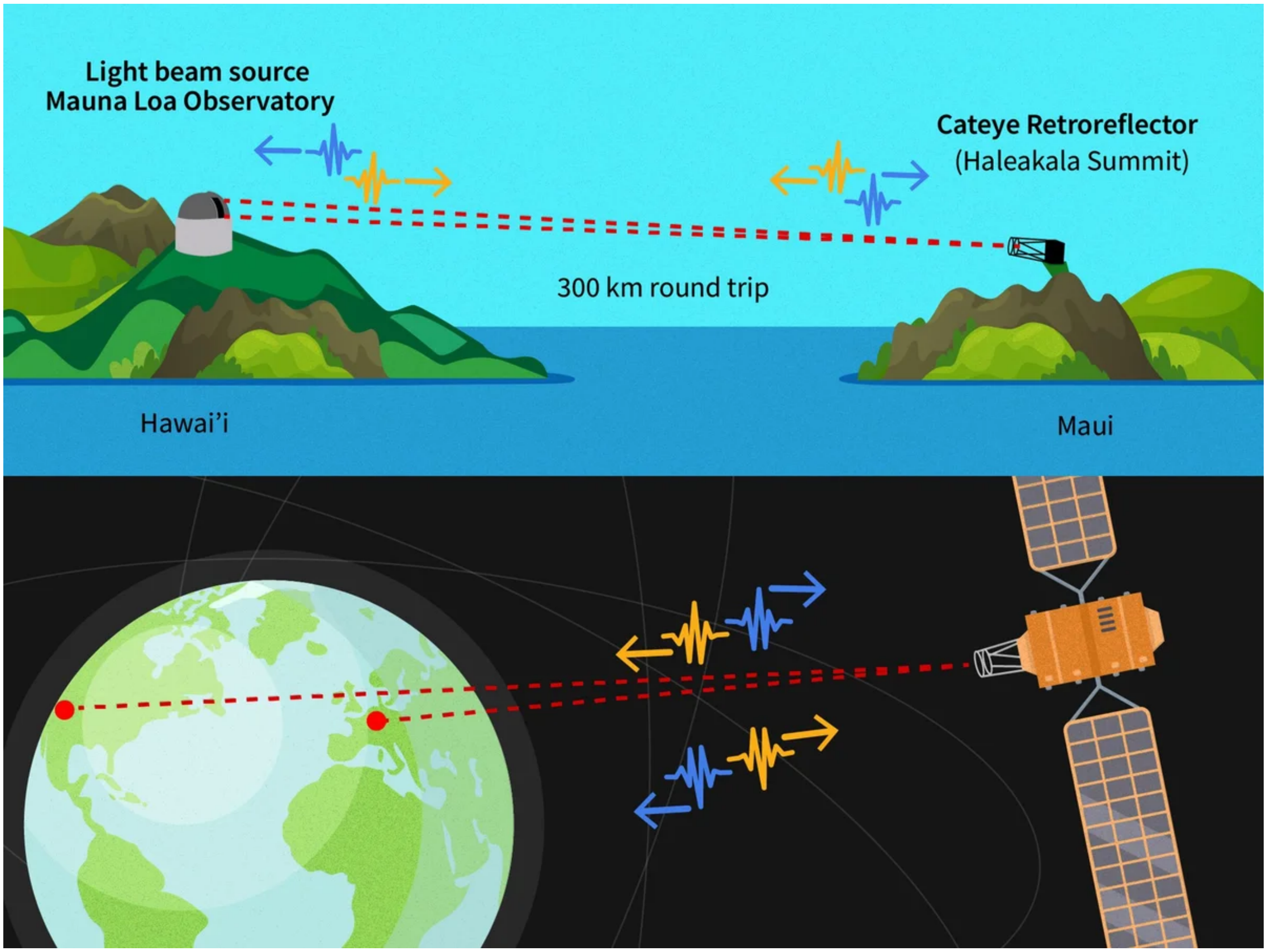
IEEE Spectrum

NEWS AEROSPACE

Laser-Comb Clocks Pierce Femtosecond Barrier › Portable, ultraprecise timekeeping will usher in high-res GPS and gravity mapping

BY CHARLES Q. CHOI

25 JUN 2023



Synchronizing clocks across the planet with femtosecond accuracy could become

Synchronizing clocks across the planet with femtosecond accuracy could become reality by applying a laser frequency comb technique recently developed at NIST. The team tested their technique by beaming frequency comb pulses between mountains on two islands in Hawaii, demonstrating the fidelity necessary to link clocks via satellite even if the signal is very weak. B. HAYES/NIST

BY FIRING A LASER FROM A VOLCANO IN HAWAII, scientists now reveal they can synchronize atomic clocks to 320 billionths of a billionth of a second (0.32 femtoseconds or 320 attoseconds) over a distance of more than 300 kilometers. This new study joins a range of findings over the past two decades that point toward satellite arrays of synchronized atomic clocks with femtosecond precision. These clocks would help support advanced satellite navigation and sensor networks to find everything from hidden underground structures to dark matter.

Atomic clocks are the most precise timekeepers created yet. “Time is the physical quantity that humans can measure with the greatest precision,” says study coauthor Nathan Newbury, a physicist at the National Institute of Standards and Technology (NIST) in Boulder, Col.

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The new work bests current satellite state-of-the-art time synchronization by 10,000 times.

Whereas grandfather clocks keep time by tracking swinging pendulums, atomic clocks monitor the quantum vibrations of atoms. Optical atomic clocks, which use intersecting laser beams to entrap and monitor the atoms, are currently accurate down to 1 attosecond, or a billionth of a billionth of a second.

"This means that if these clocks started running right after the Big Bang, they would have drifted less than a second in the 13.7 billion years since," Newbury says.

Atomic clocks have many possible applications besides keeping time. For instance, they are key to the precisely timed signals that GPS (short for global positioning system) and other GNSSs (global navigation satellite systems) rely on to help users pinpoint their own locations.

In addition, the atoms in atomic clocks are very sensitive to any form of disturbance, such as the gravitational pull of Earth. This means that mobile atomic clocks traveling over Earth in a vehicle or satellite can map how the strength of the planet's gravitational field varies over its surface, due to hidden density anomalies such as oil, minerals, and water. Atomic clocks may even find use in more esoteric work, such as hunting for dark matter, the invisible and largely intangible substance that researchers think makes up about five-sixths substance that researchers think makes up about five-sixths of all matter in the universe.

How do atomic clocks synchronize?

In order to use networks of atomic clocks in these applications, scientists need to keep them synchronized. Laser signals transmitted over fiber-optic cables or through the air can help link optical clocks together. However, such optical time transfer has faced challenges in remaining stable in the face of vibrations and temperature fluctuations near the cables and turbulence in the air.

Now researchers at NIST and their colleagues have shown they can synchronize optical atomic clocks more than 300 km apart down to 0.32 femtoseconds. The new findings suggest they could help ground clocks synchronize with satellites 36,000 km away in geosynchronous orbit with femtosecond precision, Newbury says. This is 10,000 times as precise as existing state-of-the-art satellite approaches.

In experiments, the scientists transmitted signals between the volcanoes Mauna Loa on the island of Hawaii and Haleakala on the island of Maui. The clocks were both stationed at an observatory high on the flank of Mauna Loa to help the research team monitor the devices. and the infrared laser signals were bounced off a reflector on the summit of Haleakala. The volcanoes are located about 150 km apart, for a round trip of roughly 300 km for the laser signals.

Researchers were able to reach the quantum limit—the bare minimum signal strength needed to keep their clocks in sync.

The new findings depended on “optical frequency combs,” which each convert a pulse of light from a single laser into a series of pulses equally spaced in time and made up of different, equally spaced frequencies of light, a bit like the teeth of a comb. By measuring the difference in arrival time of pulses sent from sets of clocks and combs at either end of an optical link, scientists can calculate the time difference between the clocks to see how close they are to synchronization. Sending pulses from both combs at the same time through the link can eliminate any deterioration in timing precision due to the cables or the air.

In 2022, researchers in China used optical frequency combs for optical time transfer over 113 km between two mountains in Xinjiang. However, this work relied on high-power optical frequency combs and telescopes fitted with complex optics systems.

In contrast, the new study used combs that required as little as 40 microwatts of output, about one-thirtieth the power a laser pointer uses and 25,000 times less “launched” power than previous attempts. This meant the setup also needed smaller telescopes with less complex optics.

“This means that in planning for future ground-to-geosynchronous-orbit links, we can plan for modest apertures and launch powers lowering the cost, size, weight, and power of future experiments,” Newbury says.

These findings were made possible with the aid of a new invention from the research team, a time-programmable frequency comb. Prior work used combs that were set to pulse at different fixed rates. Although these rates aligned now and again to help detect any time differences between the clocks, most pulses from the combs were out of sync and so went to waste. In contrast, the new time-programmable frequency combs let the scientists precisely modify their pulse rates to quickly bring them into sync.

All in all, with the aid of digital signal processing, the scientists were able to synchronize the clocks with 10,000 times less received power than previous attempts, with less than one photon in a billion reaching the target. This revealed the new technique operated at the quantum limit—the bare minimum signal strength needed to keep the devices in sync.

“Even though over half the time the received power was below our detection threshold, the time transfer system could both acquire the timing signal and then synchronize the two sites,” Newbury says.

The scientists now aim to reduce the size, weight, and power of the system to help make it mobile. In addition, in order for it to find use in satellites, “we need to expand this system to work on platforms moving at high speeds,” as satellites with these clocks may hurtle at speeds of up to 36,000 km per hour relative to one another, Newbury says.

The scientists detailed their findings online 21 June in the journal *Nature*.