High-precision laser Doppler velocimetry off an airborne target

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Laser Doppler velocimetry relies on measuring the Doppler shift of a laser beam reflected off a target to precisely infer the in-line velocity of that target. The excellent phase stability of commercial lasers, combined with modern techniques for robustly transmitting these ultra-stable laser beams over long atmospheric links [1], enable the possibility of performing precise laser Doppler velocimetry to moving targets. However, the high optical frequencies employed result in extreme directionality, and large Doppler shifts for even moderate inline velocities, which respectively lead to tracking, and detection bandwidth challenges.

We developed an optical terminal capable of tracking the target sufficiently to enable single-mode coupling of the reflected optical beam. The tracking terminal was designed through a two-tiered approach. An imaging camera was used to coarsely track the target, and an astronomical mount was used to provide the coarse pointing corrections. A quadrant-photodetector was then used to control a fast-steering mirror to provide fine pointing corrections.

To overcome the detection bandwidth challenge, we developed a laser transmission system that actively measures and compensates for the experienced link Doppler shift by varying the frequency of the transmitted laser signal. This is the same technique used to actively suppress link noise in phase-stabilised optical transfer systems [1]. This compensation means that all photodetection is performed on narrowband signals, and the dynamic range of the velocity measurement becomes limited by the frequency offset range instead of the photodetector bandwidth.

We used the optical terminal and laser transmission system to experimentally demonstrate long-range laser Doppler velocimetry to a moving airborne drone at a distance of 600 m. The system was capable of continuously tracking the airborne target, both in terms of lateral pointing to within 10 s of μrad, and in phase to well within an optical wavelength of 1550 nm, despite movement of the target. We achieved an in-line velocity precision of 2 nm/s with 10 seconds of averaging. Careful noise analysis additionally enabled an estimate of the absolute target distance to within a few metres.

[1] Dix-Matthews, Benjamin P. *et al.* 'Point-to-Point Stabilized Optical Frequency Transfer with Active Optics'. *Nature Communications* 12, no. 1 (2021): 515. https://doi.org/10.1038/s41467-020-20591-5.