Invited Review

A Comprehensive Overview of Atomic Clocks and their Applications

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ABSTRACT

Time is ubiquitous, and integral to our everyday lives. Precise measurement of time intervals is basic to various activities humans are dependent up on, such as accurate positioning using satellite navigation, telecommunication, aviation, definition of International Time, secondary applications using positioning, military applications etc. Atomic clocks formulate the heart of precise time measurement and hence enable the positioning and navigation and niche time and frequency dependent technologies that we rely upon directly or otherwise. This paper gives a comprehensive overview of history of time measurement and evolution of clocks towards atomic clocks. It broadly covers various types of atomic clocks ranging from laboratory clocks to miniature commercial clocks along with the key applications with a focus on microwave atomic clocks (or frequency standards). Further, the satellite navigation systems operational around the globe by various countries and the types of clocks used for such navigation systems are briefly covered with a focus on the rubidium atomic frequency standard and other space clocks.

Keywords: Atomic Clocks, Frequency stability, Frequency Standards, GNSS, Metrology, Rubidium, Space Clocks, Satellite Navigation, Time measurement.

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EVOLUTION OF TIME MEASUREMENT

Precise measurement of time is useful for mankind in everyday life.[1,2] Our ancestors Figured as early as 3000 B.C. that there is a need to have a measure of time to track the events that occur in nature around us, which we know as Stonehenge. Further, various time measuring techniques evolved, which improved in precision as shown in Figure 1. Few landmark inventions are tower clocks during 1300 AD, Huygen's Pendulum clock (1650), Harrison marine chronometers (1750) and the precise measurement of earth's rotation using telescopes in observatories (1900). A giant leap took place during 1930s by the invention of quartz oscillators, as even today most of the wristwatches are based on this technology. Another excellent innovation was made during 1950s when atomic clocks were demonstrated using the method of atomic/molecular spectroscopy. This incredible innovation was possible because of understanding and exploration of the quantum world.

Starting from early clocks during 1950s till date, many types of atomic clocks have been developed and the process is ongoing to make better, smaller, reliable, and cost-effective atomic clocks due to their implications on our lives. Today's best demonstrated clocks in the world are the optical frequency standards. Optical clocks based on optical lattice confinement have reached ~10^{-18} levels, or better.[3,4] In other words, one can say that these clocks change by ±0.1 ps over a day, or ±1s over the age of the universe (13.7 billion years).

As seen in Figure 1, the development of atomic clocks started seven decades ago. The idea to build a clock using an atomic beam magnetic resonance was proposed by Isidor Rabi in 1945.[5] Based on Rabi's technique,[6] NIST (formerly known as National Bureau of Standards (NBS)) built the first atomic clock using ammonia molecules in 1949. Following to that, Essen and Parry at National Physical Laboratory (NPL) built the first thermal cesium beam clock[7] in 1955. These developments vindicated the International System of Units (SI) in 1967 to define the SI second as 9,192,631,770 periods of vibration of the ground state hyperfine transition in an unperturbed cesium-133 atom,[8] and later in 1997 it was affirmed that this definition refers to a cesium atom at rest at a temperature of 0 K.

Various types of atomic clocks were developed since then including the cesium thermal beam clocks,[9,10] active and passive hydrogen masers,[11,12] lamp-pumped rubidium cell standards,[13-15] cesium cold atomic fountain clocks,[10] optical-lattice clocks,[16] ion-trap clocks[17-20] and chip-based cold atom clocks.[21-23] However, for the applications that demand to address the issues of performance, portability, reliability, cost, weight and power consumption, the rubidium cell standards are advantageous over

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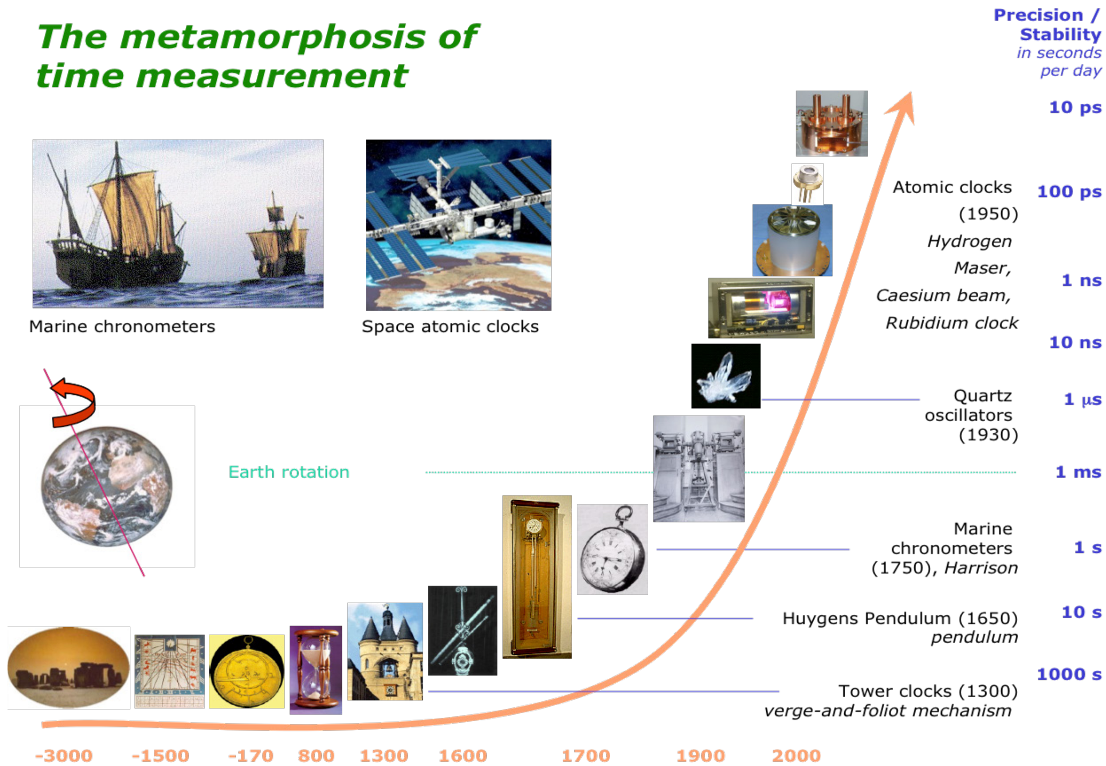

Figure 1: The evolution of measurement of time intervals and achievable precision per day. Image courtesy: Prof. G. Mileti, University of Neuchatel, Switzerland.

other kinds of clocks.[24] Presently, the industrial lamp pumped Rb clocks are used in telecom and navigation systems. However, the constant demand for improved next generation applications requires pushing the limits on the performances of the portable clocks.

Atomic clocks have various everyday applications; for instance, in maintaining the Coordinated Universal Time (UTC) that is based on International Atomic Time (TAI),[25] accurate positioning and navigation systems[26-28] (Global Positioning System (GPS), Galileo, Global Navigation Satellite System (GLONASS), Compass etc.), high-speed data transfer and synchronization in telecommunications.[27] They are also used in synchronizing time for banking and stock transactions, military applications, regulation of power grids to avoid power losses,[29] radio and television broadcasting, geophysics, metrology and other scientific endeavors such as deep space navigation and studies (e.g. Cassini Huygens).[26,30] Other scientific applications are the search for variation in fine-structure constant,[31] test of Einstein's special theory of relativity,[32] and including one of the recent experiments on the precise measurement of the speed of neutrinos.[33] Safronova and team have recently proposed to use atomic clocks for dark matter detection.[34] These applications testify to the broader implications of atomic clocks not only for our daily lives but also for basic scientific discoveries to expand our horizons to understanding our universe.

WHAT IS AN ATOMIC CLOCK?

In general, the atomic frequency standards (atomic clocks) exploit a ground-state hyperfine transition to provide a stable atomic frequency reference to which the frequency of a quartz oscillator is stabilized.[13,15,35,36,37] A general interrogation and quartz stabilization scheme is shown in Figure 2. The output of a macroscopic oscillator is utilised to interrogate the atoms (that are confined in a small region of space) at resonating frequencies (matching the energy levels) and the resulting output will be a spectroscopic atomic signal. Further, this atomic signal is used in a servo loop configuration to correct for the changes of the macroscopic oscillator. This overall loop is known as *clock loop*.

The resulting output frequency of the macroscopic oscillator is stabilised by transferring the stability of atomic signal. Therefore, in short, we can say that an atomic clock is a devise which *"adjusts and maintains the frequency of an oscillator to a reference atomic transition frequency"*. This is a basic conceptual principle of how an atomic clock works. Various physical conditions such as temperature effects on atoms, electronics noise, perturbations due to external instruments, signal-to-noise ratio, low noise interrogation sources, confining the atoms in a space with limited perturbations, magnetic effects, light effects etc., need to be in control for an atomic clock to with good performances. However, one must note it is possible to isolate the atoms better than a macroscopic device, hence enabling improved performances.

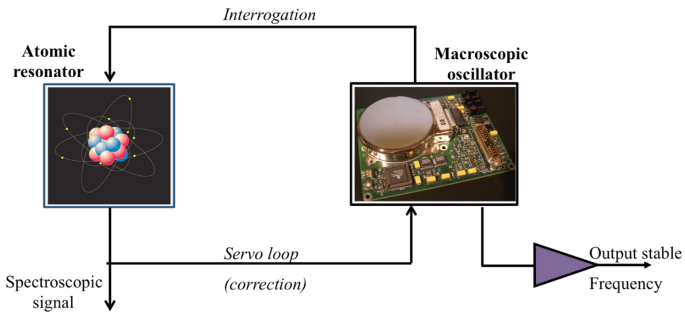

Figure 2: General clock principle showing interrogation of atoms to get a spectroscopic signal and servo correction feedback to stabilize a macro-oscillator (quartz) to obtain the clock signal.

TYPES OF ATOMIC CLOCKS

Atomic clocks can be broadly classified into three categories based on their complexity, mass, volume, portability, reliability, and application, as follows:

Laboratory based atomic clocks

This category includes primary frequency standards–cesium cold atom fountains, lattice, and ion – microwave and optical clocks.[3,16,17,19,37] Generally, these clocks occupy a large laboratory space and must be operated in a highly-controlled environmental conditions–temperature, humidity, vibrations, electromagnetic interferences etc. These clocks are confined to a laboratory space since their inception and built to sustain longer term research and operations, albeit with necessary maintenance. Comparison of such clocks between distant laboratories is typically performed, however this review doesn't cover the details of clocks synchronization and characterization.

Ground based portable, miniature, and commercial atomic clocks

This category includes cesium beam standards, Active Hydrogen MASER (AHM), Passive H-MASER (PHM), compact rubidium standards and miniature clocks such as Chip-Scale Atomic Clocks (CSAC).[11,12,38,39,40,41] The MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation. The National Metrological Institutes (NMIs) are the laboratories spread around the world, where ultra-stable atomic clocks are hosted and clock outputs are continuously measured and the clock information is provided to BIPM (Bureau International des Poids et Mesures) situated in Paris, where the TAI is maintained formulating UTC. The cesium beam clocks and AHM clocks are the workhorses of the NMIs contributing to maintain the precise world time.

Space based atomic clocks

The key requirements for space-based clocks are low power consumption, reduced mass, and low volume, but high performance, and excellent reliability. The clocks that have satisfied above criteria are compact rubidium standards, cesium beam standards and PHM. It is worth noting the recent developments of ion-based compact high-performance clocks, and the developments of the rubidium pulsed clocks, and cold atom clocks for space-based navigation and scientific missions.[24,42-46] The next section covers further details of the space based atomic clocks and overview of various navigation systems that contribute to Global Navigation Satellite Systems (GNSS).

STATE OF THE ART IN THE FIELD OF PORTABLE SPACE CLOCKS

Lamp-pumped rubidium clocks onboard GPS satellites exhibit a stability of $5x10^{-14}$ over one day time scales (86,400s), giving the positioning accuracy of about 1 meter or better after signal corrections. Reliability of Rb standard is already proven by demonstrating it outside earth's orbit in the Cassini-Huygens mission, launched in 1997, to study the Doppler wind speed in Saturn and its moons.[47] Rb standards are limited in positioning precision because of their limitation in frequency stability at medium to long-term time scales, which is mainly due to the interaction of Rb atoms with the buffer gases and the vapor cell walls.[35] This also leads to frequency drift ($\sim 10^{-13}$/day) and ageing ($\sim 10^{-10}$/month) processes, therefore requiring frequent calibrations.[13,35] However, for the position and navigation needs, Rb clocks satisfy the requirements of the GNSS by providing the needed precision and stabilities.

Presently, the best onboard clocks onboard a navigation satellite system are passive hydrogen masers[49] that are in-orbit in ESA's Galileo navigation system. The passive H-masers are however bulky in comparison to rubidium standards:[24,45] having a volume of 28 dm^3 (3 dm^3 for Rb), mass of 18 kg (4 kg for Rb) with a power consumption of 80 W (18 W for Rb). On the other hand, the laboratory clocks like primary Cesium (Cs) fountains and optical clocks exhibit excellent stability of $\sigma_Y(t)$ $\sim 1x10^{-13}$ $\tau^{-1/2}$, but are bulkier occupying a room space and expensive. Even the cold atom clocks or optical lattice clocks proposed for space applications target outlines of 1 m^3 volume, 230 kg mass, and 450 W power consumption.[50] Alternatively, a state-of-the-art compact and portable linear ion trapped Hg+ clock developed at JPL, NASA for deep-space navigation and science missions has been demonstrated to work exceptionally well onboard a technology demonstration mission.[46] The recently developed rubidium clock for the Navigation with Indian Constellation (NavIC) system has performances required to meet navigational needs, showing promise to sustain an indigenous navigation programme.

JPL's Deep-Space Atomic Clock delivers the fractional frequency stability of 10^{-15} levels in a shoebox-sized package with a drift of no more than 1 ns in 10 days. All the existing space-based clocks are distinguished in Figure 3 based on their weights. A clear indication of Hg+ clock's (JPL-DSAC ion clock) smaller mass and excellent performance is seen. This clock has been tested in a space-like environment for longer-term performances over a

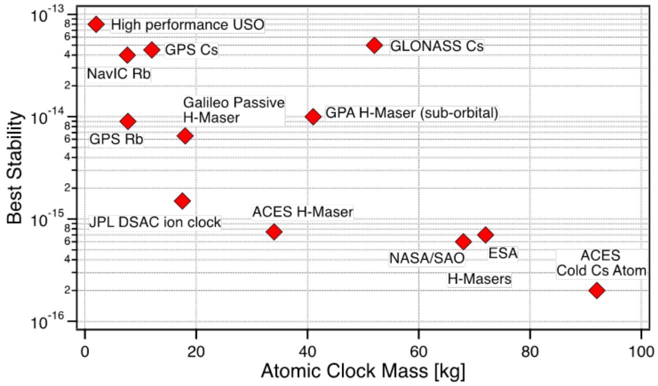

Figure 3: Space-based atomic clocks overview.

four-year period, hence confirming its reliability for deep-space applications.

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

Navigation is an indispensable part of everyday human life in the present world, for instance the use of direct satellite navigation signals through mobile phones is embedded in our daily activities such as use of Google maps, apps reliant on positioning information such as Uber, delivery and tracking, accurate weather information feed etc., to name a few. Atomic clocks form the heart of each onboard GNSS satellite. Conceptually speaking, the atomic clock's heart-beat frequency depends on the atomic species chosen to build the clock. For instance, a clock made using rubidium atoms oscillates about 6.8 billion times in a second. These atomic clocks give a precise frequency and therefore timing output which helps to locate the precise position for navigating.[13,42-45] Usefulness of atomic clocks is not only limited to earth, but beyond the earth's orbit for deep space tracking and navigation.[46,51,52]

The lamp pumped Rb clocks are used in almost all Global Navigation Satellite Systems (GNSS). Other classes of present onboard clocks are Space Passive Hydrogen Maser (SPHM) and cesium (Cs) beam clocks.[42,43] These are of high-performance, but bulkier and expensive than Rb standards. Table 1 shows the existing GNSS constellations, involved countries and respective onboard atomic clocks. It is explicit that Rb clock is a common technology in mostly all the systems, because of its low -power, -mass, -volume, excellent reliability, robustness, and proven technology.

The Global Positioning System (GPS) development started in 1973 and first GPS satellite was launched in 1978. Initially, GPS was primarily built to serve the US military uses, later it was opened to public usage after 1994, although there were directions to do it earlier. The GPS constellation has a total of 31 satellites orbiting at an altitude of 20,180 km. 6-12 satellites are visible at any instance from any point on the globe. The onboard clocks are synchronized to a master reference clock located at the US Naval Observatory (USNO). Global Navigation Satellite System (GLONASS) is operated and maintained by Russia. The development started in 1976 and the first satellite was launched in 1982 and is in full operation since 1995. There are 29 satellites in operation orbiting at an altitude of 19,130 km. Realizing the importance of space-based navigation; the European Commission (EC) and European Space Agency (ESA) jointly ventured to form the Galileo navigation system. Galileo constellation started in 2011 and consists of 30 satellites at an altitude of 23,222 km. BeiDou Navigation System (BDS) or Compass satellite navigation system is operated and maintained by Republic of China. The system was built in three stages – the regional navigation system, the first stage was in operation since 2000 and the second stage of regional navigation covered the Chinese land mass area, followed by the global navigation system, that is in operation providing services since 2019. The BeiDou constellation has a total of 35 satellites operating at an altitude of 24,000 km. Quazi-Zenith Satellite System (QZSS) is a regional time transfer and augmentation system for GPS covering Japan. It consists of 3 to 4 satellites with an aim to increase the signal reception in the cities amidst skyscrapers and deep canyons.

Navigation with Indian Constellation (NavIC) or Indian Regional Navigation Satellite System (IRNSS), as the name suggests, is a regional navigation system autonomously developed by Indian Space Research Organisation (ISRO). The initial system has seven satellites and two additional satellites, covering Indian sub-continent and surrounding region up to 1500 km. The first satellite was launched in 2013 and is fully operational by providing navigation signals since 2016. The IRNSS' goal is to achieve user position accuracy of <20 m with continuous signal reception. Presently, the best achieved position accuracy is 3.5 m. Figure 4 shows the NavIC configuration of seven satellites. Three are in geostationary orbit and remaining four are in geosynchronous orbit, as shown in the Figure. Later, to avoid Doppler effect, the GEO satellites were set to a minimum inclination angle. The Satellites in inclined orbits trace a Figure of '8' on the earth and when any two inclined satellites are at equator, other two are at

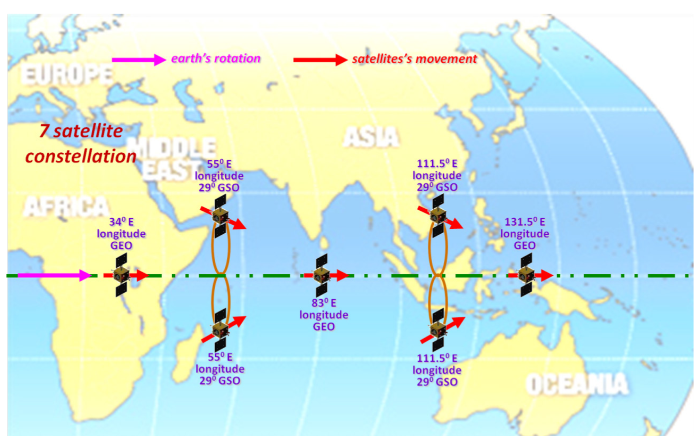

Figure 4: IRNSS configuration showing satellites and their orbits. Image courtesy/credit: ISRO.

Table 1: Present GNSS constellations, associated countries and onboard atomic clocks.

GNSS	Countries involved	Onboard Clocks
Navstar, Global Positioning System (GPS)	USA	Cesium beam clock, Rubidium clock
Global Navigation Satellite System (GLONASS)	Russia	Cesium beam clock, Rubidium clock
Galileo	European Union	Rubidium clock, Passive Hydrogen Maser (PHM)
Quazi Zenith Satellite System (QZSS)	Japan	Rubidium clock, Quartz Oscillator
Compass, BeiDou Navigation System (BDS)	China	Rubidium clock, PHM
IRNSS/NavIC	India	Rubidium clock

extreme positions – thereby, ensuring the required geometrical coverage. Onboard each NavIC satellite three rubidium atomic clocks are housed. One is active, second is hot redundant–to switch immediately in case of any failure of the first clock, and third is cold redundant. This configuration will enable to enhance the life of the mission.

As seen in Table 1, Rb atomic clocks are the most common and widely used clocks in GNSS, hence indigenous Rb clock has been developed independently at ISRO.[53-56] Due to their reliable operation in GNSS, with importance to Rb standards, we will cover its operation in brief in the next section. A typical space qualified Rb clock used in GNSS consists of an Electronic Power Conditioner (EPC) from which the power distribution to the clock package is given; base plate for temperature regulation of the clock; Rb atoms confined inside the physics package; local oscillator (quartz) and related control electronics. The mass of Rb clocks range from is 3.2 kg to 14 kgs with a volume of 2.4 liters to 16 liters. Depending upon the design and characterization of the Rb clock, the short-term frequency stability may range from $5\times10^{-12}\ \tau^{-1/2}$ to $8\times10^{-13}\ \tau^{-1/2}$ and stability at 10^4 s to 1 day may range from 5×10^{-14} to 8×10^{-15} (drift removed). In the next section, the working principles of Rb clocks are explained briefly.

RUBIDIUM ATOMIC CLOCK PRINCIPLE

Figure 5 shows a generic rubidium vapor cell atomic clock and Figure 6 shows the Rb energy levels scheme. The rubidium discharge lamp optically pumps and creates the population imbalance between the hyperfine ground states of the ^{87}Rb atoms in the resonance cell (pumping the atoms from *F=2* to *F=1* via excited states), resulting in increasing the transmitted light intensity. The microwave field in the cavity, that is resonant at Rb hyperfine levels, ν_{hfs}, transfers the atoms back from *F=1* to *F=2* and decreases the transmitted light intensity. The derivative of the detected atomic resonance curve by measuring the transmitted light intensity is used as a correction signal for the crystal oscillator, OCXO. As the *optical*- and *microwave*- resonances with -*atoms* give rise to *atomic signal*, it is known as Double-Resonance (DR) method. The atomic signal typically has a Lorentzian line shape and the stabilisation of the quartz oscillator to the center of this reference signal, realises the clock.[13,15,35,45,57] The theoretical basics and further details of Double-Resonance (DR) spectroscopy and clock are explained in the references.[13,15,35,36,57]

Figure 6 shows ^{87}Rb and ^{85}Rb energy level schemes representing the Rb discharge lamp, filter cell and resonance cell, respectively. Each transition line (dotted and solid) shown here is a combination of two fluorescence lines from the $5^2P_{1/2}$ state to $5^2S_{1/2}$ (D1, λ=795 nm) and $5^2P_{3/2}$ (D2, λ=780 nm). The ground states are split into two hyperfine levels, characterised by quantum number F. Due to fortuitous coincidence of nature, the ^{87}Rb transition from excited states to *F=2* level is of almost same frequency as that of ^{85}Rb's *F=3*, which helps in filtering the light and thereby aids in creating the population imbalance (or polarisation) in the resonance cell between *F=1* and *F=2* states of ^{87}Rb. Then the microwave de-pumps the atoms from *F=2* to *F=1* states at the hyperfine resonant frequency, ν_{hfs}, giving rise to a resonant atomic signal. Typical DR atomic signal of a Rb clock has a Lorentzian shaped curve[24,35] with a narrow linewidth of 1kHz or lower, and a signal contrast of up to 30%-if it is a laser pumped clock[36,57] or typically a contrast of up to 2.5% for a lamp pumped clock.[13,45] At the heart of a conventional rubidium atomic frequency standard, atomic rubidium in vapor phase and buffer gases are contained in a glass enclosure, called vapor cells. Buffer gases help to prevent the polarized Rb atoms from colliding on to the cell walls and reduce the mean free path of a Rb atom to less than the microwave photon's wavelength of few centimeters, thereby giving rise to narrow resonance lines, this is known as Dicke narrowing.[35,58,]

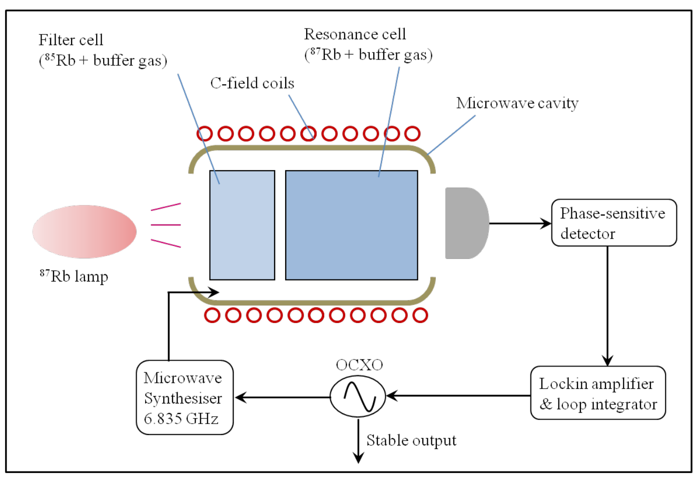

Figure 5: Rubidium clock principle showing the interrogation of Rb atoms confined in a vapor cell by lamp and microwave.

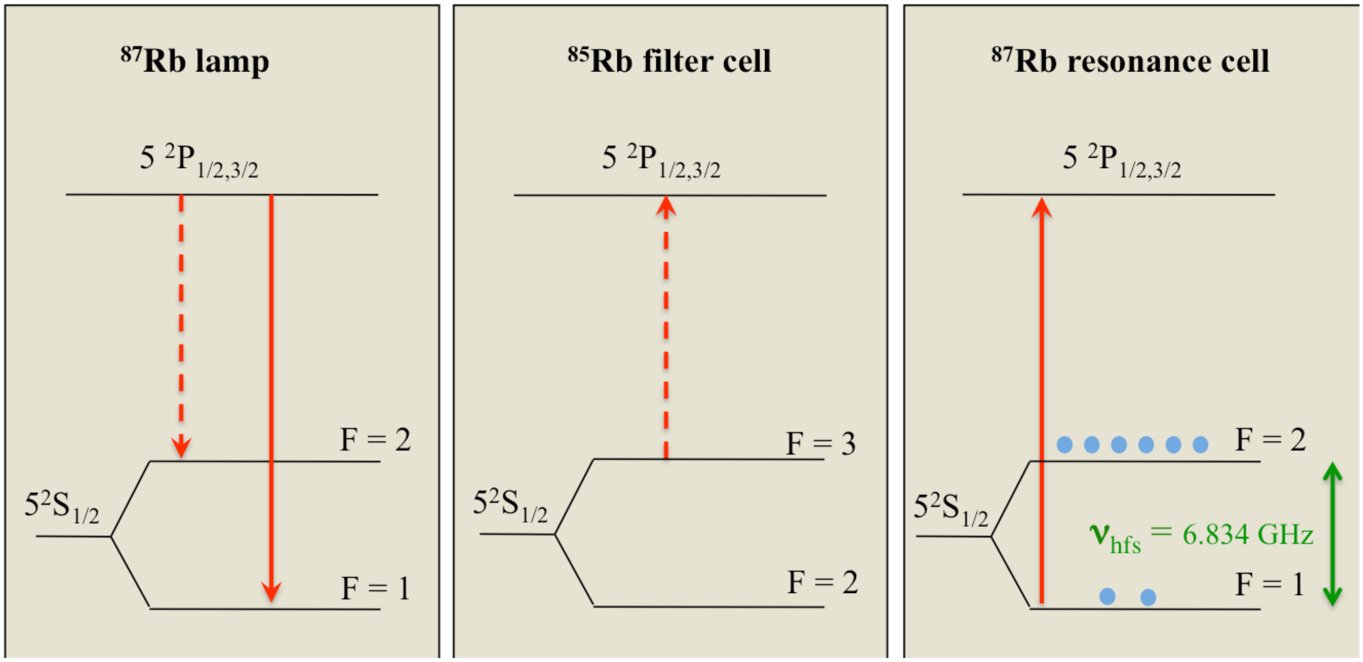

Figure 6: [87]Rb and [85]Rb energy level schemes representing the Rb discharge lamp, filter cell and resonance cell, respectively. The optical and microwave resonant transitions in [87]Rb are shown.

The vapor cell is mounted inside a resonant microwave cavity[59] that has the capability to drive the vapor atoms to precise atomic resonance frequencies giving rise to atomic signal. The interactions of the atoms inside a vapor cell with the microwave field of the cavity has been imaged measuring the Rabi oscillations to determine the population and coherence times.[60] There has been a significant development on laser-pumped Rb atomic clocks,[61] but a reliable product towards space is yet to be realized.

Alternative to using buffer gases for preserving the polarization by avoiding collisions of atoms with the glass walls, an evacuated glass cell whose inner walls are coated with an anti-relaxation material and filled with Rb vapor could be adopted as an alternative method for the clocks.[62-64] The first studies on collisions between alkali atoms and coatings, such as paraffins $(CH_2)n$ or silanes (e.g., dimethyldichlorosilane) were done by Bouchiat and Brossel[65] during the 1960s by adopting the Franzen's method of relaxation in the dark.[66] Although the idea to use wall-coated cells in an atomic frequency standard was suggested by Robinson[63] in the late 1950's, it was not realized due to the limitations in operating temperatures of such cells (incompatible with the use of lamps for optical pumping) and other technological difficulties, such as control of the coating quality. Part of these drawbacks is overcome with laser optical pumping. A Rb clock using tetracontane cell was demonstrated[67] in a laboratory exhibiting the stability of $<3\times10^{-12}\ \tau^{-1/2}$. However, a reliable commercial product is yet to be realized. Recently, the interest in wall-coated cells for high-precision spectroscopy and metrology is growing again, because coated cells represent good candidates to realize high-performance or micro-fabricated devices, such as miniaturized atomic clocks and/or atomic magnetometers.[67,68] Basic studies on the application of wall-coated cells for Rb frequency standards have been reported.[70-72]

ATOM INTERACTIONS IN RESONANCE VAPOR CELL

In this section, a descriptive overview of the Rb atom interactions in an enclosed resonance vapor glass cell is explained. For a detailed and through analysis, the reader is directed to these references.[35,36]

Collisions

Polarized Rb atoms undergo collisions with the buffer gas atoms, other unpolarized Rb atoms and with the walls of the container cell. All these collision interactions destroy the polarization created by the light and therefore should be controlled well. Note the buffer gas atoms help keep atoms from losing the polarization state for few milliseconds, during which the microwave resonant interrogation is performed.

Static magnetic field

A static magnetic field known as C-field is applied using solenoid coils (Figure 5) collinear with light propagation. In presence of this field, the atomic ground state degeneracy is split into their respective Zeeman levels. The $5^2S_{1/2}$ $|F=1, m_F=0$ to $|F=2, m_F=0$ transition is of interest to us which is the *clock transition*.

Resonant interaction with the optical beam

As mentioned in previous section, the light from discharge lamp optically pumps atoms in the resonance cell to create the population imbalance. The interaction Hamiltonian is given as,

$\hat{H} = -\vec{d} \cdot \vec{E}$, where d is the electric dipole moment and E is the electric field.

Resonant interaction with a microwave field

Similar to the atom interaction with the E-field of the light, the magnetic interaction of the atom with the microwave field inside the cavity can be written as $\hat{H} = -\vec{\mu} \cdot \vec{B}_{RF}$, where μ is the magnetic dipole moment and B_{RF} is the interrogation microwave field inside the cavity.

RB CLOCK SHORT-TERM FREQUENCY STABILTY

An atomic standard's frequency or phase fluctuations are typically characterized in time domain, statistically in terms of Allan deviation.[73-75] The short-term frequency stability of a clock (in terms of Allan deviation) is inversely proportional to the atomic Q-factor and signal-to-noise (S/N) ratio.[24,35,57] This implies that a narrow linewidth of the atomic signal increases the Q-factor and hence improves the short-term clock stability. The conventional high-performance space rubidium frequency standards use lamps for optical pumping[76,77] and give a short-term stability of $5\times10^{-12}\,\tau^{-1/2}$ or at best down to $1\times10^{-12}\,\tau^{-1/2}$. With recent developments using laser optical pumping, the short-term stabilities have been improved by more than one order of magnitude.[15,36,57,75] The state-of-the-art demonstrated short-term stability for a continuous wave DR signal Rb clock[57] is $1.36\times10^{-13}\,\tau^{-1/2}$. The S/N and Q dependent short-term stability of the clock is characterized by the equation:

$$\sigma_y(\tau) \propto \frac{\tau^{-1/2}}{Q\,(S/N)}$$

Rb clock's short-term stability related to S/N is limited due to the noises (or perturbations) associated with the light fluctuations, photodetector noise, buffergas collisions with the Rb atoms, microwave local oscillator's phase noise etc. Therefore, control and precise regulation of all the influencing parameters is necessary to have a good, stable clock.

RB CLOCK MEDIUM TO LONG-TERM FREQUENCY STABILTY

The medium- to long-term clock stability, typically characterized between 10^2 s to 10^4 s to 1 day or longer timescales, is influenced by AC Stark shift (light intensity and frequency perturbations), microwave power shift, temperature associated shifts, cavity pulling and other related physical effects.[35,36,57] Figure 7 shows the perturbing physical effects on the clock physics package. The metrological quantitative detailed measurements and thorough understanding of these parameters is of utmost relevance for having a precise control operation of the clock.

Figure 8 compares stabilities of various portable, commercial, and space-based microwave atomic clocks characterized in terms of Allan deviation. The cesium (Cs) beam, cold Cs and DSAC ion clocks have negligible drifts. The cold Rb clock is developed by Spectradynamics Inc., showcasing the latest benchtop product in the market with added benefits of laser cooled atoms. The vapor cell based Rb clocks and H-MASERS exhibit systematic drifts after 10^4 s. The linear drifts can be generally removed, resulting in a slight performance benefit in the medium to long-term frequency stability of the clocks.

CONCLUSION

This review article covers a comprehensive overview of the types of atomic clocks and their applications, mostly focused through microwave atomic clocks or frequency standards. The metamorphosis of the measurement of time since 3000 BC and the evolution towards more precise atomic clocks has been explained. In general, the atomic clock principle and a broad classification of the types of atomic clocks around the world is covered, providing a perspective on the existing atomic clocks. Further, the state of the art in the space atomic clocks has been covered with an overview of the GNSS. The footprint impact and the usefulness of the space rubidium atomic clock for the satellite navigation along with its working principle and insight into the complex metrology involved in achieving short, medium, and long-term stability performances has been explained. Finally, a comparison of the commercially available key microwave clocks and the space-based microwave clocks is shown characterized in terms of Allan deviation stability. The long-proven heritage of rubidium standards in space empowering the satellite-based navigation in achieving position accuracies below one meter or better shows promise to continue with rubidium standards

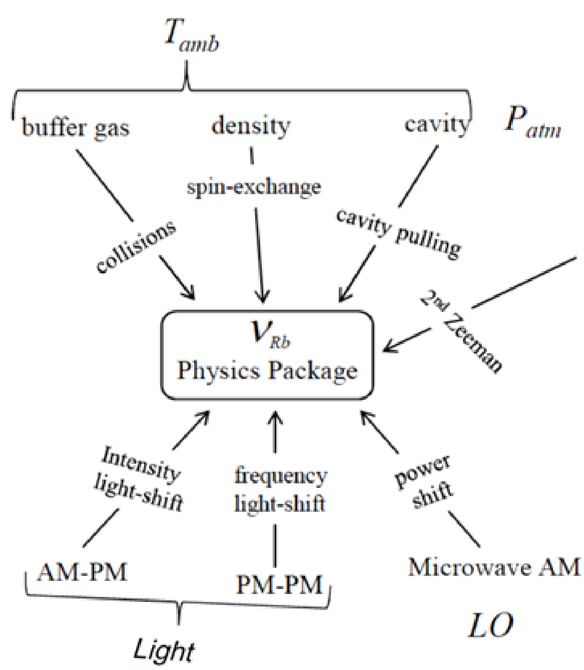

Figure 7: Physical effects and their corresponding sources of fluctuations affecting the clock frequency stability in medium-long-term time scales.

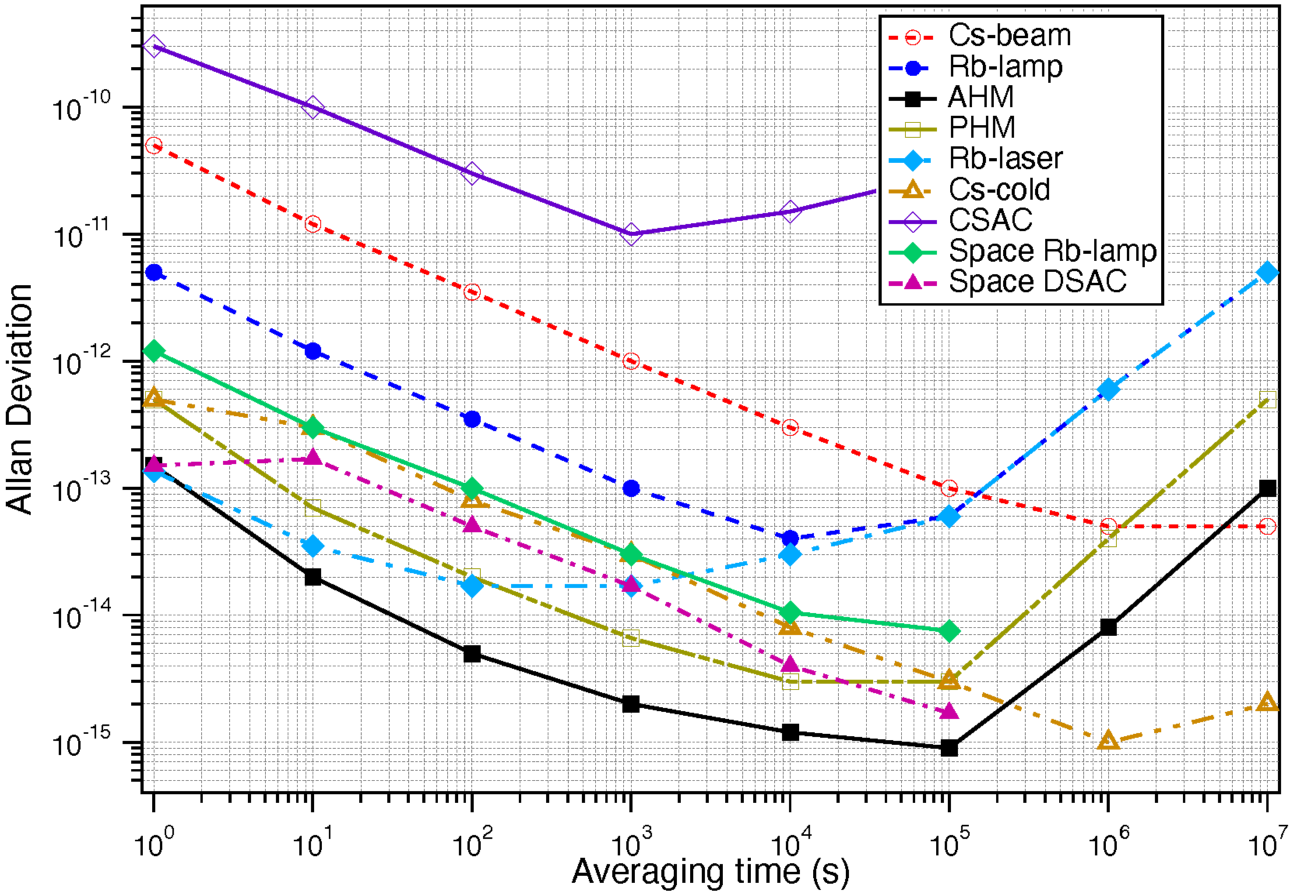

Figure 8: Stability comparison of portable commercial and space-based microwave atomic clocks.

for navigational needs for a long-term, until the other clock technologies mature and prove their mettle generating heritage in harsh space environment.

From a point of view of biology, the GPS/GNSS based migration studies of land and marine species has been of considerable interest for understanding the behavior and conservational studies.[79] In a not so far distant future, use of atomic clocks, precision timing synchronization and navigation technologies for biological studies could become a reality. It is worth noting the already demonstrated application using the magnetic precision spectroscopy–a variant of atomic clock principle that, direct biological non-invasive and extremely sensitive imaging is possible.[80,81]

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

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