A Method for Comparing Remote Optical Clocks over a Free-Space Optical Link

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Abstract: We demonstrate a method to compare optical clocks approaching 10^{-17} uncertainties through the exchange of optical pulses from phase-locked frequency combs. We discuss results over a 120 m air path and prospects for longer distances.

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The next generation of optical clocks are reaching accuracies of 10^{-17} and lower [1, 2]. At these levels, several interesting applications emerge [3]. First, time and relativity become completely intertwined, even on the surface of the earth, where the gravitational red shift is ~10^{-16}/m. This relationship can be exploited for precision tests in relativity and geodesy (measurement of the earth's gravitation field), as well as to test the constancy of fundamental constants. Finally, the higher accuracy can translate to more accurate time/frequency standards to support navigation and sensing. However, all these applications require the comparison of two physically separated clocks. Standard microwave-based clock comparisons are inadequate at the 10^{-17} level. Coherent optical links through fiber can support comparisons at this level, but only if fiber path length fluctuations can be cancelled through perfectly reciprocal two-way transmission [4-6]. This method limits comparisons of optical clocks to fixed sites that are separated by bidirectional point-to-point fiber links. Free-space laser links nicely avoid the need for such fiber links and would add considerable flexibility to future clock comparisons, though line-of-sight paths are required. Researchers have explored coherent optical free-space links with a cw laser in an approach following coherent transfer over fiber [7]. Here we discuss a different approach that relies on the exchange of pulses between two remote frequency combs, each phase-locked to their own local clock.

Our approach, illustrated in Fig. 1, mimics two-way time transfer systems in the microwave domain. A comb at each site is phase-locked to a clock local to that site, thereby transferring the timing of the clock to the repetition rate of the pulse train with fs-level residual jitter. The pulse trains are exchanged over a hybrid fiber/free-space link between the sites; each site receives a pulse train from the other "remote" site for comparison with its local clock. Direct photodetection of the received pulse train would result in unacceptably high ps-level timing jitter. To preserve the comb's fs-level timing, we detect the received pulse train through heterodyne linear optical sampling (LOS) against the local comb, which permits fs-level time interval measurements [8, 9]. The difference of the time interval measured at each site cancels the path delay variations, leaving only the clock timing delay variations. This cancellation requires the path be perfectly reciprocal, which is ensured for a single-mode free-space link over time scales shorter than the characteristic turbulence time scale [10, 11]. This approach allows the link to be interrupted; as long as the combs remain phase-locked to the clocks, the measurement resumes when the link is reestablished.

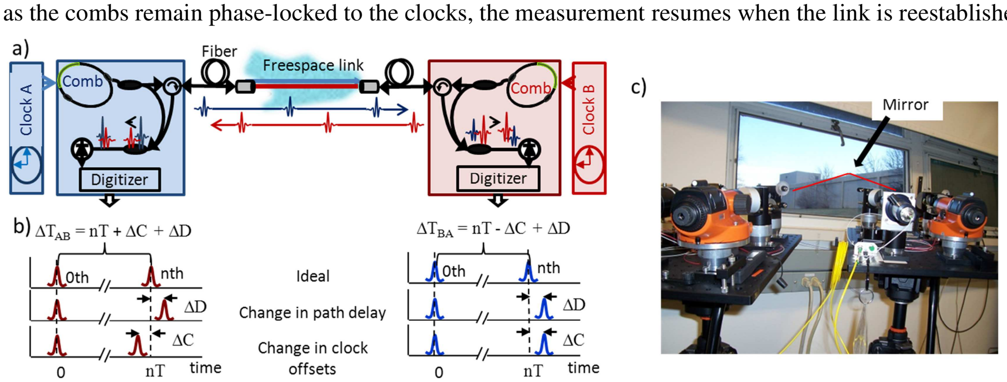

Fig. 1. a) Schematic of optical two-way transfer. Comb pulses are exchanged between the two sites (each site's telescope both transmits the local comb and receives the remote comb pulses) and a time interval is measured at each site. b) The time interval is shifted in the same direction by an effective path-delay change (ΔD), but in opposite directions, by an accumulated time offset between clocks (ΔC). c) Photograph of the setup for the preliminary demonstration showing two telescopes, each fiber-coupled back to its respective comb.

For an initial demonstration, the two systems use a common "optical clock" provided by a pair of cavity-stabilized lasers, as we are interested in evaluating only the residual timing/frequency jitter associated with the link. The two frequency combs are Er:fiber fs lasers, each locked to the reference optical clock such that they have similar repetition periods ($T_{A(B)}$~10 ns) that differ by a small but exactly known amount (δT=300 fs). Each comb's light is coupled through 10 m of optical fiber to a telescope, exits the laboratory through a window, reflects from a mirror ~60 m away, and is collected with the other system's telescope in the same laboratory, giving a path length of 120 m (See Fig 1c). Free-space power levels are 1 to 4 mW, well below the eye-safe limit of 9.6 mW.

The remote comb's pulse train is measured by sampling with the local comb using the LOS technique [9] (Fig. 1b). Due to the 300 fs repetition period difference the local comb pulse train "walks through" the remote pulse train (overlapping every T = 0.3 ms), effectively sampling the optical field of the remote pulses with a 300 fs resolution. To extract the delay between the *n*th and first pulse overlaps, they are Fourier-transformed, and the spectral phase across the *n*th pulse overlap is subtracted from the corresponding phase of the first pulse overlap; the slope of this phase difference corresponds to the differential time interval measured at each site, ΔD ± ΔC, where ΔD is the path delay and ΔC the clock timing delay; ΔC has opposite signs for the two measurement directions, whereas ΔD has the same sign. The symmetric and antisymmetric combination of the time interval measurements from both sites yields the path delay and residual clock timing delay between the two systems.

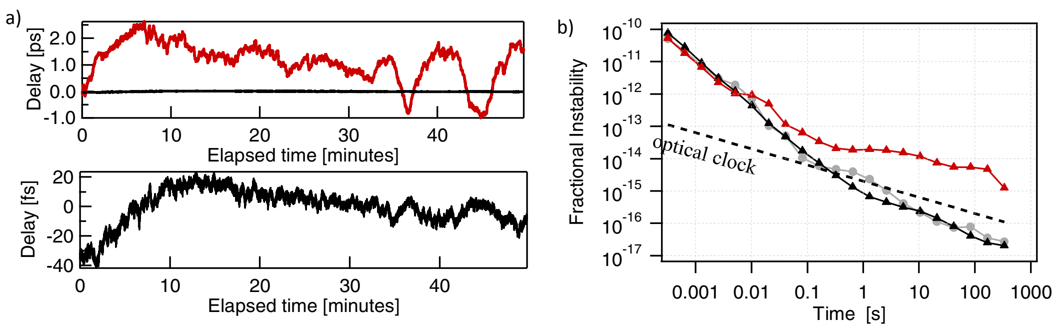

Fig. 2. a) Measured delay relative to unperturbed arrival time, boxcar-smoothed with a 3 s window, for the path delay, ΔD, (red trace) and residual clock-timing delay, ΔC (black trace). Lower plot: Expanded view of the residual clock timing delay. b) Fractional instability (modified Allan deviation) corresponding to the path delay (red trace) and residual clock timing delay (black trace). Also shown is the result from shorting the free-space path (grey circles) and the current best absolute stability of Al ion clocks (dashed line) [1].

Fig. 2 shows results acquired over a 50 min. period. The path delay shows 3 ps time excursions due to atmospheric turbulence; the clock timing, however, varies by 60 fs pp with a standard deviation of 11.8 fs. This variation is likely caused by drift in out-of-loop fiber paths within the system and could be reduced. Fig. 2b) shows the corresponding modified Allan deviation. The initial slope of $\tau^{-1.5}$ corresponds to white phase noise. At integration periods longer than 1 s, the slope flattens, probably due to fiber-path drift; however, the link instability is still sufficiently low to support the timing fidelity of optical clocks. Also shown is a shorted path measurement, where the free-space link is replaced with a short optical fiber. This result lies on top of the link measurement, indicating that we are not limited by the free-space link, lending optimism to future measurements over longer paths.

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