Extending Dual-Comb Spectroscopy Path Length to 14.5 km by Separating Receiver from Transmitter

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Abstract: We present dual-comb spectroscopy across a 14.5-km path using remote receiver and data acquisition. This configuration results in lower link losses compared to open-path configurations with co-located transmitter and receiver.

Open-path dual-comb spectroscopy (DCS) has been demonstrated for monitoring city emissions using path lengths up to 3.35 km [1]. However such paths are not truly city-scale and path lengths on the order of 10-100 km are desirable to quantify emissions from a medium to large size city. To date, open-path DCS mostly uses a configuration with DCS system, transmitter, receiver, and data acquisition co-located and the light probing a path between a transceiver telescope and a remote retroreflector. While convenient, such folded paths have an optical path length L which is twice the physical path length. Even worse, one invariably overfills the retroreflector leading to a L^{-4} scaling for return power and thus SNR, making it very difficult to scale this folded geometry to longer distances.

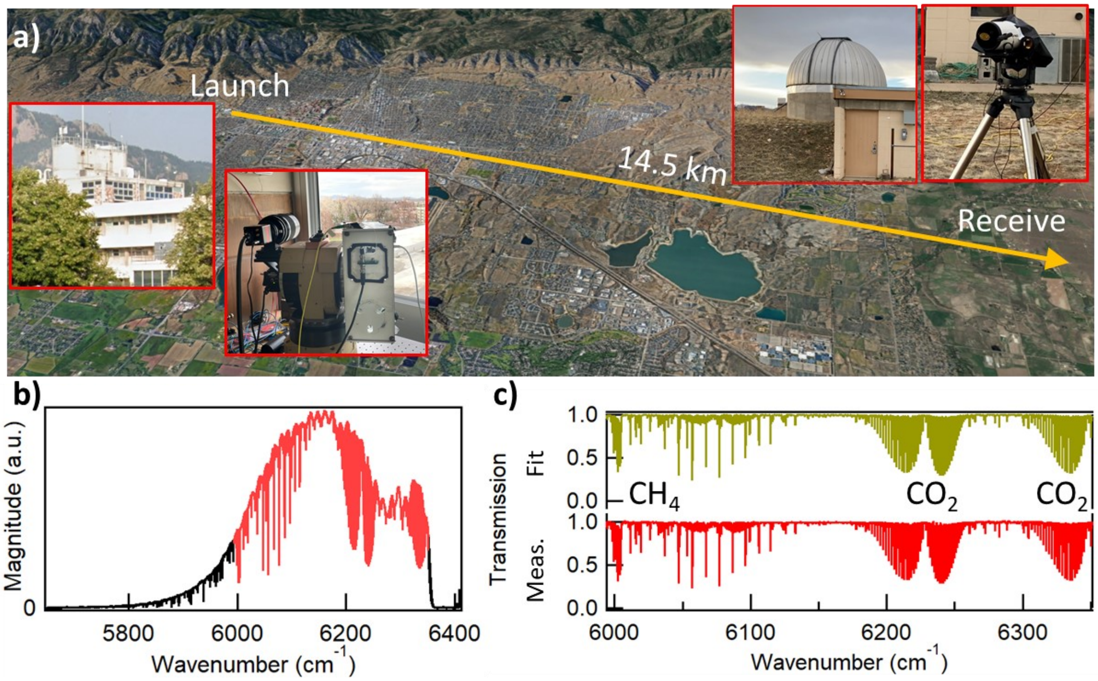

Figure 1: overview. **a)** Google earth image showing the 14.5-km link between NIST Boulder launch site (insets: rooftop laboratory containing combs and launch telescope; launch telescope) and Table Mountain receive site (insets: dome containing receive telescope; receive telescope prior to being placed in dome). **b)** Raw DCS spectrum acquired across the 14.5 -km link (two-minute averaging time); red: part of spectrum used for fitting. **c)** Bottom panel: measured transmission spectrum corrected for baseline using a piecewise polynomial fit. Top panel: spectral fit based on HITRAN 2020 database [2] with Voigt line shapes.

Here, we demonstrate a new open-path geometry where the DCS transmitter and receiver are separated on the two ends of the path, which means splitting the launch site from the data acquisition at the opposite end of the path. This "unfolded" geometry has equal optical and physical path lengths and results in a more favorable L^{-2} power scaling, allowing us to achieve high signal-to-noise ratio (SNR) over significantly longer paths. In this demonstration, we separate the transmitter and receiver by 14.5 km as shown in Figure 1. However this comes at the cost of some increased system complexity as coherent averaging of DCS interferograms requires that the acquisition electronics be synchronized with the frequency comb repetition rate and dual-comb interferogram length. This is straightforward in a classical folded geometry since launch combs and receive electronics are co-located, so the frequency comb directly clocks the acquisition electronics. In the unfolded geometry we introduce a common time base between the launch site (combs) and receive site data-acquisition using a GPS disciplined oscillator on each site. This along with a real-time computational timing and phase correction of the acquired interferograms at an 8 Hz rate allows for successful coherent co-adding of interferograms for arbitrary averaging times without penalty in signal strength.

Using the remote receiver and data acquisition configuration, we measure atmospheric trace gasses across the 14.5-km path (see Fig. 2) over twelve days. The system is based on a pair of Er:fiber frequency combs measuring in the 1560 nm -1700 nm spectral region with a 200 MHz point spacing. The light from both combs was launched from a custom telescope with a 6-cm launched electric field diameter located on an azimuth-elevation gimbal. The telescope gimbal pointing was manually realigned every couple of hours to compensate for slow telescope pointing drifts. At the remote end, the light was received with a 15-cm-diameter telescope, which stayed aligned without adjustment during the measurement period. The average received power was 12 µW for 10 mW of launched optical power, sufficient for high-fidelity DCS operation. The measured interferograms were coadded for 2-minute averaging time. Overall, 283 hours of data were collected.

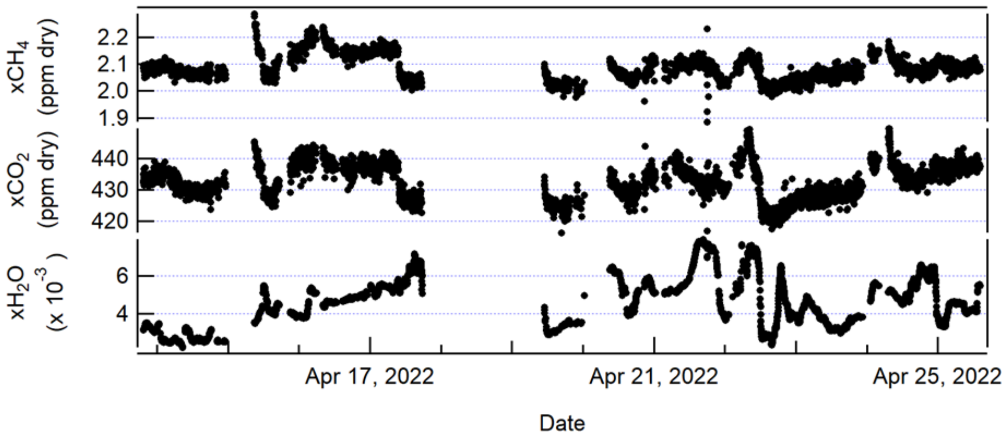

Figure 2: Extracted CH_4, CO_2 and H_2O concentrations across the 14.5 km link showing good system uptime during a twelve-day measurement period.

Figure 2 shows the extracted atmospheric CO_2, CH_4 and H_2O concentration over the twelve-day measurement period. The transmission spectrum is fitted to a model based on HITRAN 2020 [2] and Voigt line shapes, with trace gas concentrations as well as path-averaged temperature and pressure (not shown here) floating. CO_2 and CH_4 show significant correlated variation due to atmospheric variation coupled with local/regional emissions. The sensitivity is estimated to be 5 ppm and 0.03 ppm for CO_2 and CH_4, respectively at two-minutes of averaging. Improvements to the acquisition system are expected to increase this sensitivity.

These results indicate that separating receiver and transmitter allows to scale up dual-comb spectroscopy path lengths to encompass city-scale green-house gas emissions measurement. Additionally, the turbulence for this city-scale path length was quite strong ($C_n^2 \approx 4 \times 10^{-14}$ $m^{-2/3}$) [3], reducing the average transmitted power. Vertical paths, or slant paths of a few degrees, would experience orders of magnitude less turbulence and could be pushed to even longer distances, potentially enabling ground to stratospheric balloon measurements of greenhouse gasses.

1. Waxman et al., Atmos. Chem. Phys., 19, 4177–4192 (2019)
2. I. E. Gordon, et al., J. Quant. Spectrosc. Radiat. Transf. 277, 107949 (2022)
3. Bodine et.al., APL Photonics 5,076113 (2020)