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Title: The Use of Lidar for the Evaluation of Traffic-Related Urban Pollution

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ABSTRACT

Lidar (Light Detection and Ranging) is demonstrated as a tool for the detection and tracking of sources of aerosol pollution. Existing elastic lidars have been used to demonstrate the potential of the application of this technology in urban areas. Data from several experiments is shown along with analysis methods used for interpretation of the data. The goal of the project is to develop a light-weight, low-cost, lidar system and data analysis methods which can be used by urban planners and local air quality managers. The ability to determine the sources, i.e. causes, of non-attainment may lead to more effective use of tax dollars. Future directions for the project are also discussed.

1. BACKGROUND

For a several years, Los Alamos National Laboratory, with a number of commercial and university collaborators has endeavored to adapt lidar technology to the study and remediation of urban air pollution. To that end, a number of experiments have been conducted in order to study the problem and develop the required technology and data collection/analysis methodology. These projects have included studies in Mexico City, Mexico, Barcelona, Spain, and Albuquerque and Las Cruces, New Mexico. This paper will show some of the types of data which have been collected and the type of information which can be gained.

Much of the data shown comes from the study in Barcelona, Spain during the Summer Olympics. This project was a combined experimental and modelling effort to study the chemistry, origins, and transport of urban air pollution in the Barcelona region of Spain. The Summer Olympics offered a unique environment to observe the effect of modifying the generation of air pollution on a near-city-wide scale because of traffic restrictions and security measures in place. The miniature elastic backscatter lidar was employed to monitor how the restriction of traffic flow affects mesoscale production of atmospheric particulates.

The reduction of private vehicular traffic in urban areas is one approach proposed for air pollution remediation in the United States (and is already in place in Mexico City). The results from these experiments will provide additional input to federal and state agencies responsible for the development of air quality standards and to urban planners on the possible effects of the implementation of mass transit systems. In general, the use of lidar as a wide area tool for identifying the sources and transport mechanisms of pollution will provide urban planners with more information with which to make better, more cost-effective decisions on pollution abatement.

2. EQUIPMENT/METHODOLOGY

A lidar is a type of laser radar which uses a short, intense pulse of laser light instead of radio waves. This pulse is emitted into the atmosphere where the various constituents of the atmosphere interact with that beam and scatter light back to the receiving telescope. At the back of the telescope, the returning light is separated by wavelength and converted to an electrical signal. This electrical signal is sampled and converted to digital data at rates approaching 100 MHz (approximately 1.5 meter resolution) and stored in computer memory. Because the time of flight of the light from a particular atmospheric feature is recorded, its distance from the lidar can be calculated. Lidars are specialized to particular applications primarily by choice of the laser wavelength and interaction.

The lidar used in these studies is an elastic backscatter lidar. This refers to a device which samples the re-emission of incident light from scattering particles (be they molecules or aerosols) at the same wavelength as the original laser pulse. This type of system requires only a single laser and detector, operating at a fixed wavelength. When using a near infra-red laser such as the Nd:YAG laser used in the miniature system, the return signal from aerosols is much larger than that from molecules and small dust particles. Since we are interested primarily with man-made particulates which are generally micron size and larger, this greatly simplifies the processing required to interpret the return. Elastic lidars are especially useful in that the return signal is large, which enables the devices to be made smaller, scan faster, and 'see' farther. The combination of farther and faster means that a much larger volume of space can be examined much faster and regularly. Although particulates are not often a pollutant of interest, they can be used as a tracer. In tracking pollutant plumes, tracking the aerosols is much easier than tracking a specific molecule of interest. If both the micron-sized aerosols and molecular species of interest are generated together, they will migrate together.[1,2,3]

The lidar return power, as measured at the detector, can be expressed as follows:

$$P(\lambda, r) = \frac{CE(\lambda)\beta(\lambda, r)e^{-2\int_0^r \alpha(\lambda, r')dr'}}{r^2}$$

$P(\lambda,r)$: amplitude of the lidar signal at range r and wavelength λ, the rate at which photons are scattered back to the telescope (Joules/s);

r: range from the lidar (meters);

$\beta(\lambda,r)$: backscatter coefficient at range r and wavelength λ (1/meter-steradian);

$\alpha(\lambda,r)$: extinction coefficient at range r and wavelength λ (1/meter);

C: system constant, a term which combines the effects of optical transmission efficiencies in the telescope and filters as well as the efficiency of the detector and the effective telescope collection area;

$E(\lambda)$: laser energy per pulse at wavelength λ (Joules).

The miniature lidar system used in Barcelona, Albuquerque and Las Cruces uses a Nd:YAG laser, operating at a wavelength of 1.064 μm. The laser has a maximum energy of 125 milliJoules and a 10 nanosecond pulse width. The laser head is mounted on top of an eight inch Cassegrain telescope. The power supply and chiller are mounted in a box with a standard 19" rack. A similar box contains the power supply for the stepper motors and a power supply for the silicon avalanche photodiode (APD). These two boxes are approximately 22 inches on a side and weigh less than 100 lbs each. The telescope and laser head are contained in a third box. Stepper motors for the azimuth and elevation motion are incorporated into the telescope mount. A portable computer and a CAMAC minicrate containing the electronics which digitize the signals and measure the laser energy are also required to operate the device. The computer controls the motion of the system and the electronics in the CAMAC crate as well as receiving the digitized data and storing it.

The entire system is computer-controlled. Most of the electronics may be adjusted from the computer using the data collection program. The user may manually input a desired scan or may program a sequence of scans. Because of the computer control, the system is fast and collects the desired data in the minimum amount of time. Periodically, the system must be taken off-line and the data archived to optical disks.

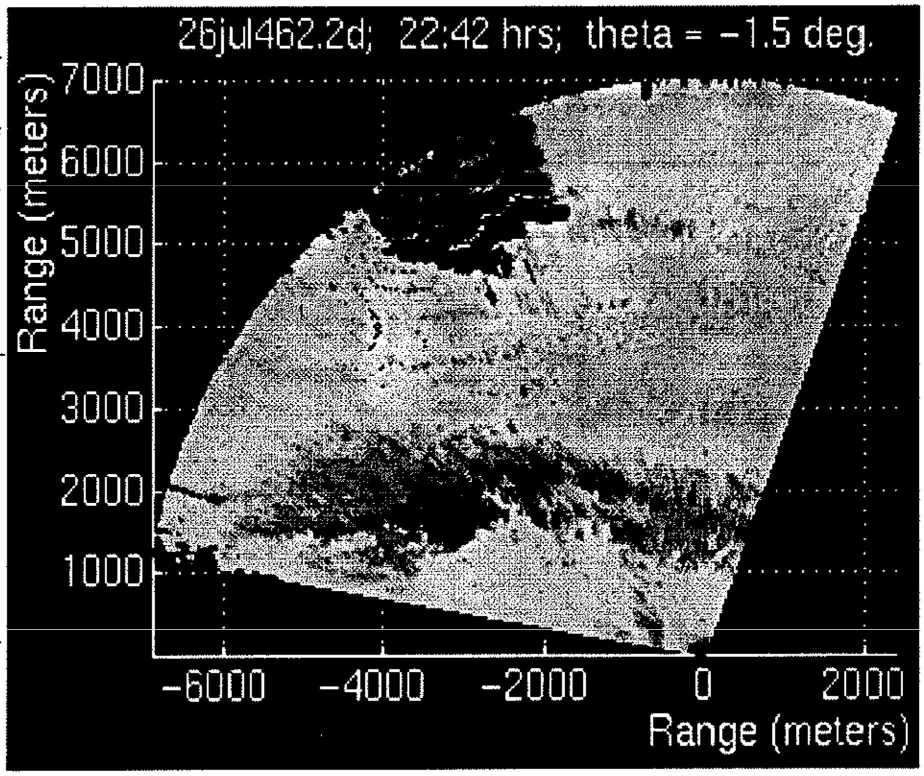
A number of laser pulses along a single line of sight may be summed to increase the signal to noise ratio and to extend the working range. By holding the azimuth constant, and changing the elevation angle on the system, an image can be created which represents the concentration of some observable at all points in a vertical slice of the atmosphere, referred to as a vertical scan. Similarly, by holding the elevation constant and scanning in the horizontal direction, the concentrations along a horizontal slice of the atmosphere can be determined. The systems are capable of three dimensional scanning as well in which both the azimuth and elevation angles are varied in a predetermined manner to create a three-dimensional picture of the atmosphere.

Regular scanning sequences are programmed into the data acquisition program and executed approximately hourly. In Barcelona, these scanning patterns executed a series of vertical scans beginning at five degrees azimuth and ending at 175° azimuth with an azimuthal step size of ten degrees; at each fixed azimuthal angle, the lidar device scanned vertically from minus three degrees in elevation to a maximum of forty degrees elevation with an elevation step size of one-half degree yielding eighteen vertical scans. A set of correlation scans, to determine mean wind velocity, were also done each hour, at 15 degree intervals.

The goal of this scanning methodology was to provide detailed hourly information about locations and activity patterns of effluent sources within Barcelona, and to provide information about how aerosols generated at low levels interact within the turbulent mix layer. In addition, it was hoped that these scans would reveal the source of several upper level aerosol layers which were observed each evening, after sunset. This pattern was intended to be a balance between detailed examination of a limited number of special sites and a large scale examination of air flows and patterns over the city.

FIGURE 1: Horizontal Scan

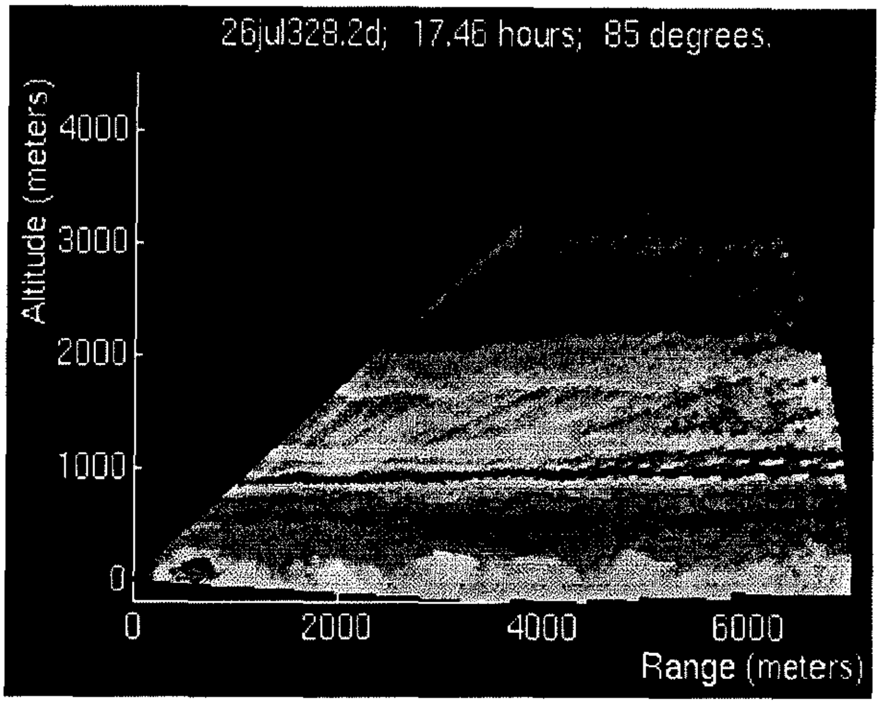
Figure 1 is an example of a horizontal scan over the city of Barcelona. This scan is slightly below horizontal and shows the aerosol concentrations with location over the city. The lidar is located at the apex of the scan. Dark colors are highest concentrations, lightest colors are lowest. In this scan, one can see the large aerosol concentration at x = -3500 m, and y = 1500 meters over the soccer stadium. At the time of this scan, one of the Olympic Soccer Games was being held. There are several lines extending from the stadium area to the right. These concentrations are located over the Av. Diagonal, a major thoroughfare (roughly comparable to a US six lane intracity highway).



Three dimensional scans have also been acquired during our studies. Three dimensional scans must be temporally short when compared to the evolution and motion of the structures being studied. Generally, three dimensional scans were done when there was a visible atmospheric structure isolated in space (fireworks, plumes, or effluent smokestacks, for instance). The data was taken to further develop three dimensional visualization capabilities since three dimensional data sets hold information about the direction of mean winds in addition to providing a capability to directly trace an effluent aerosol structure directly to its source. Three dimensional data sets scan both azimuthally and vertically. Both IBM (on their RISC 6000 machine) and Los Alamos (on Silicon Graphics computers) are working on better and more intuitive displays of the data.

FIGURE 2: Vertical Scan

Figure 2 is an example of a vertical scan between Montjuic and the Llobregat River Valley. This scan represents a vertical slice of the atmosphere along that path. Again, dark colors are high concentrations and light colors are lowest. In the lowest 600 meters of the atmosphere one can see large convective plumes rising above the city. These plumes are created by the warming of the air by the sun. Also visible are intense sources of aerosols located near the ground. These sources most often correspond to major roads or intersections, but may be nearly any type of industrial or commercial source.



3. RESULTS

3.1 Examples of Data Collected

The three images in figure 3 reveal several large aerosol sources where roadways, intersections and Metro (Subway) stations are located. They are typical of the type of information which is obtained from the lidar. These images are taken along the 35 degree azimuth from the lidar at various times. It should be noted that the resolution of the data is 7.5 meters (about 24 feet). Thus each of these scans can be expanded to study a given area in great detail. One of the observations made in Barcelona was that the subway stations appear to be large sources of aerosols. The reasons for this are not yet known.

FIGURE 3: Sources at Thirty-Five Degrees

The large source within the first kilometer corresponds to Ronda de Dalt.

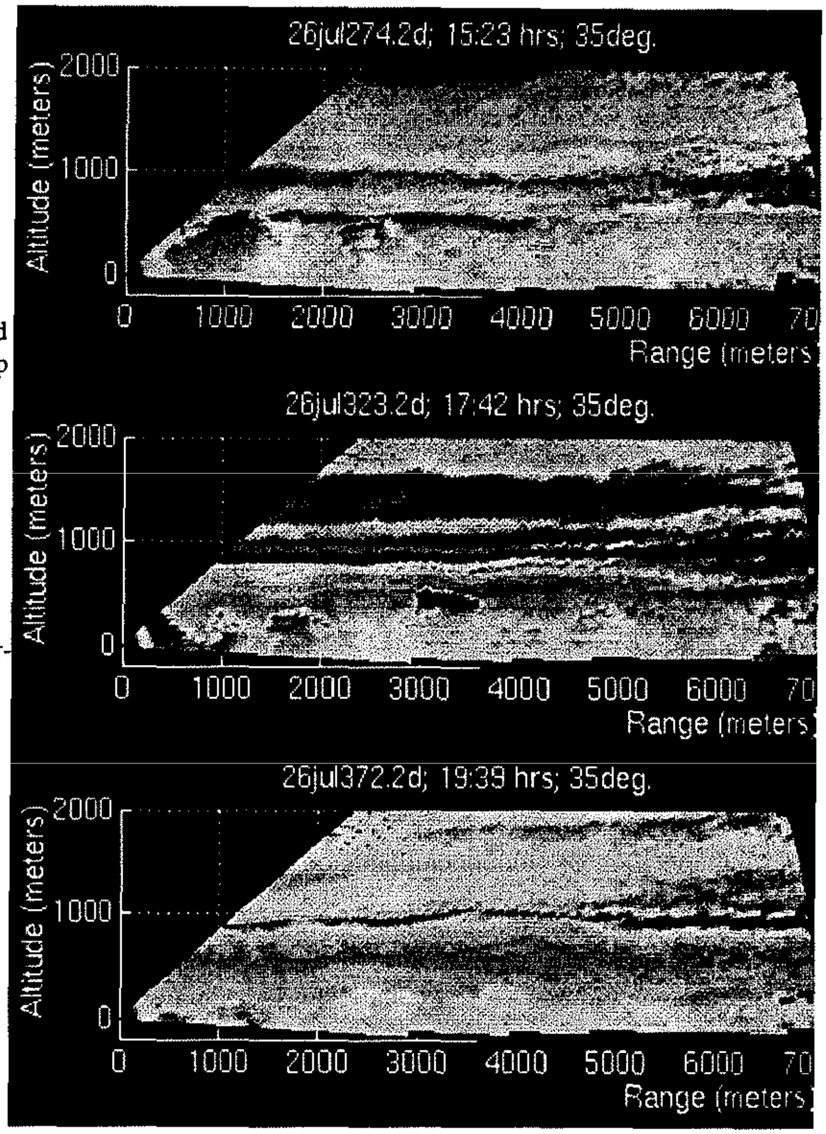
Production around two km correlates with the Maria Cristina Metro Station and the intersection of Gran Via Carles III and Av. Diagonal. Several large buildings are also near this intersection.

The large source near three km correlates with the area just north of the Numancia and Trav. Corts intersection. There may be a stop light at this intersection.

The area in the region of the large source/ sources around four km includes Escola Enginyers, a cut across Comte d'Urgell and the Hospital Clinic Metro Station.

The sources around 4.5 km to five km are near the Comte d'Urgell and Av. Roma intersection and the Av. Roma and Arago intersections.

There also appears to be a large aerosol source around 6.5 km in the vicinity of the Catalunya and Urquinaona Metro Stations.



3.2 Sample Data Analysis.

The source integration methodology is used to compare the amount of aerosols in a given area as a function of time in a localized area. The data reduction algorithm for source integration is similar to reduction methods used to display the data with a few key differences. Data was corrected for background noise, smoothed radially with a low pass (gaussian) filter to suppress high frequency fluctuations, range corrected for the inverse r^2 decay of the return power and corrected for a minimum path extinction of 3.7×10^{-05} per meter. This path extinction was applied in order to achieve better comparisons of aerosol integrations at long ranges with aerosol integrations at short ranges as well as improve image appearance. In addition to this, the data were also corrected for different APD bias voltages since the digitized signal value were dependant upon changes in the APD bias voltage.

To compute the integrals, the data was first averaged within range bins. The bin size chosen was 50 meters in altitude and 70 meters in range. This leads to an average concentration per unit area above regions of interest along the lidar's line of sight (the unit area is 3500 m^2). Due to the fact that the path of the lidar beam diverges with increasing range, range bins near the lidar device have a higher sampling density than range bins farther away from the lidar device. For instance, the bin in the lower right corner may only have 10 values fall within its averaging area while the bin in the lower left corner may have 70 values fall within its averaging area. The value of the actual integration region usually averaged four to six of these unit areas. Again, the result is an average concentration per unit area.

The time period of the following analysis begins on Sunday, July 25 and ends on Tuesday, July 27. This time period was chosen because data sets were acquired at reasonably regular time intervals. These intervals were roughly one hour long, beginning around 8:30 on Sunday, July 26 and continuing through midday on Tuesday, July 28 when the flash lamps were changed.

FIGURE 4: Sunday, July 26 to Tuesday, July 28; Lowest 50 meters.

The intersection of Gran Via Carles III essentially exhibits two peaks in the aerosol concentration in the lowest 50 meters. One around noon and another around midnight.

Also note that concentrations are increasing between 1 am and 6 am on Tuesday, July 28. This is because aerosols lofted to altitudes during Monday are dropping to street level in the early morning hours Tuesday, decreasing the overall air quality during this period. This feature was not observed during the early morning hours of Monday. However, industrial pollution is expected to increase during the week when people return to work after the weekend.

Bottom plot is a record of traffic patterns in Barcelona. This plot represents hourly percentage of traffic which passed by this location on this day. Sum of hourly values is one-hundred percent. On a working day, the first peak would move slightly to the left, 08:00-09:00. It is not known by the authors, in which area of Barcelona this traffic pattern was observed. [4]

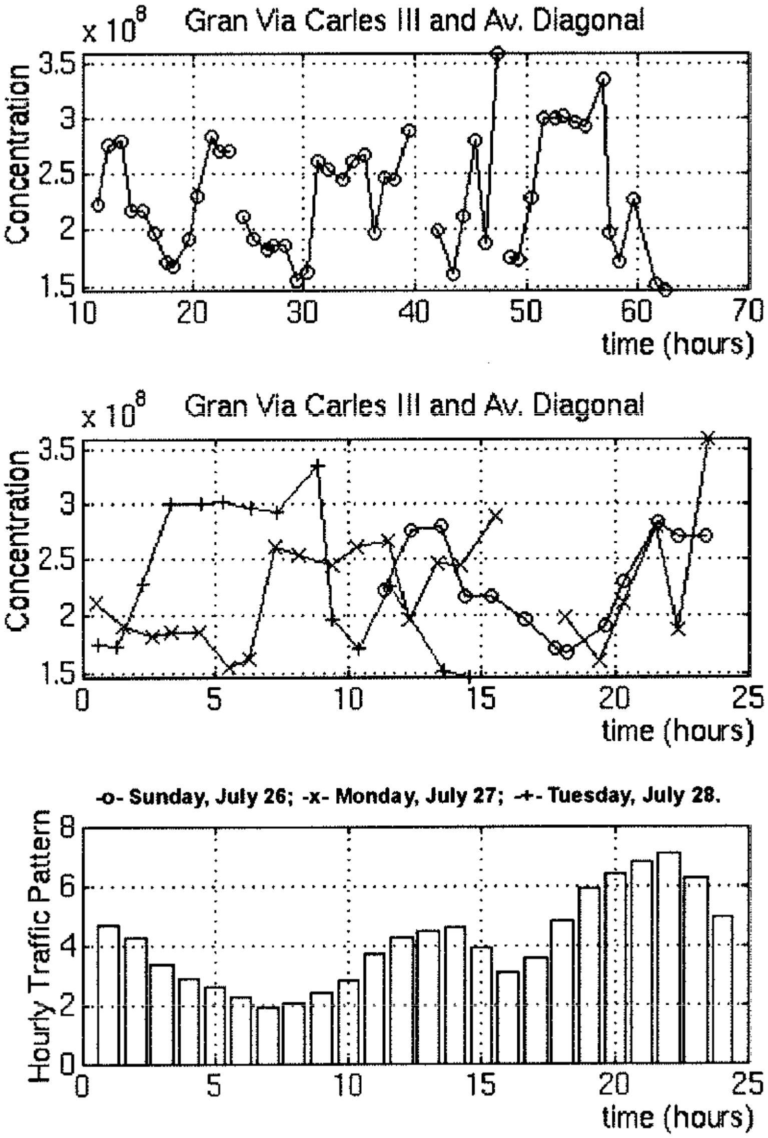
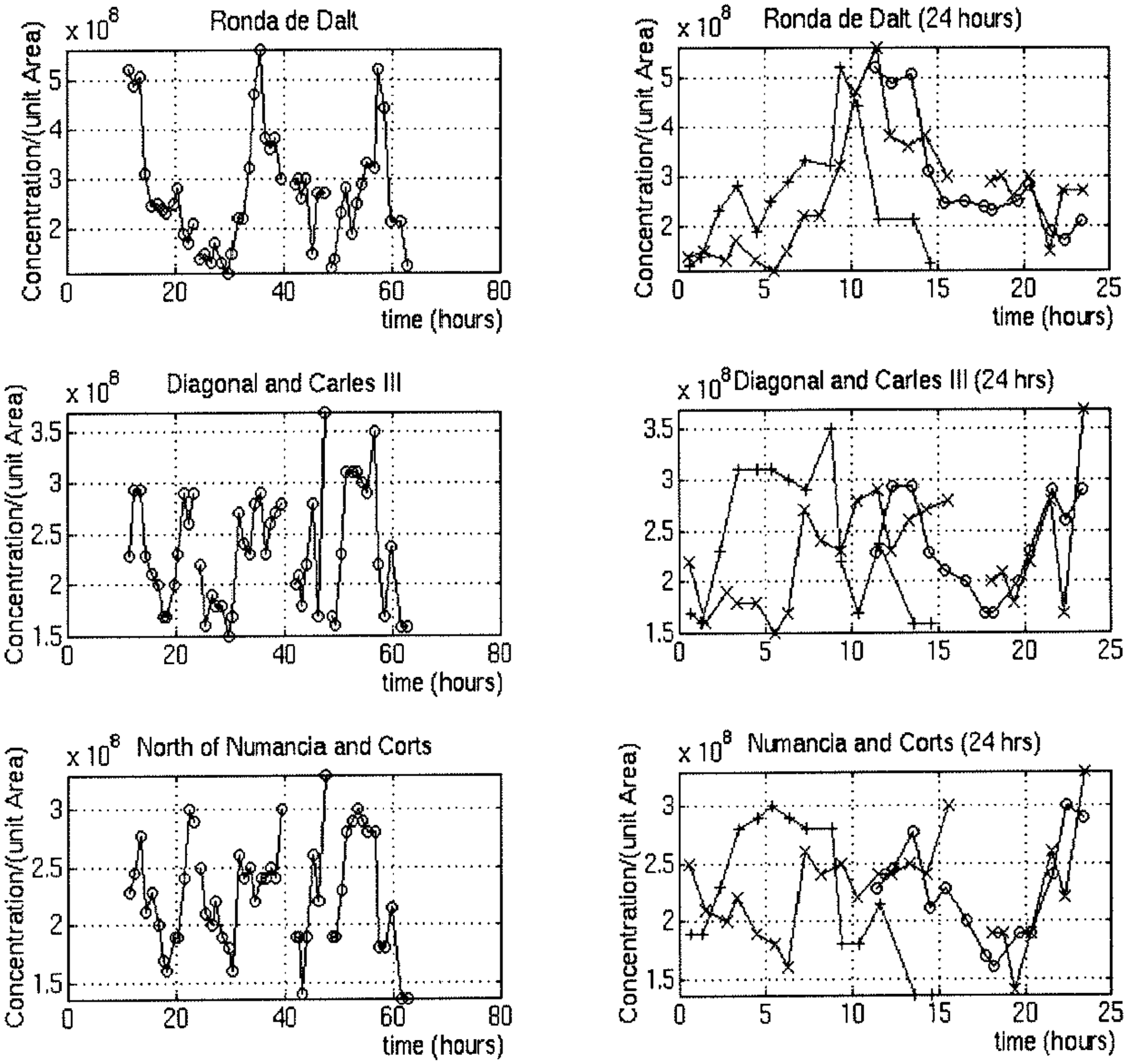


FIGURE 5: Lowest Two Hundred Meters, Range is Approximately 2.2 Kilometers



Ronda de Dalt is approximately 500 m away and 150 m below the lidar.

Av. Diagonal and Gran Via Carles III intersect approximately 2.15 km away.

Numancia and Trav. Corts intersect approximately 2.95 km away.

-o- Sunday, July 26; -x- Monday, July 27; -+- Tuesday, July 28

3.3 Verification of the KarlsRuhe Model

Dr. Thomas Flassak of the University of Karlsruhe along with collaborators at the IBM Bergen Scientific Research Center developed the atmospheric modelling codes used in the Barcelona Project. This code is in fact of combination of codes, the Mesoscale Meteorological Model (MEMO), the Eulerian Transport Model for Passive Pollutants in the Atmosphere (TRAPPA), and the Deposition Model (DEPO). This code was first applied to studies in Athens, Greece [5,6].

One of the predictions of this model is that of drainage winds - - that late at night and during the early morning hours, air will flow down the Llobregat and Besos river valleys and out to sea. This air flow will transport polluted air from inland basins through the city and out into the Mediterranean. The two scans in figure 6 are horizontal scans across the Llobregat valley. These figures show a large, aerosol dense mass of air moving down the valley. Because of the height of the lidar over the valley, these figures show only the tops of the air masses. A horizontal scan taken just after dawn shows a clear atmosphere, indicating that the seaward motion of pollutants is done.

FIGURE 6. Drainage Flow of Aerosols Down the: Llobregat Valley

These two images show the flow of aerosols down the Llobregat Valley during the early morning hours. These scans are taken looking horizontally across the valley to the right of the lidar. The other side of the valley is about six kilometers away, just beyond the end of the lidar signal. The Mediterranean Sea is about 8 km away towards the top of the scans.

These scans should be compared to the predictions of the Karlsruhe Model. Figure 7 shows the predicted concentrations of NO over the city at midnight. NO, like aerosols, are directly generated by traffic and should correlate. Note the similarity between the model prediction of strong concentrations flowing down both the Besos and Llobregat valleys and the lidar data.

Note that the plumes in the top scan have moved to the left about 1200 meters in the bottom. This is indicative of a 0.3 m/s crosswind in the valley.

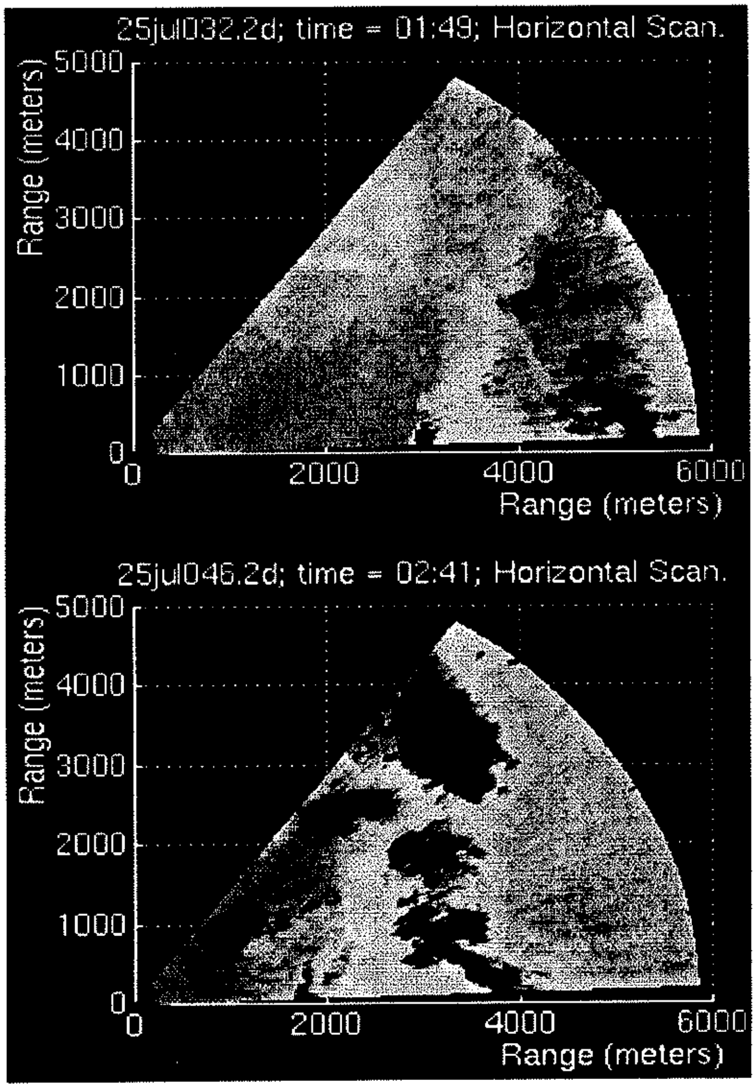
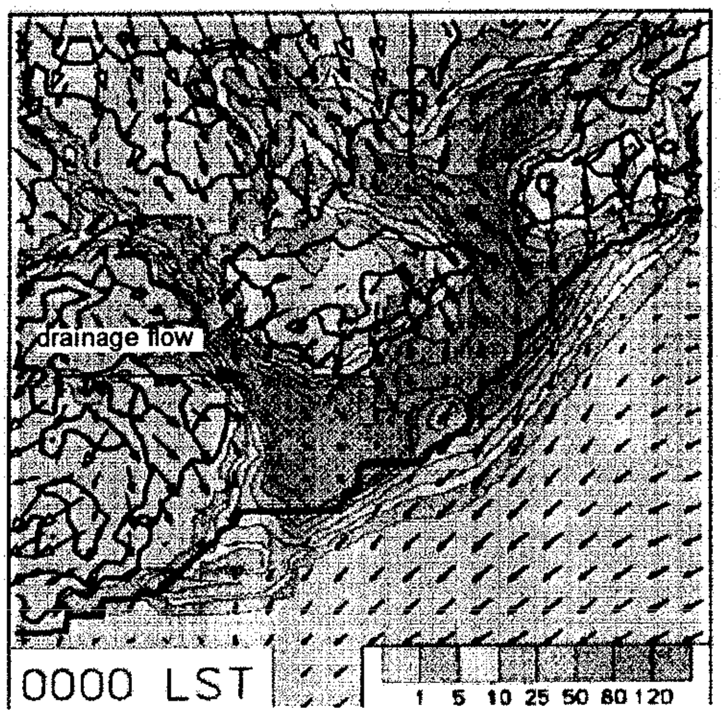


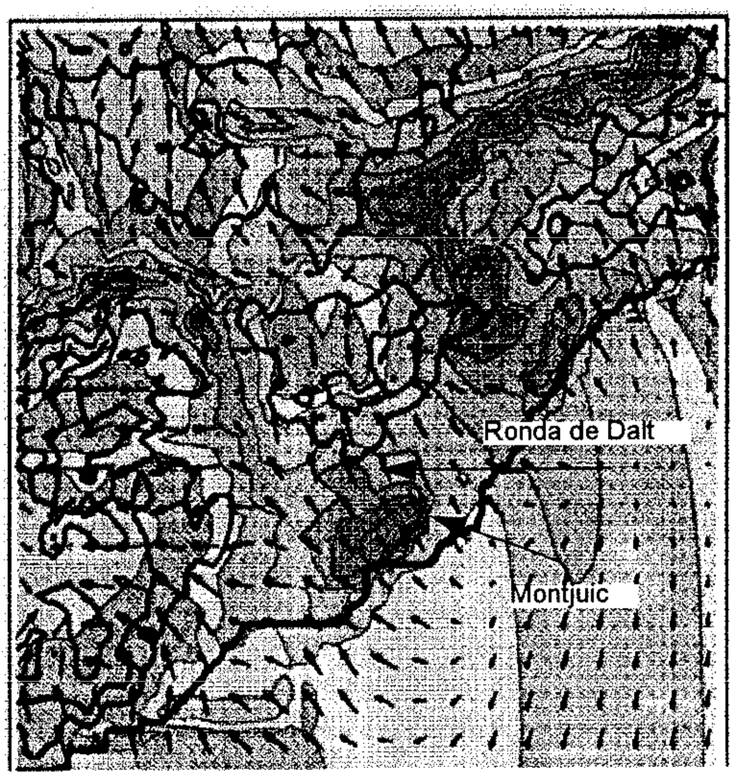
FIGURE 7: Karlsruhe Model Predictions of Pollutant Concentrations, 00:00 hours

This figure shows the predictions of the Karlsruhe model for the flow of NO during early morning hours. Because NO and aerosols are emitted simultaneously from vehicular traffic, they should migrate together. The arrow points to the drainage flow in the Llobregat Valley. This area is also the area examined by the lidar in figure 6. The concentration scale is at the bottom right of the figure.



Karlsruhe Model Predictions of Pollutant Concentrations, 1200 hours

During the day, the model predicts large concentrations of pollutants in the vicinity of the Rhonda Dalt and over the Montjuic area. The lidar shows the same large concentrations of aerosols over the Rhonda Dalt.



4. OTHER DATA ANALYSIS TECHNIQUES

As mentioned previously, the lidar can be used to measure the mean wind velocity by means of a correlation method. This method essentially tracks the movement of atmospheric structures and determines a mean wind velocity from this information. Work is continuing to measure the average size of the atmospheric structures as a function of their height above the ground. This information is of value to atmospheric modellers and is related to the type and rate of vertical transport of aerosols and molecular pollutants. The ability of the lidar to accurately measure the altitude of the various layers in the atmosphere gives us the ability to study the urban heat island effect. In this effect, the excess heat generated by the urban areas causes the layers to loft over the city as compared to nearby rural areas. Work also continues on improved methods of inverting lidar data to determine more precisely the concentration of aerosols.

5. FUTURE DIRECTIONS

There are two basic directions which need to be accomplished. The first is the construction of an eyesafe lidar system. Such systems have been built. They are however, slow and relatively short-ranged. Such a system would greatly enhance the ability of the lidar to examine areas close to the ground without the limitations of present systems.

In as much as the needs of air quality planners concerns the concentrations of specific molecules, a lidar system capable of the detection of a number of specific molecules should be built. Such systems have been demonstrated on a molecule by molecule basis. This type of lidar would be larger and slower than the present "miniature" system and have a shorter range. However, the benefits of being able to quantify the concentrations of a number of different molecules would be of great value.

6. ACKNOWLEDGMENTS

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