Topical:
Frequency Comb Based Optical Time Transfer

Nathan R. Newbury
National Institute of Standards and Technology (NIST)
325 Broadway, Boulder, CO 80305
Phone: 303-497-4227
e-mail: nathan.newbury@nist.gov

Emily Caldwell, University of Colorado, Boulder CO

Ian Coddington, National Institute of Standards and Technology (NIST), Boulder CO

Jean-Daniel Deschenes, Octosig Consulting inc., Quebec Canada

Laura Sinclair, National Institute of Standards and Technology (NIST), Boulder CO

Benjamin Stuhl, Space Dynamics Laboratory, Albuquerque NM

William Swann, National Institute of Standards and Technology (NIST), Boulder CO

I. Introduction

Time-frequency transfer between the ground and satellites has been accomplished for many decades through microwave/rf signals. With the advent of highly precise optical clocks and oscillators, these microwave/rf transfer techniques are no longer appropriate since their residual noise is much higher than that of the optical clocks. Not surprisingly, as atomic clocks move into the optical domain, so too must time-frequency transfer. Figure 1 summarize the achievable performance of time-frequency transfer techniques in terms of the modified Allan deviation, which is a measure of the fractional uncertainty in frequency or time.

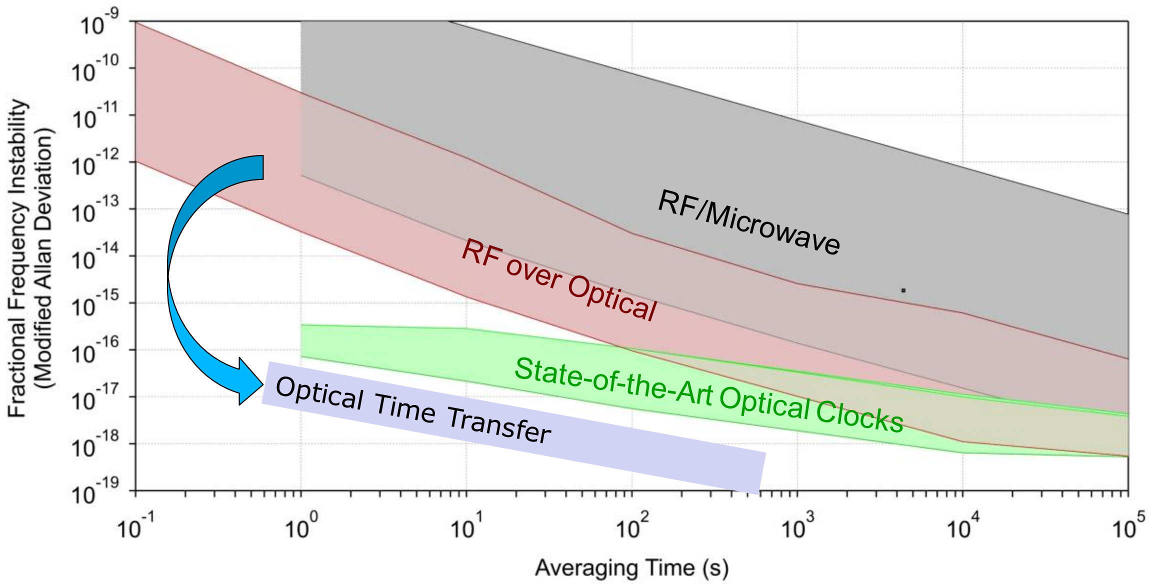

Figure 1: Residual fractional uncertainty of time-frequency transfer methods versus averaging time, as well as current absolute uncertainty for state-of-the-art optical atomic clocks (green band). The grey band represents techniques where both timing signals and transmission are in the microwave/RF domain. The red band represents techniques where the timing signals are in the microwave/RF domain but transmission is via an rf-modulated laser beam, e.g. pulsed laser. Finally, the blue band represents techniques where both timing signals and transmission remain in the optical domain through a self-referenced frequency comb. See Ref 1 for references that support the general bands shown in the figure.

To this end, several techniques have been developed for optical frequency transfer. Fiber-optic optical frequency transfer has shown excellent ability for frequency comparisons between optical clocks via “Doppler cancelled links” across a dark fiber or dark channel [2–5]. However, this approach is best suited for the continuous links provided by optical fiber connections. In contrast, a ground-to-space link will be highly intermittent due to air turbulence, weather, and orbit-related visibility between the satellite and ground stations. To deal with link intermittency, free-space time-frequency transfer techniques should be “phase-sensitive” and able to re-acquire the relative timing without ambiguity. In that case, one can “ride over” link dropouts and compare the elapsed time between clocks with minimal performance penalty. Given the 5-fs period of a cw laser at 1550-nm, this is effectively impossible for a Doppler cancelled link using a cw laser, but it is possible by use of a pulsed source, such as a frequency comb, that has a much broader timing ambiguity range.

For this reason, NIST and collaborators have developed frequency-comb-based techniques for optical time-frequency transfer [6–16]. This approach relies on the coherent exchange of frequency comb pulse trains, each phase-locked to their local clock, between the distant sites. It exploits the reciprocal nature of a single-mode optical link, which allows one to compare the timing of the two clocks independently from the time-of-flight. It is very similar to current rf two-way satellite time-frequency transfer [17–19], except that it uses the much higher bandwidth optical signals to enable high precision, femtosecond-level measurements of the clock time offset, independent of variations in the time-of-flight due to satellite motion and atmospheric turbulence.

II. Comb-based Optical Time Transfer: Background

This approach has been demonstrated, thus far, over free space links at terrestrial ~15-km distances and terrestrial ~25 m/s velocities. Note that the turbulence along many of these links far exceeds that encountered in future ground-to-space links. These demonstrations have included operation to a quadcopter-mounted retroreflector [9,10], operation across a three-node network [14], and frequency ratio comparison of two state-of-the-art optical lattice clocks (Yb and Sr) at 18 digits [20,21]. Figure 2 illustrates a few of these experiments.

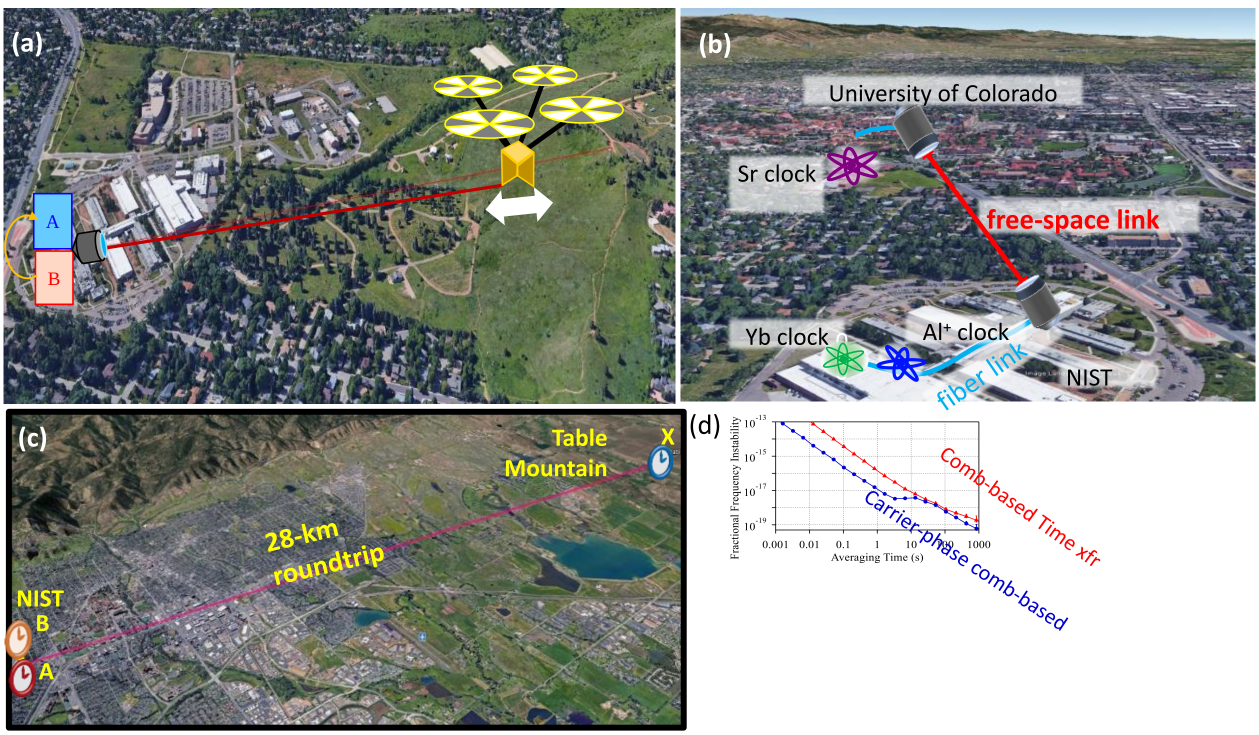

Figure 2: Demonstrations of comb-based optical time transfer (a) to a quadcopter-mounted retroreflector, (b)between state-of-the-art Sr and Yb lattice clocks, (c) over a 3-node network across 28 km of turbulent air. (d) Example modified Allan deviation of residual noise.

In all cases, the residual timing and frequency noise was well below that required for the "Fundamental Physics with a State-of-the-Art Optical Clock in Space (FOCOS)" mission [1] or other optical clock missions.

III. Comb-based Optical Time Transfer: Future Development for Satellites

However unlike conventional rf or microwave approaches, comb-based time transfer has not yet been demonstrated at the distance and relative velocities needed for ground-to-satellite links. Figure 3 provides context for the existing demonstrations compared to the future space-based links.

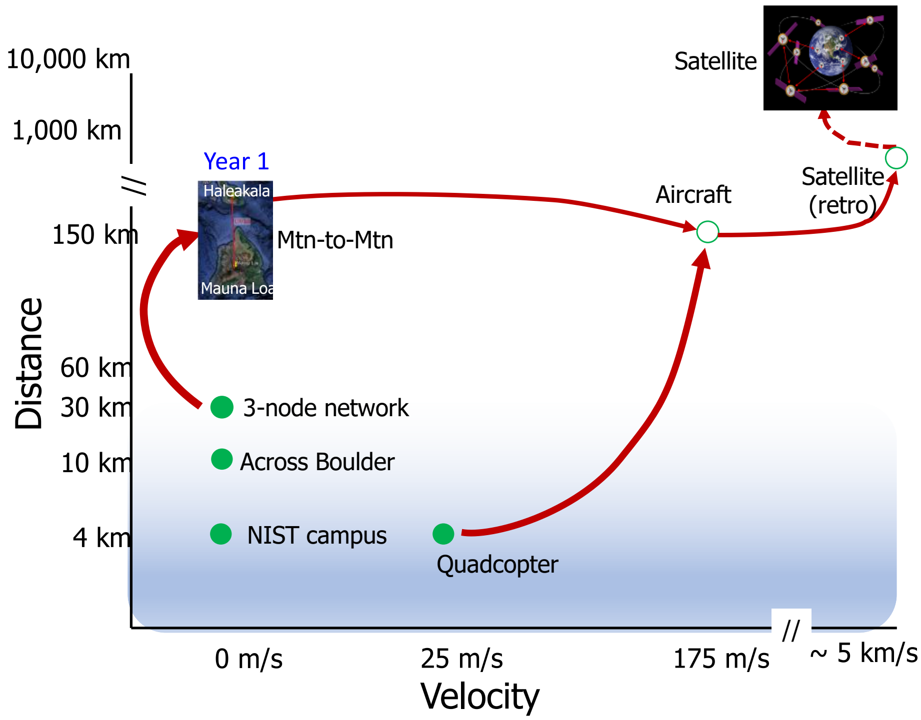

Figure 3: Comb-based Optical time-frequency transfer demonstrations (solid green circles) and the potential path (red lines) towards operation over ground-to-satellite links.

A significant technology development effort is required to address three inter-related issues:

1) Size, Weight and Power: There are two critical subsystems: the frequency combs and free space optical terminals. The only current option for the frequency comb is a fiber-based system as these can be self-referenced to provide the requisite femtosecond timing, exist in small form factor, and produce sufficient optical power. (The alternatives of electro-optic combs or microresonator based combs are generally not self-referenced, have a significantly larger system size, and output very low power.) Fortunately, there has been recent significant progress towards space-based operation of frequency combs and 10-Watt systems seem viable[22–25]. Similarly, free-space optical communications are driving the development of relatively inexpensive, low-SWAP optical terminals for space-based optical communications in both Europe and the US[26–28]. As these communication systems move toward higher data rates, they necessarily use coherent processing which has many of the same requirements, e.g. single mode operation, as optical time transfer. As a result, comb-based optical time transfer can leverage much of this technology development for a low SWAP system.

2) Long distance operation: In the previous demonstrations, the comb-based time transfer had a required received power of a few nanoWatts. A recent trade study has indicated this threshold could be even lower, depending on the configuration [15]. To put this in the context of a free-

space optical communication link, a 10 Gbps system at only 10 photons per pulse would require a similar 10 nW of received power. Therefore, the comb-based time transfer optical power requirements are very similar to optical free-space communication requirements. As noted above, for this reason comb-based time transfer can leverage continued improvements in the SWAP of coherent free-space optical terminals for space-based optical communications. Nevertheless, additional trade studies, algorithm modifications, hardware modifications and long-range experimental tests are needed to verify operation at very long distances. As noted in Figure 4, one possible testbed is to demonstrate operation between the Mauna Loa Observatory and Haleakala. A "round trip" link with a retoreflector located on Haleakal would have a total link loss equivalent to future ground-to-MEO point-to-point link.

3) <u>Operation at extremely high closing velocities</u>: While comb-based optical time transfer has been shown to perform without degradation at terrestrial velocities of ~ 25 m/s, future satellite-based networks will require operation at over 100x greater closing velocities. Although there do not appear to be any fundamental roadblocks, the effects of motion are of course amplified dramatically at the much higher velocities associated with satellite motion.The fundamental relativistic effects can be calculated and corrected. The systematic effects, for example related to Doppler shifts combined with system dispersion, are much more insidious and will require a significant effort to identify and then correct. In addition to the Doppler shifts caused by the high closing velocities over the link, motion perpendicular to the link causes point ahead issues. Fortunately both simulation and experiment indicate timing issues associated with point ahead are manageable[29–32]. Finally, we note that any modification to the system design to account for these high Doppler shifts must be compatible with both low SWAP and long distance operation. Therefore, the approach will focus on more sophisticated signal processing algorithms over the addition of hardware.

Figure 4 provides a roadmap to address these three issues through field experiments that provide a low-risk path towards future space-based optical time transfer.

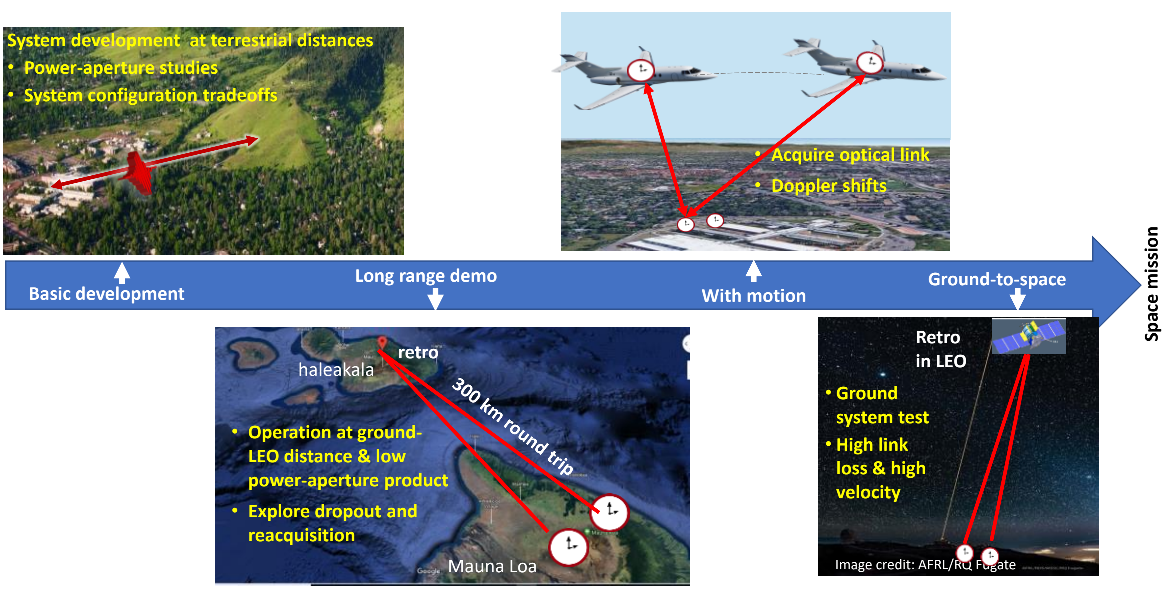

Figure 4: Example roadmap for the technological development of comb-based optical two-way time-frequency transfer. In all cases, the demonstrations could include optical atomic clocks.

IV. References

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