

Transportable atomic clocks achieve laboratory precision

When deployed in field-based experiments, the devices could improve timekeeping standards and test fundamental physics.

The 1967 General Conference on Weights and Measures defined the SI unit of time, the second, based on an atomic transition—specifically, between two hyperfine levels of the ground state of cesium-133. (See *PHYSICS TODAY*, August 1968, page 60.) Although Cs atomic clocks remain the standard, their time might be running out. Their underlying atomic transition is excited by radiation with a microwave frequency around 9×10^9 Hz, and after decades of advances, a Cs clock's frequency can be measured with a fractional uncertainty $\Delta\nu/\nu_0$ of about one part in 10^{16} .

But clocks based on optical transitions operate at frequencies around 10^{14} Hz, which gives them an advantage in the push for lower uncertainty. (See the article by James Bergquist, Steven Jefferts, and David Wineland, *PHYSICS TODAY*, March 2001, page 37.) The current record, 9.4×10^{-19} , was set in 2019 by an aluminum ion-based optical atomic clock at NIST.

In some applications, optical clocks can't yet provide any practical benefit over their microwave counterparts.¹ For example, atomic clocks around the world are regularly compared with each other to maintain International Atomic Time. Those comparisons are done via satellite intermediaries, but the clocks on those satellites use microwave transitions, so even if the Earth-based laboratory clocks were more precise, their comparisons

wouldn't be. The comparisons also rely on precise geodetic measurements that can be difficult and time-consuming to obtain. According to general relativity (GR), gravity slows the passage of time, so a clock at sea level ticks more slowly than one on a mountaintop. Atomic clocks don't need a mountain to register that difference: For clocks with a precision level of 10^{-18} , even a few centimeters matters.

Small, transportable optical clocks could replace Cs ones for high-precision applications. Mounting them on satellites would facilitate worldwide clock synchronization and improve GPS accuracy, and networks of optical clocks could measure geopotential differences with centimeter-level precision. They would be a valuable tool to test Lorentz invariance and search for dark matter. But the frequency uncertainty in transportable optical clocks has lagged behind that of lab-based devices.² The tradeoff is between portability and precision: The best timekeepers are laboratory-based atomic clocks that rely on large, heavy equipment like optical tables to create well-controlled, mechanically isolated environments.

The pair of optical clocks shown in figure 1 have now achieved a fractional uncertainty of 5×10^{-18} while operating outside the lab—an order of magnitude better than previous transportable clocks.³ The devices were developed by Masao Takamoto and Noriaki Ohmae at Japan's

RIKEN research facility, Ichiro Ushijima and Hidetoshi Katori at the University of Tokyo, and their colleagues at other Japanese institutions.

Keeping cool

Optical atomic clocks fall into two categories: optical lattice and single ion. Each has pros and cons. Lattice clocks rely on measurements of many atoms for precision, and they have the potential to outperform single-ion clocks. However, atoms in lattice traps are more sensitive to electric field perturbations—from the trapping lasers, charges on nearby surfaces, and ambient blackbody radiation (BBR)—than those in ion traps. The energy-level shifts caused by those perturbations can obliterate performance gains over not just single-ion clocks but also clocks with microwave-range transitions.

Takamoto, Katori, and colleagues demonstrated the first optical lattice clock at the University of Tokyo in 2003. Strontium was a convenient choice because the energy levels for its clock transition and for laser cooling are excited by diode lasers. Since then, the researchers have refined their optical lattice clock. For example, they improved the stability of clock comparisons by rejecting the noise from the clock laser, and they precisely determined the conditions under which the lattice lasers would least disturb the Sr atoms' energy levels. Those advances and others were incorporated into the transportable clocks.

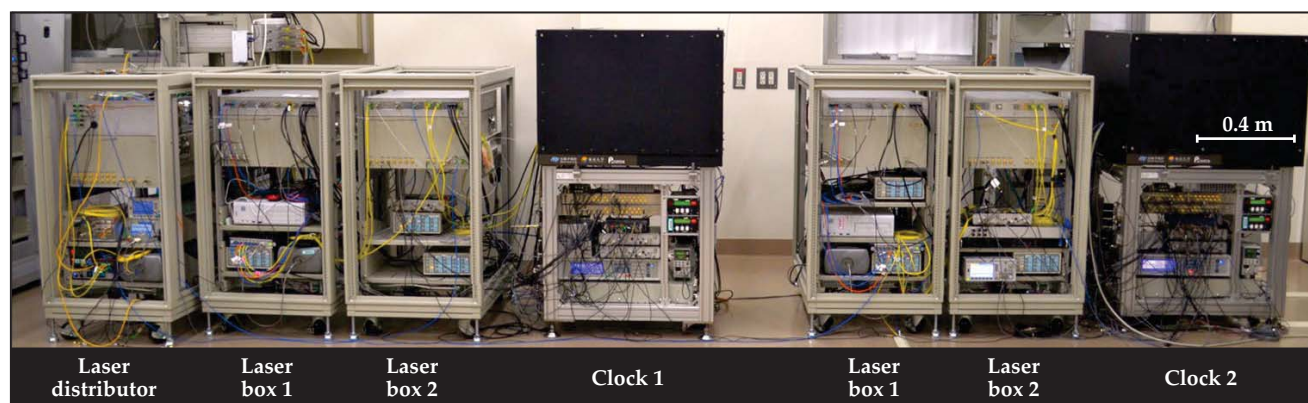


FIGURE 1. TWO TRANSPORTABLE OPTICAL ATOMIC CLOCKS carry spectroscopy chambers (black boxes) and supporting equipment. Each clock also has two laser boxes. Box 1 includes three lasers, two for cooling and one for repumping. Box 2 encloses lasers for creating an optical lattice trap, further cooling, and exciting the atoms for timekeeping. The two clocks are connected by a telecommunications fiber through the laser distributor. (Adapted from ref. 3.)

To protect the Sr atoms from stray photons, the RIKEN researchers developed BBR shields, which they have installed in their clocks since 2015. Then as now, the first step in each measurement of the clock transition is to cool Sr atoms down to a few microkelvin and load them into a one-dimensional optical lattice trap formed in a ring cavity (figure 2). A pulse from one of the two lattice lasers then nudges the trapped atoms into an 18-mm-long temperature-controlled chamber—the BBR shield—whose inner walls are painted with a high-absorbance black coating to prevent any stray photons from bouncing around.

Inside the BBR shield, the Sr atoms undergo a final cooling step before having their clock transitions measured. The device keeps time by probing the frequency of radiation corresponding to the $^1S_0 \rightarrow ^3P_0$ transition, but it doesn't measure that frequency directly. Rather, the frequency of the clock laser is tuned to match the Sr clock transition as closely as possible. The laser is directed at the atoms, and the more closely it matches the clock transition, the more atoms it excites. The trap then carries the atoms back out of the chamber so the fraction of excited atoms can be measured, and the clock laser's frequency is adjusted to find the maximum.

Improving precision in a lab-based clock is one thing; maintaining that precision in a transportable clock is another. "Four or five years ago, we were just happy with clock comparisons at 10^{-18} using laboratory-based machines," says Katori. "At that point it was possible to think about the experiment, but it was technically too hard to do." Making the clocks compact and stable enough to leave the lab required specialized, maintenance-free equipment. The lasers had no adjustment knobs, and the optical components were welded in place. The researchers also collaborated with the Shimadzu Corp to develop electronic devices, such as laser controllers and oscilloscopes, without the bulky control panels and displays of commercial equipment. All the clocks' components were controlled remotely through a single personal computer.

Onward and upward

One use of atomic clocks is to precisely measure a gravitational redshift—the frequency difference between two identical clocks at different gravitational po-

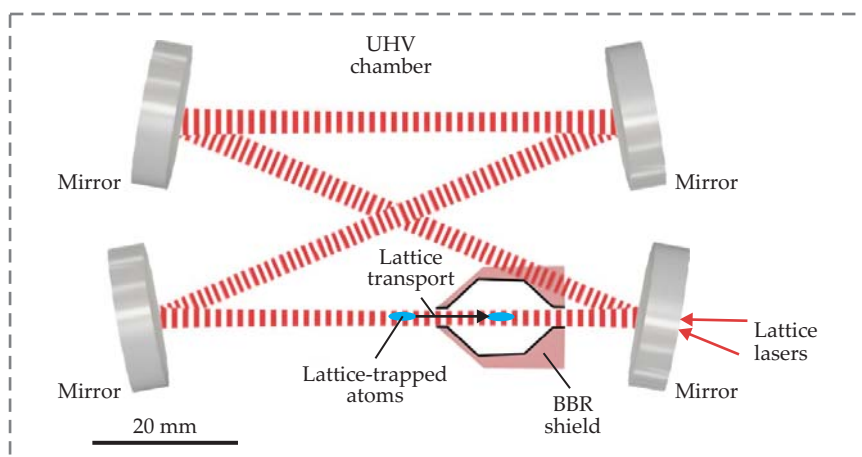


FIGURE 2. THE SPECTROSCOPY CHAMBER for each transportable strontium atomic clock contains a ring cavity that creates a one-dimensional optical lattice trap. Once a collection of atoms is trapped, a pulse from one of the lattice lasers transports it into a blackbody radiation (BBR) shield that protects the atoms from stray IR photons and strontium atoms. While inside the chamber, the atoms undergo an additional cooling step before excitation. (Adapted from ref. 3.)

tentials. Detecting the difference isn't particularly difficult; GPS satellites adjust their times by 38 μ s every day to account for relativistic effects (see the article by Neil Ashby, *PHYSICS TODAY*, May 2002, page 41). But precise measurements of gravitational redshifts can rigorously test GR's predictions. Some more complete descriptions of the universe require modifications to GR to account for, say, dark energy or the unification of gravity with the other fundamental forces. Measuring a deviation—or lack thereof—from GR's predictions would help point theoreticians in the right direction.⁴

The fractional frequency shift between two clocks is related to their gravitational potential difference ΔU by $\Delta\nu/\nu_1 = (1 + \alpha) \Delta U/c^2$ where ν_1 is one of the clock frequencies and c is the speed of light. If GR is correct, α is exactly zero. Tests of GR's gravitational redshift predictions try to establish the value of α as accurately as possible, and they're facilitated by two parameters: a large gravitational potential difference and a precise measurement of the resulting frequency difference.

As a demonstration of their clocks, Takamoto, Ohmae, and Ushijima took the clocks to the Tokyo Skytree broadcasting tower to measure a gravitational redshift. They placed one clock at the tower's base and brought another up to the 450-m-high observatory floor. The height difference between the clocks was established with centimeter precision by using navigation satellites and laser ranging, and a pair of gravimeters determined the clocks' local

gravitational accelerations. Putting that together with the frequency measurements from the two clocks, the researchers calculated a value of $\alpha = (1.4 \pm 9.1) \times 10^{-5}$. It's the best constraint on α from a ground-based measurement and is nearing the limit established by space-based experiments done using satellites separated by thousands of kilometers.⁵

The Skytree tower proved to be a challenging environment for the clocks because vibrations from nearby trains were unexpectedly large. The clock laser is particularly sensitive to noise, and even after the researchers added active vibration isolation, the vibrations limited the precision of the frequency comparison between the clocks. Although the researchers could have chosen a more amenable environment, they thought it was important to develop an optical clock with the ability to perform in adverse conditions. Katori sees it as a surmountable challenge: "By developing and installing a more stable laser system in the future, we will be able to significantly improve the stability of the clocks."

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References

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4. See, for example, A. Derevianko, M. Pospelov, *Nat. Phys.* **10**, 933 (2014).
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