Free Space Optical Frequency Comparison Over Rapidly Moving Links

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The comparison of ultra-stable optical clocks will allow for unprecedented tests of fundamental physics. Optical clocks are already capable of testing Einstein's theory of General Relativity in the weak field regime [1, 2], providing extremely precise measurements of gravitational redshift. Their impact will be seen in geodesy, providing new means of defining and measuring the geoid [2, 3], as well as contributing to the redefinition of the SI second [4].

However, traditional optical frequency comparison techniques [5-8] are limited by the relative motion between local and remote sites. The extreme Doppler shifts experienced in rapidly moving optical links, such those formed between targets in space and on ground (±4 GHz for a 1550 nm carrier), prevent the narrow-band detection required to compare optical frequencies at the highest levels of stability.

Here we report on a system that uses an electro-optic phase modulator (EOM) with an actuation bandwidth sufficient to enable frequency comparison between ground and space. We are currently experimentally validating this system over rapidly moving free-space links to drones and helicopters.

Our preliminary work to date was conducted over a 1.7-2.3 km retroreflected link to a drone flying with a maximum in-line velocity of 15 m/s, equivalent to a Doppler shift of 20 MHz. The system successfully tracked 300 Mcyc of accumulated optical phase (a range of 300 m). The laser residual difference, in terms of phase (range) and frequency (velocity), is on the order of ±0.1 cyc (±0.1 μm) and ±100 Hz (±100 μm/s), respectively. The modified Allan deviation (MDEV) fractional frequency is shown in Fig. 1, with a best value of 2×10^{-17} at $\tau = 2$ s.

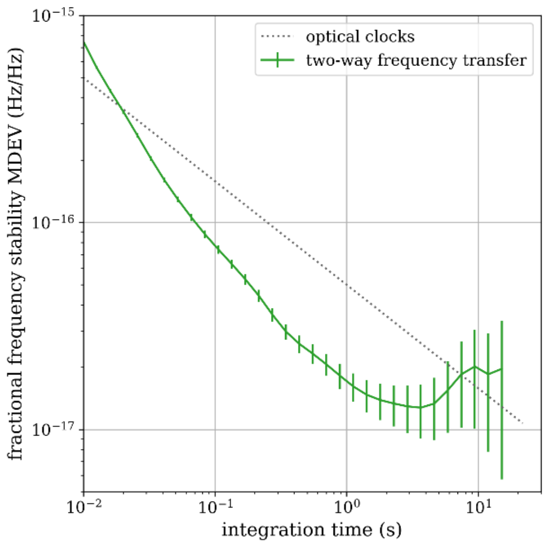

Fig. 1: Modified Allan deviation for two-way frequency transfer to a moving target. Optical clock performance is shown as the dotted line.

This system can be extended to ground-to-space optical frequency transfer with the addition of an *a priori* frequency sweep applied to the EOM.

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