ATOMIC PHYSICS

An optical clock to go

Bringing next-generation atomic clocks out of the lab is not an easy task, but doing so will unlock many new possibilities. As a crucial first step, a portable atomic clock has now been deployed for relativistic geodesy measurements in the Alps.

Andrew D. Ludlow

Atomic clocks have a long history as an enabling technology for a broad range of applications, among them global navigation, advanced communication systems and information networks, and radio astronomy. Next-generation atomic clocks, otherwise known as optical clocks, have recently demonstrated performance orders of magnitude beyond even the best conventional atomic clocks. More than just improving on existing operations, their level of performance opens the door to exciting new applications in science and technology. However, such realization often requires that the complex apparatus of these experimental clocks will operate outside the carefully controlled laboratory environment they normally enjoy. Writing in *Nature Physics*, Jacopo Grotti and colleagues[1] from a multinational European collaboration have made a big step towards this goal, transporting and operating an advanced optical clock outside a traditional laboratory to make measurements rooted in general relativity (Fig. 1).

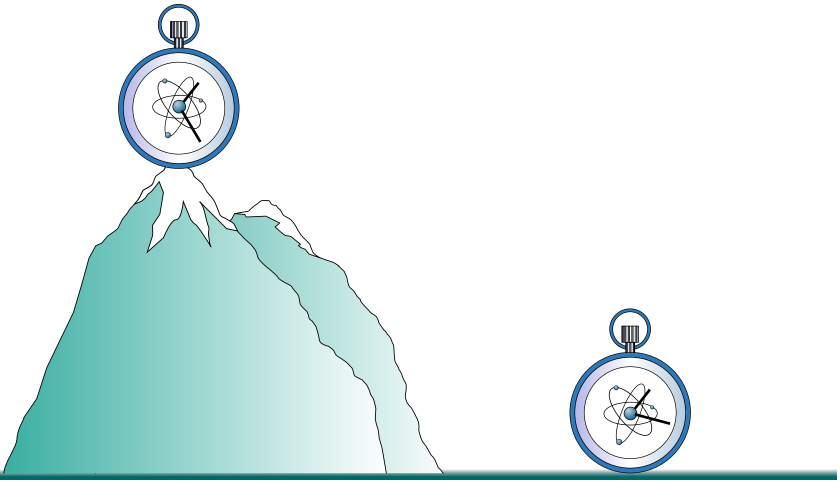

Fig. 1 | Relativistic geodesy. To an outside observer, time evolves slower in gravity. An atomic clock in the relatively low-lying city of Torino runs more slowly compared to one positioned high in the Alps. By measuring how much an optical lattice clock's timebase changes when moved from one location to the next, it's possible to deduce the change in gravitational potential between locations. This is the essence of relativistic geodesy. An advanced clock that can operate and measure outside the lab while being moved from location to location offers the potential for high-precision geodetic measurements.

Any atomic clock measures time by counting oscillations of an electron bound to the atom. To make the very best clocks, the atoms at the heart of the clock must be kept in carefully designed conditions to eliminate or control effects which would otherwise compromise the intrinsic atomic timebase of these oscillations. For example, an optical lattice clock uses ultracold atoms that have been laser cooled to just above absolute zero and are confined in a specially designed periodic laser trap — an optical lattice[2]. The atoms are then prepared into a single quantum state, at which point electron oscillations are driven by a highly frequency-stabilized laser that permits coherent atom–laser interaction times up to or exceeding one second[3,4]. Since these oscillations are at optical frequencies, one second is exceedingly long, as nearly 10^{15} cycles evolve, dividing time into ultrafine intervals. Repeated measurements on these ultracold trapped atoms are stitched together to make the optical clock.

The end result is impressive: the best optical clocks can now make measurements at a fractional precision[4,5] approaching one part in 10^{18} — more precise than any other type of physical measurement humankind can make. At that level, scientists can easily observe one of Einstein's basic predictions from general relatively: the gravitational redshift, or the idea that to an outside observer time evolves more slowly in the presence of gravity. While the effect is typically small on Earth, atomic clocks can measure it. An advanced optical clock could measure it precisely, and in so doing makes a measurement of the gravitational potential. In this way, an optical clock becomes a gravity sensor — a concept known as relativistic geodesy.

While laboratory-based measurements of this phenomenon have been carried out before[6,7], Grotti et al. looked ahead to making these clock-based gravity measurements at geodetically interesting locations, employing an optical lattice clock that could be moved out of the lab[8]. In this case, they relocated it from its home base in Braunschweig, Germany, to the Alps of Modane, France. Since the gravitational redshift is a relativistic effect, its measurement requires a comparison between clocks in different gravitational reference frames.

Using a specialized optical frequency transfer system over fibre optic, the authors were able to compare the timebase of their transportable clock in the Alps to those of atomic clocks located in the National Institute of Metrological Research in Torino, Italy, some 100 km away[9]. They later relocated the transportable clock to Torino, for a series of complementary local measurements between the clocks. Ultimately, they were able to determine both the gravitational redshift and the corresponding difference in gravitational potential between the two measurement locations of the portable clock.

Doing this is much easier said than done. Indeed, Grotti et al. report the first ever measurement campaign where an optical lattice clock has been used outside a metrology laboratory. To do so, the authors needed to realize the careful quantum control, manipulation and measurement that these clocks require, in a system that could be transported and operated in less-than-ideal conditions. Some of the challenges they faced while in the Alps include maintaining a small army of stabilized lasers properly tuned to distinct atomic transition frequencies and carefully aligned for atomic manipulation, as well as compensating for effects from a variety of electromagnetic fields on the atoms.

As would be expected for this type of pioneering effort, the measurement campaign was not perfect. There were periods of time when the portable optical clock would not function, and the accuracy of the measurements were limited below the capability of optical clocks. And while the relativistic geodetic measurement agreed nicely with conventional geodetic measurements, its accuracy was two orders of magnitude below the conventional techniques.

Nevertheless, the measurement campaign represents a very important proof of principle and a significant milestone. By carrying out the first successful measurements of a transportable optical clock outside the lab, the authors have showcased these systems' tremendous potential and affirmed their bright future. As the precision of these portable clocks reaches current state-of-the-art levels and beyond, as new quantum technologies are employed, and as these advanced systems continue to mature, clock-based geodetic measurements will complement or even outperform conventional techniques in some applications.

Beyond geodesy, these portable optical clocks can enhance other applications in both science and technology, such as searches for dark matter or improved tests of fundamental physics including general relativity and extensions to the standard model. Ultimately, they will aid worldwide clock measurements, which play an important role in present-day global efforts toward a redefinition of the International System of Units (SI) second and coordination of international atomic time. ❐

Andrew D. Ludlow
Time and Frequency Division at the National Institute of Standards and Technology, Boulder, CO, USA.
e-mail: *ludlow@boulder.nist.gov*

https://doi.org/10.1038/s41567-018-0047-6

References

1. Grotti, J. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-017-0042-3 (2018).
2. Katori, H., Takamoto, M., Pal'chikov, V. G. & Ovsiannikov, V. D. *Phys. Rev. Lett.* **91**, 173005 (2013).
3. Boyd, M. et al. *Science* **314**, 1430–1433 (2006).
4. Schioppo, M. et al. *Nat. Photon.* **11**, 48–52 (2017).
5. Nicholson, T. et al. *Nat. Commun.* **6**, 6896 (2015).
6. Chou, C. W., Hume, D. B., Rosenband, T. & Wineland, D. *Science* **329**, 1630–1633 (2010).
7. Takano, T. et al. *Nat. Photon.* **10**, 662–666 (2016).
8. Koller, S. B. et al. *Phys. Rev. Lett.* **118**, 073601 (2017).
9. Pizzocaro, M. et al. *Metrologia* **54**, 102–112 (2017).

QUANTUM INFORMATION

Enter the machine

Quantum tomography infers quantum states from measurement data, but it becomes infeasible for large systems. Machine learning enables tomography of highly entangled many-body states and suggests a new powerful approach to this problem.

Pantita Palittapongarnpim and Barry C. Sanders

Rapid development of quantum technology creates a need to verify that the generated quantum states meet specification. Quantum tomography serves this purpose through a measurement process leading to a statistical inference of the unknown state[1]. Detrimentally, standard quantum tomography of complex many-body systems requires measurements whose number rises exponentially with the number of particles in the system, making this approach infeasible for practical applications. Now, writing in *Nature Physics*, Giacomo Torlai and colleagues[2] have shown that quantum tomography of certain entangled many-body states can be achieved much more efficiently by exploiting the capability of machine learning to unravel complex patterns through low-dimensional representations of data. The authors trained a restricted Boltzmann machine (RBM) on simulated independent measurements of many-body states and showed that they could reconstruct states accurately from the data.

Restricted Boltzmann machines comprise a layer of visible neurons, connected as a complete bipartite graph to a layer of hidden neurons[3], corresponding physically to a particular class of quadratic-spin Hamiltonian[5]. The coefficients of the Hamiltonian are edge and neuron weights, and act as parameters that are optimized to fit closely to the training data. Taking the modulus and the phase of the states derived from two distributions obtained from exponentiating this RBM Hamiltonian leads to a RBM representation.

The authors' machine learning approach trains a RBM to represent the quantum states that are being subjected to tomographic reconstruction[4]. The RBM representation is constructed from simulated measurement data for the correct state, with measurement degrees of freedom encoded into the visible neurons of the RBM and tunable parameters encoded into the hidden neurons (Fig. 1). The quality of the learned edge weights is quantified by the overlap between the RBM wavefunction corresponding to this exponentiated Hamiltonian and the wavefunction for the correct state.

The power of this RBM method was studied by Torlai et al. for certain types of many-body entangled states. They first considered W states, which are superpositions of qubits with all but one in the 0 state and one qubit in the 1 state. For the second type, they studied ground states and quench dynamics of quadratic-spin Hamiltonians, namely the transverse-field Ising and the XXZ models[6]. This was done by taking the ground state for one Hamiltonian and evolving it for a fixed time according to a different one. The resulting state reconstruction exhibits high overlap with the correct state for all these cases, and the entanglement entropy[7] computed from the reconstructed state agrees well with the correct entanglement measure for quadratic-spin Hamiltonians.

The RBM can be excellent for learning a probability from a training set but can also fail — for example, due to overfitting[8] or due