

A preliminary study of CO₂ flux measurements by lidar

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Abstract

A mechanistic understanding of the global carbon cycle requires quantification of terrestrial ecosystem CO₂ fluxes at regional scales. In this paper, we analyze the potential of a Doppler DIAL system to make flux measurements of atmospheric CO₂ using the eddy-covariance and boundary layer budget methods and present results from a ground based experiment. The goal of this study is to put CO₂ flux point measurements in a mesoscale context. In June 2007, a field experiment combining a 2- μ m Doppler Heterodyne Differential Absorption Lidar (HDIAL) and in-situ sensors of a 447-m tall tower (WLEF) took place in Wisconsin. The HDIAL measures simultaneously: 1) CO₂ mixing ratio, 2) atmosphere structure via aerosol backscatter and 3) radial velocity. We demonstrate how to synthesize these data into regional flux estimates. Lidar-inferred fluxes are compared with eddy-covariance fluxes obtained in-situ at 396m AGL from the tower. In cases where the lidar was not yet able to measure the fluxes with acceptable precision, we discuss possible modifications to improve system performance.

1. Introduction

A mechanistic understanding of the global carbon cycle requires quantification of terrestrial ecosystem CO₂ fluxes at regional scales. Flux towers measurements above different type of forest or cultures are usually used to characterize the CO₂ exchanges of a specific surface [Desai et al. 05]. These 'in-situ studies' are then use to build a coupled model of land surface physics, carbon exchange and atmosphere to infer CO₂ fluxes and concentrations at larger scale in a 'bottom-up' view [Wang et al. 07]. CO₂ flux measurements from very tall towers have also been used in synergism with footprint and ecosystem models to directly infer the CO₂ fluxes of different type of vegetation [Wang et al. 06]. In the 'top-down' view, CO₂ concentrations in synergism with a Lagrangian transport model are used to retrieve CO₂ surface fluxes. However, these different attempts to infer CO₂ fluxes from the small (0.1 – 1 km) to larger

scales (10 – 100 km) need a real experimental verification.

An airborne Doppler DIAL system has the ability to make direct range resolved flux measurements using an eddy-covariance method and to address the issue of CO₂ surface flux variability in link with the spatial heterogeneity of the surface (soil, water vegetation) [Giez et al. 99, Kiemle et al., 2007].

In this paper, we present a preliminary study of CO₂ flux measurements by lidar using the different data (backscatter signal, radial velocity, CO₂ mixing ratio) collected during a field experiment in Wisconsin, in June 2007, nearby an instrumented 447-m tall tower (WLEF).

2. Study site, instrumentation and method for simultaneous Lidar CO₂ and velocity measurements

The field experiment took place in June 23, 2007 at the WLEF tall tower site in the Chequamegon National Forest in northern Wisconsin (45.95°N, 90.27°W, 472 m above sea level). The region is a heavily forested zone of low relief. The tower is a 447 m tall television transmitter. Two minute mean CO₂ mixing ratios are sampled at six levels (11, 30, 76, 122, 244, and 396 m) by two infrared gas analyzers (IRGA) (LiCor Model Li-6251) to give CO₂ profiles. Turbulent winds, virtual potential temperature and H₂O mixing ratio are also measured by three sonic anemometers and other IRGAs at 30, 122 and 396 m above the ground. A ground based meteorological station provides also others observations such as net radiation and surface pressure, temperature and moisture.

The NASA Langley 2- μ m Doppler DIAL was positioned underneath the tower, approximately 40-m away from the tower's centreline. The 2- μ m lidar transmitter is a 90-mJ, 140-ns, 5-Hz pulsed Ho,Tm:YLF oscillator injection seeded by continuous-wave (CW) lasers. The pulsed laser has been described in detail in other publications [Koch et al., 2004, 2007]; its relevant parameters are summarized in Table 1.

Pulse energy	90 mJ		
Pulse repetition rate for a wavelength pair On-Off	2.5 Hz		
Pulse width/ Line width	140 ns/ 3 MHz		
Off-line/ On-line	2053.410/ 2053.242 nm		
Spectral locking (On-line)	±1.9 MHz		
Telescope aperture	100 mm		
Detection	heterodyne	Dual balanced photodiodes	InGaAs
Signal digitization	8 bits/ 500 MHz		
Signal processing Estimators	- Squarer (power)	- Levin-like (power, velocity)	

Tab.1. Experimental set up

The On-line wavelength of the transmitter is locked onto the side of the R22 CO₂ absorption line at 2053.204 nm (within ±1.9 MHz) whereas the Off-line is the non-absorbed wavelength positioned 0.25 nm away. The atmospheric heterodyne signal consists in AC radio frequency (RF) voltage for On- and Off-wavelength (index i):

$$S_i(t) \propto \gamma_i \sqrt{P_i(t)} \exp[j(2\pi\nu_{H,i}t + \varphi_i)] \quad (1)$$

where γ_i is the heterodyne efficiency ($0 \leq \gamma_i \leq 1$) and P_i is the atmospheric scattered power collected by the receiver telescope.

Here, the RF frequency $\nu_{H,i}$ is the difference between the return signal frequency (including a Doppler frequency shift ($\pm \Delta\nu_D$) due to aerosol particles in motion) and the heterodyne reference frequency i.e. $\nu_{H,i} = \nu_{ref,i} \pm \Delta\nu_D$:

$$\Delta\nu_D = -2V_r / \lambda \quad (2)$$

where V_r is the radial velocity of the scatterers along the line of sight (LOS).

In our experiment, the signals are digitized with 8 bits at a 500 MHz sampling frequency and then stored on a PC. Later processing is made using MATLAB software and Squarer and Levin-like estimators for both signal power and radial velocity estimates. The atmospheric signals are accumulated in range gate of 112.5 m (Δz) or 0.75 μ s duration ($\Delta t = 2\Delta z/c$, c being the light velocity) along the line-of-sight that result in mean scattered power at the two frequencies at range R :

$$P_{Off}(z) = \langle |S_{Off}(t)|^2 \rangle \text{ and } P_{On}(z) = \langle |S_{On}(t)|^2 \rangle.$$

The signal strength difference between the On- and Off-signals is due to the CO₂ differential absorption (α). For two On- and Off-frequencies close enough that the residual term in backscatter and attenuation different from CO₂ absorption is negligible it comes at range R :

$$\frac{P_{Off}}{P_{On}}(z) = \exp\left(2 \int_0^z \alpha(r) dr\right) \quad (3)$$

Now, the CO₂ optical depth (OD) between ranges 0 and R , $\tau = \int_0^R \alpha(r) dr$, can be written as:

$$\tau = \frac{1}{2} Ln\left(\frac{P_{Off}}{P_{On}}\right) \quad (4)$$

A mean differential CO₂ absorption coefficient can be retrieved from measurements as:

$$\bar{\alpha} = \left[\frac{d\tau}{dz} \right] \quad (5)$$

The ‘‘slope method’’ considers a plot of increasing OD as a function of increasing altitude [Gibert et al. 06]. A least square fit of the data accounting for standard deviation enables derivation of the slope $\bar{\alpha}$. For normally distributed measurement noise this corresponds to a maximum likelihood estimate. The accuracy on the slope $\bar{\alpha}$ depends on 1) the maximum range (i.e. more points for linear regression whereas range is limited by propagation/attenuation properties) and instrument parameters (i.e. pulse energy, telescope size and detection efficiency), and 2) the standard deviation for one observation that depends on signal to noise ratio. In order to express the dependence on CO₂ mixing ratio ρ_{CO_2} , the OD is written as:

$$\tau = \int_0^z \rho_{CO_2}(r) WF(r) dr \quad (6)$$

where $WF(r) = n_a(r, p, T) \Delta\tilde{\sigma}(r, p, T)$ is a weighting function at range r , p and T are the atmospheric pressure and temperature, $\Delta\tilde{\sigma}$ is the effective differential absorption cross section between the On- and Off wavelengths, $n_a(r) = p / [kT(1 + \rho_w)]$ is the dry-air density, ρ_w the water-vapor mixing ratio and k the Boltzmann constant.

The weighting function is computed using new spectroscopic data [Toth et al., 06, 07] and WLEF *in-situ* sensors measurements of temperature, pressure and specific humidity. We extrapolate the meteorological sensors measurements up to 3 km assuming a linear decrease of temperature and an exponential decrease of the surface pressure. The specific humidity is assumed to be constant in the ABL and negligible in the free troposphere. Then, a mean CO₂ mixing ratio in the HDIAL line of sight is obtained by:

$$\bar{\rho}_{CO_2} = \frac{\bar{\alpha}}{WF} \quad (7)$$

3. Methods to infer CO₂ flux estimates from Lidar measurements

Knowing the vertical gradient of CO₂ concentration and the height of the ABL, we are able to infer CO₂ surface flux measurements using a boundary-layer mass budget [Gibert et al. 07]. The Doppler DIAL system, providing both vertical velocities and range resolved CO₂ mixing ratio measurements, can also be used to make direct eddy-covariance (EC) range-resolved flux measurements. We address these two different methods in the two following parts.

Boundary-layer budget and comparison with WLEF EC flux measurements

A mass balance approach shows that the rate of change in the mean CO₂ mixing ratio in the ABL is driven by the sum of the fluxes across boundaries of an air column extending from the ground to the top of the layer considered:

$$n_a h \frac{d\langle \rho_{CO_2} \rangle}{dt} = NEE + \rho \frac{dh}{dt} (\rho_{CO_2,+} - \langle \rho_{CO_2} \rangle) \quad (8)$$

where n_a is the mean air density, h is the ABL height, $\rho_{CO_2}(z, t)$ is the mixing ratio profile of CO₂ in the ABL, NEE is the mean net ecosystem exchange, $\rho_{CO_2,+}$ is the CO₂ mixing ratio in the layer above the ABL (residual layer or free troposphere). $\langle \rho_{CO_2} \rangle$ is the mean CO₂ mixing ratio in the ABL.

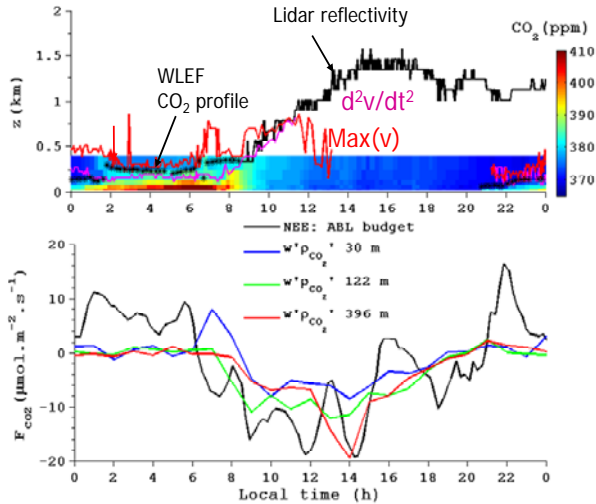


Fig. 1: Top: ABL height calculated using lidar reflectivity during the day (black solid line) and wind properties during the night using either lidar radial velocities (red and purple solid lines) or in-situ CO₂ mixing ratio profiles (WLEF tower) (colour map and black markers).

Bottom: in-situ eddy-covariance flux measurements at the three levels of the tower (30, 122 and 396 m) and NEE estimated by the boundary-layer budget and lidar measurements.

The height and the structure of the ABL are directly inferred by lidar measurements. During the day, the height of the ABL is estimated using the second derivative of lidar backscatter signal. During the night, we use slant measurements of the lidar in two directions to get a vertical profile of wind speed and direction. We inferred like that a nocturnal layer height that we compared with the height calculated from the second derivative of in-situ CO₂ profile from the tower (Fig. 1, top). Using both in-situ and lidar measurements we retrieved the NEE (Fig. 1, bottom).

During the day time, in-situ and ABL-budget fluxes are in good agreement with a slight underestimation between 8 and 14 h and more fluctuations at the end of the afternoon though. During the night the ABL method over estimate the eddy-covariance fluxes measurements as expected. Indeed, the storage of CO₂ is not negligible during the night as we have a strong vertical gradient of CO₂ from the ground to the top of the nocturnal layer. Then to compare the NEE from the ABL budget and eddy-covariance measurements we have to use the following equation:

$$NEE = \overline{w' \rho_{CO_2}'} + \int_0^z \frac{\partial \rho_{CO_2}}{\partial t} \partial z \quad (9)$$

3.2 Eddy-covariance method

To infer a CO₂ flux estimate using the eddy-covariance method we need (as for in-situ data) high frequency measurements of CO₂ and velocities. We are looking for a correlation between the fluctuations of CO₂ mixing ratio and vertical velocities due to turbulence only. The CO₂ EC flux is given by:

$$F_{CO_2} = \overline{\langle w' \rangle \cdot \overline{\langle \rho_{CO_2}' \rangle}} \quad (10)$$

where $\langle \rangle$ and $\overline{}$ are respectively for the vertical and time resolution of lidar CO₂ and velocities measurements.

As a first step, we estimated the error on EC flux estimates knowing the error on CO₂ mixing ratio and velocities measurements from the lidar. The reference for a zero error on the flux calculations is taken when the fluctuations in CO₂ and velocities are due to turbulence only. The theoretical turbulence variance of CO₂ is calculated using Moeng and Wyngaard, 1984 and WLEF tower surface data:

$$\overline{\rho_{CO_2}^2} = \frac{f(z/z_i) \overline{w' \rho_{CO_2,0}^2}}{w_*^2} \quad (11)$$

where $\overline{w' \rho_{CO_2,0}'}$ is the in-situ CO₂ surface flux, z_i is the top of the ABL and $f(z/z_i) \approx 2$ for $z = z_i/2$.

The vertical and time resolution of lidar measurements are respectively 1 km and 2 min 30 s. For such conditions, the vertical velocity and CO₂ mixing ratio standard deviations were 0.3 m.s⁻¹ and 30 ppm (Fig. 2). Using the lidar time series we can only infer a 1-h flux measurement with a precision of ~ 120 %. For comparison, we also show the in-situ sensors parameters in Figure 2. With a typical 1.6 ppm of standard deviation, the in-situ sensor provides a 1-h flux measurement with ~ 15 % of precision. However, EC flux estimates by lidar seem to be still achievable if we average the flux measurement over several hours.

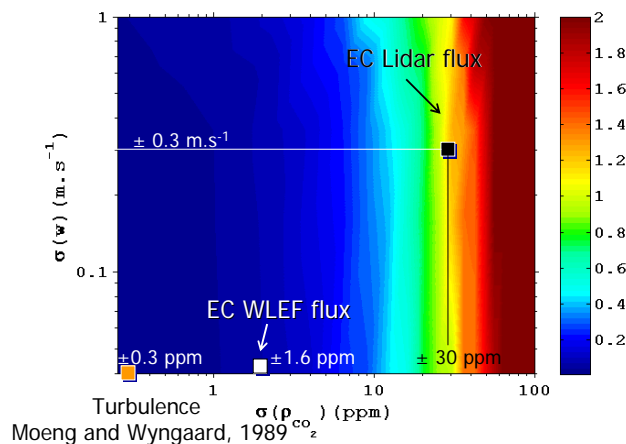


Fig. 2: Relative error on mean 1h-EC flux calculations as a function of vertical velocity and CO₂ mixing ratio standard deviation.

4. Conclusion

In this paper, we analyzed the potential of a 2- μ m Doppler DIAL system to address the issue of representativity of CO₂ in-situ flux measurements. Using simultaneous measurements of reflectivity, radial velocity and CO₂ mixing ratio, we showed two different methods to make flux measurements. The first one, the boundary-layer budget method uses accurate mean CO₂ mixing ratio measurement and knowledge of the ABL structure and gradient. Using both in-situ and lidar measurements we showed a good agreement of daytime in-situ and ABL-budget fluxes. We are currently analyzing the night time discrepancies. The second one, the eddy-covariance method uses high frequency measurements of CO₂ mixing ratio and vertical velocity with a moderate precision. A preliminary study of this method showed that due to the

instrument limitations, only mean daytime flux measurements could be estimated with a good precision (< 50 %). New results will be presented at the conference.

References

- Desai A.R., P.V. Bolstad, B.D. Cook, K.J. Davis, E.V. Carey, 2005: Comparing net ecosystem exchange of carbon dioxide between old-growth and mature forest in the upper Midwest, USA. *Agri. Forest Meteor.*, **128**, 33-55.
- Koch, G.J., B.W. Barnes, M. Petros, J.Y. Beyon, F. Amzajerdian, J. Yu, R.E. Davis, S. Ismail, S. Vay, M.J. Kavaya and U.N. Singh, 2004: Coherent differential absorption lidar measurements of CO₂. *Appl. Opt.*, **43**, 5092-5099.
- Koch, G.J., J.Y. Beyon, B.W. Barnes, M. Petros, J. Yu, F. Amzajerdian, M.J. Kavaya and U.N. Singh, 2007: High-Energy 2- μ m Doppler Lidar for Wind Measurements. *Opt. Eng.* **46**.
- Gibert F., P.H. Flamant, D. Bruneau and C. Loth, 2006: Two-micrometer heterodyne differential absorption lidar measurements of the atmospheric CO₂ mixing ratio in the boundary layer. *Appl. Opt.*, **45**, 4448-4458.
- Gibert F., M. Schmidt, J. Cuesta, E. Larmanou, M. Ramonet, P.H. Flamant, I. Xueref, P. Ciaï, 2007: Retrieval of average CO₂ fluxes by combining in-situ CO₂ measurements and backscatter Lidar information. *J. Geophys. Res.*, **112**, D10301, doi:10.1029/2006JD008190.
- Giez A., G. Ehret, R. L. Schwiesow, K.J. Davis, D.H. Lenschow, 1999: Water vapor flux measurements from ground-based vertically pointed water differential absorption and Doppler lidars. *J. Ocean. Atmos. Tech.*, **16**, 237-250.
- Kiemle C., W.A. Brewer, G. Ehret, R.M. Hardesty, A. Fix, C. Senff, M. Wirth, G. Poberaj and M.A. LeMone, 2007: Latent heat flux profiles from collocated airborne water vapour and wind lidars during IHOP 2002. *J. Ocean. Atmos. Tech.*, **24**, 627-639.
- Moeng, C.-H. and J.C. Wyngaard, 1984: Statistics of conservative scalars in the convective boundary layer. *J. Atmos. Sci.*, **41**, 3161-3169.
- Wang W. K.J. Davis, B.D. Cook, M.P. Butler and D.M. Ricciuto, 2006: Decomposing CO₂ fluxes measured over a mixed ecosystem at a tall tower and extending to a region: a case study. *J. Geophys. Res.*, **111**, G02005, doi:10.1029/2005JG000093.
- Wang J.-W., A.S. Denning, L. Lu, I.T. Baker, K.D. Corbin, and K.J. Davis, 2007: Observations and simulations of synoptic, regional, and local variations in atmospheric CO₂. *J. Geophys. Res.*, **112**, D04108, doi:10.1029/2006JD007410.