Precision heterodyne oxygen-calibration spectrometry: vertical profiling of water and carbon dioxide in the troposphere and lower stratosphere

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ABSTRACT

We describe the continued development of a new laser heterodyne radiometry (LHR) technique: Precision Heterodyne Oxygen-Calibration Spectrometry, or PHOCS. The prototype instrument is equipped with two active laser channels for oxygen and water (measured near 1.28 micrometers) and carbon dioxide (near 1.57 micrometers) determinations. The latter may be substituted by a heterodyne receiver module equipped with a laser to monitor atmospheric methane near 1.65 micrometers.). Oxygen measurements provide dry gas corrections and – more importantly – determine accurate temperature and pressure profiles that, in turn, improve the precision of the CO_2 and H_2O column retrievals. Vertical profiling is enabled by interrogating the very low-noise, absorption lines shapes collected by the O(10^{-3} cm^{-1}) instrument. PHOCS complements results from the Orbiting Carbon Observatory (OCO-2), Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), and ground-based Fourier transform spectrometers. The presentation will describe the development of the instrument by Mesa Photonics and will present the results of initial tests in the vicinity of Washington, DC during 2019.

Theoretical Background

Laser heterodyne radiometry (LHR) is a technique for detecting weak signals that was adapted from radio receiver technology. Incoming light is combined with light from a narrow-band laser source (the local oscillator or LO) on a photodetector. The detector output will contain AC electronic signals at the (optical) difference frequencies. PHOCS heterodyne signals are proportional to the solar spectrum at the LO wavelength. When the LO coincides with an optical absorbance, the heterodyne signal intensity will drop by an amount proportional to the absorbance. The formal theory of heterodyne spectroscopy begins with an electric field representation of the two optical inputs, Eq.(1), where t is time, and SUN refers to sunlight. LO – local oscillator –refers to the light from the diode laser.

$$E_{TOTAL}(\nu, t) = E_{SUN}(\nu_{SUN})\sin(2\pi\nu_{SUN}t + \phi_{SUN}) + E_{LO}(\nu_{LO})\sin(2\pi\nu_{LO}t + \phi_{LO}) \qquad \text{Eq. 1}$$

Theoretical Background (contd.)

The frequency difference term, highlighted in red in Eq. 2, is the source of the heterodyne signal. (All other frequencies are in the 10^{14} Hz range that far exceed the time response of optical detectors.) When a wavelength-tunable laser is used as the local oscillator, and the laser wavelength overlaps the absorption line, the difference frequencies are in the rf range. The range of rf frequencies that can be acquired is the electronic detection bandwidth, B_{IF}, and is represented pictorially below. All of the sunlight within the solid blue region contributes to the heterodyne signal. The electronic bandwidth is narrower than any absorption linewidth and significantly wider than the laser (local oscillator) optical linewidth of 0.1 to 1 MHz. That means it is possible to recover directly the shape of the absorption lines.

$$
\begin{aligned}
I(\nu,t) &= \left|E(\nu_{TOTAL},t)\right|^2 \\
&= \left|E_{SUN}(\nu_{SUN})\sin(2\pi\nu_{SUN}t+\phi_{SUN}) + E_{LO}(\nu_{LO})\sin(2\pi\nu_{LO}t+\phi_{LO})\right|^2 \\
&= I_{SUN}(\nu_{SUN},t) + I_{LO}(\nu_{LO},t) \\
&\quad + \frac{1}{2}E_{SUN}(\nu_{SUN})E_{LO}(\nu_{LO})\left[\cos\left(2\pi(\nu_{SUN}-\nu_{LO})t+\Delta\phi\right) - \cos\left(2\pi(\nu_{SUN}+\nu_{LO})t+\Sigma\phi\right)\right]
\end{aligned}
\qquad \text{Eq. 2}
$$

Instrument Description

PHOCS builds on earlier work by using continuously tunable, near-infrared diode lasers (Eblana Photonics) as heterodyne local oscillators, conventional fiber optics, and low-noise room temperature detectors. In addition, PHOCS includes recently developed rf power sensors that have -70 dBm noise floors and that are USB-powered and readout directly through a USB interface. The prototype instrument is equipped with two active laser channels for oxygen (measured in the a $^1\Delta_g$ band near 1.27 μm) and carbon dioxide (a portion of the 30012 $\leftarrow$ 00001 vibrational transition near 1.57 μm) determinations.

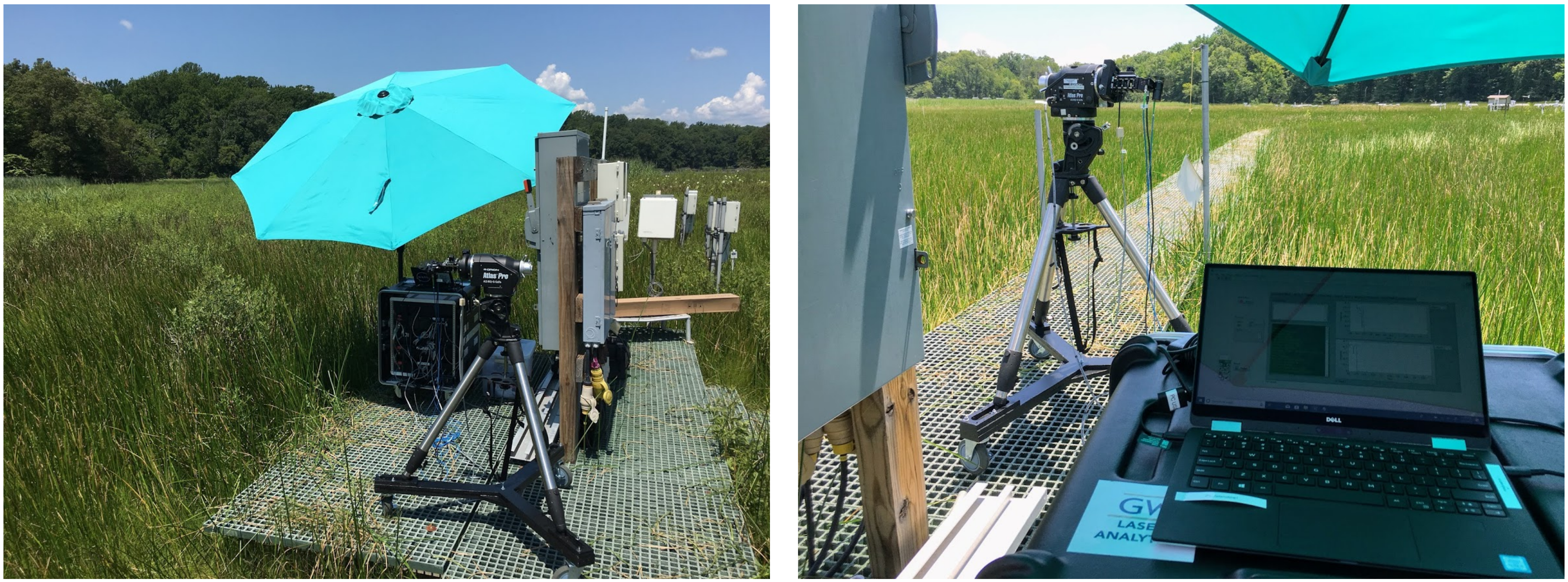
The instrument consists of two components: a sun tracker/ telescope and an electronics chassis (Figure 1).

Instrument Description (contd.)

PHOCS instrument deployed at George Washington University in Washington, DC.

FIGURE 1

Initial Field Deployment



PHOCS deployment at the The Global Change Research Wetland (GCREW) during Summer 2019. Located at the Smithsonian Environmental Research Center in Edgewater, Md., this 70-hectare brackish marsh is home to several long-term experiments designed to predict what the future holds for coastal wetland ecosystems as they cope with accelerated sea-level rise. [https://serc.si.edu/gcrew]

FIGURE 2

Retrieval

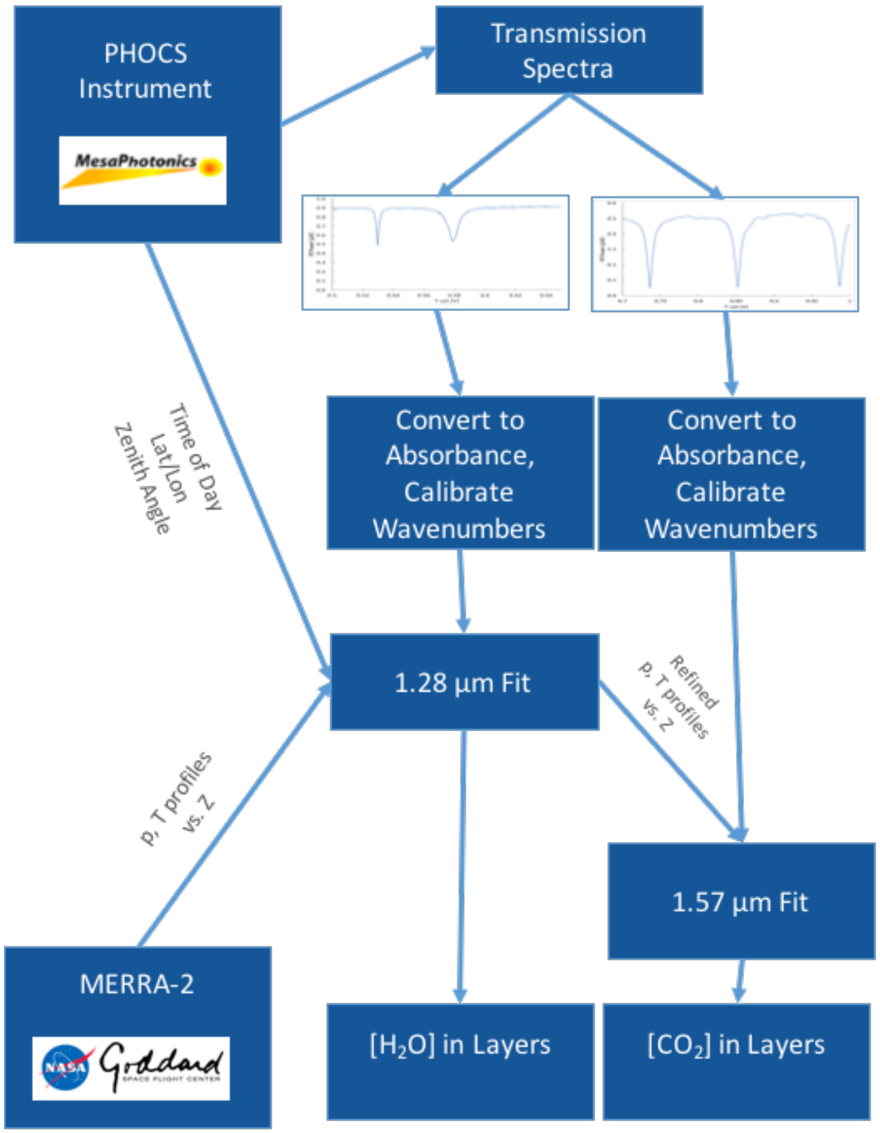


Illustration of data retrieval algorithm. For each laser wavelength region, spectra are collected as sensor location, sun angle, and time of day, e are recorded. An atmospheric model is used as input to spectral calculations that calculate the path-integrated absorption. Because of the incredible spectral resolution in the experiment, it is possible to extract from the fits concentrations for greenhouse gasses in several atmospheric layers.

Representative Fit: H_2O and O_2

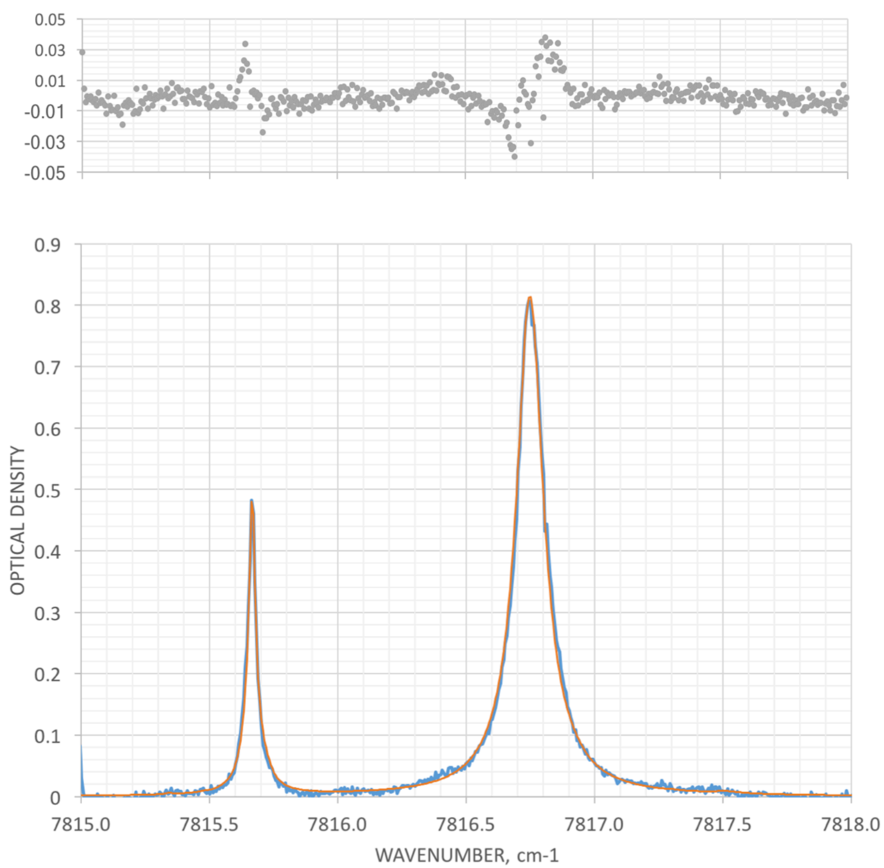


FIGURE 3

Atmospheric spectra are simulated for the column using a spectral simulation package developed at The George Washington University. This software uses physical parameters from the HITRAN Spectral database to model spectra. The integrated path absorption spectrum is calculated using the initial sun angle and pressure and temperature profiles taken from Modern-Era Retrospective Analysis for Research and Applications (MERRA). concentration profiles for O_2 and H_2O can then be iterated by adjusting the pressure and temperature profiles to best fit the oxygen spectrum.

Acknowledgements

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