FAA-AEE-02-04
DTS-34-FA34T-LR1
Federal Aviation Administration
Office of Environment and Energy
Washington, D.C. 20591

PRELIMINARY REPORT:

THE USE OF LIDAR TO CHARACTERIZE AIRCRAFT INITIAL PLUME CHARACTERISTICS

Roger L. Wayson
Gregg G. Fleming
Brian Kim
U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Environmental Measurement and Modeling Division, DTS-34
Air Quality Facility, Kendall Square
Cambridge, MA 02142-1093

Wynn L. Eberhard
W. Alan Brewer
NOAA Environmental Technology Laboratory
Optical Remote Sensing Division

Letter Report

October 2002

U.S. Department of Transportation
Federal Aviation Administration

INTRODUCTION

The goal of this study was to measure the initial plume characteristics of jet exhaust plumes. Cross-sections of the plume were measured at a variety of distances behind the aircraft during takeoff roll between May 17 and 24, 2001. The initial behavior was expected to depend on aircraft characteristics, including physical size of the engines and their position on the airframe. Initial plume behavior was also expected to vary somewhat with atmospheric stability and local wind speed. Dispersion is inherently a random process, so many experimental cases are required to determine the mean behavior and typical variability. This preliminary reporting is based on an analysis of all data (4138 sweeps or cross sections) collected at a large North American airport. This study and preliminary report provide new insights into aircraft plume behavior, and data for more accurate modeling of plume rise and spread. This data set will be further evaluated for the final report with the aim of refining these values (e.g., for specific aircraft types) and removing as much conservatism as possible. Additional studies are planned (based on available funding) to analyze potential changes in the derived parameters due to site characteristics (e.g., elevation, weather conditions). The results of these follow-on studies will be separately reported at a later date.

APPROACH

LIDAR (LIght Detection And Ranging) was used in this study to observe the time-varying position and geometry of the jet exhaust. LIDAR is well suited for measuring the geometry of plumes that contain light-scattering particles as the tracer. A LIDAR transmits a pulse of light in a narrow beam and detects the backscatter from light scattering particles as a function of time as the pulse propagates away. The concentration of light scattering particles as a function of range along the pulse's path can be inferred from the time series of detected light intensity. By scanning the LIDAR's pointing direction over a period of time of many LIDAR pulses, the distribution of particles over the region of the sweep (e.g., a vertical plane or plume cross section) can be determined.

Although the use of LIDAR to characterize aircraft plumes is a new concept, LIDAR has been used for several pollution studies in the past. Examples of these studies include: (1) an EPA study on remote sensing of automobile emissions[1], (2) work by the University of Iowa/Los Alamos National Laboratory to investigate traffic particulate emissions[2], (3) work by the South Coast/Southeast Desert Air Basin for pollution transport using an EPA aircraft mounted LIDAR system[3], and (4) work by the University of Colorado/NOAA for

[1] U.S. EPA, Remote Sensing of Automobile Emissions using Raman LIDAR, Contract Number 68D00262 http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1704, Project Dates September 1, 2000 through March 1, 2001.

[2] University of Iowa/ Los Alamos National Laboratory, Measurement of Traffic Particulate Emissions and Incident Detection, www.iihr.uiowa.edu/projects/new_jersey .

[3] California Air Resources Board, Utilization of Remote Sensing Data In the Evaluation of Air Pollution Characteristics in the South Coast/Southeast Desert Air Basin, www.arb.ca.gov/research/abstracts/a2-106-32.htm.

power plant plumes[4]. For example, the first study by EPA stated that LIDAR is an excellent way to do remote sensing for the plume from automobile exhaust. Also, the report concluded, "The UV Raman LIDAR system is expected to enable a variety of commercial environmental monitoring products, including automobile emissions monitoring, light and heavy duty truck emissions monitoring, aircraft emission monitoring, warning systems for toxic chemical spills, and fence line monitoring." In the second study by University of Iowa/Los Alamos National Laboratory, the shape of exhaust plumes from motor vehicle traffic were captured by using LIDAR. Since use of LIDAR is relatively new for this type of application, established data analysis and reduction procedures do not exist. However, this study states that the shape of these plumes can be determined once data analysis and reduction procedures are defined for the individual application. The third study in California pointed out that if methods were developed, LIDAR could be used to make quick effective testing for pollutant transport. Many examples also exist for stationary sources, such as the fourth study example by the University of Colorado/NOAA. In the study, LIDAR was used to measure the plume characteristics from stationary sources (as was done in this report for aircraft). Although only four example reports are discussed above, there are many other reports that include similar details and results. These various studies point out that LIDAR is a viable remote sensing tool for plume characterization. Therefore, it was thought that LIDAR could be used to measure plume parameters of jet aircraft, and methods could be derived to accomplish this goal from the raw collected data.

Two LIDAR units were used in this research on aircraft plume behavior; one using the infrared wavelength and the other using the ultra-violet wavelength. The more successful of the two was OPAL (Ozone Profiling Atmospheric LIDAR) operating at the ultraviolet wavelength of 0.355 µm (after slight modification for this study to measure only aerosol backscatter and not generate the additional wavelengths used to measure ozone). Only the results from this LIDAR (OPAL) are discussed in this preliminary report. Additionally, only one path (or a cross section at one stationary position behind the moving aircraft) is presented in this preliminary report. This path, or horizontal plane of the LIDAR sweep, is shown in Figure 1 as the red line. If additional funding can be identified for NOAA data reduction, the final report may include data from the infrared scanning LIDAR, which collected data at the other sweep angles shown in Figure 1.

After data collection, initial quality control was performed by NOAA personnel to eliminate any anomalies. Computer graphics were then used to illustrate the plume. Figure 2 shows such an example illustration of a sweep. In the Figure 2 example, the center of the plume can be easily identified by the area of greatest concentration (red center). This represents the height of the plume, or plume rise. The outer boundaries of the plume are also easily identified allowing the width and height of the plume to be

---

[4] University of Colorado / NOAA, Airborne lidar characterization of power plant plumes during the 1995 Southern Oxidants Study, www.agu.org/pubs/abs/jd/98JD02625/tmp.html, 1995.

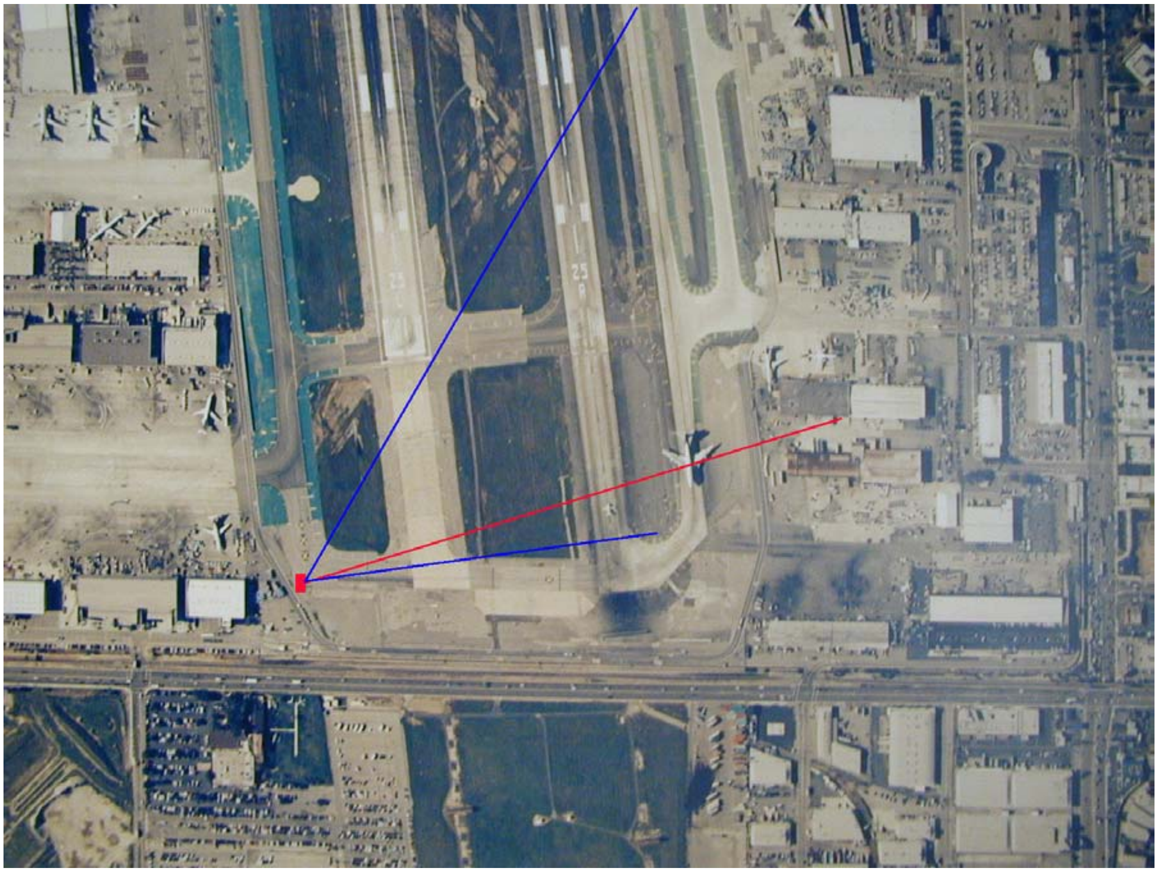


Figure 1: Sweep Angles For LIDAR Units (Only the Red Sweep is Discussed in This Report)

quantified. For each sweep (cross section) care was taken to carefully determine the height of the center of the plume (Z_{center}), which represents the plume rise. The outer boundaries of the plume were also carefully determined for each sweep. The scale on the side of the chart should also be noted. To make sure that the plume was accurately represented, and not other concentrations or interferences, the plume was only measured to the well-defined boundaries. In the Figure 2 example, this was to the light brown (i.e., 0.54 ρ_{pl} / ρ_{bkg}) fringe as shown. Since the scale is the measured density or concentration of aerosol to the background (ρ_{pl} / ρ_{bkg}) the ratio of concentrations from the center (red) to defined outer fringe could be determined since:

$$(\rho_{plc} / \rho_{bkg}) / (\rho_{plf} / \rho_{bkg}) = (\rho_{plc} / \rho_{plf}) \qquad [1]$$

where: ρ_{plc} = density (concentration) of plume center
ρ_{plf} = density (concentration) of plume fringe

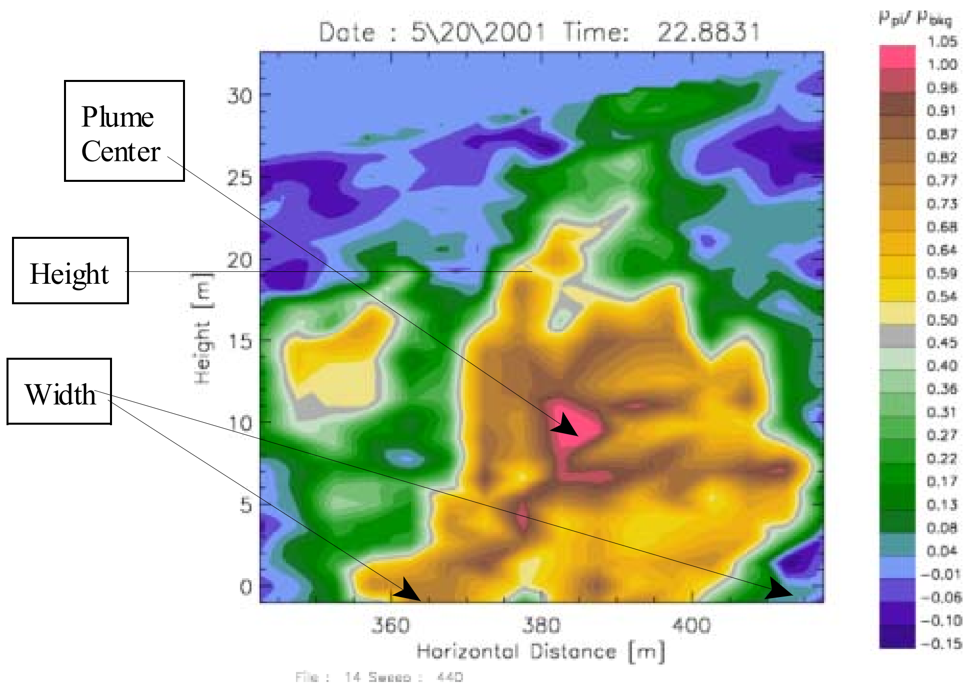


Figure 2. Example of Computer Enhanced LIDAR Image

Unfortunately, not all sweeps were as easy to determine the center and fringes as the example shown. The example is a well-behaved plume. Plume break-up, multiple centers, high plume rise, and irregular shapes required engineering judgment in many cases. The only way to accurately determine the plume was to review the time series of events (sweeps) behind the aircraft and envision the plume in total. This process was difficult due to the effect of the high velocity jet from the aircraft, which tended to cause irregular mixing and false centers of the actual plume. These data were carefully reduced in such a way to allow for a more systematic recreation of a symmetric plume in the final analysis. This recreation provides added quality assurance of the data presented in this preliminary report.

Once the center of the plume and the plume fringe were determined for each sweep used in the analysis, the plume rise for the aircraft event was determined. The plume rise was based on the sweep corresponding to two samples (or sweeps) when the plume had risen to the final measured height with the second greatest height or elevation used in the final plume rise determination. This approach provided a level of conservatism as compared with selecting the sweep with the greatest height or plume rise. A conservative approach was also used to determine the standard deviation of the plume. For the standard deviation determination, the same sweep used for the plume rise was used. The ratio of the concentrations was determined as well as the distance to the fringe from the center of the plume. Using this information, and the basic Gaussian equation, the instantaneous standard deviation was determined. It should be noted that the Gaussian models use time-averaged standard deviations, but the use of multiple aircraft events will result in values, which more closely represent time-averaged values.

All data was then included in a commercially available spreadsheet and the initial plume parameters derived.

CONCLUSIONS

This first analysis is based on all of the useable data collected. From this data (4138 sweeps) events were characterized for each aircraft event. The second highest value for plume rise was then selected. This resulted in 377 events for large commercial aircraft and 52 events for commuter aircraft.

It can be concluded that significant plume rise occurs. It can also be concluded that initial plume spread is also significant. Findings in this report represent overall values for plume rise and initial plume standard deviations. The final, overall values are:

Large Commercial Aircraft (primarily turbofan engines)

Sigma Y = 10.8 meters
Sigma Z = 4.1 meters
Plume Rise = 11.9 meters

Commuter Aircraft (primarily turboprops)

Sigma Y = 10.3 meters
Sigma Z = 4.1 meters
Plume Rise = 12.1 meters

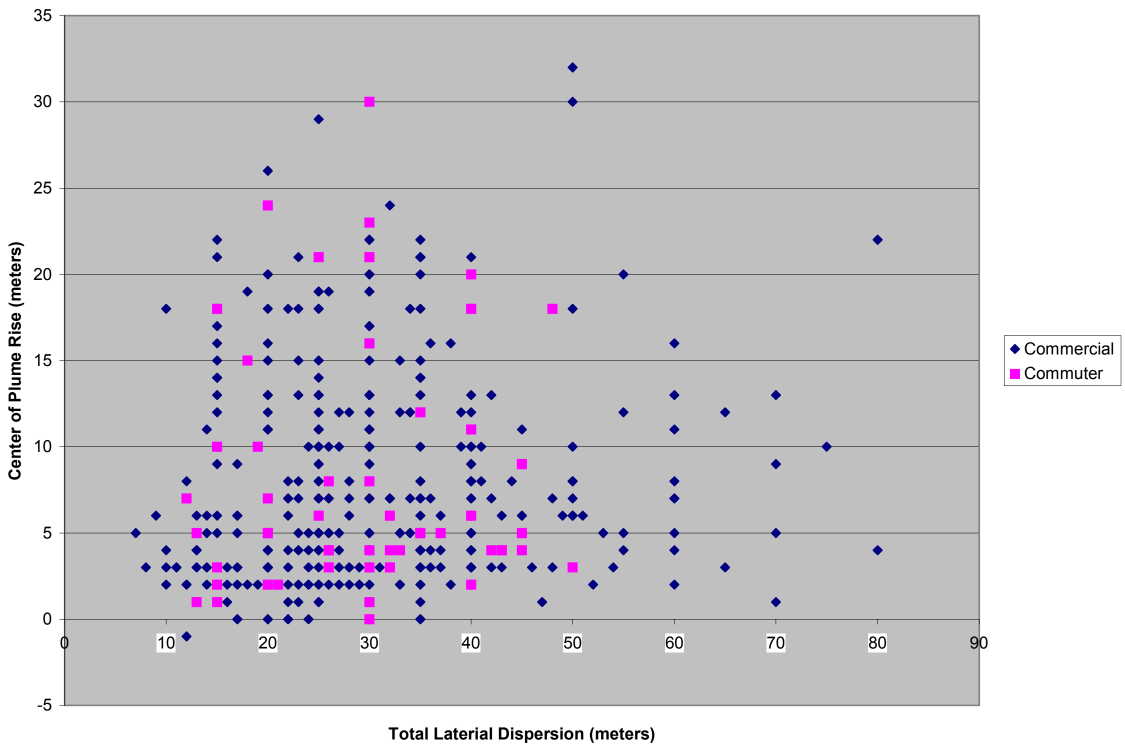
Although the larger aircraft did display greater horizontal spreading in some cases, due to the similarities in these preliminary values, it is recommended that a single set of values be utilized until the additional follow-on analysis is complete. The single set of derived values is as follows:

Sigma Y = 10.5 meters
Sigma Z = 4.1 meters
Plume Rise = 12 meters

This study and preliminary report provide new insights into aircraft plume behavior, and data for more accurate modeling of plume rise and spread. This data set will be further evaluated for the final report with the aim of refining these values and removing as much conservatism as possible.

For example, the trend of similar results for the larger commercial aircraft and the smaller commuter aircraft was explored in more detail. Figure 3 shows the graphical comparison. The x-axis (absicca) is the value of the total plume spread while the y-axis (ordinate) is the center of the plume after plume rise has occurred.

Figure 3. Comparison of Large Commercial and Smaller Commuter Aircraft Trends



It can be seen in Figure 3 that trends are very similar, just as the derived numbers report. However, it is also obvious that many events for the lateral dispersion are greater for the larger commercial aircraft. This result will be further explored by breaking the data into small groups by aircraft types and analyzing the results.

Additional studies also are planned (based on available funding) to evaluate potential changes in the derived parameters due to site characteristics, such as elevation and weather. These will be topics of follow-on studies and additional reporting.