequency instability of a $^{87}$Sr optical lattice frequency standard from LNE-SYRTE.
Curve shows the stability of a single standard (SYRTE-SrB) inferred from the analysis of
a multipartite comparison with SYRTE-Sr2, NPL-Sr and PTB-Yb+. In red: stability of a
Paris-Strasbourg-Paris link developed within equipex REFIMEVE+ project coordinated by
LPL.](image)

Optical frequency combs are of utmost importance for optical frequency
standards. They enable comparisons between optical frequency references at
different wavelengths. They enable conversion of optical frequency references
to the microwave domain and thereby, connection with all existing time and
frequency methods and infrastructures, in particular comparisons between optical and microwave standards. Optical frequency combs developed and found applications in many other different fields which are reviewed for example in [126][127]. Here, we highlight developments directly connecting to highly accurate frequency standards. One key aspect was the development of reliable femtosecond lasers based on erbium-doped fiber technology. Combs based on this technology readily connect to the wavelength of 1.5 µm used in optical fiber links (see below) and in best ultra-stable lasers to date. Such combs can transfer the stability between ultra-stable optical references with degradation no higher than $4 \times 10^{-18}$ at 1 s, a level which surpass by far the stability of best ultra-stable lasers [128]. Optical to microwave conversion was also developed to minimize noises from all processes involved in the comb architecture [129][130]. Reliable optical frequency comb systems can deal with multiple wavelengths simultaneously and support complex optical and microwave frequency standard comparisons and microwave generation applied to atomic fountains [131][132][133][134][135][136][45][137][138].

Optical fiber links made tremendous progress over the last decade. Coherent optical fiber links transmit an ultra-stable laser light at 1.5 µm and are therefore directly adapted to the comparison of distant optical frequency standards. From initial proof of concept experiments [139][140][141], this method was extended to continental distances [142][143]. It enabled comparison of optical frequency standards over continental distances with unprecedented stability and accuracy [137]. Figure 5 shows the stability of a Paris-Strasbourg-Paris link obtained for 2 weeks of operation. This link enables comparison to $10^{-18}$ in less than 2000 s. In France, the first industrial-grade link of this type was recently implemented and tested [144]. It proved the readiness of this technology for commercialization and applications. Coherent optical fiber links reach fractional frequency instability below $10^{-18}$ for measurement duration of $10^4$ s for length of several hundreds to 1500 km. Accuracy of the frequency transfer is verified to better than $10^{-19}$. Over continental distances, they surpass satellite-based methods by 3 to 4 orders of magnitude. Besides frequency transfer using a coherent optical carrier, time transfer using optical fibers is actively developed with, here also, the promise to surpass existing methods by orders of magnitude (see, for instance [145][146][147][148]). Relativistic effects in optical fiber links are studied from a theoretical standpoint in [149]. In addition to comparisons of optical frequency standards and dissemination of time and frequency references, optical fiber links are used or considered for applications in chronometric geodesy (see section 8 below), in measurement of Earth’s rotation [150][151], in earthquake detection [152] and in fundamental physics (see e.g. [153]).

6. Test of fundamental physical laws

Physics is underpinned by two fundamental theories: general relativity and the standard model of particle physics. This theoretical framework is extremely successful in describing a huge number of observations. Nonetheless, it is not
free of significant problems. One difficulty is that the standard model is a quantum field theory while general relativity is not. This is giving an heterogeneous picture of the three fundamental interactions. To date, a unified theory of gravitational, electroweak and strong interactions is still missing. A second difficulty arises in the need to introduce dark matter and dark energy to reproduce rotation curves of galaxies and the accelerating expansion of the Universe, in the so-called ΛCDM cosmological model of the Universe. In this model, dark matter and dark energy introduced in an ad hoc manner represent 95% of mass and energy in the Universe.

In this context, many experiments and many observations are used to test fundamental physical laws. One can refer for instance to [11][10][9][154][155] for an overview. Here, we will highlight tests using highly accurate atomic frequency standards. Unlike tests based on observations over geological and cosmological timescales, tests using atomic frequency standards are present day laboratory experiments which do not require a particular cosmological model for their interpretation. Also, they can be repeated for verification purposes. For these reasons, they are good tools for revealing physics beyond general relativity and the standard model and for providing experimental constraints to guide the development of unified theories (see for instance [156][157][158]).

Within its uncertainty, an atomic frequency standard give access to the unperturbed atomic frequency of the chosen transition. Comparisons of atomic frequency standards based on different atomic transitions determine atomic frequency ratios. These frequency ratios are dimensionless quantities given by nature, independently of any system of units. A variation of atomic frequency ratios would be violation of the framework defined by general relativity and the standard model of particle physics and of its founding principles. This can be tested with repeated measurements of atomic frequency ratios. Time series of such measurements are used to search for signals indicative of variations induced by putative phenomena. Linear variations with time could be a present day effect of evolution of the Universe over cosmological timescale. Variations synchronous with the Earth’s motion around the Sun could be an effect of an extraneous coupling to the gravitational field of the Sun or to additional field(s) finding its source in the Sun. Sinusoidal variations could be due to an extraneous coupling to certain candidate dark matter field condensed on our galaxy. For example, linear variations of the fine-structure constant $\alpha$, of the electron-to-proton mass ratio $\mu = m_e/m_p$ and of the quark mass $m_q/\Lambda_{QCD}$ are tested with uncertainties of $2.3 \times 10^{-17}$ yr$^{-1}$, $7.5 \times 10^{-17}$ yr$^{-1}$ and $1.8 \times 10^{-15}$ yr$^{-1}$. Variations with respect to gravity (null redshift test) are tested with uncertainties of $1.0 \times 10^{-7}$, $8.8 \times 10^{-7}$ and $2.3 \times 10^{-6}$ (see, for instance, [159][11] and references therein). Searches for dark matter with frequency standards are reported in [12][13][160]. All these tests improve regularly with the steady progress of atomic frequency standards.

Time and frequency metrology provide many other tests of local position invariance and local Lorentz invariance. New possibilities are frequently emerging, like for instance, use of fiber links [153] for special relativity tests, of GALILEO satellites for gravitational redshift test [161]. The ACES space mis-
sion [162][163][164][165] will provide improved tests and new opportunities. It is worth noting here that the third component of Einstein’s equivalence principle, the universality of free-fall, was recently tested with improved uncertainty with the MICROSCOPE space mission (see [166] and references therein).

7. Toward a redefinition of the SI second

Optical frequency standards now surpass $^{133}$Cs fountain primary standards by more than 2 orders of magnitude, both in stability and uncertainty. This naturally creates a strong incentive to redefine the SI second based on optical transition(s). The advent of this possibility was anticipated shortly after the demonstration of the first optical frequency comb. In 2001, Consultative Committee for Time and Frequency (CCTF) recommended that a list of secondary representations of the second (SRS) be established [167], as one of the key processes to engage into a possible redefinition of the second. In 2004, International Committee for Weights and Measures (CIPM) adopted the first SRS, the $^{87}$Rb hyperfine frequency based on developments and measurements made at LNE-SYRTE [168][169]. To date, the list of SRS comprises 9 transitions, 8 of which are optical transitions [50]. SRS are atomic transitions used to realize frequency standards with excellent uncertainties and which are measured in the SI system with accuracies close to the limit of $^{133}$Cs fountain standards. The recommended fractional frequency uncertainties of SRS range from $4 \times 10^{-16}$ to $1.9 \times 10^{-15}$ in the last version of the list of recommended standard frequencies of the CIPM [43][50]. The recommended values of SRS come from the work of the joint CCL-CCTF Frequency Standard working group of the CIPM. Values are determined based on the least-square adjustments to high accuracy measurements found in peer-reviewed publications [170][171][50]. This work enables checking the consistency of published measurements and the status of atomic frequency standards with the lowest uncertainties.

In view of a possible redefinition of the second, a key aspect of the process is to link the optical frequency domain to the present definition. In the current status of the list of recommended standard frequencies, this is achieved by some 55 highly accurate absolute frequency measurements of optical transitions. The 698 nm $^{87}$Sr $^1S_0-^3P_0$ transition used in optical lattice standards gathers by far the largest number of measurements and the ones with the highest accuracy from LNE-SYRTE [78][136] and PTB [172]. These measurements are limited by the accuracy of best realizations of the second based on the $^{133}$Cs hyperfine transition. Measurements used to establish the list of recommended values also include a still limited number of optical-to-optical frequency ratios (8 measurements of 5 ratios). Such measurements are not limited by $^{133}$Cs fountain. The best measurements so far have a fractional frequency uncertainties near 5 parts in $10^{17}$ [173][174]. Among optical-to-optical frequency ratios, only the $^{199}$Hg/$^{87}$Sr is measured independently in at least two laboratories (RIKEN [175] and LNE-SYRTE [138]) with uncertainties below the current realization of the SI second. Optical-to-optical ratios measured independently provide means to check the status of optical frequency metrology beyond the limit imposed by
A redefinition of the SI second must not have negative consequences on the elaboration of TAI. This implies that sustainable capability of calibrating TAI scale interval against optical transition(s) must be proven before the redefinition. Most of the current TAI architecture and infrastructure operates in the microwave domain and it will remain so for many more years. Combs enable dividing the frequency of an optical reference to the microwave and RF domains with a limited degradation of its accuracy. An optical frequency standard can thereby readily be inserted in lieu of \(^{133}\)Cs fountains in the TAI calibration processes of metrology institutes, provided that its reference transition is adopted as a secondary representation of the second \(^{42}\). The minimum requirement is to being able to calibrate the mean frequency of a local oscillator linked to TAI (typically, a hydrogen maser) over 5 days of a conventional grid. This was pioneered by LNE-SYRTE using the \(^{87}\)Sr \(^1\)S\(_0\)-\(^3\)P\(_0\) transition. A first series of TAI calibrations with this SRS is reported in the BIPM Circular T350 \(^{47}\). These first calibrations were not used to steering the frequency of TAI. At the beginning of 2019, Circular T372 was published with the first TAI calibrations by optical standards used for steering, still with \(^{87}\)Sr. Reliable operation and use of \(^{87}\)Sr optical lattice standards to this end is described in \(^{136}\). Along the same line, application of a \(^{87}\)Sr optical lattice standard for realizing a representative sample local timescale is reported in \(^{172}\). Remote comparison of \(^{87}\)Sr optical lattice standards over intercontinental baseline via satellite-based methods and for almost 1 day is reported in \(^{177}\). In both cases, the architecture of the timescale and links is in the microwave domain. It remains a topic of investigation to define novel architectures and infrastructures that can take full benefit of the 2 orders of magnitude improved characteristics of optical frequency standards \(^{178}\). Such architectures and infrastructures may include optical fibers links, optical local oscillators, optical clockwork like the one demonstrated in \(^{179}\), and novel methods.

Altogether, CCTF, in its strategy document, keeps a list of requirements for a redefinition of the second based on optical transition(s) to become possible. The aim is to make a choice that will last long, to ensure continuity, to guaranty gapless dissemination in particular via the elaboration of TAI and to validate the uncertainty of optical frequency standards \(^{50}\). CCTF and the joint CCL-CCTF Frequency Standard working group monitor progress of the field in this direction.

8. Chronometric geodesy

Remote comparisons between two identical frequency standards show a frequency ratio \(\nu_2/\nu_1 = [1 - (U_2 - U_1)/c^2]\) where \(U_1\) and \(U_2\) are gravitational potentials at the location of the two standards. This gravitational redshift already mentioned in section 4 amounts to \(\sim 10^{-18}\) per centimeter of elevation in the vicinity of the Earth’s surface. Frequency standards can be viewed as sensors to determine gravitational potential differences for the purpose of geodesy.
and Earth’s science. This method called chronometric geodesy was proposed several decades ago (see for example [180] and references therein). However, it is only now that progress in optical frequency standards and in optical frequency metrology makes this method potentially relevant.

A few years ago, chronometric geodesy gained significant interest from both time and frequency metrology and geodesy communities. Several aspects need being covered. One is to develop methodologies to use data from frequency standards in conjunction with other data already used in gravity field modelling. In this context, optical frequency standards can be considered as sensors of the potential with a point-like spatial response function, since the spread of the atomic sample is less 1 mm. Instead, space-based gravity measurements (GRACE, GOCE missions) gives 1st or higher derivatives of the potential with a spatial response function with characteristic size of 100 km. Gravimeters and gradiometers on ground give the 1st and 2nd derivatives of the potential respectively with a point-like response (0.1 m–1 m), and so on. Geodetic methods to link the potential at the location of a frequency standard to larger and global scale are described in [137][181][182]. These methods were applied to several places in Europe and provided improvements over previous similar determination [183][184][185]. Specific gravimetry and levelling measurements in the vicinity (up to few 10 km) of frequency standard location are required to connect to the regional and global scale to the $10^{-18}$ or equivalently to the 1 cm level. Time variations must be taken into account since tides can produce local gravity potential changes of up to $10^{-16}$. This is described in [186].

Another aspect of investigations of chronometric geodesy is to understand and define cases where data from optical frequency standards can bring the most to applications in geodesy and geophysics. Reference [187] reports one of the first quantitative studies along this line. Representative cases of hilly areas were studied to determine how much adding data from optical frequency standards can improve high spatial resolution gravity modelling. A fully synthetic simulation framework was developed that will be further refined and applied to other cases of potential interest, like for instance, coastal areas. Interest can be two fold: improvement of reference systems and studies of geophysical phenomena. Some possibilities are discussed in [188][189][190][191]. Within the last few years, working groups within the International Association of Geodesy (IAG) were initiated to consider potentialities of chronometric geodesy.

A third aspect is the further development of instrumental capabilities. The long term goal would be to have ruggedized field-compatible optical frequency standards with uncertainties $\leq 10^{-18}$ and means of comparing them from any place of interest on Earth. First proof-of-concept experiments used coherent optical fiber links between laboratories with already existing state-of-the-art optical frequency metrology programs [137][62]. Over the years, transportable optical frequency standards were developed and currently achieve uncertainties in the $10^{-17}$ range [192][193][194], also with the aim to increase technology readiness for space. Recently, one of these devices was used for another proof-of-concept experiment [195] again in conjunction with coherent optical fiber link. Solutions for remote comparisons that reach $10^{-18}$ firstly without optical
fiber link and secondly over intercontinental distances are still missing. For the former, free-space optical links studied in [196][197][198][199] could be extended to a few 100 km distances with the help of an airborne platform.

The further advancement of all the above studies shall lead to first pilot chronometric geodesy programs designed for geodesy, geophysics and Earth's science applications.

9. Conclusions

We described the status of the realization of the SI unit of time according to its current definition. We reported on the tremendous progress of optical frequency metrology over the last 20 years. We mentioned how the CIPM monitors the situation of the field in view of a possible redefinition. To date, work remains to be done to meet all milestones of the CCTF strategy document and to prepare for long-term commitments of the post redefinition era. When this will be achieved, progress of frequency and time metrology and its applications will not need being limited by $^{133}$Cs standards any more. Secondary representations of the second and highly accurate redundant measurements of a sufficient number of optical-to-optical frequency ratios will permit a smooth passage through the redefinition. On the basis of these considerations and taking into account the time for due process at the CIPM and at the CGPM, a redefinition seems possible before 2030. The new definition must last long. Paradoxically, the persistent vitality of research on optical frequency standards could be a reason to delay the redefinition, if new breakthroughs suggest even better choices than those being currently consolidated. One possible choice for the redefinition would be to mimic the present definition and select one single optical transition. In this case, secondary representations will be useful, even needed in practice. The possibility, the shape and the relevance of a system using several transitions on an even basis remain to be explored.

The choice of one particular transition of one particular atom (or a set of them) remains a kind of artefact. Atoms are already complex assemblage of elementary particles and transition frequencies are by far not calculable at the level of uncertainty to which they can be realized by atomic frequency standards. The article of C. Bordé in the present issue of Comptes Rendus presented the deeper foundations of the international system of units, its links with geometry of space-time and with the system of units introduced by Planck based on five fundamental constants. The system adopted by the 26th CGPM is based on fixing $\Delta \nu_{\text{Cs}}$, $c$, $h$, $e$, $k_B$. Moving to a system of units founded solely on most fundamental aspects of physical laws would require to abandon atomic transition(s) for the definition of the unit of time. Referring to Planck’s system, that would mean fixing the gravitational constant $G$ to define Planck’s time $\sqrt{\hbar G/c^3}$. Another somewhat intermediate possibility could be to fix the mass of an elementary particle, for instance, the electron $m_e$ which defines the unit of time as $\hbar/m_e c^2$. Given the utmost importance of practical aspects of the actual implementation of the SI system, it does not seem presently possible to opt for one of these fundamental definitions of time because we do not know how to
realize them with the same exquisite accuracy of atomic frequency standards. Research shall investigate how to measure $G$ or $m_e$ with radically improved accuracy in the SI system of units attached to atomic transitions.

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11. References

References

[1] Comptes rendus de la 13ième CGPM (1967/68) (1969) 103. URL https://www.bipm.org/en/worldwide-metrology/cgpm/resolutions.html

[2] H. Lyons, Spectral Lines as Frequency Standards, Annals of the New York Academy of Sciences 55 (5) (1952) 831–871. doi:10.1111/j.1749-6632.1952.tb26600.x

[3] J. V. L. Essen, L.and Parry, An atomic standard of frequency and time interval: A caesium resonator Nature 176 (4476) (1955) 280–282. URL http://dx.doi.org/10.1038/176280a0

[4] W. Markowitz, R. G. Hall, L. Essen, J. V. L. Parry, Frequency of cesium in terms of ephemeris time Phys. Rev. Lett. 1 (1958) 105–107. doi:10.1103/PhysRevLett.1.105 URL http://link.aps.org/doi/10.1103/PhysRevLett.1.105

[5] T. Quinn, Fifty years of atomic time-keeping: 1955 to 2005, Metrologia 42 (3). doi:10.1088/0026-1394/42/3/E01

[6] C. Salomon, The measurement of time / La mesure du temps: Foreword, Comptes Rendus Physique 16 (5) (2015) 459–460. doi:10.1016/j.crhy.2015.05.006

[7] Comptes rendus de la 17ième CGPM (1983) 10.

[8] Comptes rendus de la 26ième CGPM.

[9] J.-P. Uzan, Varying constants, gravitation and cosmology Living Reviews in Relativity 14 (2). URL http://www.livingreviews.org/lrr-2011-2

[10] C. M. Will, The confrontation between general relativity and experiment Living Reviews in Relativity 17 (1) (2014) 4. doi:10.12942/lrr-2014-4 URL https://doi.org/10.12942/lrr-2014-4
[11] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, C. W. Clark, Search for new physics with atoms and molecules, Rev. Mod. Phys. 90 (2) (2018) 025008. doi:10.1103/RevModPhys.90.025008.

[12] K. Van Tilburg, N. Leefer, L. Bougas, D. Budker, Search for ultralight scalar dark matter with atomic spectroscopy, Phys. Rev. Lett. 115 (2015) 011802. doi:10.1103/PhysRevLett.115.011802 URL http://link.aps.org/doi/10.1103/PhysRevLett.115.011802

[13] A. Hees, J. Guéna, M. Abgrall, S. Bize, P. Wolf, Searching for an oscillating massive scalar field as a dark matter candidate using atomic hyperfine frequency comparisons, Phys. Rev. Lett. 117 (2016) 061301. doi:10.1103/PhysRevLett.117.061301 URL http://link.aps.org/doi/10.1103/PhysRevLett.117.061301

[14] N. Ramsey, Experiments with separated oscillatory fields and hydrogen masers, Rev. Mod. Phys. 62 (1990) 541. doi:https://doi.org/10.1103/RevModPhys.62.541

[15] J. Vanier, C. Audoin, The Quantum Physics of Atomic Frequency Standards, Adam Hilger, 1989.

[16] C. N. Cohen-Tannoudji, Nobel lecture: Manipulating atoms with photons, Rev. Mod. Phys. 70 (1998) 707–719. doi:10.1103/RevModPhys.70.707 URL http://link.aps.org/doi/10.1103/RevModPhys.70.707

[17] W. D. Phillips, Nobel lecture: Laser cooling and trapping of neutral atoms, Rev. Mod. Phys. 70 (3) (1998) 721–741. doi:10.1103/RevModPhys.70.721

[18] S. Chu, Nobel lecture: The manipulation of neutral particles, Rev. Mod. Phys. 70 (1998) 685–706. doi:10.1103/RevModPhys.70.685 URL http://link.aps.org/doi/10.1103/RevModPhys.70.685

[19] M. Kasevich, E. Riis, S. Chu, R. de Voe, RF spectroscopy in an atomic fountain, Phys. Rev. Lett. 63 (1989) 612.

[20] A. Clairon, C. Salomon, S. Guellati, W. Phillips, Ramsey resonance in a Zacharias fountain, Europhys. Lett. 16 (1991) 165.

[21] A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, S. Lea, M. Bahoura, A cesium fountain frequency standard: recent results, IEEE Trans. on Inst. and Meas. 44 (2) (1995) 128.

[22] G. Santarelli, P. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, C. Salomon, Quantum projection noise in an atomic fountain: A high stability cesium frequency standard, Phys. Rev. Lett. 82 (23) (1999) 4619.
[23] J. Guéna, M. Abgrall, D. Rovera, P. Laurent, B. Chupin, M. Lours, G. Santarelli, P. Rosenbusch, M. Tobar, R. Li, K. Gibble, A. Clairon, S. Bize, "Progress in atomic fountains at LNE-SYRTE," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on 59 (3) (2012) 391–410. doi:10.1109/TUFFC.2012.2208 URL https://doi.org/10.1109/TUFFC.2012.2208

[24] J. Guéna, R. Li, K. Gibble, S. Bize, A. Clairon, "Evaluation of Doppler shifts to improve the accuracy of primary atomic fountain clocks," Phys. Rev. Lett. 106 (13) (2011) 130801. doi:10.1103/PhysRevLett.106.130801 URL https://doi.org/10.1103/PhysRevLett.106.130801

[25] R. Li, K. Gibble, "Evaluating and minimizing distributed cavity phase errors in atomic clocks," Metrologia 47 (5) (2010) 534. URL http://stacks.iop.org/0026-1394/47/i=5/a=004

[26] F. Pereira Dos Santos, H. Marion, S. Bize, Y. Sortais, A. Clairon, C. Salomon, "Controlling the cold collision shift in high precision atomic interferometry," Phys. Rev. Lett. 89 (2002) 233004.

[27] D. J. Papoular, S. Bize, A. Clairon, H. Marion, S. J. J. M. F. Kokkelmans, G. V. Shlyapnikov, "Feshbach resonances in cesium at ultralow static magnetic fields," Phys. Rev. A 86 (2012) 040701. doi:10.1103/PhysRevA.86.040701 URL http://link.aps.org/doi/10.1103/PhysRevA.86.040701

[28] K. Szymaniec, W. Chalupczak, E. Tiesinga, C. J. Williams, S. Weyers, R. Wynands, "Cancellation of the collisional frequency shift in caesium fountain clocks," Phys. Rev. Lett. 98 (15) (2007) 153002. doi:10.1103/PhysRevLett.98.153002

[29] K. Gibble, "Scattering of cold-atom coherences by hot atoms: Frequency shifts from background-gas collisions," Phys. Rev. Lett. 110 (12) (2013) 180802. doi:10.1103/PhysRevLett.110.180802 URL http://link.aps.org/doi/10.1103/PhysRevLett.110.180802

[30] K. Szymaniec, S. Lea, K. Liu, "An evaluation of the frequency shift caused by collisions with background gas in the primary frequency standard NPL-CsF2," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on 61 (1) (2014) 203–206. doi:10.1109/TUFFC.2014.6689789

[31] K. Gibble, "Difference between a photon’s momentum and an atom’s recoil," Phys. Rev. Lett. 97 (7) (2006) 073002. doi:10.1103/PhysRevLett.97.073002 URL http://link.aps.org/abstract/PRL/v97/e073002

[32] R. Li, K. Gibble, K. Szymaniec, "Improved accuracy of the NPL-CsF2 primary frequency standard: Evaluation of distributed cavity phase and microwave lensing frequency shifts," Metrologia 48 (5) (2011) 283. URL http://stacks.iop.org/0026-1394/48/i=5/a=007
[33] K. Gibble, Ramsey spectroscopy, matter-wave interferometry, and the microwave-lensing frequency shift, Phys. Rev. A 90 (2014) 015601. doi:10.1103/PhysRevA.90.015601
URL http://link.aps.org/doi/10.1103/PhysRevA.90.015601

[34] W. Itano, L. Lewis, D. Wineland, Shift of $^2S_{1/2}$ hyperfine splittings due to blackbody radiation, Phys. Rev. A. 25 (1982) 1233.

[35] R. Jefferts, S. P. Heavner, T. E. Parker, T. H. Shirley, J. A. Donley, E. N. Ashby, F. Levi, D. Calonico, G. A. Costanzo, High-accuracy measurement of the blackbody radiation frequency shift of the ground-state hyperfine transition in $^{133}$Cs, Phys. Rev. Lett. 112 (2014) 050801. doi:10.1103/PhysRevLett.112.050801
URL http://link.aps.org/doi/10.1103/PhysRevLett.112.050801

[36] T. P. Heavner, E. A. Donley, F. Levi, G. Costanzo, T. E. Parker, J. H. Shirley, N. Ashby, S. Barlow, S. R. Jefferts, First accuracy evaluation of NIST-F2, Metrologia 51 (3) (2014) 174.
URL http://stacks.iop.org/0026-1394/51/i=3/a=174

[37] F. Levi, D. Calonico, C. E. Calosso, A. Godone, S. Micalizio, G. A. Costanzo, Accuracy evaluation of ITCsF2: a nitrogen cooled caesium fountain, Metrologia 51 (3) (2014) 270.
URL http://stacks.iop.org/0026-1394/51/i=3/a=270

[38] A. Jallageas, L. Devenoges, M. Petersen, J. Morel, L. G. Bernier, D. Schenker, P. Thomann, T. Südmeyer, First uncertainty evaluation of the FoCS-2 primary frequency standard, Metrologia 55 (3) (2018) 366. doi:10.1088/1681-7575/aab3fa

[39] R. Wynands, S. Weyers, Atomic fountain clocks, Metrologia 42 (3) (2005) S64.
URL http://stacks.iop.org/0026-1394/42/i=3/a=S08

[40] F. Riehle, 8th symposium on frequency standards and metrology 2015, Journal of Physics: Conference Series 723 (1) (2016) 011001.
URL http://stacks.iop.org/1742-6596/723/i=1/a=011001

[41] J. Guéna, P. Rosenbusch, P. Laurent, M. Abgrall, D. Rovera, G. Santarelli, M. Tobar, S. Bize, A. Clairon, Demonstration of a dual alkali Rb/Cs fountain clock, Ultrasons, Ferroelectrics and Frequency Control, IEEE Transactions on 57 (3) (2010) 647. doi:10.1109/TUFFC.2010.1461
URL https://doi.org/10.1109/TUFFC.2010.1461

[42] J. Guéna, M. Abgrall, A. Clairon, S. Bize, Contributing to TAI with a secondary representation of the second, Metrologia 51 (1) (2014) 108.
URL http://stacks.iop.org/0026-1394/51/i=1/a=108
See the list of Secondary Representations of the SI second and of other recommended values of standard frequencies on the BIPM website.

URL http://www.bipm.org/en/publications/mep.html

A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, P. Uhrich, Comparison between frequency standards in Europe and the USA at the $10^{-15}$ uncertainty level, Metrologia 43 (1) (2006) 109–120.

URL http://stacks.iop.org/0026-1394/43/109

J. Guna, S. Weyers, M. Abgrall, C. Grebing, V. Gerginov, P. Rosenbusch, S. Bize, B. Lipphardt, H. Denker, N. Quintin, S. M. F. Raupach, D. Nicolodi, F. Stefani, N. Chiodo, S. Koke, A. Kuhl, F. Wiotte, F. Meynadier, E. Camisard, C. Chardonnet, Y. L. Coq, M. Lours, G. Santarelli, A. Amy-Klein, R. L. Targat, O. Lopez, P. E. Pottie, G. Grosche, First international comparison of fountain primary frequency standards via a long distance optical fibre link, Metrologia 54 (3) (2017) 348.

URL http://stacks.iop.org/0026-1394/54/i=3/a=348

G. Petit, F. Arias, G. Panfilo, International atomic time: Status and future challenges, Comptes Rendus Physique 16 (5) (2015) 480 – 488, the measurement of time / La mesure du temps.

doi: http://dx.doi.org/10.1016/j.crhy.2015.03.002

URL http://www.sciencedirect.com/science/article/pii/S1631070515000635

See Circular T and fountain reports on the BIPM website.

URL https://www.bipm.org/fr/bipm-services/timescales/time-ftp/Circular-T.html

T. E. Parker, Invited review article: The uncertainty in the realization and dissemination of the SI second, Review of Scientific Instruments 83 (2) (2012) 021102.

doi:10.1063/1.3682002

URL http://link.aip.org/link/?RSI/83/021102/1

G. Petit, G. Panfilo, Comparison of frequency standards used for TAI, Instrumentation and Measurement, IEEE Transactions on 62 (99) (2013) 1550.

doi:10.1109/TIM.2012.2228749

F. Riehle, P. Gill, F. Arias, L. Robertsson, The CIPM list of recommended frequency standard values: guidelines and procedures, Metrologia 55 (2) (2018) 188.

URL http://stacks.iop.org/0026-1394/55/i=2/a=188

H. Hachisu, G. Petit, F. Nakagawa, Y. Hanado, T. Ido, SI-traceable measurement of an optical frequency at the low $10^{-16}$ level without a local primary standard, Opt. Express 25 (8) (2017) 8511–8523.

doi:10.1364/OE.25.008511

URL http://www.opticsexpress.org/abstract.cfm?URI=oe-25-8-8511

W. F. McGrew, X. Zhang, H. Leopardi, R. J. Fasano, D. Nicolodi, K. Beloy, J. Yao, J. A. Sherman, S. A. Schäffer, J. Savory, R. C. Brown,
S. Römisch, C. W. Oates, T. E. Parker, T. M. Fortier, A. D. Ludlow, Towards Adoption of an Optical Second: Verifying Optical Clocks at the SI Limit, arXiv:1811.05885 [physics] arXiv:1811.05885.

[53] N. Ashby, T. P. Heavner, S. R. Jefferts, T. E. Parker, A. G. Radnaev, Y. O. Dudin, Testing Local Position Invariance with four cesium-fountain primary frequency standards and four NIST hydrogen masers, Phys. Rev. Lett. 98 (2007) 070802. doi:10.1103/PhysRevLett.98.070802 URL http://link.aps.org/abstract/PRL/v98/e070802.

[54] N. Ashby, T. E. Parker, B. R. Patla, A null test of general relativity based on a long-term comparison of atomic transition frequencies, Nature Physics (2018) doi:10.1038/s41567-018-0156-2.

[55] A. Bauch, S. Weyers, D. Piester, E. Staliuniene, W. Yang, Generation of UTC(PTB) as a fountain-clock based time scale Metrologia 49 (3) (2012) 180. URL http://stacks.iop.org/0026-1394/49/i=3/a=180.

[56] S. Peil, J. L. Hanssen, T. B. Swanson, J. Taylor, C. R. Ekstrom, Evaluation of long term performance of continuously running atomic fountains, Metrologia 51 (3) (2014) 263. URL http://stacks.iop.org/0026-1394/51/i=3/a=263.

[57] G. D. Rovera, S. Bize, B. Chupin, J. Guéna, P. Laurent, P. Rosenbusch, P. Uhrich, M. Abgrall, UTC(OP) based on LNE-SYRTE atomic fountain primary frequency standards, Metrologia 53 (3) (2016) S81. URL http://stacks.iop.org/0026-1394/53/i=3/a=S81.

[58] G. Petit, F. Arias, A. Harmegnies, G. Panfilo, L. Tisserand, UTCr: a rapid realization of UTC, Metrologia 51 (1) (2014) 33. URL http://stacks.iop.org/0026-1394/51/i=1/a=33.

[59] T. W. Hansch, Nobel lecture: Passion for precision, Reviews of Modern Physics 78 (4) (2006) 1297. doi:10.1103/RevModPhys.78.1297 URL http://link.aps.org/abstract/RMP/v78/p1297.

[60] J. L. Hall, Nobel lecture: Defining and measuring optical frequencies Reviews of Modern Physics 78 (4) (2006) 1279. doi:10.1103/RevModPhys.78.1279 URL http://link.aps.org/abstract/RMP/v78/p1279.

[61] W. F. McGrew, X. Zhang, R. J. Fasano, S. A. Schäffer, K. Beloy, D. Nicolodi, R. C. Brown, N. Hinkley, G. Milani, M. Schioppo, T. H. Yoon, A. D. Ludlow, Atomic clock performance enabling geodesy below the centimetre level, Nature (2018) doi:10.1038/s41586-018-0738-2.
[62] T. Takano, M. Takamoto, I. Ushijima, N. Ohmae, T. Akatsuka, A. Yamaguchi, Y. Kuroishi, H. Munekane, B. Miyahara, H. Katori, Geopotential measurements with synchronously linked optical lattice clocks, Nat Photon advance online publication. URL [http://dx.doi.org/10.1038/nphoton.2016.159](http://dx.doi.org/10.1038/nphoton.2016.159)

[63] N. Huntemann, C. Sanner, B. Lipphardt, C. Tamm, E. Peik, Single-ion atomic clock with $3 \times 10^{-18}$ systematic uncertainty, Phys. Rev. Lett. 116 (2016) 063001. doi:10.1103/PhysRevLett.116.063001 URL [http://link.aps.org/doi/10.1103/PhysRevLett.116.063001](http://link.aps.org/doi/10.1103/PhysRevLett.116.063001)

[64] 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, W. L. Tew, J. Ye, Systematic evaluation of an atomic clock at $2 \times 10^{-18}$ total uncertainty, Nature Communications 6 (2015) 6896. URL [https://doi.org/10.1038/ncomms7896](https://doi.org/10.1038/ncomms7896)

[65] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, H. Katori, Cryogenic optical lattice clocks, Nat Photon 9 (2015) 185. URL [http://dx.doi.org/10.1038/nphoton.2015.5](http://dx.doi.org/10.1038/nphoton.2015.5)

[66] B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bischof, X. Zhang, W. Zhang, S. L. Bromley, J. Ye, An optical lattice clock with accuracy and stability at the $10^{-18}$ level, Nature 506 (2014) 71. URL [http://dx.doi.org/10.1038/nature12941](http://dx.doi.org/10.1038/nature12941)

[67] K. Beloy, N. Hinkley, N. B. Phillips, J. A. Sherman, M. Schioppo, J. Lehman, A. Feldman, L. M. Hanssen, C. W. Oates, A. D. Ludlow, Atomic clock with $1 \times 10^{-18}$ room-temperature blackbody stark uncertainty, Phys. Rev. Lett. 113 (2014) 260801. doi:10.1103/PhysRevLett.113.260801 URL [http://link.aps.org/doi/10.1103/PhysRevLett.113.260801](http://link.aps.org/doi/10.1103/PhysRevLett.113.260801)

[68] P. Dubé, A. A. Madej, M. Tibbo, J. E. Bernard, High-accuracy measurement of the differential scalar polarizability of a $^{88}$Sr$^+$ clock using the time-dilation effect, Phys. Rev. Lett. 112 (2014) 173002. doi:10.1103/PhysRevLett.112.173002 URL [http://link.aps.org/doi/10.1103/PhysRevLett.112.173002](http://link.aps.org/doi/10.1103/PhysRevLett.112.173002)

[69] T. Middelmann, S. Falke, C. Lisdat, U. Sterr, High accuracy correction of blackbody radiation shift in an optical lattice clock, Phys. Rev. Lett. 109 (2012) 263004. doi:10.1103/PhysRevLett.109.263004 URL [http://link.aps.org/doi/10.1103/PhysRevLett.109.263004](http://link.aps.org/doi/10.1103/PhysRevLett.109.263004)

[70] J. A. Sherman, N. D. Lenke, N. Hinkley, M. Pizzocaro, R. W. Fox, A. D. Ludlow, C. W. Oates,
High-accuracy measurement of atomic polarizability in an optical lattice clock, Phys. Rev. Lett. 108 (2012) 153002. doi:10.1103/PhysRevLett.108.153002
URL http://link.aps.org/doi/10.1103/PhysRevLett.108.153002

[71] M. Doležal, P. Balling, P. B. R. Nisbet-Jones, S. A. King, J. M. Jones, H. A. Klein, P. Gill, T. Lindvall, A. E. Wallin, M. Merima, C. Tamm, C. Sanner, N. Huntemann, N. Scharnhorst, I. D. Leroux, P. O. Schmidt, T. Burgermeister, T. E. Mehlstäubler, E. Peik, Analysis of thermal radiation in ion traps for optical frequency standards, Metrologia 52 (6) (2015) 842. URL http://stacks.iop.org/0026-1394/52/i=6/a=842

[72] J. Lodewyck, M. Zawada, L. Lorini, M. Gurov, P. Lemonde, Observation and cancellation of a perturbing dc stark shift in strontium optical lattice clocks, Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on 59 (3) (2012) 411 –415. doi:10.1109/TUFFC.2012.2209

[73] P. G. Westergaard, J. Lodewyck, L. Lorini, A. Lecallier, E. A. Burt, M. Zawada, J. Millo, P. Lemonde, Lattice-induced frequency shifts in Sr optical lattice clocks at the 10^{-17} level, Phys. Rev. Lett. 106 (21) (2011) 210801. doi:10.1103/PhysRevLett.106.210801

[74] R. C. Brown, N. B. Phillips, K. Beloy, W. F. McGrew, M. Schioppo, R. J. Fasano, G. Milani, X. Zhang, N. Hinkley, H. Leopardi, T. H. Yoon, D. Nicolodi, T. M. Fortier, A. D. Ludlow, Hyperpolarizability and Operational Magic Wavelength in an Optical Lattice Clock, Phys. Rev. Lett. 119 (25) (2017) 253001. doi:10.1103/PhysRevLett.119.253001

[75] S. L. Campbell, R. B. Hutson, G. E. Marti, A. Goban, N. Darkwah Oppong, R. L. McNally, L. Sonderhouse, J. M. Robinson, W. Zhang, B. J. Bloom, J. Ye, A fermi-degenerate three-dimensional optical lattice clock, Science 358 (6359) (2017) 90–94, arXiv:http://science.sciencemag.org/content/358/6359/90.full.pdf, doi:10.1126/science.aam5538
URL http://science.sciencemag.org/content/358/6359/90

[76] V. I. Yudin, A. V. Taichenachev, C. W. Oates, Z. W. Barber, N. D. Lemke, A. D. Ludlow, U. Sterr, C. Lisdat, F. Riehle, Hyper-ramsey spectroscopy of optical clock transitions, Phys. Rev. A 82 (1) (2010) 011804. doi:10.1103/PhysRevA.82.011804

[77] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, T. Rosenband, Frequency comparison of two high-accuracy Al^+ optical clocks, Phys. Rev. Lett. 104 (7) (2010) 070802. doi:10.1103/PhysRevLett.104.070802
[78] R. Le Targat, L. Lorini, Y. Le Coq, M. Zawada, J. Guéna, M. Abgrall, M. Gurov, P. Rosenbusch, D. G. Rovera, B. Nagó, R. Garton, P. G. Westergaard, M. Lours, G. Santarelli, A. Clairon, S. Bize, P. Laurent, P. Lemonde, J. Lodewyck, Experimental realization of an optical second with strontium lattice clocks, Nat Commun 4 (2013) 2109.
URL http://dx.doi.org/10.1038/ncomms3109

[79] J. R. W. S. L. C. M. B. X. Z. W. Z. S. L. B. J. Y. B. J. Bloom, T. L. Nicholson, A new generation of atomic clocks: Accuracy and stability at the $10^{-18}$ level, arXiv:1309.1137.

[80] Y. Huang, H. Guan, P. Liu, W. Bian, L. Ma, K. Liang, T. Li, K. Gao, Frequency comparison of two $^{40}$Ca$^{+}$ optical clocks with an uncertainty at the $10^{-17}$ level, Phys. Rev. Lett. 116 (2016) 013001.
doi:10.1103/PhysRevLett.116.013001
URL http://link.aps.org/doi/10.1103/PhysRevLett.116.013001

[81] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt, Optical atomic clocks, Rev. Mod. Phys. 87 (2015) 637–701.
doi:10.1103/RevModPhys.87.637
URL http://link.aps.org/doi/10.1103/RevModPhys.87.637

[82] J. Bergquist, W. Itano, D. Wineland, Recoilless optical absorption and doppler sidebands of a single trapped ion, Phys. Rev. A 36 (1987) 428.

[83] W. Paul, Electromagnetic traps for charged and neutral particles, Rev. Mod. Phys. 62 (1990) 531.

[84] D. Leibfried, R. Blatt, C. Monroe, D. Wineland, Quantum dynamics of single trapped ions, Rev. Mod. Phys. 75 (1) (2003) 281–324.
doi:10.1103/RevModPhys.75.281

[85] H. Katori, Spectroscopy of strontium atoms in the Lamb-Dicke confinement, in: Proc. of the 6th Symposium on Frequency Standards and Metrology, World scientific, Singapore, 2001, p. 323.

[86] H. Katori, M. Takamoto, V. G. Pal’chikov, V. D. Ovsiannikov, Ultrastable optical clock with neutral atoms in an engineered light shift trap, Phys. Rev. Lett. 91 (17) (2003) 173005.
doi:10.1103/PhysRevLett.91.173005

[87] J. Ye, H. J. Kimble, H. Katori, Quantum state engineering and precision metrology using state-insensitive light traps, Science 320 (5884) (2008) 1734–1738.
arXiv:http://www.sciencemag.org/content/320/5884/1734.full.pdf
doi:10.1126/science.1148259
URL http://www.sciencemag.org/content/320/5884/1734.abstract
[88] S. M., C. Brown R., F. McGrew W., H. N., J. Fasano R., B. K., H. Yoon T., M. G., N. D., A. Sherman J., B. Phillips N., W. Oates C., D. Ludlow A., Ultrastable optical clock with two cold-atom ensembles, Nat Photon 11 (1) (2017) 48–52. URL http://dx.doi.org/10.1038/nphoton.2016.231

[89] N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lenke, K. Beloy, M. Pizzocaro, C. W. Oates, A. D. Ludlow, An atomic clock with $10^{-18}$ instability, Science 341 (6151) (2013) 1215–1218. arXiv:http://www.sciencemag.org/content/341/6151/1215.full.pdf, doi:10.1126/science.1240420. URL http://www.sciencemag.org/content/341/6151/1215.abstract

[90] M. Takamoto, T. Takano, H. Katori, Frequency comparison of optical lattice clocks beyond the Dick limit, Nat Photon advance online publication (2011) –. URL http://dx.doi.org/10.1038/nphoton.2011.34

[91] T. L. Nicholson, M. J. Martin, J. R. Williams, B. J. Bloom, M. Bishof, M. D. Swallows, S. L. Campbell, J. Ye, Comparison of two independent Sr optical clocks with $1 \times 10^{-17}$ stability at $10^3$ s, Phys. Rev. Lett. 109 (2012) 230801. doi:10.1103/PhysRevLett.109.230801. URL http://link.aps.org/doi/10.1103/PhysRevLett.109.230801

[92] A. Al-Masoudi, S. Dörscher, S. Häfner, U. Sterr, C. Lisdat, Noise and instability of an optical lattice clock, Phys. Rev. A 92 (2015) 063814. doi:10.1103/PhysRevA.92.063814. URL http://link.aps.org/doi/10.1103/PhysRevA.92.063814

[93] G. E. Marti, R. B. Hutson, A. Goban, S. L. Campbell, N. Poli, J. Ye, Imaging Optical Frequencies with 100 µHz Precision and 1.1 µm Resolution, Phys. Rev. Lett. 120 (10) (2018) 103201. doi:10.1103/PhysRevLett.120.103201

[94] C. W. Chou, D. B. Hume, M. J. Thorpe, D. J. Wineland, T. Rosenband, Quantum coherence between two atoms beyond $Q = 10^{15}$, Phys. Rev. Lett. 106 (16) (2011) 160801. doi:10.1103/PhysRevLett.106.160801

[95] K. Numata, A. Kemery, J. Camp, Thermal-noise limit in the frequency stabilization of lasers with rigid cavities, Phys. Rev. Lett. 93 (25) (2004) 250602. doi:10.1103/PhysRevLett.93.250602. URL http://link.aps.org/abstract/PRL/v93/e250602

[96] M. Swallows, M. Martin, M. Bishof, C. Benko, Y. Lin, S. Blatt, A. Rey, J. Ye, Operating a $^{87}$Sr optical lattice clock with high precision and at high density, Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on 59 (3) (2012) 416–425. doi:10.1109/TUFFC.2012.2210
[97] S. Häfler, S. Falke, C. Grebing, S. Vogt, T. Legero, M. Merimaa, C. Lisdat, U. Sterr, $8 \times 10^{-17}$ fractional laser frequency instability with a long room-temperature cavity, Opt. Lett. 40 (9) (2015) 2112–2115. doi:10.1364/OL.40.002112 URL http://ol.osa.org/abstract.cfm?URI=ol-40-9-2112

[98] T. Kessler, C. Hagemann, C. Grebing, T. Legero, U. Sterr, F. Riehle, M. J. Martin, L. Chen, J. Ye, A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity, Nature Photonics 6 (10) (2012) 687–692. doi:10.1038/nphoton.2012.217

[99] D. G. Matei, T. Legero, S. Häfler, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle, U. Sterr, 1.5 µm lasers with sub 10 mHz linewidth, Phys. Rev. Lett. 118 (2017) 263202. doi:10.1103/PhysRevLett.118.263202 URL https://link.aps.org/doi/10.1103/PhysRevLett.118.263202

[100] G. D. Cole, W. Zhang, M. J. Martin, J. Ye, M. Aspelmeyer, Tenfold reduction of brownian noise in high-reflectivity optical coatings Nat Photon 7 (8) (2013) 644–650. doi:10.1038/nphoton.2013.174

[101] Q.-F. Chen, A. Troshyn, I. Ernsting, S. Kayser, S. Vasilyev, A. Nevsy, S. Schiller, Spectrally narrow, long-term stable optical frequency reference based on a Eu$^{3+}$:Y$_2$SiO$_5$ crystal at cryogenic temperature, Phys. Rev. Lett. 107 (2011) 223202. doi:10.1103/PhysRevLett.107.223202 URL http://link.aps.org/doi/10.1103/PhysRevLett.107.223202

[102] M. J. Thorpe, L. Rippe, T. M. Fortier, M. S. Kirchner, T. Rosenband, Frequency stabilization to $6 \times 10^{-16}$ via spectral-hole burning, Nat Photon 6 (2011) 688. doi:10.1038/nphoton.2011.215

[103] O. Gobron, K. Jung, N. Galland, K. Predel, R. L. Targat, A. Ferrier, P. Goldner, S. Seidelin, Y. L. Coq, Dispersive heterodyne probing method for laser frequency stabilization based on spectral hole burning in Yb$^{3+}$:Y$_2$SiO$_5$, Opt. Express 25 (13) (2017) 15539–15548. doi:10.1364/OE.25.015539 URL http://www.opticsexpress.org/abstract.cfm?URI=oe-25-13-15539

[104] D. Yu, J. Chen, Optical clock with millihertz linewidth based on a phase-matching effect, Phys. Rev. Lett. 98 (5) (2007) 050801. doi:10.1103/PhysRevLett.98.050801 URL http://link.aps.org/abstract/PRL/v98/e050801

[105] D. Meiser, J. Ye, D. R. Carlson, M. J. Holland, Prospects for a millihertz-linewidth laser, Physical Review Letters 102 (16) (2009) 163601. doi:10.1103/PhysRevLett.102.163601 URL http://link.aps.org/abstract/PRL/v102/e163601
[106] M. A. Norcia, J. R. K. Cline, J. A. Muniz, J. M. Robinson, R. B. Hutson, A. Goban, G. E. Marti, J. Ye, J. K. Thompson, Frequency Measurements of Superradiance from the Strontium Clock Transition, Phys. Rev. X 8 (2) (2018) 021036. doi:10.1103/PhysRevX.8.021036

[107] S. Wehner, D. Elkouss, R. Hanson, Quantum internet: A vision for the road ahead, Science 362 (6412) (2018) eaam9288. doi:10.1126/science.aam9288

[108] C. L. Degen, F. Reinhard, P. Cappellaro, Quantum sensing, Rev. Mod. Phys. 89 (2017) 035002. doi:10.1103/RevModPhys.89.035002
URL https://link.aps.org/doi/10.1103/RevModPhys.89.035002

[109] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, D. J. Wineland, Spectroscopy using quantum logic, Science 309 (5735) (2005) 749–752. URL http://www.sciencemag.org/cgi/content/abstract/309/5735/749

[110] D. J. Wineland, Nobel lecture: Superposition, entanglement, and raising Schrödinger’s cat, Rev. Mod. Phys. 85 (2013) 1103–1114. doi:10.1103/RevModPhys.85.1103
URL http://link.aps.org/doi/10.1103/RevModPhys.85.1103

[111] C. F. Roos, M. Chwalla, K. Kim, M. Riebe, R. Blatt, “designer atoms” for quantum metrology, Nature 443 (7109) (2006) 316–319. URL http://dx.doi.org/10.1038/nature05101

[112] D. Leibfried, B. DeMarco, V. Meyer, M. Rowe, A. Ben-Kish, J. Britton, W. M. Itano, B. Jelenković, C. Langer, T. Rosenband, D. J. Wineland, Trapped-ion quantum simulator: Experimental application to nonlinear interferometers, Phys. Rev. Lett. 89 (2002) 247901. doi:10.1103/PhysRevLett.89.247901
URL http://link.aps.org/doi/10.1103/PhysRevLett.89.247901

[113] J. Keller, T. Burgermeister, D. Kalincev, A. Didier, A. P. Kulosa, T. Nordmann, J. Kiethe, T. E. Mehlstäubler, Controlling systematic frequency uncertainties at the 10⁻¹⁹ level in linear Coulomb crystals, Phys. Rev. A 99 (1) (2019) 013405. doi:10.1103/PhysRevA.99.013405

[114] I. Bouchoule, K. Mølmer, Preparation of spin-squeezed atomic states by optical-phase-shift measurement, Phys. Rev. A 66 (4) (2002) 043811. doi:10.1103/PhysRevA.66.043811

[115] D. J. Wineland, J. J. Bollinger, W. M. Itano, F. L. Moore, D. J. Heinzen, Spin squeezing and reduced quantum noise in spectroscopy, Phys. Rev. A 46 (1992) R6797–R6800. doi:10.1103/PhysRevA.46.R6797
URL http://link.aps.org/doi/10.1103/PhysRevA.46.R6797

28
[116] P. J. Windpassinger, D. Oblak, P. G. Petrov, M. Kubasik, M. Saffman, C. L. G. Alzar, J. Appel, J. H. Müller, N. Kjærgaard, E. S. Polzik, Nondestructive probing of Rabi oscillations on the cesium clock transition near the standard quantum limit, Phys. Rev. Lett. 100 (10) (2008) 103601. doi:10.1103/PhysRevLett.100.103601 URL http://link.aps.org/abstract/PRL/v100/e103601

[117] A. Louchet-Chauvet, J. Appel, J. J. Renema, D. Oblak, N. Kjaergaard, E. S. Polzik, Entanglement-assisted atomic clock beyond the projection noise limit, New Journal of Physics 12 (6) (2010) 065032. URL http://stacks.iop.org/1367-2630/12/i=6/a=065032

[118] O. Hosten, N. J. Engelsen, R. Krishnakumar, M. A. Kasevich, Measurement noise 100 times lower than the quantum-projection limit using entangled atoms, Nature 529 (7587) (2016) 505–508. URL http://dx.doi.org/10.1038/nature16176

[119] J. Lodewyck, P. G. Westergaard, P. Lemonde, Nondestructive measurement of the transition probability in a Sr optical lattice clock, Physical Review A (Atomic, Molecular, and Optical Physics) 79 (6) (2009) 061401. doi:10.1103/PhysRevA.79.061401 URL http://link.aps.org/abstract/PRA/v79/e061401

[120] G. Vallet, E. Bookjans, U. Eismann, S. Bilicki, R. L. Targat, J. Lodewyck, A noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime, New Journal of Physics 19 (8) (2017) 083002. URL http://stacks.iop.org/1367-2630/19/i=8/a=083002

[121] N. Shiga, M. Takeuchi, Locking the local oscillator phase to the atomic phase via weak measurement, New Journal of Physics 14 (2) (2012) 023034. URL http://stacks.iop.org/1367-2630/14/i=2/a=023034

[122] R. Kohlhaas, A. Bertoldi, E. Cantin, A. Aspect, A. Landragin, P. Bouyer, Phase locking a clock oscillator to a coherent atomic ensemble, Phys. Rev. X 5 (2015) 021011. doi:10.1103/PhysRevX.5.021011 URL http://link.aps.org/doi/10.1103/PhysRevX.5.021011

[123] I. Kruse, K. Lange, J. Peise, B. Lcke, L. Pezz, J. Arlt, W. Ertmer, C. Lisdat, L. Santos, A. Smerzi, C. Klemt, Improvement of an Atomic Clock using Squeezed Vacuum, Phys. Rev. Lett. 117 (14) (2016) 143004. doi:10.1103/PhysRevLett.117.143004

[124] I. D. Leroux, M. H. Schleier-Smith, V. Vuletić, Orientation-dependent entanglement lifetime in a squeezed atomic clock, Phys. Rev. Lett. 104 (25) (2010) 250801. doi:10.1103/PhysRevLett.104.250801

[125] I. D. Leroux, M. H. Schleier-Smith, V. Vuletić, Implementation of cavity squeezing of a collective atomic spin, Phys. Rev. Lett. 104 (7) (2010) 073602. doi:10.1103/PhysRevLett.104.073602
[126] S. A. Diddams, The evolving optical frequency comb [invited], J. Opt. Soc. Am. B 27 (11) (2010) B51–B62. doi:10.1364/JOSAB.27.000B51
URL http://josab.osa.org/abstract.cfm?URI=josab-27-11-B51

[127] N. R. Newbury, Searching for applications with a fine-tooth comb, Nature Photonics 5 (2011) 186–188. doi:10.1038/nphoton.2011.38

[128] D. Nicolodi, B. Argence, W. Zhang, R. Le Targat, G. Santarelli, Y. Le Coq, Spectral purity transfer between optical wavelengths at the $10^{-18}$ level, Nat Photon 8 (2014) 219.
URL http://dx.doi.org/10.1038/nphoton.2013.361

[129] X. Xie, R. Bouchand, D. Nicolodi, M. Giunta, W. Hnsel, M. Lezius, A. Joshi, S. Datta, C. Alexandre, M. Lours, P.-A. Tremblin, G. Santarelli, R. Holzwarth, Y. Le Coq, Photonic microwave signals with zeptosecond-level absolute timing noise, Nat Photon 11 (1) (2017) 44–47.
URL http://dx.doi.org/10.1038/nphoton.2016.215

[130] F. N. Baynes, F. Quinlan, T. M. Fortier, Q. Zhou, A. Beling, J. C. Campbell, S. A. Diddams, Attosecond timing in optical-to-electrical conversion, Optica 2 (2) (2015) 141–146. doi:10.1364/OPTICA.2.000141
URL http://www.opticsinfobase.org/optica/abstract.cfm?URI=optica-2-2-141

[131] N. Ohmae, N. Kuse, M. E. Fermann, H. Katori, All-polarization-maintaining, single-port er:erbium fiber comb for high-stability comparison of optical lattice clocks, Applied Physics Express 10 (6) (2017) 062503.
URL http://stacks.iop.org/1882-0786/10/i=6/a=062503

[132] Y. Le Coq et al., Peignes de fréquences femtosecondes pour la mesure des fréquences optiques, Revue Franaise de Métérologie 32 (2012) 35.

[133] J. Millo, M. Abgrall, M. Lours, E. M. L. English, H. Jiang, J. Guéna, A. Clairon, M. E. Tobar, S. Bize, Y. L. Coq, G. Santarelli, Ultralow noise microwave generation with fiber-based optical frequency comb and application to atomic clocks, Applied Physics Letters 94 (14) (2009) 141105. doi:10.1063/1.3112574
URL http://link.aip.org/link/?APL/94/141105/1

[134] S. Weyers, B. Lipphardt, H. Schnatz, Reaching the quantum limit in a fountain clock using a microwave oscillator phase locked to an ultrastable laser, Phys. Rev. A 79 (3) (2009) 031803. doi:10.1103/PhysRevA.79.031803
URL http://link.aps.org/abstract/PRA/v79/e031803

[135] B. Lipphardt, V. Gerginov, S. Weyers, Optical stabilization of a microwave oscillator for fountain clock interrogation, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 64 (4) (2017) 761–766. doi:10.1109/TUFFC.2017.2649044
[136] J. Lodewyck, S. Bilicki, E. Bookjans, J.-L. Robyr, C. Shi, G. Vallet, R. L. Targat, D. Nicolodi, Y. L. Coq, J. Guéna, M. Abgrall, P. Rosenbusch, S. Bize, Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock, Metrologia 53 (4) (2016) 1123. URL http://stacks.iop.org/0026-1394/53/i=4/a=1123

[137] C. Lisdat, G. Grosche, N. Quintin, C. Shi, S. Raupach, C. Grebing, D. Nicolodi, F. Stefani, A. Al-Masoudi, S. Dorscher, S. Hafner, J.-L. Robyr, N. Chiodo, S. Bilicki, E. Bookjans, A. Koczwarra, S. Koke, A. Kuhl, F. Wiotte, F. Meynadier, E. Camisard, M. Abgrall, M. Lours, T. Legero, H. Schnatz, U. Sterr, H. Denker, C. Chardonnet, Y. L. Le Coq, G. Santarelli, A. Amy-Klein, R. L. Targat, J. Lodewyck, O. Lopez, P.-E. Pottie, A clock network for geodesy and fundamental science, Nat Commun 7 (2016) 12443. URL http://dx.doi.org/10.1038/ncomms12443

[138] R. Tyumenev, M. Favier, S. Bilicki, E. Bookjans, R. L. Targat, J. Lodewyck, D. Nicolodi, Y. L. Coq, M. Abgrall, J. Guéna, L. D. Sarlo, S. Bize, Comparing a mercury optical lattice clock with microwave and optical frequency standards, New Journal of Physics 18 (11) (2016) 113002. URL http://stacks.iop.org/1367-2630/18/i=11/a=113002

[139] G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonneau, A. Clairon, O. Lopez, A. Amy-Klein, C. Chardonnet, Transmission of an optical carrier frequency over a telecommunication fiber link in: Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, Optical Society of America, 2007, p. CMKK1. URL http://www.opticsinfobase.org/abstract.cfm?URI=CLEO-2007-CMKK1

[140] H. Jiang, F. Kéfélian, S. Crane, O. Lopez, M. Lours, J. Millo, D. Holleville, P. Lemonde, C. Chardonnet, A. Amy-Klein, G. Santarelli, Long-distance frequency transfer over an urban fiber link using optical phase stabilization, J. Opt. Soc. Am. B 25 (12) (2008) 2029–2035. URL http://josab.osa.org/abstract.cfm?URI=josab-25-12-2029

[141] G. Grosche, O. Terra, K. Predehl, R. Holzwarth, B. Lipphardt, F. Vogt, U. Sterr, H. Schnatz, Optical frequency transfer via 146 km fiber link with 10−19 relative accuracy, Opt. Lett. 34 (15) (2009) 2270–2272. doi:10.1364/OL.34.002270 URL http://ol.osa.org/abstract.cfm?URI=ol-34-15-2270

[142] K. Predehl, G. Grosche, S. M. F. Raupach, S. Droste, O. Terra, J. Alnis, T. Legero, T. W. Hnsch, T. Udem, R. Holzwarth, H. Schnatz, A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place.
[143] O. Lopez, A. Haboucha, B. Chanteau, C. Chardonnet, A. Amy-Klein, G. Santarelli, Ultra-stable long distance optical frequency distribution using the internet fiber network, Opt. Express 20 (21) (2012) 23518–23526. doi:10.1364/OE.20.023518 URL http://www.opticsexpress.org/abstract.cfm?URI=oe-20-21-23518

[144] F. Guillou-Camargo, V. Ménoiret, E. Cantin, O. Lopez, N. Quintin, E. Camisard, V. Salmon, J.-M. L. Merdy, G. Santarelli, A. Amy-Klein, P.-E. Pottie, B. Desruelle, C. Chardonnet, First industrial-grade coherent fiber link for optical frequency standard dissemination, Appl. Opt., AO 57 (25) (2018) 7203–7210. doi:10.1364/AO.57.007203

[145] F. Frank, F. Stefani, P. Tuckey, P. E. Pottie, A Sub-ps Stability Time Transfer Method Based on Optical Modems, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 65 (6) (2018) 1001–1006. doi:10.1109/TUFFC.2018.2833389

[146] O. Lopez, F. Kflian, H. Jiang, A. Haboucha, A. Bercy, F. Stefani, B. Chanteau, A. Kanj, D. Rovera, J. Achkar, C. Chardonnet, P.-E. Pottie, A. Amy-Klein, G. Santarelli, Frequency and time transfer for metrology and beyond using telecommunication network fibres, Comptes Rendus Physique 16 (5) (2015) 531 – 539, the measurement of time / La mesure du temps. doi:http://dx.doi.org/10.1016/j.crhy.2015.04.005 URL http://www.sciencedirect.com/science/article/pii/S1631070515000754

[147] L. Sliwczynski, et al., Dissemination of time and RF frequency via a stabilized fibre optic link over a distant fiber, Metrologia 50 (2) (2013) 133. URL http://stacks.iop.org/0026-1394/50/i=2/a=133

[148] O. Lopez, A. Kanj, P.-E. Pottie, D. Rovera, J. Achkar, C. Chardonnet, A. Amy-Klein, G. Santarelli, Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network Applied Physics B: Lasers and Optics 110 (2013) 3, 10.1007/s00340-012-5241-0. URL http://dx.doi.org/10.1007/s00340-012-5241-0

[149] J. Geršl, P. Delva, P. Wolf, Relativistic corrections for time and frequency transfer in optical fibres, Metrologia 52 (4) (2015) 552. URL http://stacks.iop.org/0026-1394/52/i=4/a=552

[150] S. Schiller, Feasibility of giant fiber–optic gyroscopes. Phys. Rev. A 87 (2013) 033823. doi:10.1103/PhysRevA.87.033823 URL http://link.aps.org/doi/10.1103/PhysRevA.87.033823
[151] C. Clivati, D. Calonico, G. A. Costanzo, A. Mura, M. Pizzocaro, F. Levi, Large-area fiber-optic gyroscope on a multiplexed fiber network, Opt. Lett. 38 (7) (2013) 1092–1094. doi:10.1364/OL.38.001092
URL http://ol.osa.org/abstract.cfm?URI=ol-38-7-1092

[152] G. Marra, C. Clivati, R. Luckett, A. Tampellini, J. Kronjäger, L. Wright, A. Mura, F. Levi, S. Robinson, A. Xuereb, B. Baptie, D. Calonico, Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables, Science (2018) eaat4458 doi:10.1126/science.aat4458

[153] 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. Rau-pach, U. Sterr, I. R. Hill, R. Hobson, W. Bowden, J. Kronjäger, G. Marra, A. Rolland, F. N. Baynes, H. S. Margolis, P. Gill, Test of special relativity using a fiber network of optical clocks, Phys. Rev. Lett. 118 (2017) 221102. doi:10.1103/PhysRevLett.118.221102
URL https://link.aps.org/doi/10.1103/PhysRevLett.118.221102

[154] S. Reynaud, C. Salomon, P. Wolf, Testing general relativity with atomic clocks, Space Science Reviews 148 (1) (2009) 233–247.
URL http://dx.doi.org/10.1007/s11214-009-9539-0

[155] D. Mattingly, Modern tests of lorentz invariance, Living Reviews in Relativity 8 (5).
URL http://www.livingreviews.org/lrr-2005-5

[156] W. Marciano, Time variation of the fundamental “constants” and Kaluza-Klein theories, Phys. Rev. Lett. 52 (1984) 489.

[157] T. Damour, A. Polyakov, The string dilaton and a least coupling principle, Nucl. Phys. B 423 (1994) 532.

[158] T. Damour, Theoretical aspects of the equivalence principle, Classical and Quantum Gravity 29 (18) (2012) 184001.
URL http://stacks.iop.org/0264-9381/29/i=18/a=184001

[159] J. Guéna, M. Abgrall, D. Rovera, P. Rosenbusch, M. E. Tobar, P. Laurent, A. Clairon, S. Bize, Improved tests of local position invariance using $^{87}$Rb and $^{133}$Cs fountains, Phys. Rev. Lett. 109 (2012) 080801. doi:10.1103/PhysRevLett.109.080801
URL http://link.aps.org/doi/10.1103/PhysRevLett.109.080801

[160] P. Wcislo, P. Morzynski, M. Bober, A. Cygan, D. Lisak, R. Ciurylo, M. Zawada, Experimental constraint on dark matter detection with optical atomic clocks.
[161] P. Delva, N. Puchades, E. Schönenmann, F. Dilssner, C. Courde, S. Bertone, F. Gonzalez, A. Hees, C. Le Poncin-Lafitte, F. Meynadier, R. Prieto-Cerdeira, B. Sohet, J. Ventura-Traveset, P. Wolf, Gravitational Redshift Test Using Eccentric Galileo Satellites, Phys. Rev. Lett. 121 (23) (2018) 231101. doi:10.1103/PhysRevLett.121.231101

[162] F. Meynadier, P. Delva, C. le Poncin-Lafitte, C. Guerlin, P. Wolf, Atomic clock ensemble in space (ACES) data analysis, Class. Quantum Grav. 35 (3) (2018) 035018. doi:10.1088/1361-6382/aaa279

[163] P. Laurent, D. Massonnet, L. Cacciapuoti, C. Salomon, The ACES/PHARAO space mission, Comptes Rendus Physique 16 (5) (2015) 540 – 552, the measurement of time / La mesure du temps. doi:http://dx.doi.org/10.1016/j.crhy.2015.05.002 URL http://www.sciencedirect.com/science/article/pii/S1631070515000808

[164] L. Cacciapuoti, C. Salomon, Space clocks and fundamental tests: The ACES experiment, The European Physical Journal Special Topics 172 (2009) 57–68. doi:10.1140/epjst/e2009-01041-7 URL http://dx.doi.org/10.1140/epjst/e2009-01041-7

[165] L. Cacciapuoti, N. Dimarcq, G. Santarelli, P. Laurent, P. Lemoide, A. Clairon, P. Berthoud, A. Jornod, F. Reina, S. Féltham, C. Salomon, Atomic clock ensemble in space: Scientific objectives and mission status, Nuclear Physics B - Proceedings Supplements 166 (2007) 303 – 306, proceedings of the Third International Conference on Particle and Fundamental Physics in Space. doi:DOI:10.1016/j.nuclphysbps.2006.12.033 URL http://www.sciencedirect.com/science/article/pii/S0920563206010425

[166] P. Touboul, G. Métris, M. Rodrigues, Y. André, Q. Baghi, J. Bergé, D. Boulanger, S. Bremer, P. Carle, R. Chlun, B. Christophe, V. Cipolla, T. Damour, P. Danto, H. Dittus, P. Fayet, B. Foulon, C. Gageant, P.-Y. Guidotti, D. Hagedorn, E. Hardy, P.-A. Huynh, H. Inchauspe, P. Kayser, S. Lala, C. Lämmerzahl, V. Lebat, P. Leseur, F. m. c. Liorzou, M. List, F. Löffler, I. Panet, B. Pouilloux, P. Prieur, A. Rebray, S. Reynaud, B. Rievers, A. Robert, H. Selig, L. Serron, T. Sumner, N. Tanguy, P. Visser, MICROSCOPE mission: First results of a space test of the equivalence principle, Phys. Rev. Lett. 119 (2017) 231101. doi:10.1103/PhysRevLett.119.231101

[167] Consultative Committee for Time and Frequency (CCTF), Report of the 15th meeting (june 2001) to the international committee for weights and measures, Tech. rep., BIPM (2001).
[168] H. Marion, F. Pereira Dos Santos, M. Abgrall, S. Zhang, Y. Sor-tai, S. Bize, I. Maksimovic, D. Calonico, J. Grünert, C. Mandache, P. Le monde, G. Santarelli, P. Laurent, A. Clairon, C. Salomon, Search for variations of fundamental constants using atomic fountain clocks, Phys. Rev. Lett. 90 (2003) 150801. doi:10.1103/PhysRevLett.90.150801 URL https://doi.org/10.1103/PhysRevLett.90.150801

[169] S. Bize, P. Laurent, M. Abgrall, H. Marion, I. Maksimovic, L. Cacciapuoti, J. Grünert, C. Vian, F. Pereira dos Santos, P. Rosenbusch, P. Lemonde, G. Santarelli, P. Wolf, A. Clairon, A. Luiten, M. Tobar, C. Salomon, Advances in $^{133}$Cs fountains, C. R. Physique 5 (2004) 829.

[170] H. S. Margolis, P. Gill, Least-squares analysis of clock frequency comparison data to deduce optimized frequency and frequency ratio values, Metrologia 52 (5) (2015) 628. URL http://stacks.iop.org/0026-1394/52/i=5/a=628

[171] L. Robertsson, On the evaluation of ultra-high-precision frequency ratio measurements: Examining closed loops in a graph theory framework, Metrologia 53 (6) (2016) 1272–1280. doi:10.1088/0026-1394/53/6/1272

[172] C. Grebing, A. Al-Masoudi, S. Dörscher, S. Häfner, V. Gerginov, S. Weyers, B. Lipphardt, F. Riehle, U. Sterr, C. Lisdat, Realization of a timescale with an accurate optical lattice clock, Optica 3 (6) (2016) 563–569. doi:10.1364/OPTICA.3.000563 URL http://www.osapublishing.org/optica/abstract.cfm?URI=optica-3-6-563

[173] T. Rosenband, D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist, Frequency ratio of Al$^+$ and Hg$^+$ single-ion optical clocks; metrology at the 17th decimal place, Science 319 (2008) 1808.

[174] N. Nemitz, T. Ohkubo, M. Takamoto, I. Ushijima, M. Das, N. Ohmae, H. Katori, Frequency ratio of Yb and Sr clocks with $5 \times 10^{-17}$ uncertainty at 150 seconds averaging time, Nat Photon 10 (4) (2016) 258–261. URL http://dx.doi.org/10.1038/nphoton.2016.20

[175] K. Yamanaka, N. Ohmae, I. Ushijima, M. Takamoto, H. Katori, Frequency ratio of $^{199}$Hg and $^{87}$Sr optical lattice clocks beyond the SI limit, Phys. Rev. Lett. 114 (2015) 230801. doi:10.1103/PhysRevLett.114.230801 URL http://link.aps.org/doi/10.1103/PhysRevLett.114.230801

[176] H. Hachisu, F. Nakagawa, Y. Hanado, T. Ido, Months-long real-time generation of a time scale based on an optical clock, Scientific Reports 8 (1) (2018) 4243. doi:10.1038/s41598-018-22423-5
[177] H. Hachisu, M. Fujieda, S. Nagano, T. Gotoh, A. Nogami, T. Ido, S. Falke, N. Huntemann, C. Grebing, B. Lipphardt, C. Lisdat, D. Piester, Direct comparison of optical lattice clocks with an intercontinental baseline of 9000 km, Opt. Lett. 39 (14) (2014) 4072–4075. doi:10.1364/OL.39.004072
URL http://ol.osa.org/abstract.cfm?URI=ol-39-14-4072
[178] F. Riehle, Optical clock networks, Nat Photon 11 (1) (2017) 25–31.
URL http://dx.doi.org/10.1038/nphoton.2016.235
[179] D. Herman, S. Droste, E. Baumann, J. Roslund, D. Churin, A. Cingoz, J.-D. Deschênes, I. H. Khader, W. C. Swann, C. Nelson, N. R. Newbury, I. Coddington, Femtosecond Timekeeping: Slip-Free Clockwork for Optical Timescales, Phys. Rev. Applied 9 (4) (2018) 044002. doi:10.1103/PhysRevApplied.9.044002
[180] P. Delva, H. Denker, G. Lion, Chronometric geodesy: methods and applications, 2019.
URL https://www.springer.com/us/book/9783030114992
[181] H. Denker, L. Timmen, C. Voigt, S. Weyers, E. Peik, H. S. Margolis, P. Delva, P. Wolf, G. Petit, Geodetic methods to determine the relativistic redshift at the level of $10^{-18}$ in the context of international timescales, Journal of Geodesy doi:10.1007/s00190-017-1075-1
URL https://doi.org/10.1007/s00190-017-1075-1
[182] H. Denker, Regional Gravity Field Modeling: Theory and Practical Results, in: G. Xu (Ed.), Sciences of Geodesy, Vol. II, Chapter 5, Springer Berlin Heidelberg, 2013, pp. 185–291. doi:10.1007/978-3-642-28000-9_5
[183] M. Weiss, N. Pavlis, A re-evaluation of the relativistic redshift on frequency standards at NIST, Boulder, Colorado, USA, Metrologia 54 (2017) 535. doi:10.1088/1681-7575/aa765c
[184] D. Calonico, A. Cina, I. H. Bendea, F. Levi, L. Lorini, A. Godone, Gravitational redshift at INRIM, Metrologia 44 (5) (2007) L44.
URL http://stacks.iop.org/0026-1394/44/i=5/a=N03
[185] N. K. Pavlis, M. A. Weiss, The relativistic redshift with $3\times10^{-17}$ uncertainty at NIST, Boulder, Colorado, Metrologia 40 (2) (2003) 66.
URL http://stacks.iop.org/0026-1394/40/i=2/a=311
[186] C. Voigt, H. Denker, L. Timmen, Time-variable gravity potential components for optical clock comparisons and the definition of international time scales, Metrologia 53 (6) (2016) 1365. doi:10.1088/0026-1394/53/6/1365
[187] G. Lion, I. Panet, P. Wolf, C. Guerlin, S. Bize, P. Delva, Determination of a high spatial resolution geopotential model using atomic clock comparisons.
[188] T. E. Mehlstäubler, G. Grosche, C. Lisdat, P. O. Schmidt, H. Denker, Atomic clocks for geodesy, Rep. Prog. Phys. 81 (6) (2018) 064401. doi:10.1088/1361-6633/aab4a0

[189] J. Müller, D. Dirkx, S. M. Kopeikin, G. Lion, I. Panet, G. Petit, P. N. a. M. Visser, High Performance Clocks and Gravity Field Determination, Space Sci Rev 214 (1) (2018) 5. doi:10.1007/s11214-017-0431-z

[190] R. Bondarescu, A. Schrer, A. Lundgren, G. Hetnyi, N. Houli, P. Jetzer, M. Bondarescu, Ground-based optical atomic clocks as a tool to monitor vertical surface motion, Geophysical Journal International 202 (3) (2015) 1770–1774. arXiv:/oup/backfile/content_public/journal/gji/202/3/10.1093_gji_ggv246/1/ggv246.pdf, doi:10.1093/gji/ggv246

[191] R. Bondarescu, M. Bondarescu, G. Hetnyi, L. Boschi, P. Jetzer, J. Balakrishna, Geophysical applicability of atomic clocks: direct continental geoid mapping, Geophysical Journal International 191 (1) (2012) 78–82. doi:10.1111/j.1365-246X.2012.05636.x

[192] K. Bongs, Y. Singh, L. Smith, W. He, O. Kock, D. wierad, J. Hughes, S. Schiller, S. Alighanbari, S. Origlia, S. Vogt, U. Sterr, C. Lisdat, R. L. Targat, J. Lodewyck, D. Holleville, B. Venon, S. Bize, G. P. Barwood, P. Gill, I. R. Hill, Y. B. Ovchinnikov, N. Poli, G. M. Tino, J. Stuhler, W. Kaenders, Development of a strontium optical lattice clock for the SOC mission on the ISS Comptes Rendus Physique 16 (5) (2015) 553 – 564, the measurement of time / La mesure du temps. doi:http://dx.doi.org/10.1016/j.crhy.2015.03.009

[193] S. B. Koller, J. Grotti, S. Vogt, A. Al-Masoudi, S. Dörscher, S. Häfner, U. Sterr, C. Lisdat, Transportable optical lattice clock with $7 \times 10^{-17}$ uncertainty Phys. Rev. Lett. 118 (2017) 073601. doi:10.1103/PhysRevLett.118.073601

[194] S. Origlia, M. S. Pramod, S. Schiller, Y. Singh, K. Bongs, R. Schwarz, A. Al-Masoudi, S. Dörscher, S. Herbers, S. Häfner, U. Sterr, C. Lisdat, Towards an optical clock for space: Compact, high-performance optical lattice clock based on bosonic atoms, Phys. Rev. A 98 (5) (2018) 053443. doi:10.1103/PhysRevA.98.053443
[195] J. Grotti, S. Koller, S. Vogt, S. Häfner, U. Sterr, C. Lisdat, H. Denker, C. Voigt, L. Timmen, A. Rolland, F. N. Baynes, H. S. Margolis, M. Zampaolo, P. Thoumany, M. Pizzocaro, B. Rauf, F. Bregolin, A. Tampellini, P. Barbieri, M. Zucco, G. A. Costanzo, C. Clivati, F. Levi, D. Calonico, Geodesy and metrology with a transportable optical clock, Nature Physics (2018) doi:10.1038/s41567-017-0042-3.

[196] K. C. Cossel, E. M. Waxman, F. R. Giorgetta, M. Cermak, I. R. Coddington, D. Hesselius, S. Ruben, W. C. Swann, G.-W. Truong, G. B. Rieker, N. R. Newbury, Open-path dual-comb spectroscopy to an airborne retroreflecter, Optica 4 (7) (2017) 724–728. doi:10.1364/OPTICA.4.000724.
URL http://www.osapublishing.org/optica/abstract.cfm?URI=optica-4-7-724

[197] J.-D. Deschênes, L. C. Sinclair, F. R. Giorgetta, W. C. Swann, E. Baumann, H. Bergeron, M. Cermak, I. Coddington, N. R. Newbury, Synchronization of distant optical clocks at the femtosecond level, Phys. Rev. X 6 (2016) 021016. doi:10.1103/PhysRevX.6.021016.
URL http://link.aps.org/doi/10.1103/PhysRevX.6.021016

[198] F. R. Giorgetta, W. C. Swann, L. C. Sinclair, E. Baumann, I. Coddington, N. R. Newbury, Optical two-way time and frequency transfer over free space, Nat Photon 7 (6) (2013) 434–438.
URL http://dx.doi.org/10.1038/nphoton.2013.69

[199] K. Djerroud, O. Acef, A. Clairon, P. Lemonde, C. N. Man, E. Samain, P. Wolf, Coherent optical link through the turbulent atmosphere, Opt. Lett. 35 (9) (2010) 1479–1481.
URL http://ol.osa.org/abstract.cfm?URI=ol-35-9-1479