A LIDAR for Making Range Resolved CO2 Measurements Within the Planetary Boundary Layer

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1. Introduction.

There is a growing consensus within the climate community that the large increases being observed in atmospheric greenhouse gases will start to exert a major impact on global climate within the next hundred years. Rising temperatures are a driver for climate change. Expected changes include rising sea levels, shifting precipitation patterns, higher temperatures and stronger storms. The most important greenhouse gas, CO2, is rapidly increasing due to anthropogenic activity; it is increasing at approximately 1.5 ppmv per year with a current value is ~380 ppmv. Sources for CO2 are well characterized but the observed increases in atmospheric CO2 are approximately half of what is expected given the known amount of fossil fuel being burned and the ocean’s uptake. It is believed that this missing CO2 is being sequestered in terrestrial sinks but their location and mode of operation is not understood. New instruments designed to help identify these sinks by monitoring CO2 transport from both space and the surface are under development. One, the Orbiting Carbon Observatory currently scheduled for launch in 2008, is a passive instrument using sunlight to make total column measurements of CO2 at a precision of 1 ppmv. Laser based instruments operating at 1.57 and 2.05 microns are under development to retrieve total column CO2 from space at a precision of 1 ppmv. Techniques to study transport processes within the planetary boundary layer (PBL) and identify the location of terrestrial sinks at high-resolution using ground based instruments include both tall towers with in-situ instruments and lidar. Although the maximum altitude of the lidar is several times that of a tall tower (3000 meters vs. 500 meters) both offer the ability to characterize the spatial and temporal changes in CO2 at high resolution. These measurements can be combined with a transport model to characterize CO2 fluxes. Inverse modeling techniques can employ the fluxes to identify CO2 sinks with high precision.

2. Instrument.

At NASA’s Goddard Space Flight Center we are developing a Differential Absorption Lidar (DIAL) to profile CO2 within the planetary boundary layer. Two lasers are employed operating at separate but closely spaced wavelengths in the CO2 vibrational-rotational absorption band near 1.57 μm. This spectral region is nearly free from interference from H2O and other molecules, and the narrow separation (~0.15nm) between the on and off-line laser wavelengths minimizes differences in transmittance due to factors other than CO2 absorption. At the profiler’s maximum operational altitude of 3000 meters Rayleigh scattering alone is too weak at these wavelengths to provide adequate signal returns for the proposed system. However, Mie scattering from boundary layer aerosols, with backscattering coefficients that range from 10^-7 to >10^6 m^-1 sr^-1 at 1.57 μm will provide sufficient returns [Chudamani et al., 1996; Srivastava et al., 2001]. The close separation in wavelength guarantees that other sources of attenuation impact both wavelengths identically. This absorption band falls within the telecommunications “L-band,” allowing us to leverage the private sector’s investment in developing semiconductor lasers, fiber amplifiers, detectors, and other instrument components optimized for this wavelength region. The wavelength is within an ‘eye safe’ region of the optical spectrum making it suitable for a "no-hazard and eye safe" autonomous lidar. To minimize the impact of atmospheric motions on the measurement the laser repetition rate is between 10-20 kHz.

Two different laser systems are being tested for use with the profiler. The first combines two DFB diode lasers with an erbium doped fiber amplifier in an all fiber system (figure 1). Fiber systems have a number of significant advantages: they are compact, efficient and have been space qualified. They operate CW and have extremely narrow linewidths and very high wavelength stability – required to minimize the measurement
uncertainty. Range resolved measurements benefit from short pulses preferably much shorter than the resolution being sought and this requirement effectively lowers the duty cycle to ~0.1% meaning that only 0.1% of the system’s photons participate in making a measurement. Preliminary data has been obtained with this system. On and offline extinction profiles are shown in figure 2. The first profile is online, the second offline. The online signal is much stronger due to it having a much stronger laser. The interface between the PBL and free troposphere is clearly seen. This suggests that it will be possible to obtain returns from within the free troposphere and thereby monitor transport processes across this boundary. The second approach employs an optical parametric amplifier (OPA) pumped by a micro pulse Nd:YAG laser. The OPA employs a nonlinear technique to convert the pump radiation into two longer wavelength photons, the signal and idler. This approach leverages investments by the Department of Defense in technology focused on identifying chemical agents on the battlefield. Pulse widths are ~1 nanosecond, repetition rates are 10 kHz and the demonstrated conversion efficiency from 1064 to 1570 nm is 40%. The OPA is seeded by two DFB lasers tuned to the required wavelengths. To achieve the measurement precision goal of 1 ppmv the frequency jitter must be held to <140 MHz. This requires the lasers be temperature stabilized and that the output wavelengths be locked with high precision to predetermined values. This is accomplished using a hollow core fiber (5 meters) filled with several hundred mbars of CO₂. With both systems the temporal spacing between both wavelengths is ~25 microseconds thus insuring that atmospheric fluctuations will not impact the measurement. The current detector of choice is a photomultiplier tube using an InGaAs photocathode and capable of operating at >1700nm. The high quantum efficiency, currently 4%, permits direct as opposed to coherent detection thereby simplifying the instrument.

The CO₂ profiler is one of two laser instruments under development at Goddard Space Flight Center to measure atmospheric CO₂. The second, a laser sounder being developed by James Abshire, is designed to measure the total atmospheric column from space. Unlike OCO the sounder will be able to acquire data under both day and nighttime conditions and is not impacted by atmospheric aerosols, optically thin clouds and subvisible cirrus. Both instruments share a similar measurement strategy and employ identical laser and detector components.

The Orbiting Carbon Observatory is planned to be the first satellite instrument dedicated to measuring atmospheric CO₂ abundance, with a nominal launch date of 2008. The stringent measurement requirements and the potential for systematic biases [Kuang et al., 2002; Rayner et al., 2002] dictate that a rigorous validation effort will be required. Current validation plans for OCO call for surface concentration measurements combined with aircraft profiles from in situ sensors and upward looking high-resolution spectrometers. Once the capabilities of the profiler have been demonstrated, it will be well suited for duplication and deployment in a network configuration for validation efforts. The addition of a profiling lidar network to the OCO validation strategy would fill a critical intermediate gap in connecting routine surface observations to the total column measurements provided by the spectrometers.

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References.


Figure 1 Schematic of CO₂ Profiling Lidar

Figure 2 On and offline extinction