



Measuring space-time with optical lattice clocks

A M Guzmán^{1,2}

¹*Universidad Nacional de Colombia, Departamento de Física,
Bogotá, Colombia*

²*Universidad del Atlántico, Barranquilla, Colombia*

In memory of Professor Gallieno Denardo, ICTP Italy

Time measurement has reached the accuracy required to observe the relativistic redshift that causes clocks to run slower in stronger gravitational fields, within terrestrial height differences of the order of centimeters. With this accuracy we are indeed measuring the four-dimensional spacetime continuum rather than performing separate measurements of distance and time. The best cesium microwave clocks measure the SI second to within one second in 100 million years, using the time-of-flight technique of a “cloud” of cold atoms. In 2001, Hidetoshi Katori of the University of Tokyo proposed the first clock of strontium atoms trapped in a horizontal optical lattice, with a transition at 430 THz in the red range of visible light. By the 2010s, this clock held the record for accuracy of one second in 15 billion years, exceeding the estimated age of the universe. In July 2024, Jun Ye's group at JILA, NIST, presented a vertically oriented one-dimensional optical lattice clock of strontium atoms with a total systematic uncertainty of 8.1×10^{-19} in fractional frequency units, representing the lowest uncertainty of any clock to date. We provide a timeline of key scientific advancements, challenges, and progress in verifying the global consistency of optical clocks, a critical step toward the redefinition of the second by the International Committee on Weights and Measures, anticipated in 2030. Additionally, we highlight recent contributions of optical lattice clocks to quantum metrology, precision quantum sensing, fundamental physics invariance, and the exploration of the relationship between quantum physics and general relativity. © Anita Publications. All rights reserved.

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1 Introduction

Already at the dawn of spectroscopy, Maxwell and Lord Kelvin realized that atoms, like hydrogen and sodium, could be used as a frequency standard, since they are equal in all their physical properties, particularly in their spectral frequencies, and can be used in large quantities. At the time they also postulated that the frequency of atomic transitions will be time-invariable and position-independent in the whole universe. General relativity theory (GRT) was still in the future and with its advent, it ruled out the existence of an absolute and privileged reference system and predicted the relativistic gravitational redshift (GRS) of atomic frequencies.

On Earth, GRS is proportional to the local gravitational potential. A clock at higher gravitational potential will tick faster than an otherwise identical clock at a lower potential. The atomic frequency difference between an atomic transition of frequency ν_h at a height h (in cm) above earth's surface and the frequency of the same atomic transition ν at earth's surface is [1]:

Corresponding author

e mail: amguzmanh@unal.edu.co (A M Guzmán)

$$\Delta v = v_h - v \approx vgh/c^2 = v h \times 1.09 \times 10^{-18}. \quad (1)$$

Before lasers, conventional optical wavelength resolution was, at best, $\Delta v/v \sim 10^{-8}$, ruling out terrestrial measurements of GRS. In 1959, Pound & Rebka at Harvard University proposed the first direct, terrestrial measurement, of the gravitational red shift using recoilless resonance absorption of ^{57}Co gamma rays by ^{57}Fe , with a very narrow line width ($\Delta v/v \sim 5 \times 10^{-13}$) due to the Mössbauer effect. They performed a measurement of the GRS [2] in a tower 74-feet high by transmitting γ rays from a source to a scatterer and observing what relative velocity yields maximum scattering. They measured the frequency shift for a “two-way” path with the γ rays rising (source at bottom) and with the γ rays falling (source at top), and obtained agreement with the theoretical prediction within 10%, with frequency increasing in falling as expected.

Atomic clocks became a reality in 1955, with Essen’s Cs beam atomic clock at the National Physical Laboratory (NPL) in the United Kingdom. Essen realized that microwaves frequencies could be used to measure time intervals up to billionths of a second and be locked to a natural resonance of the Cs atom in the gigahertz range to create highly precise and stable atomic clocks. Essen’s clock meant, as he stated, the “death of the astronomical second and the birth of atomic time.” The NBS-1 cesium-beam atomic clock began operation in 1959 at the National Bureau of Standards (now the National Institute of Standards and Technology - NIST) laboratories in Boulder, Colorado. NBS-2 and NBS-3 followed in 1960 and 1963, respectively and served as the USA national primary frequency standard.

Nearly a decade after Essen’s microwave clock, in 1967, the standard SI unit of time, the second, was redefined at the 13th General Conference on Weights and Measures as “the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom” at a temperature close to the absolute 0 Kelvin. Two atomic beam clocks (PTB-CS1 and PTB-CS2) at the German National Metrology Institute, PTB in Braunschweig, were put into operation in 1969 and 1985 respectively, and are still currently used as primary clocks to define the international atomic time (TAI). Atomic-beam Cs clocks reached uncertainties over five orders of magnitude lower than Essen’s clock.

In [section 2](#), we present the advances on laser cooling in the eighties that led to a major improvement in the accuracy of cesium clocks, by using laser-cooled cesium gas instead of Cs beams. Cs fountain clocks have reached accuracy of the order of 10^{-16} , nearly six orders of magnitude more precise than Essen’s original clock, which is now housed in the Science Museum in London. TAI (International Atomic Time) is computed by the International Bureau of Weights and Measures (BIPM) in Paris. BIPM gathers time readings from roughly 450 atomic clocks — mostly cesium and hydrogen maser clocks — housed at 80+ metrology labs worldwide. Each clock’s data is weighted according to its frequency stability over the past year, then combined via a weighted-average algorithm to produce an uncalibrated atomic timescale, EAL (Échelle Atomique Libre). EAL is highly stable but can drift slightly in absolute frequency over time, so BIPM calibrates it against primary and secondary frequency standards to yield TAI. The calculation of TAI is a fundamental input to the Universal Coordinate Time (UTC), which rules time for the global navigation systems, finances and telecommunications. In 2018, the BIPM assigned to that standard frequency the exact numerical value 9192631770 Hz. We also describe briefly the development of the laser frequency comb, fundamental step to bridge the measuring gap between microwave and optical frequencies.

The last decade, our accuracy to measure time has increased again in more than two orders of magnitude, with optical lattice and single-ion atom clocks based on transitions in the visible rather than in the microwave regime. Optical clocks work at transitions at visible light frequencies ($\sim 10^{15}$ Hz) with long lifetimes and short linewidth, so that the frequency uncertainty for the clock transition is 105 times smaller. In [section 3](#), we describe the challenges that were overcome at the dawn of the optical lattice clocks to develop highly precise optical lattice clocks (OLC) with fractional frequency uncertainties of 10^{-18} that can measure

the relativistic atomic frequency redshift between locations on earth differing in attitude by a few centimeters and even at sub-centimeter scale [3], compelling us to abandon the Newtonian concepts of 3D-space and universal absolute time as separate entities.

The current key research goal coincides with Essen's back then: to have an atomic clock able to operate for a long time with the highest precision and stability. In section 4, we discuss fractional uncertainty and the systematic effects that still are being overcome to reach fractional frequency uncertainties below 10^{-18} . The record of lower systematic uncertainty (8×10^{-19}) in OLC for time measurement is currently held by the ^{87}Sr neutral atom OLC at NIST [4]. This level of precision is equivalent to an uncertainty less than 1 s over the lifetime of the Universe.

In section 5, we summarize the main characteristics of optical clocks that are currently classified as secondary frequency standards by BIPM and present the international coordinated efforts to compare the precision, stability and reproducibility of atomic clocks located in different countries, as mandatory criteria to fulfill towards the redefinition of the second, foreseen for 2030. Accurate comparisons of the standard frequency at separate locations, require leveling geodetic methods and Global Navigation Satellite Systems (GNSS) [5]. Observations in astronomy, geodesy, and metrology require four-dimensional spacetime reference systems.

In section 6, we describe the new research possibilities that highly precise and stable OLCs are opening up. Among these are high-precision measurements of the stability of fundamental constants, studies of gravitational redshift to probe the interplay between general relativity and quantum mechanics, and the development of highly sensitive gravimeters.

2 From laser cooling and trapping to optical lattices

Laser cooling

Laser cooling and trapping are essential to atomic clocks. I had the opportunity to attend as a Ph D student the "First International Conference on Laser Cooling", which took place in Tvärminne, Finland in March 1984 [6]. By using a pair of opposing laser beams, each atom absorbs more strongly from the beam moving against its direction of motion, and by using three pairs of mutually perpendicular lasers, the process of Doppler cooling can be performed in three dimensions lowering the gas's temperature. The net effect on the atoms is a viscous damping force proportional to the velocity of the atom [7].

In 1978 Wineland, Drullinger and Walls demonstrated laser cooling of Mg II ions confined in a Penning trap [8], but a 3D viscous confinement of atoms in the intersection of six lasers in a 3D arrangement was first observed in 1985 by Chu *et al* [9]. Their scheme was not a trap, but could confine atoms in a small region in space for times on the order of 0.1 sec, a confinement time consistent with the diffusive motion of atoms in a viscous fluid of photons, that they named as "optical molasses".

In 1987 Gould, Lett, and Phillips [10] found a large discrepancy between the measured molasses lifetime as a function of the laser frequency detuning and the Doppler cooling theory. The experimental lifetime maximum occurred at a laser detuning above 3 linewidths instead of below one linewidth as predicted by Doppler cooling theory. In subsequent experiments Phillips' group implemented the time of flight (TOF) method to measure the atomic temperature, allowing the ballistic expansion of the atomic cloud by switching off the cooling laser beams. The TOF distribution of the cloud was obtained by measuring the time distribution of the atomic fluorescence of a probe laser beam. They confirmed sub-doppler laser cooling [11] since the TOF measured temperature of a gas of sodium atoms released from the optical molasses was $43 \pm 20 \mu\text{K}$, well below the Doppler cooling limit temperature of $240 \mu\text{K}$. Furthermore, they observed that the atomic temperature depended on the polarization of the molasses laser beams and was highly sensitive to the ambient magnetic field.

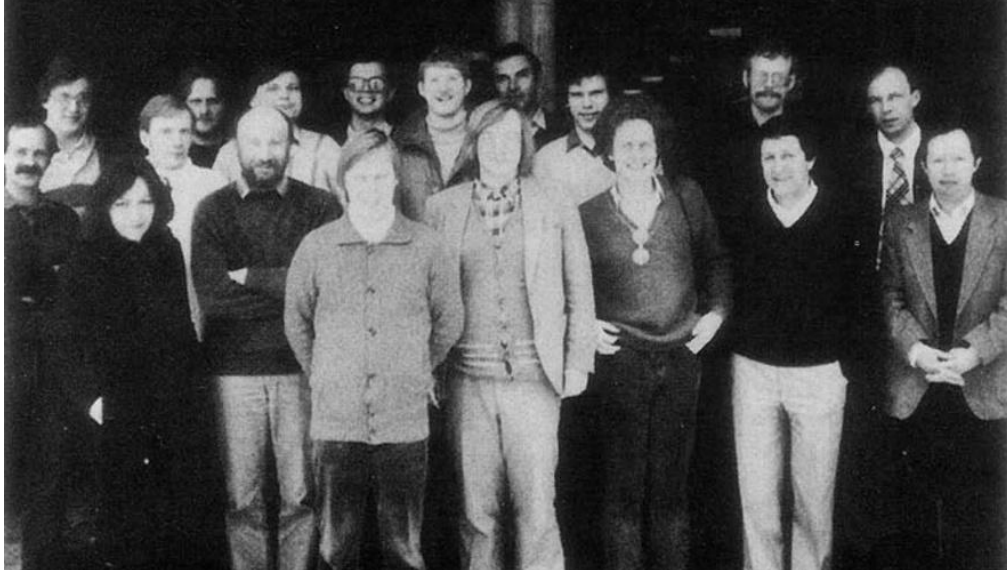


Fig 1. Stig Stenholm's "First International Conference on Laser Cooling" in Tvärminne, March 1984. Back row, left to right: Juha Javanainen, Markus Lindberg, Stig Stenholm, Matti Kaivola, Nis Bjerre, (unidentified), Erling Riis, Rainer Salomaa, Vladimir Minogin. Front row: Jürgen Mlynek, Angela Guzman, Peter Jungner, Wolfgang Ertmer, Birger Ståhlberg, Olli Serimaa, Jean Dalibard, Claude Cohen-Tannoudji, Victor Balykin. Photo from Ref [6].

Aware of these and their own results, Cohen-Tannoudji and Dalibard [12] developed the Sisyphus cooling theory based on laser polarization gradients. In a 1D array of two counterpropagating beams with orthogonal linear polarization, light shifts of the ground-state Zeeman sublevels are sinusoidally modulated in space. An atom in the $m = +1/2$ Zeeman sublevel climbs a potential hill and at the top is optically pumped to the valley of the optical potential for the $m = -1/2$ sublevel, to start climbing again a potential hill. The process resembles King Sisyphus punishment from Greek mythology to endlessly push a boulder up a hill, only for it to roll back down each time he reached the top. The successive optical potential climbing diminishes the kinetic energy of the atoms and leads eventually to atom trapping in one of the discrete levels of the potential wells.

The localization of atoms to less than an optical wavelength (Lamb-Dicke regime) in 3D potential wells was demonstrated [13] by measuring the spectrum of the resonance fluorescence from sodium atoms in the optical molasses. It showed a very narrow feature in the center of a Doppler broadened spectrum corresponding to the molasses temperature. The narrow component indicates a sub-wavelength localization of the atoms, in what are now called optical lattices, where the light shifts caused by an array of cooling lasers induce periodic microscopic dipole force potential wells where atoms become trapped and well localized.

The Laser frequency combs

Another essential step towards the implementation of optical atomic clocks was the development of laser optical frequency combs [14], for which Theodor Hänsch and John Hall were awarded the Nobel Prize 2005. They act as precise rulers for light, generating hundreds of thousands of evenly spaced laser frequencies ($\omega_n = n\omega_r + \omega_{off}$), like teeth on a comb. In a mode-locked Ti:Sapphire laser, the repetition frequency is inversely proportional to the round-trip time — the time taken by a pulse of light to complete one round trip in the laser cavity. The cavity's length can be controlled by applying a voltage to a piezoelectric transducer (PZT), or by placing an Acousto-Optic Modulator (AOM) inside the cavity. In an erbium-doped

fiber laser, the effective cavity length is adjusted by modulating the pump laser current. To span the comb frequencies over an octave, pulsed femtosecond-lasers are needed. The comb-envelope of a 10fs laser pulse covers 100THz and can be broadened to span an octave. The offset frequency (ω_{off}) can be determined as the difference frequency between the ω_n doubled frequency, $2\omega_n = 2n\omega_r + 2\omega_{\text{off}}$, and the ω_n octave frequency, $\omega_{2n} = 2n\omega_r + \omega_{\text{off}}$.

Frequency combs work as a perfect clockwork mechanism producing an octave-spanning spectrum that connects phase-coherently the clock's optical frequency to microwave frequencies. The repetition frequency (ω_r) is typically locked to a stable external reference (e.g., a rubidium atomic clock or a Hydrogen maser) using an electronic feedback loop. An error signal from the comparison is fed back to the control mechanism to maintain a constant, stable comb spacing. One nearby tooth of the comb is phase locked to the clock laser frequency. All the other comb line frequencies are then rational multiples of the optical reference frequency, bridging the gap between radio frequencies and optical frequencies in a single step.

3 The dawn of optical lattice clocks

The magic wavelength

Tightly confined neutral atoms in optical lattices interact with light without individual recoil [15] similarly to the Mössbauer effect in solids. Recoil and first order Doppler effect are nullified. This makes them good candidates for optical lattice clocks, provided the frequency shifts caused by the optical lattice field and by collisions can be controlled. AC-Stark shifts are large and depend on the individual position of the atoms in the lattice. The unperturbed transition frequency ν_0 of atoms, when exposed to the lattice electric field E is AC-Stark shifted:

$$\hbar\nu = \hbar\nu_0 - 1/4 \Delta\alpha(\hat{\epsilon}, \omega) E^2 - 1/64 \Delta\gamma(\hat{\epsilon}, \omega) E^4 - \dots, \quad (2)$$

where $\Delta\alpha(\hat{\epsilon}, \omega)$ and $\Delta\gamma(\hat{\epsilon}, \omega)$ are the differences between the AC polarizabilities and hyperpolarizabilities of the ground and excited atomic states, respectively. In general, they depend on the light wave frequency ω and polarization $\hat{\epsilon}$. The difference in polarizabilities $\Delta\alpha(\hat{\epsilon}, \omega)$ leads to an AC Stark shift that is dependent on the laser optical intensity at the atom location in the lattice.

Katori *et al* proposed the ^{87}Sr OLC [16] the forbidden $5s^2 \ ^1S_0 \rightarrow 5s \ 5p \ ^3P_0$ ($\lambda_0 = 698 \text{ nm}$) transition with a lifetime of 150s as the clock transition. They addressed the AC Stark shift challenge by means of an engineered light shift trap designed to adjust the dipole polarizabilities for the ground and excited states of the clock transition to set $\Delta\alpha(\hat{\epsilon}, \omega) = 0$. By tuning the lattice laser frequency, they found that the Stark shift coefficient for both ground and excited state is the same at a wavelength $\lambda_L \sim 800\text{nm}$. At that frequency, the same light shifts are generated for the two states, cancelling light field perturbations on the measured spectrum and leaving the atomic resonance frequency unchanged in space [17]. The light-shift cancellation is independent of the laser intensity $I \propto |E|^2$, as long as higher-order corrections $O(E^4)$ are negligible. This wavelength, where the AC Stark shift for the transition frequency is minimized, is called the “magic wavelength,” and the frequency that corresponds to this wavelength is called the “magic frequency”.

The collisional shift in 3D OLCs

The understanding of interactions among lattice-confined atoms played a crucial role in increasing OLC's accuracy. Ensembles of neutral bosonic atoms in sparsely occupied 3D-lattices were considered first [18], since the atomic spacing could be kept at least at half wavelength to reduce the atomic interactions among colliding atoms that result in frequency shifts. In 1998, we developed [19] a many-body theory of the quantum dipole-dipole interaction in 3D-optical lattices, using a Wannier functions representation for deep trapped atoms. We discussed the most important two-body effects, bound-bound (on-site) and bound-free (inter-site) dipole-dipole interactions in optical lattices, concentrating on the case of $J = 1/2 \leftrightarrow J = 3/2$

transitions. We found that the dipole-dipole interaction introduces anisotropy-induced transport & scattering leading to directional hopping processes, where atoms preferentially tunnel along specific lattice axes. The atomic hopping between sites can be accompanied by flipping of the atom spin state, enabling directionally correlated hopping and spin-exchange processes.

To limit in-site atomic interactions in OLCs, clocks of identical ^{87}Sr fermions at ultracold temperature were considered since the Pauli exclusion principle reduces on site interactions suppressing s-wave collisions. The study of the evolution of a system of ^{87}Sr atoms trapped in a deep 3D lattice at the “magic” wavelength when considering dipole-dipole interactions [20] the lattice geometry strongly affects the magnitude of the shift, which can be quite large in lattice configurations where the interactions between atoms add constructively. The magnitude of the shift is also larger for a perfectly filled lattice. For high-density, a band insulating state in a 3D optical lattice was achieved [21] by filling a 3D optical lattice with a nuclear-spin-polarized degenerate Fermi gas of ^{87}Sr , with one atom per site in the ground motional state.

The WS vertical OLCs and the “magic depth”

Horizontal optical lattices on Earth are always under the action of gravity, which causes trapped atom losses. In 2001, we investigated how gravity modifies the energy spectrum of ultracold atoms trapped in a vertical 1D-optical lattice [22], oriented along the z-axis. We model atoms in a sinusoidal optical potential plus a linear gravitational tilt with the effective Hamiltonian:

$$H = p^2/2m + V_0/2 \cos(2k_L z) + mgz, \quad (3)$$

where m is the atomic mass, $k_L = 2\pi/\lambda_L$ is the optical lattice laser wavenumber, g is the local gravitational acceleration, mgz is the gravitational potential, and

$$V_0 = \frac{\hbar\Omega^2}{4(\omega_L - \omega_0)} \quad (4)$$

is the depth of the optical lattice. Ω is the Rabi frequency of the atomic transition of frequency ω_0 used for trapping, and ω_L is the frequency of the optical lattice laser, or magic frequency. Using a Floquet-based representation of Wannier states, this static problem is converted into a time-periodic eigenvalue problem—yielding complex eigenvalues. The periodic Bloch bands develop into a Wannier–Stark (WS) ladder, a structure of discrete energy levels equally spaced by the gravitational potential difference between neighboring sites, whose position is given by the real parts of eigenvalues:

$$E_n = E_0 + n\Delta E, \quad (5)$$

where E_0 is the ground band zero-point energy, n is the lattice site index, $\Delta E = mgd$ is the constant energy spacing induced by gravity, and d is the lattice spacing (usually $d = \lambda/2$). In Fig 2(a) we represent the energy structure in units of the lattice photon recoil energy E_{rec} , for a shallow lattice.

The imaginary part (width) describes the state’s lifetime, which quantifies the atoms tunneling rate out, into continuum states. Through numerical simulations, we demonstrated (a) clear WS ladder structure in deep to intermediate lattice depths, (b) variation of resonance widths with lattice depth, with deeper lattices reducing tunneling and increasing resonance lifetimes, and (c) atomic Bloch oscillations within the lattice with period $T_B = \hbar/mgd$ tied to WS level spacing. By measuring this period, the value of g can be precisely determined, or a known g can be used to measure time. Bloch oscillations function as a reference oscillator, analogous to the quartz crystal in electronic clocks. But perhaps their more important application is their use in vertical OLCs, that confine atoms in vertical lattices where gravity induces WS ladders.

Understanding and controlling WS ladders is essential for atom interferometry, precision gravimetry, and coherent quantum control with optical lattices. It also allows for better minimization of frequency shifts, improving clock stability and reducing the effect of atomic interactions. Aeppli *et al* [23] considered a

many-body system of nuclear spin-polarized fermionic ^{87}Sr atoms in a shallow vertical 1D optical lattice at the strontium magic wavelength $\lambda_L = 813\text{nm}$. They studied and monitored fermionic interactions that are adjustable via spin-orbit coupling by varying the lattice depth and found that the relative strength of the on-site (p-wave) and off-site (s-wave) interactions can be tuned to achieve a zero-density shift at a “magic” lattice depth. The implementation of the WS vertical OLC with precise control of the atomic motional states in the lattice was demonstrated with the JILA Sr1 OLC [24], operating with a fractional frequency uncertainty of 3.5×10^{-19} .

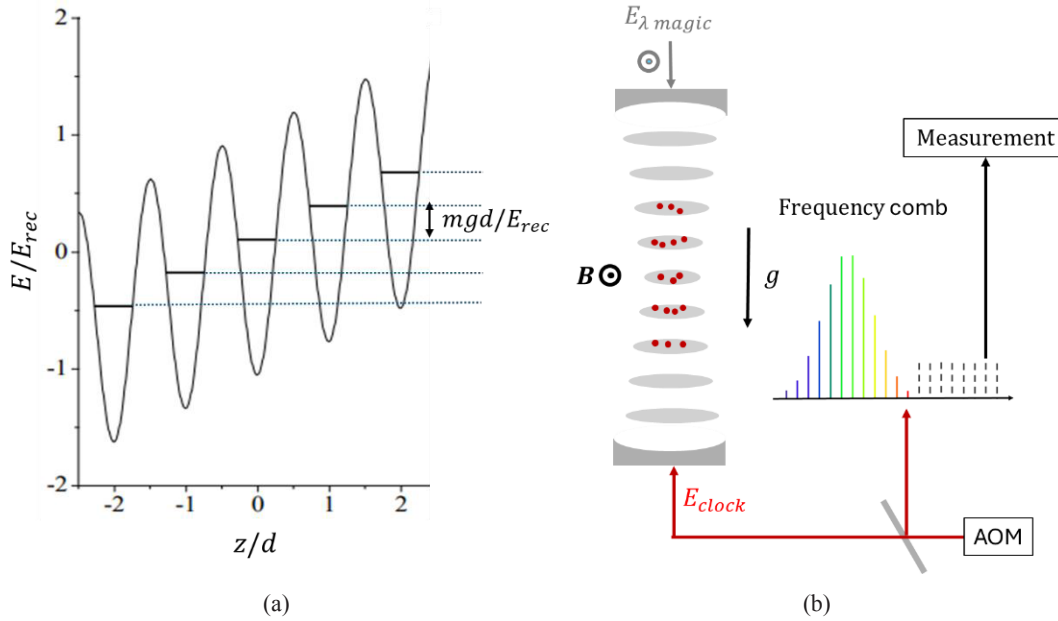


Fig 2. (a) Tilted periodic potential and Wannier-Stark energy ladders in units of E_{rec} as functions of z [22]. (b) Schematic representation of an OLC. A vertical 1-D optical lattice at the magic wavelength and depth traps the atoms at its antinodes. A well stabilized laser probes the clock transition, and the frequency of maximum absorption is locked to a frequency tooth of the frequency comb and related to a RF frequency for measurements.

In Fig 2(b) we show a simplified scheme of a vertical OLC, with atoms trapped in the antinodes of a shallow 1D optical lattice established within an optical cavity oriented along the direction of gravity. The lattice is engineered at the magic lattice wavelength and the magic lattice depth. A very stable laser is tuned across the atomic clock transition. The frequency of highest absorption is locked to a tooth of a laser frequency comb that links the optical frequency to a frequency in the RF range where measurements are performed.

4 On the accuracy and stability of OLCs

The total fractional frequency uncertainty $\Delta\nu/\nu$, describes the overall limit on how precisely the clock's frequency can be known. The BIPM (International Bureau of Weights and Measures) divides the fractional frequency uncertainties into two categories: systematic (u_B) and statistical (u_A) uncertainties. The total fractional frequency uncertainty is typically the root-sum-square of u_A and u_B , and describes the overall limit on how precisely the clock's frequency can be known. The best optical clocks potentially lose less than one second over tens of billions of years, while standard cesium fountain clocks, which are the current basis for global time, are accurate to within a second over tens of millions of years.

Systematic uncertainty

The systematic uncertainty accounts for all non-random, reproducible inaccuracies, such as the frequency shifts of the clock transition caused by laser light: first and second order Zeeman effect [25]: blackbody radiation (BBR): gravity: and ultracold atom collisions between trapped atoms within the same or neighbor lattice sites, or between loosely trapped atoms and background gas atoms [4]. Unlike random noise, each factor is a constant, repeatable known error that shifts the measured frequency in one direction. The clock's accuracy (u_B) is the root-sum-square of all the systematic uncertainties.

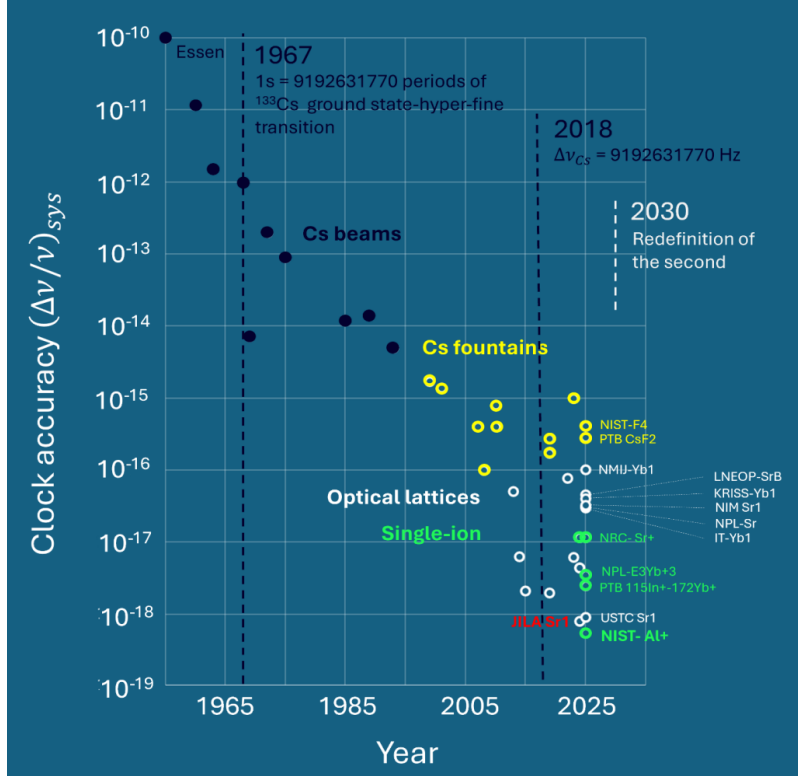


Fig 3. Evolution of clock accuracy (systematic fractional frequency uncertainty u_B) since the birth of atomic clocks. Cs fountain clocks (yellow) increased the clock accuracy obtained with Cs beams (dark blue) in circa two orders of magnitude in this century. Optical lattice clocks (white) and single-ion clocks (green) have increased accuracy in more than two orders of magnitude in the last decade. The most accurate nowadays, JILA Sr1, has been highlighted in red. The BIPM has started the process to achieve a new redefinition of the second in 2030.

The most significant source of uncertainty is due to BBR. Thermal radiation induces an ac Stark shift of the atomic energy levels, conventionally known as Black Body Radiation (BBR) shift. It is the largest contribution to systematic uncertainty for optical lattice clocks (OLCs) based on Yb and Sr at room temperature. The frequency shift due to BBR can be expressed as a function of the temperature of the clock environment as [26]:

$$\Delta\nu_{BBR} = -\frac{\Delta\alpha_s \langle E^2(T) \rangle}{2h} (1 + \eta(T)), \quad (6)$$

where $\Delta\alpha_s$ is the differential static polarizability for the clock transition, $\langle E^2(T) \rangle \propto T^4$ is the mean-squared electric field in a BBR environment, and $\eta(T)$ is a small dynamic correction to the BBR shift. Between the

strategies used to reduce the uncertainty due to BBR shift we can mention: temperature probes to accurately measure the temperature inside the clock chamber of JILA Sr1 [27]; copper thermal shield inside the vacuum chamber to enhance the temperature uniformity of the atomic environment of KRISS – Yb1 [28]; Hidetoshi Katori at RIKEN (Japan) has reach a systematic uncertainty of 7.2×10^{-18} for the Sr-1 cryogenic clock operated at 95K [29]; USTC (China) reported a BBR shift uncertainty of 7.6×10^{-19} , corresponding to an uncertainty of 7.5 mK at atoms' location, by using the finite element method to analyze the thermal radiation within the clock chamber taking in account the geometry and material properties of the components enclosing the atoms [26]. A new design of a cryogenic NIST Yb-OLC utilizes a dynamically actuated radiation shield to BBR that closes by rotation the laser windows once cooling has been performed [20] rejecting external thermal radiation at the part-per-million level during clock spectroscopy. With this procedure the BBR contribution to fractional frequency uncertainty has been reduced to 1.7×10^{-20} , the lowest up to date.

In Fig 3, we show the evolution of clock accuracy (systematic fractional frequency uncertainty u_B) since the birth of atomic clocks. Cs fountain clocks are currently the primary reference clocks but OLCs and single-ion clocks have increased clock accuracy in circa two orders of magnitude in the last decade.

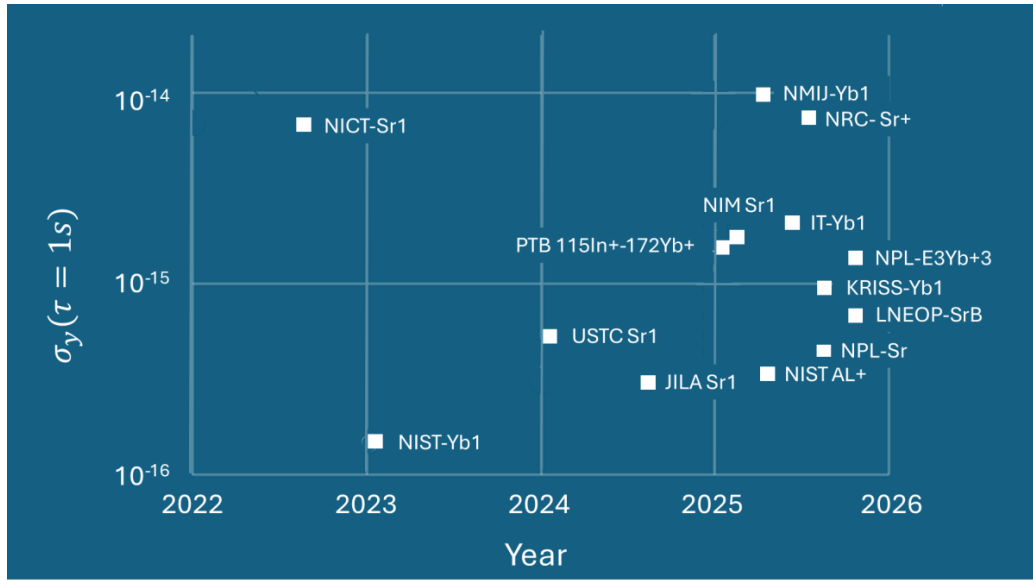


Fig 4. Allan deviation at an averaging time of one second for several OLCs and some single-ion clocks. $\sigma_y(\tau = 1s)$ is the relative root mean square (RMS) frequency instability between two consecutive one-second measurements. A lower value indicates better clock stability over that period.

The lowest uncertainty of any OLC to date has been achieved by JILA with an ^{87}Sr optical lattice clock, whose total systematic uncertainty is 8.1×10^{-19} in fractional frequency units [4]. To reduce the second order Zeeman effect, the clock transition is the ultranarrow $^1S_0 \rightarrow ^3P_0$ transition, more specifically, the least magnetically sensitive transition $^1S_0 m_F = \pm 5/2 \rightarrow ^3P_0 m_F = \pm 3/2$. Atoms are trapped in a vertically oriented, shallow, one-dimensional optical lattice. The optical lattice operates at a “magical” lattice depth ($\sim 15 E_R$) that, as already mentioned, cancels on-site p-wave and off-site s-wave interactions and reduces the density shift caused by p-wave collisions [23]. The shallow lattice also reduces light shifts [24] due to the motional states along the tightly confined direction by ensuring that only the lowest band population is measured. Collisions between trapped strontium atoms and background gas, in this case hydrogen molecules introduce a systematic shift, which is inversely proportional to the vacuum lifetime.

However, as shown in Fig 3, the record of precision until now was achieved with a single $^{27}\text{Al}^+$ ion optical clock [29] with fractional frequency uncertainty of 5.5×10^{-19} and fractional frequency stability (Fig 4) of $5 \times 10^{-16}/\sqrt{\tau/s}$.

Gravitational Red Shift

The gravitational red shift after Eq (1) depends on both the value of the local gravity g and the height h of the reference clock. To reduce the gravitational red shift locally, an appropriate accurate determination of the gravity field at the clock location is needed, which requires high-accuracy position measurement systems like Differential GPS (DGPS) or advanced Global Navigation Satellite Systems (GNSS). Or the other way around, accurate atomic clocks can be used as gravimeters.

Statistical Uncertainty

The statistical uncertainty (u_A) is a measurement of the frequency stability of the clock transition over the measurement period and is evaluated by the statistical analysis of repeated measurements over certain period. It accounts for the inherent instability and the statistical noise of the clock and is calculated as the Allan deviation $\sigma_y(\tau)$, divided by the square root of the number of independent measurements, $u_A = \sigma_y(\tau)/\sqrt{N}$. When considering the total averaging time τ , and a measuring time τ_0 , the Allen deviation can be written as $\sigma_y(\tau) \approx \sigma_y(\tau_0)/\sqrt{\tau/\tau_0}$. As the averaging time τ increases, the Allan deviation (statistical noise) decreases, ideally reaching a point where it is significantly lower than the systematic uncertainty. The variation of the slope of the Allan deviation log-log plot helps identify the dominant noise sources at different time scales. White noise, which is the dominant noise for most of the OLC's clocks, has a slope of $-1/2$, i.e., $\sigma_y(\tau) = \sigma_y(\tau = 1s)/\sqrt{\tau}$. In Fig 4 we compare Allan deviation values at an averaging time of one second for several OLCs and single-ion clocks.

5 Towards the redefinition of the second

The BIPM opens in 2026, the process towards redefining the second in 2030. There are mandatory criteria [30] to be fulfilled by an optical frequency standard that had not reached the appropriate fulfilment level as of 2022. Besides accuracy budgets and their validation, atomic clocks should perform regular contributions to TAI, demonstrate availability for sustainable techniques for clock comparison with adequate knowledge of the local geopotential, and accessibility to the realization of the new definition. The TAI (International Atomic Time) is calculated monthly by the International Bureau of Weights and Measures (BIPM) by first taking the weighted average of more than 400 atomic clocks located in approximately eighty metrology laboratories worldwide. This average is checked against frequency standards from a pre-approved list. Most are cesium microwave standards, but in recent years the contribution of optical standards has increased.

The optical clocks that have been accepted to perform regular contributions to TAI are listed in Table 1. They include trapped ion optical clocks that work with single ions trapped by electric fields within a vacuum.

The two LNEOP Sr clocks have two different OL cavities. SrB works with $\sim 10^3$ atoms trapped in an OL created by an L shaped cavity with pure linear polarization, while Sr2 works with $\sim 10^4$ atoms trapped in an OL within a linear shaped cavity with smaller waist. Both work in the Lamb Dicke regime with a large trap depth (~ 100 ER) at the magic wavelength.

Recently a multi-ion 1D chain, a Coulomb crystal clock based on $^{115}\text{In}^+ - ^{172}\text{Yb}^+$ ion chains reached a systematic uncertainty of 2.5×10^{-18} and an instability of $1.6 \times 10^{-15}/\sqrt{\tau/s}$ for operation with a chain of one In^+ and 3 Yb^+ [36]. A reduction of the instability to $9.2 \times 10^{-16}/\sqrt{\tau}$ was achieved when operating with four $^{115}\text{In}^+$ clock ions.

Table 1. Optical clocks that have been accepted as secondary standards by BIPM and perform regular contributions to TAI. Data were obtained at https://webtai.bipm.org/ftp/pub/tai/data/PSFS_reports, except for specific bibliographic citations. (*) We included the data of the JILA-Sr1, which holds the OLC's record for minimum frequency uncertainty and larger long-time stability, but is not included between the clocks that make regular contributions to BIPM.

Optical Clock	Atom/ion	Frequency Evaluation Period	Clock accuracy (u_B) ($\times 10^{-17}$)	$\sigma_y \sqrt{\tau(sec)}$ ($\times 10^{-16}$)	Uptime	Country
LNEOP-SrB	^{87}Sr	10/31-11/25/25	4.6	7	>80%	France
LNE-SYRTE-Sr2	^{87}Sr	12/21/22-1/15/23	3.8	10	86.1%	France
NRC-Sr+1	$^{88}\text{Sr}+$	11/20-11/25/25	1.17	38		Canada
NPL-E3Yb ⁺³	$^{171}\text{Yb}+$	9/26-10/21/25	0.35	15	94.18%	UK
NPL-Sr1	^{87}Sr	7/3-7/28/25	3.13	4.5	71.7%	UK
NMIJ-Yb1	^{171}Yb	28/07-2/08/25	10.2	100	80.9%	Japan
NIST-Yb1	^{171}Yb	30/1-24/23	0.62	1.5	4.7%	USA
NIM-Sr1	^{87}Sr	29/1-28/2/25	3.3	18	20.4%	China
NICT-Sr1	^{87}Sr	7/29 -8/28/22	7.8	70 [33]	2.7%	Japan
KRISS-Yb1	^{171}Yb	7/28-8/22/25	4.1	7.9	78.7%	Korea
IT-Yb1	^{171}Yb	6/3-6/26/25	3	20 [34]	34.7%	Italy
NIST Sr1*	^{87}Sr		0.08	0.48 [35]		USA

Continuous operation

The reliability of optical lattice clocks demands the reduction of dead time and the possibility of continuous work for long spans of time. The uptime for the OLCs and single-ion atomic clocks has been included in Table 1. The LNE strontium optical lattice clock spans several weeks, with more than 80% uptime [37]. But the leading uptime is held by UK with the single-ion NPL-E3Yb⁺³ clock.

Efficient atom replenishment in optical lattice clocks is essential for enhancing duty cycle, stability, and long-term operation. Recent advancements have introduced several methods to address atomic losses and extend continuous operation. For example, the JILA Sr and NIST Yb clocks employ sequential reloading from a magneto-optical trap (MOT), where atoms are transferred into the optical lattice, interrogated, and then the lattice is reloaded. However, this approach introduces significant dead time. To mitigate this, alternative strategies are under development, such as quantum non-demolition (QND) measurements for non-destructive state detection—allowing atoms to remain trapped for subsequent cycles—and dual-ensemble systems, where two independent lattices alternate between loading and interrogation phases. Additionally, JILA has pioneered hybrid tweezer–lattice architectures, enabling atoms to be loaded into optical tweezers before transfer to the lattice for interrogation. This last innovation has demonstrated coherence times of several seconds and represents significant progress toward scalable arrays for advanced metrology and quantum control.

In SYRTE Sr systems, atoms are accumulated in a long-lived metastable state over several seconds before being pumped into the lattice. RIKEN OLCs and PTB Sr clocks employ continuous or interleaved loading, utilizing moving optical lattices as "optical conveyor belts" to deliver atoms while interrogation occurs in separate regions or time windows. They also aim a different approach, sustaining a continuous cold atomic beam for efficient lattice loading. We developed a theoretical framework for a coherent atomic-beam generator [38], or "atom laser," that could serve this purpose. In our scheme, a damped gas of cold bosons confined by a two-dimensional potential and quantized motion in a one-dimensional Fabry-Perot cavity undergoes a transition to Poissonian statistics, achieving a lasing mode, i.e., generating a coherent beam of cold atoms propagating at a specific velocity.

Availability of sustainable techniques for Optical Frequency Standards comparisons

A mandatory criterion in the roadmap towards the redefinition of the second is the validation of optical clock uncertainties through the comparison of both local systems and systems developed independently in different laboratories around the world. Inter-comparisons between optical clocks in several European laboratories have been performed in the European project Robust Optical Clocks for International Timescales (ROCIT) [39], whose overall objective was to bring European optical clocks to contribute regularly to TAI as secondary frequency standards. The project involved (i) the Sr and Hg clocks at LNE in Paris; Yb clock at INRIM, Italy; the Sr, Sr⁺ and Yb⁺ at PTB and the In⁺ at LUH, Germany, linked via optical fiber. (ii) the Sr and Yb⁺ clocks at NPL in UK linked via GNSS to two Sr OLCs at UMK, Poland, to the 88Sr⁺ optical clock VTT MIKES at the Finnish national metrology institute, and to the NMIJ-Yb1 clock in Japan [40]. LNE-SYRTE-Sr2, NPL and PTB were all able to demonstrate unattended optical clock operation with uptimes exceeding 80 % over 2 weeks for at least one of their optical clocks.

6 Applications of OLCs in high precision measurements

More than a decade ago Katori [41] envisioned the large applications of OLCs on quantum metrology, testing laws of physics and developing relativistic geodesy. OLCs are not only candidates as primary frequency standards for redefining the SI second in the next future but have opened the possibility of highly accurate time measurement for diverse applications.

Atomic clocks and fundamental physics

Ye and Zoller [42] wrote recently an essay with their vision of the future on highly precise and accurate quantum-enabled sensing allowing to explore connections between quantum physics and general relativity. OLCs, as quantum objects in the curved spacetime, enable the study of those connections. The internal energy difference $\hbar\omega_0$ between excited $|e\rangle$ and ground $|g\rangle$ states of the clock transition is shifted by a gravitational redshift (GRS) (or gravitational time dilation) dependent on the n-index of the WS-ladder state E_n (see Eq 5):

$$\Delta E_n = \frac{\hbar\omega_0}{c^2} + gd n. \quad (6)$$

This GRS introduces a linear frequency gradient across the OL, that has been measured within a single millimetre-scale sample of ultracold strontium [43], heralding the need of considering intra-lattice corrections for gravitational perturbations. The sample consisted of a shallow 1D optical lattice, with approximately 100,000 87 Sr atoms at about 100 nK, with its longitudinal axis oriented along gravity.

The second-order Doppler effect (SDS) (motional time dilation in special relativity) leads to a local modification of the zero-point energy:

$$\Delta E_0 = -\frac{\hbar\omega_0}{2Mc^2} E_0. \quad (7)$$

If both GRS and SDS shifts are simultaneously observed in the same system [44], the total energy shift can be translated by mass-energy equivalence into a difference in the rest mass of the atom in the excited and ground states, $M_e = M_g + \hbar\omega_0/c^2$.

The search for dark matter

Networks of initially synchronized atomic clocks will become desynchronized during the encounter with an extended dark-matter object [45]. Topological defects in encounters with the Earth can lead to temporary shifts in the frequencies and phases of measuring devices, and hence to discrepancies between spatially separated clocks. These discrepancies are expected to exhibit a distinct signature of the structure of the dark-matter object and its interaction strength with atoms.

Some models postulate dark matter composed of ultralight bosonic particles that cause apparent oscillations in the fundamental constants. Atomic clock frequency ratios are sensitive to changes in fundamental constants and thus well suited to study this class of dark-matter models. The frequency ratios of a network of optical clocks based on $^{27}\text{Al}^+$ [29], ^{87}Sr [43] and ^{171}Yb [32] were measured [46] and improved constraints on the potential coupling of ultralight bosonic dark matter to standard model fields were derived.

Search for gravitational waves

Two spatially separated satellites with two synchronized OLCs serving as narrowband detectors of the local frequency of a shared laser light constitute a space-based gravitational wave (GW) detector [47]. A passing GW induces periodic changes in the light travel time between emitter and detector. Synchronous clock comparisons allow detection of GWs via the effective Doppler shift of the shared laser light.

The proposal for "SAGE: A Space Atomic Gravity Explorer" based in this idea [48], was selected by the European Space Agency (ESA) for a feasibility study, but not a fully funded/launched mission. Its objective was to investigate gravitational waves, dark matter, and other fundamental aspects gravity using optical atomic clocks and cold atom interferometry.

Temporal variations of fundamental constants

The foundations of physics and atomic clocks implicitly assume the time- and space-invariance of fundamental constants. By comparing two different kinds of atomic clocks, the temporal stability of the fine structure constant α can be tested. Limits of yearly drifts of α have been established by comparisons of ^{87}Sr -OLC frequency with $^{199}\text{Hg}^+$, $^{171}\text{Yb}^+$ and H data [49]. NIST measurements of the frequency ratio of the Al^+ and Hg^+ optical clocks over a year [50] constrain the temporal variation of α to $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}/\text{yr}$.

The Local Position Invariance (LPI) predicts that the GRS is independent of the atomic species involved in the clock and depends only on the change of the gravitational potential ΔU (see Eq 1). Given two clock frequencies ν_1 and ν_2 , a parameter α_{LPI} used to LPI tests is introduced by:

$$\frac{\nu_2 - \nu_1}{\nu_1} = (1 + \alpha_{LPI}) \frac{\Delta U}{c^2} \quad (10)$$

The gravitational potential on the earth surface changes annually due to the elliptical orbit of the earth around the Sun. Hence, a frequency comparison between two different atomic clocks spanning more than one year established a limit of $\alpha_{LPI} = 2.1 \times 10^{-5}$ to LPI violation [51].

Building networks of atomic clocks

The route towards the redefinition of the second as well as tests of fundamental physics, distributed coherent sensing, and geodesy will require large-scale free-space networks connecting ground-based optical clocks and future space-based optical clocks. Optical attosecond time transfer over distances of 300 km and link losses of 102 dB have already been demonstrated [52]. A quantum network of atomic clocks at different geographical locations, using nonlocal entangled states combined with quantum communication techniques, could guarantee security both from internal and external threats [53]. In the scheme, each clock keeps the time by interrogating its qubits periodically and allocates some of its qubits to form entangled states stretching across all nodes of the network.

Katori's group [54] reported measurements of the GRS between RIKEN and The University of Tokyo [55] and at Tokyo Skytree [56] using transportable ^{87}Sr – OLCs. The transportable clock consists of a physics package that includes an ultra-high vacuum chamber in which the clock spectroscopy is performed. The physics package is linked via optical fibers to two laser boxes containing the lasers for cooling, trapping, generating the OL, and performing spectroscopy. From the comparison of two portable OLCs at the Tokyo Skytree ($\Delta h = 450$ m) they obtained $\alpha_{LPI} = (1.4 \pm 9.1) \times 10^{-5}$.

The International Collaboration on Clocks and Oscillators (ICON) network [57] brings together premier metrology laboratories—including NIST, JILA, PTB, RIKEN, SYRTE, and NPL—that operate state-of-the-art optical lattice and ion clocks. ICON's core initiatives encompass global optical clock comparisons, advanced frequency transfer via optical fiber and satellite links, development of transportable optical clocks, and collaborative research in fundamental physics, including tests of relativity, investigations into variations of fundamental constants, and geodetic applications utilizing relativistic redshift. For clock comparisons, ICON uses portable optical clocks in Japan and Europe, whose reproducibility after transport between countries was sufficient to determine geopotential height offsets of 4cm.

Geodesy

OLCs are a precise tool for measuring geopotentials. A worldwide network of transportable OLCs would enable real-time monitoring of dynamic changes of geopotentials at the centimeter level caused by seismic or volcanic activity, opening new applications in geophysics [54]. OLCs change their ticking pace when their height varies in a few centimeters and hence are bringing changes in geodesy methods by involving relativistic concepts of space-time in our daily experience on Earth.

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Ángela Guzmán

Ángela Guzmán is Professor Emerita and a distinguished alumna of the Department of Physics at the National University of Colombia. She holds a Ph D in Physics from Ludwig Maximilian University in Munich, Germany, and an Honorary Doctorate in Education from Khachatur Abovyan Pedagogical University in Yerevan, Armenia. In 1989, she was elected an associate member of the Abdus Salam International Centre for Theoretical Physics in Trieste and was promoted to senior associate member in 1998. She is a Fellow of OPTICA in recognition of her contributions to quantum and atomic optics and her efforts to promote optics in developing countries. From 2008 to 2017, she served as Secretary General of the International Commission for Optics, chaired the Trieste System Advisory Group on Optical Sciences and Applications (TSOSA), and coordinated the UNESCO Workshop on Active Learning in Optics and Photonics (ALOP) in Latin America. She also served as a Science Officer for the International Science Council's Regional Office for Latin America and the Caribbean. She is a full member of the Colombian Academy of Exact, Physical, and Natural Sciences, and currently serves as President of the Colombian Optical Society and Vice-President of the Colombian Network of Women Scientists.