

High-Performance Free-Space Photonic Links for Frequency/Time Transfer

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Abstract: We discuss optical two-way time and frequency transfer over air to connect remote optical clocks/oscillators. This method can link remote sites with a residual timing noise of femtoseconds and a residual fractional accuracy below 10^{-18} .
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Optical clocks and oscillators can now reach femtosecond timing jitter and fractional accuracies below 10^{-17} .^{1,2,3} At these levels, many interesting applications emerge including high-precision navigation, multi-static distributed sensing using either active or passive arrays, and precision tests in relativity and geodesy (measurement of the earth's gravitation field). However, all these applications require the transmission of frequency/time signals between two physically separated clocks/oscillators at ultra-high precision and accuracy; current microwave-based approaches cannot transmit signals at femtosecond levels or sub- 10^{-17} accuracies. Instead, optical oscillators require optically based transfer methods. Coherent optical links over fiber-optics are a proven and viable solution, but only between optical clocks at fixed sites separated by a dedicated bidirectional fiber link.^{4,5} Here, we discuss the alternative approach of a free-space laser link. This free-space approach avoids the need for installed optical fiber between the clocks/oscillators (though line-of-sight is required) and could enable many applications. Our approach is based on the two-way exchange of pulses from coherent optical frequency combs over a single-mode free-space optical link (see Fig. 1). This approach mimics rf-based two-way time transfer, but since it is accomplished at higher optical frequencies, it achieves lower residual noise. Despite the effects of turbulence, we achieve residual timing deviations below 1 femtosecond, residual instability of 10^{-18} at 1000 seconds, and fractional offset below 3×10^{-19} over a 2-km link.⁶

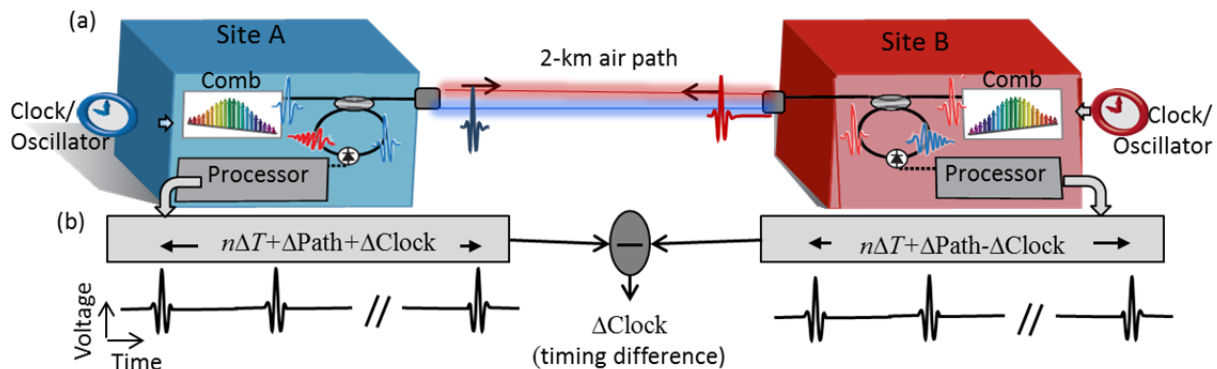


Fig. 1. a) Schematic of optical two-way transfer based on the coherent exchange of pulses from optical frequency combs. In our measurements, both sites (A and B) were co-located and used the same clock. The free-space path was a 2-km round-trip path across the NIST campus in Boulder, CO. b) Each site measures an interferogram between the received and local pulse trains at a nominal time separation per interferogram of T (black lower trace). The measured time interval after n interferograms is shifted in the same direction by an effective path-delay change (ΔPath), but in opposite directions by an accumulated time offset between clocks (ΔClock), which is the desired quantity. Because the same clock was used, we expect $\Delta\text{Clock} = 0$, however the transfer results in some small residual timing noise, shown in Figure 2.

Our approach is illustrated in Fig. 1. A comb (i.e., pulsed femtosecond fiber laser) at each site is phase-locked to an optical oscillator (cavity-stabilized lasers), thereby transferring the timing of the optical oscillator to the repetition rate of the pulse train with femtosecond-level residual jitter. The repetition rate of the combs at each site are set to a precise difference of $1/T$. The pulse trains are exchanged over a hybrid fiber/free-space link between the sites. Because direct photodetection of the received pulse train would result in unacceptably high ps-level timing jitter, instead the received pulse trains are heterodyned against the local pulse train at each site leading to a series of interferograms that will be separated by T in the absence of clock timing differences or air path length variations. As shown, the measurement of the interferogram separation at each site allows us to extract the clock timing difference independent of the path-length variations (and possibly apply a correction to “rephrase” the clocks, depending upon the application.) The two-way cancellation of the otherwise overwhelming psec-level path-length changes, denoted ΔPath in Figure 1, relies on the reciprocity of single-mode free-space links.⁷ The approach is robust to temporary loss of the free-space link due to turbulence because once the link is re-established the n th interferogram arrival time can still be coherently compared to the 0th interferogram arrival time to measure any intervening clock timing drift between sites.

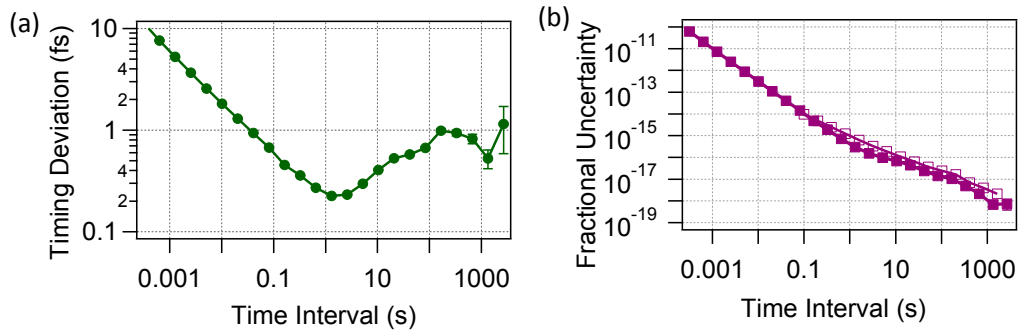


Fig. 2. a) Residual timing deviation of the free-space/fiber link as a function of measurement time interval. This quantity is relevant, for example, for “syntonizing” two remote oscillators. (b) The residual fractional frequency uncertainty, or Allan deviation, over the free-space/fiber link from the same data set as in (a). The solid squares represents all data including some periods with no signals across the link. The open squares are calculated from data limited to only a 100-ms period at the start and end of the time interval.

Fig. 2 shows results for the residual timing deviation as a function of observation time from a series of 2-3 hour runs, with a total run time of 24 hours. These data were acquired at turbulence strengths of $C_n^2 \sim 10^{-14} - 10^{-15} \text{ m}^{-2/3}$ over the 2 km link. The timing deviation averages to below 1 fsec beyond 25 msec and then reaches a flicker floor. The corresponding residual Allan deviation drops below 10^{-18} at 1000 s observation period, more than sufficient to support the best optical clocks. This performance appears, so far, to be limited by the transceiver rather than the free-space link, lending optimism to future measurements over longer paths.

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