Sundial to the Atomic Clock*

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The clock—one of the earliest inventions in modern science—has evolved from sundials to atom-based systems over the last several centuries. Over its long evolution, timekeeping requisites have shifted! Today, it is not just limited to organizing rituals promptly but has unavoidable applications in the most advanced, sophisticated technologies and exploring fundamental science in the present day. Thus humanity never lost interest in building further accurate clocks over the last 700 years. To explain the best accuracy of the state-of-the-art optical atomic clock in simple words: Supposedly, it has been running uninterruptedly over the last 35 billion years, then it misses just a single second. Due to the immense importance of highly accurate timekeeping, the miss of a single second cannot be tolerated. Hence, humanity is not yet satisfied with the best of present atomic clocks’ unprecedented accuracy and is still exploring betterment.

This article shall give a brief history of the evolution of clocks—from the sundial to the atomic clock—timekeeping and international standardization of second, and describe the operation of microwave and optical atomic clocks.

Introduction

Many readers are aware of the famous book *A Brief History of Time: From the Big Bang to Black Holes* by Stephen Hawking; here, instead of ‘time’, I shall describe ‘timekeeping’. Timekeeping refers to the accurate generation, maintenance, and dissemination of ‘second’, the internationally accepted unit to measure the time interval between two incidenacies, whereas the absolute

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Time starts from the Big Bang. Time is a phenomenon that is not under human control as it neither can be manipulated nor can be stored or created. On the other hand, timekeeping is a technique to measure the time difference between two incidences and correlate that to the daytime for all practical purposes. The practice of timekeeping is much older than the beginning of modern science; the study and related instrumentation is known as ‘horology’. Humanity discovered a naturally occurring repeatable incidence, that is, the basis of horology, about 30,000 years ago when they mapped the lunar phase. However, the concept of using that for timekeeping came much later as the need emerged. Since ancient times, the need for time measurement and its required level of accuracy has changed with the advancement of technologies. As the needs became more stringent, the related clock machinery evolved from sundials to atoms. At present atomic clock is one of the most accurate machines that mankind has ever built. Timekeeping with atomic clocks has reached a state-of-the-art level, giving unprecedented accuracy and stability in performance.

1. Timekeeping

There are several myths about the necessity of timekeeping during ancient times: most likely, the need was to ring a bell to
conduct the prayers. For that purpose, humanity has used hourglass, sundials, candles, water clocks, and so on to measure time intervals over a short duration. Chinese were using oil-lamp-based clocks where the reservoir size measured its burning duration. These were probably used to complete a religious ceremony within a pre-decided specific duration. A modified version of the lamp clock is the candle clock, where markings are used to define the time span as it burns. Egyptians invented the water clock, where a marked empty container with a small hole in its center was placed on a water reservoir; as the water started to flow into the empty container, it measured the time span until it got filled or sank. The Indus valley civilization also used such clocks known as the ‘ghatika yantra’. In the early 13th century, hourglasses were very popular, particularly in marines, and they either used liquids or fine granules of particles like sand. A much more accurate mechanical clock was invented in the middle age. Ancient Egyptians used sundials to measure day-times in a solar day, and later on, other ancient civilizations such as Iraqis, Greeks, and Romans also used it. In India, a sundial was constructed at the Sun Temple of Konark in the 13th century. During the 18th century, King Jai Singh built the world’s largest and most accurate sundials in Jaipur and, later, in Delhi. These Jantar-Mantar sites are equipped with various other astronomical instruments as well. There are more recent sundials at the Indian Institute of Technology, Roorkee (IIT Roorkee), and the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune. Photographs of the mentioned sundials are shown in Figure 1.

Though sundials were popular instruments, their operation was position and time of the year specific, as the Sun’s altitude decreases with the increase in Earth’s latitude. Additionally, over a year, the Sun is observable over different trajectories from a fixed position on the Earth. Moreover, Earth’s rotation speed changes due to tidal friction and mass redistribution, and the axis itself rotates over a circle repeating in 26,000 years, which causes a slow drift of the solar day. Over thousands of years, sundials became more accurate until the early 19th-century [1]. However, sundials

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also don’t do the timekeeping independent of the Earth’s rotation dynamics. Hence they cannot be utilized as a ‘standard’ for accurate timekeeping. The revolution came in 1657 when Christiaan Huygens invented the pendulum, which is considered the start of modern horology. It is important to mention that John Harrison, a British carpenter in the 18th century, became famous for inventing accurate clocks, notably the chronometer. Harrison’s clock was able to maintain time within 3 s accuracy over one day of runtime without any external correction. A chronometer contains a reference clock that accurately measures the time of a fixed location. A sailor at an unknown location measures the time difference at his noon relative to the chronometer’s reference clock and estimates its longitude from the relative time difference. Harrison’s invention revolutionized navigation, particularly long-distance travel through the sea. For this, Harrison was awarded huge prize money by the British Parliament.

After the invention of the accurate pendulum clock and chronometer, inter-continental travel became more and more popular. Consequently, international standardization of timekeeping became a necessity, which was otherwise maintained using different local units until then. For example, according to Hindu scriptures Surya Siddhanta, Vedas, time in ancient India was measured using the units nimesh, khashth, kaal, muhurta, ahoratram, masa, ritu, and samvatsara [2]. One ahoratram, masa, and samvatsara correspond to one day, month and year, respectively. Figure 1. shows improvement of clock accuracy over the last 700 years, during which the vertical axis shows possible run-time of the clocks to segregate 1 s inaccuracy. While going through the brief history of different ancient clocks, it is worth noting that each of these clocks was free running, as there was no standardization or reference to a common source since there was no internationally accepted unit of timekeeping. The importance of ‘standardization’ wasn’t realized until several centuries later, when transportation, mainly through railways, became popular. For example, in 1847, Britain started using regulated mechanical clocks named ‘railway time’. Following this, the Royal Observatory of
Greenwich started disseminating time signals in 1855. Soon after this, dividing the world into different time zones was introduced in 1958. By mid 19th century, most of the clocks in Britain were set to Greenwich’s daytime, which became the country’s official time in 1880 and was named the Greenwich Mean Time (GMT). Still, international standardization was yet to be adopted.

1.1 Time Standard

Since the 19th century, daytime measurement has always been relative to the Earth’s rhythmic celestial motion, spinning around its axis (rotation) and orbiting around the Sun (revolution). Following that, a second was defined as $86400^{-1}$ of a solar day between 1862 to 1960, which changed to $31556925.9747^{-1}$ of a tropical year from 1960 to 1967. These International Standard

**Figure 2.** Improvement of clock’s accuracy over the last 700 years. The vertical axis indicates the time span over which the clocks segregate 1 s inaccuracy. The present state-of-the-art optical atomic clocks are accurate to 1 s over $10^{18}$ s, i.e., about the age of the universe. The arrows on its right mention some phenomena corresponding to the respective time spans.
(SI) definitions of second are known as 'mean solar time' and 'ephemeris time', respectively. In 1930, upon discovering that the Earth's rotation slows by $\sim 2.5$ ms in every century due to tidal friction, mass redistribution affected the angular momentum; the definition of second was changed to ephemeris time. However, this new definition was based on the lower oscillatory frequency than Earth's rotation, meaning longer averaging to reach the same level of accuracy, which was not desirable. With the advent of technologies during the era of the Second World War, particularly in the sectors of inter-continental navigation and broadcasting for strategic reasons, ultra-high accurate timekeeping and interconnecting to the phase and frequency of a radio-frequency (rf) reference were utterly needed. Scientists started to search for new oscillators which are not influenced by the movement of Earth. Such a 'reference' oscillator can be used for absolute timekeeping irrespective of any changes in a solar day and also able to measure any variations in it.

In 1945, Isidor Isaac Rabi proposed to build NMR-driven clocks using atoms as an oscillator. Using the concept proposed by Rabi, the National Bureau of Standards (NBS), USA, built the first atomic clock based on the ammonia absorption line in 1949. In 1945, Isidor Isaac Rabi, who already owned a Nobel Prize for discovering a technique for using nuclear magnetic resonance (NMR) to discern the magnetic moment and nuclear spin of atoms, proposed to build NMR-driven clocks using atoms as an oscillator. Using the concept proposed by Rabi, the National Bureau of Standards (NBS), USA, presently renamed the National Institute of Standard and Technology (NIST), built the first atomic clock based on the ammonia absorption line in 1949. This first-generation atomic clock was accurate to a few parts in $10^{10}$, which has improved to a few parts in $10^{13}$ in the last 70 years. Louis Essen and Jack Parry at the National Physical Laboratory, UK, demonstrated the cesium-atom atomic clock in 1955, and soon after, it was commercialized in 1958, which was accurate to a few parts in $10^{10}$ [3]. In the next few decades, NBS developed a different generation of microwave beam clocks named NBS-i, where the index $i$ refers to generation numbers 1, 2, etc. Similar clocks were developed in a few other developed countries. On 13 October 1967, the 13th General Conference on Weights and Measures defined the SI second based on the cesium-based atomic clock.
Since then, the world’s timekeeping system no longer has an astronomical basis. Following this new atomic definition, one SI ‘second’ is the duration of 9192631770 periods of the radiation between the two hyperfine levels of the cesium’s $^{133}\text{Cs}$ unperturbed ground state when it is at rest, i.e., at 0 K. The internationally accepted time standard that is the Coordinated Universal Time (UTC) was adopted in 1967, which is the leap second corrected atomic time maintained by the Bureau International des Poids et Mesures (BIPM), Paris, France.

1.2 Time Zones

In 1858, Italian mathematician Quirico Filopanti first introduced the idea of describing regional solar days depending on their longitudes, dividing the Earth by 24 time zones considering Greenwich as the reference. Hence, every 15° longitudinal separation corresponds to +1 and -1 hour of daytime difference along the East and West of the prime meridian that is zero-longitude passing through the royal observatory of Greenwich (longitude 0°0’0” & latitude 51°28’38” N). In 1884, International Meridian Conference proposed adopting this time zone concept considering 12:00:00 midnight at Greenwich as reference 00:00:00 of GMT starting a day at that time zone and consecutively at the other
The history of standard time in India reveals an astronomical treatise of the 4th century, namely *Surya Siddhanta*. This mentions the Prime Meridian passes through Avanti (Ujjain) at 23°10'58" N, 75°45'38" E and Rohitaka (Rohtak) at 24°54'0" N, 76°38'0" E being used as standard time in India, which had wider geographical extent than now. In 1733, King Sawai Jai Singh built the Jantar Mantar observatory in Jaipur to determine local time relative to the Sun's position. During the British rule, in 1884, when GMT was already internationally accepted, present geographical extent of India was split into two time zones: Bombay (Mumbai) and Calcutta (Kolkata), corresponding to UTC+5:54 and UTC+4:51, respectively. As the Indian railways already gained momentum, different time zones introduced confusion due to lack of technical infrastructure and automation. That forced railways to use a separate single time-zone for the entire country, known as the Madras (Chennai) time corresponding to UTC+5:21, also known as Indian Railway Time. However, it is not user-friendly when the transport system follows a different time standard compared to national one. Apart from these, 'Port Blair Mean Time' i.e. a
separate time zone for the Andaman and Nicobar Islands also existed. Following Plantations Labour Act of 1951, the tea gardeners of Assam set their own local time zone, namely ‘Chai Bagaan Time’, which is an hour ahead of the IST. In 1884 proposals were put forward to adopt a single time zone, however, in 1906 that came into force and since 1 September 1947, it became the official time of independent India. Even after the introduction of IST, Mumbai and Kolkata continued following Bombay and Calcutta times until 1948 and 1955, respectively, at present, the entire nation follows IST. The Parliament designated the National Physical Laboratory (NPL) in New Delhi to generate, maintain and disseminate the IST. They are the custodian of country’s primary timescale setup that generates country’s official time, which is traceable to the BIPM [4].

1.4 Timekeeping at International Standard

The present standard way of maintaining any country’s standard time is through a designated institute. Typically, the National Measurement Institute (NMI) realizes UTC(\(k\)) using their own ‘primary timescale’ setup and makes it traceable to the UTC. Here, \(k\) represents the name of the designated national labs, e.g., for India, \(k\) is NPLI representing NPL-India. The timescale consists of a constellation of atomic clocks, international time and frequency intercomparison setup, and various other associated hardware. Since different atomic clocks operate at different transition frequencies \(f_0\), e.g., for Cs-clocks \(f_0 = 9192631770\) Hz,

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ment. The UTC is disseminated by different navigation satellite constellations such as GPS of the USA, GLONASS of Russia, Galileo of the EU, BeiDou of China, QZSS of Japan, and NAVIC of India. For example, GPS is discriminating daytime beginning midnight of 5–6 January 1980 with approximately 14 ns accuracy. At the start of a primary time scale, a timestamp (epoch time) is given to it for incorporating the correct daytime, which comes from one or more of the above satellite constellations through a calibrated accurate timing receiver. While providing the epoch, the time offset between UTC(GPS) and UTC(k) will be unwillingly added to the timescale, which can be corrected by long-term stability analysis of its output, discriminating the constant offset from its dynamic behavior that decides the performance.

2. Atomic Clocks

Like all other clocks, the atomic clock also comprises an oscillator and a counter. However, the atomic oscillator is highly stable, making it superior to all the others. In comparison to other clocks, electrons bound in an atom vibrate much faster between two of its shells (energy levels) which serve as the oscillator in an atomic clock. A forbidden electronic transition with a narrow natural line width in specific atoms or atomic ions is chosen to get the desired level of accuracy. Advanced measurement tools count these oscillation frequencies \( f_o \pm \delta \) upon probing such a transition via spectroscopic technique, where \( \delta \) refers to the inaccuracy. Nearly error less counting (\( \delta < 1 \text{ Hz} \)) of such atomic transition frequency, as depicted in Figure 4, is then converted to second. These atomic transition frequencies range from \( f_o = 10^9 \) to \( 10^{15} \text{ Hz} \)—those are from the microwave to optical wavelengths—and the clock’s accuracy increases with increasing \( f_o \). At high frequency, the erroneous measurement of a single count leads to less timing inaccuracy than a counting mistake at a low \( f_o \). Hence optical clocks are naturally more accurate than microwave clocks. The clock experiment aims measurement with the highest accuracy & stability. However, in practice, they reach a situation of inaccurate but stable measurement. Due to the repeatability (that refers to high
<table>
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<th>Atomic oscillator: $f_0$</th>
<th>Accuracy</th>
<th>Stability at 1 s</th>
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<tbody>
<tr>
<td>H-Maser; 1420405752 Hz</td>
<td>$10^{-13}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>Rb-clock; 6834682608 Hz</td>
<td>$10^{-11}$</td>
<td>$10^{-11}$</td>
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<tr>
<td>Cs-clock; 9192631770 Hz</td>
<td>$10^{-14}$</td>
<td>$10^{-12}$</td>
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<td>Cs-fountain; 9192631770 Hz</td>
<td>$10^{-16}$</td>
<td>$10^{-12}$</td>
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<tr>
<td>Optical clock; $10^{15}$ Hz</td>
<td>$10^{-18}$</td>
<td>$10^{-16}$</td>
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**Table 1.** Variety of atomic clocks and their typical performances.

stability) of the measured values, their average gets low statistical uncertainty. The actual value is determined by incorporating systematic inaccuracies to the measured frequencies resulting from instrumental errors or environmental fluctuations. This step involves rigorous analysis and makes the ‘precision measurement’, where the result is systematically limited but not statistically complex from any regular ones. The atomic clocks are designed to measure $f_0$ with the greatest precision, and the machines are built in such a way that measurements are repeatable. To express the unprecedented accuracy of the best atomic clock in simple words: imagine it started ticking since the Big Bang and has been operational until now, which is about 13.8 billion years; even then, it will not give an error of even 1 second.

Atomic clocks are divided into two categories—microwave and optical clocks—depending on their operating $f_0$, which use different sophisticated experimental tools and state-of-the-art techniques for their operations. For example, the accuracy of an atomic clock improves by about 100000-fold while reducing the temperature of the atoms a hundred thousand times than the room temperature. The technicalities of cold atom-based clocks are entirely different and more complex than a room-temperature atomic clock. However, it is important to pursue these critical technologies since their needs are unavoidable in coping with advanced technologies and exploring fundamental science. A comparison of the various atomic clocks and their typical accuracy are listed in Table 1.

Commercially available hydrogen maser (H-maser), rubidium clock
(Rb-clock) and cesium clock (Cs-clock) are based on near room-temperature atoms. Microwave fountain clocks are based on laser-cooled and trapped cesium and rubidium atoms. According to the current definition, SI second is derived from the cesium fountain (Cs-fountain) clocks where atoms are nearly at rest. A re-definition of second is expected in the near future based on the orders of magnitude more accurate optical clocks. The atomic fountain and optical clocks need to be customized in a lab but are not commercially available yet. The development of these most advanced atomic clocks is significant for a nation, not only for accurate timekeeping but also for advanced scientific studies and sophisticated technologies. Due to strategic reasons, all advanced and developing nations, including India, pay great attention to the indigenous development of the atomic clocks, which have national importance due to accurate targeting, surveillance, national security, navigation, communication, and many more. In India, NPL developed a Cs-fountain clock [6] and IUCAA, NPL, IISER-Pune, IIT-Tirupati are engaged in developing optical atomic clocks for their interests either for time and frequency metrology or for studying fundamental science.

2.1 Cesium Fountain Clock

In a water fountain, the droplets coming out of a jet are pushed upwards, reaching a certain height against gravity depending on their initial velocities. From their highest reaching point, these droplets fall back due to gravity. In cesium fountains, instead of water droplets, cesium atoms follow the same process. However, unlike in a water fountain, cesium atoms follow a complicated preparation protocol before they are thrown upwards like in a water fountain, as depicted in Figure 5. The bulk cesium inside of a reservoir is evaporated by heating to a temperature much above its melting point, i.e., 28.5°C. The vaporized atoms then come out through a tiny orifice of the reservoir and propagate at their thermal velocities, which is widespread following the Maxwell–Boltzmann distribution law. These hot atoms are not used in the fountain as otherwise, individual atoms will reach
different heights depending on their velocities and add inaccuracy to the clock. These hot atoms are first cooled to a nearly zero temperature using laser cooling and magneto-optical trapping (MOT) techniques for using them in the fountain. The Nobel Prize in Physics was awarded to Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips for developing sophisticated methods to cool and trap atoms using laser light. Without going into technical details, the name itself is self-explanatory! Laser cooling reduces the atoms’ thermal energy and brings them nearly to rest. MOT confines an ensemble of atoms (the order of one billion atoms) within a tiny volume, typically a sphere of diameter 1 mm, and prepares a cold sample for the fountain. In simple words, to explain the laser cooling: upon absorbing a resonant photon, the atom reaches the excited state and, after its lifetime, again falls back to a lower energy level by releasing a photon (fluorescence). This atom-photon interaction is a continuously repeatable phenomenon provided all laser(s) parameters are tuned to stay resonant. The shower of unidirectional photons from a laser (spatially coherent) plays a crucial role in laser cooling. Multiple absorptions of unidirectional photons (on the order of a few million) but fluoresce them along all possible directions in space gives a net momentum transfer to the atom along the propagation direction of the laser beam, as the sum of the momentum vectors due to all fluorescence photons averages to zero. This results in the slowing of the atom (cooling) if the laser is applied opposite to its velocity.

Three orthogonal sets of counter-propagating lasers, as shown in Figure 5, are necessary to stop atoms from moving around in all directions. Counter propagating laser beams produce a balancing force at a single point where the atoms are finally at rest. For confinement, i.e., trapping, laser-cooled atoms are forced to stay together within a volume with the help of a spatially dependent force. Thus, the atom moves further out from its rest position a more decisive kick brings it back. This restoring force, which vanishes at the rest position and increases further out from there, is obtained by applying a null magnetic field gradient at the atom’s rest position. The laser cooling and MOT produce a cold
ensemble of cesium atoms (stage-a in Figure 5), which is then pushed upward using a laser beam for the fountain. A microwave (MW) cavity is placed in the fountain’s path (stage-b in Figure 5), and the atomic ensemble travels up and downwards through it. While moving against the gravity followed by free fall, the size of the atom cloud expands as they are not trapped anymore during in-flight. A cold sample of atoms restricts the expansion of the cloud as the atoms have the bare minimum thermal energy to move apart. If the MW frequency is tuned to be resonant, the atoms interact with it while passing through the cavity. Following the above description, the atoms interact twice, while going upward and during the downfall, with a time lag in between, which depends on the atoms’ velocity, to the identical MW-frequency (stage-c in Figure 5). As a result, the MW may appear at a certain phase difference to the atoms at different velocities resulting in interference, giving rise to a fringing pattern within the Maxwell–Boltzmann spectrum. The central fringe of the spectrum with sub-Hz linewidth allows accurate determination of cesium’s transition frequency, which is detected by signing a probe laser light.
Figure 6. Pictorial representation of atomic clocks. 
(a) Optical lattice clock. (b) Trapped single-ion clock. In the case of the neutral atom clock, MOT, optical lattice, and the lattice formation (in the inset) are shown. The single ion is trapped in an end-cap type Paul trap. The arrows indicate the lasers required to produce the ion, laser cooling, and probing the clock transitions. The instantaneous shape of the ion confining potential is shown in the inset.

and scanning its frequency (stage-d in Figure 5). When the MW cavity is tuned to be resonant at 9192631770 Hz, the best signal can be obtained by the Ramsey spectroscopic technique, named after N. F. Ramsey, who won the Nobel Prize in 1989 for this invention. Currently, Cs-fountain clocks from a few countries in the world, such as the USA, UK, France, Italy, Germany, and Japan, are operational [7], which have reached their best accuracy few parts in $10^{16}$.

2.2 Optical Clocks

Optical atomic clocks are built using highly forbidden optical excitation of neutral atoms or atomic-ions [8, 9]. Most of the trapped-ion clocks use Al$^+$, Hg$^+$, Yb$^+$, Sr$^+$, Ca$^+$, and In$^+$, whereas popular neutral atoms are Sr, Hg, and Yb. Optical clocks acquire orders of magnitude higher accuracy due to their operations at a frequency few 100000 times higher than the MW clocks. Naturally, the atoms/ions are freely moving due to their residual kinetic energy; hence have a minimum chance to interact with a resonant clock laser light. Thus, confining the atoms/ions within a well-controlled tiny volume is necessary for such high-accuracy measurements, where all parameters, such as electric, magnetic fields, etc., which add systematic uncertainties to the measurement, can either be canceled or precisely measured. In neutral atoms, the cold ensemble created by laser cooling and MOT is loaded in an optically created, egg-carton-shaped storage bas-
ket, known as an optical lattice created by interfering with two counter-propagating laser beams. Schematic of the neutral atomic clock experiment is shown in Figure 6a.

On the other hand, the singly charged ions are confined using oscillating electric fields known as the Paul trap as shown in Figure 6b. Wolfgang Paul won the Nobel Prize in 1989 for developing this ion-trapping technique. In an optical lattice, a few thousand atoms are separated in an ordered manner; on the contrary, only a single trapped ion is used since multiple ions give rise to a Coulomb shift to $f_o$, which is not desired for the clock’s application. The atoms/ions thermal motions are reduced to micro-K temperature by laser cooling and trapping. The trapping and laser cooling suppress many systematic shifts of the clock transitions and allow for accurate and reliable precision measurement. Upon producing the cold atomic/ionic sample confined in their respective traps, the clock transition is probed using an ultra-stable and narrow linewidth laser light. Excitation is ensured either by detecting the fluorescence or by the quantum entanglement technique. Production of the ultra-stable (typically $10^{-17}$ in 1 s or better) and sub-Hz linewidth laser is another state-of-the-art technology that uses a reference optical resonator, namely Fabry–Perot cavity. Essentially, the ultra-high stability of this external cavity is imprinted on the clock laser, and only a certain optical frequency sustains while resonating inside it.

The next step is errorless counting of the measured atomic transition frequency using another essential tool, the optical frequency comb. This also bridges MW and optical frequencies, which are important for intercomparison and dissemination. The frequency comb outputs an array of equally spaced, discrete optical frequencies, separated by about 100 MHz and spread over a wide band. Since frequencies of each output from the comb are known due to the way it works, one can measure the clock laser’s frequency by accurate frequency and phase comparison with one of the comb’s outputs. Optical frequencies referenced to an optical atomic clock need to be disseminated to distant locations for practical applications. Regular optical fiber communication does not work for
this. It involves complex technology to stabilize the length of a long optical fiber to an atomic length scale. This is called phase stabilization of the optical fiber to disseminate the reference optical photons without losing their phase information. Since optical clocks involve complex technologies, so far, only a few advanced countries, e.g., the USA, Canada, Germany, France, UK, Italy, and Japan, have operational optical atomic clocks, which have reached their best accuracy: a few parts in $10^{19}$. The optical clock is an unavoidable future requisite for the forthcoming quantum-enabled technologies, such as quantum communication, quantum internet, GPS-free navigation, etc., and exploring fundamental science. Keeping all these in mind, at IUCAA, we are developing a Yb$^+$ optical atomic clock.

**Conclusion**

Timekeeping has reached unprecedented accuracy to meet its demand in several technologies—those we use in daily life as well as those in strategic sectors and advanced research. The accurate microwave cesium fountain clocks derive the current international standard of second and support most of the technological requirements. However, we must be equipped with more advanced optical clocks to meet future demands. For example, quantum communication, quantum internet, GPS-free navigation, etc., are some of the emerging technologies that will require the use of optical clocks. On the other hand, several open science questions, such as temporal constancy of the dimensionless fundamental constants, possible violations of the fundamental symmetries, probing of the dark matter and dark energy, etc., can be pursued using either optical or further accurate clocks. Hence, better-and-better clock making, packaging in a way to make them transportable or space-qualified, inter-continental and also long-distance networking among them will always be in high demand for scientific and technological development of a country, which has direct influence to uplift the economy of the country and better living quality of its populace.
Suggested Reading

[5] A. Agarwal et al., Reduction of uncertainty of primary time scale generating UTC(NPL) to 2.8 ns, 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC), New Delhi, India, pp.1–3, 2019, 10.23919/URSI-AP-RASC.2019.8738624.

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