Application of A High-Pulse-Rate, Low Pulse-Energy Doppler Lidar for Pollution Transport Measurement

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ABSTRACT

Availability of optical fiber technology has stimulated commercial development of compact high pulse rate, low energy solid-state Doppler lidar transceivers for boundary layer measurements. At NOAA's Earth System Research Laboratory we are investigating the feasibility of co-deploying such an instrument alongside the NOAA Tunable Optical Profiler for Aerosol and oZone (TOPAZ) ozone/aerosol lidar and University of Colorado Airborne Multi-AXis Differential Optical Absorption Spectrometer (AMAX-DOAS) on a Twin Otter aircraft for regional air pollution studies. A field test program during the summer of 2009 was carried out to evaluate the measurement capability of the compact Doppler lidar in the arid summer urban boundary layer around Denver, Colorado. The campaign consisted of two parts: a two-day observational intercomparison with the NOAA High Resolution Doppler Lidar (HRDL) to compare measurement sensitivity and precision, followed by a week of aircraft flights on the Twin Otter alongside the ozone DIAL and AMAX-DOAS instruments. Results of the experiment showed the feasibility of adding a compact Doppler lidar to the Twin Otter. Combining ozone and Doppler lidar measurements enables investigation of a multiple phenomena associated with pollution transport in complex terrain, including inter-basin movement of pollutants, upslope/downslope flows, and mountain venting of pollution to the free troposphere.

1. INTRODUCTION

At NOAA's Earth System Research Laboratory, we have deployed an airborne ozone/aerosol differential absorption lidar (DIAL) during a number of field campaigns to map and study transport and mixing of pollution in regions where air pollution is a significant problem. We recently added an Airborne Multi-Axis Differential Optical Absorption Spectrometer (AMAX-DOAS) to the aircraft to provide information on other pollutants such as NO_2 and glyoxal. Calculating the flux of a pollutant such as ozone provides a measure of how much pollution is generated and exported by regional sources such as a urban or industrial areas. To calculate horizontal transport of ozone downwind of source regions, we typically measure the ozone enhancement within the plume and then apply interpolated data from local sources such as wind profiler networks and/or balloon soundings to estimate the wind speed and direction at locations within the plume [1]. The technique works reasonably well for locations and situations where the wind speed and direction is relatively uniform across an extended area. However, when the wind field exhibits significant spatial and temporal variability, such as in regions where mountain-valley flows, land-sea breeze circulations, or flow over barriers can occur, a more precise method of estimating the local wind speed is highly desirable.

To provide a better representation of the local wind characteristics at the location of the ozone measurement, we carried out a short pilot study investigating the feasibility of co-deploying a compact commercially-available, high pulse rate, low pulse energy Doppler lidar on the Twin Otter alongside the ozone/aerosol lidar and AMAX-DOAS instruments. The feasibility study included a ground based-comparison with the NOAA HRDL system, followed by two aircraft flights over the eastern Colorado plains near Denver. Efficacy of co-deploying a DIAL instrument and Doppler lidar on an aircraft for flux measurements was first demonstrated during the International H_2O Project, when observations of horizontal and vertical wind speed and water vapour concentration were analysed to map moisture transport and vertical flux over the US Southern Great plains [2,3].

2. AIRBORNE WIND MEASUREMENTS

Ozone studies utilizing the TOPAZ lidar are focused on sources, sinks and transports of pollution in the boundary layer and lower troposphere. The TOPAZ system is specifically designed to provide high vertical resolution (90 m gates) estimates of ozone at 10 s intervals from just below flight level (typically 4 to 4.5 km) to the surface. Because the Twin Otter flies relatively slowly (~ 60 m s^{-1}) mapping of ozone is carried out at horizontal resolution of approximately 600 m.

The technique envisioned to obtain coincident vector wind measurements from the Twin Otter is to employ a downward-looking conical scan consisting of up to 4 azimuth angles plus a zenith-looking observation within the 10 s ozone measurement interval. Assuming roughly one-half to one s for movement of the beam among the five pointing positions allows one to one and a half s for each Doppler estimate. Note that four measurements provide some redundancy (only two components are required to estimate the horizontal wind field), such that higher temporal resolution can be achieved by employing only two of the conical pointing positions. Because the wind profile under certain conditions can be characterized by significant vertical structure, vertical resolution equal to or better than the 30 m resolution of the HRDL system is desirable for the airborne Doppler measurements.

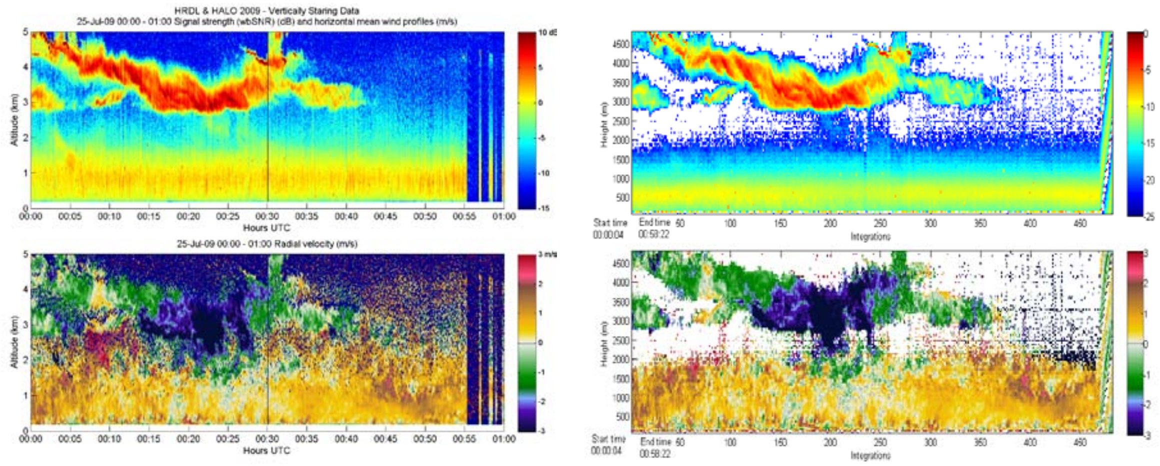

Figure 1. *Preliminary comparison of intensity (top) and velocity (bottom) estimates for NOAA HRDL (left) and Salford Halo lidar (right) taken over a one hour period. Observations from the two instruments show excellent correlation.*

Downward-looking aircraft measurements under polluted conditions have the advantage of probing into a region where aerosol structure is typically increasing with range, partially mitigating range and extinction effects. Given flight altitudes of 4.5 km, and assuming a 20 degree cone angle, a Twin Otter Doppler instrument needs to be able to measure winds to ranges of at least 5 km. Measurement precision for each radial wind estimate should be better than 0.3 m s^{-1} in order to achieve the desired 1 m s^{-1} precision when the estimate is projected onto the horizontal.

3. INSTRUMENT DESCRIPTIONS

As noted, the NOAA TOPAZ lidar, University of Colorado AMZ-DOAS were deployed on the Twin Otter alongside the Doppler lidar for the flight tests. The TOPAZ ozone/aerosol lidar, designed specifically for studying pollution in the boundary layer, was first deployed in 2006 [4]. Employing a quadrupled Nd:YAG laser to pump a tuneable Ce:LiCAF cavity, the system produces sequential pulses at 3 UV wavelengths that can be tuned from 285 to 310 nm. Pulse energy ranges from 0.2 to 0.8 mJ, with pulses transmitted at a 1 kHz pulse repetition rate.

The University of Colorado AMAX-DOAS instrument, similar to the instrument described in [5], is a passive scanning spectrometer configured to measure a variety of trace gases in the ultraviolet and short wavelength visible region of the spectrum, including NO2, SO2, and possibly BrO, IO, formaldehyde, glyoxal, and ozone. The instrument was first tested on the Twin Otter during the summer of 2008, then was redeployed during summer 2009 alongside the TOPAZ lidar for preliminary pollution studies in California prior to the lidar tests described here.

Because size, weight, and power consumption are limited for multi-instrument Twin Otter deployments, the University of Salford Halo Doppler lidar [6] was selected for deployment on the Twin Otter. The all-solid-state Salford lidar transmits low energy, 1.6 µm eyesafe pulses at a 20 kHz pulse rate. Returns backscattered from atmospheric aerosols are accumulated over multiple pulses and then processed to produce real-time estimates of radial velocity and backscatter cross-section, which are stored on a disk and displayed on a laptop computer.

4. GROUND-BASED CHARACTERIZATION

Prior to the aircraft tests, we performed a side-by-side comparison of measurements from the Salford lidar with those from the NOAA HRDL instrument [7], which has been used extensively over the past several years in a number of field experiments. HRDL produces significantly more energy per pulse and operates at a lower pulse rate (200 Hz vs 20 KHz), and as such should provide measurements to longer ranges or be able to measure to lower backscatter thresholds..

The two instruments were set up adjacent to each other and operated with similar temporal and range resolution over a period of approximately 28 hours (the comparison was terminated due to onset of rain). Comparative measurements were obtained for both vertical and nearly-horizontal (~2.5 degree elevation angle) pointing configurations. Conditions during the ground-based comparisons were fairly typical of dry summer conditions in Colorado, with daytime temperatures around 30º C and dew points less than 10º C.

Figure 1 shows a one hour time series of vertical velocity and intensity measurements obtained by the HRDL and Salford lidars while operating in a zenith pointing mode. Boundary layer height during the measurement period can be seen from the observations to be about 2 km. Although HRDL provides slightly better sensitivity above the boundary layer, as expected, both lidars provide excellent coverage of the entire boundary layer and the overlying cloud feature. Visually, correlation of the measurements taken by the two systems for even the smallest features is quite impressive. The complete data set is currently being analyzed to obtain a more complete statistical comparison of the two measurements.

5. AIRCRAFT INSTALLATION

Following the ground base comparison measurements, the Salford lidar was installed in the Twin Otter Aircraft. Figure 2 shows the installation near the rear door of the Twin Otter. We developed a configuration

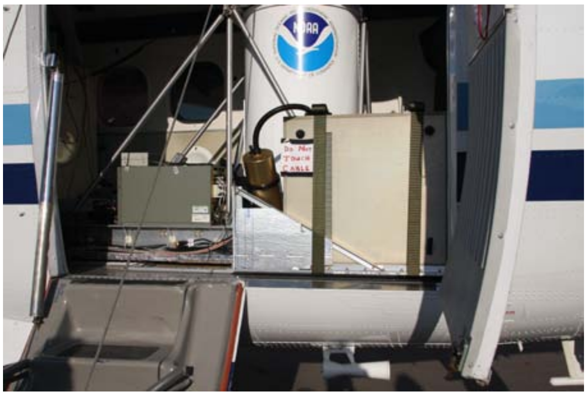

Figure 2. *Photo of the Salford Halo lidar as installed in the Twin Otter. The lidar includes a control unit (rectangular box with straps) plus a laser head (cylinder with umbilical). The TOPAZ lidar telescope, positioned directly over the nadir port, can be seen behind the Salford lidar.*

to share the nadir port on the aircraft with the TOPAZ lidar by mounting the Salford lidar just outside the nadir port and directing the beam through the port at a fixed angle of 30º off nadir (Figure 3). The beam was positioned to point directly transverse to the longitudinal axis of the Twin Otter, in order to minimize Doppler shift of the scattered radiation resulting from aircraft motion. Eventually, for full scientific deployments, a scanner (to obtain two azimuth angles) and motion compensation system will need to be added to obtain accurate vector winds. However the fixed pointing configuration utilized here enabled evaluation of sensitivity and Doppler stability, the primary goals of the experiment.

During the flight, pitch and yaw angle of the aircraft can change by a few degrees as fuel is consumed and crosswinds vary. These changes in aircraft attitude introduce aircraft-motion-induced Doppler shift into the Salford lidar return. During post-processing we remove aircraft motion effects by computing the Doppler shift of the return from ground and subtracting it from the computed Doppler shift of the backscattered signal at each range gate.

Because the Twin Otter flies unpressurized, temperature and pressure vary significantly during the climb to flight attitude and descent. However, as a result of its all solid state design, the Salford lidar was relatively unaffected by these changes, requiring only minor adjustments after the aircraft reached flight altitude. The only modification to the instrument prior to installation was replacement of the floating-head disk drive used for data storage with a solid state disk.

6. FLIGHT RESULTS

Although we planned to fly at least 3 flights during the week-long aircraft test period, unusually cool, wet, and cloudy weather limited flight opportunities. As a result, we were only able to squeeze in two flights before the required aircraft download date. An additional adverse effect of the cool weather was the lack of significant ozone production along the Front Range, eliminating our objective of investigating upslope transport of ozone into mountainous areas west of Denver.

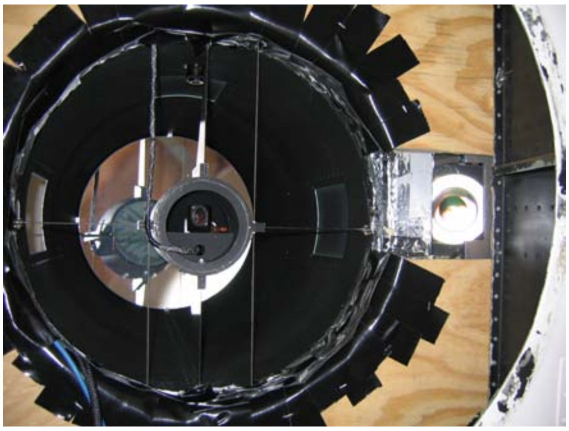

Figure 3. *Photo looking upward into the aircraft nadir port showing the TOPAZ lidar telescope aperture with the Salford lidar aperture on the right*.

Figure 4 shows the flight track for the second of the two test flights on Friday, July 31. Because of a hard deadline to begin offloading the plane by early afternoon, the flight began at 8 AM local time. Morning ozone forecasts indicated low ozone levels over most of the region with little increase predicted during the day. In an effort to make the best of the less than ideal situation, we developed a flight plan to fly to the northeast along the South Platte Valley, then attempt to measure SO_2 concentrations downwind of the Pawnee power plant near Sterling, Colorado. Our hope was that we would be able to observe a predicted morning ozone deficit in the Platte Valley as a result of titration within the advected Denver plume. The flight plan was also developed to repeat several legs in the opposite direction to compare Doppler measurements between legs.

Figure 5 shows preliminary time-height representations of the radial wind profile measured by the Salford lidar and the ozone profile from TOPAZ during the eastbound portion of the flight indicated by the arrows in Figure 4. The flight portion shown in Figure 5 corresponds to approximately 50 km. Several interesting features can be noted in the figure. The shallow boundary layer, as indicated by the observed low levels of ozone deficit that extend from the surface to

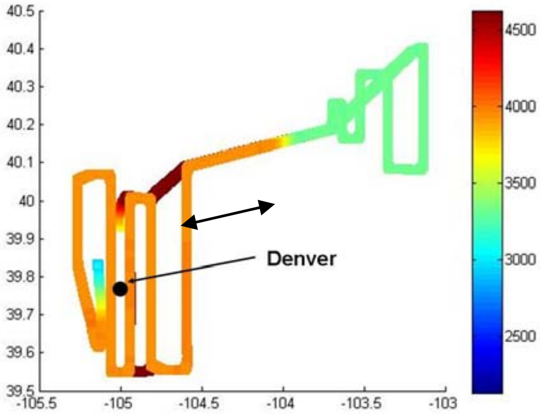

Figure 4. *Flight track for July 31 flight showing flight altitude. Coordinates are in N latitude and W longitude*.

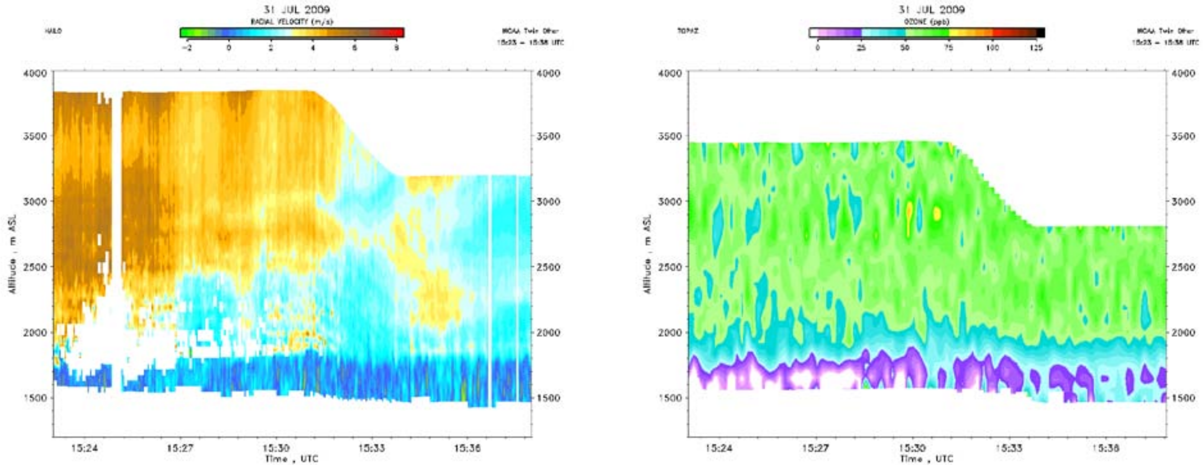

Figure 5. *Time height diagrams of radial wind speed (left) and ozone concentration (right) measured from the Twin Otter along the section shown in Figure 4. White areas in the wind estimate indicate low signal regions.*

about 1800 m ASL, deepens as the plane progresses eastward. Ozone concentrations are near zero in this layer due to titration, while above the layer they are on the order of 60 ppb. The region of low ozone corresponds to light radial winds observed by the Doppler lidar. Because the radial winds are measured at a 30º nadir angle, horizontal wind speed is computed by multiplying the radial measurement by 1/ cos 30º = 1.15, assuming negligible vertical motion. Also, note that because only a single component of the wind is being observed, the measurement corresponds to the roughly SSE component of the wind. The SSE component is seen to diminish as the plane moves eastward.

Figure 6 shows a single profile of ozone and radial wind speed measured by the TOPAZ and Salford lidars at 15:33. Both show similar structure – low values in the boundary layer with higher values observed aloft. Note that an estimate of transport to the NNW could be computed from each pair of ozone and wind estimates shown in Figures 5 and 6. Although not very interesting for the data from this summer's flights, such measurements would be extremely useful for characterizing pollution transport when the ozone and wind fields exhibit significant 3-dimensional structure.

7. FUTURE PLANS

Although the preliminary analysis described here is extremely promising, we plan to move forward with a more complete evaluation of the feasibility of co-deploying a small Doppler lidar in the Twin Otter. This evaluation will include both an estimate of sensitivity and performance as well as an assessment of the difficulty of adding scanning capability within the rather limited spatial and weight constraints imposed by the Twin Otter. Our intention, if funding can be found, is to deploy the lidar during a planned summer 2010 field experiment to study pollution in southern and central California.

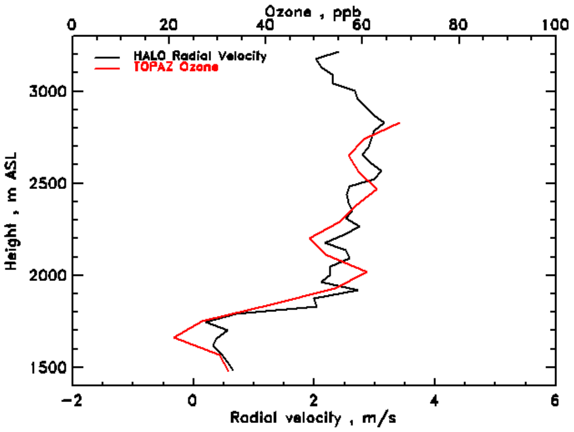

Figure 6. *Simultaneous wind and ozone profiles measured by Salford and TOPAZ lidars.*

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