Optical atomic clocks, time, and the future of metrology

TARA MICHELE FORTIER[1,2,*], ANDRE LUITEN[3], AND HELEN MARGOLIS[4]

[1] Time and Frequency Division, National Institute of Standards and Technology, MS 847, Boulder CO 80305
[2] Time Department, Bureau Internationl des Poids et Mesures, Sevres France
[3] National Physical Laboratory, Teddington Middlesex, UK
[4] University of Adelaide, Institute for Photonics and Advanced Sensing, Division of Research and Innovation, Adelaide South Australia, Australia
[*] tara.fortier@nist.gov

Compiled October 31, 2024

Atomic clocks, first developed in the 1950's have become a mainstay of modern synchronization, navigation and communication. With an unprecedented frequency accuracy, now surpassing 1 part in 10^{18}, If run continuously, the best atomic clocks would lose only 1 second in 15 billion years. This level of accuracy could be used to measure a meter stick with length resolution at quark level, and is currently being employed as tabletop experiments to search for physics beyond the standard model. This mini review takes a tutorial and forward-facing perspective on the evolution of atomic clocks, how they help keep international time, their enabling technologies, and developing applications. More specifically, we will approach the topic from the lens of the laser scientist, exploring the optical techniques at the heart of atomic clocks and how these enabling technologies are poised to advance the field of precision metrology.

http://dx.doi.org/10.1364/ao.XX.XXXXXX

1. INTRODUCTION

While the philosophical nature of time may be difficult to pin down, the definition of a base unit of time has been pragmatically selected to meet human needs. The precise definition, control, and measurement of time are foundational to the coordination of complex activities, the synchronization of global networks, and the seamless operation of communication, navigation, and scientific exploration. Since 1967, microwave atomic clocks based on the hyperfine transition of ^{133}Cs. ^{133}Cs atoms have defined the SI second and served as the global standard for timekeeping. These clocks provide an essential reference for maintaining an absolute and universally consistent measure of time, enabling the synchronization of systems across vast distances and time scales.

Prior to 1967, the second was defined in relation to Earth's rotation, specifically as 1/86,400th of a mean solar day [1]. While Earth's rotation is remarkably stable given its motion through a near vacuum (changing by only microseconds per year), it is still subject to variations caused by tidal forces, seismic activity, and even seasonal changes, such as the growth of foliage in spring and summer. These fluctuations rendered Earth's rotation inadequate as a timekeeping standard, conflicting with the goals of the 1875 Metre Convention, which sought 'international unification and the perfection of the Metric System.

In 1967, the international definition of time shifted away from the variability of planetary rotation toward the precision of atomic systems [2]. Clocks based on atoms exploit the inherent regularity of long-lived electronic resonances in atoms, which provide near-perfect oscillatory behavior. The unperturbed frequency of these atomic transitions can be treated as a fundamental constant of nature, much like the speed of light, governed by immutable physical laws. In the current SI definition, the second is based on the hyperfine transition of the ^{133}Cs atom where ν_{Cs} = 9,192,631,770 Hz. Thus, one second is defined as the accumulation of exactly 9,192,631,770 cycles, or periods, of this transition frequency.

A. Why use atoms for timing?

Atoms serve as exceptional references for several key reasons: (1) They are abundantly produced in nature, providing a universally available resource. (2) They are intrinsically reproducible—atoms of a given isotope are fundamentally identical in structure. Unlike earlier man-made artifacts that were once used to standardize the meter and kilogram, atomic resonance structures, in principle, remain invariant, as they are governed by unchangeable physical laws. (3) Atoms represent highly isolated systems where internal forces, such as the interactions between electrons and the nucleus, dominate over external perturbations. For instance, even uncontrolled collisions between atoms typically lead to fractional frequency shifts in the clock transition, $\Delta f/f$, at less than 1 part per 10 billion, or at the $\sim 10^{-10}$ level. While this shift may appear large compared to the present accuracy of Cs fountain clocks—about 1 part in 10^{16}, or 1 billionth of a part in 10 million—it far surpasses the precision of other SI units. For example, the kilogram, the next best-defined unit, has an accuracy of only 2 parts in 10^8.

B. How better timing might impact modern day applications of atomic clocks and timekeeping.

Keeping better time was originally conceived to help coordinate activities over large networks, but technological advances were most powerfully motivated by the desire for more precise navigation. From this standpoint not much has changed regarding modern day timekeeping with atomic clocks. The

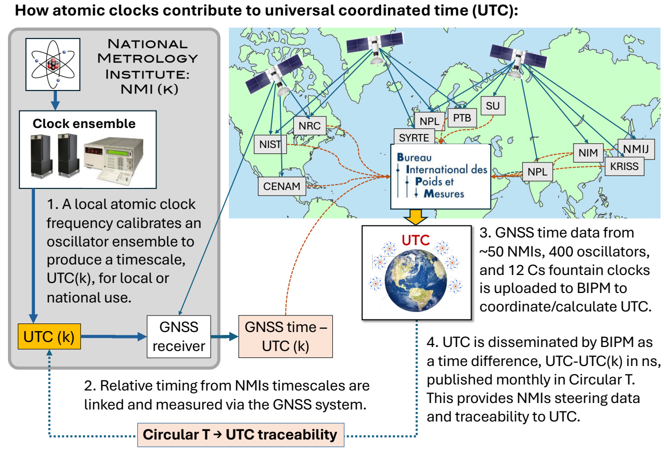

Fig. 1. Schematic of how atomic references worldwide contribute to universal coordinated time (UTC) through the global navigation satellite system (GNSS), and via the Bureau International des Poids et Mesures (BIPM). There are many atomic clocks that contribute to UTC, serving as either primary (Cs clocks that define the second) or secondary references. The simplest and least expensive time scales comprise a single commercial atomic beam clock referenced to a GNSS receiver. Even with no traceability to UTC, such systems can provide long-term timing accuracy at the 10 ns level. For optical atomic references, local and/or intercontinental dedicated fiber links can facilitate relative clock measurements. To data, optical links are the only links that can support high fidelity signal dissemination from optical atomic clocks.

first satellites with onboard commercial clocks were launched in the late 1970s, which helped facilitate the global position system (GPS), which came online in the 1980s for civil use. Currently the global navigation satellite system (GNNS) comprises 5 network constellations, GPS (USA), BeiDou (China), GLONASS (Russia), Galileo (European Union), and QZSS (Japan) with a total of 140+ satellites. The prominence of GNSS in modern day life is impressive. It is estimated that worldwide there are 6.5 billion installed GNSS devices. GNSS supports industries as far and wide as agriculture, financial systems, mining, utilities networks, surveying, military applications, and geodesy. In 2019, the US National Institute of Standards and Technology (NIST) estimated that GPS generated \$ 1.4 trillion in U.S. economic benefits since it first came online, and that failure of the GPS constellations would cost the US economy approximately 1 billion dollars/day [3]!

To date, very few commercial or military timing applications take advantage of the full accuracy and resolution of the current best microwave atomic standards. There are a few reasons for this. Aside from challenges associated with high-fidelity time dissemination, which will be discussed in Section X, high frequency resolution at timescales < 1s can be easily achieved using less complex, and less expensive, sapphire or quartz oscillators. Atomic accuracy is only needed when a system requires stability at times longer than 1 s. To put this time frame into distance, 1 s is the time it would take for light to circle the earth about 8 times. As a result, systems like radar, with detection ranges of 3000 km, don't generally require the stability of atoms, just low noise oscillators.

The long term timing from atomic clocks is principally applied to systems that rely on: 1) 'absolute' timing signals, such as Coordinated Universal Time (UTC), which is essential for accurate positioning and navigation; 2) minimal drift over long averaging times (greater than 1 second), such as very long baseline interferometry with radio telescopes and high-precision research metrology, where accurate time measurements are critical for data interpretation; and 3) systems spanning vast distances, including deep-space navigation, where precise timing coordination via earth-based clocks require multi week holdover times. For comparison, satellite-based clocks usually require communication with high accuracy ground-based clocks a few times per day to correct their drift.

C. How atomic time is kept and disseminated.

To be clear, the atomic transition defines time, but atomic clocks are physically employed as frequency standards not time standards. A frequency standard defines the rate at which time advances. A time standard provides a continuous reference for measuring time intervals and for defining the current time. These definitions results in a fundamental difference between how time and frequency are kept. To keep frequency, one "simply" needs to turn on a standard and observe that its frequency is the same as, or consistent with, the last measurement and all previous measurements. To keep time, one has to measure how the phase of a frequency stable signal has evolved since you decided to define time, perhaps as long ago as 1967. As a result, ideally if you keep time, you can never lose track of a single oscillatory cycle.

Figure 1 shows how NMIs worldwide produce their own national timescales, UTC(k), from atomic frequency references, and how the ensemble of timescales are compared and coordinated for contribution to UTC. Local to a nation, UTC(k) is disseminated to the public using internet time servers, GNSS satellites, radio stations and cell towers. At the National Institute of Standards and Technology in Boulder CO, its time servers, which help to synchronize X% of the worlds portable electronic devices, receive 100 time more hits per day that the Google search engine!

Universal co-ordintated time is deduced by comparing the timing of global timescales using the GNNS and two-way satellite time transfer. Although any link that can facilitate a timing comparison is acceptable, GNSS is most widely used because it can connect remote labs over global distances and because it is accessible with relatively inexpensive receivers. Even if GNNS time exhibits timing errors, because it is common to all measurements, most of its noise and errors are removed in post processing when calculating the relative difference between timescales, $UTC(K_1) - GNSStime - [UTC(K_2) - GNSStime] = UTC(K_1) - UTC(K_2) + \delta t_{residualGNSSnoise}$. Two way satellite time transfer, conversely, enables the direct generation of time differences between remote clocks connected bidirectionally across the link. The BIPM uses statistical algorithms to generate UTC from the time differences from a multitude of contributing timescales. Once computed, the BIPM then published the time difference of each reporting timescale versus UTC, UTC-UTC(k) in nanoseconds. This information then serves as a slow tuning signal for NMIs to steer their local time standard, UTC(k), to a globally referenced and traceable UTC.

This process is currently how atomic clocks keep the world in synch and on time.

D. Accuracy versus stability

When discussing atomic clocks it is important to consider the subtlety between accuracy and stability. More specifically, evaluating either quality always requires comparison against at least one other standard. Having just one standard is like being the world's best archer with no target to aim at—there's no way to prove performance. And because no exact theory provides the natural frequency of most clock transitions (except in hydrogen), a single measurement doesn't reveal an absolute "true" value, only our best attempt to measure it. Therefore, in the quest for perfection, a multitude of standards, and a multitude of measurements are combined, and the most reproducible and consistent results establish our best estimate of the "truth". This is a big reason why UTC needs as many global clock contributions as possible.

Accuracy measures how close repeated measurements are to the central, or "true," value of a frequency. It's assessed by repeatedly "hitting" this central value across multiple trials. Stability, in contrast, refers to how consistently measurements cluster together, regardless of their closeness to the true value. **Stability** concerns the spread of results around a mean, while accuracy is concerned with where that mean falls relative to the true value. As seen in Fig. 5, it is possible to have a standard with excellent stability but poor accuracy, high accuracy with low stability, or any combination of the two.

In atomic clocks, people often focus on accuracy. However, stability also impacts a clock's practical performance. Also illustrated in Fig. 5, a clock with good accuracy but poor stability will require longer measurement times to reach a target precision compared to one with high stability. Unlike accuracy, which is a static value, stability varies over time. Stability is quantified by evaluating the spread of measurements taken at different averaging intervals. If a clock's mean frequency drifts over a measurement period, it may exhibit good short-term stability, but as time progresses, the stability deteriorates, and the mean becomes poorly defined.

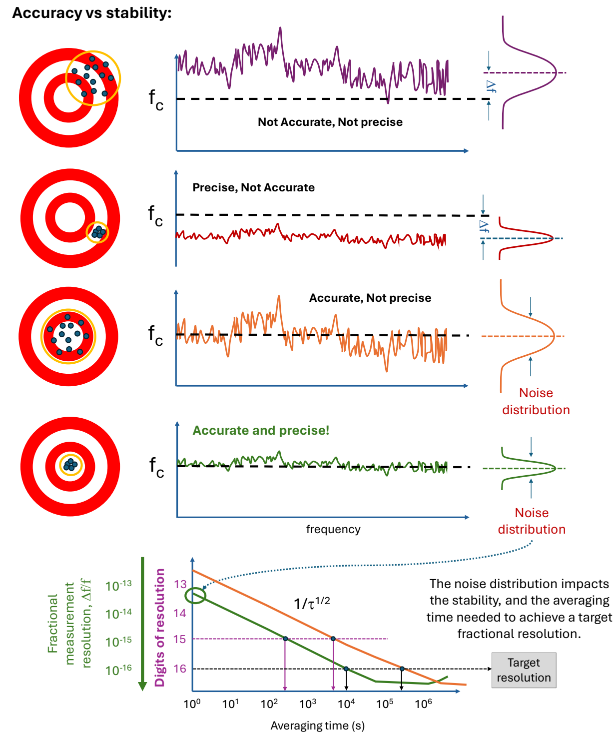

Fig. 2. Comparison of clock accuracy and stability. Targets on the left illustrate different combinations of clock accuracy and stability, with corresponding frequency time records shown to the right. Top left: A clock with low accuracy and high scatter (low stability,) where points are loosely clustered around the point offset from the target center. The fourth target demonstrates high accuracy and high stability, showing data points centered but with low scatter. Bottom center: The stability plot at the bottom shows how increased scatter in frequency measurements reduces the measurement resolution for all averaging times. Lower starting stability can significantly impact the averaging time, τ needed to reach a specific frequency resolution. For systems, like atomic clocks, which generally exhibit white frequency noise, or frequency noise with a Gaussian noise distribution, the frequency resolution improves at a rate of $1/\tau^{-1/2}$. This means that a gain of one digit in frequency resolution takes 100 times more averaging time! So if it takes 1 day to reach a resolution of 1 part in 10^{15}, it will take 100 days of measurement to reach 1 part in 10^{16}!

E. Challenges, limitations and opportunities in the global realization of atomic time.

Accuracy of atomic clocks. The current algorithm governing UTC gives greater weight to clocks with higher performance. As a result, although about 400 atomic clocks contribute to UTC, UTC is most strongly steered by the highest performance clocks in the global ensemble. As a result, adding more lower performance clocks will not have appreciable impact on UTC performance. Better UTC accuracy will require the addition of more high performance clocks as well as higher performance clocks. The more clocks the better for the global community to best estimate "true" time. Currently, ^{133}Cs fountain clocks, which are the primary standards for the SI second, are limited in accuracy to about 1.5 parts in 10^{16}. This accuracy currently limits the precision of UTC on a global scale. As mentioned previously, in a perfect world a redefinition to optical atomic time would improve the acccuracy in the definition of the second by two orders of magnitude. As a result, one of the primary beneficiaries of a redefinition to the SI second to optical atomic clocks is UTC.

Relativity and the geoid. The contribution of optical standards as primary representation of the second to UTC, however, will not enable a factor of 100 gain in accuracy. This is because the global comparison of atomic clocks will be limited by our knowledge of the earth's geopotential. According to general relativity, clocks in gravitational fields experience time dilation, meaning clocks positioned closer to Earth's center of gravity (e.g., at sea level) tick more slowly than those at higher altitudes. Uncertainties in our understanding of Earth's gravitational field over large distances can introduce time dilation errors of approximately 1 part in 10^{17}, equivalent to absolute change in altitude of ± 0.1 m. Over local regions (within a 20 km radius), the combination of satellite and ground based gravimetry measurements, can be used to constrain relative variations in the static geoid below the mm-level. However, fast temporal variations, such as those caused by changes in the water table in regions like the United Kingdom, can as introduce variations at the 10 cm level, corresponding to time dilation at the 10^{-17} level. To achieve the highest relative clock measurement accuracy over remote distances, knowledge of the time dilation shifts due to static

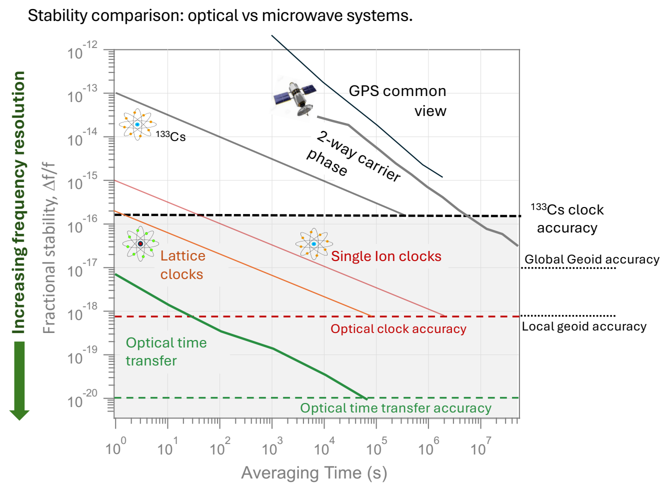

Fig. 3. Frequency resolution versus averaging time for microwave and optical atomic clocks, alongside optical and microwave time transfer links. The curves illustrate the superior frequency resolution of optical clocks compared to microwave clocks over increasing averaging times. Both fiber and free-space optical time transfer links demonstrate enhanced stability over satellite microwave links, supporting higher precision in time and frequency comparison. The accuracy limitations imposed by the geoid are represented by a threshold, showing the point at which gravitational potential uncertainties due to Earth's shape and density variations restrict achievable clock accuracy. This highlights some of the challenges in maintaining precision across global clock comparisons, where the geoid-based potential differences introduce a fundamental limit. ** I need to include microwave transfer over optical links, VLBI for clock comparisons, CW free-space time transfer... anything else?!

and temporal variations of the geoid are required. Ultimately if the SI second is redefined based on optical atomic times, even with clocks operating locally at the 10^{-18} level, current models and measurement of the geoid will limit the accuracy of time realization in UTC near the 10^{-17} level.

National and global time and frequency dissemination. While atomic clocks can generate electromagnetic signals with exceptional periodicity and minimal noise, preserving this signal purity during dissemination outside controlled laboratory environments remains a significant challenge. For instance, transmitting signals over free space using radio waves, GNSS satellites, and other mediums exposes them to wavefront distortions from ionospheric and tropospheric delays, atmospheric turbulence, and time dilation due to relative motion and varying gravitational fields. GNSS satellites, for example, travel at approximately 5 kms and experience gravitational fields around 25% weaker than those at ground level, necessitating relativistic corrections for accurate timekeeping and positioning. Without these corrections, GPS positioning would be inaccurate by nearly 10 km! One-way GNSS receivers mitigate some timing errors by leveraging environmental modeling and precise satellite orbit data. In microwave satellite transmission, time errors can be corrected to the 10^{18} level using two-way, dual-frequency and geosynchronous links. These allow direct measurement and cancellation of timing errors from orbital imperfections and the ionosphere for lower noise transmission with greater accuracy. However, these high-precision links are not widely implemented due to the high costs and limited commercial demand for sub-nanosecond accuracy. Also, the recent emphasis on all-optical technologies has shifted government funding away from more practical microwave system upgrades.

Signal noise in GNSS transmission further limits performance. In addition to systematic errors, statistical noise must be addressed as it impacts the averaging time needed to reach a target resolution. Currently, averaging over approximately three weeks is required to achieve fractional frequency and timing resolutions of 1 part in 10^{16}. In contrast, leading optical clocks can reach this resolution within seconds! To bridge this performance gap in stability, high-fidelity all-optical fiber links have been developed for precision time and frequency transfer. Europe has implemented dedicated fiber networks linking national metrology laboratories across France, the United Kingdom, Italy, and Germany, as well as to local research institutes. These fiber links enable relative atomic clock measurements and the dissemination of stable optical and microwave signals with additive inaccuracies on optical signals as low as 1 part in 10^{20}, achievable within less than a day of averaging. These kinds of fiber links are developing worldwide because, aside from clock comparisons, access to high stability optical and microwave frequency and time references can advance the technical capabilities of research laboratories. For instance, Italy's NMI, INRIM, uses fiber links to disseminate stable timing signals to radio telescopes for improved imaging in VLBI.

Unfortunately, metrology institutes in the Americas lack access to dedicated research grade fiber links and are hgihly geographically dispersed. This significantly complicates the ability to perform high-precision clock comparisons between NMIs. To address this, ground-to-ground free-space optical links with fractional inaccuracies comparable to fiber links are under development. These have been demonstrated over baselines up to 400 km, despite significant optical losses that require detection sensitivities at the microwatt level []. Links are operated in a 2-way configuration with laser terminals at both ends. An optical interferogram is produced via the interference of the outgoing and incoming optical signals. Because the link is reciprocal for the counter propagating lasers, post processing allows for nearly complete removal of timing errors induced by atmospheric effects.

Accessibility of UTC. While redefinition of the SI second will improve the long-term realization of UTC by a factor of 10 in accuracy the nations who stand to benefit the most are the ones with NMIs contributing the highest performance atomic clock data, and those with access to the most advanced time dissemination infrastructure. As a result, UTC suffers national accessibility issues. Institutions with commercial atomic beam clocks and one-way receivers will be limited by GNSS timing and receiver calibration uncertainties, likely at the same level of accuracy that they obtain today.

An additional challenge regarding UTC is that it provides official steering updates once per month via Circular T. For institutions with lower performance and higher drift commercial clocks, a one month wait time can result in significant time deviation from UTC. For this reason, UTC rapid, UTC_R was developed to provide "quicker," weekly steering information. However, this cannot replace the benefit or real time updates that would provide faster steering for clocks around the world. To fill this GAP for institutions in the Americas, NIST has developed GNSS receiver systems that allow users to link their clocks and oscillators to UTC(NIST), which enables near real time updates at 10 minute intervals of individual clocks versus UTC(NIST) and all others clocks on the network.

F. Does the world need better timing?

While ^{133}Cs currently allows us to split the second by one part in 10^{16}, atomic clocks operating at optical frequencies have surpassed them in performance, enabling improved uncertainty near 10^{-18}. These improvements have mobilized the international community to reconsider a redefining the SI second from a microwave to an optical atomic standard. The target date for redefinition is in 2030 and would represent the Xth redefinition of SI units since they were originally established in 1875 by the meter convention.

Despite a limited number of commercial applications that require time or frequency accuracy at the 10^{-18} level, the ability to better subdivide the second has important consequences to scientific research and discovery. Currently, we use time and frequency techniques developed by the atomic clock community to study the dynamics of quantum systems, to provide precise relative timing in large scale physics facilities such as free electron lasers, for absolute time stamping across a global array of radio telescopes to help resolve the first images of black holes, for exoplanet searches, clocks for deep-space navigation, and for synchronization in quantum networking. Additionally, the development of a better time/frequency standards is pushing the development of higher fidelity dissemination techniques that might one day make the improved timing possible with optical clocks more widely available.

Finally, when operated at their highest level of accuracy, atomic systems make for high-resolution field sensors, and exquisite table top experiments that can allow us to search for new physics beyond the standard model. As will be discussed in Section X, these capabilities are opening up new applications for optical clocks beyond timing.

2. HOW ATOMIC CLOCKS WORK

A. Microwave vs optical clocks

The main difference between microwave and optical clocks is their transition frequency. Microwave clocks operate in the GHz regime, whereas optical clocks have transition frequencies in the optical regime (100's THz to 1 PHz). Operationally, optical and microwave clocks are quite similar as they both leverage electronic transitions made by valence electrons as frequency references.

Microwave atomic clocks, such as those utilizing cesium (Cs) and rubidium (Rb), primarily operate on transitions associated with hydrogen-like atoms, characterized by a single valence electron and clock transitions rooted in ground state hyperfine splittings. In contrast, optical clocks exploit helium-like electronic configurations, where the larger energy separations are afforded by fine structure transitions. The relatively simple atomic structure of both hydrogen-like and helium-like systems minimizes electron-electron interactions, thereby yielding well-defined energy levels with extended upper state lifetimes, crucial for achieving precisely defined clock transitions. Currently, the field of atomic recognizes only two well-established species of microwave atomic clocks, ^{133}Cs and ^{87}Rb. In stark contrast, the development landscape for optical clocks features well over ten species, with the most prominent and highest accuracy implementations derived from ^{171}Yb, ^{87}Sr, ^{27}Al^{+}, 88Sr+, ^{171}Yb+ and 40Ca+. For a more comprehensive overview of these atomic species and their respective characteristics, please refer to Table 1.

The massive benefit of moving to optical transitions is that higher transition frequencies naturally yield gains in frequency accuracy and stability. One of the reasons that frequency is the best measured physical quantity is that it is periodic with quantized cycles that are easily counted. Counting is the highest performance and easiest manner with which to perform metrology. A second reason that frequency is the best measured physical quantity is that atoms provide exquisite signals for counting. For this reason, the SI second, kilogram, meter, ampere all rely on some form of frequency measurement for their realization. As a quick estimate of frequency counting resolution, if $\pm$ 1 cycle represent the measurement error per unit time, in principal, the more cycles that are counted in the measurement time, T_{meas}, the better the fractional measurement error, or $\pm 1 cycles/[(cycles/second) * T_{meas}(s)]$. From this equation, we also see that the longer we measure, the better the achievable fractional frequency resolution.

Microwave standards based on ^{133}Cs have essentially reached a limit in accuracy near 1 part in 10^{16}. To achieve this accuracy, the ^{133}Cs transition frequency must be controlled to within an error equivalent to one millionth of a single clock cycle over the course of a three-week measurement campaign! In comparison, achieving the same level of precision with an optical atomic clock requires that its frequency be controlled to within one one-tenth of a cycle over a one-second averaging time. As previously mentioned, this advantage arises because optical clocks can leverage higher transition frequencies, allowing them to reach higher accuracy with significantly lower averaging times. The elevated transition frequencies of optical clocks, in principle, also enable them to operate at better fractional accuracy with less stringent environmental control. For this reason, optical systems are being explored as high-performance portable clocks for field-sensor applications and to provide timing in GPS-denied environments. Impressively, the accuracy of optical clocks has improved by a factor of 25 per decade, far outpacing Moore's law, which predicts only a doubling of performance per decade! In 2018, the ^{27}Al^{+} clock broke the 10^{-18} barrier, followed by the ^{87}Sr lattice clock in 2024, both achieving estimated accuracies in the high 10^{-19} range. Despite the swift improvement in performance, optical clocks still have room for improvement as they push past the 10^{-18} level.

While both neutral atom and single ion clocks have

B. Clock accuracy: an art of purity and control

In building an atomic clock, the goal is to preserve the perfection of the atom's natural, unperturbed transition while managing the relatively "dirty" job of trapping, cooling, and preparing atomic transition for measurement. While the isolation of electronic transitions within the environment of the atom is impressive, it is insufficient to achieve the best demonstrated accuracy near 10^{-18}. This is because the energy structure of the atom shifts when perturbative forces deform the electron cloud.

Unfortunately, it is all to easy to disturb an electron's behavior. Perturbations include Coulomb forces from the electron clouds of neighboring atoms, static or alternating electric and magnetic fields, interactions between electron spins and magnetic fields, dipole effects from laser light, stray light, and blackbody radiation. During atomic clock operation, many of these field effects are present because fields are essential for controlling and measuring the atomic state. This is similar to their use in precision atomic and molecular physics experiments, such as Bose-Einstein condensation and spectroscopy, as well as in devices like atomic magnetometers and gravimeters.

B.1. Environmental shielding

To mitigate the effects of perturbative interactions, the atomic sample is housed in a vacuum with multiple layers of magnetic shielding. The environment is also maintained at a constant temperature and stray fields are minimized and measured. Although some lasers and magnetic fields used for cooling can be turned off when measuring the clock transition frequency, trapping fields, the Earth's gravitational field, and photons emitted at 10 m from room-temperature surfaces cannot. Consequently, the influence of applied and stray fields on the transition frequency must be well modeled, and the field strengths measured using precisely placed and calibrated sensors. Perturbative models are developed by evaluating how the clock frequency shifts in response to various fields at different strengths. These measurements estimate the magnitude of frequency shifts due to specific fields and the dependence of these effects. Because sensors cannot be place at the location of the atoms, models are also used to estimate the atom-experienced field strengths. Continuous monitoring of the field sensors during clock operation helps minimize operational instability by removing time varying operational shifts through post processing.

It is the uncertainty in the shifts that ultimately limit the accuracy of the atomic clocks. These comprise uncertainties in the models, in the measurement of the fields (including sensor calibration), and in the estimated field strengths at the atoms' location. Unfortunately errors in the models or the measurement can lead to unexpected errors in the calculation of the natural clock transition frequency, or "dark" uncertainty that manifests as inconsistency in the mean value of the measurement, outside the expected performance based on statistical and systematic uncertainties.

B.2. The clock error budget

. To meaningfully assess the consistency of worldwide clock performance, requires that clocks report measure frequencies against a common set of reference conditions. These conditions assume the clocks are operated at 0 Kelvin, in an environment devoid of perturbing fields, and at mean sea level (MSL), a well-defined ellipsoid with respect to the physical Earth which serves as a geodetic and gravitational reference for defining elevation differences []. The published unperturbed values are compiled by the BIPM to recommended values for various atomic references as secondary frequency standards (https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies).

Because clocks are normally operated under laboratory conditions (often at room temperature and in the presence of perturbing fields), the measured operational frequencies need to be corrected to the reference conditions for comparable assessment against others worldwide. Atomic clocks typically report the magnitude and uncertainty of the shift in Hz. Commonly reported shifts are the following: shifts from magnetic fields (1st and 2nd order Zeeman shifts), laser fields (1st and 2nd order light shifts), electric fields (DC and/or AC Stark shifts), and black body radiation (BBR) shifts from 10 m thermal photons radiating from the surrounding environment. Frequency shifts can also arise from errors in feedback systems, and Coulomb interactions with other atoms (density shifts). Aside from perturbative fields, relativity in measurement impacts the observed clock frequency, manifest as time dilation and the shifts due to the classical and relativistic Doppler effects. As mentioned previously, the gravitational potential is a limiting effect in realizing UTC. This sensitivity has been exploited by optical atomic clocks, whereby local measurements of the gravitational potential were resolved to the millimeter level in altitude, which amounts to a fractional frequency shift in clock transition frequency of 10^{-18}.

The total clock accuracy is estimated by creating a table with meaningful perturbative effects, the magnitude of each shift, $\Delta\nu_{shift_i}$, as well as the estimated uncertainties, $\delta\nu_{shift_i}$. This table forms the clock error budget. By tabulating the total systematic shifts and adding them to the measured operational transition frequency, one can estimate the natural transition frequency in the presence of zero fields and at mean sea level,

$$\nu_{clock}(natural) = \nu_{clock}(operational) + \sum \Delta_{\nu shift_i}.$$

Adding all the uncertainties from the systematic shifts in quadrature, which assumes no correlation between perturbative effects, yields the total frequency uncertainty in Hz for a given optical atomic frequency standard, $\sum \Delta_{\nu shift_i}$. Dividing this value by the natural transition frequency gives the clock fractional uncertainty,

$$\frac{\delta\nu}{\nu} = \sqrt{\sum(\delta\nu_{shift_i})^2}/\nu_{clock}(natural)$$

It is important to stress that a reported clock error budget does not represent a measurement of clock accuracy. Instead, it estimates the level of control that is anticipated during clock operation. Actual measurements of clock accuracy can only be made against a second reference, comprising an independent atomic clock, preferably with similar or better accuracy. Atomic clock comparisons will be discussed in Section X.

C. Clock operation

As seen in Figure 4, atomic clocks are operated in cycles that begin with cooling and trapping and end with a measurement, or interrogation of the transition frequency. The sample begins with hot atoms that are obtained by heating the element of choice in vacuum. Ions are produced by ionizing atoms to produce the correct charging. Atomic vapours need to be slowed to velocities of **cm/s?** so that they can be efficiently trapped and measured. A **Magneto-optical trap (MOT)** works to cool atoms from room temperature to the milliKelvin range (atom velocities of 10's of cm/s). Magnetic trapping works by combining magnetic field gradients with laser cooling to confine and cool neutral atoms. The key to this process is the interaction between the magnetic field gradient and the atom's magnetic moment, which causes a spatially varying Zeeman shift in the atomic energy levels. This shift, in turn, makes atoms selectively absorb light from counter-propagating laser beams depending on their position in the trap.

C.1. Laser cooling, trapping and state preparation

Laser cooling, is often perceived as counterintuitive because it involves adding momentum to an atom to reduce its kinetic energy. Laser cooling is typically implemented with six counter-propagating laser beams that constrain atoms in three dimensions. The laser frequency is slightly detuned below the cooling transition, chosen for its short excited-state lifetime, strong coupling to the ground state, and accessible wavelength. Due to the atoms' thermal motion, atoms moving toward a beam experience a Doppler shift, which brings the laser into resonance

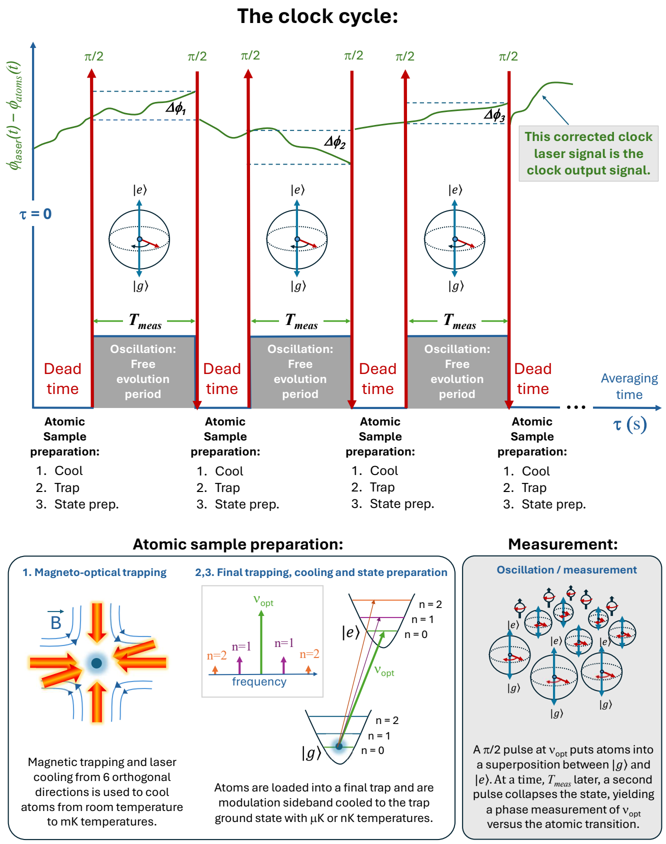

Fig. 4. The atomic clock cycle. The atomic clock cycle begins with a period of dead time where the atomic cloud is created, cooled, trapped and the electronic state is prepared for measurement. Following this period, the atoms undergo a measurement phase, T_{meas}, in which atoms are excited to an oscillating superposition between the clock ground, $|g>$ and excited state, $|e>$. This part of the clock cycle allows for precise phase measurement of the atomic transition frequency versus the clock laser that excites the oscillation. At the end of the measurement period, the measured phase difference is used to steer the clock laser to the atomic transition frequency. Repeated clock cycles allow for periodic correction of the clock laser drift, $\Delta\phi_i$, keeping it on frequency and phase with atomic transition. The corrected, phase discontinuous, laser signal represents the atomic clock output, $\nu_{opt}(t)$. Measurement of the clock laser frequency over multiple cycles (often many hours, or possibly days) allows for an improvement in resolution of the atomic transition frequency. Unfortunately, the existence of dead time between measurement periods results in aliasing of the clock laser frequency noise onto the measurement, known as the Dick effect []. Another consequence of dead time is a loss of phase coherence between individual clock cycle measurements resulting in clock signal whose resolution improves only by $1/\tau^{-1/2}$. If clocks were phase coherent, their frequency resolution would improve by $1/\tau$.

with the cooling transition. This resonance causes the atom to absorb a photon, exciting it to the upper state of the cooling transition. The absorbed photon's momentum slows the atom in the direction of its motion. The atom then re-emits a photon, randomly imparting a small momentum kick, or a recoil momentum. Over multiple cycles of absorption and emission, the atom slows further in all directions due to the multi-beam configuration.

This technique leads to a steady-state temperature known as the "Doppler cooling limit," T_D, where cooling from photon absorption balances the heating effect of spontaneous photon re-emission. The Doppler limit is proportional to the linewidth of the cooling transition, Γ, such that, $T_D = \hbar K_B/(2\Gamma)$, where K_B is Boltzmann's constant. Laser cooling brings atoms to within a few microKelvin above absolute zero. To achieve even lower temperatures, a second cooling stage is often used, employing a narrower linewidth transition that yields a lower Doppler temperature limit. This two-stage cooling significantly reduces motion-induced Doppler shifts in the clock transition measurement.

After initial cooling, the atoms are loaded into a trap that further localizes them for measurement and allows for a final cooling stage, often using **sideband cooling**, to bring the atoms to the trap's ground state. Traps confine atoms within a potential well (see Fig. 4 bottom inset,) resulting in discrete quantized motional states, similar to the quantized energy levels within an atom. Sideband cooling selectively removes energy from the atoms by using laser light tuned to the lower motional sideband of the atomic transition frequency. This approach gradually reduces the atoms' motional energy, bringing them step-by-step to the lowest possible motional state in the trap.

Clock are operated in the Lamb-Dicke regime, a condition where atomic motion is effectively frozen relative to the wavelength of the interrogating light. This minimizes Doppler broadening and recoil effects during measurement, leading to longer interrogation times and improved frequency resolution. The energy potential depth of the trap plays an important role in achieving the Lamb-Dicke regime. The "deeper" the trap the more it confines the atom's motion, and the greater the energy separation in between trap excited states, $n = 0, n = 1, n = 2$, etc. As a result, even though recoil kicks move atoms to higher trap motional states, the trap's ground state transition is easily resolved from the excited motional states. The result is that perturbations reduce the signal to noise in the central transition, but cause minimal broadening to the transition itself.

Once trapped and cooled in this way, and the atoms' internal states are prepared, and their clock transition frequency is measured against a stable local oscillator. Prior to measurement, to ensure that the electron population starts in the transition ground state, a 're-pumping' laser is used. This laser cycles any electrons remaining in the excited state (due to its long lifetime) back to the ground state by briefly exciting them to a higher, short-lived state that quickly decays to the ground state.

C.2. Optical dipole traps and neutral atom lattice clocks

The traps for neutral atoms are formed using lasers to create either a 2D "optical lattice" that exerts a dipolar force on the neutral atoms. The 2D traps create pancake shaped optical potentials that each hold only a few atoms per lattice site. (As an aside, this type of trap is used in neutral atom quantum computers. These computers work by entangling the high lying Rydberg states of trapped atoms. The states of neighboring atoms are entangled by controlling nearest neighbor coupling by tuning the spacing between lattice sites. Atoms whose electrons are excited to Rydberg states are also used for high resolution sensing of RF fields. Rydberg states are used in both applications because the high lying states are further from the domineering forces of the nucleus. This allows them to be easily more easily perturbed by external RF fields, or mixed via the Coulomb interaction of a neighboring electron cloud. **Is that really right?**)

In lattice clocks, the trap depths are carefully engineered to confine only a few atoms per lattice site, selectively trapping atoms with the lowest kinetic energy. This approach minimizes collisional shifts by reducing the probability of interactions between atoms in the same trap site, and it also helps limit motional effects that can induce Doppler shifts, though the atoms are typically still subject to some residual motion within the trap.

The trapping light field produces a dipole force that holds the atoms in the lattice. However, this force also causes an AC Stark shift (commonly just called the Stark shift) on the atomic transition frequency, displacing it from its unperturbed value. In the highest-accuracy optical lattice clocks, a "magic" wavelength is chosen so that the trapping light shifts the ground and excited states by exactly the same amount. This relies on the electronic structure of the atom, particularly the relative symmetry in the fine structure of the electronic states. By operating the lattice laser at this magic wavelength, the residual "lattice light shift" can be reduced to fractions of a Hz on an optical frequency, achieving an uncertainty near the 10^{16} level.

In practice, models of the lattice light shift for specific atomic species, such as ^{171}Yb and ^{87}Sr, allow clock operators to further constrain the uncertainty in this shift to the 10^{-18} level with precise measurements of the lattice wavelength. During clock operation, it is crucial to keep the lattice laser precisely at the magic wavelength within the picometer range, requiring stabilization of the lattice lasers to a high-stability passive optical cavity, with active drift compensation throughout the measurement to avoid time-dependent shifts in the clock frequency.

C.3. Ion traps and ion based optical clocks

Optical clocks based on single ions use an oscillating quadrupolar RF field (typically in the MHz range). In these traps, the RF field oscillates rapidly, creating an effective potential well that confines the charged ion in all three dimensions. Traps using a linear configuration can be scaled up to include many ions, or ion crystal clocks [4, 5].

Since many ion clock transitions are in the UV range, background gas atoms can occasionally become ionized by scattered UV photons. These ions can then lead to unwanted charging of the trap electrodes, which may shift the minimum position of the effective potential and thus bias the ion's position slightly away from the trap center. This phenomenon can affect the ion's motional state and lead to a shift in the trap's effective electric field. Additionally, any residual thermal motion (slow secular motion), or motion induced by the trap itself (faster micromotion), of the ion within the RF trap can induce relativistic Doppler shift on the clock transition frequency. Because micromotion is faster it results in larger Doppler shifts with higher additive uncertainty at levels close to 10^{17} if not carefully controlled. For context, atoms travelling at 4 cm/s would induce a relativistic Doppler shift (time dilation), fractionally at 1 part in 10^{19} on a 1 PHz transition.

Laser and sideband cooling help to mitigate micromotion-induced uncertainty. Also, precise techniques are used to compensate the ion's position, typically through adjustments to the DC or RF trapping fields. Additionally, careful control of background gas pressure is required to minimize unwanted charging of the electrodes. Overall, reducing micromotion and maintaining an ultra-high vacuum environment are critical for achieving the highest accuracy in single-ion optical clocks.

C.4. Cycling and measuring the atomic transition

A laser tuned to the atomic resonance sets the atom in a superposition state between the ground and excited states of the clock transition. The most common method for achieving this is Ramsey spectroscopy, which employs a single "$\pi/2$" pulse. The integrated intensity of this pulse (calculated over time versus optical power) is just enough to place the atom in an equal superposition of the ground and excited states. After this, the superposition state evolves freely without the applied field, with phase evolution that is proportional to the transition frequency.

Following a chosen "free evolution time" (or probe time), the clock laser applies a second $\pi/2$ pulse, which collapses the superposition state. This process allows for precise measurement of the difference in the evolved phase of the atomic state relative to the applied laser field. The resulting interferometric measurement acts as an error signal, which adjusts the phase of the laser field to keep it in resonance with the clock transition frequency. Using this technique, the fractional resolution is $\pm$ 1 cycle over the total cycles evolved within the free evolution time, or $1/(\nu_{clock} * T_{meas})$. The total frequency resolution is $\Delta\nu = \nu_{clock}/(\nu_{clock} * T_{meas}) = 1/T_{meas}$.

(Aside: In Cs fountain clocks, the atoms are cooled but not trapped. To enable Ramsey spectroscopy atoms are launched into the air and pass twice through a microwave cavity whose geometry supports a resonant mode at the clock transition frequency. On the way up an RF local oscillator, locked to a cavity mode, sets the atoms in a superposition state between the clock ground and excited state. At the end of their descent, the RF field in the cavity applies its second $\pi/2$ pulse to measures the relative phase evolution between the atomic cloud and the RF field. In this setup, the height of the fountain, limited by how fast the atomic cloud expands, set the transit time under gravity, and hence the free evolution time.)

The phase-corrected clock laser signal is the frequency output of the optical atomic clock. This electromagnetic signal embodies the stability and accuracy of the atomic resonance through the timing of its optical cycles. This reliable and precise signal has various applications: it can be counted in cycles per second to measure its frequency in Hertz; it can serve as a frequency reference for measuring and characterizing other signals; and it can define the second by establishing its transition frequency in Hertz as a constant of nature.

3. THE FUTURE OF ATOMIC CLOCKS: PUSHING THE QUANTUM LIMIT

.

In a perfect world, with no technical noise, the measurement resolution of the clock transition frequency would be set by the number of atoms contributing to the signal, N, the transition frequency, ν_{clock}, the transition's upper state lifetime, T, and how long you are willing to keep averaging, τ. This is called the quantum standard limit or the quantum projection noise:

$$\sigma_y = \frac{1}{\nu_{clock}\sqrt{NT_e\tau}} \quad \textbf{(1)}$$

The upper state lifetime, T_e, determines the how long the state can undergo free evolution before it begins to decohere through population decay. The longer the free-evolution time, the narrower the transition linewidth, the better the transition frequency can be resolved. Even if an upper state lifetime were 1000 seconds, as in ^{87}Sr, technical noise in clock operation usually limits the free evolution time by decoherence of the atomic

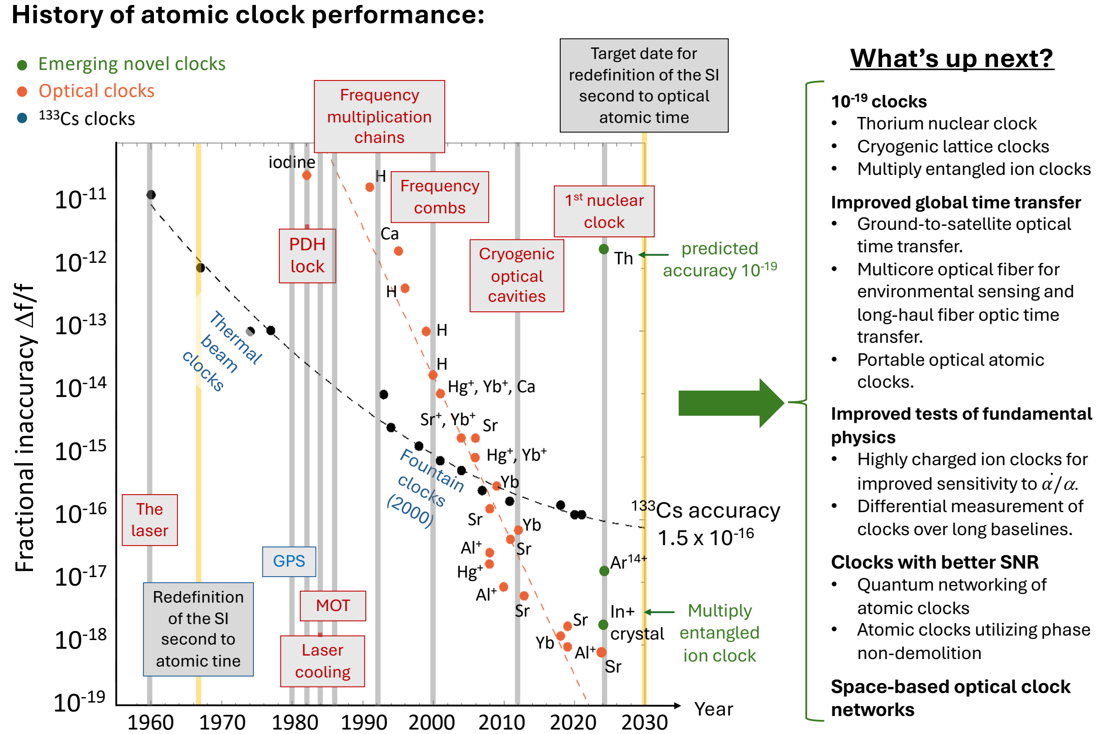

Fig. 5. Representation of microwave and optical atomic clock accuracy as a function of time including seminal technological advances that have been central in improving clock performance. Impressively, optical clocks demonstrated a factor of 25 improvement per decade from 1990 to the present.

system. This decoherence is primarily achieved by heating the atomic sample, though magnetic field instabilities or via laser-atom decoherence. The latter refers the drift in frequency and phase between the atomic resonance and the free-running laser that drives the system into oscillation. Ultimately, the end of the free evolution time determines end a single clock cycle. In their operation, many cycles are strung together to perform measurements on distinct atomic samples whereby continuity in phase information is lost between cycles.

(Aside: The upper state lifetime is influenced by the coupling strength between the excited state and the ground state. In atomic clocks, the clock transition is typically chosen between two states where single-photon transitions are disallowed due to conservation laws, such as spin conservation. This selection ensures that the clock transition has specific properties that enhance stability and precision. Without weak coupling between the electronic states and the nucleus—often referred to as spin-orbit coupling—the mixing of the ground and upper states would be minimal, resulting in a very low or zero transition probability. This lack of coupling would make it impossible to cycle the clock transition effectively, as there would be insufficient interaction to facilitate the excitation and subsequent relaxation of the atoms between the states)

4. OPTICAL SUBSYSTEMS OF ATOMIC CLOCKS

optical reference cavities

optical frequency combs

5. ATOMIC CLOCKS AND THE FUTURE OF METROLOGY

REFERENCES

1. J. Kovalevsky, Metrologia **1**, 169 (1965).
2. R. E. Beehler, R. C. Mockler, and J. M. Richardson, Metrologia **1**, 114 (1965).
3. A. C. O'Connor, M. P. Gallaher, K. Clark-Sutton, *et al.*, (2019).
4. H. Hausser, J. Keller, T. Nordmann, *et al.*, arXiv preprint arXiv:2402.16807 (2024).
5. D. R. Leibrandt, S. G. Porsev, C. Cheung, and M. S. Safronova, Nat. Commun. **15**, 5663 (2024).

6. ACKNOWLEDGMENTS

Thank you everyone!