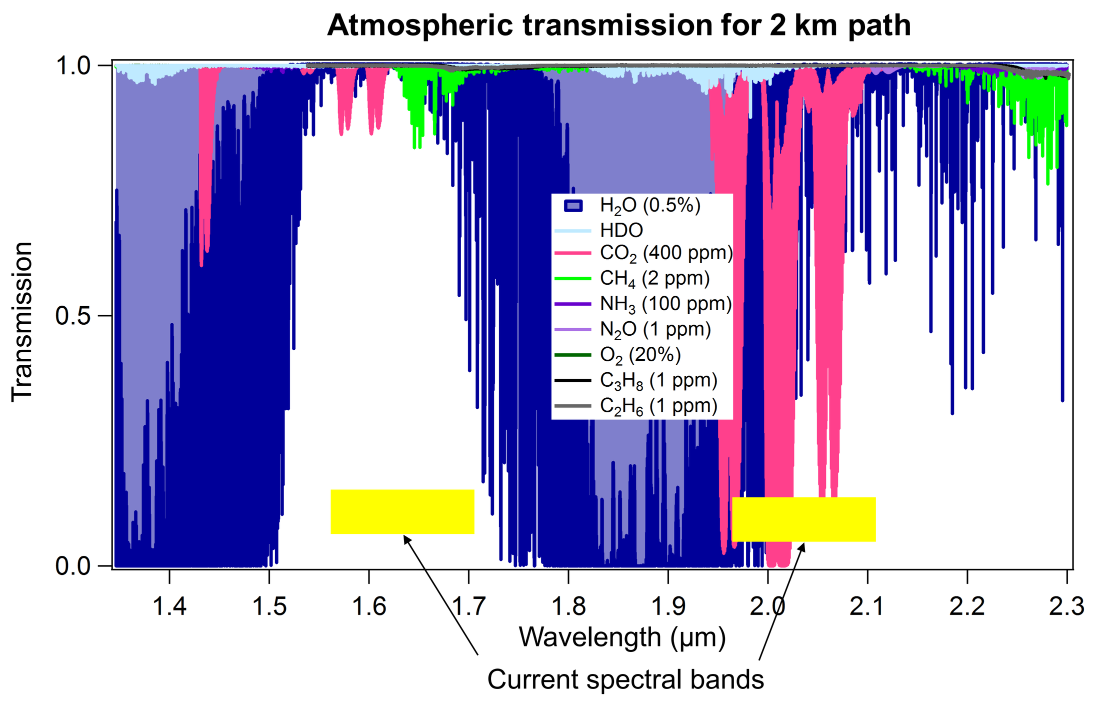
A portable dual frequency comb spectrometer for atmospheric applications

Kevin C. Cossel,[1,*] Eleanor M. Waxman,[1] Gar-Wing Truong,[1] Fabrizio Giorgetta,[1] William Swann,[1] Ian Coddington,[1] Nathan R. Newbury[1,@]
[1]NIST Boulder, Physical Measurement Laboratory, Applied Physics Division, Boulder, CO 80305. [*]kevin.cossel@nist.gov. [@]nathan.newbury@nist.gov

Why Dual-comb Spectroscopy?

- Extremely high resolution (0.0067 cm^{-1})
- Small size: 0.7 L box per comb
- No moving parts
- No instrument line shape
- Broad spectral coverage = multi-species detection
- Well-suited to lab studies in multi-pass cells
  - Near-flat signal/reference ratio
  - Fast (20 second) time resolution
  - Ability to average for minutes to hours
- Well-suited to outdoor studies
  - Can propagate >1 km with spatial coherence
  - Optimal for city-scale measurements
  - Low sensitivity to air path turbulence



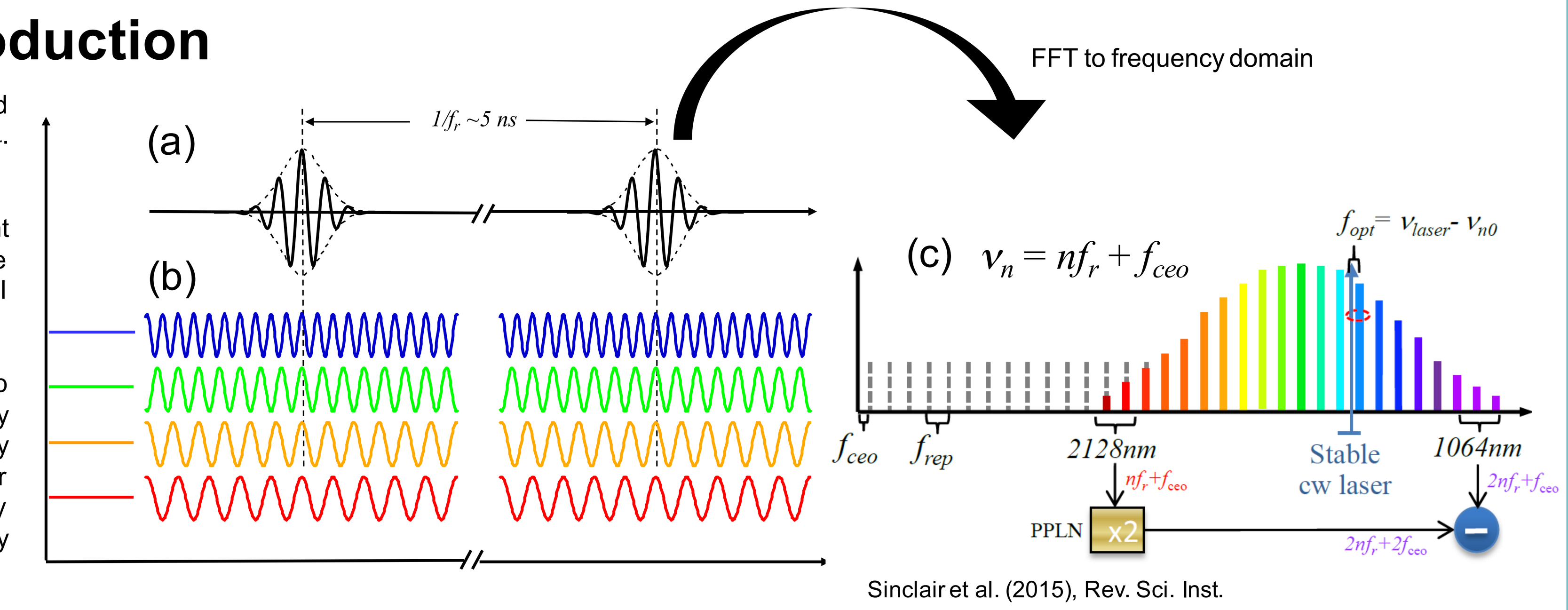
Frequency Combs

Frequency comb introduction

(a): A frequency comb laser emits femtosecond pulses at a precisely-known repetition rate f_r. Here, f_r is nominally 200 MHz.

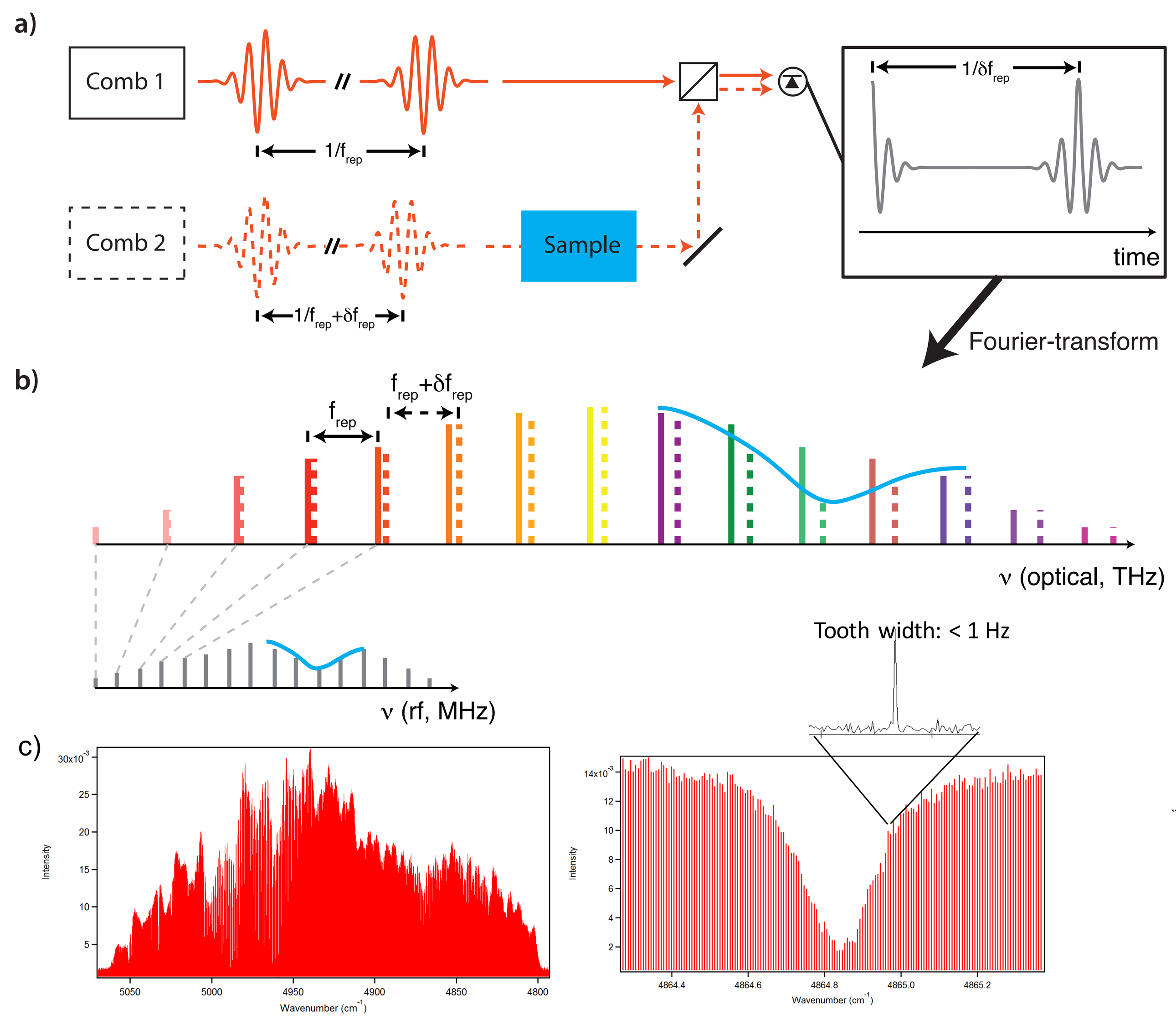
(b): Each pulse is made up of many different wavelengths. A pulse is formed when the wavelengths add up constructively (at vertical dashed line).

(c): In the frequency domain, a comb is made up of individual frequencies (teeth) separated by precisely f_r = 200 MHz. The comb is stabilized by locking one tooth to a stable cw (non-pulsed) laser (f_{opt}), and the phase of the pulse is determined by comparing two teeth whose frequencies differ by exactly a factor of two.



Sinclair et al. (2015), Rev. Sci. Inst.

Dual comb spectroscopy

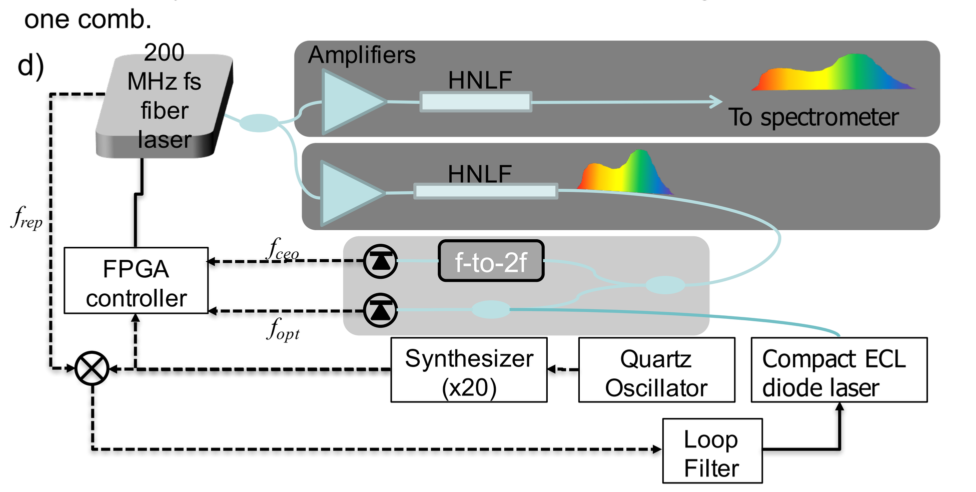


(a): Two combs are pulsed at slightly different f_r frequencies. The pulses from the two combs walk across each other, which results in interferograms just like in FTIR. The interferograms repeat in time with a frequency of Δf_r.

(b): In the frequency domain, the two overlapping combs in the near-IR produce a third comb in the radiofrequency (corresponding to the difference frequency between neighboring optical comb teeth) with tooth spacing of $\Delta f_r = f_{r2} - f_{r1}$. Each tooth in the rf can be mapped to a pair of teeth in the optical and converted back to the optical domain. The resulting spectrum has comb teeth spaced by f_r. Here this is 200.039565 MHz = 0.0067 cm^{-1}.

(c): Comb spectrum at 2 microns with CO_2 absorption. Lines are visible from 4950-5000 cm^{-1} (strong 2.01 μm band) and between 4850-4900 cm^{-1} (weaker 2.06 μm band). The first zoom shows individual teeth underneath a CO_2 absorption line. The second zoom shows an individual rf tooth.

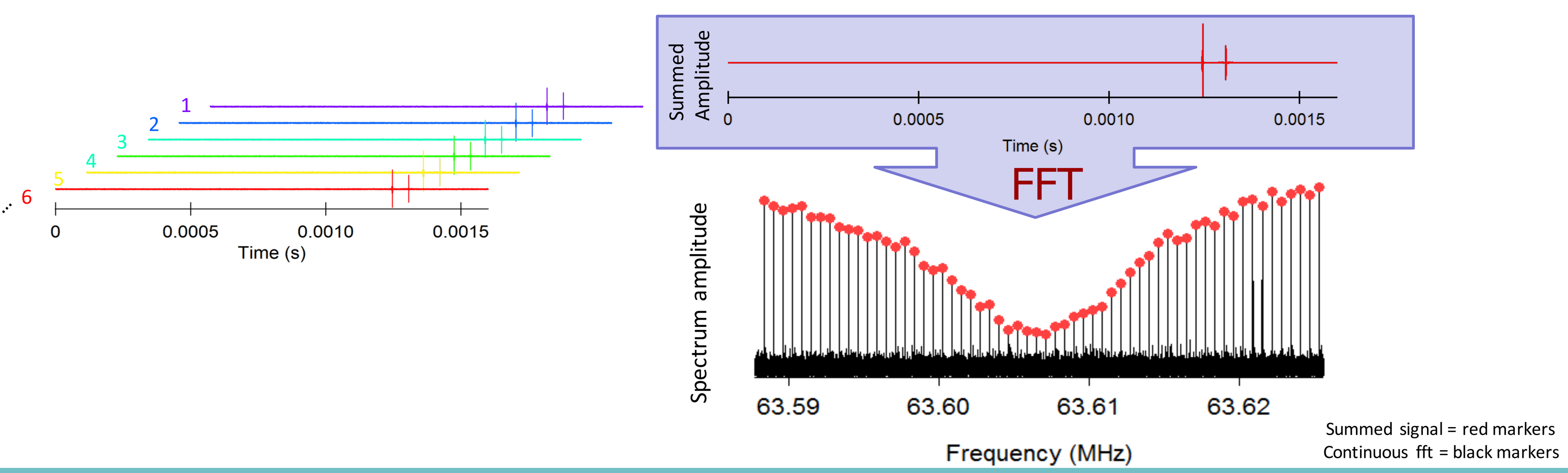
(d): Sketch of an individual stabilized comb system. The stabilization is necessary to maintain coherence between the combs. Separate amplifiers and highly non-linear fiber (HNLF) are used to provide light for stabilization and for spectroscopy. The reference cw laser is stabilized using the repetition rate of one comb.



Coherent averaging

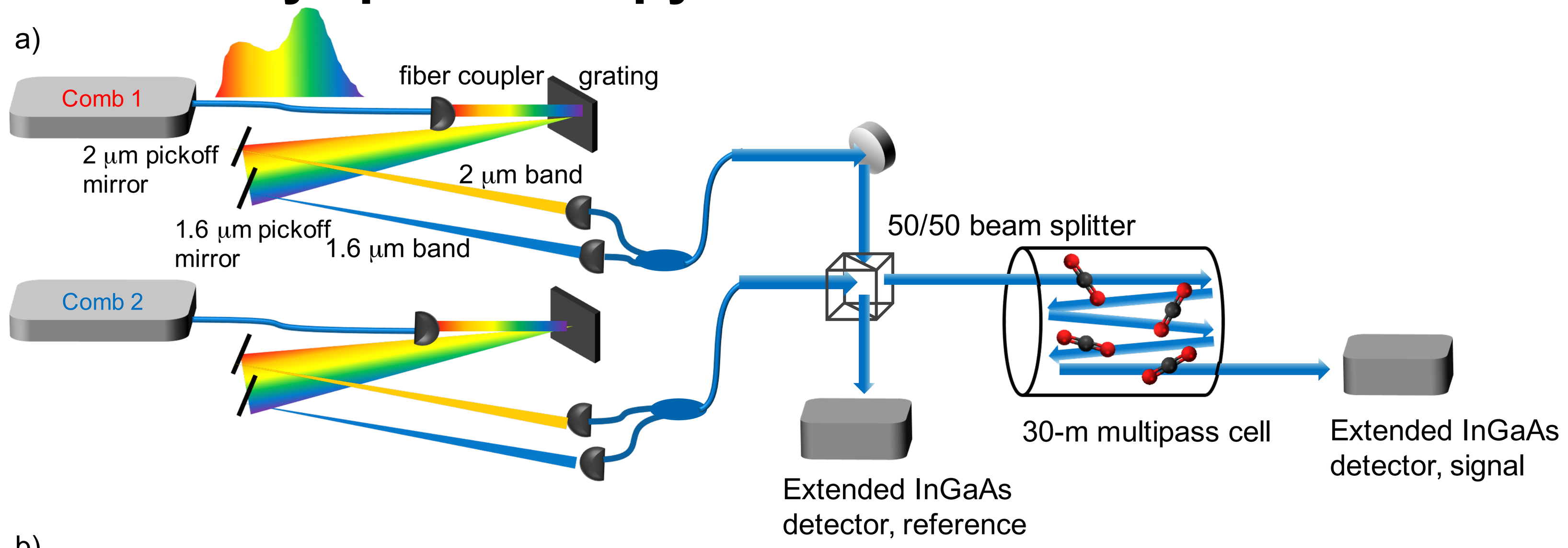
Saving every interferogram causes difficulties with data acquisition and storage. We solve this by coherent averaging the interferograms:

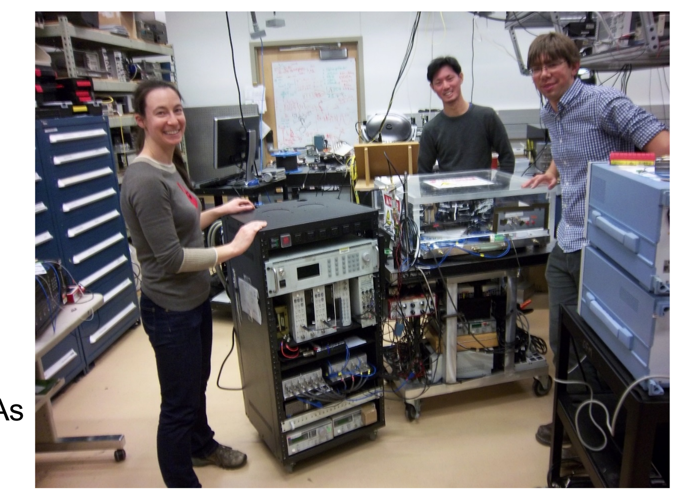
1) Align consecutive interferograms in time & phase
2) Point-by-point sum
3) Fourier transform
4) No loss of accuracy/ resolution

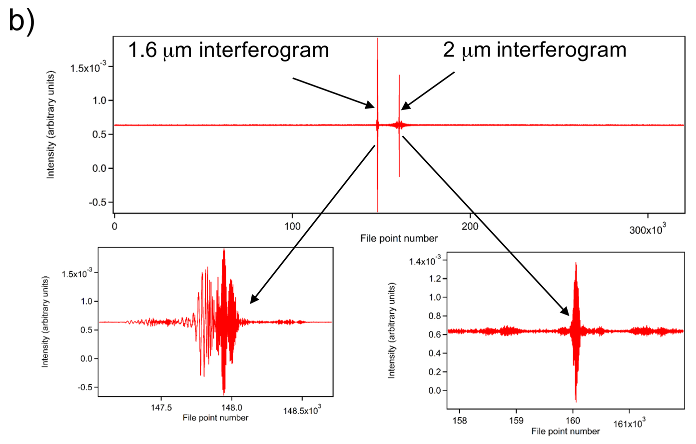


Applications

Laboratory spectroscopy





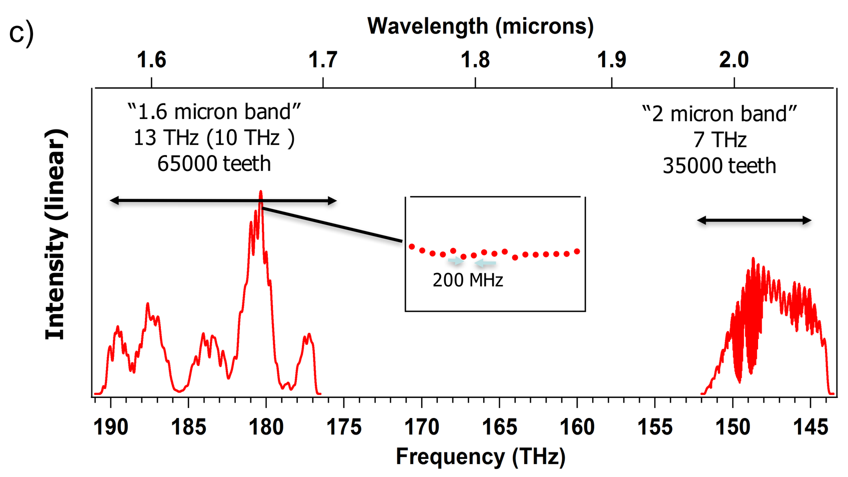


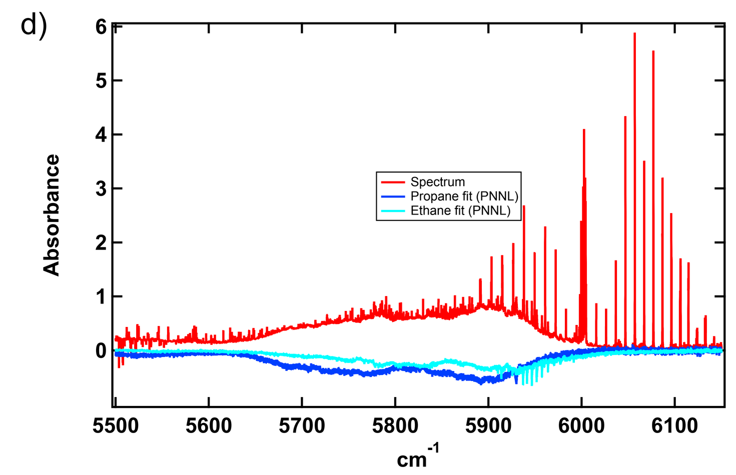
(a): Two combs are filtered to remove light outside of absorption bands at 1.6 microns and 2 microns, combined, and used for measurements. Filtering reduces noise in interferograms and allows us to tune the spectral regions for the species of interest (e.g. CO_2 & CH_4 versus CH_4, C_2H_6, and C_3H_8). The combs are then combined on a beamsplitter and one arm is sent to a 30-m multipass cell and then to an extended InGaAs photodetector. The other arm is sent directly to a photodetector for a reference channel.

(b): An example coherently averaged intergerogram showing two center bursts due to the two spectral bands. One averaged interferogram is recorded every 19.2 seconds.

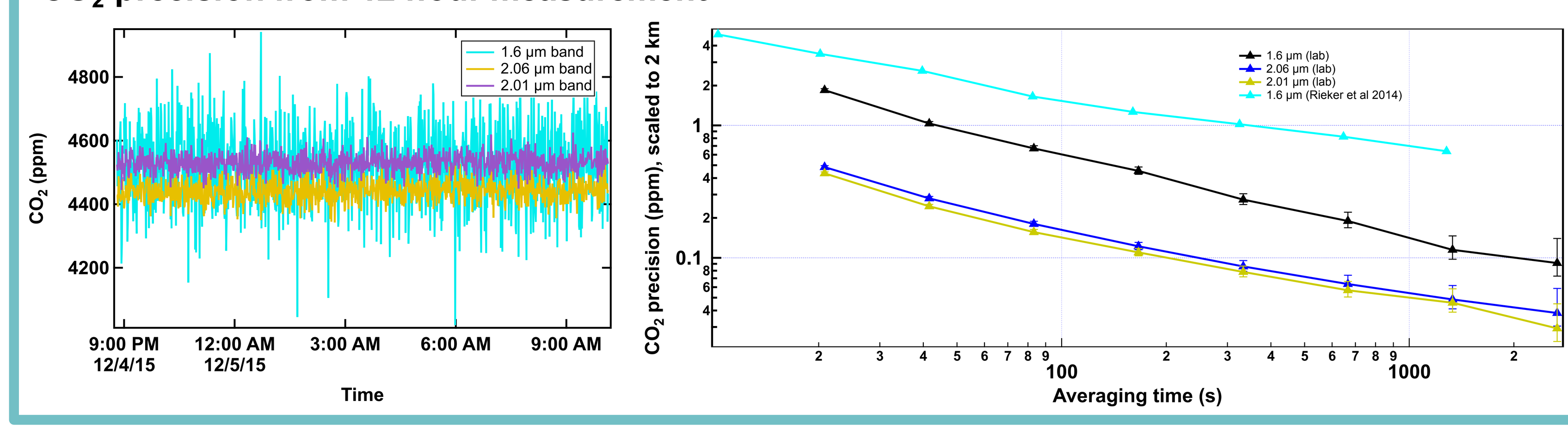
(c): Transmission spectrum (50 minute average) of CO_2 from the multipass cell.

(d): Spectrum of a mixture of methane, ethane, and propane illustrating the advantage of broadband spectral coverage.





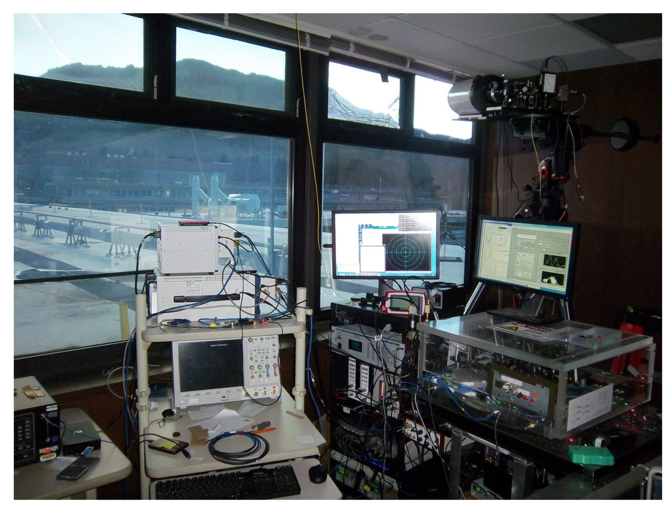
CO_2 precision from 12 hour measurement

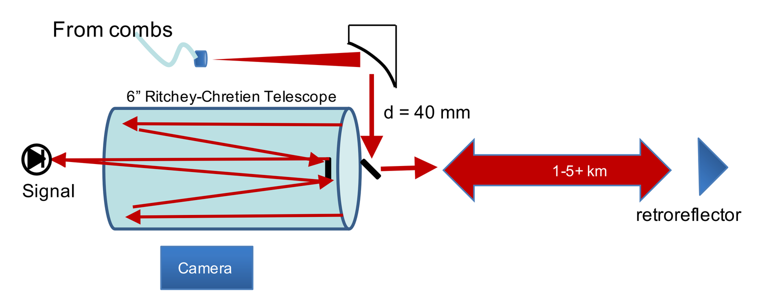


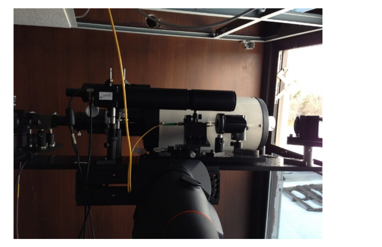
Precise measurement of relative HITRAN linestrengths

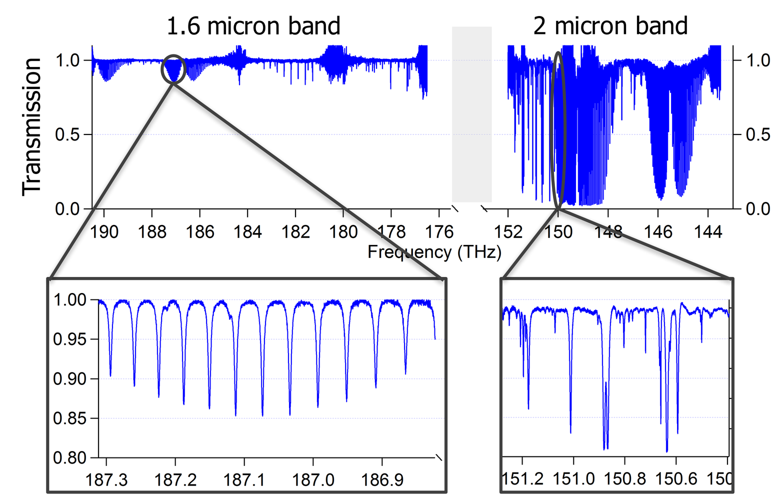
CO_2 Band	Mean (ppm)	Ratio to 2.06 band
1.6 μm	4520(4)	1.018
2.01 μm	4531(1)	1.020
2.06 μm	4442(1)	1

Long-path spectroscopy









Dual-comb setup for outdoor spectroscopy: Combs are housed in a mobile setup with a volume of about 0.5 m^3 that contains all optics and electronics. The combs are overlapped in a fiber beamsplitter, and launched with a power of about 5 mW. The light bounces off of a 5" retroreflector located between 1 and 6 km away (2-12 km round trip path) and then returns, where it is collected on a 6" diameter telescope. The returned light is then sent to the signal detector. Return power over 2 km path is approximately 1 mW, or 20% of the light.

Transmission spectrum: Dual-band atmospheric transmission for a 2 km path (138 minute coherent average).

References and Acknowledgements

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