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Aglite: A 3-Wavelength Lidar System for Quantitative Assessment of Agricultural Air Quality and Whole Facility Emissions

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Abstract. *Ground based remote sensing technologies such as scanning lidar systems (light detection and ranging) are increasingly being used to characterize ambient aerosols due to key advantages (i.e., wide area of regard (10 km²), fast response time (s^{-1}), high spatial resolution (<10 m) and high sensitivity). Scanning lidar allows for 3D imaging of atmospheric motion and aerosol variability, which can be used to quantitatively evaluate particulate matter (PM) concentrations and emissions. Space Dynamics Laboratory, in conjunction with USDA ARS, has developed and successfully deployed a lidar system called Aglite to characterize PM in diverse settings.*

Aglite is a portable scanning elastic lidar system with three wavelengths (355, 532, and 1064 nm), 6 m long range bins, and an effective range from 0.5 to 15 km. Filter-based PM samplers, optical particle counters, and various meteorological instruments were deployed to provide environmental and PM conditions for use in the lidar retrieval method. The developed retrieval algorithm extracts aerosol optical parameters, which were constrained by the point measurements, and converts return signals to PM concentrations. Once calibrated, the Aglite system can map the spatial distribution and temporal variation of the PM concentrations. Whole facility or operation-based emission rates were calculated from the lidar PM data with a mass balance approach. Concentration comparisons with upwind and downwind point sensors were made to verify data quality; lidar-derived PM levels were usually in good agreement with point sensor measurements. Comparisons of lidar-based emissions with emissions estimated through other methods using point sensor data generally show good agreement.

Keywords. Remote sensing, lidar, emissions, flux, particulate matter, point sensor.

Introduction

The movement of urban populations into agricultural production areas, combined with the increasing size of these facilities to capture economies of scale and meet global food needs, has elevated the issue of agricultural production air emissions to national attention. Accurate measurement of specific operations and whole facility aerosol emissions, especially those that contain large percentages of organic matter, is technically challenging. Currently, regulations of Concentrated Agricultural Feeding Operations (CAFO) and other particulate matter (PM) emission sources are based on multiple point-sampled measurements and combined with models to account for wind and time variation (ISU and U of I Study Group, 2002).

In this paper, we discuss the potential of using remote sensing to map and track the evolution of emission plumes from agricultural facilities. Our approach is the utilization of a multi-wavelength lidar (Aglite), capable of taking simultaneous measurements at many points along a line, that is real-time calibrated using a suite of standard point sensors, defined herein as an instrument measuring a small volume (<20 Lpm) at a single point, to distinguish between different aerosol mixtures. The Aglite lidar is a robust, agile, and easily operated system that displays emitted PM distributions in a few seconds under most meteorological and diurnal conditions. The resulting combination of point samplers and scanning lidar provides near real-time measurements of facility operations, which can be used to evaluate emission fluxes.

Measurements and Methods

The Aglite lidar system has been previously described by Marchant et al. (2009), and is shown in Figure 1a. Aglite is a trailer-mounted, monostatic laser transmitter equipped with a 28-cm receiver telescope. The laser is a three-wavelength, 10-kHz, pulsed Nd:YAG laser operating at 1064 nm, 532 nm and 355 nm with a ~40 ns pulsewidth. The minimum system range gate is 6 m. The laser output beam can be scanned from -10 to +45° in elevation and ±140° in azimuth using a motorized mirror mounted on the roof of the trailer. Angular scan rates from 0.1 – 1°/s were used to develop 3D maps of PM around the source(s).
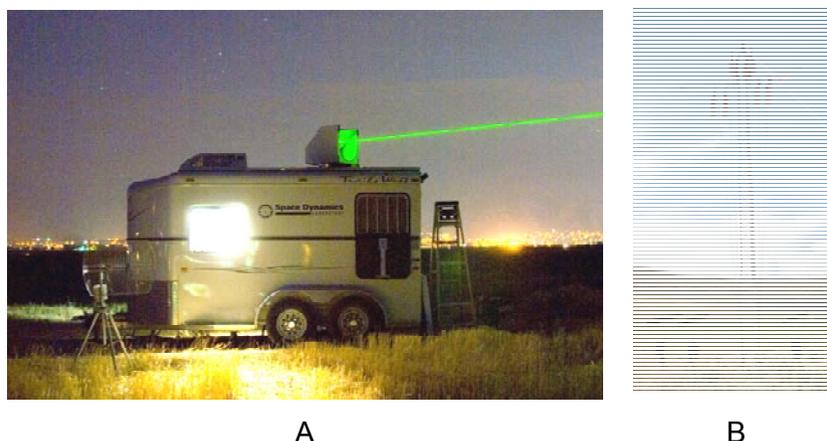

A   B

Figure 1. A) The Aglite lidar system at dusk, scanning a harvested wheat field. B) A calibration tower with MiniVols and OPCs attached.

Our approach to aerosol characterization relies on an array of point sensors to provide ground truth data on aerosol composition, which is then used to calibrate the Aglite return signals. We utilize both optical size distribution (Met One Instruments, Inc. Aerosol Profiler, Grants Pass,

Ore.) and aerodynamic mass fraction (Airmetrics, Inc. MiniVol, Eugene, Ore.) sensors to develop the calibration data set (Figure 1b). The MiniVols are portable, self-contained, filter-based impactor PM samplers configured to provide $PM_{2.5}$, PM_{10} or TSP. Aerosol Profilers, or optical particle counters (OPCs), provide single particle counts over a range of bin sizes from 0.3 to >10 μm. During periods of data collection the Aglite laser was regularly directed to calibration points where a cluster of MiniVols and an OPC were operating. In this way, all three instruments could interrogate the same volume of air. Meteorological profile information was provided by two 15.3 m towers, each instrumented with five Gill 3-cup anemometers (RM Young, Traverse City, Mich.) and five Vaisala model HMP45C temperature and relative humidity sensors (Oulu, Finland) logarithmically spaced between 2 and 15.3 m, with a Met One Instruments, Inc. Model 024A wind vane (Grants Pass, Ore.) at 15.3 m. All data were logged at a central command post for data storage and experiment management.

Lidar Retrieval and Calibration

The lidar equation (1) describes the lidar return signal as a function of range z for wavelength λ:

$$P_\lambda(z) = P_0 \cdot L \cdot \frac{c\tau}{2} \cdot A_\lambda(z) \cdot \frac{\beta_\lambda(z)}{z^2} \cdot \exp\left(-2\int_0^z \sigma_\lambda(z')\partial z'\right)$$

(1)

The term $P_\lambda(z)$ is the measured reflected power for distance z and is measured in photon counts. P_o is the output power of the lidar, L is the lidar coefficient, which represents system efficiency, c is the speed of light, τ is the pulse width of the lidar, $A_\lambda(z)$ is effective area function (also known as the geometric form factor, GFF), $\beta_\lambda(z)$ is the atmospheric backscatter coefficient, and $\sigma_\lambda(z)$ is the atmospheric extinction coefficient. The backscatter and extinction coefficients are functions of temperature, pressure, humidity, and the sampled PM. When quantifying the PM flux from a facility, the solution of equation (1) requires knowledge of the optical parameters of both the background and emitted PM, which need to be measured at one or more reference points upwind (background) and downwind (background plus source) of the facility. The details of our lidar calibration and retrieval process are discussed by Marchant et al. (2009) and Zavyalov et al (2009). The algorithm used to retrieve aerosol physical parameters from a raw Aglite lidar signal is shown schematically in Figure 2. The preprocessing step accounts for the geometrical form factor of the receiving optics and scattered sunlight radiation. The algorithm then calculates the optical parameters (backscatter and extinction coefficients) of the background and source aerosols, utilizing the in-situ OPC and MiniVol data as an input to either Klett's (1985) analytical solution for two scattering components or an extended Kalman filter described by Marchant et al. (2011B). The mass conversion factor (MCF) is derived from OPC and MiniVol data to convert volume concentration to mass concentration.

Zavyalov et al. (2009) and other unpublished data show that comparisons between Aglite, OPC, and MiniVol levels from multiple studies were generally in good agreement or within stated errors. In addition, Zavyalov et al. states that the measured accuracy, expressed as the 95% confidence interval (CI) about the mean PM_{10} level, was between 10% and 50% of background and varied with multiple factors, including background loading. Marchant et al. (2011A) found an average PM_{10} 95% CI of ~30%, or 10 μg/m^3, during a dairy PM emissions study.

Facility Flux Measurements

The lidar's capability to accurately sample 3D aerosol concentrations entering and leaving an operation in near real time (1-3 minutes) makes it possible to measure facility emissions with approximately twice that time resolution. Figure 3 shows the mass balance concept behind our approach; the source strength is determined using the mean flow rate through the facility, based

on wind speed measurements, and the difference in PM concentrations entering and leaving the facility (Bingham et al., 2009). Figures 3B and 4 show example outputs of our flux analysis. Lidar-estimated PM emission rates and factors for swine finishing (Bingham et al., 2009), dairy (Marchant et al., 2011), and various tillage (unpublished data) operations averaged 4% lower than those calculated through inverse modeling using AERMOD coupled with the collected point sensor PM measurements, but with a standard deviation of ± 75%. Estimated emissions from both methodologies are usually within the range of values reported in the literature.
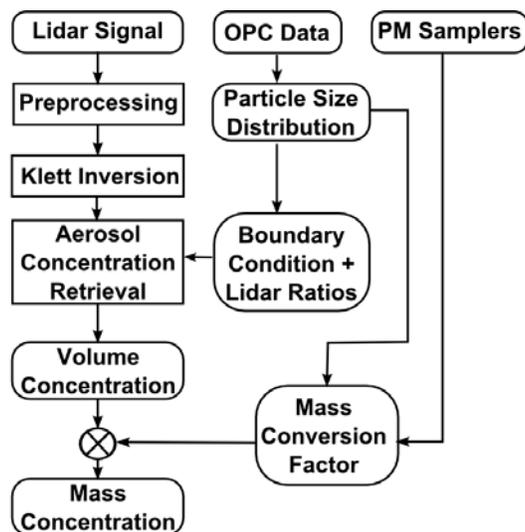

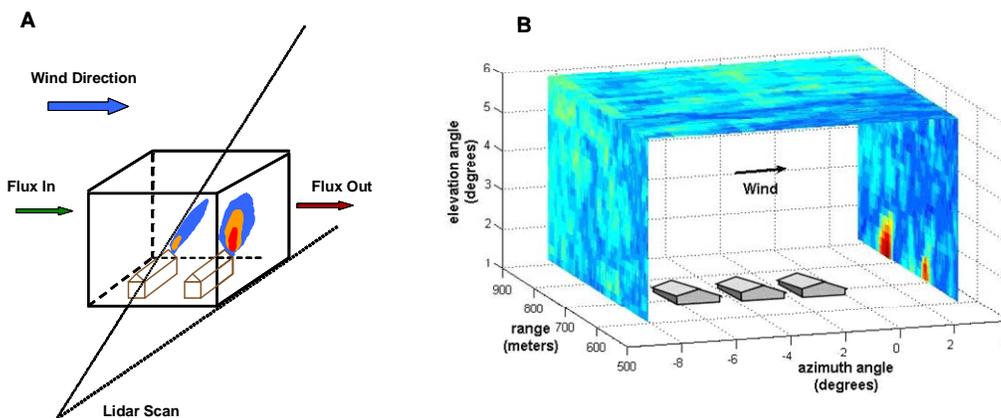Figure 2. Schematic of lidar mass concentration algorithm.

Figure 3. A) Conceptual illustration of the method using lidar to calculate time-resolved whole facility PM fluxes. B) An example "staple" lidar scan over a facility showing PM concentrations.

Flux Measurements of Mobile Emission Sources

Our current research is focused on extending our flux algorithm to the active tracking and characterization of mobile aerosol sources, such as large agricultural implements being used in the field (e.g., Figure 5). For mobile emission sources, the PM concentration near the source

(i.e., at the tractor) is large but is difficult to characterize using existing point sensor methods. The Aglite lidar system, due to its portable platform and highly articulate pointing mirror, is uniquely qualified to track moving aerosol plumes, which can be used to help characterize the plume concentrations during transient source events. An elegant and robust method for real-time mass flux calibration of moving plumes remains an ongoing direction of research.
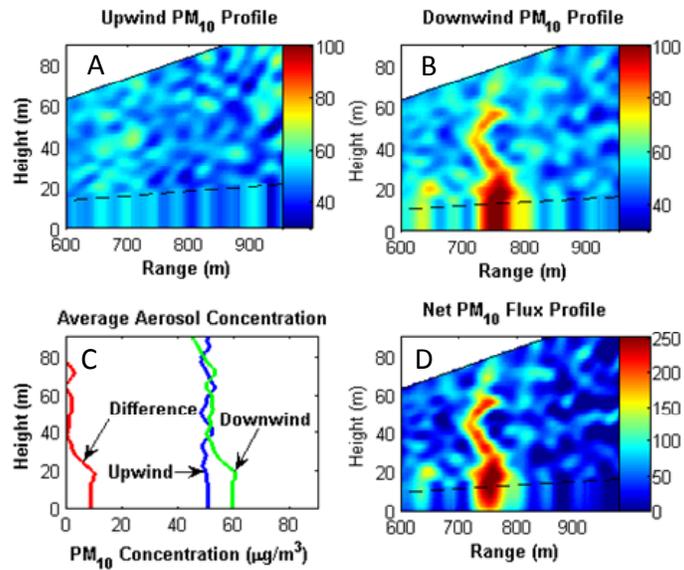

Figure 4. Single PM$_{10}$ scans at a swine finishing facility, showing the distribution of the upwind (A) and downwind (B) PM concentrations (µg/m^3), the horizontally averaged PM$_{10}$ concentrations and their difference (C), and the PM$_{10}$ flux (µg/m^{2}s) distribution (D) calculated when the difference is multiplied by the wind speed profile.

Figure 5. A tractor cultivating a field offers an example of a moving plume. Note the plume and sample towers on the downwind (left) side of the tractor and the Aglite lidar trailer in the distance on the far right.

Conclusions

Space Dynamics Laboratory has developed Aglite, a three-wavelength portable scanning lidar system, to derive spatial information of aerosol distribution over remote distances. Aglite uses

an integrated approach to retrieve PM mass concentration, fusing together in-situ and remotely measured data. In-situ measured data were used as boundary conditions for lidar retrievals, to determine the parameters of the lidar equation, and to establish a calibration factor, the MCF, for converting lidar data to mass concentration. The lidar system and retrieval approach have been tested during several field campaigns measuring PM levels around and emissions from swine finishing, dairy, almond harvesting, cotton ginning, and tillage operations. Test results show the ability of lidar measurements to characterize PM emissions quantitatively and represent spatial and temporal variations of the emitted plume as 3D/2D mass concentration fields. To the best of the authors' knowledge, this is the first attempt to characterize the agricultural emission sources as PM density fields (TSP, PM_{10}, and $PM_{2.5}$). The lidar PM levels generally agreed with point sensor measurements within the stated error values; emissions estimated from lidar data on average were 4% lower than those estimated through an inverse modeling method based on the same dataset, though with a standard deviation of ± 75%.

Acknowledgments

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