LIDAR METHOD TO CHARACTERIZE THE SIZE, GROWTH, AND RISE OF JET ENGINE EXHAUST PLUMES

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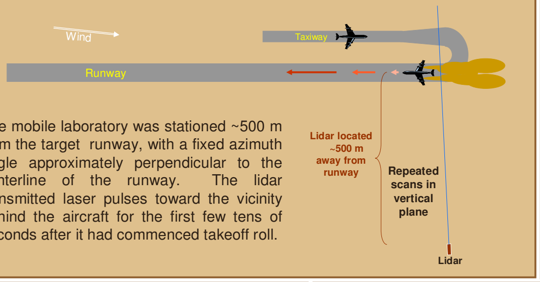
INTRODUCTION

NOAA's Earth System Research Laboratory (ESRL) conducted studies of aerosol plume behavior from jet engine exhaust using lidar. Observation campaigns were completed at Los Angeles International Airport (LAX) in 2001, Hartsfield-Jackson Atlanta International Airport in 2004, and at another large U.S. airport in 2006. Vertical cross-sections of backscatter from the exhaust plume were measured during aircraft takeoff roll. The goal was to determine plume extent and rise for various types of aircraft and meteorological conditions. The evolution of plume extent (height and width) as determined from lidar backscatter is being used to improve air quality models, in particular the Federal Aviation Administration's (FAA) Emissions and Dispersion Modeling System (EDMS).

Instrument Set Up for Plume Observation



The mobile laboratory was stationed ~500 m from the target runway, with a fixed azimuth angle approximately perpendicular to the centerline of the runway. The lidar transmitted laser pulses toward the vicinity behind the aircraft for the first few tens of seconds after it had commenced takeoff roll.

INSTRUMENTATION

The Ozone Profiling Atmospheric Lidar (OPAL) emits pulses at 355-nm wavelength to remotely sense tropospheric aerosols. The aerosol particles in aircraft exhaust have mass size distributions that peak typically between 30 and 100 nm. The 355-nm wavelength is nearly optimum for detecting these small particles in the presence of scattering from molecules and ambient particles.

LIDAR OPERATING PARAMETERS

Parameter	Value
Wavelength	355 nm
Pulse Energy	8 mJ
Pulse Repetition Rate	10 s^{-1}
Pulse Length	10 ns
Range Gate Resolution	5 m
Telescope Diameter	0.2 m
Elevation Angle Resolution	0.2 degrees

The lidar scans in elevation angle only, sweeping between -3 and 22 degrees through a side window. It can also point vertically through a top window. The near channel had a minimum range of "full overlap" of 200-300 m. The system can also operate in single-stare or step-stare modes. Data from stare modes (vertical and horizontal stares) were used to calibrate the lidar and to monitor the ambient extinction coefficient.

SOLVING THE LIDAR EQUATION FOR β_p

The equation for the raw received signal, X_0, as a function of range, *R,* for a single pulse can be expressed as:

$$X_0(R) = CER^{-2}\,[\beta_m(R) + \beta_h(R) + \beta_p(R)]\times[\,t_m^2(R)t_h^2(R)t_p^2(R)] + O + EMI(R)$$

C = lidar calibration constant
O = background light/receiver DC offsets
β_m = molecular backscatter coefficient
β_h = ambient aerosol (haze) backscatter coefficient
β_p = backscatter coefficient of particles from the engine
E = pulse energy monitor reading
EMI = Electromagnetic interference
$t_m(R)$ = transmission due to molecular extinction
$t_p(R)$ = transmission due to extinction of engine generated particles
$t_h(R)$ = transmission due to ambient aerosol extinction

The processing method solves this equation for $\beta_p(R)$. After the application of the basic engineering factors, and applying a R^2 correction, the equation becomes:

$$X_1 = C_1\,[\beta_m(R) + \beta_h(R) + \beta_p(R)]\,t_m^2(R)t_h^2(R)t_p^2(R) \text{ where } C_1 = CE$$

A $t_m^2(R)t_h^2(R)$ factor was applied based on values of constant ambient extinction coefficient determined by occasional horizontal stares when no plumes were present. The ambient variation in $\beta_h(R)$ and the $t_p^2(R)$ factors were approximated by adjusting the backscatter measured through the plume region to make the average backscatter value in the postplume region the same as in the foreplume region for each pulse.[a]

C_1 was determined in one of two ways. In one, a "clean" layer aloft was selected in vertical stares where backscatter is contributed principally from molecules and could be calculated from a density profile. A Fernald-Klett retrieval was used to correct for the aerosol extinction profile. In the other, the slope method was applied on horizontal stares with no plume present to find the extinction coefficient, removing the aerosol component of the backscatter with an assumed value of the aerosol extinction-to-backscatter ratio and extrapolating the molecular backscatter back to zero range.

Applying the extinction and calibration gave $X_2 = \beta_m + \beta_h + \beta_p(R)$, subtracting the ambient backscatter values from X_2 leaves only the backscatter attributed by the aircraft exhaust plume, $\beta_p(R)$. [b]

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[a] The corrections are generally small in magnitude, but are important in estimating the β_h for weak plume signals.

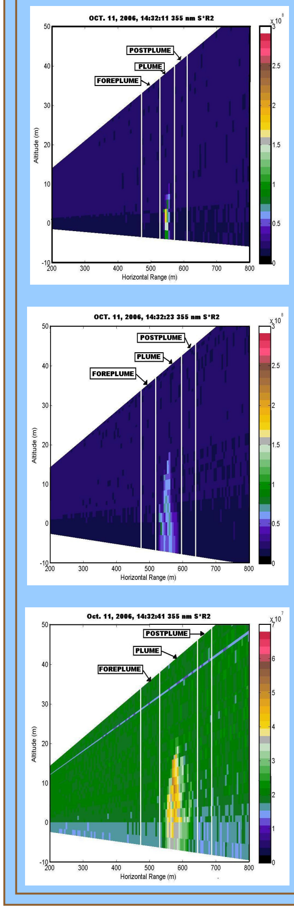
[b] The molecular and ambient aerosol values are assumed constant with range for each pulse.

SCAN STRATEGY AND MEASUREMENTS

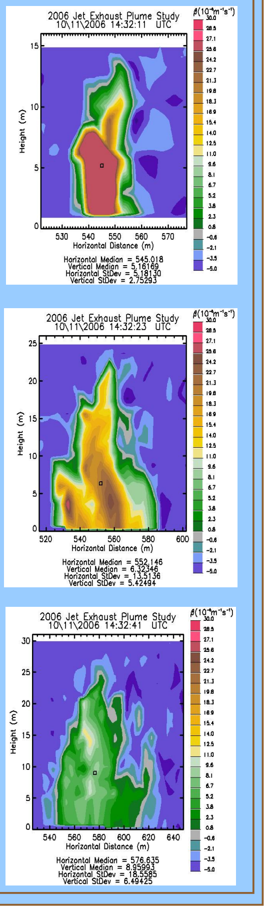
The scan strategy was designed to take measurements from very near ground level through the entire vertical extent of the plume and slightly above. The distance behind the aircraft and age of the plume increased with each sequential scan. The data were interactively inspected scan by scan to determine an exhaust plume (enhanced signal) region along with regions (ambient return signal), both foreplume and postplume. The figures below in the left column depict scans, while observing an MD83 aircraft, of un-calibrated aerosol backscatter with each region designated.

MD83 Aircraft Observations

Uncalibrated backscatter as a function of vertical height from the scanner (~12 ft. AGL) and horizontal distance from lidar



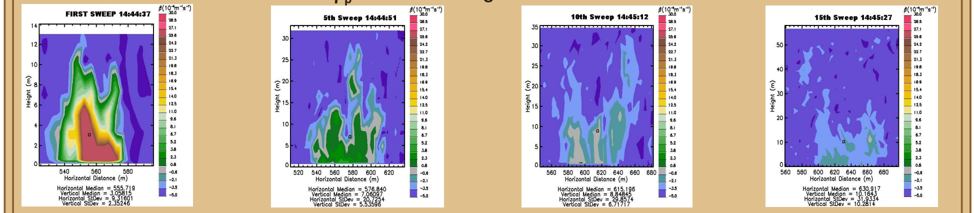
Enhanced calibrated backscatter, β_p, from the aircraft exhaust plume. Data has been interpolated to a rectangular grid, and referenced to the runway height and distance from the lidar



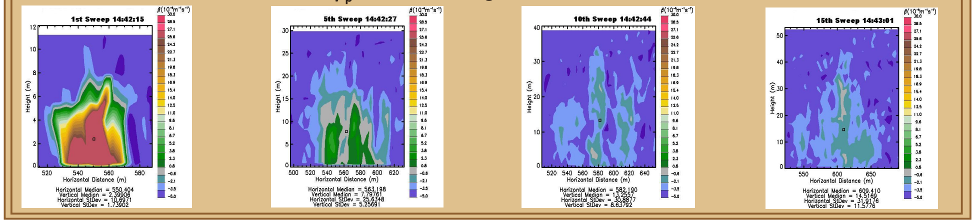
PLUME GEOMETRY

The lidar took measurements that allowed plume geometry to be determined from over 1200 aircraft during 3 field campaigns. Methods were developed to isolate the enhanced backscatter due to the particles emitted by the engines, even when weak in the presence of backscatter from the air and ambient aerosol particles. Using the 2-D distribution of β_p in cross sections behind aircraft, the inferred descriptions of plume height and size as initial conditions for air quality models have improved the estimates of surface pollutants near airports.

Time Series of 2-D cross sections of β_p behind a Boeing 737-500 Aircraft



Time Series of 2-D cross sections of β_p behind a Boeing 757-200 Aircraft



EMISSIONS AND DISPERSION MODELING SYSTEM AND DATA

The EDMS previously has assumed a single passive point source as the emission source. This assumption ignored the rapid dynamic growth of the exhaust plume immediately after leaving the engine. The studies of aircraft exhaust plumes with OPAL have produced a wealth of data to support increased accuracy of air dispersion models. The table below shows the recommendations made based on the lidar measurements.

The LAX column lists the values incorporated into EDMS after the 2001 campaign. These did bring the model's predictions of surface concentration of pollutants significantly closer to those measured by monitoring networks.

The all airport, all type column in the table gives the most recent recommendations based on the larger data set combining results from all three airports.

RECOMMENDATIONS FOR EDMS

Airport Aircraft Type	LAX All	All All	All Wing	All Fuselage	All Commuter
z_{rise} (m)	12	10.8	10.4	12.9	7.6
s_z (m)	10.5	12.5	13.9	11.8	9.6
s_y (m)	4.1	4.8	4.7	5.5	3.1

The measurements indicate that consideration should be given to aircraft type. A separation of aircraft into three categories would be reasonable.

Two **large** aircraft categories:
- i.) wing mounted engines
- ii.) fuselage mounted engines

A third category for all **smaller** aircraft:
- iii.) commuter aircraft

The differences among the three categories are indicated by the data, but the number of statistical samples is not yet sufficient to unequivocally separate them.