Quantum-limited time transfer for future ground-to-space optical links

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Recent terrestrial demonstrations of free-space optical time transfer show the technique can withstand the link loss expected between the ground and a satellite in geostationary orbit (GEO).[1] Here, we present noise simulations and analysis to estimate the expected performance of comb-based free-space optical time transfer to a geostationary satellite for intercontinental clock comparisons and coherence transfer for future distributed sensing (e.g. space-based VLBI nodes).

We also present preliminary work to expand the compatibility of comb-based free space optical time transfer to other orbits, namely low earth (LEO) and mid earth orbits (MEO). Satellites in these orbits exhibit high radial velocities (up to 5 km/s) and we propose a hybrid comb-CW laser system to overcome some of the challenges associated with these speeds.

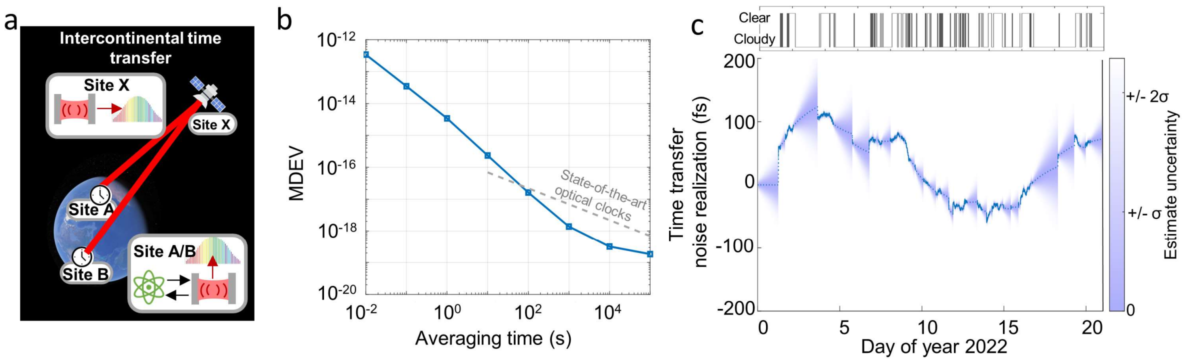

Fig. 1: Intercontinental clock comparison via GEO mission concept. (a) Ground-based optical atomic clocks are compared through comb-based free-space optical time transfer to a satellite in geostationary orbit. The space-based node does not include a clock, rather comb-based time transfer and a low size, weight, and power (SWaP) cavity stabilized laser enable the comparison. (b) Projected fractional frequency instability (MDEV) of the time transfer noise (blue) compared to state-of-the-art optical atomic clocks.[2] (c) Example realization of time transfer noise with cloudy periods. Top plot shows a clear-sky mask for visibility from a satellite in GEO to metrology institutes in Germany, the UK, or France and Boulder measured in 2022.[3,4] Bottom plot shows a realization of time transfer noise tracked by a Kalman Filter. During cloudy periods the Kalman Filter estimates the time transfer noise with growing estimate uncertainty. A brief clear period is enough to collapse the uncertainty to a few femtoseconds. Here, the ground clocks are assumed to be perfect with no frequency offset. During an actual measurement, similar time transfer noise would be added onto the differential clock noise and any constant frequency offset between the ground clocks would show up as a slope in the measured clock offset.

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[1]E.D. Caldwell, et al., Nature, vol. 618, 721–726, 2023.
[2]Boulder Atomic Clock Optical Network Collaboration et al., Nature, vol. 591, 564–569, 2021.
[3]EUMETSAT Meteosat cloud mask MSG 0 degree. https://data.eumetsat.int/, 2022.
[4]NOAA GOES-R Binary Cloud Mask. https://www.goes-r.gov/, 2022.