Ultracold atoms and precise time standards

BY GRETCHEN K. CAMPBELL* AND WILLIAM D. PHILLIPS

Joint Quantum Institute, National Institute of Standards and Technology, Gaithersburg, and University of Maryland, College Park, MD, USA

Experimental techniques of laser cooling and trapping, along with other cooling techniques, have produced gaseous samples of atoms so cold that they are, for many practical purposes, in the quantum ground state of their centre-of-mass motion. Such low velocities have virtually eliminated effects such as Doppler shifts, relativistic time dilation and observation-time broadening that previously limited the performance of atomic frequency standards. Today, the best laser-cooled, caesium atomic fountain, microwave frequency standards realize the International System of Units (SI) definition of the second to a relative accuracy of $\approx 3 \times 10^{-16}$. Optical frequency standards, which do not realize the SI second, have even better performance: cold neutral atoms trapped in optical lattices now yield relative systematic uncertainties of $\approx 1 \times 10^{-16}$, whereas cold-trapped ions have systematic uncertainties of $9 \times 10^{-18}$. We will discuss the current limitations in the performance of neutral atom atomic frequency standards and prospects for the future.

Keywords: ultracold atoms; atomic clocks; primary frequency standards

1. Microwave atomic clocks

The basic idea of atomic clocks is to lock the frequency of a local, external oscillator to the frequency of a particular atomic or molecular transition. In the 1940s and 1950s, inspired by the advances in microwave spectroscopy, a number of groups began pursuing atomic clocks. At the time, the most stable frequency standards were quartz oscillators, which had fractional frequency instabilities of $2 \times 10^{-8}$. With this stability, these oscillators could already measure variations in the Earth’s rotation, which at that time was used for the definition of the second in the International System of Units (SI). However, quartz oscillators had a number of disadvantages, in particular their sensitivity to temperature, and the fact that no two quartz oscillators were identical. A standard based on an unperturbed atomic transition could be realized anywhere, and seemed a natural choice for a frequency standard. The challenge was in choosing the best atomic reference, and in creating an ‘unperturbed’ environment to perform spectroscopy. In choosing an atomic reference, there are two important considerations, both related to minimizing the relative transition linewidth. In atomic and molecular spectroscopy, resonant radiation is used to induce transitions between two energy states. The fractional width of the measured resonance scales as $\Delta \nu/\nu \propto 1/\tau \nu$.

*Author for correspondence (gretchen.campbell@nist.gov).

One contribution of 15 to a Discussion Meeting Issue ‘The new SI based on fundamental constants’.
where $\nu$ is the transition frequency, $\Delta\nu$ is the measured linewidth and $\tau$ is the interaction time, i.e. the length of the radiation pulse. From this scaling, two things become apparent: the best accuracy is achieved by choosing a reference with a high-frequency transition, and by using long interaction times (assuming that natural decay and other sources of decay are negligible).

In early atomic and molecular beam experiments, a single, long microwave pulse was used to excite the transition. These early experiments were limited by two effects: Doppler shifts and limited interaction times. These effects limited both the accuracy of the measured transition frequency and the fractional frequency stability. An important shift was caused by Doppler effects. Atoms or molecules at room temperature move with velocities of the order of hundreds of metres per second. The average thermal velocity at room temperature scales inversely with the square root of the mass of the atom. Caesium, a relatively heavy atom, has a typical thermal velocity of only $v = 130 \text{ms}^{-1}$ at room temperature, compared with $1600 \text{ms}^{-1}$ for hydrogen. Choosing a heavy atom as a reference helped to minimize Doppler shifts; however, even the relatively low velocity of caesium made precision spectroscopy difficult. In addition to the usual (first-order, non-relativistic) Doppler shift, the thermal velocity also causes a shift due to relativistic time dilation (second-order Doppler). The combined first- and second-order Doppler shifts lead both to a broadened lineshape, caused by the wide spread of velocities in a thermal beam, and also a shift of the resonance frequency. For an atom moving with velocity $v$, the frequency shift caused by first-order Doppler scales as $\delta\nu/\nu = (v/c)$, where $c$ is the speed of light. For caesium, this corresponds to a fractional frequency shift of close to $10^{-6}$. This made it essential to perform spectroscopy using ‘Doppler-free’ techniques. However, even with Doppler-free techniques, residual effects still remained, including the second-order, relativistic Doppler shift, with $\delta\nu/\nu = (1/2)(v/c)^2 \approx 10^{-13}$. The thermal velocity also limited possible interaction times. For room temperature caesium, even in a 1 m long apparatus, the interaction time was limited to approximately 10 ms, giving an interaction-limited linewidth of $\approx 100$ Hz.

A major improvement in microwave spectroscopy was made by the separated oscillatory field method demonstrated by Ramsey [1], which was used by the first caesium frequency standards. In 1968, these caesium (Cs) clocks became the primary standard when the second was redefined [2]. In Ramsey spectroscopy, the atomic beam is interrogated twice using microwave ‘pulses’ spatially separated by a distance $d$, and temporally separated by $t$ for atoms moving with velocity, $v = d/t$. In figure 1, a schematic of a caesium primary frequency standard using the Ramsey method is shown. In Ramsey spectroscopy, an atomic beam is first collimated and the spin state selected using Stern–Gerlach methods. The spin-polarized beam then enters a cavity with two interaction regions separated by $d$. In each interaction region, the sample experiences a microwave pulse of duration $\tau$. After the cavity, a Stern–Gerlach field separates the atomic beam into spin states and the resulting population in each state is measured. For $d = 1$ m, the Ramsey linewidth is given by $\Delta\nu = v/(2d) \approx 50$ Hz. The Ramsey method is Doppler-free for high $Q$ microwave cavities, where $Q$ is the quality factor; however, residual first-order Doppler effects remain owing to cavity imperfections and the second-order Doppler shift remains. Such frequency standards using Ramsey spectroscopy were able to achieve relative inaccuracies of less than $10^{-14}$, but were fundamentally limited by both the interaction time and residual Doppler effects.
In 1953, Zacharias [3] proposed a modified scheme that had the potential to increase interaction times by a factor of ≈100. In his ‘atomic fountain’, Zacharias proposed using a vertical beam trajectory with one microwave interaction region. A beam of atoms would be launched upwards, interacting with the microwave cavity once on the way up, and once on the way down, with the transit time set by the initial velocity of the atoms. For slow atoms, in the tail of the thermal beam, a transit time of 1 s could potentially be achieved. Unfortunately, owing to collisions that scattered slow atoms out of the thermal beam, no signal was ever measured; the fountain experiment built by Zacharias failed. However, in future decades, with the advent of laser cooling and trapping, this method would find success and become an essential technique.

2. Laser cooling and optical molasses

In the 1950s, the first caesium clocks had a reported fractional frequency stability of $1 \times 10^{-9}$ [4]. In the following decades, on average, clocks improved by a factor of 10 every 10 years. However, by the mid-1970s, it looked like the accuracy would eventually become limited by effects related to the thermal velocity. Such effects were among the key issues that motivated the development of laser cooling and trapping techniques. In 1975, two papers independently proposed laser cooling: Hänsch & Schawlow [5] and Wineland & Dehmelt [6]. Both these papers proposed what is now known as ‘Doppler cooling’, with Hänsch & Schawlow proposing neutral atom cooling, and Wineland & Dehmelt proposing ion cooling. In the usual conception of Doppler cooling, counter-propagating laser beams are tuned just below resonance to cool atoms. Because of the Doppler shift, if the beams are detuned red of the atomic transition, the atoms will absorb more photons from the beam opposing their velocity. When an atom absorbs and re-emits a photon, its momentum decreases on average by $\hbar k$, the momentum of the absorbed photon or ‘recoil momentum’, where $k = 2\pi/\lambda$ is the wavevector for
a laser with wavelength $\lambda$. Because the absorption of a photon transfers the atom from a ground to an excited state, before absorbing another photon, the atom must first emit a photon and return to the ground state. During the emission process, the atom will again receive a recoil kick; however, as the emitted photon is in a random direction, the velocity kicks associated with emission average to zero. In free space, the use of three pairs of counter-propagating beams, one in each orthogonal direction, ensures that the cooling process works, regardless of the direction of atomic motion. In a trap, a single beam with components along all principle axes is sufficient. Experimental demonstrations of Doppler cooling quickly followed the initial proposals, with demonstrations in 1978 by two groups, Wineland et al. [7] and Neuhauser et al. [8]. Both of these initial demonstrations of laser cooling were for trapped ions. An advantage of ions was that traps could be created deep enough to trap even room temperature ions. The ions were first trapped and then cooled. Such deep traps did not exist for neutral atoms, and laser cooling could not immediately be applied to neutral atom atomic clocks. However, a number of groups set out to demonstrate that laser cooling and trapping could also be achieved with neutral atoms.

In Gaithersburg, initial work by Phillips and co-workers focused on developing a scheme to first slow an atomic beam from above room temperature velocities (hundreds of metres per second) to velocities where trapping was possible (approx. $10\,\text{m/s}$). Building on the idea of Doppler cooling, a single laser beam could potentially be used to slow down the atomic beam; however, a few challenges had to be overcome first. For alkali-metal atoms, such as caesium or sodium, the element first studied by the Gaithersburg group, the recoil velocity (the velocity corresponding to the recoil momentum) is on the order of $\approx 1\,\text{cm/s}$. This means that to cool an atom from above room temperature to rest, of the order of $10^4$ photons must be scattered. At the maximum scattering rate, atoms spend half their time in the ground state and half their time in the excited state. This maximum rate is given by half the natural linewidth for the atomic transition (i.e. the radiative decay rate). For alkali atoms, this maximum rate is typically of the order of $3 \times 10^7\,\text{s}^{-1}$, and one photon can be scattered every $30\,\text{ns}$. At this rate, in theory, atoms could be brought to rest in 1–2 ms; however, once again Doppler shifts come into play. Doppler cooling assumes that the laser is detuned red of the resonance, such that as the atom moves towards the beam, the effect of the Doppler shift is to bring it into resonance. However, as an atom scatters photons, the velocity slows down. A slower velocity means a smaller Doppler shift, and very quickly the atom is no longer resonant with the cooling beam. In fact, the scattering of only a few hundred photons is typically sufficient to decrease the velocity of an atom by enough to change the Doppler shift by a linewidth, bringing it substantially out of resonance with the cooling beam.

A second effect was optical pumping. Up until now, our discussion of laser cooling has assumed a two-level atom. The atom will always absorb a resonant photon, then emit a photon, returning to the original state. However, alkali metals have hyperfine structure. For caesium, there are two ground hyperfine levels: the $F = 3$ and $F = 4$ states. Typically, caesium is cooled with light resonant with $F = 4$ atoms. An atom excited out of this state can re-emit a photon and end up in the $F = 3$ state. If there is only one laser resonant with $F = 4$ atoms, then over time, all atoms will be ‘pumped’ into the ‘dark’ $F = 3$ state, shutting off the absorption of photons. This problem of ‘optical pumping’ can be solved by adding

Phil. Trans. R. Soc. A (2011)
a second laser resonant with atoms in the wrong hyperfine state. The problem of slowed atoms Doppler-shifting out of resonance was more difficult to solve. One possible solution, which was suggested by Letokhov et al. [9], was to change, or chirp, the laser frequency so that the laser would stay in resonance as the atoms slowed. A second possible solution, which was pursued by the Gaithersburg group, was to instead use a magnetic field to tune the resonant frequency of the atoms. In this scheme, a magnetic coil with a decreasing field profile was used to tune the Zeeman shift of the atoms. As the velocity of the atoms decreased, a corresponding change in the magnetic field ensured that the atoms were always in resonance. Furthermore, using a circularly polarized slowing laser with the Zeeman slower significantly reduces optical pumping problems. Both the Zeeman technique and the chirped laser technique have been widely used to decelerate atomic beams.

With slowed atomic beams, groups could finally demonstrate Doppler cooling with neutral atoms. Initial experiments used three pairs of propagating laser beams detuned below resonance. Initially, measurements of the temperature of the laser-cooled atoms [10] were consistent with the predicted temperature limits (≈240 μK for Na; ≈130 μK for caesium). But in 1988, time-of-flight temperature measurements at the National Institute of Standards and Technology (NIST) revealed temperatures of 40 μK, much smaller than the lowest limits thought to be possible [11]. This led to a flurry of activity, which was guided by a new theoretical understanding of laser cooling from Paris [12] and Stanford [13], which showed that these sub-Doppler temperatures were in fact a consequence of the hyperfine structure of alkali atoms. Sub-Doppler cooling occurred because of an interplay between the polarization gradient created by the interfering laser beams, and the light shifts experienced by different Zeeman sublevels in different polarizations. By 1995, a gas of caesium atoms had been cooled to $T = 700 \text{nK}$, corresponding to a thermal velocity, $v < 1 \text{ cm/s}^{-1}$ [14]. This final velocity was more than a factor of 10 better than what had been originally predicted by Doppler cooling, and a dramatic improvement over room temperature beams.

Such laser cooling or ‘optical molasses’, as it came to be known, offered velocity damping, but no restoring force. As the name implies, the motion of the atoms is similar to motion in a viscous medium, and it did not provide trapping. Concurrent with work on laser cooling, groups also pursued possible avenues for trapping cooled atoms using both magnetic and optical techniques. This included magnetic trapping, first demonstrated by the Gaithersburg group [15], where a magnetic quadrupole trap was used to confine the atoms, and optical trapping, first demonstrated at Bell laboratories by Chu et al. [16], where the dipole force from a single, strongly focused laser beam was used to trap laser-cooled atoms. Magneto-optical traps (MOTs) combine cooling and trapping caused by radiation pressure [17]. Laser-cooling methods combined with magnetic trapping and evaporative cooling methods [18] led to the demonstration of Bose–Einstein condensation in 1995 [19,20].

### 3. Atomic fountain clocks

With the demonstration of ultracold temperatures, groups returned to the idea of fountain clocks as originally proposed by Zacharias [3]. The first fountain clock using laser-cooled Na atoms was built by the Chu group in 1989 [21], and the first
Figure 2. Fountain clocks. (a) Caesium atoms loaded from a background vapour are first cooled using six counter-propagating laser beams. (b) The cooled atoms are launched upwards by detuning the frequency of the two vertical cooling beams. (c) After the launch, a single spin state (|1⟩) is selected using a combination of optical pumping and resonant laser light. The atoms then traverse a microwave cavity. The effect of the microwave field is to put the atoms into a coherent superposition of state |1⟩ and state |2⟩. On the return trip, the atoms again traverse the cavity. If the microwave frequency is on resonance, then the number of atoms transferred to state |2⟩ is maximized. The number of atoms in state |2⟩ is detected using resonant laser light. (Online version in colour.)

caesium fountain clock, which realized the Zacharias proposal, was built in Paris by Clairon et al. [22]. Today, fountain clocks using optical molasses to first cool the atoms have become the standard for primary frequency standards worldwide, with relative accuracies of less than 10^{-15}.

A sample schematic of a caesium fountain clock is shown in figure 2 (e.g. see [23–25]). Caesium atoms loaded from a background vapour are cooled by six counter-propagating laser beams, two along each direction, achieving temperatures of ≈1 μK and a final thermal velocity of ≈10 mm s^{-1}. The cooled atoms are then launched upwards by detuning the frequency of the two vertical cooling beams, such that the atoms are launched with a velocity of ≈4 m s^{-1}. A combination of optical pumping and resonant laser light is used to select only atoms in the \( |F = 3, m_F = 0 \rangle \) state (labelled |1⟩ in figure 2); all others are removed. The state-selected atoms then enter the microwave cavity for the first time, the effect of gravity having slowed their speed to ≈3 m s^{-1}. The atoms again traverse the cavity on the return trip. Using resonant laser light, the number of atoms that have been transferred to the \( |F = 4, m_F = 0 \rangle \) state (labelled |2⟩ in figure 2) by the microwave pulses is then detected. The total transit time is of the order of 1 s, leading to a final linewidth of ≈0.5 Hz, a factor of ≈100 improvement over thermal beam clocks. It is important to note that had the temperature only been as low as Doppler cooling initially predicted, the atomic fountain would have been extremely inefficient. However, owing to the temperatures achieved using sub-Doppler cooling, the fountain clock led to a rapid increase in clock accuracy.
The best atomic fountain clocks based on laser-cooled atoms, in national metrology laboratories around the world, now realize the definition of the second to a fractional uncertainty of $<5 \times 10^{-16}$, with reported uncertainties as low as $3.3 \times 10^{-16}$ [23–26], and improvements are still being made. A number of systematic effects (e.g. collisions, light-shifts from thermal blackbody radiation, etc.) currently limit this accuracy. Although it may be possible to reduce it to $\approx 1 \times 10^{-16}$, a different approach using optical transitions instead of microwave transitions offers even more substantial improvements.

### 4. Optical frequency standards

The fractional frequency stability of a frequency standard scales as $\delta \nu_{\text{noise}}/\nu \propto (1/Q)(1/(S/N))\sqrt{1/\tau}$, where the line quality factor, $Q = \nu/\Delta \nu$, is given by the ratio of $\nu$, the frequency of the transition, to $\Delta \nu$, the measured linewidth. $S/N$ is the signal-to-noise ratio, and $\tau$ is the averaging time. From this equation, one can see that changing from a microwave transition to an optical transition can lead to an immediate increase in stability. From early on in the development of atomic clocks, this advantage was a consideration, and in fact, the high frequency of the caesium microwave transition in comparison with other alkali metals was one of the reasons why it was chosen. Going to an optical frequency would be an even bigger advantage. However, in much the same way, laser cooling enabled the development of fountain clocks, the availability of two key components was necessary for the development of optical frequency standards.

In our discussion of microwave standards, so far we have focused only on the development of stable atomic spectroscopy. However, in order to develop a frequency standard, one must first develop a number of separate clock components. The first necessary item is an ultra-stable local oscillator. For microwave references, stable microwave electronics already existed, and the need for a stable local oscillator could be fulfilled using crystal-controlled oscillators and microwave synthesizers. An ultra-stable laser system is required for an optical clock. Furthermore, one must be able to count the frequency of the stable oscillator. For microwave clocks, this was also not a problem, as direct measurement of microwave frequencies was straightforward. For optical frequency standards, this was a major challenge. This requirement is now fulfilled using an octave-spanning femtosecond frequency comb [27,28]. Finally, in order to have a stable oscillator that does not vary over time, one needs a stable atomic reference on which to perform spectroscopy, such that one can feed back to the local oscillator. In choosing a stable atomic reference for optical standards, two of the important considerations are: stability, for which it is advantageous to have both a high line $Q$, and a high $S/N$ ratio, and accuracy, for which it is important to choose an atomic transition that is relatively insensitive to external perturbations.

Today, groups are rapidly pursuing optical frequency standards, with research focusing on two different systems. The first system, which has been under development for a number of years is single trapped ions (see Gill [29] for a more complete discussion of ion clocks). Cold, trapped ions have a number of advantages over traditional neutral atom clocks: the low temperatures and tight confinement of ion traps essentially eliminate Doppler effects and allow for long interrogation times. Furthermore, as there is only one ion, there are
no intra-species collisional effects. As an optical standard, using large ensembles of neutral atoms, such as those used in fountain clocks, still offers an obvious benefit in signal size owing to large atom numbers. Among the disadvantages of free neutral atoms are residual Doppler shifts, collision shifts and, while improved, the interaction time is still limited to only $\approx 1s$. By confining neutral atoms in tight optical lattices, neutral atom lattice clocks can combine the best of ion traps and neutral atoms. A large trapped sample can achieve a high $S/N$ ratio, and as with ion traps, the tight confinement of the lattice allows for effectively Doppler-free interrogation and long interrogation times.

For microwave clocks, the alkali atoms caesium and rubidium have been the most popular elements. However, for an optical clock, alkaline-earth atoms offer a number of advantages. Alkaline-earth atoms as well as the alkaline-earth-like Yb all share a similar structure. For clock operation, the biggest advantage is obtained by using the spin-forbidden $^1S_0-^3P_0$ clock transition, which has an ultra narrow linewidth. By using a two-stage MOT, the first on the broad $^1S_0-^1P_1$ transition, followed by cooling on the narrow $^1S_0-^3P_1$ transition, one can reach temperatures of less than $1\mu K$. A number of alkaline-earth elements are being pursued as possible standards today. The two undergoing the most rapid developments are Sr and Yb. Both of these have a number of stable isotopes with relatively high natural abundance. For bosons, the narrow clock transition is completely forbidden so one must add a mixing field in order to use the clock transition. However, for the fermionic isotopes, which all have nuclear spin, hyperfine-induced mixing between the singlet and triple state allows for a small transition linewidth.

As an example system, we here focus on the development of lattice clocks using the fermion, $^{87}$Sr. For $^{87}$Sr, the hyperfine-induced mixing gives rise to a very narrow linewidth, predicted to be only $1\text{mHz}$ [30–33]. Conveniently, all of the cooling transitions are accessible using diode-laser-based systems, and because the clock transition is a $J = 0$ to $J = 0$ transition, the frequency is relatively insensitive to magnetic fields. In addition to the transition linewidth, there is another advantage to using a fermionic isotope. Because of anti-symmetry, spin-polarized ultracold fermions do not collide, leading to a suppression of density-dependent collisional shifts. Finally, by confining the atoms to an optical lattice, Doppler effects are minimized, and long interrogation times can be achieved. One challenge for optical lattice trapping is how to minimize light shifts caused by the lattice. A deep optical lattice potential could potentially lead to a large AC Stark shift caused by the trapping confinement, leading to both a shift in the transition frequency as well as a broadening of the lineshape because of the in-homogeneous trapping potential. However, for Sr, as well as a number of the other alkaline-earth elements, it has been shown that the lattice wavelength can be tuned to the so-called ‘magic wavelength’ (see the review by Ye et al. [34]), where the shift of the ground and excited states are identical. This cancels the differential light shift, and also gets rid of light shift-induced line broadening. For $^{87}$Sr, trapped in a magic wavelength optical lattice, if one assumes a 1 Hz interrogation laser, and $10^6$ atoms, then it has been estimated that a 1 s fractional frequency stability of $10^{-18}$ could potentially be achieved [30].

Optical lattice clocks have made rapid progress in the last few years. The first experiments used a one-dimensional optical lattice to tightly confine the atoms [35–38]. The laser beam used for spectroscopy is carefully aligned along the lattice.
axis so that the spectroscopy is both Doppler free and recoil free (figure 3). Using this high-precision spectroscopy, with Sr, a linewidth of 1.8 Hz was demonstrated by Boyd et al. [39], corresponding to $Q = 2.4 \times 10^{14}$. It is important to note that the linewidth was limited not by the coherence time of the atomic sample, but instead was limited by the linewidth of the spectroscopy laser. Recently, by improving their laser linewidth, Jiang et al. [40] demonstrated a 1 Hz linewidth with a Yb lattice clock, corresponding to $Q = 5 \times 10^{14}$.

To evaluate the performance of these new optical standards, it is essential to compare their performance with other optical standards under development, as well as with current microwave primary frequency standards. To date, the optical lattice clock with the lowest systematic uncertainties is the JILA Sr clock [41]. To evaluate the strontium systematics, a remote comparison was made between the JILA Sr clock and the NIST Ca optical standard, using a phase-coherent fibre link between the two laboratories. Comparing with an optical standard as opposed to a microwave standard allows for a more rapid evaluation of clock systematics. In fact, by comparing against an optical standard, Ludlow et al. [41] achieved a final uncertainty of $1.5 \times 10^{-16}$, a sixfold improvement from previous evaluations [39]. With the exception of the blackbody radiation shift, which was limited partially by theory, this final uncertainty was limited purely by the statistics of the measurement. Since this evaluation, further improvements have been made that should reduce this uncertainty to $<1 \times 10^{-16}$ [42], and as better local oscillators are developed, the final uncertainty should continue to improve. The systematic
Ultracold atoms and time standards

An uncertainty of $\approx 1 \times 10^{-16}$ now surpasses the performance of the best caesium clocks. Although, to date, this is the lowest systematic uncertainty of any neutral atom clock, a number of Sr- and Yb-based clocks are under development, with a number reporting uncertainties $<10^{-15}$, comparable with caesium standards [41, 43–46]. In addition to evaluating the systematic uncertainties, several groups have also measured the absolute frequencies of the optical clock transitions. Absolute frequency measurements of the Sr transition performed worldwide are in remarkable agreement. In fact, the most recent measurements by the JILA and Paris groups agree within the uncertainties of the caesium references used to measure them [47].

5. What is next for neutral atom clocks?

In the last two decades, laser cooling and trapping techniques have helped microwave atomic clocks to reach unprecedented levels of precision. Optical frequency standards have reached even higher levels of precision, including both the neutral atom optical lattice clocks discussed here, and those based on single ions discussed elsewhere in Gill [29], which have reported uncertainties of less than $9 \times 10^{-18}$ [48]. Optical lattice clocks have yet to reach their full potential. A number of hurdles still remain, including blackbody radiation shifts and the need for better local oscillators. In the future, it will also become essential for remote comparisons of these new optical frequency standards.

References