Illustration by Phil Saunders/spacechannel.org

Optical Lattice Clocks

Christopher W. Oates and Andrew D. Ludlow

A new breed of atomic clock—the “ticking” of which comes from transitions in thousands to millions of cooled atoms, trapped in optical standing waves created by tightly focused lasers—is pushing scientific timekeeping to previously unknown frontiers of precision.

Time, though philosophically hard to grasp, can be measured far more precisely than any other physical quantity—a characteristic that has driven both new technologies and the development of basic science. Since the mid-20th-century, atomic clocks, harnessing the well-defined oscillation of electrons bound to an atom, have emerged as the gold standard for precision measurement of time and its inverse, frequency. Yet, notwithstanding dramatic improvements in atomic clocks, today's best workhorse models—based on transitions in the microwave domain for rubidium and cesium atoms—are running up against fundamental limits to accuracy, at around one part in 10^{16}. And that raises the question: Where will the next milestones in precision timekeeping come from?

The leap in performance promised by optical lattice clocks could drive new tests of fundamental physics, aid in the search for dark matter, and even prompt a possible redefinition of our unit of time, the SI second.

The answer likely lies in new clocks based on atomic transitions in the optical domain, which have already advanced performance well beyond that of atomic clocks operating in the microwave range. And in the past several years, a new type of optical atomic clock, the optical lattice clock, has pushed performance into new frontiers, with instabilities approaching one part in 10^{18} and uncertainties not far behind.

The leap in performance promised by these clocks could drive new tests of fundamental physics, aid in the search for dark matter, and even prompt a possible redefinition of our unit of time, the SI second (currently pegged to the ground-state hyperfine transition in cesium-133). Realizing that promise will require overcoming some interesting technical challenges to move these remarkable instruments from the lab into real-world applications.

The optical clock advantage

The advantages of optical clocks over conventional microwave rubidium and cesium atomic clocks, operating in the GHz range, stem from the much higher frequencies accessible in the optical domain. All else being equal, the instability of an atomic clock varies inversely with the transition frequency—and optical clocks have governing frequencies as much as 10^5 higher than microwave clocks. In principle, the higher stability, by allowing more precise measurements of systematic shifts, can also reduce uncertainty, the other key parameter in measuring clock performance (see sidebar on facing page).

Despite these inherent advantages, the first optical clocks didn't come on the scene until 2001, with the coalescing of several key technologies—laser cooling and trapping techniques, Hz-level laser stabilization, and the creation of broadband, mode-locked, fs laser frequency combs. The first optical clocks were based either on single, trapped ions or on ensembles of millions of laser-cooled neutral atoms. Each variety faced limitations, however: measurements with the former, being based on a single quantum particle, offered a limited signal-to-noise ratio; measurements with the latter, while benefiting from the large number of atoms—analogous to averaging millions of individual clocks simultaneously—was compromised by residual Doppler effects, because the atoms were cooled, but not trapped.

Lattice clocks strive to combine the best aspects of both systems, by confining large numbers of neutral atoms in the trap of an optical lattice, a standing wave of light formed by tightly focused laser beams. The lattice holds the atoms for more than one second (an extremely long period on the atomic timescale), which enables measurement of the electronic "tick" with ultrahigh resolution. And, though the atoms trapped in the lattice still move around, their net motion is zero, which greatly reduces atomic-motion effects, such as the Doppler effect, during a measurement.

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Finding the right timekeeper

Creating an optical lattice clock requires finding the right neutral atom to act as the timekeeper. Neutral atoms, lacking a net charge, can't be confined without significantly perturbing their electronic states and, in principle, the transitions between them. An intense laser beam can distort a bound electron, giving the atom an induced dipole moment—a "handle" with which to hold the atoms—but such an act significantly shifts the atoms' energy levels, the very thing being measured in an atomic clock. The solution to this dilemma lay in trapping suitably chosen atoms in such a way that their relevant electronic states experience large but identical energy level shifts, so that a sharp transition between those states is virtually free from shifts due to the trap potential.

A good candidate atom is the two-valance-electron element strontium. Two-electron atoms have a singlet-triplet electronic structure that offers both strong transitions that are convenient for manipulating the atoms with lasers and weak transitions that are ideal for clock references. The narrow-linewidth clock transitions are between states with very long lifetimes (more than 10 seconds) and with very little dependence on the lattice laser polarization (a notoriously difficult quantity to control experimentally). When the wavelength of the lattice laser is tuned to a so-called magic value, the ground and excited states of the clock transition are equally shifted, which leaves the ticking rate of the clock insensitive to the presence of the trap itself.

The first lattice clock, based on strontium, was demonstrated in 2003 at the University of Tokyo. Other strontium clocks followed soon after at JILA in Boulder, Colo., USA, and at Systèmes de Référence Temps-Espace (SYRTE) in Paris, France, along with a demonstration at the U.S. National Institute of Standards and Technology (NIST) in Boulder of an optical lattice clock based on the rare-earth element ytterbium. More recently, progress has also been made exploring lattice clocks using mercury and magnesium. More than 20 lattice clocks are now under development worldwide, with still more in the planning stages.

Setting the (atom) trap

All lattice clocks share a number of key features, starting with the overall design of the optical lattice trap. Optical lattices can be formed in one, two or three dimensions; for the widely used 1-D version, the lattice is formed by focusing roughly one watt of laser light to a "waist" of size 50-100 µm, and then retroreflecting the light back onto itself to create a standing-wave pattern. The depth of each energy well where the atoms are trapped is roughly tens of microkelvins, expressed in temperature units. At these values, the lattice cannot confine fast-moving atoms, and so the atoms must be cooled before trapping. Most existing lattice clocks use two stages of laser cooling and trapping: one to accumulate large numbers of atoms rapidly, and the other to cool them below the lattice trap depth.

The clock transition can't be measured during the cooling, or while the atoms are being loaded into the lattice. And, of course, the atoms trapped in the lattice do not stay there forever, but are instead ejected after a few seconds due to collisions with the few room

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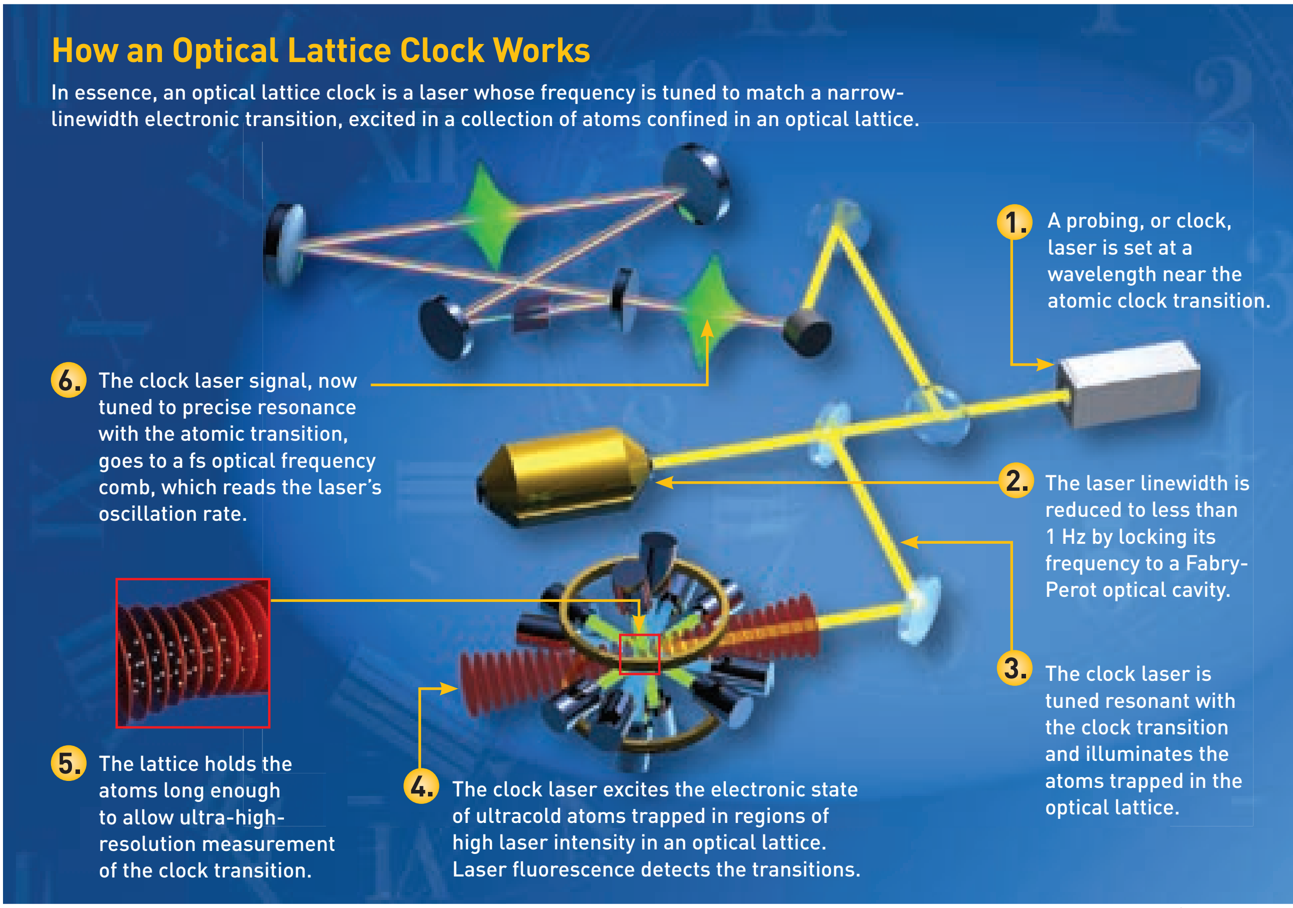
Measuring clock performance

Any clock consists essentially of an oscillator—something that "ticks," from the rotation of the Earth to a quartz crystal to individual atomic transitions—and some type of counter incremented by the ticks. Deviations of the clock's performance from the theoretical ideal are usually measured using two parameters:

Instability. Instability is a measure of variations in the length of the ticks themselves; thus instability relates directly to measurement precision. Mathematically, the fundamental limit to an atomic clock's instability, σ, is given by $\sigma \sim \Delta\upsilon/[\upsilon_0\,(N\tau)^{0.5}]$, where $\Delta\upsilon$ is the measured atomic transition linewidth, υ_0 is transition frequency, τ is the averaging time, and N is the number of atoms in the atomic sample. Thus a high transition frequency, a large number of individual "ticking" atoms, a long averaging time, and a narrow transition linewidth all serve to lower clock instability and increase theoretical clock precision. All of these attributes are present in optical lattice clocks—indeed, these clocks have already demonstrated instabilities about 100 times lower than that of their microwave counterparts, and have still not reached their quantum limits.

Uncertainty. This parameter measures systematic differences or shifts between the underlying ticking rate and the actual desired value, given by the unperturbed frequency difference between the energy levels of the clock transition. Thus, whereas a clock's stability largely determines its precision, uncertainty defines the clock's accuracy. Reducing clock uncertainties, by tweaking system and environmental variables, is one important challenge in clock studies (see main text).



Infographic by Phil Saunders/spacechannel.org

temperature particles left in the ultrahigh vacuum where the lattice is located. Thus optical lattice clocks operate with a repeated measurement cycle. The cycle commences with a period as short as 50 ms, during

For the first time, an atomic clock can measure to a precision of nearly one part in 10^{18}. That's equivalent to one second across the age of the Universe.

which about one million atoms from a laser-slowed atomic beam are loaded into a magneto-optic trap (MOT) based on a strong transition.

For strontium and ytterbium clocks, there follows a second-stage MOT based on a weaker transition, which reduces the atomic temperature from a few millikelvins to the microkelvin regime, below the lattice trap depth. During this second stage, a fraction of the atoms accumulate in the potential wells of the optical lattice (typically 10 to 20 atoms per well in a 1-D lattice). The trapped atoms are loosely bound in the two transverse directions, and are tightly confined (to less than a wavelength of light) in the direction of lattice laser propagation, which allows for measurement free of Doppler shifts.

Measuring the clock transition

Once the atom "clocks" are in place, the next step is measuring their natural ticking rate. A probing laser, tuned to be near-resonant with the clock transition, illuminates the trapped atoms with a pulse typically lasting several hundred milliseconds, placing some of the atoms in the excited state. Laser fluorescence techniques then precisely measure the fraction of atoms excited, and the fluorescence signal in turn allows the laser frequency to be iteratively tuned into exact resonance with the electronic transition. This measurement cycle is repeated indefinitely one or more times a second.

The narrower the transition linewidth, the more sensitively the laser frequency can be monitored and adjusted to stay in exact resonance with the atoms. Unfortunately, a typical single-mode laser has a linewidth thousands or millions of times broader than the sub-Hz linewidth of an optical atomic clock transition; hence the clock laser must be extensively pre-stabilized to generate spectral features near or below the Hz level. The solution lies in locking the clock laser frequency to a narrow resonance of a Fabry-Perot optical cavity, which consists of two high reflectivity mirrors separated by a glass spacer. Such cavities provide high-signal-to-noise, high-bandwidth feedback signals ideal for laser narrowing. However, the cavities are physical objects prone to mechanical instability, and reducing those problems—through low-expansion materials, vibration isolation, and other techniques—is a very active subfield of optical clock research.

At NIST we have observed atomic spectral features in ytterbium with linewidths as narrow as 1 Hz, corresponding to a line quality factor of more than 5×10^{14}. The frequency of the clock laser is stabilized to the atomic transition on timescales longer than a few seconds. By comparing the frequency output from two similar optical clocks, it's possible to measure the clock rate stability, which determines the precision of the clock. And the stability of these clocks has indeed advanced enormously in the past two years: multiple lattice clock systems now have achieved unprecedented levels of stability on both short (around 3 s) and long (30,000 s) timescales. For the first time, an atomic clock can measure to a precision of nearly one part in 10^{18}. That's equivalent to one second across the age of the Universe.

Reducing clock uncertainty

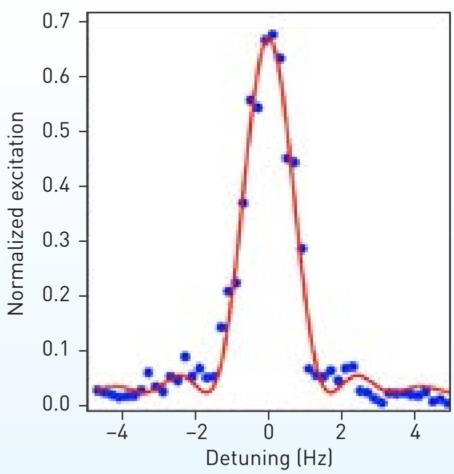
While exceptional clock stability can lead to exceptional precision, we also need to know that the clock rate itself is accurate. That involves understanding a second parameter, the systematic uncertainty of the atomic clock frequency. And determining that uncertainty—which requires a thorough investigation of all physical effects that can shift the clock frequency—can be exhausting work.

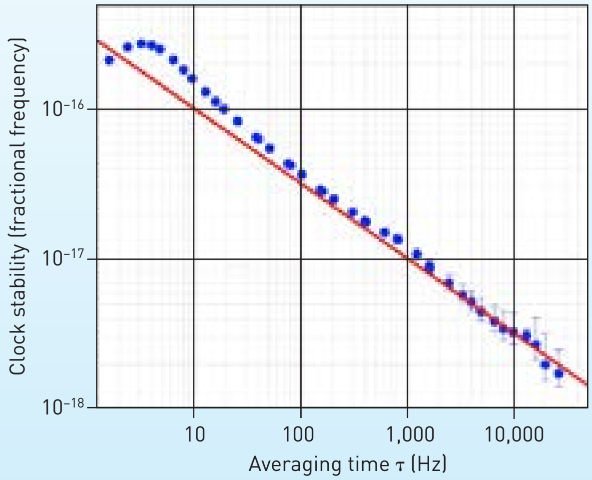
For lattice clocks, frequency shifts can arise from a number of important sources:

Atom-atom interactions.

When ultracold, lattice-trapped atoms interact or collide with each other, their electronic states can be perturbed, leading to a shift in the clock frequency. This was an important concern early in the development of the optical lattice clock, since these systems use large numbers of atoms. Fortunately, the effect can be reduced through the use of atomic isotopes which are fermions: at ultracold temperatures, quantum statistics dictate that identical fermions have suppressed collisions, and thus reduced interaction shifts. Tweaking the details of the lattice

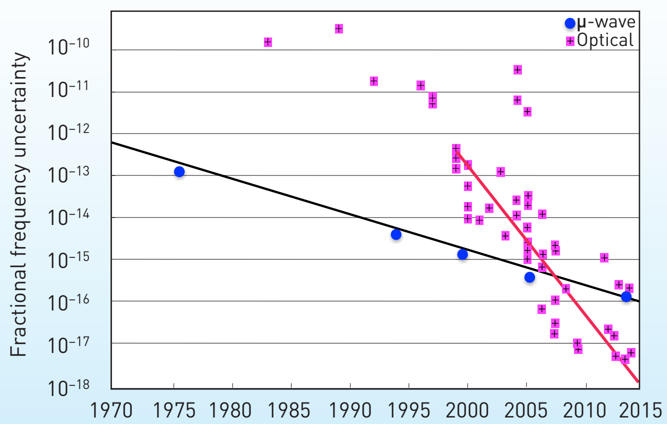
INCREASING PRECISION AND STABILITY





A normalized fluorescence signal from an ytterbium optical lattice clock (top) shows linewidth approaching 1 Hz. These narrow optical linewidths have allowed the lattice clock's stability and precision (bottom) to far exceed that of traditional atomic clocks, approaching the unprecedented level of one part in 10^{18}. Blue dots are data; red line in lower diagram gives the stability asymptote $3.2 \times 10^{-18}/\tau^{0.5}$.

TAMING UNCERTAINTY



Over the past decade, optical clocks have reduced atomic clock uncertainty by almost two orders of magnitude, putting them well ahead of state-of-the-art microwave atomic clocks.

confinement and atom excitation leads to shifts that are manageable in size.

Lattice field shifts.

Residual lattice light shifts represent another fundamental concern. Thus far, addressing those shifts has been straightforward, involving simply changing the intensity and wavelength of the lattice light and measuring the resultant shifts. This approach lets us take advantage of the high clock stability to determine the magic

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wavelength (and higher-order effects) to the desired precision. As we push the precision further than the current one-in-10^{18}, it may be necessary to take into account still more subtle effects in the lattice fields.

Blackbody radiation.

A more formidable problem arises from radiation emitted by the ambient environment that surrounds the trapped atoms. These mainly infrared photons interact weakly with the clock energy levels, thereby shifting the clock frequency fractionally by parts in 10^{15} at room temperature.

Minimizing this shift uncertainty requires an accurate knowledge of both the atomic response to blackbody radiation and the temperature environment seen by the atoms. Atomic blackbody response coefficients are now sufficiently well understood that lattice clock researchers have been able to focus much effort lately on characterizing the blackbody field, and on taking steps to address it. Groups in Germany and Japan have constructed mini-chambers into which strontium atoms can be transported; these chambers can themselves be cooled to cryogenic temperatures (<100K) at which the blackbody shift is reduced by a factor of one hundred. A group at JILA has used a high-precision temperature probe, situated near the lattice-trapped atoms, to sample the radiative environment experienced by the atoms. And our group at NIST has constructed a room temperature chamber that surrounds the atoms throughout the entire experimental cycle. The chamber has exceptional temperature uniformity, and multiple precision temperature sensors can measure the absolute temperature at the 5 mK level.

All three approaches have enabled significant reduction of the blackbody shift uncertainty, some now reaching one part in 10^{18}. With these important systematic shifts under control, two lattice clock systems have reported total uncertainties below one part in 10^{17}, with other groups poised to follow. A Japanese group recently found a fractional relative agreement between two clocks of less than 2×10^{-18}, an order of magnitude better than any previous clock comparison.

Moving to practical applications

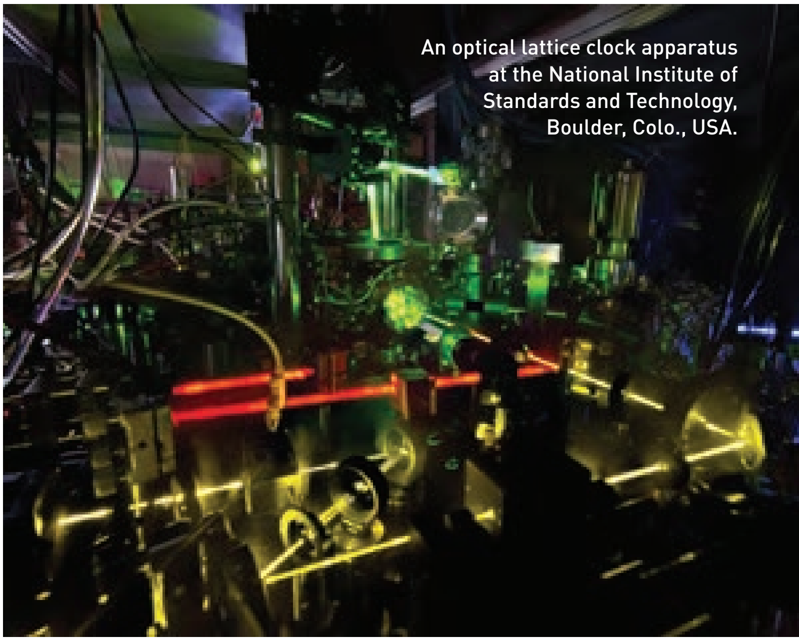
Looking ahead, clock researchers will obviously continue to push forward reductions in clock instabilities and uncertainties, to move lattice clock precision toward the previously unthinkable 19^{th} digit. But the field of optical clocks, both ion- and optical-lattice-based sytems, has reached a point where it makes sense to be thinking beyond the lab, and toward real-world applications. And already, considerable plans are under way to transform optical clock systems—at present still mainly complicated laboratory research projects—into carefully engineered, robust instruments for advanced timekeeping, for both technology and basic science.

Traditional atomic clocks already play a significant role in many key technologies, such as global positioning systems, advanced communications and networks, synchronization, and radio telescopy. As optical clocks, which operate with orders of magnitude higher performance, mature, it is likely that similar applications will benefit. Additionally, deep space navigation and photonically generated low-noise electronic signals can also capitalize on this level of optical timekeeping and related technologies.

While historically the most exciting applications for new clock systems have typically followed many decades after initial demonstrations, optical clocks have already made important contributions to tests of fundamental physics, using their unprecedented precision to set reduced limits on the possible drift of the fine-structure constant, α, and on the size of a possible coupling between gravity and fundamental constants. In fact, connections between the measurement of time and gravitational fields are quite deep and could have important implications for future optical atomic clock research.

In particular, gravitational fields shift clock frequencies via the gravitational redshift predicted by general relativity. That relationship is a double-edged sword: It means that clock redshifts could be used to measure fluctuations in gravitational potentials and to detect gravitational waves through measurements within a network of optical clocks. But it also has serious implications for building future atomic clocks on Earth, since a change in altitude of only one centimeter leads to a fractional clock shift due to the change in the gravitational field of one part in 10^{18}.

The high sensitivity of optical clocks makes this effect important for even small changes in elevation, and future earth-based clocks will have to account for fluctuations in Earth's gravitational field due to tidal and other forces, which could lead to relativistic clock shifts of more than 1 part in 10^{17}. A timekeeper's dream would be to put an optical clock into the microgravity of space, and such a clock has indeed been proposed for precision tests of fundamental physics. Perhaps, one day, a space-based "master clock," circling the earth on the International Space Station, will beam down precision timing signals for use in a range of applications.


An optical lattice clock apparatus at the National Institute of Standards and Technology, Boulder, Colo., USA.

Nate Phillips, NIST

Meanwhile, here on Earth, the maturing of optical clocks raises the task of considering a redefinition of the basic unit of time, the SI second, in terms of one (or more) of these optical timekeepers. Many groups are now carefully calibrating optical clocks, based on lattices or trapped ions, against themselves and the existing cesium primary standards to guarantee consistency, should such a redefinition eventually occur. OPN

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