Ultra-Low Power Time Transfer: 300 Attosecond Synchronization with 300 fW Over 300 km of Air

Emily D. Caldwell, Jennifer Ellis, William C. Swann, Nathan R. Newbury, Laura C. Sinclair
National Institute of Standards and Technology (NIST)
Boulder, CO, USA
emily.caldwell@nist.gov

Benjamin K. Stuhl
Space Dynamics Laboratory
North Logan, UT, USA

Jean-Daniel Deschenes, Hugo Bergeron
Octosig Consulting
Quebec City, Canada

***Summary*— We demonstrate free-space time transfer across a 300 km atmospheric link with greater than 100 dB of loss. With received powers of only a few hundred femtowatts we synchronize two optical oscillators to 300 attoseconds and reach a fractional frequency instability of 3.1×10^{-19}, all without the use of large telescope apertures or adaptive optics. This work demonstrates a viable path for future time transfer between ground and satellite nodes in a global optical clock network with performance commensurate with state-of-the-art optical clocks and a low power-aperture product design.**

Keywords—optical time-frequency transfer, optical free-space links, ground-to-space clock networks

I. Introduction

Future networks of ground and space-based optical clocks promise clock-based geodesy [1], thousand-fold improvements in global time dissemination [2], and better tests of fundamental physics [3]. These networks hinge on high precision, free-space optical time transfer that can operate at the high losses needed to send light to satellites. Here, we leverage a time-programmable frequency comb [4] to demonstrate optical time transfer and synchronization at 10,000x lower received power than previous approaches [5,6], without sacrificing performance. Optical time-frequency transfer is demonstrated across 300 km between mountaintops in Hawaii, USA at launched powers as low as 40 μW, with synchronization reaching 320 attoseconds in time and 3.1×10^{-19} in frequency. This method operates with a mere 4 mW of frequency comb power and tolerates up to 102 dB of loss, which is greater than the losses expected for time transfer to geostationary orbits.

II. Time transfer over 300 km of air

We performed the experiments across a 300 km round trip path between Hawaiian islands with the two time transfer nodes (Site A and Site B) co-located at the Mauna Loa Observatory on the island of Hawaii and a cateye retroreflector located atop the Haleakala summit on Maui (Fig. 1a). The co-location of the sites enabled out-of-loop verification of the synchronization although this method could also be used in point-to-point [6] and three-node [5] configurations.

Each site is built around two frequency combs, a clock comb which is used to transmit time to the other site and a tracking comb that is used to detect the timing of the incoming pulses. All combs are run at nominally the same repetition rate of 200 MHz. Each site has a cavity stabilized laser which is used as the reference oscillator, though this laser could be replaced by atom-steered light from an optical clock if that is the desired reference. A fiber-based optical timing discriminator measures the timing offset between the incoming clock comb pulses and local tracking comb pulses, generating a timing signal that is used as feedback to steer the local tracking comb to follow the timing variations of the incoming clock comb (Fig. 1c).

Since the clock comb pulses are transmitted over the atmosphere, atmospheric phase noise is added to the timestamps of the incoming clock pulses. Due to the reciprocity of a single mode link, the same phase noise is written on the timestamps detected at the other site, and combining of the two sites' timestamps removes the atmospheric noise leaving the time offset between the two reference oscillators. For synchronization we use this time offset to steer the Site B clock comb into synchronization with the Site A clock comb. We verify this synchronization via an out-of-loop verification measurement also shown in Fig. 1c.

Fig. 1d-e shows results from the demonstration. The fractional frequency instability of the out-of-loop verification follows $(2.7\times10^{-17})\tau^{-3/2}$ reaching 3.1×10^{-19} at ~1000 seconds. With sufficiently high link margin we operated sending both the full comb power (4 mW) or 20 dB less (40 μW) with only a modest degradation in performance.

III. Implications for future ground to space links

High precision time transfer at low power-aperture product is a promising and necessary step towards time transfer between ground and satellites as well as between small terrestrial nodes.

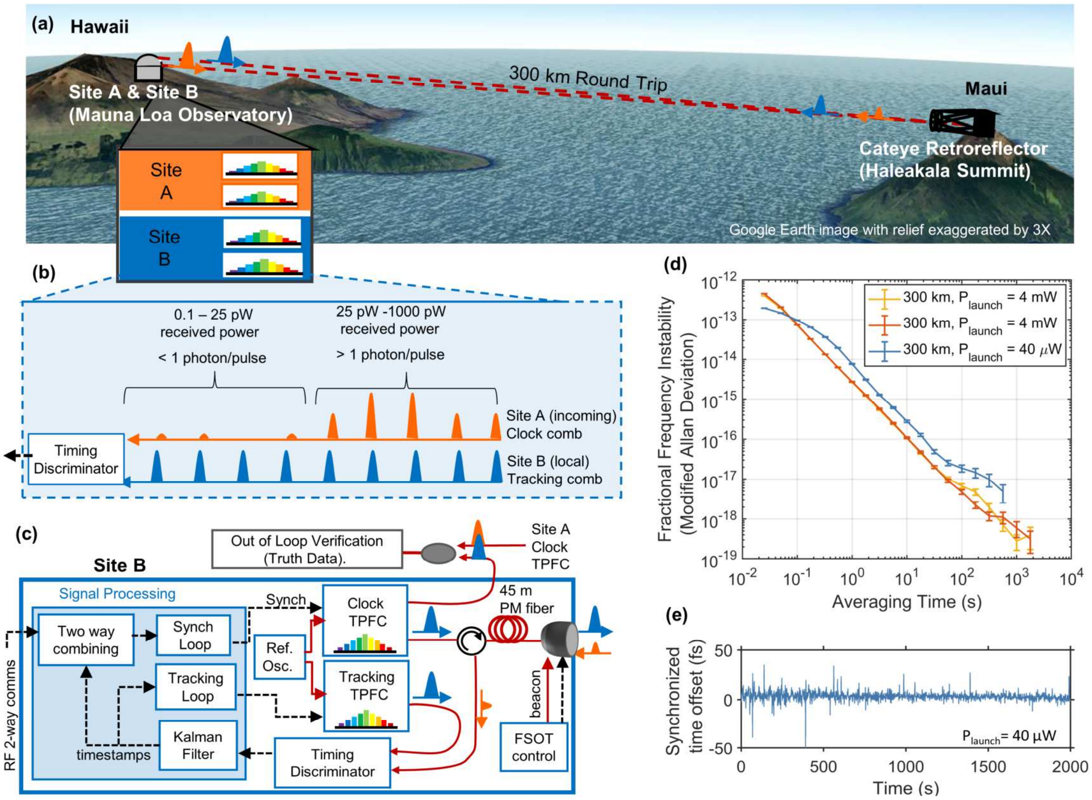

Fig. 1. (a) Schematic of the 300 km roundtrip free-space link between mountaintops in Hawaii. Here we used a folded link geometry with both Site A and Site B co-located at the Mauna Loa Observatory to enable out-of-loop verification of the synchronization. (b) Illustration of low power versus high power operation. The sensitivity of this system comes from running both the Site A incoming clock comb (orange pulses) and Site B local tracking comb (blue pulses) at the same repetition rate. The optical timing discriminator generates the time offset signal between the two combs that is used to feedback to the timing of the local tracking comb which acts as a tracking local oscillator. (c) Schematic of Site B which is built around two time programmable frequency combs (TPFCs) [4] which are locked to the same cavity stabilized laser (Ref. Osc.). The output of the timing discriminator steers the tracking TPFC to follow the incoming Site A clock TPFC. Combining the timestamps from both sites gives a real-time measurement of the timing offset between the sites and we use this to adjust the Site B clock TPFC to synchronize (synch loop) with Site A's clock TPFC. Pulses from the Site A and Site B clock TPFCs are combined and their offset measured for out-of-loop verification. The free-space link is acquired and stabilized using the free-space optical terminal (FSOT) control which uses a separate beacon laser for tip-tilt rastering and closed-loop control. Site A is identical to Site B minus the synchronization control to the Site A clock comb. (d) Modified Allan deviation of the out-of-loop verification data for synchronization across the 300 km free space link at full launch power (yellow and orange) and attenuated launch power (blue trace). Data further discussed in [7]. (e) Out of loop verification time trace for attenuated 40 μW launch in (d) shown with 1 second averaging.

The demonstrated operational parameters of 10 cm terminal apertures, 4 mW comb power, and up to 102 dB link loss are well matched to future low size-weight-and-power (SWaP) time transfer missions from geostationary orbits to portable ground-based clocks. For 10 cm ground and space apertures we estimate a loss of 91 dB for the 36,000 km trip from ground to geosynchronous orbit [7].

IV. Conclusion

We have demonstrated comb-based optical time transfer across a 300 km free space link, tolerating up to 102 dB of link loss and requiring 10,000× less received power than previous demonstrations. In these conditions we synchronized distant optical oscillators to $<10^{-18}$ in frequency, performance that is compatible with state-of-the-art optical clocks.

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