AGLITE: A Multiwavelength Lidar for Aerosols

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Abstract

Agricultural operations produce a variety of particulates and gases that influence air quality. Agriculture, through wind erosion, tillage and harvest operations, burning, diesel-powered machinery and animal production operations, is a source of particulate matter that can enter human lungs and cause pulmonary problems. These emissions can negatively impact human health, property values, and the environment. The presence of buildings and other structures often make whole facility measurement capability a requirement for understanding the source strength and characteristics. The ability to use standoff methods to determine the movement and concentrations of emissions on a whole facility basis opens new capabilities for model development and verification. We report on the design, construction and operation of a new multiwavelength lidar developed with the Agricultural Research Service of the United States Department of Agriculture and its program on particle emissions from animal production facilities. The lidar incorporates a laser emitting simultaneous, pulsed NdYAG laser radiation at 355, 532 and 1064 nm at a pulse rate of 10 kHz. Lidar backscatter and extinction data are modeled to extract the aerosol information. All-reflective optics combined with dichroic and interferometric filters permit all the wavelength channels to be measured simultaneously, day or night, using photon counting by PMTs, an APD, and high speed data acquisition. The lidar is housed in a transportable trailer for all-weather operation at any accessible site. The laser beams are directed in both azimuth and elevation to targets of interest. We describe application of the lidar in a multidisciplinary atmospheric study at a swine production farm in Iowa. Aerosol plumes emitted from the facility were prominent phenomena, and their variations with temperature, turbulence, stability and feed cycle were studied, using arrays of particle samplers and turbulence detectors. Other lidar measurements focused on air motion as seen by long duration scans of the farm region. Successful operation of this lidar confirms the value of multiwavelength, eyesafe lidars for agricultural aerosol measurements.

The AGLITE Lidar System

The AGLITE lidar instrument used in this study is a three-wavelength lidar system (infrared, visible and ultraviolet emissions) designed and built at the Space Dynamics Laboratory (SDL) under contract from the Agricultural Research Service (ARS) of the United States Department of Agriculture. Figure 1 shows a schematic layout of the lidar system.

The commercial laser unit indicated on the left has four components: (1) a laser diode pump that drives (2) a Nd:YAG crystal laser at 1064 nm, (3) a frequency-doubling crystal to generate 532 nm, and (4) a mixing crystal for frequency-tripled output at 355 nm. These frequencies are employed simultaneously to probe the optical scattering by particles in the atmosphere. The physical properties of particles are then inferred from the observed variation of scattering with wavelength.

Figure 2 shows AGLITE mounted in the trailer used for field work at agricultural sites. Adjustments and final calibrations were most conveniently carried out at night to establish baseline optical signals without daytime interference. An exterior view of the lidar trailer is shown in Figure 3. After final optical adjustment in Utah, the lidar trailer was hauled to Iowa for field trials at a swine production facility, where the lidar was put into operation without needing any further adjustment. Lidar measurements at the Iowa site are also described elsewhere in the Workshop proceedings (Bingham et al., 2006; Hipps et al. 2006; Martin et al., 2006; Silva et al., 2006; Zavyalov et al., 2006).

The AGLITE laser system produces short pulses of light (~10 nsec duration) that are elastically backscattered by atmospheric particles into the steerable telescope, which, along with the laser output, is scanned in elevation and azimuth using the beam director. The Newtonian telescope has a diameter of 28 cm and a FOV of 0.46 mrad. Time resolution of each lidar "return" provides information on the density of particles as a function of distance ("range") from the lidar. The high laser repetition rate of 10 kHz allows the use of low pulse energy for eye safe operations at the close ranges required for agriculture applications. The time interval between successive 10 kHz pulses is long enough that unambiguous lidar range measurements can be made out to a distance of 15 km. The laser specifications on average output power provided by Photonics Industries are 4.1, 0.85 and 1.15 Watts, respectively, at 1064, 532 and 355 nm.

The closest lidar range for usable data is set by the effective entrance aperture of the telescope relative to the divergence of the laser transmission (Measures, 1984). We optically expand the Photonics Industries laser beam to a diameter of 10 mm and beam divergence approximately 0.2-0.3 mrad. This effectively determines our closest useful lidar range to be about 500 meters. Outgoing laser energy is monitored by photo-sensors, and this information is recorded in the data processing unit. The beam-separation unit (upper right, Figure 1) splits the backscattered light into the three wavelength channels appropriate to the laser transmission. Fluorescence observations are not employed in the present work.

For agricultural studies in general, the ability to operate in daytime is essential, because of the roles of sunlight, transpiration, convection and turbulence in the processes of interest. This requires that the lidar signals be observable against the intense daylight solar background. We have adopted photon-counting as the detection regime, in order to detect low intensity returns simultaneously on each channel, consistent with eye safety. Interference filters and an etalon are used in each detector channel to suppress optical cross talk between channels and background skylight, particularly at 532 nm. The detectors chosen for 355 and 532 nm are the photomultiplers (type 9954-A) made by Electron Tubes, Ltd. For the near IR light at 1064 nm we used the avalanche photodiode (SPCM Module) now made by Perkin Elmer, Inc. Approximate limits on the maximum count rate for the detectors are 50 million/sec for the PMTs and 10 million/sec for the APD. Details of the electronic system for AGLITE have been described by Cornelsen (2005).

Pulse counts from the photon counters are read out during each lidar return at a time resolution of 32 – 40 nsec by a digital processing unit. Counts are averaged across a predetermined set of laser pulses, displayed in a real time, and stored for further processing. Typical settings for the lidar operations are the following: time averaging of the return signal of 0.5-3 sec per one measurement (5,000-30,000 laser pulses), range resolution of 5-15 m up to maximum ranges of 0.5-15 km, and azimuth and elevation scans of 0.05-2^{o} per sec. The AGLITE electronic control system automatically coordinates and synchronizes all the functions of the lidar, scanning turret, data acquisition system, digital camera, and weather station to provide a complete data package and makes it available to the operator for further analysis.

Technical details of the design and procedures of the Iowa lidar experiments are described by Zavyalov et al. (2006) in the proceedings of this Workshop. The AGLITE trailer was deployed approximately 650 meters east of the swine barn facility that was the target of the investigation. This location of the lidar system allowed full 3D volume measurements of particulate emission off of the three barn feeding operations from a single observation point.

Application of Lidar to Describe Air Masses and Air Motions

The particle density and motion of selected volumes of air can be visualized in various ways using lidar. The methods described here depend upon the existence of spatial variations of aerosol density and the fact that small aerosol particles are borne along with the wind and turbulent motions. This use of aerosols as tracers for air motion is an important addition to the sampling and analysis of aerosol size and chemistry. When plumes of fine particles are emitted from installations such as the swine barns studied in Iowa, their upward convection and subsequent downwind motion can be seen using sequential lidar scans in altitude and azimuth. Examples of azimuth and elevation scans are also discussed by Zavyalov et al. (2006). In addition, the persistence and motion of cloud and dust layers extending over large areas around a lidar station can be observed by means of azimuth scans at fixed angles of elevation.

Figure 4 shows an azimuth scan of cloud layers taken at 45º elevation, where the ranging capability of the lidar detects thick dust and cloud layers at various altitudes over the azimuth range of ± 20º about the west direction. (Because of the elevation angle, the altitude equals 0.71 times the lidar range.) Here the black/white color scale codes increasing lidar signal strength, and thus the relative aerosol density, as white. Successive azimuthal lidar scans, if they are taken sufficiently quickly, can provide details of the horizontal wind speed and its variation with altitude (Wilkerson et al., 2001). Though cloud and aerosol layers can also be detected using a lidar staring vertically above the lidar site, the simple zenith record is less informative about air motion patterns than the scans in azimuth and elevation.

Figure 5 is a set of elevation scans taken 5.79 minutes apart, showing large plumes of aerosol laden air in the atmospheric boundary layer out to distances of 2000 meters. An important aspect of these scans is the direction of the scan relative to the direction in which the plume is moving. For falling plumes of aerosols, a "down scan" follows the plume motion longer than for an "up scan". Therefore the image of a falling plume is lengthened in the "down" case and compressed in the "up" case and, vice versa, is distorted oppositely for a rising plume. The resulting effects in the images of the top of the aerosol layer (~ 500 meters) are clearly illustrated by the alternating scans in Figure 5.

For well defined clouds of aerosols, these elevation scans enable us to measure both the size and vertical velocity of clouds. In Iowa, making such visual observations during nighttime lidar scans near the swine barns, we were able to estimate upward velocities of aerosol plumes to be about 0.5 – 1.0 meter/sec at a height of 5-10 meters above ground. For well defined plumes rising or falling as they are borne along with the wind, the elevation traces taken like those in Figure 5 display prominent tilts toward or away from the lidar origin depending on both the motion and scan directions, and thus provide information on the vertical and horizontal transport in the boundary layer.

Conclusions

The three-wavelength AGLITE lidar has proved to be a fieldworthy, reliable and self contained system for monitoring and profiling the density and motion of aerosols in the air around agricultural installations. The use of three laser wavelengths has enabled us to observe significant variations in backscatter profiles depending on the particle origins. Time dependent records of vertical and horizontal motions have revealed both small scale and large scale motions of aerosol laden air masses originating from unpaved roads, large swine barn facilities, and ordinary atmospheric phenomena such as clouds and hazes.

In principle, atmospheric probing by lidar is able to obtain time dependent, three dimensional pictures of aerosol distributions in any region of interest such as the air space around animal feedlot and production facilities. Aerosols serve as valuable tracers of air motion. In practice, this faces limitations due to the time scale of atmospheric changes, such as turbulence versus the time required to make complete lidar scans of the region. In this paper and in companion papers in the Workshop, we illustrate that, by making the time dependent observations in two dimensions at a time, namely the lidar range versus a single geographic dimension (elevation or azimuth), one can obtain valuable information on the extent of clouds and on low altitude air motions both along and across the lidar beam direction. Then the synthesis of 3D interpretations of aerosol motion can follow from such 2D records as needed. We will continue to apply these lidar methods to the meteorological interpretation of aerosol motions seen in the emission of particulates from agricultural installations.

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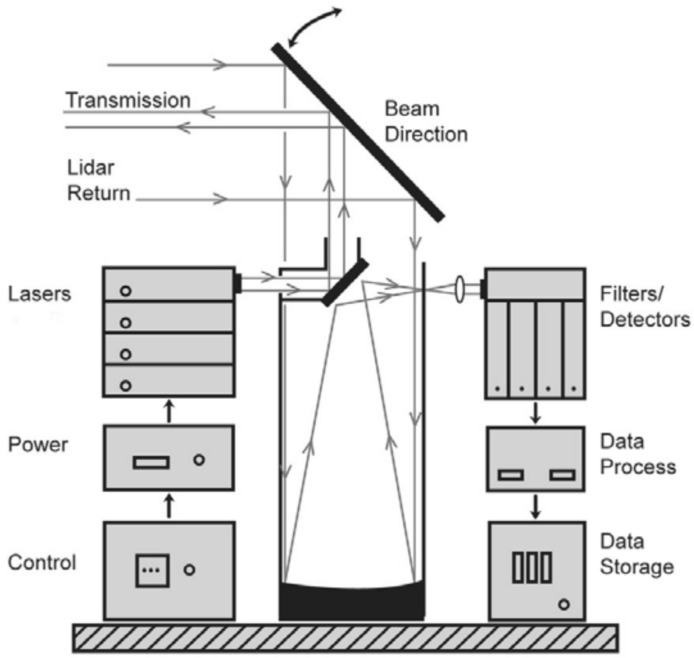

Figure 1. Schematic of AGLITE lidar design and construction.

Figure 2. AGLITE lidar mounted vertically, viewed through open back door of trailer.

Figure 3. Field deployment trailer for AGLITE lidar.

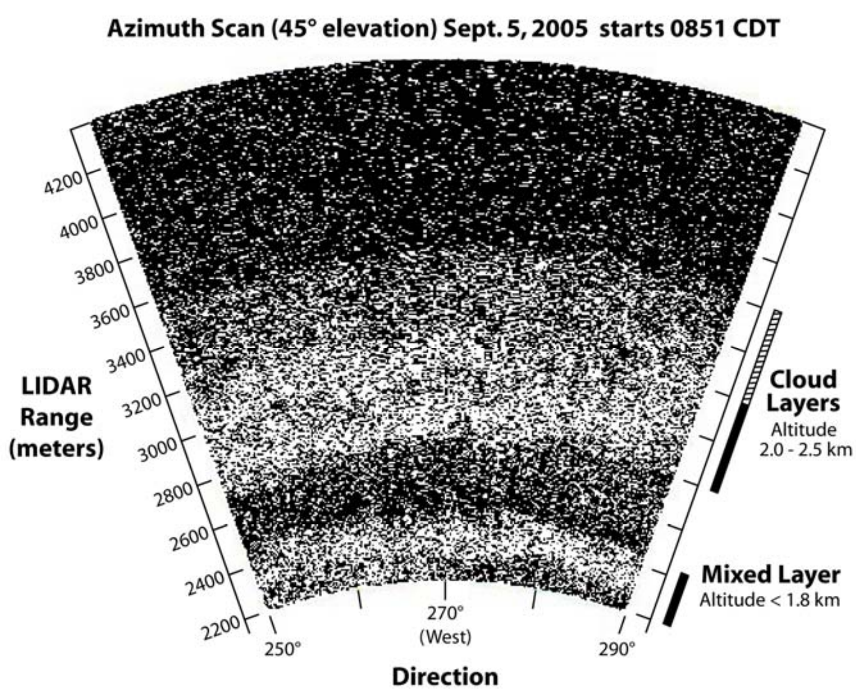

Figure 4. An azimuth lidar scan at 45ºelevation showing cloud and aerosol layers to the west of the lidar site. Successive scans provide useful records of air motion.

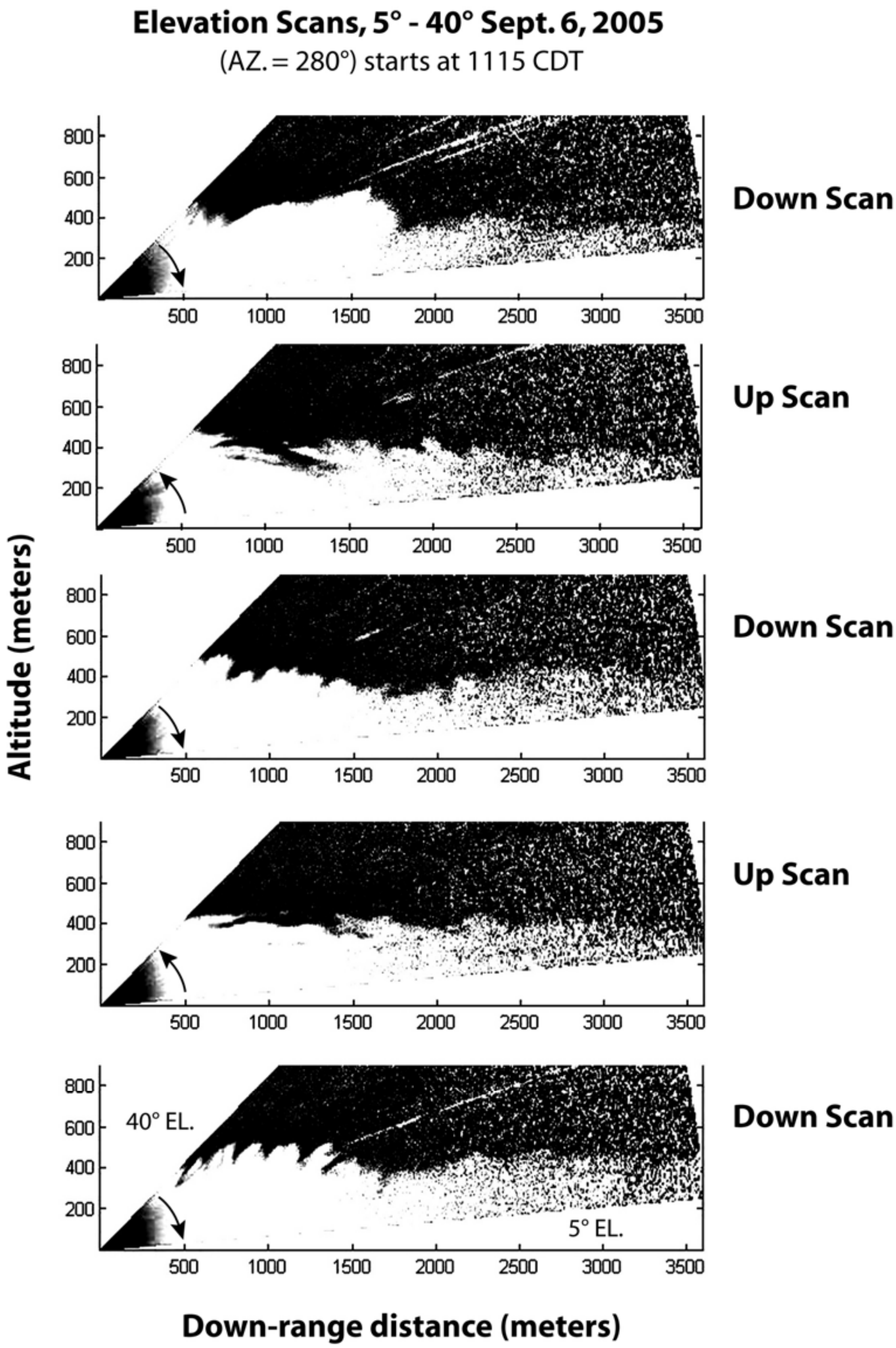

Figure 5. Successive lidar elevation scans at 5.79-minute intervals, looking upwind into boundary layer aerosols (lidar signal increases from black to white).