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## Towards a redefinition of the second based on optical atomic clocks



## Vers une redéfinition de la seconde basée sur les horloges atomiques optiques

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## ABSTRACT

The rapid increase in accuracy and stability of optical atomic clocks compared to the caesium atomic clock as the primary standard of time and frequency asks for a future redefinition of the second in the International System of Units (SI). The status of the optical clocks based on either single ions in radio-frequency traps or on neutral atoms stored in an optical lattice is described, with special emphasis on the current work at the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany). Besides the development and operation of different optical clocks with estimated fractional uncertainties in the  $10^{-18}$  range, the supporting work on ultra-stable lasers as core elements and the means to compare remote optical clocks with transportable standards, optical fibres, or frequency ratios is reported. Finally, the conditions, methods and next steps are discussed, which are the prerequisites for a future redefinition of the second.

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## R É S U M É

L'amélioration rapide en termes de précision et de stabilité des horloges atomiques optiques par rapport à l'horloge atomique au césium, qui constitue la référence primaire pour le temps et la fréquence, appelle une future redéfinition de la seconde dans le système international d'unités (SI). L'état d'avancement des horloges optiques basées sur des ions uniques dans des pièges radiofréquence ou sur des atomes neutres confinés dans le réseau optique est décrit, en insistant particulièrement sur le travail en cours à la Physikalisch-Technische Bundesanstalt (PTB, Brunswick, Allemagne). À côté du développement et de la mise en œuvre de différentes horloges optiques avec des incertitudes fractionnelles estimées d'un ordre de grandeur de  $10^{-18}$ , les travaux sous-jacents sur les lasers ultra-stables comme éléments centraux ainsi que les moyens de comparer les horloges optiques lointaines avec des étalons transportables, des fibres optiques ou des rapports de fréquence

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sont exposés. Finalement, les conditions, les méthodes et les prochaines étapes sont discutées, qui sont des prérequis à une redéfinition de la seconde.

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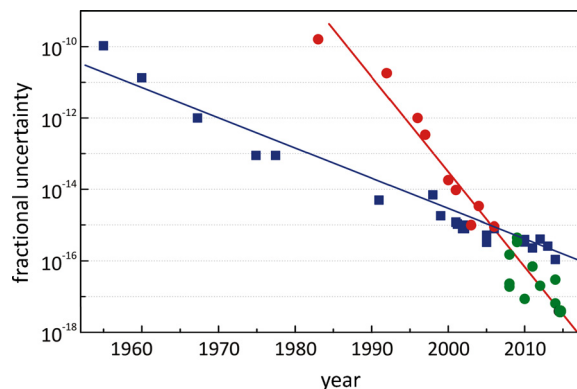
## 1. Introduction

Since 1967, the second as the base unit of time in the International System of Units (SI) is defined via an unperturbed hyperfine transition in atomic caesium [1] that is interrogated by a radiofrequency of 9 192 631 770 Hz. In the past five decades, the uncertainty to which the centre of this hyperfine transition can be found in the best caesium atomic clocks could be reduced typically by an order of magnitude in each decade (Fig. 1). A few years ago, optical atomic clocks (see e.g., [2,3]) where a laser is stabilised to a suitable optical transition have fulfilled their long-standing promise to supersede caesium atomic clocks with respect to their lower frequency instability and their lower inaccuracy. Accuracy is here understood as the ability to reference the frequency of a clock to an unperturbed atomic or ionic transition. However, none of these “better” optical clock transitions with superior precision can realise the second more accurately than the best caesium atomic clock they have been compared to. It can therefore be anticipated that at some time the SI second will be redefined via an optical clock transition [4]. Already in the year 2001, the Consultative Committee for Time and Frequency (CCTF) discussed the situation and formed a working group that later became the Working Group on Frequency Standards (WGFS) under the auspices of CCTF and CCL (Consultative Committee for Length) to recommend *Secondary representations of the second* (whether optical or microwave), that could be used to realise the second in parallel to the caesium clock. The establishment of these secondary representations of the second would furthermore help with the detailed evaluation of reproducibility at the highest level, and significantly aid the process of comparing different standards in the preparation of a future redefinition [5]. In 2006, the first five secondary representations (one in the microwave domain and four optical standards) were recommended by the International Committee of Weights and Measures (CIPM) on its 95th session [6]. In 2012, the CIPM, on its 101st session, updated and augmented that list [6], which can be found on the website of the International Bureau of Weights and Measures (BIPM) [7].

The quantum projection noise limited instability of a clock that is referenced to an atomic transition is given by

$$\sigma_y(\tau) = \kappa \frac{\Delta\nu}{\nu} \sqrt{\frac{T_{\text{int}}}{N\tau}} \quad (1)$$

where  $\kappa$  is a number of order unity that depends on the type of interrogation,  $\nu$  is the frequency of the optical clock,  $\Delta\nu$  is the linewidth at the interrogation time  $T_{\text{int}}$ ,  $N$  is the number of absorbers interrogated, and  $\tau$  is the averaging time. The advantage of optical clocks results from the optical clock frequency that can be up to five orders of magnitude higher than that of a microwave standard. There are two different types of optical atomic clocks. One uses radio-frequency traps to store ionised particles for the required long interrogation times, the other one employs optical lattices tuned to the so-called “magic wavelength” to confine neutral atoms. In order not to perturb the ionic clock transition, only a single ion or a few ions can be interrogated in the field-free region of the trap, even though attempts are made to enlarge the number of ions in multiple ion trap clocks [8]. The single ion trap clocks have therefore a higher instability according to Eq. (1) as compared to neutral atom clocks where  $N$  can easily approach or exceed  $10^4$ . On the other hand, particular optical transitions in ions like  $\text{Al}^+$  [9] are extremely insensitive to external perturbations, e.g., the electromagnetic radiation of the ambient temperature field [10]. It is therefore presently not clear which type of clocks will eventually be the best one for a redefinition of the



**Fig. 1.** (Colour online.) Fractional uncertainty of primary caesium atomic clocks to realise the second in the SI (squares) and optical frequency standards (dots). Green dots represent optical clocks with estimated standard uncertainties whose optical frequency can be determined only with the accuracy of the frequency comparison with a primary caesium clock.

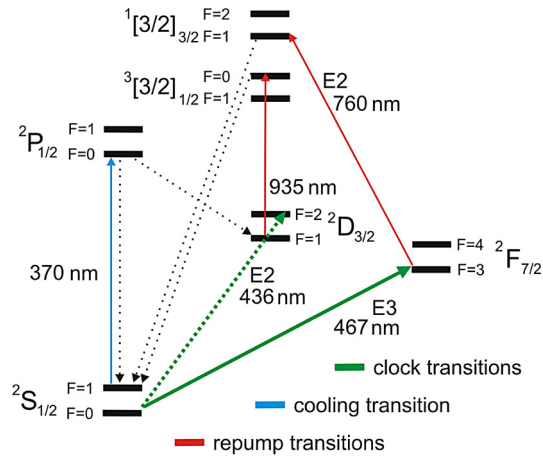


Fig. 2. (Colour online.) Energy-level diagram of the relevant transitions for Yb<sup>+</sup> clocks.

second. Consequently, PTB investigates both approaches operating single ion Yb<sup>+</sup> and Al<sup>+</sup> (Section 2) and neutral atom Sr lattice clocks (Section 3). In Section 4, the most challenging problems of these state-of-the-art clocks are discussed as well as the additional tasks undertaken to support the path towards a future redefinition of the second (Section 5).

## 2. Single-ion clocks

Single-ion clocks employ an oscillating radiofrequency field to trap the ion in a field-free centre between the electrodes. Different electrode configurations are used in optical frequency standards like the Paul trap arrangement [11], the end cap trap [12], or the linear trap [13]. The first two arrangements lead to a point-like field-free region for only a single ion, whereas the linear trap has a weaker confinement on a line between the linear electrodes that permits the storage of a chain of multiple ions. To use a transition with a small natural linewidth often a quadrupole transition (e.g.,  $2S_{1/2}$ – $2D_{5/2}$ ) is employed like in the Ca<sup>+</sup> [14–16], Sr<sup>+</sup> [17,18], Hg<sup>+</sup> [19], or Yb<sup>+</sup> [20,21] clocks (Fig. 2). All these transitions have a natural lifetime that supports a linewidth on the order of a Hertz or below.

*Yb<sup>+</sup> single-ion clock* Besides the  $2S_{1/2}$ – $2D_{3/2}$  quadrupole transition in Yb<sup>+</sup>, the  $2S_{1/2}$ – $2F_{7/2}$  octupole transition with an extremely high natural line quality factor ( $Q \approx 10^{23}$ ) has been used as a reference in an optical frequency standard at the National Physical Laboratory (UK) [20] and at PTB [21]. Both the quadrupole and octupole clock transitions and the transitions used for cooling and manipulation in Yb<sup>+</sup> are easily accessible by diode lasers. For the quadrupole transition, a fractional uncertainty of  $1.1 \times 10^{-16}$  has recently been estimated, dominated by the contribution of the frequency shift due to thermal radiation at room temperature [22].

Since the octupole transition is very weak, high irradiance of the probe laser is required to interrogate this clock transition, therefore leading to a considerable ac Stark shift. Recently, a method has been devised [23] and employed [24] to cancel the light shift by a suitable interrogation sequence. The light shift is compensated by a detuning of the clock laser during the interaction pulses of the interrogation. The detuning is controlled by interleaved interrogations with single-pulse Rabi excitations. An additional  $\pi$  pulse removes the linear dependence between the uncompensated light shift and the frequency of the central resonance feature, leaving only a third-order dependence. With this method, the light shift can be suppressed in the low  $10^{-18}$  regime. The presently largest contribution to the systematic uncertainty is the Stark shift caused by the ambient thermal radiation, which is in turn limited by the 50% relative uncertainty in the static differential polarisability. A more precise measurement of this property using near-infrared laser radiation and a detailed study of the thermal environment in combination with the suppressed light shift of the probe laser promises a total uncertainty in the low  $10^{-18}$  range. In addition to this low uncertainty, the octupole transition is known for its particularly high sensitivity to temporal variation of the fine structure constant  $\alpha$ . Repeated measurements of both clock transition frequencies versus caesium fountain clocks with improved accuracy over the last 7 years have recently confirmed the previous limit on  $d\alpha/dt$  and provide the most stringent limit on a temporal variation of the proton-to-electron mass ratio [20,21]. With this exceptionally small uncertainty, the Yb<sup>+</sup> octupole clock is one of the optical clocks with the smallest estimated uncertainties. As one of the next steps the frequencies of two independent Yb<sup>+</sup> clocks of PTB will be compared.

*<sup>27</sup>Al<sup>+</sup> quantum logic clock* The optical <sup>27</sup>Al<sup>+</sup> clock makes use of a transition ( $\lambda = 267$  nm) between the  $1S_0$  and  $3P_0$  states with vanishing angular momenta  $J = 0$ . Such transitions have no quadrupole shift and only the small nuclear magnetic moments contribute to the linear and quadratic Zeeman shift. The <sup>27</sup>Al<sup>+</sup> clock transition can be reached with conventional technology, but the transitions usually used for laser cooling and state detection are in the far ultraviolet. Wineland's group at NIST has devised a scheme where an auxiliary so-called *logic ion* (e.g., <sup>9</sup>Be<sup>+</sup>) provides sympathetic laser cooling, state

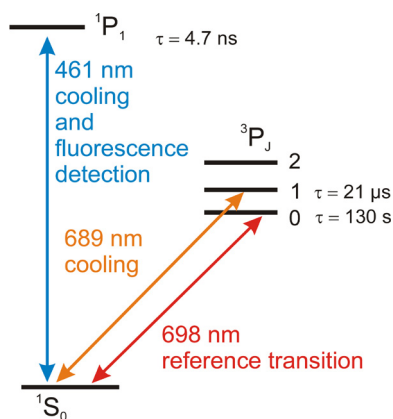


Fig. 3. (Colour online.) Energy level diagram of the relevant optical transitions in the Sr optical atomic lattice clock.

initialisation, and detection for a simultaneously trapped  $^{27}\text{Al}^+$  clock ion. The NIST group has operated two such clocks with estimated fractional uncertainties in the  $10^{-18}$  range and their frequencies agreed within the combined uncertainties [9]. A number of institutes have started to set up their own optical  $^{27}\text{Al}^+$  clock, among them PTB. In PTB's set-up,  $\text{Ca}^+$  is used as the logic ion, since the transitions can be addressed with diode lasers, and cooling is sufficient [25]. PTB's  $^{27}\text{Al}^+$  clock will be used as a transportable clock for comparisons of remote optical clocks and for novel applications, e.g., together with fibre links in relativistic geodesy experiments.

### 3. Neutral atom clocks

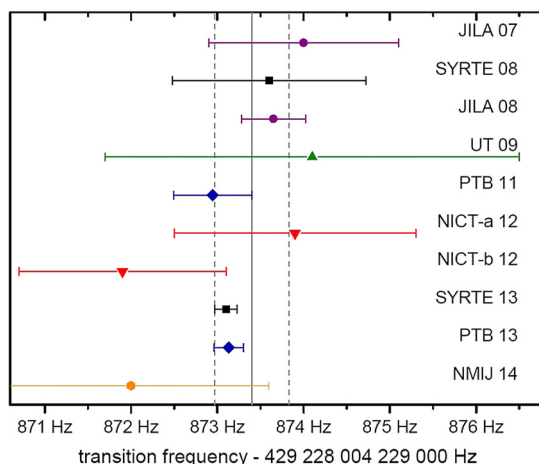
Neutral atomic clocks have become competitive to the best ion clocks again only after the discovery by Katori [26] that the huge light shift of the atomic levels used for the clock transition can be made equal in a magic wavelength optical dipole trap. The basics are described elsewhere in this dossier and need not be considered here in more detail.

*PTB's Sr lattice clock* From all optical atomic lattice clocks employing, e.g., Sr, Yb, or Hg, the Sr lattice clock is currently the one that has found most widespread use, either already in operation (see, e.g., [27–32]) or under investigation. The clock transition  $\lambda = 698$  nm between the ground state  $^1\text{S}_0$  and the  $^3\text{P}_0$  state (see Fig. 3) is weakly allowed in the  $^{87}\text{Sr}$  isotope with nuclear spin  $F = 9/2$  with an excited state life time of about 130 s due to the hyperfine interaction.

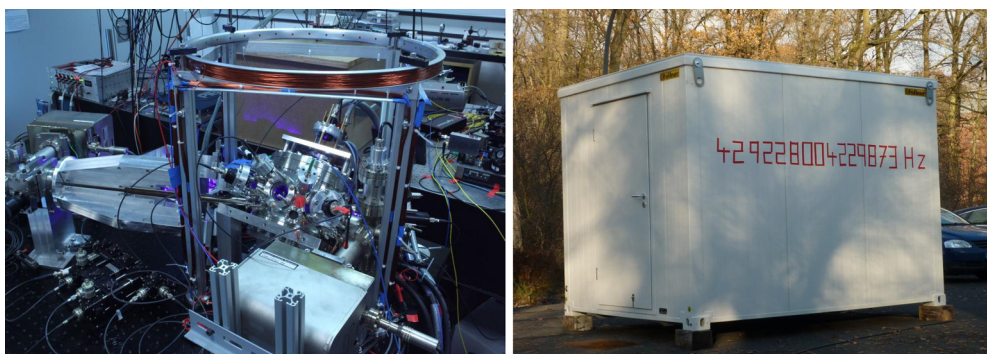
The Sr atoms are first cooled on the  $^1\text{S}_0$ – $^1\text{P}_1$  transition with  $\lambda = 461$  nm and in a second stage on the  $^1\text{S}_0$ – $^3\text{P}_1$  transition before being trapped in an optical lattice operated at the magic wavelength of  $\lambda = 813.4$  nm. PTB has built and operates a Sr lattice clock [33,34,30] that has a similar physics package as the clocks in other institutes. The fractional instability of PTB's Sr stationary lattice clock is currently  $\sigma(1 \text{ s}) = 2.6 \times 10^{-16}$  and falls off like  $\tau^{-1/2}$  into the upper  $10^{-18}$  range. The fractional uncertainty of this clock was estimated to be  $3 \times 10^{-17}$  [30]. Even lower estimated standard uncertainties at the  $10^{-18}$  level have been derived for a clock based on Sr atoms kept in a room-temperature environment [28] or in a cryogenic housing [27].

A considerable number of frequency measurements of the  $^{87}\text{Sr}$  optical lattice clocks with respect to primary caesium clocks has been performed over the past years either by local comparisons in the same institute or by linking the optical standards to remote clocks via fibres or satellites (Fig. 4). The upper six measurements displayed in Fig. 4 have been used to recommend the frequency of this transition as  $\nu_{87\text{Sr}} = 429\,228\,004\,229\,873.4$  Hz, with a relative standard uncertainty of  $1 \times 10^{-15}$  estimated for the secondary representation of the second. The four most recent measurements fall into the estimated uncertainty band, but seem to tend towards a lower frequency. From the total of the measurements displayed here, the CIPM might recommend at its next meeting a slightly lower value and also slightly reduce the estimated uncertainty of this recommendation, since the larger number of independent measurements with reduced uncertainties gives a higher confidence to the estimated value.

*Transportable Sr lattice clock* Today, the estimated optical frequencies of clocks like the ones presented in Sections 2 and 3 can only be compared with such low uncertainties via optical fibres [42] or free-space links. Therefore attempts are made in several projects or institutes to set up transportable optical clocks that are capable to be used for clock comparisons with appropriate low uncertainties. A multinational consortium sponsored by the European Union Seventh Framework Program [43] is developing a transportable standard based on a Sr lattice clock that later could also be used for space applications [44]. PTB has set up a transportable Sr lattice clock (Fig. 5) to be used for comparisons of remote optical clocks and for novel applications, e.g., in relativistic geodesy. In contrast to the two other approaches, this transportable clock is not aiming towards ultimate compactness, but it will be operated in a transportable container with stable environmental conditions at any place. The transportable Sr lattice clock of PTB is in principle not very different from that of the stationary clocks with a few specific properties [45]. The diode laser systems have been designed for stability and compactness and are similar



**Fig. 4.** (Colour online.) Frequency measurements w.r.t. primary caesium atomic clocks. JILA07: [35]; SYRTE08: [36], JILA08: [37], UT09: [38], PTB11: [33], NICT-a 12: [39], NICT-b 12: [40], SYRTE 13: [29], PTB13: [30], NMIJ14: [31]. The full vertical line indicates the value for use as a secondary representation of the second with the estimated uncertainty (dashed lines) recommended by the CIPM [41].



**Fig. 5.** (Colour online.) Physics package of PTB's transportable lattice clock (left) and container for the transportation of the clock (right).

to the ones described in [44]. The transportable standard uses a Zeeman slower with permanent magnets for decelerating the Sr atoms towards the magneto-optic trap in order to reduce the electric power of the system. Since one of the largest contributions to the uncertainty of the Sr lattice clocks results from the black body shift, care was taken to achieve a homogeneous temperature environment of the vacuum chamber that can be correctly measured. A low uncertainty is achievable since the sensitivity coefficient is very well established [34].

First measurements with the transportable clock show a fractional instability of  $1 \times 10^{-16}$  at 500 s. Its frequency agrees with that one of the stationary standards within the current estimated uncertainty of  $10^{-15}$ . From the evaluation of the uncertainty budget very similar to the one presented in [30], a final fractional uncertainty in the low  $10^{-17}$  region is expected. After the final evaluation, the transportable clock will be used for comparisons of remote optical clocks and for novel applications, e.g., together with fibre links in relativistic geodesy experiments.

#### 4. Challenges to be met on the way to a redefinition of the second

With the current status of the optical clocks (Fig. 1) as outlined above, the question is often asked *when and how a redefinition of the second might take place*. P. Gill [4] has addressed this question a few years ago and it is timely to revisit his arguments and complement them. In trying to answer this question, it is helpful to ask two other questions: *what are the requirements to be met for a redefinition?* And *who will benefit from a redefinition of the second?* In the next paragraphs, I first shall concentrate on the technical challenges to be met as prerequisites for answering the first question.

*Ultra-stable lasers for interrogation of the clock transition* The achievable quality of an optical clock depends crucially on the stability of the laser used to interrogate the clock transition. The investigation of all the systematic effects limiting the achievable uncertainty in the  $10^{-18}$  regime and below can be achieved only in a reasonable time if the instability of the interrogating laser is smaller than the instability allowed for by interrogating the clock transition.

Currently three different techniques are used or are under investigation to obtain super-stable lasers. The most widespread scheme relies on the stabilisation of the laser frequency to a high-finesse and super-stable optical Fabry-Pérot



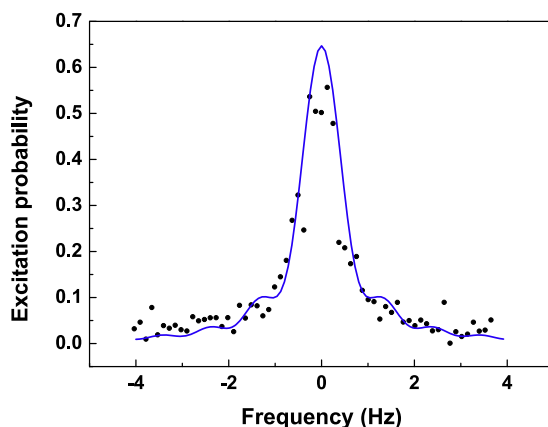


Fig. 6. (Colour online.) Measured 0.9-Hz linewidth of the Sr clock transition using a 50-cm-long ULE resonator stabilised laser [54].

resonator by means of the Pound–Drever–Hall frequency stabilisation scheme [46]. An interesting alternative to this approach has recently been investigated, where the laser is stabilised to spectral holes burnt into an ensemble of Eu dopant ions in a solid at cryogenic temperatures [47–49]. Another method with high potential has been proposed that uses an active light source based on having alkaline-earth atoms in an optical lattice. These atoms can collectively emit photons on an ultra-narrow clock transition into the mode of a high- $Q$  resonator [50]. PTB’s clock lasers use a pre-stabilisation to a Fabry–Pérot interferometer. High-finesse mirrors optically contacted to a spacer made from a material with low thermal expansion coefficient at the operating temperature like Ultra Low Expansion glass (ULE) or silicon [51] are employed. To reduce the influence of ambient vibrations on the optical path length between the mirrors and, hence, on the eigenfrequencies of the resonator, a number of provisions has to be made. Different ways to achieve a vibration insensitive mounting of the resonator have been realised (see, e.g., [52] and references therein). Since PTB operates different optical clocks with different optical frequencies, several ultra stable optical resonators are in use that can be compared and together with femtosecond optical frequency combs used for connecting the different clocks [53]. With the best resonators, linewidths of around one Hertz (Fig. 6) are readily obtained when narrow transitions like in the Sr lattice clock (Section 3) are interrogated. This linewidth is Fourier limited due to the short interaction time of about 1 s and it has been shown that a special laser could support a linewidth of 40 mHz (at 1.5  $\mu\text{m}$ ) [51]. However, to resolve the natural linewidth of about 8 mHz in the Sr clock, challenging improvements of the pre-stabilised lasers are needed to reduce their phase fluctuations, necessary for the required long interrogation times.

*Comparisons of optical clocks remote from each other* The frequent comparisons of clocks that are necessary to maintain the International Atomic Time Scale TAI and the International Coordinated Time Scale UTC rely on well-established technologies using radiofrequency signals from and via satellites (see, e.g., [55] in this dossier). The frequencies of two Sr lattice clocks between Japan and Germany were compared via two-way carrier phase time and frequency transfer using a geostationary satellite in a first demonstration [56]. The fractional uncertainty of  $1.6 \times 10^{-15}$  for a measurement time of one day shows that the currently available standard techniques are not capable to support the accuracy and instability of optical clocks in the  $10^{-18}$  range. With a larger transponder bandwidth, this situation could be improved. The *Atomic Clock Ensemble in Space* (ACES) project [57], planned for the International Space Station after 2016, will make use of a microwave link that should lead to a fractional instability and inaccuracy of  $3 \times 10^{-16}$  for a one-day measuring time. Optical links, either free space [58] or via optical telecommunication fibres [42], are even more promising. On a fibre link between PTB and the Max Planck Institute of Quantum Optics at Garching, near Munich, it could be shown that over 920 km a fractional frequency instability (modified Allan deviation) of  $5 \times 10^{-15}$  in a one-second integration time could be achieved, reaching  $10^{-18}$  in less than one hundred seconds. At the time of this writing, PTB and SYRTE are setting up a continuous fibre link between Braunschweig and Paris to allow for frequency comparisons of their optical clocks during the next years. Similar links, e.g., between NPL and SYRTE, in Italy, and at several other places, are currently also implemented. This topic is addressed elsewhere in this dossier. To conclude this paragraph, dedicated fibre links are capable and used already to compare optical clocks on a continental scale without compromising the performance of the best optical clocks. However, to intercompare the frequencies of the optical clocks on the  $10^{-18}$  level, a very accurate knowledge of the difference in the gravitational potential at the locations of the clocks corresponding to a cm-height level would be necessary, which is currently not yet available. This requires challenging improvements in geodetic modelling. For the next years, therefore, transportable standards are necessary to achieve this goal and seem furthermore to be the only choice to compare the best optical clocks on an intercontinental scale.

Since the technology of transportable clocks, however, is in general based on an earlier stage of development, their accuracy and stability often will not be competitive to the newest developments in stationary clocks. This lag in performance

of transportable clocks with respect to the most evolved stationary clocks will limit the assessment of the real performance of the latter ones. This lag could be overcome by using optical frequency ratios.

*Frequency ratios of optical clocks* To evaluate and validate the different optical clocks with the highest accuracy, it will be necessary to compare these clocks next to each other at the same gravitational potential and without making a detour via microwave clocks. The measurement of direct optical frequency ratios between different optical standards in the same laboratory will allow one to overcome the aforementioned limitations, since such a ratio is independent of the frequency of the caesium clock. The use of such ratios promises a means to evaluate the combined uncertainty of the optical standards with an accuracy limited by the standards themselves. In the simplest case, two independent clocks of the same type are operated in the same laboratory in the  $10^{-18}$  regime, like in the case of the  $^{27}\text{Al}^+$  clock [9] or the Sr lattice clock [27]. The numerical value of frequency ratios measured between optical clocks whose frequencies are very different can easily be transported to another laboratory that uses the same clock combination. As an example, consider the ratio of the frequencies of the  $\text{Yb}^+$  octupole and quadrupole standards that are investigated both at PTB [21] and NPL [20]. The comparison of the frequency ratios measured in both institutes with high accuracy will give a means to evaluate and validate the estimated uncertainties. Another example would be the ratio between the frequencies of the Yb and Sr neutral lattice standards operated at NIST [59] and JILA [28] in Boulder, USA, or in the Tokyo metropolitan area. Furthermore, if enough such frequency ratios between clocks with optical frequencies  $\nu_A$ ,  $\nu_B$ , and  $\nu_C$  are available, they could be combined to make a closure like, e.g.:

$$\frac{\nu_A}{\nu_B} \times \frac{\nu_B}{\nu_C} \times \frac{\nu_C}{\nu_A} = 1? \quad (2)$$

The joint working group WGFS of the CCL and the CCTF of the CIPM are currently developing methods and procedures to collect and make use of such data to boost the confidence into the particular measurements from the consistency of the ensemble. Such a broad confidence is prerequisite for a future redefinition of the second by optical atomic clocks.

*Novel applications and supporting developments as drivers for a redefinition of the second* Today, the present definition of the second based on the caesium transition is well suited for the most industrial applications but the first high-tech companies ask for access to fibre optical links with optical frequencies since the current microwave technology does no longer satisfy their needs. The current drivers for better optical atomic clocks are mainly basic research, time and frequency metrology and novel applications. The search for better limits for the constancy of the constants [20,21], secondary representations of the second, and a future *Relativistic Geodesy* represent one of several examples from each of these applications. As it is well known according to General Relativity, two optical clocks in a different gravitational potential show different frequencies [60] when compared, and this effect is taken into account for a long time for the comparison of atomic clocks in the international time scales TAI and UTC. With a difference of the fractional frequency  $\delta\nu/\nu \approx 10^{-16}$  per meter of height difference near the surface of Earth, the expected  $10^{-18}$  fractional uncertainty of the best optical clocks requires either the determination of the exact gravitational potential equivalent to 1 cm in height or allows one to determine the difference in the gravitational potential at the locations of the two clocks. The potential of such a Relativistic Geodesy has been recognised a long time ago [61], but it now can be realised provided that suitable transportable clocks and fibre links are available.

If the nowadays already available and planned fibre links for dissemination of optical frequencies with unprecedented frequency stability and accuracy described before can be financially secured, they will serve as a metrological fibre backbone in Europe. This backbone—mostly used to compare the best optical clocks—will then allow in a second stage to connect national networks that can deliver these frequency and time resources to virtually all interested customers and clients. Such an opportunity will boost novel applications and services from the very beginning.

A wider use of optical clocks in this and in other fields will depend heavily on a higher degree of compactness, reliability, and increased operation time and commercial availability. Even though the basic building blocks for such clocks are currently developed, e.g., for the transportable optical clocks or for space applications, there are further engineering steps required. Optical clocks for special applications like Relativistic Geodesy and other ground and space applications will then immediately find the entrance into the well-established fields where atomic clocks are used today, e.g., for time keeping and all other fields of frequency metrology.

## 5. Conclusions and possible roadmap

The status of the optical atomic clocks reported here at the example of the work at PTB and others shows that the increase in accuracy and stability continues with unbroken pace thereby leaving behind more and more the best realisation of the definition of the second in the SI—the caesium atomic clock. In preparation for a future redefinition of the second in terms of an optical atomic clock, several issues have been identified that are necessary or desirable prerequisites. Let us now come back to the question: *who will benefit from a redefinition of the second?* Due to the already very low uncertainty of the primary caesium clocks approaching  $10^{-16}$ , it seems safe to conclude that the present caesium definition will serve for some time most of industrial needs and the secondary representations will serve most of the necessities in science. In the planned revision of the SI in 2018 [62] “four of the SI base units—namely the kilogramme, the ampere, the kelvin and the mole—will be redefined in terms of constants; the new definitions will be based on fixed numerical values of the Planck

constant ( $h$ ), the elementary charge ( $e$ ), the Boltzmann constant ( $k_B$ ), and the Avogadro constant ( $N_A$ ), respectively". After this revision, all base units, except for the mole, will essentially be derived from the value of the second in the SI. Since this realisation at present is several orders of magnitude more accurate as needed for the other SI base units, there is no direct need to redefine the second under this aspect. On the other hand the new SI will not be affected in any negative way by a soon redefinition of the second. The cost associated with a redefinition would be very low, since the caesium technology would be still available and used in all applications where the current accuracy is sufficient.

After a redefinition the generation of the time scales would benefit directly by the available more stable and more accurate clocks that could be included into the generation of TAI and UTC and replace the caesium clocks gradually. The first steps along this line have been taken already [29,63]. A redefinition in conjunction with optical telecommunication fibre networks allows the much higher accuracy and stability to be delivered to virtually all places where phase-coherent fibre links are available or can be installed. The short cycle times for exchange in the fibre networks for improved efficiency will allow such an installation of phase-coherent components step by step on a broad scale. Such an opportunity will boost novel applications and services from the very beginning.

From these points of view an early redefinition is possible and very desirable. There are, however, considerations that ask for a little more patience. There are currently a number of different optical clocks with the prospects for further improvement. Currently there is no definite argument for a decision between atomic and ionic species, and in both classes there are several promising candidates for a redefinition of the second. It can be expected that the stunning pace in the development of optical atomic clocks seen in Fig. 1 will at some time slow down and could reduce the large number of the present candidates. On the other hand, there might be novel concepts with prospects to achieve, e.g., a reduced interaction of the clock transition with all sorts of environmental perturbations. A transition between two isomeric states in  $^{229}\text{Th}$  has attracted much consideration (see, e.g., [64] in this dossier) for such a possibly better-isolated clock transition. PTB has a project [65] to find this clock transition via bridge processes [66] in ion clouds and in crystals doped with  $^{229}\text{Th}$ . One should also keep in mind that many of the groups contributing to the rapid progress in optical clocks are motivated by questions from basic science, like performing improved tests of fundamental principles in quantum physics and relativity. Many of these studies have benefited from the available variety of different atomic clocks, with different sensitivities to specific interactions. It therefore may be detrimental to scientific progress to narrow the choice of investigated systems prematurely as long as the current pace goes on with unbroken speed (Fig. 1).

Eventually a consensus has to be found for the most suitable candidate. The achievable uncertainty is one, but not the only one criterion. There are also other arguments for particular candidates as the prospects of the future advancement or the ease of operation and use. With all these issues in mind, we are in the position to develop an updated roadmap (similar to the one published by Euramet [67]) that could lead to a redefinition of the second by an optical atomic clock within the next two decades.

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