# AIRBORNE AND SCANNING LIDAR RESULTS OBTAINED DURING THE PACIFIC 2001 AIR QUALITY FIELD STUDY

**Kevin B. Strawbridge[(1)]**

[(1)]*Meteorological Service of Canada, Air Quality Processes Research Division, Centre For Atmospheric Research Experiments, 6248 Eighth Line, R.R. #1, Egbert, Ontario, Canada, L0L 1N0, Kevin.Strawbridge@ec.gc.ca:*

**ABSTRACT**

Two different lidar platforms were employed in the Pacific 2001 Air Quality Field Study. A simultaneous upward/downward airborne lidar system called AERIAL (AERosol Imaging Airborne Lidar) was flown aboard the National Research Council of Canada, Convair 580 (CV580). The primary task of this platform was to establish a regional picture of particulate matter (PM) concentrations in the Lower Fraser Valley (LFV) of British Columbia. The high temporal and spatial resolution of the lidar provided images of PM stratification and boundary layer structure along predetermined flight lines. The flight lines were divided into a series of north-south and east-west lines to provide a snapshot of the LFV as well as provide aerial support for four ground sites. There were 9 flights flown between 14 August and 30 August, including 2 night flights. The primary purpose of the night flights was to map PM transport in the lake valleys along the north range of the LFV.

A scanning lidar facility called RASCAL (Rapid Acquisition SCanning Aerosol Lidar) was part of a suite of instruments making longer term measurements at the Langley Lochiel ground site. The lidar system was programmed to take three elevation scans (west, north and east) of the troposphere from the horizon to near zenith. Measurements were conducting for approximately 16 hours per day except longer during aircraft night flights. Results from both the airborne and scanning lidar facilities will be presented.

## 1. INTRODUCTION

The Pacific 2001 Air Quality Field Study was primarily interested in understanding the role of both anthropogenic and biogenic aerosols on air quality in the Lower Fraser Valley (LFV) of British Columbia. The study had two major thrusts: a ground-based monitoring network with high frequency measurements and a aircraft component providing less frequent measurements during specific times and over areas of interest. There were two aircraft involved in the study: a Convair 580 (CV580) aircraft owned and operated by the National Research Council of Canada (NRCC) and a Cessna 188 owned and operated by the Canadian Forestry Service. The Cessna was primarily tasked with providing in situ boundary layer measurements above and around the ground sites, while the CV580 provided a more regional picture of the LFV. Flight planning was based on daily weather briefings and a pre-arranged set of flight lines comprised of several north-south and east-west legs.

The primary instrument aboard the CV580 was a simultaneous upward/downward lidar system known as AERIAL. Airborne lidar measurements were also obtained during an earlier study in the LFV, called Pacific'93 [1]. Although the same aircraft was used for both measurement campaigns, there were significant changes to both the flight planning and equipment onboard. During Pacific '93, the aircraft performed both the in situ and lidar measurements, limiting the amount of spatial coverage possible. In addition the aircraft only flew during daytime hours. This in part, was the motivation for using two aircraft during Pacific 2001. Since the Cessna is a small, more maneuverable aircraft, with less flight restrictions, it was more conducive to boundary layer measurements and ground site characterization. Conversely, the extended flight time of the CV580, could then be dedicated to providing a more comprehensive regional picture of particulate matter (PM) concentrations within the LFV. The addition of night flights and the extension of the north-south flight legs were planned primarily to look at transport of PM into the tributary valleys to the north of the LFV as suspected in Pacific'93 [2,3].

A scanning lidar facility known as RASCAL was used to provide fast elevation scanning profiles of the lower troposphere with a resolution of 3m along the laser beam axis. RASCAL data provides a comprehensive optical picture of the atmosphere in three dimensions. This helps interpret the temporal variation of aerosol optical properties within a widely inhomogeneous atmosphere.

One of the tasks of RASCAL was to provide information on the height and structure of the planetary boundary layer (PBL). The PBL is the lowest part of the troposphere and plays an important role in our everyday lives as it represents the air that most of us breathe. Because air pollution concentrations are significantly higher in the PBL than the rest of the atmosphere, it tends to play an important role in the understanding and assessment of air pollutants. The height of the boundary layer is therefore a crucial quantity for air quality modelling or forecasting and is essential for the interpretation of atmospheric constituents. Lidar has been shown for many years to provide accurate measurements of the top of the boundary layer [4-7]. The fundamental premise takes advantage of the large gradient in aerosol concentration generally evident between the boundary layer aerosols and those found in the free troposphere. The entrainment zone is the transition zone between the PBL and the free troposphere and depending on the time of day can be highly variable. The top of the PBL, in the idealized case, is therefore taken to be the midway point of the entrainment zone. The technique discussed here uses a combination of critical threshold, constrained gradient methods and the benefit of high spatial resolution scanning lidar data.

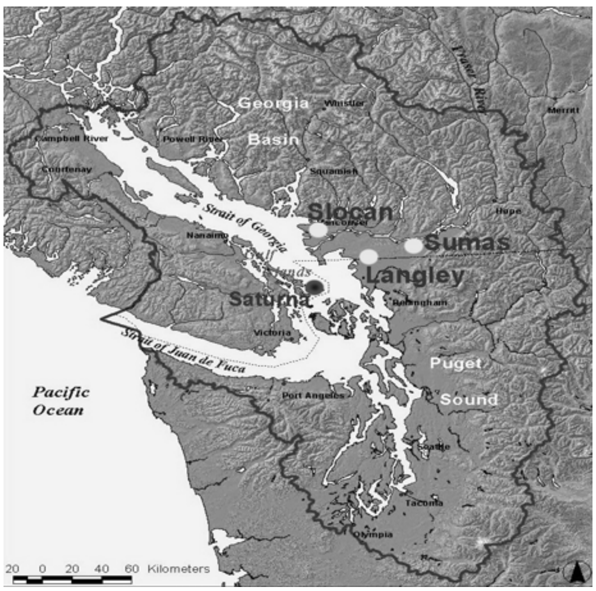


FIG. 1. A map of the Lower Fraser Valley showing the location of the various ground sites during Pacific 2001 (courtesy of B.J. Snyder).

## 2. LIDAR INSTRUMENTATION

### 2.1 AERIAL Facility

AERIAL consisted of modified Continuum Surelite II, Nd:YAG lasers operating at the fundamental wavelength of 1064 nm at a repetition rate of 20 Hz. A Stanford Research Systems (model DG535) four Channel Digital Delay/Pulse Generator was used to externally trigger both lasers and the data acquisition system. Each laser was fitted with a beam diverger unit to expand the beam to meet eye-safety requirements. Output energies from each lidar configuration were measured to be approximately 360 mJ for the upward lidar and 420 mJ for the downward lidar. A small fraction of the laser output power was measured by a Molectron J25 probe, attached to each laser head, and controlled by a Molectron JD2000 Joulemeter. A Computer Boards DAS-802/16 A/D card monitored the JD2000 and displayed and stored the value in real time. The detector included a 35.6 cm Celestron Schmidt-Cassegrain telescope, with an 8 mrad field-of-view, that focused the captured light on a 3 mm (large area) RCA 30956E avalanche photodiode (APD). The upward lidar system used linear amplifiers made by Analog Modules and the downward lidar incorporates logarithmic amplifiers, made by Optech Inc., to increase dynamic range. This is particularly important when operating the lidar where aerosol concentrations vary significantly; such as the region below the aircraft. The signal was then sent to a Gage 12-bit, 100 MHz, PCI card where the information was digitized. The Gage card was generally operated in dual channel 50 MHz mode yielding a 3m resolution along the beam axis. The dual channel option is generally used to measure depolarization data as well. The main graphical interface consisted of two a-scope displays, plotting all four data channels, a single false-colour backscatter ratio plot showing the results from the upward and downward lidar data during acquisition and a laser interlock control window. The real-time display is extremely valuable when working with others on the aircraft who depend on real-time information to adjust the flight plan for gathering in situ measurements.

### 2.2 RASCAL Facility

RASCAL was mounted in a 26 foot mobile laboratory to allow for remote operation. To aid in the safe operation of RASCAL a marine radar was placed on the roof of the vehicle. The radar was modified with a flexible waveguide in order to reduce ground clutter and improve its ability to detect aircraft. The vehicle had an electronic leveling system to provide a stable, level environment for scanning lidar operation. The basic components of a scanning lidar system consist of a laser, beam directing/collection optics and a telescope with a detection package to convert the signal into the appropriate information that can be processed, displayed and saved in real time. RASCAL was based on a two-mirror design (61 cm mirrors) with the first mirror being fixed and the second mirror free to rotate via an azimuth and elevation rotational stage. The detection system was identical to that used for AERIAL. The laser was a Continuum NY-61, Nd:YAG, operating at the fundamental wavelength of 1064 nm. The output energy of the laser was approximately 650 mJ with a repetition rate of 10 Hz. A new Continuum 8020 laser generating 1.2 J @ 20 Hz was added to RASCAL in the summer of 2002.

## 3. RESULTS FROM PACIFIC 2001

The flight tracks were generally constrained by a latitude/longitude grid box of the Model3/CMAQ model domain. The boundary was just past Victoria to the west and extended to Chilliwack to the east. The northern legs were extended past the Pacific'93 boundary to measure PM burdens further up the tributary valleys [8]. The southern boundary was also extended beyond the Pacific'93 boundary to look at the influence of cross-border sources on the air quality within the LFV airshed. As the flights were limited to approximately five-hour duration, it was necessary to adjust flight planning to the meteorological conditions. The majority of the flight was dedicated to the acquiring of AERIAL data. However, the CV580 usually performed two vertical profiles and a low-level flight over the water, to provide valuable data for model initialization. The aircraft was flown at an approximate pressure altitude of 15 kft and the final lidar plot altitudes are determined by the "ground return" signal acquired over the water. AERIAL data was obtained at either 1 second or 0.5 second average yielding a horizontal resolution of approximately 120m or 60m assuming an aircraft speed of 120 m $s^{-1}$. It was also a priority during each flight to obtain at least one east-west transit down the "axis" of the LFV, which shall be referred to as L24. During most afternoon flights, L24 was flown at the beginning and end of the sortie (see Fig.2). This was a measure of how variable the PM burden was over the duration of the flight.

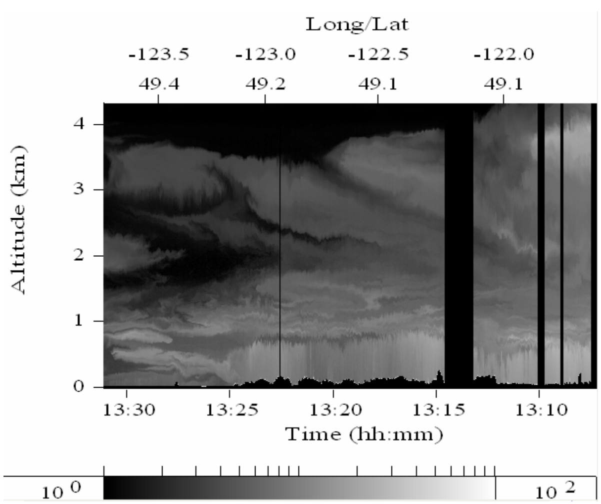


FIG 2: AERIAL plot showing an east-west flight leg down the axis of the Lower Fraser Valley on 15 August. Note the increased PM concentrations to the east.

The PBL heights derived from the RASCAL facility offered valuable data in which to study the temporal evolution of the mixing height at Langley Lochiel ground site. During data collection, a modified algorithm [9] was used to calculate the PBL height at a selected angle and create a daily plot in real-time as an aid to the other in situ measurements being acquired at the field site. Each elevation scan started just above the tree line (2°) to an upper scanning angle of 70° and took approximately 3 minutes to acquire. The scan speed was set low enough to provide good vertical resolution in support of tethersonde measurements being made to the north at the Langley Poppy High School.

The PBL heights are plotted as metres above sea level (masl), which for the case of the Langley Lochiel site, requires the addition of 80m to the heights determined from the RASCAL data. The average value of the PBL calculated from the PBL height profile generated for each elevation scan and its associated standard deviation (the error bars) are plotted for each azimuth scan (see Fig. 3). Therefore, larger error bars are an indication of more variability in the PBL height, which is generally related to a more turbulent boundary layer. On many days there were significant variations in PBL height depending on the azimuth orientation. Most of the variation was found with the East scans, perhaps indicative of less sea breeze influence and more convective turbulence. Where available, PBL heights calculated from AERIAL data has been added to the PBL height plots. There is generally very good agreement between the AERIAL and RASCAL values, particularly with the North scans, since the AERIAL data was obtained from north-south flight legs over the Langley Lochiel ground site.

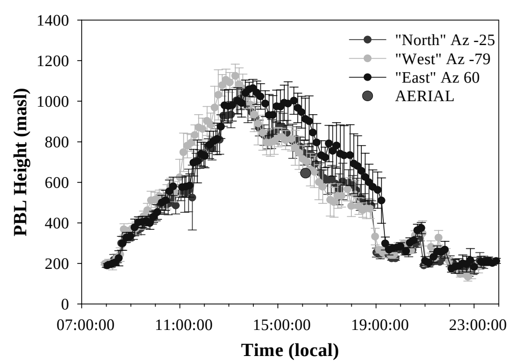


FIG 3: PBL height determined from RASCAL data at all three azimuths. Note the sharp decline in PBL height around 19:00 likely related to wind speed.

Composite vertical lidar plots were obtained from the Langley Lochiel ground site (see Fig. 4). RASCAL data can be thought of as a series of zenith pointing lidars, spaced 3 m apart, acquiring data sequentially. Fig.4 shows the equivalent of having a zenith pointing lidar situated 600m from the RASCAL facility obtaining a vertical profile every 10 minutes. These images were extracted from RASCAL data obtained on the 26 August, by splicing vertical profiles of data together at a fixed range to the north and east of the lidar. The figures show elevated aerosol layers aloft during the morning hours on both days. One can see the influence of the sea breeze in the afternoon (16:00 PDT) as mixed layer decreases and the PM concentrations drop.

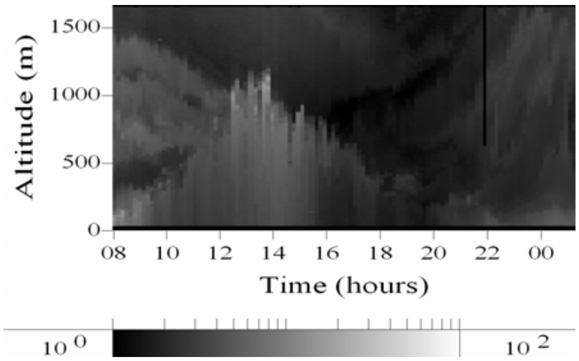


FIG. 4. Composite RASCAL plot from 26 August at a distance of 600 m from lidar (west scan)

## 4. SUMMARY AND FUTURE WORK

Since PM transport is a three-dimensional problem, airborne lidar has the advantage over airborne or ground-based in-situ measurements in determining the vertical extent and spatial distribution of PM over such regions as the LFV. The increased vertical resolution and signal sensitivity of AERIAL provided detailed measurements of the spatial variability of PM throughout the flight domain with particular interest in the diurnal variations within the northeastern tributary valleys. RASCAL data has been shown to be a powerful tool for understanding the three-dimensional picture of a highly inhomogeneous atmosphere. The PBL height plots from the Langley Lochiel site during Pacific 2001 have distinct similarities when grouped together by meteorological conditions. The variability between scan directions was pronounced in the presence of a strong sea breeze. On several days, it was shown that there was a rapid collapse of the boundary layer around 19:00 PDT when wind speed declined sharply.

The next important step will be to compare the airborne lidar results with air quality models of the region. The complex flow of PM can at least be measured by airborne lidar as the first step in understanding its origin, content and air quality impact on the region.

## 5. ACKNOWLEDGEMENTS

Partial funding for this project was provided by Environment Canada, the Georgia Basin Ecosystem Initiative and by the Panel on Energy Research and Development (PERD). The authors would like to thank Michael Harwood, Michael Travis (Meteorological Service of Canada, MSC) and Marc Lilley (McGill University) for their involvement both in the development of RASCAL and AERIAL as well as their attentive data collection before and during Pacific 2001. The authors would also like to thank Mark Barton and Roxanne Vingarzan for their significant contribution towards the acquiring of the RASCAL data set, the technical support from Bruce Thomson and Wayne Belzer in the Environment Canada Pacific and Yukon Region and the Greater Vancouver Regional District, especially Ken Stubbs. The efforts of the NRC pilots and staff and Walter Strapp (Cloud Physics Division, MSC) during the planning and flight operations were greatly appreciated.

## 6. REFERENCES

1. Hoff R.M., et al. Use of Airborne Lidar to determine Aerosol sources and movement in the Lower Fraser Valley (LFV), BC. *Atmospheric Environment*, 31 (14), 2123-2134. 1997.
2. Banta R.M., et al. Nocturnal cleansing flows in a tributary valley. *Atmospheric Environment*, 31(14), 2147-2162. 1997.
3. McKendry I.G., et al. Elevated polluted layers and vertical downmixing over the Lower Fraser Valley, B.C. *Atmospheric Environment*, 31(14), 2135-2146. 1997.
4. Cohn S.A., et al., The Lidars in Flat Terrain (LIFT) Experiments. *Bull. Amer. Meteor. Soc.*, 79, 1329-1343. 1998.
5. Hageli P., Steyn D.G. and Strawbridge K.B. Spatial and Temporal Variability of Mixed-Layer Depth and Entrainment Zone Thickness. *Bound.-Layer Meteor.*, 97, 47-71. 2000.
6. Hoff R.M., et al. Lidar, nephelometer and in-situ aerosol experiments in Southern Ontario. *J. Geophys. Res. Atmos.*, 19 (D10), 199-209. 1996.
7. Melfi S.H., Spinhirne J.D., Chou S.-H. and Palm S.P. Lidar observation of vertically organized convection in the planetary boundary layer over the ocean. *J. Climate Appl. Meteor.*, 24, 806-821. 1985.
8. Strawbridge K.B., and Snyder B.J. Daytime and nighttime aircraft lidar measurements showing evidence of particulate matter transport into the northeastern valleys of the Lower Fraser Valley, B.C. *Atmospheric Environment* (in press).
9. Strawbridge K.B. and Snyder B.J. Planetary boundary layer height determination during Pacific 2001 using the advantage of a scanning lidar instrument. *Atmospheric Environment* (in press).