Synchronizing optical clocks to one quadrillionth of a second

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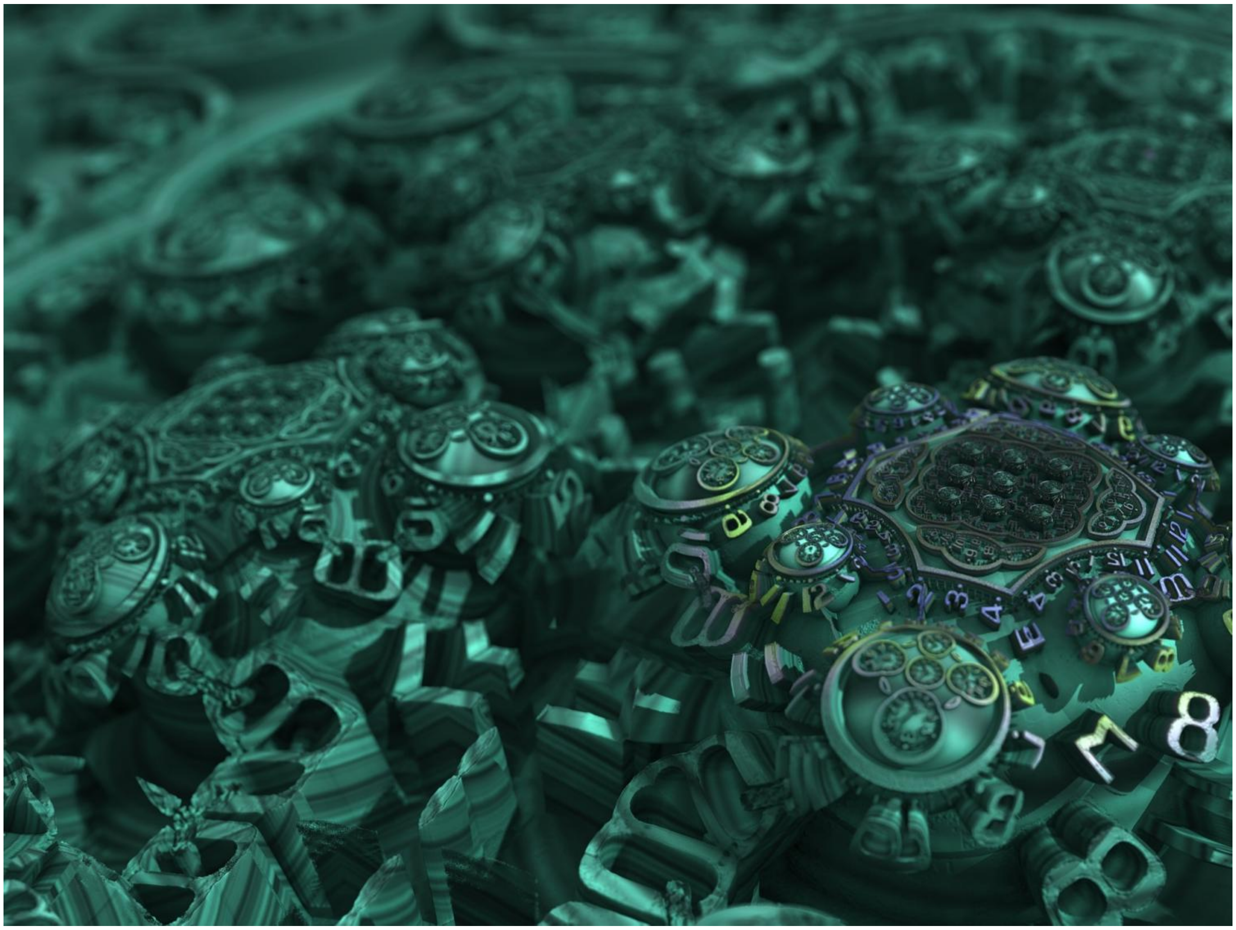

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An international team of researchers, led by the National Institute of

Standards and Technology (NIST), based in Gaithersburg, Maryland, has advanced their work with synchronizing a remote optical clock with a master clock by exploring what happens to time signals that need to travel through 12 kilometers (km) of turbulent air, which is known to distort optical signals.

As the team reports this week in *Applied Physics Letters*, they were able to demonstrate real-time, femtosecond-level clock synchronization across a low-lying, strongly turbulent, 12-km horizontal air path by optical two-way time transfer.

Their work relies on a tool known as a "frequency comb," for which John Hall and Ted Hänsch won a Nobel Prize in physics in 2005.

A frequency comb is a specialized type of laser that puts out a very stable train of optical pulses.

"We label these pulses and use them as the 'ticks' of our clock," said Laura Sinclair, a physicist at NIST. "It's analogous to a quartz watch. But in our case, we have an oscillator running at 200 billion cycles per second (200 THz), which we combine with a frequency comb to generate ticks not every second but every 5 nanoseconds."

The researchers send these ticks—frequency comb pulses—over the air both from site A to B and from B to A. Thanks to some clever tricks, they were able to measure the arrival time of the pulses at each site to femtoseconds, or one quadrillionth of a second.

The arrival time must be measured at both sites "because of the finite speed of light—the amount of time it takes the pulse to travel across 12 km of air can change by hundreds of picoseconds during the course of hours due to the changing atmosphere or even the swaying of the building housing the clocks," Sinclair pointed out. "This can completely hide any differences in clock times."

By noting the difference in arrival times, "we can subtract out the changing path and we're left with only the difference in clock times because the atmosphere is reciprocal—meaning that the 100 picosecond change happens for both directions at the same time," she continued. "Once we measure the difference of the clock times, we can speed up or slow down the clock at site B so that it agrees with the clock at site A to within femtoseconds."

All of these measurement steps happen quickly—in less than half of a millisecond—so the team can adjust the clock at site B orders of magnitude faster than existing microwave-based methods.

The team was awed by how far they were able to go and still maintain femtosecond-level synchronization.

"The 12 km of turbulent air results in massive distortions of the laser beams—yet the two clocks agree in time to 20 digits," Sinclair noted.

These results are extremely encouraging, because the team saw "no degradation of the clock agreement with the increased distance and turbulence," Sinclair said. "This suggests that we could go even greater distances, especially if the path isn't completely horizontal—like to a mountaintop or balloon."

The team is now tackling two separate problems for the clocks.

"First: Can we still synch clocks if one of them is moving? The same Doppler effect that changes the pitch of an ambulance siren when it's coming toward us also impacts our clocks, so we need to correct for this effect to allow for the development of synchronized clock networks on mobile platforms," Sinclair explained. "Second: How far—in distance—can we really go? If we want to someday redefine the second so that it's based on an optical standard instead of a microwave standard, we'll need to be able to link up the world's best clocks and then distribute that time information."

More information: "Synchronization of clocks through 12km of strongly turbulent air over a city," Laura C. Sinclair, William C. Swann, Hugo Bergeron, Esther Baumann, Michael Cermak, Ian Coddington, Jean-Daniel Deschênes, Fabrizio R. Giorgetta, Juan C. Juarez, Isaac Khader, Keith G. Petrillo, Katherine T. Souza, Michael L. Dennis and Nathan R. Newbury, *Applied Physics Letters* on October 11, 2016, DOI: 10.1063/1.4963130

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