DE GRUYTER Adv. Opt. Techn. 2020; 9(5): 313–325

Review article

Markus Gellesch*, Jonathan Jones, Richard Barron, Alok Singh, Qiushuo Sun, Kai Bongs
and Yeshpal Singh*

Transportable optical atomic clocks for use in out-of-the-lab environments

https://doi.org/10.1515/aot-2020-0023
Received May 31, 2020; accepted August 30, 2020; published online September 23, 2020

Abstract: Recently, several reports with a strong focus on compact, nonstationary optical atomic clocks have been published, including accounts of in-field deployment of these devices for demonstrations of chronometric levelling in different types of environments. We review recent progress in this research area, comprising compact and transportable neutral atom and single-ion optical atomic clocks. The identified transportable optical clocks strive for low volume, weight and power consumption while exceeding standard microwave atomic clocks in fractional frequency instability and systematic uncertainty. Some transportable clock projects additionally address requirements for metrology or serve the joint technology development between industrial and academic stakeholders. Based on the reviewed reports on nonstationary optical atomic clocks, we suggest definitions for transportable, portable and mobile optical atomic clocks. We conclude our article with an overview of possible future directions for developments of optical clock technology.

Keywords: atomic clock; optical lattice clock; quantum technology; single-ion clock; transportable.

1 Introduction

Atomic clocks are the most stable and accurate time keeping devices known today. They play a crucial role for a number of essential applications, such as network synchronisation or positioning, navigation and—of course—for realising a time scale and providing time services. Every clock is based on an oscillator disciplined by a well-defined periodic reference. From this periodic reference, one can derive a reference frequency, time intervals and a time scale. In atomic clocks, an atomic electron transition between energy levels of a neutral atom or an ion serves as periodic reference. This transition is referred to as clock transition. For optical atomic clocks, the difference between the energy levels of the clock transition corresponds to a frequency in the optical range (hundreds of THz or ~10^{14} Hz).

To construct an optical atomic clock from an atomic reference, the frequency of the atomic transition is used to discipline a local oscillator, which in this case is the “clock laser”: a narrow-linewidth laser stabilised to an ultrastable cavity with a low short-term instability. In the cyclic operation of preparing and probing the atomic reference, an electronic feedback-loop allows to discipline the frequency of this laser to the reference frequency corresponding to the transition between the relevant energy levels (Figure 1). Without any further additions, such a system constitutes an optical frequency standard (a recent review provides a detailed overview on contemporary frequency standards [1]). For optical atomic frequency standards to form a clock, a frequency comb generator is needed as a counter [2, 3]. Such a comb generator allows to derive a clock signal in the radio-frequency range and, in combination with another atomic clock with a known reference frequency, to determine the absolute frequency of the clock laser referenced to the atomic transition.

There are two major types of optical atomic clocks: (i) single-ion optical clocks which use a single trapped ion as frequency references (frequently used ion species include $^{27}\mathrm{Al}^+$ e.g. [4, 5], $^{40}\mathrm{Ca}^+$ e.g. [6, 7], $^{88}\mathrm{Sr}^+$ e.g. [8, 9], or $^{171}\mathrm{Yb}^+$ e.g. [10, 11]) and (ii) neutral atom optical clocks where an ensemble of ultra-cold atoms is confined in an optical lattice for probing the atomic reference frequency; here, two of the most commonly reported atom species are $^{87/88}\mathrm{Sr}$, e.g. [12–15] and $^{171}\mathrm{Yb}$, e.g. [16, 17]. A number of reviews give a detailed introduction to the underlying physical principles of one or both types of optical atomic clocks [18, 19].

***Corresponding authors: Markus Gellesch and Yeshpal Singh**, University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK, e-mail: m.gellesch@bham.ac.uk (M. Gellesch); Y.Singh.1@bham.ac.uk (Y. Singh)
Jonathan Jones, Richard Barron, Alok Singh, Qiushuo Sun and Kai Bongs, University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

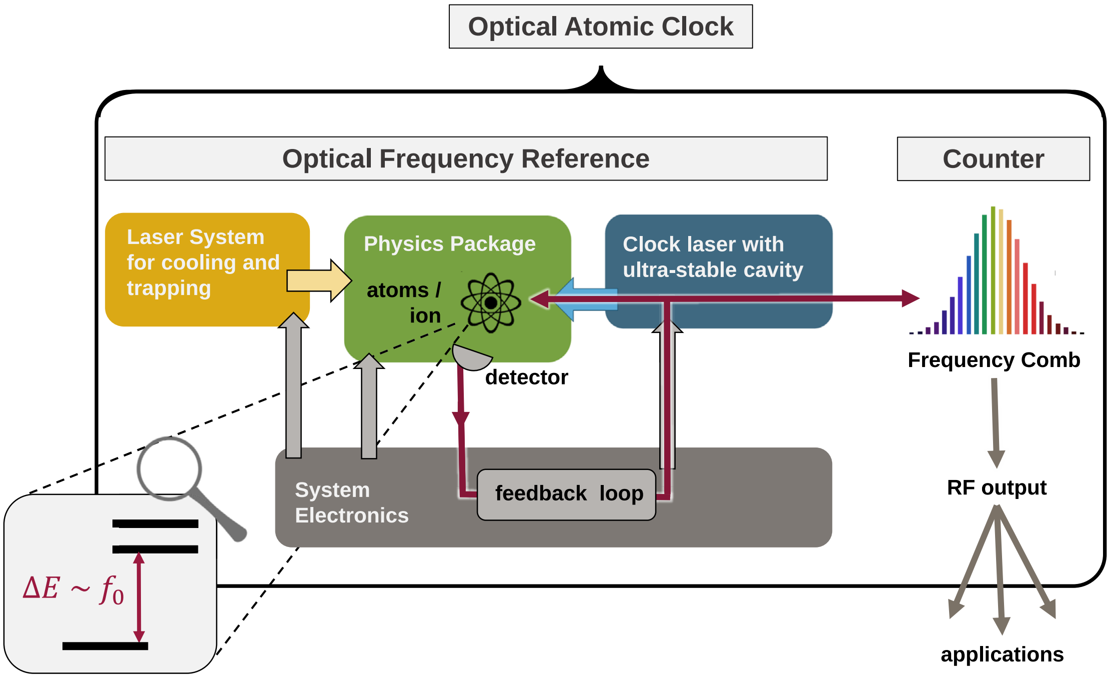


Figure 1: Simple schematic illustration of an optical atomic clock. The combination of the local oscillator, i.e., for optical atomic clocks the so-called “clock laser”—referenced to the frequency of the atomic electron transition constitutes the atomic frequency reference. The combination with an optical frequency comb generator makes up an optical atomic clock. The four major subsystems of an optical atomic frequency standard are highlighted: laser systems for the preparation of atoms or a single ion, clock laser for the interrogation of the reference transition, physics package containing the ion trap or probing chamber (“science chamber”) and system electronics. The addition of an optical frequency comb generator to the optical atomic reference allows the use of the system for applications requiring frequencies in the RF domain.

1.1 Performance criteria for optical atomic clocks

In general terms, atomic clocks are characterised by statistical uncertainties u_A and systematic uncertainties u_B, often referred to as “Type A” and “Type B” uncertainties. The former is commonly captured by the fractional frequency instability $\sigma_y(\tau)$. Systematic uncertainties on the other hand refer to how well shifts of the reference frequency are characterised. Increasing clock performance implies minimising both, fractional frequency instability $\sigma_y(\tau)$ and systematic uncertainty u_B. Equation (1) gives an expression for the fractional frequency stability for atomic clocks limited by quantum projection noise (from [18, 20]):

$$\sigma_y(\tau) \cong \frac{\Delta f}{f_0} \frac{1}{\eta} \frac{1}{\sqrt{N}} \sqrt{\frac{T_C}{\tau}} \tag{1}$$

(with τ – averaging time, f_0 – reference frequency, N – number of probed atoms or ions, T_C – the duration of the measurement cycle including preparing and probing the atomic sample, and η – factor of the order of unity accounting for different types of sequences used for spectroscopic measurement of the clock transition). As the fractional frequency instability is inversely proportional to the reference frequency f_0, a higher frequency provides a better (lower) fractional frequency instability; i.e., optical frequencies allow lower fractional frequency instabilities than a reference operating at the microwave range of the electromagnetic spectrum. Moreover, long averaging times, a large number of probed atoms and a short cycling time will be beneficial for lowering the instability of an atomic clock.

Neutral atoms operate with thousands of atoms confined in an optical lattice in order to improve the clock stability. Current neutral atom optical lattice clocks can reach fractional frequency instabilities as low as $4.8 \times 10^{-17}/\sqrt{\tau}$ [21]. Clearly, on first sight, the benefits of a large N in Equation (1) would render optical lattice clocks superior to single-ion clocks operating with a single ion as frequency reference. Yet, the performance of lattice clocks can be limited by the Dick effect [22]: high-frequency noise of the local oscillator at harmonic frequencies of the clock cycling frequency $1/T_C$ is filtered by the atomic response to probing the clock transition and converted to low frequency noise. During measurements of the clock transition, this low frequency noise cannot be distinguished from the spectroscopic clock signal, which leads to a degraded signal-to-noise ratio. The limitation of the signal-to-noise ratio by the Dick effect can be addressed by minimising the dead time of the cyclic clock operation [23].

Taking systematic uncertainties u_B into account allows to highlight the potential of single-ion optical atomic clocks. Systematic uncertainties u_B arise due to a number of factors, such as black body radiation (BBR), electric fields, quadratic Zeeman effect, micro-motion and background gas collisions (for a comprehensive list of frequency shifting effects, see Reference [24]). These factors impose systematic shifts on the atomic reference frequency, and u_B is a measure for how well these shifts are accounted for. Major shift-inducing factors are BBR and shifts due to electric fields in the direct vicinity of the ultracold atom or trapped ion sample, i.e. from charges accumulating on surfaces of the surrounding probe chamber or trap setup. Further, the atom or ion reference species is prepared in an ultra-high vacuum environment to reduce shifts from collisions with background gases. Another factor, which is only notable when comparing two atomic clocks, is the gravitational redshift [25–27]. According to Einstein's theory of general relativity, the local gravitational potential causes a frequency shift in one clock relative to another clock at a different location. Notably, a precise comparison of the redshift between two clocks at different locations can be used for chronometric levelling [28–31]. In comparison to neutral atom clocks, ion traps offer a high degree of control of the frequency reference ion, which helps to account precisely for frequency shifts. Record uncertainties at the 10^{-19} level have been achieved with optical ion clocks [4].

1.2 The role of stationary optical atomic clocks

The best-performing optical atomic clocks with instabilities at the 10^{-18} level and uncertainties nearing the 10^{-19} range so far are based on the labs of metrology institutes and dedicated research groups around the globe (e.g. [4, 28, 32, 33]). From the perspective of transportable optical atomic clocks, these high-performance setups pioneer technology developments and use cases.

On the one hand, technological innovations beneficial for transportable setups often originate from developments for stationary atomic clocks with record instabilities and uncertainties. Example clock subsystems and components are ultrastable optical resonators, e.g. [34–37]; compact laser technology for the preparation of ultracold atoms and ions, e.g. [38–41]; efficient atom sources, e.g. [42, 43]; or advanced probing chambers [44] and traps [45, 46] for ultracold atoms and single ions, respectively. These developments can be transferred, adapted, or miniaturised for use in nonstationary optical atomic clocks.

On the other hand, lab-based precision experiments can guide the way to applications of optical atomic clocks, e.g. for chronometric levelling [28], improved satellite-based positioning, navigation, and timing [47, 48], or as a master clock in space for intercontinental clock comparisons and fundamental research [49]. Notably, all these applications eventually require transportable and compact as well as robust optical atomic clock setups. Moreover, reduced size, weight and power (SWAP) will not only help unfold the potential of optical atomic clocks in those applications, but also pave the way for their usage in yet unforeseen application areas [50].

In this review article, we summarise available literature on transportable optical lattice and single-ion atomic clocks and their applications. We provide a comparative overview of the published clock systems including work from our own lab. We briefly discuss the terminology for transportable, portable and mobile optical atomic clocks. We conclude this review with an outlook on possible directions for future transportable clock developments.

2 Transportable optical atomic clocks

While there are ongoing intensive efforts in metrology and timing labs around the world to improve fractional frequency instability and systematic uncertainty of stationary optical atomic clocks further, some groups have picked up the challenge to develop transportable optical atomic clocks. A search in the Web of Science databases (Clarivate Analytics) with the terms "*portable atomic clock" yields 34 publications (as of May 2020). After close examination, we could identify a handful of transportable single-ion clocks or optical lattice clocks in operation or currently under development. About half of these projects consider strontium-based optical lattice clocks for nonstationary operation outside of laboratory environments. Table 1 provides an overview of our findings including relevant data for comparing the identified clocks and their performances. For some of these devices, not all investigated parameters (e.g. size (volume), weight or power consumption) were available.

Figure 2 displays the parameters fractional frequency instability, volume (for size), uncertainty, mass and power consumption for transportable optical atomic clocks operating or under development (in the latter case, optimum or target specifications are displayed). The graph provides a number of insights on transportable optical clock developments, which we discuss in the following paragraphs. For values of the data points and their sources, please also refer to Table 1. If not noted otherwise, here we consider the clock systems excluding the frequency comb generator.

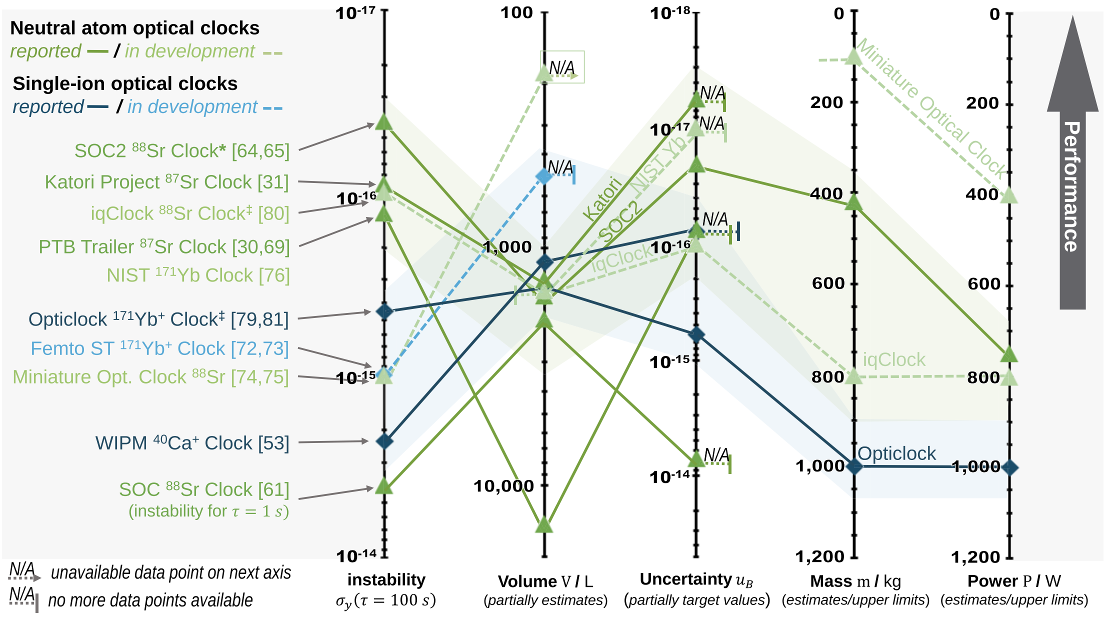
In general terms and as illustrated in Figure 2, transportable neutral atom optical clocks, most of them operating with strontium, exhibit a lower short-term fractional frequency instability and hence a better stability than single-ion clocks for periods of τ between 1 and 1000 s (first axis "instability"). Owing to the larger number of probed reference species, this observation is in line with the relation depicted in Equation (1). On the other hand, visible on the second axis "volume", transportable ion clocks have the tendency to be more compact than the reported optical lattice clocks. We attribute this observation to the fact that the miniaturisation of ion-traps and the required laser systems is more advanced than that of the physics package and laser systems required to prepare, confine and probe ultracold neutral atoms. We point out that we consider the package volume, i.e., not the sum of individual subsystems or components, but the overall transportable setup such as an air-conditioned trailer [30] or a rack system including system electronics [31]. Based on the available data, it is not possible to identify any trends in the uncertainty (third axis) when comparing both types of clock; other than that the more recently reported optical clocks systems all achieve systematic uncertainties better than 10^{-16}. Thus, nowadays, the uncertainty of transportable optical lattice clock is matching and already exceeding the uncertainty level of stationary high-performance caesium fountain clocks, e.g., $\sigma_y(\tau = 1\ \text{s}) = 1.6 \times 10^{-14}$ [51] and $u_\text{B} = 1.7 \times 10^{-16}$. When considering fractional frequency instability, transportable optical lattice clocks can outperform caesium fountain clocks by several orders of magnitude.

In 2017, Cao et al. at the Wuhan Institute of Physics and Mathematics (WIPM) reported a transportable single-ion optical clock based on $^{40}\text{Ca}^+$ with an uncertainty of $u_\text{B} = 7.8 \times 10^{-17}$ [53]. Over an averaging time of 100 s, the device could achieve a fractional frequency instability of $\sigma_y(\tau = 100\ \text{s}) = 2.3 \times 10^{-15}$ [53, 54]. In those two parameters, the system performance could exceed that of a hydrogen maser ($\sigma_y(\tau = 100\ \text{s}) = 3.1 \times 10^{-15}$; $u_\text{B} = 6 \times 10^{-15}$ [55, 1]). The Ca-ion clock can be accommodated in a 540 L-volume excluding the control electronics for the system operation. In order to allow a consistent comparison with data for the other transportable systems displayed in Figure 2, we estimated the approximate size of the electronics rack with 600 L, partially based on a similar transportable clock setup in development reported by another group [56]. A recent publication highlights progress with the laser stabilisation system for the WIPM transportable single-ion clock [54].

Table 1: Summary of reported transportable optical clock data (* indicated target values for projects under development). Instability refers to an averaging time of $\tau = 100$ s unless noted otherwise. For volume, power, and mass, values constitute estimates based on available data. As an example of a very compact and robust clock systen, the DSAC microwave atomic clock is listed for comparison.

Description	Atom/ion species	Fractional frequency instability $\sigma_y(\tau = 100\ \text{s})$	Systematic uncertainty u_B	Volume/L (estimate)	Mass/kg (estimate)	Power/W (estimate)	Reference(s)	~year
WIPM clock	$^{40}\text{Ca}^+$	2.3×10^{-15}	7.8×10^{-17}	~1140	N/A	N/A	[53]	2017
Opticlock	$^{171}\text{Yb}^+$	4.5×10^{-16}	6.0×10^{-16}*	~1440	<1000*	<1000*	[79, 81]	2020
FEMTO-ST	$^{171}\text{Yb}^+$	1.0×10^{-15}*	N/A	N/A	N/A	N/A	[72, 73]	2016
SOC	^{88}Sr	$4.0 \times 10^{-15\text{a}}$	7.0×10^{-15}	<2000	N/A	N/A	[61]	2012
SOC2	^{88}Sr	$4.1 \times 10^{-17\text{b}}$	2.0×10^{-17}	~1580	420	750	[64, 65]	2018
PTB trailer clock	^{87}Sr	1.3×10^{-16}	7.4×10^{-17}	14,520	N/A	N/A	[30, 69]	2017
Two-photon optical clock	^{87}Rb	4.0×10^{-15}	N/A	<10*	N/A	<20*	[83]	2018
JPL DSAC[c]	$^{199}\text{Hg}^+$	3.0×10^{-14}	N/A	17	16	50	[57]	2019
Katori project	^{87}Sr	9.0×10^{-17}	5.5×10^{-18}	~1350	N/A	N/A	[31]	2020
Miniature optical clock	^{88}Sr	1.0×10^{-15}*	N/A	<180	<100	<400	[74, 75]	2020
iqClock	^{87}Sr	1.0×10^{-16}*	1.0×10^{-16}*	~1500*	<800	<800	[80]	2021
NIST Yb lattice clock	^{171}Yb	N/A	$<1.0 \times 10^{-17}$*	~1500*	N/A	N/A	[76]	2021

[a] Instability for an averaging time of 1 s; [b] Instability realised with stationary local oscillator; [c] Clock system using a clock transition in the microwave range.



* instability as realised with stationary local oscillator. ‡ including frequency comb generator.

Figure 2: Parallel coordinate plot for comparing fractional frequency instability for an averaging time of 100 s, systematic uncertainty, volume (for size), mass and power consumption for reported optical atomic clocks. The axis ranges are chosen to show data from low to high performance as indicated by the arrow to the right side of the figure. For volume, the overall estimated package volume was considered (for the WIPM clock a volume of additional electronics of 600 L was assumed based on the size of an electronics rack reported for a planned comparable clock system [56]). For iqClock as well as for the opticlock system the target uncertainty values are considered [79]. Weight and mass of the clock systems—where published—constitutes an estimate (SOC2 clock) or an upper limit (Miniature Optical Clock, opticlock, iqClock, NIST Yb lattice clock, Femto ST Yb ion clock). The green and blue shaded areas indicate the region of typical parameters for transportable neutral atom clocks or transportable single-ion clocks, respectively. Care must be taken though, as the number of considered data points is particularly low for the reported ion clock systems. N/A refers to occurrences where data were not available on the adjacent coordinate axis. For data and references, please see also Table 1.

A very compact single ion mercury clock was realised at the Jet Propulsion Laboratory (JPL), California Institute of Technology for the Deep Space Atomic Clock (DSAC) mission sponsored the National Aeronautics and Space Administration (NASA) [57–59]. Unlike other transportable clock systems discussed in this review, the DSAC is based on a clock transition in the microwave range at 40.5 GHz and not on a transition in the optical range (hence, DSAC is not considered for the optical clock comparison displayed in Figure 2). However, with a SWAP of about 17 L, 16 kg and 50 W [57], it can serve as an example of a very compact and robust ion clock. The DSAC system exhibited a fractional frequency instability of 5×10^{-13} for $\tau = 100$ s and better than 4×10^{-15} at one day in ground-based performance tests [57].

A number of reports for transportable clocks relate to the Space Optical Clock “SOC” project [60–64]. In Figure 2, one can follow the continuous improvement of the demonstrator clock systems: the SOC optical lattice clock demonstrator [38, 61, 62, 66, 67] operated with ^{88}Sr and was developed with transportability in mind. Its volume is specified to be less than 2000 L and its fractional frequency instability and systematic uncertainty were in the mid-10^{-15} level. At this stage, the clock offered comparable performance to a hydrogen maser [55]. Its successor, the SOC2 demonstrator [63, 64], was integrated at the University Birmingham [63, 65] before its transport to the Physikalisch Technische Bundesanstalt (PTB), Braunschweig. The complete system comprised an approximate volume of 1580 L and an estimated weight of 420 kg. Thus, the demonstrator was compact enough for transport in a standard commercial vehicle. At its destination, the SOC2 demonstrator clock was operational within several days. With the use of a stationary cryogenic cavity, this setup could then reach a fractional frequency instability of 4.1×10^{-17} for $\tau = 100$ s and 3×10^{-18} for long averaging times [64]. The SOC2 project also included an optical lattice clock based on ^{171}Yb [62], which was transported from Düsseldorf to the Istituto Nazionale di Ricerca Metrologica (INRIM), Turin [60]. In summary, over the course of less than 10 years, the partners of the SOC and SOC2 consortia have improved the fractional frequency instability across two strontium-based demonstrator system with multiple stages by a factor of 100 and systematic uncertainty more than 300-fold. Based on the SOC2 demonstrator, the I-SOC consortium developed a concept study of an optical lattice clock for operation on-board the International Space Station with V = ~500 L, m = ~100 kg, and P = ~250 W [64].

The Katori group (RIKEN, Tokyo), recently published a report of using a pair of transportable ^{87}Sr optical lattice clocks for an in-field experiment probing the gravitational redshift due to a 450 m height difference [31]. The optical lattice clock setups make use of a shield with a low-reflectivity coating and a ring cavity for moving lattice-trapped atoms inside the science chamber to reduce BBR-induced shifts. This way, the clocks developed in the Katori group could reach record uncertainties for transportable optical lattice clocks in the mid-10^{-18} range. For an averaging time of 100 s, the clocks exhibited a fractional frequency instability in the high 10^{-17} range; for long averaging times they could reach a fractional frequency instability as low as 5×10^{-18}. Based on published data and photographs the volume of one of these clocks is estimated to be around 1350 L in total. Taking into account that the outstanding stability of the SOC2 demonstrator was achieved using an external cryogenic cavity [64], the transportable clock system of the Katori group has demonstrated a remarkable performance in terms of stability and uncertainty, clearly outperforming any microwave or hydrogen maser frequency standard in these two parameters.

The Optical Lattice Clocks group at PTB reported a milestone development of a transportable optical atomic clock system: unlike the SOC2 or the clock system of the Katori group, which both are designed as rack-based systems, the PTB transportable clock follows the concept of a miniature optical clock lab housed in an air-conditioned trailer [68, 69]. The volume in Figure 2 refers to the dimensions of this trailer [30] as this constitutes the packaged clock system in this case. Notably, the PTB team worked towards establishing a high-performing clock, comparable to lab-based metrology clocks, at the expenses of extra SWAP. The PTB transportable clock system could benefit from long-standing developments of an ultra-stable transportable optical cavity with a fractional frequency instability of 4.0×10^{-16} in the group [34, 36, 70, 71]. Prior to the work by the Katori group, the PTB team deployed their transportable clock in a joint experiment with researchers from INRIM (providing a stationary reference clock) and the National Physical Laboratory (NPL) (contributing a transportable frequency comb generator) to perform the first demonstration of chronometric levelling with a transportable optical atomic clock. In this experiment, taking place in a challenging environment [30], the clock could reach a fractional frequency instability of 1.3×10^{-16} (averaging over 100 s) and a systematic uncertainty of 7.4×10^{-17}.

Figure 2 highlights two optical clock development projects with outstanding small size: the single-ion clock project Femto-ST, which aspires to develop an ion clock with 10^{-15} stability (at $\tau = 100$ s) in the SWAP envelope of a hydrogen maser [72, 73]. Such an optical clock would be smaller in size than currently reported optical atomic clocks and provide about a factor 10 better performances than a hydrogen maser, similar as realised with the ^{40}Ca^{+}-ion clock developed by Cao et al. While the Femto-ST ion clock would not reach the fractional frequency instability and uncertainty levels of transportable optical lattice clocks, it would realize a small package size, significantly below, e.g. the SOC2 system or the opticlock demonstrator. In a similar manner, the Miniature Optical Lattice Clock, under development in our own group at the University of Birmingham, strives to deliver a neutral atom optical lattice clock with an unmatched SWAP ($V < 180$ L, $m < 100$ kg, $P < 400$ W) realised through consequent miniaturisation and a high degree of system integration [74, 75]. A third system currently under development (at the National Institute of Standards and Technology-NIST) is a transportable Yb optical lattice clock [76, 77]. This clock system is designed with a volume of around 1500 L and a targeted systematic uncertainty of less than 1.0×10^{-17} [76]. The NIST Yb optical lattice clock incorporates a compact science chamber, which can provide an uncertainty due to BBR shifts at the 10^{-18} level [77, 78]. However, as mentioned, all three systems are still in the development phase and only target specifications are currently available.

Figure 2 and Table 1 consider two more projects: “Optische Einzelionen-Uhr für Anwender (opticlock)” [79] and “iqClock” [80]. Both projects have a strong involvement of industry partners for realising a transportable optical clock. While opticlock is funded by the German Federal Ministry of Education and Research and iqClock is part of the EU H2020 Quantum Flagship, both projects have the common goal to develop a field-deployable optical atomic clock for end users and establishing supply chains for future quantum technological products. The opticlock system works with a ^{171}Yb^{+} ion as frequency reference. Currently, the fractional frequency instability of the clock is at the mid 10^{-16}-level for an averaging time of 100 s [81]. The system is realised in a compact, rack-based design occupying two full-sized 19-racks, which yields an estimated volume of 1440 L. The project specified the maximum weight and power consumption as 1000 kg and 1000 W, respectively. Notably, the opticlock device is built with in-field and hands-off operation in mind [79].

The iqClock industry clock demonstrator is a strontium optical lattice clock currently being jointly developed by the partners within the iqClock Consortium [80] and designed to achieve fractional frequency instability at the 10^{-16} level or lower. The device itself is a rack-based clock system containing all four major clock systems. Figure 3 displays an artistic render of a possible system layout. As system integration is ongoing in this case, the actual performance of the iqClock quantum clock demonstrator remains to be verified upon its completion targeted for mid-2021. The targeted SWAP of the iqClock industry clock is $V = 1500$ L, $m < 800$ kg, $P < 800$ W. Notably, the iqClock project comprises partners which span from the supply chain to the end users of emerging quantum technologies. One of the project milestones is embedding the iqClock industry clock demonstrator into a research telecoms network.

As can be seen in Figure 2, both joint industry-academic clock development projects aim to establish an optical atomic clock with excellent but not record performance and with a good, yet not outstanding SWAP. Reasons for this approach may be found in the project background, i.e, reduction of risk for realising a functional device and the goal of integrating existing technology platforms of the industry project partners into the developed optical atomic clocks.

The shaded areas in Figure 2 indicated corridors of the typical performance values for optical lattice clocks with neutral atoms (green-shaded area) and for optical single-ion clocks (blue shaded area). Neutral atom lattice clocks currently require a volume between 1000 and 2000 L for good levels of fractional frequency instability and systematic uncertainty. At the same time they require power around 700–800 W and yield a mass between 400 and 800 kg. It has to be noted though, that these ranges result also from considering proposed “target” specifications and estimates. Owing to the small number of reported transportable optical single-ion clocks, it is difficult to make a more general statement; yet they show the tendency to smaller packaging sizes when compared to transportable neutral atom clocks.

A type of optical atomic clock not considered here so far are optical atomic clocks using a two-photon excitation scheme from the ground state of the clock transition by a pair of electric and magnetic dipole-allowed transitions [82]. These clocks commonly uses vapour cells and can be operated without laser cooling; both factors offer the benefit of building these optical clocks in a compact and robust way. Martin et al. reported an optical atomic clock based on a two-photon transition in a hot ^{87}Rb vapour [83]. Their clock has a fraction frequency instability of $4 \times 10^{-13}/\sqrt{\tau}$ (for averaging times between 1 and 10,000 s) and aims at improving short- and long-term stability of existing frequency standards by a factor of 10, while maintaining a comparable SWAP envelope of less than 10 L volume and less than 20 W of power consumption [83]. Notably, a “chip-scale” optical atomic clock based on two-photon excitation in rubidium vapour was developed at NIST in collaboration with the California Institute of Technology, Stanford University and Charles Stark Draper Laboratories [84]. This very compact optical atomic clock is based on an integrated photonic architecture including a semiconducting laser source, a miniature vapour cell and two Kerr-microresonator frequency combs. The system achieved fractional frequency instability of $4.4 \times 10^{-12}/\sqrt{\tau}$ and demonstrates a possible route toward highly portable and robust optical atomic clock systems.

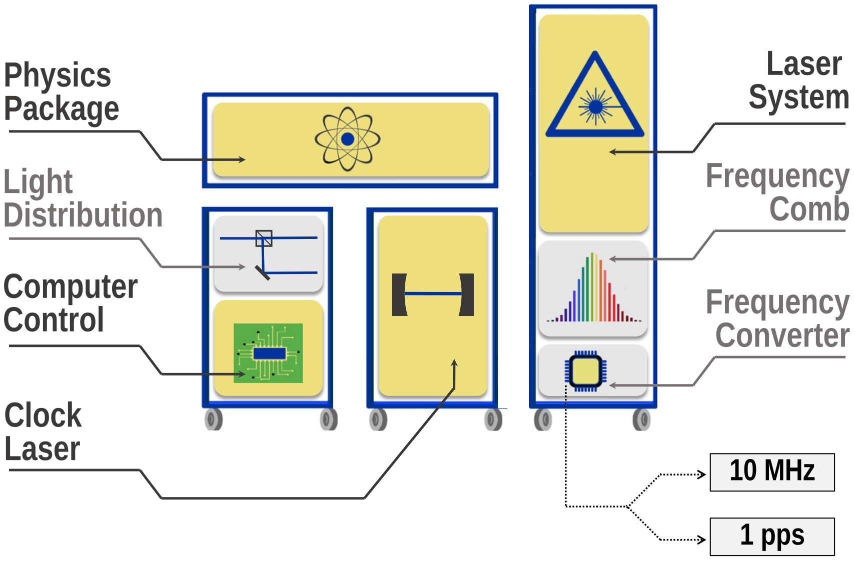


Figure 3: Schematic illustration of the concept for the transportable iqClock industry clock demonstrator. The four main subsystems (physics package, laser system, clock laser and computer control) are highlighted in yellow. Other subsystems with essential functions for the clock demonstrator are the light distribution unit for optimal and controlled light delivery from the laser system and clock laser to the physics package, the optical frequency comb generator, and the frequency converter which converts the comb output into signals (10 MHz and 1 pps) commonly used by a number of potential clock end users. As indicated, the demonstrator will be realised as rack-based system when integrated at the University of Birmingham.

2.1 Subsystems of transportable optical atomic clocks

Optical atomic clocks are frequently described to consist of four major subsystems (Figure 1): the physics package where the atom ensemble or trapped ion are prepared, a suite of cooling or trapping lasers as well as a lattice laser in the case of neutral atom clocks, the narrow-linewidth clock laser stabilised with an ultrastable optical cavity, and system electronics. Figure 4 illustrates the volume shares of these subsystems in the total system volume for four selected clock system listed in Table 1. The high-performing transportable clocks from the SOC2 and Katori project both show similar relative volume shares for the major subsystems. Unlike the SOC2 demonstrator which uses a number of off-the shelve components [63, 64], the clocks of the Katori Project use a laser system housed in compact "laser boxes" [31] allowing a gain in compactness. Notably, the six to seven necessary laser sources and laser distribution systems for the preparation of ultracold lattice trapped atoms require the largest share along with the system electronics. It is exactly those two subsystems which the Miniature Optical Clock project seeks to reduce for a significant gain in compactness [74, 75]. In Figure 4, one can also see that the WIPM Ca-ion clock requires less combined volume for laser systems, clock laser, and physics package than the former two operational optical lattice clocks. Cao et al. could reduce the size of those subsystems through an integrated design of their laser system and physics package [53].

2.2 Terminology

Notably, in the body of surveyed literature for this study, the terms "transportable", "portable" or "mobile" are used interchangeably for nonstationary optical clocks; although, as we summarised in the previous paragraphs, these clocks differ in their state of transportability and in-field operationability. Therefore, to clearly distinguish between the different types of nonstationary optical atomic clocks, we suggest the use of the following definition:

- Transportable optical atomic clocks: modular devices that are compact enough so that the modules can be transported on a standard mobile platform, e.g. a lorry or van, and are operational at their destination within a reasonable short amount of time (e.g. ~days).
- Portable optical atomic clocks: devices which are built in modular or monolithic fashion, yet as a single unit small enough to be transported by road in a conventional commercial transport vehicle. The clock is operational at its destination within short time (~hours), e.g. after a warm-up period.
- Mobile optical atomic clocks: compact devices which can operate during transport or generally on mobile platforms. Mobile clocks are units usually small enough to be handled by a single person.

According to these categories, all the above described optical atomic clock systems satisfy the criteria for transportable atomic clocks; i.e., the clock systems are designed as modular systems and the modules can be transported between locations. The PTB trailer clock is additionally built as a single trailer-housed unit. Neglecting the longer setup time of several days [30, 68], the single-unit character of this clock puts it towards the "portable optical atomic clock" category. According to above definitions, albeit not an optical atomic clock, the DSAC system is the only mobile atomic clock among the discussed clock systems here.

We also would like to point out that different use case scenarios might warrant different types of clocks. The PTB trailer clock was designed with the capacity for metrology applications in mind [30, 68]; hence the larger setup in an air-conditioned trailer for targeting a high performance. The Miniature Optical Clock, on the other hand, puts a low SWAP in the foreground to realise a very compact clock for transport, e.g., in a car boot [74]. In comparison, opticlock as well as the iqClock demonstrator have medium SWAP; yet the rack integration and form factor make those system easily adaptable to a server room environment, e.g., for integration into a telecom network. The low SWAP of the DSAC system arises from the requirements for a satellite-based system.

3 Conclusion and outlook

In summary, the work by Cao et al., the Femto-ST, the Miniature Optical Clock project, and the NIST Yb transportable optical lattice clock indicate a possible direction for the development of low SWAP optical atomic clocks with high performance through miniaturisation and smart system integration. At the same time, larger systems such as opticlock and iqClock enable industry involvement, which is crucial for developing laboratory technology into commercial systems for a wide range of applications. Ideally, both streams converge at some point in the future, helping to realise compact optical atomic clocks with uncompromised performance in a form factor comparable

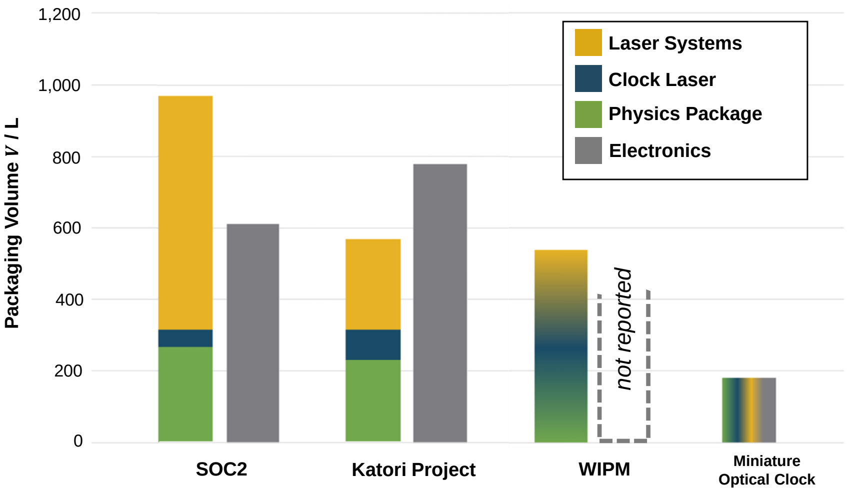


Figure 4: Comparison of subsystem volumes for selected transportable optical clock systems. For SOC2 and the clock of Katori group, it is possible to estimate volumes per each subsystem [31, 64, 65]. For the Ca-ion clock from WIPM, only the volume of the combined laser system, clock laser, and physics package are reported [53]. The volume of the system electronics is not reported, as indicated in the graph. In the Miniature Optical Clock development all four main subsystems are miniaturised and integrated to a relative high degree allowing the small package size [74, 75].

to the 30 L-large HP5071A caesium microwave clock [85] after decades of technology development [86].

Additionally, there are several alternative approaches to compact and robust optical atomic clock: optical atomic clocks based on two-photon excitation push towards chip-scale integrated optical clock systems without the need to generate ultracold atoms. On the other hand, grating chip-technology could allow optical atomic clocks operating with ultracold atoms to be realised on a very small scale [87, 88]. Yet another approach to robust and transportable atomic clocks could be based on optical tweezers to generate atomic arrays, which combines advantages from optical neutral atom and single-ion clocks [89, 90].

The authors noticed a number of other planned or ongoing transportable clock projects, e.g. the development of a compact, transportable Ca-ion clock at the University of Sussex [91], a “Miniature optical clock” project at the JPL Quantum Science & Technology Group [92], or a shipping container-based transportable Al-ion quantum logic clock laboratory at PTB [93].

In conclusion, only a small number of operational transportable optical atomic clocks are reported in literature so far. Transportable optical atomic clocks mostly range size-wise in between 1000 and 2000 L and can reach instabilities in the 10^{-17} range and uncertainties in between 10^{-16} and the mid 10^{-18} range for in-field operations. Transportable optical single-ion clocks are restricted to two operational systems reported. These reported systems have a higher fractional frequency instability but a compatible uncertainty when compared to transportable neutral atom clocks. In tendency, the reported transportable ion clock systems have a lower volume than neutral atom optical atomic clocks. Aside from one case, all herein discussed operational transportable optical clocks outperform microwave clocks and hydrogen maser with respect to stability and precision. Applications of transportable optical atomic clocks for relativistic geodesy/chronometric levelling have been demonstrated, and the two clock systems developed by joint industry-academic collaborations are lined up for field deployment in a number of use-cases. The next major milestone for optical atomic clock technology might be the demonstration of a high performing (i.e., instability at the 10^{-16}-level or lower) mobile optical atomic clock, i.e., an optical atomic clock operational during transport.

Driven by prospects of application for timing and synchronisation, relativistic geodesy, or resilient navigation, we expect the number of transportable atomic optical clocks to increase in future. Future transportable and portable optical clock systems will likely develop towards more compact, integrated and robust devices with stability and precision unmatched by any other type of commercially available clock system.

Acknowledgements: The authors are grateful for receiving funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820404 (iqClock project) and acknowledge the fruitful joint work with partners from the iqClock Consortium. We further recognise sponsorship from the UK Quantum Technology Hub Sensors and Timing (grant EP/T001046/1).

Author contribution: MG and YS wrote the manuscript with contributions from JJ, AS, QS, RB, and KB. All authors are involved with the iqClock project for realising a

transportable optical lattice clock demonstrator. All authors have reviewed and approved the manuscript.

Research funding: The authors are grateful for receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820404 (iqClock project) and acknowledge the fruitful joint work with partners from the iqClock Consortium. We further recognise sponsorship from the Quantum Hub for Sensors and Metrology (EPSRC funding within grant EP/M013294/1).

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

[1] B. L. Schmittberger and D. R. Scherer, "A review of contemporary atomic frequency standards," arXiv preprint, arXiv:2004.09987, 2020. Available at: https://arxiv.org/pdf/2004.09987.pdf.

[2] T. Fortier and E. Baumann, "20 years of developments in optical frequency comb technology and applications," *Commun. Phys.*, vol. 2, p. 153, 2019.

[3] E. Benkler, B. Lipphardt, T. Puppe, et al., "End-to-end topology for fiber comb based optical frequency transfer at the 10^{-21} level," *Opt. Exp.*, vol. 27, p. 36886, 2019.

[4] S. M. Brewer, J.-S. Chen, A. M. Hankin, et al., "27Al$^+$ quantum-logic clock with a systematic uncertainty below 10^{-18}," *Phys. Rev. Lett.*, vol. 123, p. 033201, 2019.

[5] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, "Frequency comparison of two high-accuracy Al$^+$ optical clocks," *Phys. Rev. Lett.*, vol. 104, p. 070802, 2010.

[6] P. Zhang, J. Cao, H.-L. Shu, et al., "Evaluation of blackbody radiation shift with temperature-associated fractional uncertainty at 10^{-18} level for 40Ca$^+$ ion optical clock," *J. Phys. B: Mol. Opt. Phys.*, vol. 50, p. 015002, 2017.

[7] M. Chwalla, J. Benhelm, K. Kim, et al., "Absolute frequency measurement of the ^{40}Ca$^+$ 4s^{2}S$_{1/2}$ – 3d^2 D$_{5/2}$ clock transition," *Phys. Rev. Lett.*, vol. 102, p. 023002, 2009.

[8] P. Dubé, A. A. Madej, and B. Jian, "Sr single-ion clock," *J. Phys: Conf. Ser.*, vol. 723, p. 012018, 2016.

[9] H. S. Margolis, G. P. Barwood, G. Huang, et al., "Hertz-level measurement of the optical clock frequency in a single 88Sr$^+$ ion," *Science*, vol. 306, p. 1355, 2004.

[10] N. Huntermann, C. Sanner, B. Lipphardt, and E. Peik, "Single-ion atomic clock with 3 × 10–18 systematic uncertainty," *Phys. Rev. Lett.*, vol. 116, p. 063001, 2016.

[11] R. M. Godun, P. B. R. Nisbet-Jones, J. M. Jones, et al., "Frequency ratio of two optical clock transitions in ^{171}Yb$^+$ and constraints on the time variation of fundamental constants," *Phys. Rev. Lett.*, vol. 113, p. 210801, 2014.

[12] S. Falke, N. Lemke, C. Grebing, et al., A strontium lattice clock with 3×10^{-17}inaccuracy and its frequency, *N. J. Phys.*, vol. 16, p. 073023, 2014.

[13] P. G. Westergaard, J. Lodewyck, L. Lorini, et al., "Lattice-induced frequency shifts in Sr optical lattice clocks at the 10^{-17} level," *Phys. Rev. Lett.*, vol. 106, p. 210801, 2011.

[14] T. L. Nicholson, M. J. Martin, J. R. Williams, et al., "Comparison of two independent Sr optical clocks with 1×10^{-17} stability at 10^3s," *Phys. Rev. Lett*, vol. 109, p. 230801, 2012.

[15] M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, "An optical lattice clock," *Nature*, vol. 435, p. 321, 2005.

[16] N. Hinkley, A. Sherman, N. B. Philips, et al., "An atomic clock with 10^{-18} instability," *Science*, vol. 341, p. 1215, 2013.

[17] Z. W. Barber, C. W. Hoyt, C. W. Oates, et al., "Direct excitation of the forbidden clock transition in neutral Yb 174 atoms confined to an optical lattice," *Phys. Rev. Lett.*, vol. 96, p. 083002, 2006.

[18] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, "Optical atomic clocks," *Rev. Mod. Phys.*, vol. 87, p. 638, 2015.

[19] H. S. Margolis, "Frequency metrology and clocks," *J. Phys. B: Mol. Opt. Phys.*, vol. 42, p. 154017, 2009.

[20] W. M. Itano, J. C. Bergquist, J. J. Bollinger, et al., "Quantum projection noise: population fluctuations in two-level systems," *Phys. Rev. A*, vol. 47, p. 3554, 1993.

[21] E. Oelke, R. B. Hutson, C. J. Kennedy, et al., "Demonstration of 4.8 × 10–17 stability at 1 s for two independent optical clocks," *Nat. Photon.*, vol. 13, p. 714, 2019.

[22] A. Quessada, R. P. Kovacich, I. Courtillot, et al., "The Dick effect for an optical frequency standard," *J. Opt. B: Quantum Semiclass. Opt.*, vol. 5, p. S150, 2003.

[23] J. Lodewyck, P. G. Westergaard, and P. Lemonde, "Nondestructive measurement of the transition probability in a Sr optical lattice clock," *Phys. Rev. A*, vol. 79, p. 061401, 2009.

[24] J. Vanier and C. Audoin, *The Quantum Physics of Atomic Frequency Standards*, Boca Raton, CRC Press, 1989.

[25] M. Vermeer, *Chronometric Levelling*, Helsinki: Geodeettinen Laitos Geodetiska Institutet, 1983.

[26] N. K. Pavlis and M. A. Weiss, "The relativistic redshift with 3×10^{-17} uncertainty at NIST, Boulder, Colorado, USA," *Metrologia*, vol. 40, p. 66, 2003.

[27] H. S. Margolis, "Frequency metrology and clocks," *J. Phys. B*, vol. 42, p. 154017, 2009.

[28] W. F. McGrew, X. Zhang, R. J. Fasano, et al., "Atomic clock performance enabling geodesy below the centimetre level," *Nature*, vol. 564, p. 87, 2018.

[29] H. Katori, "Optical lattice clocks and quantum metrology," *Nat. Photon.*, vol. 5, p. 203, 2011.

[30] J. Grotti, S. Koller, S. Vogt, et al., "Geodesy and metrology with a transportable optical clock," *Nat. Phys.*, vol. 14, p. 437, 2018.

[31] M. Takamoto, I. Ushijima, N. Ohmae, et al., "Test of general relativity by a pair of transportable optical lattice clocks," *Nat. Photonics*, vol. 14, p. 411–415, 2020.

[32] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, "Cryogenic optical lattice clocks," *Nat. Photon.*, vol. 9, p. 185, 2015.

[33] T. Nicholson, S. Campbell, R. Hutson, et al., "Systematic evaluation of an atomic clock at 2 x 10-18 total uncertainty," *Nat. Com.*, vol. 6, p. 1, 2015.

[34] S. Vogt, C. Lisdat, T. Legero, et al., "Demonstration of a transportable 1 Hz-linewidth laser," *Appl. Phys. B*, vol. 104, p. 741, 2011.

[35] S. Webster and P. Gill, "Force-insensitive optical cavity," *Opt. Lett.*, vol. 36, p. 3572, 2011.

[36] Q. F. Chen, A. Nevsky, M. Cardace, et al., "A compact, robust, and transportable ultra-stable laser with a fractional frequency instability of 1×10^{-15}," *Rev. Sci. Instrum.*, vol. 85, p. 113107, 2014.

[37] D. Świerad, S. Häfner, S. Vogt, et al., "Ultra-stable clock laser system development towards space applications," *Sci. Rep.*, vol. 6, p. 33973, 2016.

[38] M. G. Tarallo, N. Poli, M. Schioppo, D. Sutyrin, and G. M. Tino, "A high-stability semiconductor laser system for a 88Sr-based optical lattice clock," *Appl. Phys. B*, vol. 103, p. 17, 2011.

[39] A. Nevsky, S. Alighanbari, Q.-F. Chen, et al., "Robust frequency stabilization of multiple spectroscopy lasers with large and tunable offset frequencies," *Opt. Lett.*, vol. 38, p. 4903, 2013.

[40] S. Mulholland, H. A. Klein, G. P. Barwood, et al., "Compact laser system for a laser-cooled ytterbium ion microwave frequency standard," *Rev. Sci. Instrum.*, vol. 90, 2019, Art no. 033105, https://doi.org/10.1063/1.5082703.

[41] R. Schwarz, S. Dörscher, A. Al-Masoudi, et al., "A compact and robust cooling laser system for an optical strontium lattice clock," *Rev. Sci. Instrum.*, vol. 90, 2019, Art no. 023109, https://doi.org/10.1063/1.5063552.

[42] O. Kock, W. He, S. Świerad, et al., "Laser controlled atom source for optical clocks," *Sci. Rep.*, vol. 6, p. 37321, 2016.

[43] C. Vishwakarma, J. Mangaonkar, K. Patel, et al., "A simple atomic beam oven with a metal thermal break," *Rev. Sci. Instrum.*, vol. 90, 2019, Art no. 053106, https://doi.org/10.1063/1.5067306.

[44] W. Bowden, R. Hobson, I. R. Hill, et al., "A pyramid MOT with integrated optical cavities as a cold atom platform for an optical lattice clock," *Sci. Rep.*, vol. 9, p. 11704, 2019.

[45] I. A. Semerikov, I. V. Zalivako, A. S. Borisenko, et al., "Three-dimensional Paul trap with high secular frequency for compact optical clock," *Bull. Lebedev Phys. Inst.*, vol. 46, p. 297, 2019.

[46] M. Biethahn and K. Bergner, "Die optische Atomuhr geht in die Anwendung." *Vak. Forsch. Prax.*, vol. 31, p. 15, 2019.

[47] F. Riehle, "Optical clock networks," *Nat. Photon.*, vol. 11, p. 25, 2017.

[48] J. Yao, J. A. Sherman, T. Fortier, et al., "Optical-clock-based time scale," *Phys. Rev. Appl.*, vol. 12, p. 044069, 2019.

[49] S. Schiller, A. Görlitz, A. Nevsky, et al., "The space optical clocks project: Development of high-performance transportable and breadboard optical clocks and advanced subsystems," *IEEE Europ. Freq. Time Forum (EFTF)*, p. 412, 2012, https://doi.org/10.1109/EFTF.2012.6502414.

[50] F. Riehle, "Towards a redefinition of the second based on optical atomic clocks," *Compt. Ren. Phys.*, vol. 16, p. 506, 2015.

[51] J. Guéna, M. Abgrall, D. Rovera, et al., "Progress in atomic fountains at LNE-SYRTE," *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, vol. 59, p. 391, 2012.

[52] S. Weyers, V. Gerginov, M Kazda, et al., "Advances in the accuracy, stability, and reliability of the PTB primary fountain clocks," *Metrologia*, vol. 55, p. 789, 2018.

[53] J. Cao, P. Zhang, J. Shang, et al., "A compact, transportable single-ion optical clock with 7.8×10^{-17} systematic uncertainty," *Appl. Phys. B*, vol. 123, p. 112, 2017.

[54] S. Wang, J. Cao, J. Yuan, et al., "Integrated multiple wavelength stabilization on a multi-channel cavity for a transportable optical clock," *Opt. Exp.*, vol. 28, p. 11852, 2020.

[55] Available at: https://www.t4science.com/wp-content/uploads/2016/06/imaser3000-frequency-stability-e1479376681500.png.

[56] X. Xue, Z. Zhang, X. Zhang, et al., "A Compact Design of a Transportable Calcium Optical Frequency Standard," *IEEE Int. Freq. Symp.* (IFCS), p. 1, 2018, https://doi.org/10.1109/FCS.2018.8597454.

[57] T. A. Ely, J. Seubert, J. Prestage, et al., *2019AAS/AIAA Astrodynamics Specialist Conf.*, AIAA; 2019.

[58] T. A. Ely, D. Murphy, J. Seubert, J. Bell, and D. Kuang, *AAS/AIAA Space Flight Mechanics Meeting*, AIAA; 2014.

[59] R. L. Tjoelker, J. D. Prestage, E. A. Burt, et al., "Mercury ion clock for a NASA technology demonstration mission," *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, vol. 63, p. 1034, 2016.

[60] Available at: http://www.exphy.uni-duesseldorf.de/optical_clock/soc2/index.php [accessed: May 30, 2020].

[61] N. Poli, M. Schioppo, S. Vogt, et al., "A transportable strontium optical lattice clock," *Appl. Phys. B*, vol. 117, p. 1107, 2014.

[62] G. Mura, T. Franzen, C. A. Jaoudeh, et al., "A transportable optical lattice clock using 171Yb," in *IEEE Joint European Frequency Time Forum & International Frequency Control Symposium*. (EFTF/IFC), Prague, Czech Republic, IEEE, 2013, p. 376. https://doi.org/10.1109/EFTF-IFC.2013.6702292.

[63] K. Bongs, Y. Singh, L. Smith, et al., "Development of a strontium optical lattice clock for the SOC mission on the ISS," *Compt. Ren. Phys.*, vol. 16, p. 553, 2015.

[64] S. Origlia, M. S. Pramod, S. Schiller, et al., "Towards an optical clock for space: compact, high-performance optical lattice clock based on bosonic atoms," *Phys. Rev. A*, vol. 98, p. 053443, 2018.

[65] L. L. Smith, "A transportable strontium optical lattice clock towards space," PhD Thesis, University of Birmingham, England, 2016.

[66] M. Schioppo, G. M. Tino, N. Poli, et al., "Development of a transportable laser cooled strontium source for future applications in space," *IEEE Europ. Freq. Time Forum (EFTF)*, vol. 1, 2010, https://doi.org/10.1109/EFTF.2010.6533689.

[67] M. Schioppo, N. Poli, M. Prevedelli, et al., "A compact and efficient strontium oven for laser-cooling experiments," *Rev. Sci. Instrum.*, vol. 83, p. 103101, 2012.

[68] S. Vogt, S. Häfner, J. Grotti, et al., "A transportable optical lattice clock," *J. Phys: Conf. Ser.*, vol. 723, p. 012020, 2016.

[69] S. B. Koller, J. Grotti, S. Vogt, et al., "Transportable optical lattice clock with $7 \times 10–17$ uncertainty," *Phys. Rev. Lett.*, vol. 113, 2017, Art no. 073601.

[70] S. Häfner, "Ultra-stabile Lasersysteme für Weltraum- und Bodenanwendungen," PhD Thesis, Universität Hannover, Germany, 2015.

[71] U. Sterr, "Frequency stabilization device," German patent DE102011015489B3, 2012.

[72] C. Lacroûte, M. Souidi, P.-Y. Bourgeois, et al., "Compact Yb^+ optical atomic clock project: design principle and current status," *J. Phys: Conf. Ser.*, vol. 723, p. 012025, 2016.

[73] M. Delehaye and C. Lacroûte, “Single-ion, transportable optical atomic clocks,” *J. Mod. Opt.*, vol. 65, p. 622, 2018.

[74] M. Aldous, S. Viswam, J. Bass, et al., “Development of a Portable Optical Clock,” *IEEE Int. Freq. Con. Symp. IFCS*, 2018, https://doi.org/10.1109/FCS.2019.8856051.

[75] D. Morris, M. Aldous, M. Gellesch, et al., “Route to a Portable Optical Clock,” *IEEE Int. Freq. Con. Symp. IFCS*, 2019, https://doi.org/10.1109/FCS.2018.8597579.

[76] W. Brand, R. Fasano, R. Fox, et al., “Portable Yb Optical Lattice Clock: Towards Precision Measurement Outside the Lab,” APS 2019 E01-046, Available at: http://meetings.aps.org/Meeting/DAMOP19/Session/E01.46, 2019.

[77] R. Fasano, W. Brand, R. Fox, et al., “NIST Yb portable lattice clock: updates and analysis,” *IEEE Joint Conf. IFCS-ISAF 2020*, IEEE; 2020.

[78] K. Beloy, N. Hinkley, N. B. Phillips, et al., “Atomic clock with 1×10^{-18} room-temperature blackbody stark uncertainty,” *Phys. Rev. Lett.*, vol. 113, p. 260801, 2014.

[79] Available at: https://www.opticlock.de/info/ [accessed: May 30, 2020].

[80] Available at: https://www.iqclock.eu/ [accessed: May 25, 2020].

[81] International Conference on Quantum Metrology and Sensing 9.-13. December 2019, Paris, France, Abdel Hafiz Moustafa, Arar Bassem, Bergner Klaus, et al. Opticlock: transportable and easy-to-operate optical single-ion clock. Paris: IQuMS; December, 2019.

[82] E. A. Alden, K. R. Moore, and A. E. Leanhardt, “Two-photon E1-M1 optical clock,” *Phys. Rev. A*, vol. 90, p. 012523, 2014.

[83] K. W. Martin, G. Phelps, N. D. Lemke, et al., “Compact optical atomic clock based on a two-photon transition in rubidium,” *Phys. Rev. Appl.*, vol. 9, p. 014019, 2018.

[84] Z. L. Newman, V. Maurice, T. Drake, et al., “Architecture for the photonic integration of an optical atomic clock,” *Optica*, vol. 6, p. 680, 2019.

[85] Available at: https://www.microsemi.com/product-directory/cesium-frequency-references/4115-5071a-cesium-primary-frequency-standard#resources [accessed: May 30, 2020].

[86] L. S. Cutler, “Fifty years of commercial caesium clocks,” *Metrologia*, vol. 42, p. S90, 2005.

[87] C. Nshii, M. Vangeleyn, J. Cotter, et al., “A surface-patterned chip as a strong source of ultracold atoms for quantum technologies,” *Nat. Nanotechnol.*, vol. 8, p. 321, 2013.

[88] P. Elgee, A. Sitaram, D. Barker, et al., “Confinement of an alkaline-earth element in a grating magneto-optical trap,” arXiv preprint arXiv:2006.05369, 2020 Available at: https://arxiv.org/abs/2006.05369.

[89] I. S. Madjarov, A. Cooper, A. L. Shaw, et al., “An atomic-array optical clock with single-atom readout,” *Phys. Rev. X*, vol. 9, Art no. 041052, 2019. https://doi.org/10.1103/PhysRevX.9.041052.

[90] M. A. Norcia, A. W. Young, W. J. Eckner, et al., “Seconds-scale coherence on an optical clock transition in a tweezer array,” *Science*, vol. 366, p. 93, 2019.

[91] Available at: http://itcm-sussex.com/?page_id=333 [accessed: May 25, 2020].

[92] Available at: https://quantum.jpl.nasa.gov/?page_id=116 [accessed: Aug. 30, 2020].

[93] S. Hannig, L. Pelzer, N. Scharnhorst, et al., “Towards a transportable aluminium ion quantum logic optical clock,” *Rev. Sci. Instrum.*, vol. 90, Art no. 053204, 2019, https://doi.org/10.1063/1.5090583.

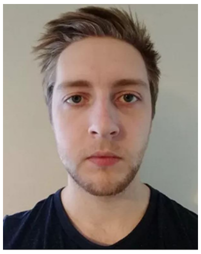
Bionotes

Markus Gellesch
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK
m.gellesch@bham.ac.uk

Dr. Markus Gellesch is an experimental physicist. Currently, he is working on transportable lattice clocks as part of the EU quantum flagship project iqClock. Markus also has a strong interest in outreach work and has recently collaborated with a local artist to realise a comic booklet on the theme of optical atomic clocks. (https://quantumclocks.the-comic.org/)

Jonathan Jones
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

Dr. Jonathan Jones is an early stage researcher with a focus on developing cold atoms and optical clock technology for application in the real world. He has published work on ion trapping, optical clocks, quantum metrology and time variation of fundamental constants. Currently he is leading the group’s work on optical cavities in addition to working on transportable lattice clocks as part of the EU quantum flagship programme “iqClock”.



Richard Barron
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

Richard Barron joined the group during his master’s project in 2016 and has carried on through to a PhD, working mostly on the production of atoms to load into a MOT. Currently on the iqClock project.

Alok Singh
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

Dr. Alok Singh is an experimental Optical and Atomic Physicist and he works at precision hyperfine frequency measurements, coherent population trapping/oscillation, Bose-Fermi mixture, dipole-dipole/quadrupole Forster resonance transitions in Rydberg atoms and cold atoms for atomic clock. He has published on the impact of cold atoms, precision frequency measurements and coherent population trapping/oscillation. His recent research focuses on atomic optical lattice clock using Sr atoms with Miniature Optical Lattice Clock project and iqClock-Integrated Quantum Clock project.

Qiushuo Sun
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

Dr. Qiushuo Sun is a knowledge exchange fellow at the Centre for Innovation in Advanced Measurement in Manufacturing (CIAMM) at the University of Birmingham. She joined the group in September 2019 and has been working on the high-finesse optical cavities and the lasers for the optical clocks. She also helps support local SMEs in Research and Development in state–of–the–art optical technologies and instruments.

Kai Bongs
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK

Professor Kai Bongs is a Principle Investigator at the UK Quantum Technology Hub Sensors and Timing, where he helps to drive the translation of gravity sensors and ultraprecise clocks into technology and applications across a diverse number of different sectors. Professor Bongs is also College Director of Innovation at the University of Birmingham. He is a Royal Society Wolfson Research Merit Fellow, as well as a Fellow of the Institute of Physics and the Institution of Engineering and Technology.

Yeshpal Singh
University of Birmingham, School of Physics and Astronomy, Birmingham B15 2TT, UK
Y.Singh.1@bham.ac.uk

Dr. Yeshpal Singh is a senior lecturer at the University of Birmingham and leads the cold atoms based Sr group. His main research interests are translation of quantum concepts to quantum technology, quantum metrology and precision measurements, Bose–Einstein condensates in microgravity, ultracold Bosons, degenerate Fermi gases and quantum phase transitions, and ultracold molecules and quantum state engineering.