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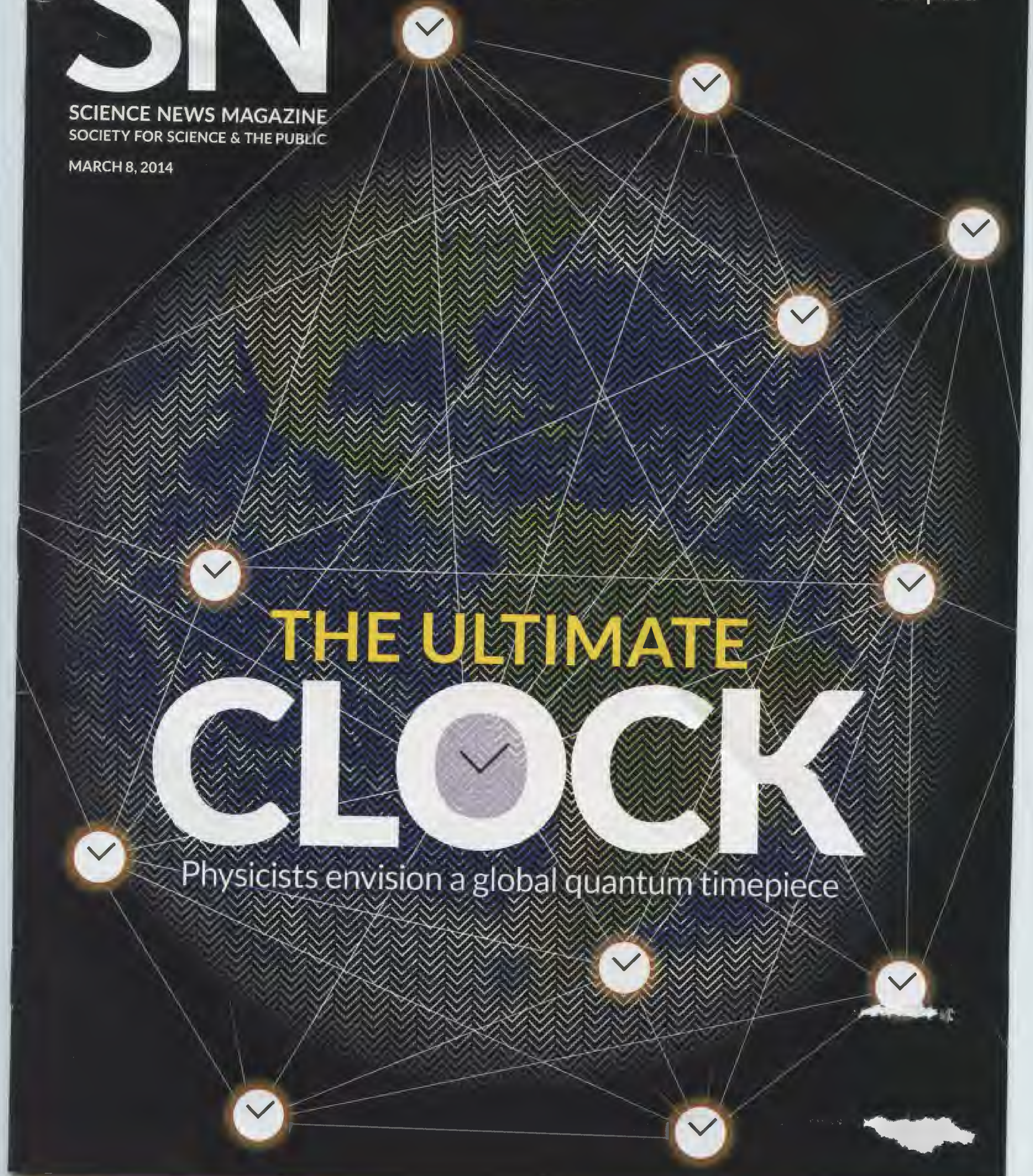


THE ULTIMATE CLOCK

Physicists envision a global quantum timepiece

QUANTUM TIMEKEEPING

Physicists are exploring the mind-blowing possibilities of linking a new generation of atomic clocks

By Andrew Grant

The best clock in the world has no hands, no pendulum, no face or digital display. It's a jumble of lasers, wires and strontium atoms in Jun Ye's lab at the National Institute of Standards and Technology (NIST) in Boulder, Colo. He keeps it cooled to about three millionths of a degree above absolute zero.

The clock, described by Ye in the Feb. 6 *Nature*, is so precise that had it begun ticking when Earth formed 4.5 billion years ago, it would not yet have gained or lost a second. Over that span, a Swiss quartz watch would stray at least a few thousand years.

Ye's atomic, or optical, clock is impressive, but it's just one step toward an ambitious timekeeping goal. He and his colleagues at JILA, a joint institute of NIST and the University of Colorado Boulder, envision 10 or more atomic clocks, installed in satellites and international labs, and intricately connected to form the equivalent of one global superclock. Whenever Ye checked the time with the atom-probing laser in his Colorado laboratory, his clock would be connected with every other clock on the network — instantaneously, regardless of distance — and deliver a reading hundreds of times as accurate as those produced by today's atomic clocks.

A network of clocks that accurate would have staggering capabilities. It would provide a level of worldwide synchronicity that is impossible with current technology. And synchronicity matters in an interconnected world in which electric utilities, Internet servers and financial companies coordinate their services to the nanosecond and want to do even better.

Remarkably, a global superclock would also be able to measure things that have no intuitive connection to time. Because time and gravity are innately linked according to Einstein's general theory of relativity, researchers would be able to use a clock as a sort of scale, correlating subtle fluctuations in a clock's ticking rate with the mass below it. Clocks flying above enemy territory could detect missing mass below the surface — perhaps the location of a secret underground tunnel or cave.

Building this clock network would be complicated but far from impossible. The key is coupling the steady advances of atomic timekeeping

S. EGTS

Atomic clocks are so precise that physicists can measure time to the quintillionth (10^{-18}) of a second with confidence. An entangled clock could do even better.

with quantum entanglement, the intricate connection of subatomic particles that is nearly as mysterious now as it was when Einstein deridingly called it "spooky" nearly 70 years ago. Exploiting this mind-bending phenomenon to create instantaneous quantum links across vast distances may yield the most complex timekeeping device in human history.

The ticket to greater certainty

Physics seemed to make a lot more sense before quantum mechanics, the theory that deals with the behavior of matter at atomic and subatomic scales, was proposed in the mid-1920s. In classical physics, objects large and small have definitive properties: An electron, for example, exists at a certain place at a certain time and possesses a certain spin. But the realm of quantum mechanics is ruled by randomness. An electron can be located in multiple places and spin in multiple directions at once — it can exist in what's called a superposition of states. Only when someone measures the electron does it settle on a specific set of characteristics.

The more scientists dug into the equations underlying quantum mechanics, the more counterintuitive the theory became. In 1935 Einstein, along with colleagues Boris Podolsky and Nathan Rosen, performed one of his famous thought experiments and realized that, in theory, multiple particles could interact and maintain a strange connection once separated. At first the particles would each remain in a superposition state, encompassing several properties simultaneously. Yet someone measuring one of the particles would immediately be able to determine the properties of the others. This instant connection held true regardless of the distance between particles: centimeters, kilometers, even light-years (*SN: 11/20/10, p. 22*).

Einstein seriously doubted that particles could maintain such an intimate long-distance relationship; he later called the illogical result "spooky action at a distance." Austrian physicist Erwin Schrödinger was far more open to the possibility. He coined the term quantum entanglement.

Today, physicists still aren't sure how multiple particles manage to coordinate their properties instantaneously. The phenomenon is most definitely real, however, and researchers are getting very good at demonstrating it in the lab.

In 2011, an Austrian team including Thomas Monz at the University of Innsbruck entangled 14 calcium atoms by squeezing them together with laser light (*SN Online: 4/10/11*). Before Monz's team made a measurement, each atom sat in a superposition of two possible electron configurations. But when the researchers measured the configuration of one of the atoms, the other 13 atoms instantly took on the same state. Due to entanglement, the 14 atoms behaved like one mega-atom.

Results like this are more than just a cool trick, says Harvard physicist Eric Kessler. In a realm ruled by randomness, entanglement is the ticket to greater certainty. A set of 14 atoms, each with two possible states, results in 16,384 possible combinations. But by entangling the atoms, Monz's team reduced the list of possibilities to two. In other words, instead of having to flip 14 coins, the researchers needed to flip only one megacoin.

A research team including Kessler and Ye proposes that scientists exploit this phenomenon to improve the accuracy of atomic clocks. Rather than flipping coins, however, they want to consolidate pendulums.

The key to a good clock is a pendulum that oscillates at a constant rate. Fortunately, nature offers the perfect pendulums: atoms. For a given atom, only discrete amounts of energy will coax one of its electrons to jump between energy levels. Over the last half-century, physicists have tuned lasers to shine with the exact energy required to hasten those electron jumps. The frequency of the laser should be the same for every clock tuned to a particular type of atom, since that frequency is tied to the atom's intrinsic, immutable electron transition energy. (For cesium-133, the atom that calibrates the world's clocks, the frequency corresponds to microwave radiation oscillating 9.2 billion times a second.) In theory, the laser taps into a pendulum that never strays (*SN: 10/22/11, p. 22*).

But in practice, the pesky randomness of quantum mechanics fundamentally limits the fidelity of frequency measurements and thus the precision of cesium clocks. Ye's new strontium clock does better because it divides time into shorter pendulum swings, using visible-light lasers that oscillate 430 trillion times a second, and it probes several thousand atoms rather than just one. But even it is not immune to quantum randomness.

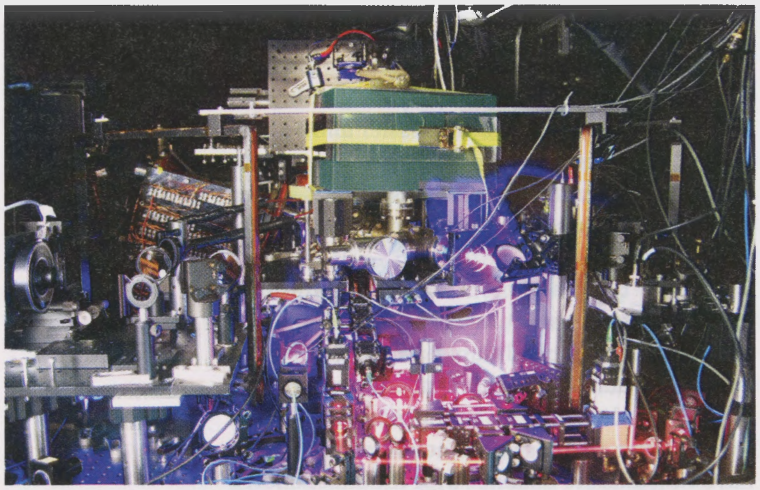
> "These atoms will act ... as one giant pendulum that can keep time much more accurately."
>
> **ERIC KESSLER**

Entanglement is the key to chipping away at that randomness, according to Ye, Kessler and their team. Their paper, posted online last October at arXiv.org, envisions a clock of entangled atoms that reduces noise by virtue of quantum connections between its components. Just as Monz's team consolidated 14 atoms into one mega-atom, Kessler says, "these atoms will act not as individual pendulums but as one giant pendulum that can keep time much more accurately."

While Ye hasn't yet entangled the atoms in his clock, he's comparing notes with a small group of quantum physicists that is already trying to devise entangled timepieces. James Thompson at JILA and Vladan Vuletić at MIT are working to squeeze clock atoms together with lasers, similar to Monz's technique. "It's really exciting talking to these guys and testing these ideas out," Ye says.

Creating individual entangled clocks is nice, but they serve no practical purpose sitting on a table in a laboratory. NIST broadcasts its cesium clock signal over the radio for use by consumers, businesses and scientists. Global positioning systems calculate a user's location by having multiple clocks compare the time it takes for microwave radiation to travel to various satellites. And the International Bureau of Weights and Measures near Paris receives time readings from clocks worldwide to set its Coordinated Universal Time, or UTC, standard. Clearly, Ye says, "linking clocks is absolutely necessary." The same goes for entangled clocks.

The world's most precise and stable clock, located in Boulder, Colo., works by tuning lasers to the exact internal frequency of strontium atoms.



YE GROUP AND BRAD BAXLEY/JILA

Transmitting time

The problem is that the faster an atomic clock pendulum swings, the more difficult it is to share that signal. Ye can't broadcast the visible-light signal from his strontium clock over the radio because it oscillates too quickly. That means scientists have to develop new technology that transmits visible-light timing signals from optical clocks. The trick is to pin down the sources of noise that skew the signal and counteract them, much like noise-canceling headphones.

Physicist Stefan Droste at the Max Planck Institute of Quantum Optics in Garching, Germany, is on the case. In September he and his team sent an optical timing signal through a 1,840-kilometer underground fiber-optic cable. He's now working with French researchers to link an optical clock in France with one in Germany. Meanwhile, in the mountains near Boulder, physicist Nathan Newbury recently reported success beaming optical signals through the air between his lab at NIST and a mesa about two kilometers away. It's a first step toward beaming signals from clocks like Ye's to and from satellites.

Droste's and Newbury's work is important because it could allow the world to share more precise time signals. But Ye and his colleagues argue that sharing isn't enough. They point out that there is no physical device that serves as a master world clock. UTC is actually a paper clock. Its "time" is derived by averaging the readings received from some 200 cesium clocks around the world — a calculation that takes time to do. The result is that nobody — not even Ye, the man with the world's best clock — knows what time it is right now (see sidebar, this page).

This lag in determining the world's time is not an easy problem to fix. No matter the performance of individual clocks scattered around the world, scientists can't share that information with each other any faster than the speed of light. "It would be nice to be able to know what time it is at different places without having to make a phone call," says Chris Monroe, a physicist at the Joint Quantum Institute at the University of Maryland in College Park.

Which brings us back to Einstein's spooky action at a distance. In their October arXiv paper, Ye and his team propose constructing a network of entangled clocks that are also entangled with each other. That means that by measuring the frequency to excite one atom in one clock, a user would in a sense have access to every atom in every clock on the network. The result would be an unprecedented world clock made up of satellite clocks that each have immediate access to the exact time. "Any clock in the network could realize the [UTC] instantaneously," says Andrew Ludlow, a NIST physicist who did not contribute to the research.

To intricately link clocks thousands of kilometers apart, physicists would have to deliver entanglement from clock to clock through a process called quantum teleportation. The idea dates back only 20 years, but physicists have already exploited teleportation — the transfer of quantum information over long distances — with impressive success. In 2007, Anton Zeilinger of the Vienna Center for Quantum Science and Technology and colleagues teleported the polarization state of one photon to another photon about 143 kilometers away (*SN: 6/30/12, p. 10*).

In the Ye team's scheme, scientists would generate a pair of entangled photons and send them via satellite or fiber-optic connection to link two clocks. The photons pass through each clock and interact with the clock's atoms, passing on the entangled state. The same process can hook up the other clocks in the network. Once all the clocks are entangled, Kessler says, measuring one atom in one clock would derive information from every atom of every clock in the global network. In effect, all those atoms would combine forces to create an extraordinarily precise pendulum.

Put all the facets of the plan together — entangling multiple clocks each made up of entangled atoms — and the result is a master world clock that gives users instant access to a time measurement with as much as 10 times the precision of Ye's cutting-edge optical clock. For the first time, the world's standard-setting clocks could be perfectly synchronized.

Sky's the limit

A supercharged quantum clock network could do much more than tell time. According to general relativity, clocks tick at slightly different rates depending on the strength of the gravitational fields acting on them. For example, atomic clocks on GPS satellites gain about 45 microseconds on ground-based clocks each day because Earth's gravitational pull is weaker on objects at high altitude than it is on objects at the surface.

Put an ultraprecise clock inside a satellite and the time will fluctuate based on more than just altitude. Earth's gravitational pull varies ever so slightly at different points on the surface depending on the amount of underlying mass. Ye says that a pair of satellites fitted with superclocks could sweep over points on Earth to discover hidden geological features, such as magma migrating underground prior to a volcanic eruption.

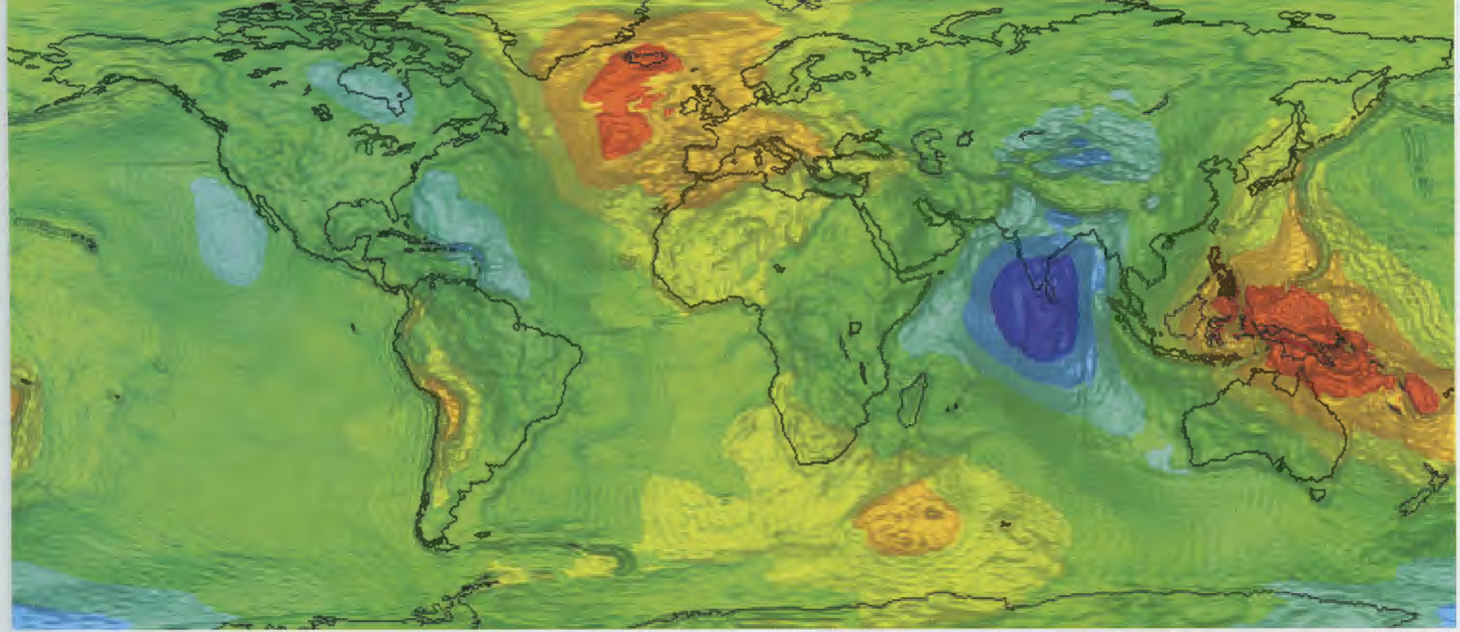
Does anybody really know what time it is?

The international time standard — Coordinated Universal Time, or UTC — is a calculation, not a physical clock. That makes timekeeping a bit fuzzy. The International Bureau of Weights and Measures near Paris collects time readings from about 200 atomic clocks in more than 50 international labs and then, once a month, averages the results.

Judah Levine, the official U.S. timekeeper for more than 40 years, does his best to align U.S. clocks with UTC. Several times a day, he sends a file to the bureau with the time he thinks it is, based on the cesium clock at the National Institute of Standards and Technology in Boulder, Colo.

Around the 10th of each month, he gets an e-mail response telling him how wrong he is, based on the previous month's data. Levine then tweaks his clock's ticking rate — usually by a nanosecond per day. "I have to make an estimate of where I am today," he says, "because I won't know until a month from now." *— Andrew Grant*

YE GROUP AND BRAD BAXLEY/JILA



Surveying Earth's gravity Maps from the GOCE satellite reveal variations in Earth's gravitational field. The colors represent the field's strength at various points on the surface: Red regions have stronger gravity than the average, blue shows zones of weaker pull. Satellites equipped with quantum-linked clocks would do far better at measuring these variations, potentially revealing secret caves and imminent volcanic eruptions.

GOCE HIGH LEVEL PROCESSING FACILITY/ESA

Monroe suggests even grander, and perhaps unnerving, applications for security and defense. He estimates that these clocks would be able to carefully map the shape of Earth's terrain down to the millimeter. "You'd be able to see someone digging a tunnel under the U.S.-Mexico border from space," he says. The military could fly a pair of satellites over an enemy landscape and map every cave potentially inhabited by terrorists. "The satellite closer to the cave will experience less gravity, and thus will tick faster, than the satellite farther away," Ye explains.

It sounds great, but physicists still have a long way to go before they can implement these Earth-scanning satellites. Entangling 14 atoms in a carefully controlled lab setting is very different from entangling thousands of atoms in a dozen clocks scattered all over the world. And although teleporting a few photons over 140 kilometers is impressive, a quantum clock network would have to consistently transport individual photons from ground stations to satellites and back, all while preserving the particles' delicate superposition states.

"We're really quite far from doing this," says Jacob Taylor, a colleague of Monroe's at the Joint Quantum Institute. Monroe agrees, but says that he's still impressed by the idea because it combines several efforts that physicists are pursuing anyway. "It brings multiple aspects of quantum information science into one big cosmic unit," Monroe says.

Cesium clock
9.2 billion
pendulum swings per second

Strontium clock
430 trillion
pendulum swings per second

By dividing time into shorter, more frequent oscillations, the strontium clock delivers greater precision.

For example, quantum computing researchers are exploring the same mechanism that enables entangled atoms to measure time (*SN: 3/10/12, p. 26*). Quantum computers would exploit the superposition states of atoms or photons — think Monz's 14 atoms before they were measured — to store and process enormous amounts of data. While 14 memory cells of a conventional computer can hold 14 bits of information, 14 quantum bits, or qubits, would hold 16,384 bits simultaneously.

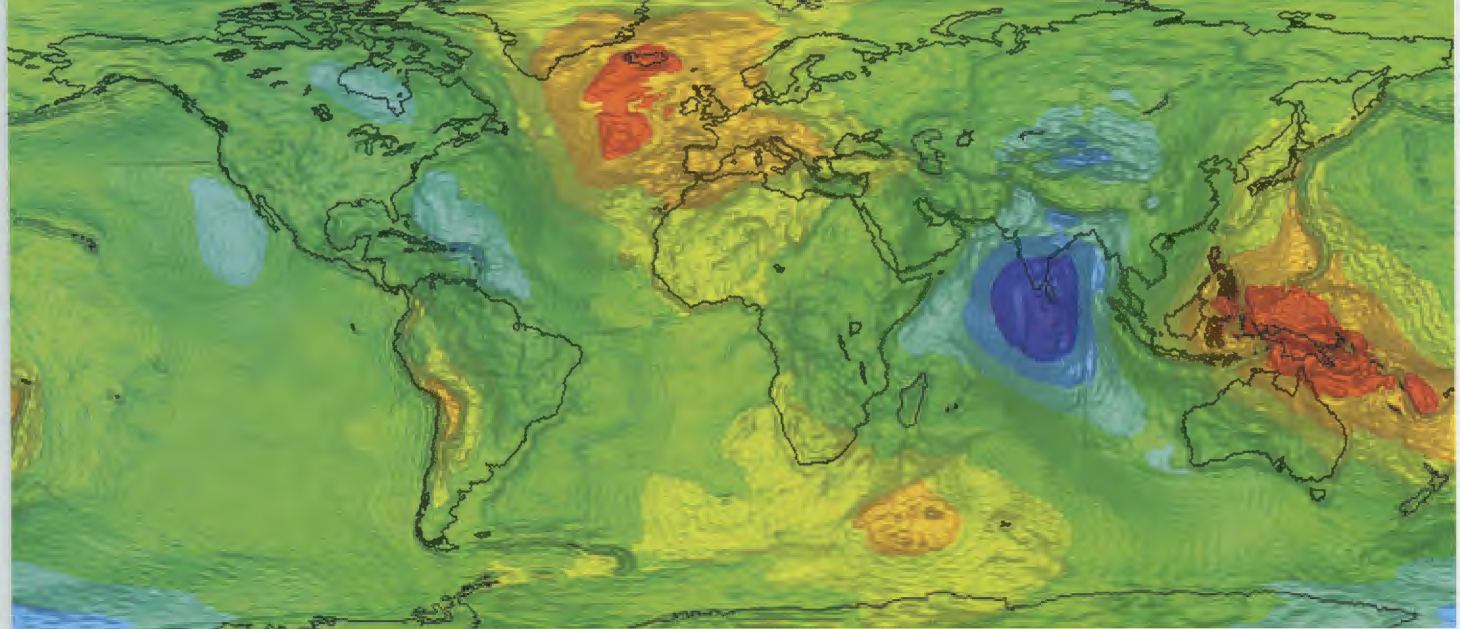
Meanwhile, the teleportation required to link up clocks could help create secure quantum communication networks. Physicists envision building quantum channels in which users exchange information encoded in atoms or photons in superposition, just like atoms in the clock. Eavesdroppers trying to listen in on a conversation would disturb that fragile superposition state, exposing their presence.

The list of potential uses for quantum entanglement and teleportation goes on, and physicists will come up with new ideas as they toy with the amazing toolbox quantum mechanics provides. "This field has been waiting for a big killer application," Monroe says.

That quantum breakthrough just might come in the form of a superclock beyond compare. "It's a big challenge to build such a global device," Kessler says. "But all the building blocks are there." ■

Explore more

- Peter Kómár *et al.* "A quantum network of clocks." arXiv:1310.6045. Posted Oct. 22, 2013.



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