Low-cost miniaturized laser heterodyne radiometer for highly sensitive detection of CO_2, CH_4, and CO in the atmospheric column

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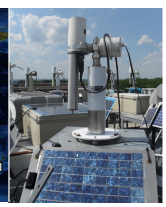
Abstract

We present a new passive ground-network instrument capable of measuring carbon dioxide (CO_2) at 1.57 microns and methane (CH_4) at 1.62 microns (key for validation of OCO-2, ASCENDS, OCO-3, and GOSAT), that could be expanded to include detection of carbon monoxide (CO) and oxygen (O_2). Designed to piggy-back on an AERONET sun tracker (AERONET is a global network of more than 450 aerosol sensing instruments), this instrument could be rapidly deployed into the established AERONET network of ground sensors. Because aerosols induce a radiative effect that influences terrestrial carbon exchange, this simultaneous measure of aerosols and carbon cycle gases offers a uniquely comprehensive approach. This instrument is a variation of a laser heterodyne radiometer (LHR) that leverages recent advances in telecommunications lasers to miniaturize the instrument (the current version fits in a carry-on suitcase). In this technique, sunlight that has undergone absorption by the trace gas is mixed with laser light at a frequency matched to a trace gas absorption feature in the infrared (IR). Mixing results in a beat signal in the RF (radio frequency) region that can be related to the atmospheric concentration. By dividing this RF signal into a filter bank, concentrations at different altitudes can be resolved. For a one second integration, we estimate column sensitivities of 0.1 ppmv for CO_2, and <1 ppbv for CH_4.

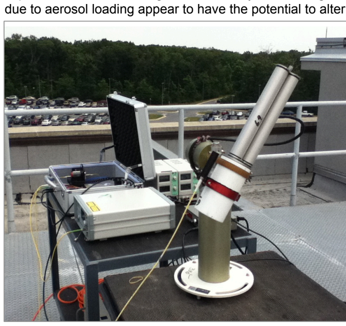
Background

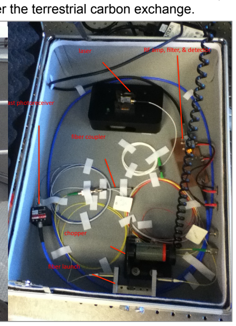
Laser heterodyne radiometry is a technique for detecting weak signals that was adapted from radio receiver technology. In a radio receiver, a weak input signal from a radio antenna is mixed with a stronger local oscillator signal. The mixed signal (beat note, or intermediate frequency) has a frequency equal to the difference between the input signal and the local oscillator. The intermediate frequency is amplified and sent to a detector that extracts the audio from the signal. In a laser heterodyne radiometer, the weak input signal is light that has undergone absorption by a trace gas. The local oscillator is a laser at a near-by frequency - in this case a low-cost distributed feedback (DFB) telecommunications laser. These two light waves are superimposed in either a beamsplitter or in a fiber coupler (as is the case in this design). The signals are mixed in the detector, and the RF beat frequency is extracted. Changes in the column concentration of the trace gas are realized through analyzing changes in the beat frequency amplitude. By separating the beat signal into a RF filter bank, trace gas concentrations can be found as a function of altitude.

Simplified Networking



Leveraging AERONET's 450+ monitoring stations worldwide (shown by red squares) makes it possible to establish a quick turn-around carbon monitoring ground network – making this technology feasible for validation and calibration of GOSAT. OCO 2, and future ASCENDS missions. An autonomous AERONET instrument is shown at right. Aerosols induce a radiative effect that is an important modulator of regional carbon cycles. Changes in the diffuse radiative flux fraction (DRF) due to aerosol loading appear to have the potential to alter the terrestrial carbon exchange.





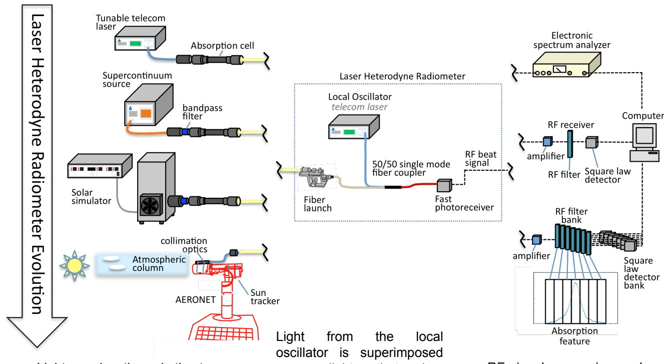
Connecting the LHR to an AERONET instrument is simple and non-invasive. A light-weight collimator connects to the AERONET sun tracker with an aluminum strap (left, shown in red). A fiber optic cable brings light from the collimator to the mobile LHR instrument.

MONITORING NETWORK	SITES USA	SITES Global	MEASUREMENTS CO_2	MEASUREMENTS CH_4	MEASUREMENTS CO	MEASUREMENTS aerosols	INSTRUMENT	INSTALLATION SIZE & DETAILS	PORTION OF ATMOSPHERE
FLUXNET	85	502	X				Infrared gas analyzer	Small building, requires operators, calibration gases	Near surface
TCCON	2	16	X	X	X		Fourier-Transform Spectrometers	Shipping container/small building, requires operators	Atmospheric column
ESRL/GMD Tall Tower	7	n/a	X	2 *sites*	X		Infrared gas analyzer	Small building, requires operators, calibration gases	Various altitudes
CCGG Aircraft (flask sampling)	17	n/a	X	X	X		gas chromatography, infrared gas analyzer, resonance fluorescence, UV absorption spectroscopy	Aircraft platform and Lab on ground. Requires operators for collection and analysis	Various altitudes
LHR/ AERONET	68	456	X	X	*future*	X	Laser Heterodyne Radiometer/ Sun photometer	Autonomous operation	Atmospheric column

While a number of networks measure carbon species, LHR would fill the gap in column validation measurements required by ASCENDS, GOSAT, and future OCO missions.

Passive Instrument Development Path

We use Laser heterodyne radiometry (LHR) to measure the concentration of trace gases in the atmospheric column by measuring their absorption of sunlight in the infrared. Each absorption signal is mixed with laser light (the local oscillator) at a near-by frequency in a fast photoreceiver. The resulting beat signal is sensitive to changes in absorption, and located at an easier-to-process RF frequency. By separating the signal into a RF filter bank, trace gas concentrations can be found as a function of altitude. The final instrument will be piggy-backed on AERONET, producing simultaneous column CO_2, CH_4, CO, and aerosol measurements.

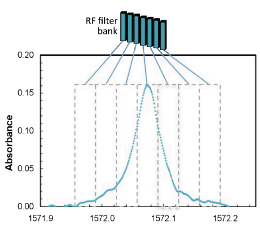


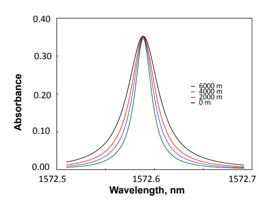
Light passing through the trace gas progresses from a telecom laser, to a supercontinuum source, to a solar simulator, and finally to sunlight. The increased complication is associated with superimposing less coherent sources with the local oscillator.

Light from the local oscillator is superimposed upon light that has undergone absorption by a trace gas, in a 50/50 single mode fiber coupler. Superimposed light is mixed in a fast photoreceiver, and the beat signal is analyzed for changes in absorption.

RF signal processing evolves from a commercially available spectrum analyzer to a RF receiver, and finally to an RF filter bank to deconvolute portions of the beat frequency more heavily weighted for different altitudes.

Resolving Altitude Profiles





The absorption cross section is broad near the Earth's surface where the atmospheric pressure is higher – and more narrow with increasing altitude as the pressure drops. This pressure broadening effect can be used to extract the atmospheric concentration of a species at different altitudes. Concentrations at higher altitudes weight the center of the feature more while concentrations near the surface weight the wings. By dividing the beat signal into a filter bank, altitude contributions can be partially resolved.

Performance Estimate

In a laser heterodyne radiometer, a weak signal is amplified by mixing it with laser light at a near-by frequency – resulting in a beat note. In this case, the weak signal is from sunlight that has undergone absorption by a trace gas and the laser light is from a low-cost telecommunications laser. The frequency of this sunlight is selected with a narrow bandpass filter to encompass a single absorption feature. The laser will be referred to as the local oscillator (LO) and the weak signal will be referred to as the source (S). The resulting beat (or intermediate) frequency (ω_{IF}) is the difference between the angular frequencies of the LO and the S (ω_{LO} and ω_S respectively) in rad/s.

$$\omega_{IF} = \left| \omega_{LO} - \omega_S \right|$$

The noise of the signal is given as

$$N_{SNL} = B\,P_{LO}$$

where B is the bandwidth in s^{-1} defined by the narrow bandpass filter and P_{LO} is the power of the local oscillator (laser) in J/s. For this bandwidth, the N_{SNL} is 6.07 x 10^7. The signal to noise ratio (S/N) can be found from

$$S/N = \frac{2(Bt)^{1/2}}{D_f\left(e^{h\nu/kT} - 1\right)}$$

For a one second integration time, the signal to noise ratio is 257. For a one minute and five minute integrations, S/N ratios reach 1990 and 4450 respectively.

For a one second integration time, we estimate the LHR instrument to be sensitive to 0.1 ppmv changes in the CO_2 column, and sensitive to <1 ppbv changes in the CH_4 column.

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