Physics

VIEWPOINT

Next Generation Clock Networks

Free-space laser links have been used to synchronize optical clocks with an unprecedented uncertainty of femtoseconds.

by Peter Wolf*

In the opening paragraphs of his 1905 paper introducing special relativity, Einstein defines time as "the position of the small hand of my watch," with the validity of this definition restricted to the immediate vicinity of the watch. He then goes on to discuss the possibility of conventionally synchronizing distant clocks using the exchange of electromagnetic signals and thus of realizing a network of clocks that can be used to provide space and time information. Such networks of clocks are today a reality, the best known ones being the global satellite navigation systems (GNSS) like GPS or Galileo. These consist of atomic clocks on the ground and onboard satellites, together with the quartz clocks that are inside the everyday GNSS receivers we use in our cars and smartphones. In recent years, Nathan Newbury from the National Institute of Standards and Technology in Boulder, CO, and colleagues have been actively pursuing the goal of taking such clock networks to the next level of accuracy, by developing new methods of synchronizing clocks using laser signals in free space (Fig. 1). They now demonstrate full clock synchronization with femtosecond uncertainty—an impressive improvement by over 3 orders of magnitude with respect to any other present-day free-space technique [1].

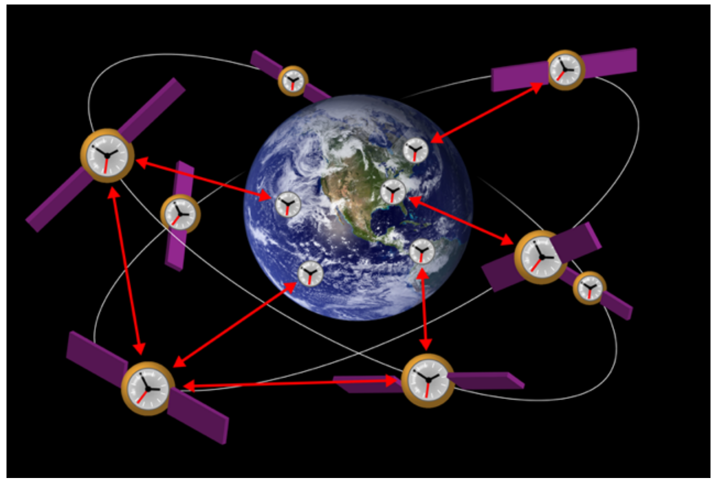

Figure 1: Artist's impression of future clock networks that use laser links (red) to synchronise clocks on the ground and onboard satellites. Newbury and co-workers [1] have demonstrated that such links can reach the femtosecond uncertainty level—a significant step towards building networks of clocks that are fully operational in this regime of uncertainty. (APS/Alan Stonebraker)

Applications of clock networks are numerous, for example, experimental tests of gravitation, interferometry for observational astronomy, navigation on the ground and in space (GNSS), telecommunications, and even high-frequency trading. Improvements in the performance of clock networks not only advance existing applications but also lead to new applications, such as the recent advent of clock-based determinations of Earth's gravitational field via the gravitational redshift of frequency due to general relativity.

Improving the network requires better clocks and better ways of comparing them over large distances. During the past decade or so, the accuracy of individual atomic clocks has improved by more than 2 orders of magnitude, and there is no hard limit in sight. The best clock uncertainties today are as low as a few parts in 10^{18} in fractional frequency—equivalent to an accumulated time error of less than 10 fs over one day. Unfortunately, techniques for comparing clocks over large distances have not followed suit, with the best radio frequency or optical methods still being limited to uncertainties of tens of picoseconds or more. Progress on reducing these uncertainties has been slow and difficult. This is mainly because of the relatively low frequency (and resulting low temporal resolution) of radio signals or the relatively broad pulses (tens of picoseconds) used in classical optical free-space links.

Optical-fiber-based techniques using continuous laser signals and their modulation have allowed researchers to bridge the gap between the performance of the best clocks and the techniques for comparing them over long distances [2, 3]. They allow clock comparisons at sub-10^{-18} uncertainty in fractional frequency, thereby satisfying the needs of today's best clocks. But optical-fiber-based techniques are limited to continental distances, are unpractical for applications "in the field" (for example, gravitational-field mapping), and are unsuitable for space clocks (for example, GNSS or fundamental-physics space experiments). Early

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attempts to transpose the fiber techniques to free space, so far for comparisons over distances of a few kilometers, have used either continuous laser signals [4] or ultrashort (approximately 100-fs) pulses [5]. These approaches have successfully demonstrated fractional frequency comparisons with uncertainties below 10^{-18} and have shown the way towards longer-baseline projects. However, until now, a full synchronization at the performance level of the best clocks—ensuring not only equal frequencies of the distant clocks but also equal time offsets so that the same "ticks" are delivered at the same time—has not been achieved. Demonstrating such full synchronization is the main achievement of Newbury and colleagues' new study. The result is a significant step towards building clock networks that are fully operational at the femtosecond uncertainty level.

The technique used by the Newbury group is based on femtosecond frequency combs—lasers that continuously deliver short (about 100-fs) light pulses at a typical rate of 100 million pulses per second. Such lasers allow the authors to solve two problems at the same time. The first is to locally generate a continuous time scale from an atomic frequency standard, that is, creating uniquely identified "time stamps" with femtosecond resolution. And the second is to transmit them to distant clocks so that they can be unambiguously identified at arrival with the same femtosecond resolution. A continuous laser, which produces a pure sinusoidal signal, is sufficient to compare frequencies with a 10^{-18} uncertainty [4], but it doesn't enable identification of which cycle of the signal is being measured, which is needed to fully synchronize the clocks. In other words, with a continuous laser, one can ensure that clocks tick at the same rate, but not that they produce the same tick at the same time. The latter requires counting ticks, something that is impossible at the typical operation frequencies (10^{14} Hz) of today's best atomic clocks. The frequency comb enables that rate to be reduced to the 100-MHz level (100 million pulses per second), but because of perturbing effects such as atmospheric turbulence, even that is still too high to unambiguously identify which pulse is being measured after transmission through free space.

The final trick to attain full synchronization is to obtain an independent coarse measurement of the time difference between the clocks, using another laser whose phase is modulated at a sufficiently low frequency but with sufficient time resolution to allow unambiguous identification of the arrival pulses. This procedure of "nested" signals (superposing several signals at decreasing frequency, the resolution of each one being sufficient to resolve the ambiguity of the previous one), from the 10^{14}-Hz clock laser, to the 100-MHz frequency comb, to the low-frequency modulation of the laser for the coarse measurement is not new; it has been used in the radio domain for decades. But Newbury and colleagues demonstrate its first full transposition into the optical regime, with a final uncertainty of the order of the period of the initial clock laser (fs) that outperforms any radio methods by several orders of magnitude.

The remaining challenges before global clock networks take the leap to the femtosecond level are as daunting as the already achieved results are impressive. The main one is to extend the relatively modest baselines of free-space laser links (as mentioned, these are a few kilometers so far [1, 4, 5]) to global scales. I expect that the first steps will focus on applications in the field, over still relatively short distances (100 km or so), possibly using an airborne relay, but without the need of optical fibers. Of course, the most challenging and most rewarding applications—such as GNSS or space tests of general relativity—will require satellite-to-ground or satellite-to-satellite links. Some prospective work in that direction is under way in order to handle the large velocities and resulting Doppler effects involved [6] and the main expected limiting factor that will come from atmospheric turbulence [7, 8]. But there is still a very long way to go.

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REFERENCES

[1] J. D. Deschênes *et al.*, "Synchronization of Distant Optical Clocks at the Femtosecond Level," Phys. Rev. X **6**, 021016 (2016).

[2] C. Lisdat *et al.*, "A Clock Network for Geodesy and Fundamental Science," arXiv:1511.07735.

[3] K. Predehl *et al.*, "A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place," Science **336**, 441 (2012).

[4] K. Djerroud, O. Acef, A. Clairon, P. Lemonde, C. N. Man, E. Samain, and P. Wolf, "Coherent Optical Link Through the Turbulent Atmosphere," Opt. Lett. **35**, 1479 (2010).

[5] F. R. Giorgetta, W. C. Swann, L. C. Sinclair, E. Baumann, I. Coddington, and N. R. Newbury, "Optical Two-Way Time and Frequency Transfer Over Free Space," Nature Photon. **7**, 434 (2013).

[6] N. Chiodo, K. Djerroud, Q. Acef, A. Clairon, and P. Wolf, "Lasers for Coherent Optical Satellite Links with Large Dynamics," Appl. Opt. **52**, 7342 (2013).

[7] L. C. Sinclair, F. R. Giorgetta, W. C. Swann, E. Baumann, I. Coddington, and N. R. Newbury, "Optical Phase Noise from Atmospheric Fluctuations and its Impact on Optical Time-Frequency Transfer," Phys. Rev. A **89**, 023805 (2014).

[8] C. Robert, J.-M. Conan, and P. Wolf, "Impact of Turbulence on High-Precision Ground-Satellite Frequency Transfer with Two-Way Coherent Optical Links," Phys. Rev. A **93**, 033860 (2016).

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