

# Lidar Applications in Regional Air Quality Studies

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**Abstract**—During recent air quality studies in the United States, NOAA's Environmental Technology Laboratory (ETL) deployed three lidars to improve characterization of the regional environment. An airborne ozone DIAL system mapped out 3-dimensional profiles of ozone and aerosol, enabling tracking of urban plumes, identification of the residual layer, and specification of ozone production efficiency and dispersion associated with power plant plumes. At surface sites, Doppler and ozone DIAL systems characterized the time evolution of wind profiles, turbulence, vertical mixing, horizontal transport from low level flows, and effects of transient events such as gust front passages. The lidar information greatly complemented observations from airborne and surface in situ sensors, and will be critical for improving understanding and modeling of regional air quality events.

## I. INTRODUCTION

Tropospheric ozone and fine particulate matter have been shown to be detrimental to human health when present in concentrations associated with urban air pollution events. In order to improve management of these pollutants in urban areas, a better understanding of the processes associated with the formation and transport of oxidants and fine particulates is critical. To model and predict changes in air quality, a thorough understanding of the chemical reactions that lead to formation and destruction of atmospheric pollutants is clearly needed. However, knowledge of meteorological processes such as vertical and horizontal transport, mixed layer characteristics, and cloud and moisture fields is often equally important to gain a full understanding of the problem. Many of these atmospheric variables can be directly measured or computed from lidar returns.

During the summers of 1999 and 2000, two major air quality experiments were conducted in the Nashville, Tennessee (Nashville99) and Houston, Texas (TexAQS2000) areas by scientists from the National Oceanic and Atmospheric Administration (NOAA) and other government and university laboratories. Both field studies incorporated a broad assortment of chemical and atmospheric sensors on aircraft and surface platforms to investigate linkages between chemical, biological, and meteorological processes that

govern the formation and accumulation of ozone and fine particulate aerosols. Among the sensors deployed during Nashville99 and TexAQS2000 were three lidar systems operated by NOAA's Environmental Technology Laboratory (ETL) to remotely observe profiles of aerosol backscatter, ozone concentration, wind speed, and atmospheric turbulence. Two of these lidars, a Doppler and an ozone profiling lidar were surface based, while the third lidar was flown on an aircraft to map out the three-dimensional distribution of ozone and aerosol in the Nashville and Houston areas. Other measurement systems deployed at Nashville and Houston included two heavily instrumented research aircraft that performed in situ chemical observations, several surface chemistry sites, and a network of wind profiling radars and surface flux stations. In both studies one of the surface sites was designated a "super site", and included additional measurements of important chemical species, ETL's Doppler and ozone lidars, a wind profiling radar, and a Differential Optical Absorption Spectroscopy (DOAS) system. The NOAA lidar measurements provided unique information on horizontal transport, regional 3-dimensional variability, vertical layering, and turbulent mixing that greatly enhanced interpretation of the in situ ground-based and aircraft observations.

## II. HORIZONTAL TRANSPORT OF URBAN AND POWER PLANT PLUMES OBSERVED WITH AIRBORNE LIDAR

During the Nashville99 experiment, NOAA/ETL's airborne lidar was used to characterize the 3-dimensional structure of ozone and aerosol in the region around Nashville, observe the horizontal transport of the Nashville urban and power plant plumes, and investigate relationships between mixed layer height, land use, and ozone concentration. The lidar system was flown on a slow flying aircraft at a height of about 3.5 km above ground level (AGL). The instrument measures profiles of ozone with better than 10 ppbv precision at a horizontal resolution of 500 m and a vertical resolution of 90 m. Aerosol backscatter measurements are also obtained with a vertical resolution of 15 m. Further technical details about the system can be found in [1].

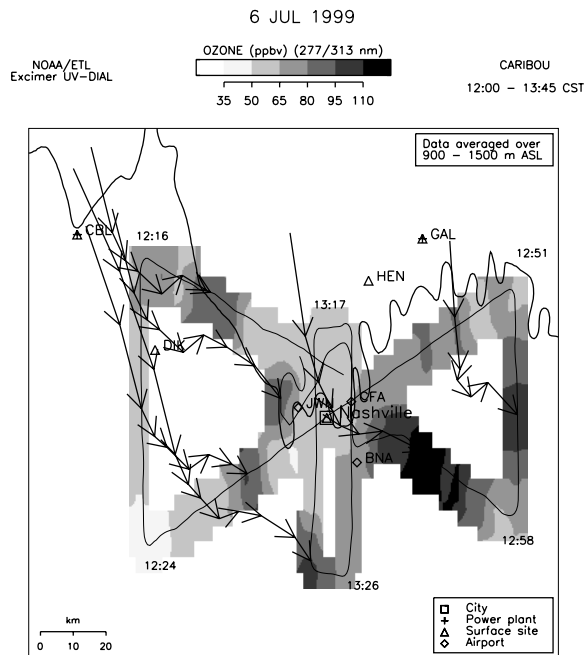


Fig. 1. Distribution of ozone in the Nashville area on July 6<sup>th</sup> as measured with airborne lidar. Back-trajectories are drawn as sequences of arrows; each arrow represents the path traveled by an air parcel in 1 hour.

As an example of the airborne lidar measurements, Fig. 1 shows the horizontal distribution of ozone concentration during the early afternoon on July 6<sup>th</sup> along a “butterfly” flight pattern centered over Nashville. The ozone data in Fig. 1 were averaged vertically between 900 and 1500 m above sea level (ASL). Several patches of high-ozone concentrations are visible east and west of the city while the urban area itself is fairly clean. To determine the origin of these high-ozone patches we calculated particle back-trajectories using data from the wind profiler network around Nashville. Back-trajectories starting at the location of the high-ozone patches and at the time the lidar overflowed them are overlaid in Fig. 1. The largest and most concentrated area of elevated ozone about 30 km southeast of the city appears to be the Nashville urban plume advected to this location by the northwesterly winds. The other regions of high ozone concentrations are associated with the plumes of the Gallatin (GAL) and Cumberland (CBL) coal-fired power plants as the trajectories can all be traced back to within a few kilometers of the power plants. This clearly highlights the importance of regional-scale transport during air pollution events and its impact on rural areas.

### III. GROUND-BASED LIDAR MEASUREMENTS AT THE NASHVILLE99 SUPER SITE

ETL’s Doppler and ozone lidars at the Nashville99 super site were intended to characterize the vertical structure and

transport of ozone and aerosol in the lowest 2-3 km above the site. In particular, observing and understanding processes associated with evening and morning transitions of the lower boundary layer from well-mixed to stable and back to well-mixed was of specific interest. Other objectives of the surface lidar measurements focused on observing the low-level jet as a mechanism for horizontal transport of pollutants at night, and understanding the extent to which vertical transport across stable layers affects chemical in situ observations near the ground.

The ETL ground-based ozone and aerosol lidar is described in [2]. The system’s beam can be scanned in a vertical plane to provide high-resolution ozone and aerosol profiles from near the surface to about 3 km altitude. The mini-MOPA Doppler lidar [3] measures radial winds with high precision (better than 10 cm s<sup>-1</sup>) and 90 m range resolution to ranges of 3-10 km, depending on aerosol loading and humidity. During daylight hours, both lidars frequently were pointed vertically to characterize mixed-layer statistics. During the morning and evening transition periods and at night, we switched to frequent vertical scans to observe the development and characteristics of low-level flows and associated changes in ozone concentration. Periodically, the Doppler lidar performed conical scans to detect changes in wind direction and to correct the orientation of the vertical scan planes. The following measurement example illustrates the kind of information and level of detail the collocated Doppler and ozone lidars were able to provide. On the evening of June 22<sup>nd</sup> a weak thunderstorm outflow boundary passed over the Nashville99 super site. The upper panel in Fig. 2 shows time series of ozone concentration measured near the surface with an in situ sensor and at 400 m and 1000 m AGL with the ozone lidar around the time of the gust front passage. The corresponding time-height cross section of horizontal winds measured with the Doppler lidar is shown in the lower panel. The cross section of horizontal winds was computed from vertical scans with the lidar pointing to the southeast. The head of the weak outflow is seen at roughly 18:18 CST, when the wind shifts from a southeasterly to a northwesterly direction. As the outflow moves through the site, it eventually reaches a depth of approximately 500 m. Beginning at about 18:30 CST, a low-level jet develops at approximately 180 m AGL; this jet persists but gradually weakens until 19:30 CST, when the vertical scans were discontinued. Prior to the event, surface ozone was decreasing while ozone concentrations aloft, insulated from ozone-destroying pollutants at the surface as the atmosphere stabilized in the evening, remained virtually unchanged. Following the passage of the gust front, surface ozone rapidly increases by nearly 20 ppbv and remains high for about 1 hour. During this time period, the ozone levels at the surface and at 400 m AGL are nearly identical. This suggests that turbulence generated by the gust front passage and by wind shear associated with the low-level jet caused a mixing down of higher ozone concentrations from aloft to the surface. As the low-level jet and the turbulence weaken, the

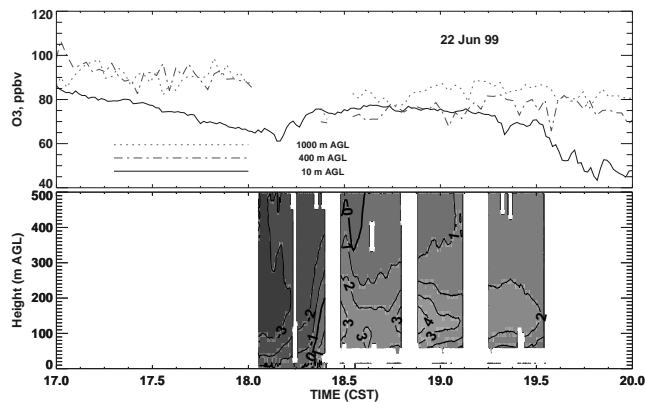


Fig. 2. (Upper panel) Ozone time series in ppbv at three altitudes during a gust front passage at the Cornelia Fort site. (Lower panel) Time-height cross section of the component of horizontal wind parallel to the lidar scan plane in  $\text{m s}^{-1}$ . Negative numbers indicate a southeasterly flow, positive numbers a northwesterly flow. Blank areas denote periods when conical scans were performed.

residual layer aloft decouples from the surface and surface ozone levels decrease again.

#### IV. AIRBORNE LIDAR MEASUREMENTS OF OZONE DISTRIBUTION NEAR A SEA BREEZE CONVERGENCE ZONE

One of the key objectives of the TexAQS2000 experiment was to study the role of pollutant recirculation during high-ozone episodes in the Houston area. Frequently, at night and during the morning hours an offshore flow develops that carries pollutants from the Houston urban area and nearby petro-chemical refineries to the south and east over Galveston Bay and the Gulf of Mexico. In the afternoon the flow reverses with the onset of the Galveston Bay breeze and the Gulf breeze; the aged pollutants are brought back and mix with fresh emissions from the Houston metro area and the refinery complexes.

Several flights of NOAA/ETL's airborne ozone and aerosol lidar were specifically designed to map out the 3-dimensional ozone distribution over the Houston area prior to, during, and after the passage of the bay and sea breeze fronts. Fig. 3 shows a vertical cross section of ozone concentration from an east-west flight leg across the coast of Galveston Bay obtained on August 30<sup>th</sup> around 17:30 CST. This cross section is located about 30 km south of Houston and was part of a sequence of five east-west transects that covered the area near the Galveston Bay shore from Texas City north to Houston. This sequence of cross sections shows an along-coast wall of very high ozone concentrations of up to 200 ppbv, extending from near the surface to about 2 km above ground level. The pollution over Galveston Bay is confined to the lowest few hundred meters due to the shallower mixing layer depth over water. The high ozone concentrations observed in the ozone cloud along the coast are likely due to the mixing of aged pollutants advected by

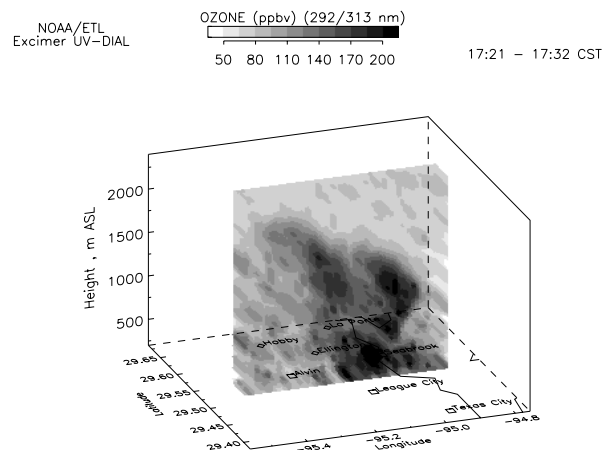


Fig. 3. Cross section of ozone concentration in ppbv in sea breeze convergence zone near the shore of Galveston Bay observed late in the afternoon on August 30<sup>th</sup> 2000.

the sea breeze with the pollution cloud that had formed over the Houston area during the day. The sea-breeze convergence zone produced additional uplift, which carried the pollution up to an altitude of 2 km. This deep upward penetration meant that the pollution was later distributed over the region to become part of the regional background on subsequent days.

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#### REFERENCES

- [1] Alvarez II, R. J., et al, 1998. Comparisons of airborne lidar measurements of ozone with airborne in situ measurements during the 1995 Southern Oxidants Study, *J. Geophys. Res.*, **103**, 31,155-31,171.
- [2] Zhao, Y., et al, 1997. ETL's transportable lower troposphere ozone lidar and its applications in air quality studies. *Proc. SPIE #3127*, San Diego, CA, 53-62.
- [3] Brewer, W. A., et al, 1998. Combined wind and water vapor measurements using the NOAA mini-MOPA Doppler lidar. *Proc. 19<sup>th</sup> ILRC*, NASA/CP-1998-207671/PT2, 565-568.