Impact of Strong Atmospheric Turbulence on Two-Way Optical Time Transfer

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Abstract: Frequency comb based optical time transfer can provide femtosecond-level timing which will support future clock networks. However, for long-distance terrestrial links, non-reciprocal atmospheric turbulence induces a timing penalty. Here, we quantify this penalty.

Precise distribution of time and frequency signals underpins a myriad of technologies including precision navigation, coherent sensing, and tests of fundamental physics. We are developing an approach to optical time transfer (OTT), “tracking-comb OTT”, which relies on the use of a time-programmable frequency comb (TPFC) [1] in conjunction with Kalman-filter based signal processing in order to detect the pulse time-of-arrival from distant clock combs at nearly the quantum-limit. As tracking-comb OTT is used over long distance terrestrial links, the impact of turbulence, even though only on the order of 10’s of femtoseconds, becomes appreciable. Here, we quantify these impacts.

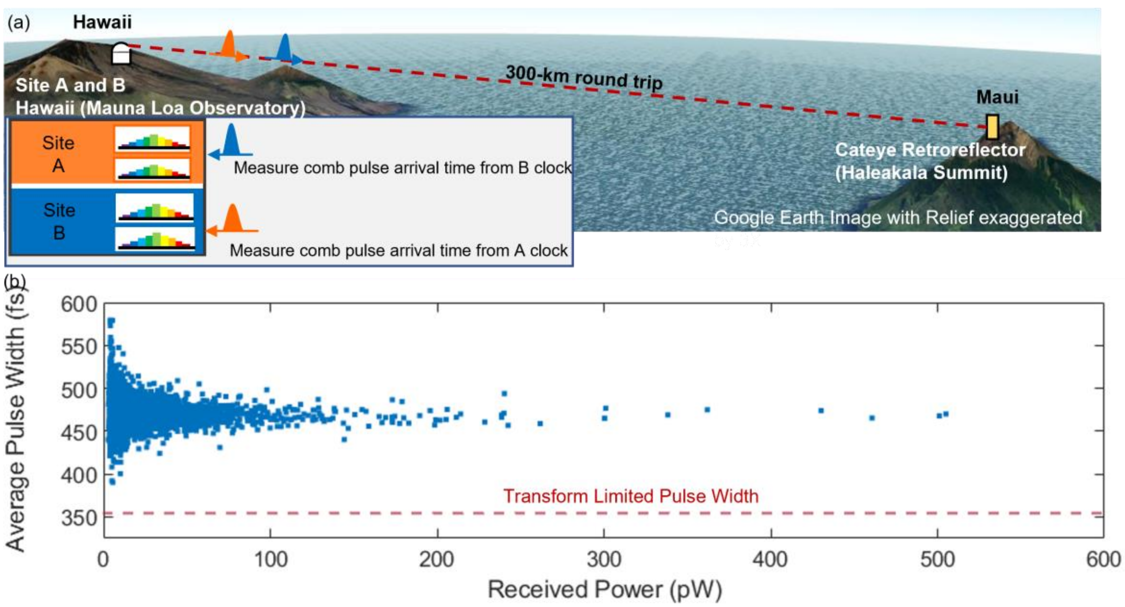

Fig. 1. Comb-based Optical Time Transfer over a 300-km terrestrial link by two-way exchange of optical comb pulses. (a) Optical pulses from the clock combs at two sites, A & B, are exchanged across a two-way free-space link. The incoming clock pulse time-of-arrival is measured with femtosecond-level precision relative to the local timescale. The difference in the pulse time-of-arrival yields the clock time offset, ideally independent of the time-of-flight including turbulence-induce noise. (b) A measure of the received comb pulse temporal width, as measured by linear optical sampling, versus received optical power. The linear optical sampling sets the averaging time for each pulse width measurement to 20 μs which is faster than expected turbulence dynamics (an average over 4000 comb pulses). As the received power decreases to close to the detection threshold, the scatter in the pulse widths increases dramatically. (Note the mean average pulse width is elevated above the transform limited pulse width by a chirp penalty of 1.3X.)

In the presence of strong atmospheric turbulence, variation in the temporal width of the frequency comb pulses (i.e. average pulse broadening) will occur in addition to the usual variation in the pulses' time-of-flight across the link from piston noise (i.e. pulse jitter) [2]. This broadening is seen in the data of Fig. 1b for comb propagation across a 300-km free-space link. This variation in the temporal width of the arriving comb pulses is an averaged result caused by turbulence-induced pulse distortions and therefore causes variations in the recorded pulse arrival times as well. This variation is found to be not fully reciprocal. Thus, it leads to a non-reciprocal noise term in the two-way timing difference used to compute the clock time offset, Δt , as well as the two-way sum, Σt , that measures the time-of-flight. (See Fig. 2.) For short distances and weak turbulence, this additional noise term will be negligible. However, with increasing pathlength, L , or turbulence strength as represented by the structure function [3], C_n^2, the reciprocal suppression is not sufficient at intermediate Fourier frequencies and the non-reciprocal excess timing noise can dominate (shaded regions of Fig. 2). This will result in elevated noise in optical two-way time transfer.

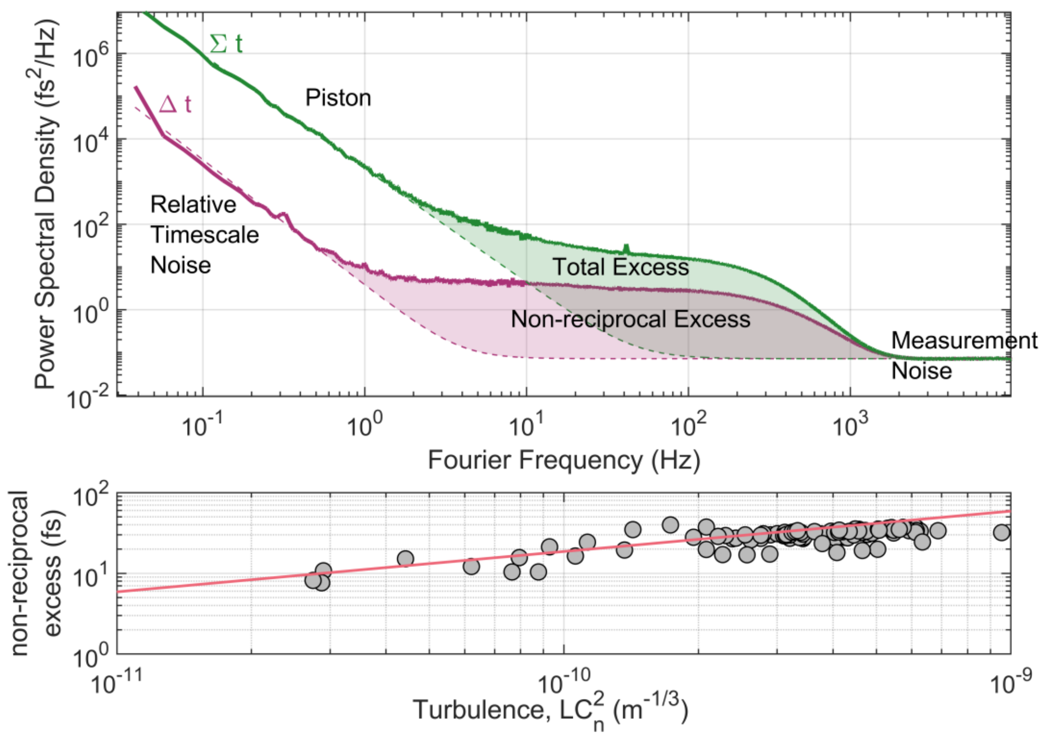

Fig. 2. (a) Representative timing power spectral densities (PSDs) for a 90 minute duration measurement over the 300 -km link for the sum of timestamps (green) and difference in the time stamps (pink). The dashed lines represent the expected PSD for the system in the absence of the excess timing noise. (b) Excess non-reciprocal timing noise as a function of LC_n^2 for the open loop Δt signal (grey circles) along with the results of a simple model (red line).

Fig. 2b quantifies the magnitude of the excess timing noise for 10-minute duration segments acquired during operation over the 300-km link. The value of LC_n^2 is obtained through a fit to the Σt PSDs assuming a constant 7 m/s wind speed. We can connect these data to a simple model based on Ref. [2] with good agreement assuming an outer-scale of 1 meter. These data show that while strong turbulence will limit the ultimate performance of comb-based OTT, the effect is only a matter of 10's of femtoseconds sufficient to support almost all applications.

References

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2. D. E. T. T. S. Kelly and L. C. Andrews, Waves in Random Media **9**, 307–325 (1999).
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