Free-Space Optical Time-Frequency Transfer Over 2 km

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Abstract: Precision free-space time-frequency transfer could advance fields where present microwave-based transfer is inadequate. We demonstrate an optical free-space link with femtosecond timing deviation and residual instability below 10^{-18} at 1000 seconds.

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A variety of fields including precision navigation, long-baseline interferometry, coherent radar arrays, clock-based geodesy, tests of fundamental physics, and comparison of a new generation of optical clocks [1-6], require time-frequency transfer substantially more precise than is possible with today's microwave-based techniques [7-9]. Optical time-frequency transfer over dedicated fiber links shows spectacular precision [10, 11]; however, free-space links are required for sea, air, space, or mobile terrestrial applications. Furthermore, optical carrier transfer as used in fiber links is inadequate for free-space links plagued by physical blockage and turbulence-induced degradation. To obtain a robust time-frequency transfer in the face of these obstacles we employ an optical corollary to microwave-based two-way time-frequency transfer (TWTFT). Optical TWTFT compares the elapsed time intervals between two sites rather than their frequencies. As such it requires only an exchange of pulses to synchronize the sites at the start and stop times of a time interval; the link can be completely interrupted between these intervals. Conventional pulse photodetection gives picosecond-level timing jitter; to obtain ~ 1 femtosecond residual timing jitter supported by the optical TWTFT (and demanded by the above-mentioned fields), we employ linear optical sampling (LOS) detection between stabilized optical frequency combs [12]. The combination of LOS detection and the inherent reciprocity of the single-mode free-space link [13, 14], allow cancellation of optical path length variations to below 300 nm over milliseconds to hours.

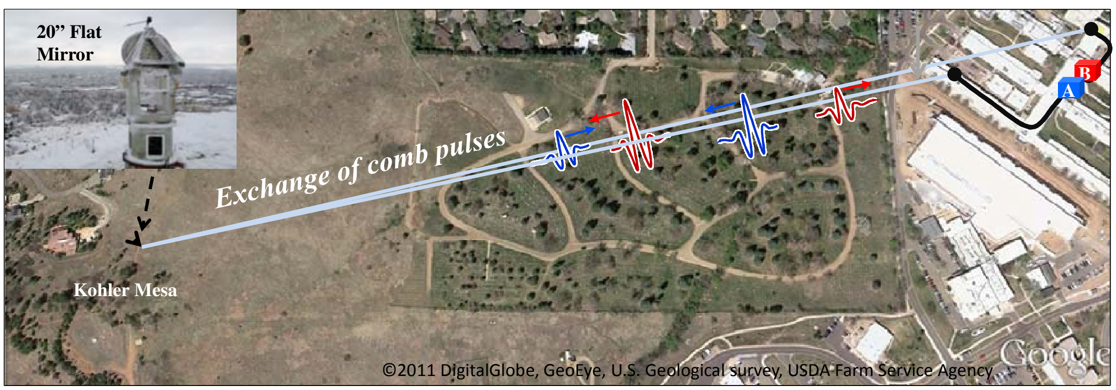

Fig. 1. Free-space link showing folded path between separate locations, and fiber links to the laboratory.

This work follows our previous demonstration over a 120-m free-space path [15]. Here, we arrange a much longer 2 km bi-directional free-space link shown in Fig. 1, and show the system can perform over these lengths. The two ends of the free-space link are at two separate locations; these locations connect to a common laboratory through ~400 m of optical fiber, allowing link ends A and B to be adjacent. Each link end is provided with a coherent pulse train from its own "local" frequency comb; this pulse train is split and part of the train is sent to the other end of the link. The two combs are locked to a common optical oscillator that serves as the clock. The comb repetition frequencies differ by $\Delta f_r=1/\tau$; LOS between the local and received pulse trains gives information on time and phase variations of the received pulse train as a train of interferograms nominally separated by τ. The time intervals between the 0^{th} and n^{th} interferograms,

$$T_A(n\tau) = n\tau + \Delta T_{Path}(n\tau) + \Delta T_{AB}(n\tau) \text{ and}$$

$$T_B(n\tau) = n\tau + \Delta T_{Path}(n\tau) - \Delta T_{AB}(n\tau),$$

are measured at sites A and B respectively. Here, ΔT_{path} is the cumulative change in the time of flight over the reciprocal path while $\Delta T_{AB} = (T_A - T_B)/2$ is the cumulative timing difference between the clock at sites A and B and is the quantity of interest. Measurements at $n = 0$ and $n = N$ are sufficient to find $\Delta T_{AB}(N\tau)$ provided the combs remain locked to the optical oscillator; interruption of the link will not affect $\Delta T_{AB}(N\tau)$. The slope on a linear fit to $\Delta T_{AB}(n\tau)$ yields the fractional frequency offset $\Delta f_{\text{clock}}/f_{\text{clock}}$, where f_{clock} is the nominal clock frequency and Δf_{clock} is any frequency difference between clocks at the two sites. Here, this offset should be zero, as the two sites share a common clock.

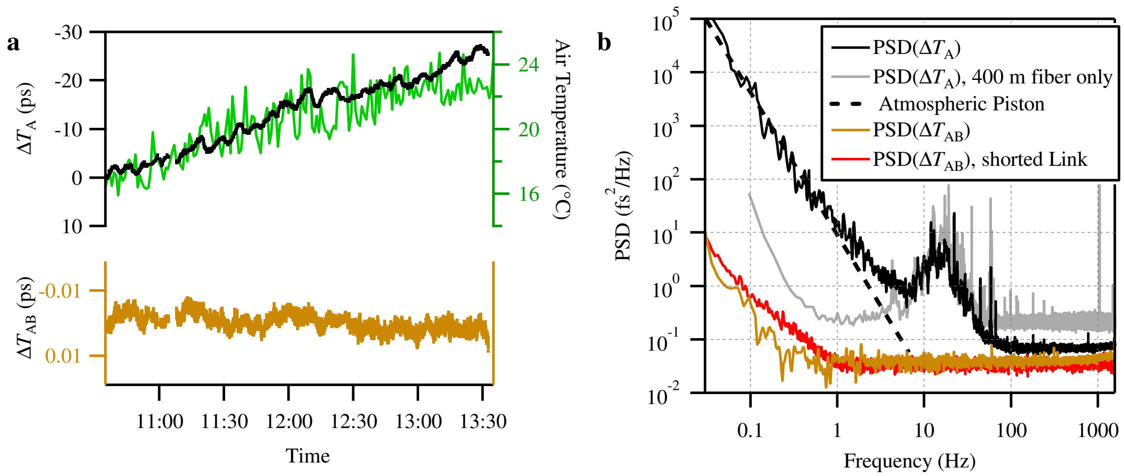

Fig. 2. **a**: One-way time-of-flight transfer ΔT_A (black) and air temperature (green); bottom, two-way time transfer ΔT_{AB}. **b**: PSD for one-way transfer (black) superposed with noise from both turbulence (dashed) and the fiber link (grey) and for the two-way time transfer (orange) along with the system noise floor (red).

Fig. 2a shows the one-way pulse time of flight and the two-way time transfer for a single data set. The one-way transfer shows tens of picoseconds variation, yet the two-way time transfer shows variations on order of a few femtoseconds. Fig. 2b shows power spectral densities (PSD) of the one-way time of flight as well as the two-way time transfer. The one-way PSD shows contributions from the 400 m fiber link noise at higher offset frequencies and from atmospheric turbulence "piston effect" (1 m/s wind speed and $C_n^2 = 2.5\times10^{-14}$ m$^{-2/3}$) at lower frequencies. The two-way PSD is unaffected by turbulence or fiber noise, and in fact lies directly on top of a background "shorted path" measurement, indicating that our 2 km free-space link (and the intervening 400 m of fiber) pose no limit, and longer links are feasible.

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