ISB

Invest to Save Budget

Improved Air Quality Forecasting
Invest to Save Report ISB52-03

Identification of key flow parameters for visualisation

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Executive Summary ISB-52-03

This report ISB52-03 was produced under Project 52 of the Invest to Save Budget, or ISB. The aim of this project is to improve atmospheric pollution dispersion models with the goal of improving air quality forecasting. During the project life, the team will be developing a better understanding of airflow near the earth's surface, focussing especially on urban meteorology. This will be achieved through the gathering of accurate 3-Dimensional wind flow data using laser radars, also called lidars, and by incorporating that new knowledge into the dispersion models.

A lidar is similar to conventional radar but uses an invisible, eye-safe, laser beam as its source of radiation. The great advantage of lidars for monitoring wind flow is that they can make more precise measurements than conventional radars and can probe to greater heights than most tall masts. In addition, lidars can make measurements in regions of the lower atmosphere above a city, which would be inaccessible to either aircraft or tethered balloons.

The lidars work by measuring the Doppler shift of light back-scattered from fine aerosol particles (water droplets, dust, etc) suspended within the atmosphere. The line of sight velocity component of the wind is then calculated. By sampling at different angles, and combining results from the two lidars, a picture of the three dimensional airflow in a scanned region can be assembled. Typically the scanned volume will be a few cubic km with the probes separated by up to 10 km.

The key meteorological parameters that the lidars will need to measure are the height of the Planetary Boundary Layer and turbulence. In order to achieve a set of observations that are representative of the statistics of pollution dispersal phenomena it is intended that the lidar beams dwell along one line of sight for at least 10 minutes, whilst ideally sampling multiple times per second. Two complementary sets of scanning patterns have been developed to ensure an optimal and meaningful set of observations for these phenomena are made.

The intended use of the data is to gain a better understanding of the dynamics of wind flow for the urban environment rather than gather data to be fed directly into forecasts. Suggestions of how an improved understanding of flow dynamics in the urban environment could be used to improve air quality forecasts are given within this report. Currently it is not possible to quantify the likely improvements to the accuracy of future forecasting of pollution dispersal through the incorporation of new knowledge derived from the lidar observations. However it is well known that all current models contain assumptions developed for the rural environment that become erroneous when applied to describe conditions within the urban environment. The replacement of such assumptions can only lead to an improved forecasting accuracy.

This is the first time that observations from separate lidars are to be combined to give an accurate description of the dynamics of wind flow. To assist in the data analysis a set of visualisation tools are being developed that will display the resultant wind field from combination of lidar observations. The key features to be visualised have been identified as being the mean wind flow in terms of direction and strength, turbulence and the structure of the PBL.

The data will be displayed in a number of formats that include: visualising rays of lidar data and wind vectors in 3D, production of a 2D snapshot of a 3D display and animations of time series.

List of contents

1. INTRODUCTION

The aim of this Project is the improvement of air quality forecasting for the urban environment through the use of lidar data. Lidar offers the ability to make some unique measurements within the urban environment that will be of great benefit to an improved understanding of pollution dispersal mechanisms within that environment. However care needs to be taken over deploying the lidars.

For example lidar achieves measurements of high angular resolution through the use of a narrow beam divergence. The down side of this is that it takes a long time for the beam to scan over a large angular range. Therefore a lidar cannot monitor a complete wind field instantaneously; also data is produced by the lidar over an extended region. Current air quality models require point source information so there is a need to map the lidar observations to the inputs of the dispersion models. There is also the requirement to ensure the lidar observations are made on scales commensurate with the models.

Previous work[1] had developed a number of scanning patterns that optimised the monitoring of airflow over the urban environment by twin pulsed lidars. However the key issue of whether to stare for long times at a relatively low number of pointing angles or cover a large number of points for a short time remained to be resolved.

That issue is addressed here; firstly a hierarchy is obtained of the flow field phenomena it is important to observe in order to understand pollution dispersal mechanisms in the urban environment. Secondly the sampling scales necessary to accurately monitor these phenomena are identified and finally an experiment that deploys lidar to make these observations is derived.

It is intended that these results be employed to define the experimental strategy for the subsequent ISB52 trials.

These findings are presented in section 2. In section 3 recent progress with the development of the flow visualisation models at Essex University is presented.

2 IDENTIFICATION OF KEY PARAMETERS TO BE MEASURED FOR USE IN THE DISPERSION MODELS.

The philosophy in this project is to develop two novel lidars to allow the monitoring of wind flow with unprecedented accuracy. It is not the intention of ISB52 to develop two fully autonomous systems that can be left in-situ. Hence there is no ability being developed to achieve more accurate pollution dispersal forecasts through continuous monitoring. Instead the aim of the project is to improve pollution dispersal forecasts through a new more sophisticated understanding of the dynamics of the wind field in the urban environment obtained from the lidar measurements made during the trial periods.

The meteorological parameters used by the various dispersion models were listed in MS1 for further consideration[2]. Of these the most important to observe are the shape of the planetary boundary layer (PBL) or mixing layer, and turbulence. The key flow parameters are mean flow, and turbulence. All dispersion models need these parameters described accurately. The currently existing models are well proven for the rural environment but would benefit from further adaptation for use in the urban. In particular this implies a better description of the more complicated turbulence in the urban environment that is driven by the greater roughness scales that occur there.

The aim of the trials is to investigate how these quantities vary over the course of a day in both the rural and urban environments. In particular it will be important to observe the diurnal changes in turbulence and structure and depth of the mixing layer.

Possible ways to exploit this new knowledge within the models includes:

- identification of the appropriate update intervals for defining the properties of the mixing layer during the forecast calculation,
- providing a more appropriate description of the spatial variation across the mixing layer, including a more accurate description of the change in the height of the PBL at the rural urban interface,
- from an understanding of the differences in evolution of the mixing layer in the urban and rural environments, use separate models to reflect the differing temporal changes within the different environments,
- modelling of the turbulence to more accurately reflect the vertical thermal structure.

To quantify the improvement in forecasting accuracy a number of comparisons can be made between the current forecasting tools and tools that have been adapted in light of the lidar observations. These would include comparisons of real atmospheric behaviour with predictions from the current models compared to predictions from models altered in the light of the lidar observations. It may also be possible to incorporate flow field data into a model to see if there is an improvement in accuracy.

It is important to note that this quantification process can only be conducted once the lidar data has been gathered and analysed, because until the completion of data analysis it will be not known how to modify the models. What can be stated now is that the replacement of current assumptions with knowledge gleaned from the lidar observations can only improve forecasts.

No single site has been found that can be considered typical of a rural urban boundary in the UK. Therefore feeding wind measurements from the trial site into a model describing another urban location is unlikely to lead to an improved forecast for the new urban location because the wind data will not be representative of the new location. However through understanding the influence of the shape of the urban environment on pollution dispersal mechanisms it becomes possible to extend the results found at the trial site to other urban locations. Hence the trial site used should yield results representative of any rural urban interface.

The main intended application of the scan patterns is to define the vertical structure of airflow in two sampling columns. It is only at these points that the lidar data is combined however this does not prevent the use of the rest of the line of sight data gathered for additional analysis.

Consideration of what to observe.

In MS1 the variables of particular importance for air quality forecasting were identified; they include:

Mixing height (possibly multiple layers).
Mean wind profiles.
Day/night transition in stability and turbulence variables.

The height of the mixing layer is a quantity of relevance for air quality forecasts because it is the height at which the pollutants are expected to disperse. It also has significant impact upon the vertical column of the air below it and so is prominent in determining the energy dissipation mechanisms that in turn control pollution dispersal.

The top of the PBL can be readily recognised from lidar measurements as the position where there is a noticeable drop in SNR of the lidar signal. (For example see the results in MS2[3]) The height of the PBL can thus be readily identified, though any further complex layer structures above the PBL may not be.

However it is at lower altitudes (2 to 5 times building height) that the suggested micrometeorological exchange processes are in doubt[4] and which therefore is the key region in which to concentrate the lidar observations. Lidar can make turbulence measurements within the urban canopy and its overlying urban boundary layer. It is this capability that the lidars offer that will make the results of ISB52 unique.

Mean wind profiles are the primary data product from the lidar observations. Turbulence can be assessed from the statistics of either the spatial or temporal variations of the velocity data. It would be useful if the lidars could measure eddy sizes directly, but a potential problem lies in the relative sizes of the lidar sampling volume in relation to the eddy size (which could be greater or smaller).

A simple method to resolve this is to ensure that the lidars are deployed on days when the eddies are of sufficient size that their turbulence levels can be accurately measured.

In addition to the above it would be useful to probe the urban roughness sub layer and monitor the rural-urban transition. As the direction of the work is towards an improved understanding of flow dynamics much of the observations need to be of a comparative nature, in particular a comparison of what is happening in the urban compared to the adjacent rural environments. It is intended that this would include observing the evolution of the mixing layers above the urban and rural environments simultaneously over the course of the day and making specific observations during the calendar year. In particular:

- Measurements in summer anticyclonic conditions to study the contrast between strong daytime convection and night time conditions,
- Measurements in winter anticyclonic conditions to study the effects of temperature inversions.

The lidar beam samples the atmosphere through volumes of air that are long and thin pencil of information (typically 112 by 1 m, the width being dependent upon how wide the beam has become due to divergence during beam propagation).

From the lidar perspective there are two spatial scales from which to map flow. These are scales less than the length of a range gate and scales longer than a range gate.

An estimate of sub range gate turbulence can be made from the spectral width of the velocity distribution observed along that range gate. This could be important if one of the main phenomena for energy dissipation is from small scale eddies which could be the case under stable conditions. It is assumed that the turbulence on scales of less than a range gate are isotropic and consequently the measure of turbulence is independent of the orientation of the 'pencil'. That is the range gate is representative of an equivalent spherical volume of air centred around that range gate. This is important because it implies direct overlap of the two lidar beams is not essential provided the lidars are probing the same spherical volume of air.

For scales larger than the length of a range gate the nature of phenomena are derived from the higher order moments of the mean velocities observed. ***To achieve a set of observations representative of the statistics of pollution dispersal phenomena it was recommended to dwell along one line of sight for at least 10 minutes, whilst ideally sampling in the order of Hertz.*** Sampling rate is set by being high enough to resolve the eddies as they are blown through the lidar beam. Here sampling rate refers to average data gathered rather than laser pulse repetition frequency, PRF.

It should be noted that the spectral width data requires a higher signal to noise ratio than velocity estimate data and consequently it is anticipated that spectral width data will only be available to a maximum range of about half that for the velocity data.

The number of laser shots integrated together to achieve an adequate SNR depends upon a number of parameters including range to be measured and the concentration of particulates embedded in the atmosphere.

The upgraded pulsed lidars have a PRF of about 10 Hz with the real time display mode activated or 50 Hz without activation. The number of shots necessary to average to achieve a satisfactory SNR depends upon the range to which it is intended to measure and the required accuracy of the measurements. For the 9 km PBL data detailed in MS2[3] 80 shots were averaged at a beam PRF of 10 Hz to give a sampling rate of 0.125 Hz. Those measurements were primarily made to observe the evolving structure of the PBL. For wind flow measurements a higher sampling rate would be used.

For wind data out to 5 km a much higher sampling of 20 Hz is potentially achievable with real time data being available. The drawback with operating at 50 Hz is the lack of real time feedback of data quality.

The actual positioning of the lidars as dictated by local terrain and available sites will determine the final separation distance. Once that is known the desired sampling frequencies can be more accurately prescribed. These considerations will be resolved within MS4 due Sep 2002.

Review of the scan patterns and experimental technique.

The lidars will be positioned close to a rural/urban interface so that they can accurately probe wind fields above each type of environment. For a successful trial it has been identified that the site will need the following features:

- Should be on the windward side of a large conurbation,
- Allow the two lidars to be separated by 5 to 7 km,

- A line of sight between the two would be desirable or failing that a third independent object is visible to both lidars for alignment purposes,
- There is no large hill between the lidar stations.

The scan patterns to be used can be categorised depending upon the observations to be made:

i) Plan Position Indicator PPI. (Also called a VAD, velocity azimuth display).

The PPI is used to determine the general wind field. This will allow the optimum direction of the lidar beams for the other scans to be determined. Note that this is a conventional PPI with the lidars operate independently of one another.

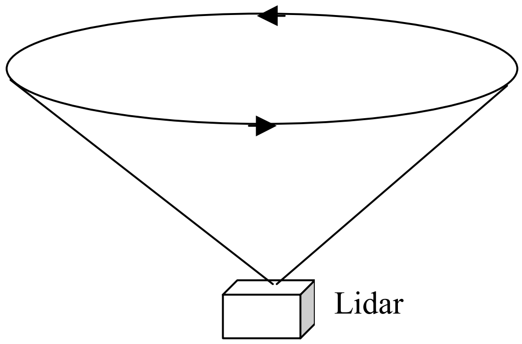

Figure 2.1 Schematic of lidar station undertaking a VAD Scan pattern.

ii) Scanning to derive the horizontal component of the wind field.

This could either be for a hemisphere centred on the mid point between the two lidars or scanning vertically through two planes which are perpendicular to one another as shown in figure 2.2. The later is preferable because of the emphasis upon on a few spatial locations and long dwell times. It is intended to sample two columns one in the rural and one in the urban environment. The emphasis of the measurements would be on observations made at lower elevations.

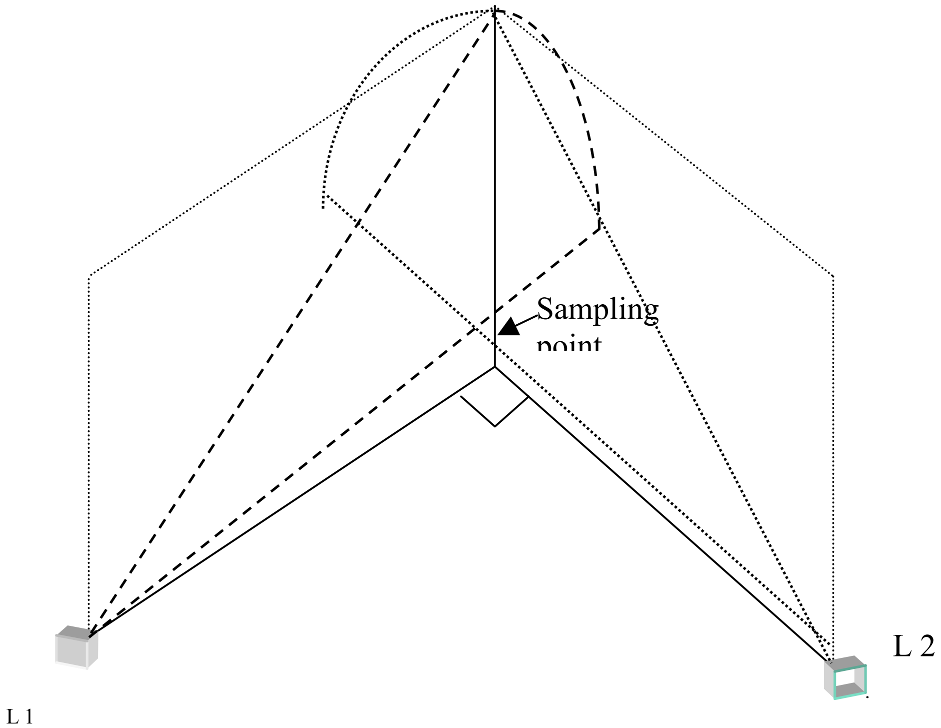

Figure 2.2. Proposal of scan scheme to derive horizontal wind flow as a function of height in a given sampling column.

iii) Scanning to derive vertical information.
This is a co-ordinated Range Height Indicator scan in the vertical plane between the lidar stations. It allows the derivation of the vertical winds and the horizontal wind flow between the two lidar stations. The vertical resolution of this scan pattern decreases with altitude, therefore a different technique is necessary to measure the vertical wind component at low altitudes.

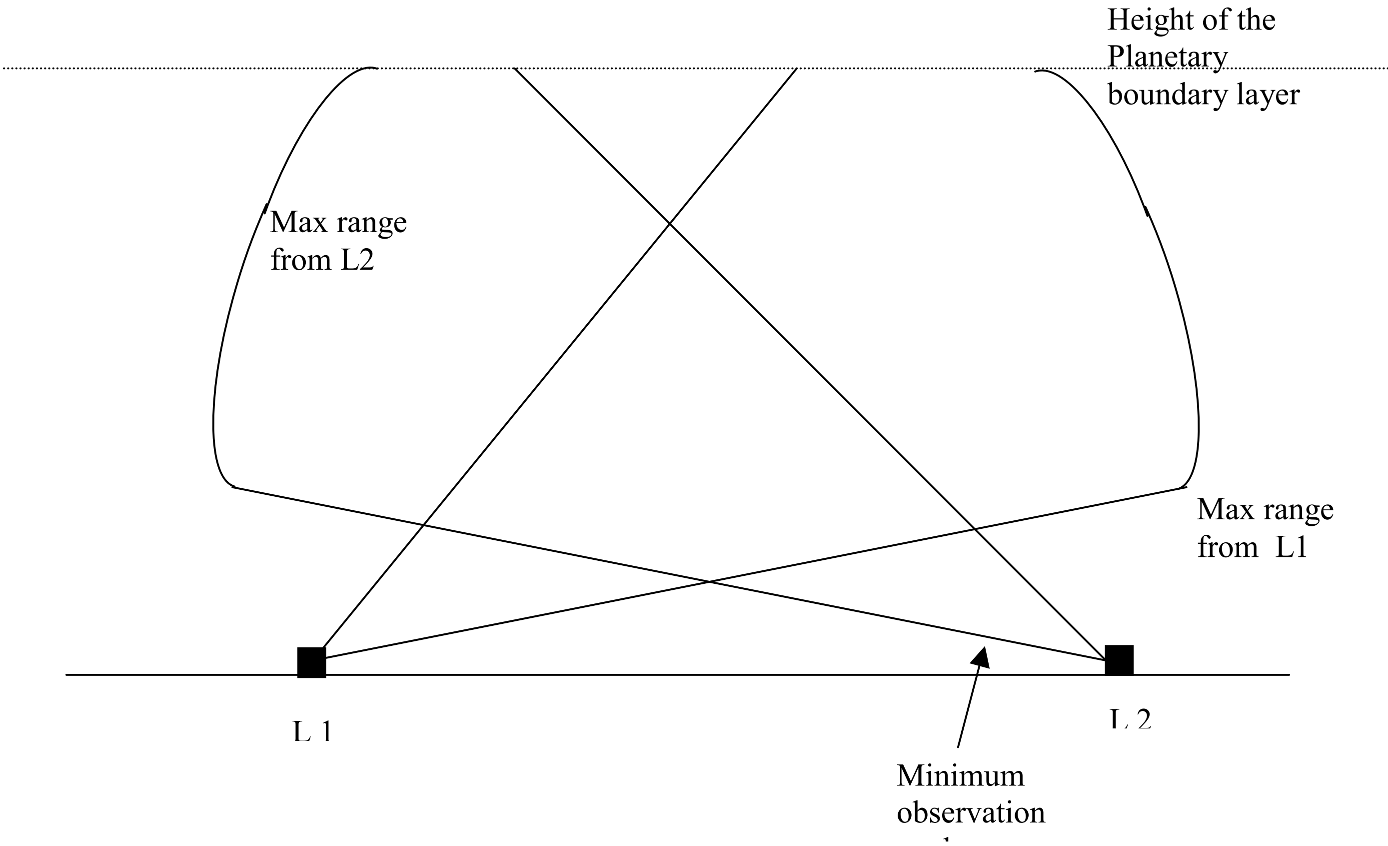

Figure 2.3 RHI scan between lidars.

Techniques to measure the vertical wind profile at the lidar station include one lidar holding its beam vertical whilst the other operates in Range Height Indicator mode and vice versa or both lidar beams pointing vertically simultaneously.

The co-ordinated RHI gives the wind component with maximum accuracy in the vertical direction; this would be supported by the information gleamed from scan pattern iii.

In practice the operation is likely to consist of patterns 1,2,3 following each other sequentially, with most of the data collection undertaken for scan pattern 2 or 3 depending upon whether observations of the vertical or horizontal wind fields took priority. This is referred to technique 1.

Patterns 2 and 3 allow the lidar line of sight velocity component to be separated into 2 of the 3 possible Cartesian components without any error or need to use assumptions. These are the horizontal wind flow data at the sampling columns for the RHI with beams perpendicular to one another and the vertical wind flow data in the plane of the lidars. As these derived wind vectors are accurately known they are referred to as being unambiguous.

Using technique 1 allows the unambiguous resolution of the horizontal and vertical wind flow, but this is only achieved for a limited number of locations. In addition to the horizontal and vertical measurements being made at separate locations the observations will also have been made at different times. There is therefore an implicit assumption that the flow field did not change dramatically during the duration of the observations. (It will be possible to check the validity of that assumption by analysis of the additional information gathered during the lidar scans).

A complementary strategy, technique 2, is to use the lidars in a crossed RHI pattern as shown in figure 3. Now the two lidars undertake separate nodding RHI scans in parallel directions. The scanning pattern for the crossed RHI works as follows. The lidars need to point in four orthogonal directions, spending an equal period pointing in each direction. Referring to figure 3 the lidar beams point in directions D2 & then D4 simultaneously. The beams are then reconfigured so that L1 points in direction D1 whilst lidar station L2 points in direction D3 that is pointing away from one another. Finally the two lidars point towards each other.

This yields the maximum amount of spatially separated data but to combine the data Cal-Chen[5] type assumptions need to be made. To help validate these assumptions data taken from the quarter when the lidar beams point towards each other can be used to accurately resolve the vertical velocities at a point on the plane that bisects the two lidars, as described in (iii) above. This will give a measure of confidence that the assumptions are valid.

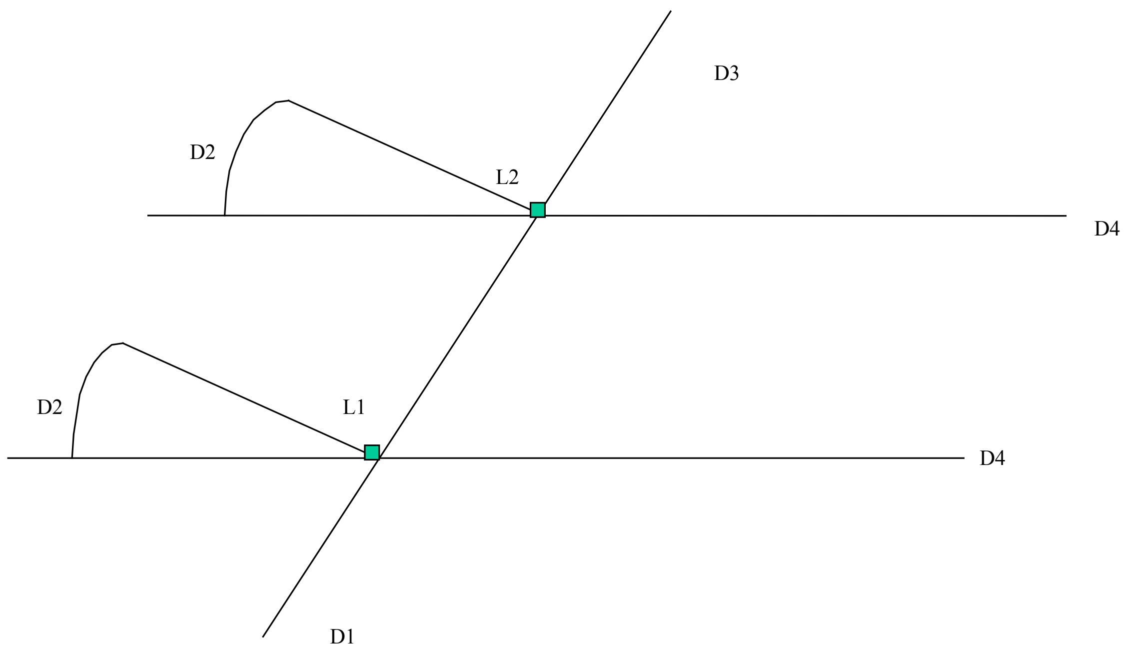

Figure 3. Proposal for crossed RHI scans.

The reason the beams are moved through 180° is that it will allow for a more accurate assessment of the variances. This is because in the opposite directions the perceived turbulence, which is derived from the vertical and horizontal turbulence, could appear different. If that is the case then from observing in the opposite directions two different sets of measurements are derived. These observations can then be combined algebraically following Cal-Chen's techniques[5] to estimate the statistics of the wind field more reliably.

It is proposed to use the different measurement techniques on separate days to assess their viability.

Scanning Technique	Scan pattern	Observations made	Resultant Information
1	VAD	Gives prevailing wind directly Useful to align beams to minimise cross talk and optimise observation of turbulence, at least for one lidar.	
	RHI with beams perpendicular to one another	To gather unambiguous horizontal flow data at a column Small number of elevations chosen Preference is for most of the measurements to be made at lower altitudes	Unambiguous horizontal wind flow data at columns Unambiguous vertical wind flow data in the plane of the lidars Wind flow along line of sight for lidar beams PBL structural information BUT observations could be uncorrelated because of length of time taken to make these measurements
	RHI in scan plane between lidars	To obtain unambiguous vertical flow data in the plane of the lidars.	To obtain unambiguous vertical flow data in the plane of the lidars.
2	Nodding RHI	Complementary scanning technique	Lidars are now constantly scanning Mainly ambiguous data gathered Lots of data from different spatial points and observations more likely to be correlated Reliant upon assumptions but the assumptions can be checked.

Table 2.1. Summary of proposed scan patterns and combination of use.

Table 2.1 summarises the proposed scanning patterns and resultant information. Whilst the data analysis may primarily focus on the beam intersection region there is a wealth of additional data collected from along the sight lines that would lend itself to further analysis. This includes obtaining structural information about the height of the PBL from backscatter strength and undertaking a Cal-Chen style analysis[5] to estimate airflow away from the positions where the lidar beams cross.

3 PROGRESS WITH THE DEVELOPMENT OF THE VISUALISATION SOFTWARE

Status of software development

With the delivery of the SGI Fuel graphics workstation in May 2002, the development of the three-dimensional display of lidar data and retrieved wind information has started. The software is being developed with the name DAViS, which stands for ***D**oppler **A**nalysis and **Vi**sualisation **S**oftware*.

DAViS currently can readily visualise lidar data and retrieved wind vectors in three dimensions provided that the data are in the agreed format. A flexible data format has been developed, that allows for changes in the location, azimuth and elevation of the lidars and accepts wind vectors as locations (*x, y, z*) and components (*u, v, w*). For test purposes an existing simple simulator of Doppler radar data has been adjusted to produce simulated lidar data for visualisation.

Structure of software

The software is object-oriented and programmed in C++. The software currently runs on IRIX which is SGI's distribution of UNIX.

For the development of DAViS mainly third-party libraries are used:

- **Open Inventor** – Object-oriented 3D Graphics library - Version 2.16 from SGI
- **Open GL** – 3D Graphics library - Version 1.2 from SGI
- **Open GL Volumizer** – Object-oriented 3D Graphics library – from SGI
- **Qt** – Object-oriented GUI[1] library for 2D Graphics and file in- and output – Version 3.0 from Trolltech

Using the visualisation software

After starting the software, a main window opens in which, through *File->Open,* a DML data file can be opened (see Figure 3.1).

[1] Graphical User Interface

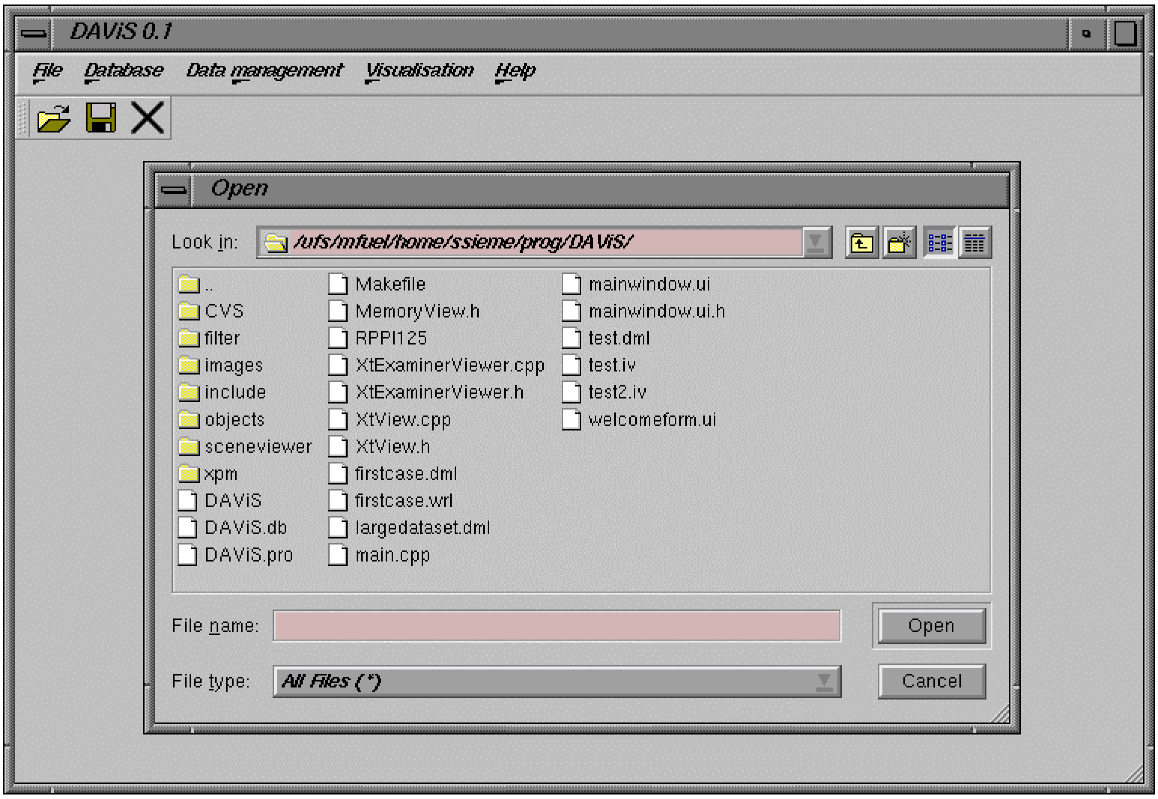

Figure 3.1: Main window with file open dialog.

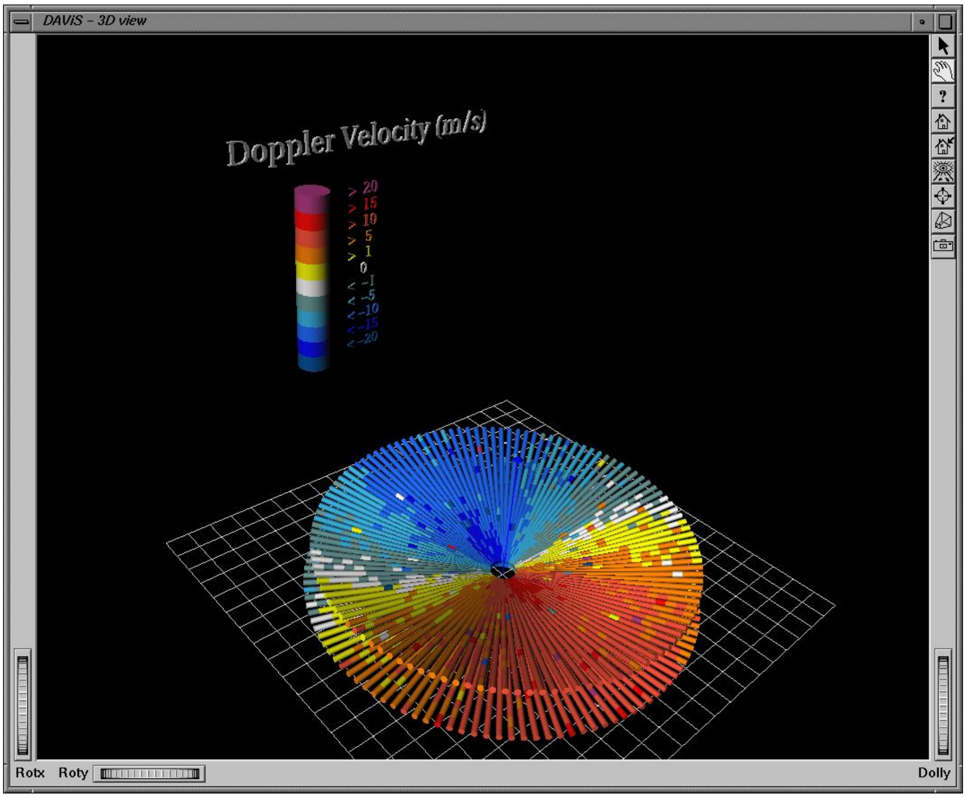

Figure 3.2: Example of the 3D display of two PPI scans at elevation angles of 1° and 10°. (Data was produced using an adapted version of an existing simulator of Doppler radar data.)

After a data file is selected the three-dimensional visualisation can be chosen under the menu point *Visualisation*. An example is given in Figure 3.2, which illustrates PPI scans arising from simulated data generated using an adaptation of a simulation program originally developed for the generation of Doppler radar data.

Functions of software

Currently the visualisation software has the following abilities:

- Reading and writing data in DML format
- Visualising rays of (lidar) data and wind vectors in 3D
- Production of a 2D snapshot of 3D display in JPEG and Bitmap format
- Saving a 3D scene in Open Inventor and VRML file format

These features enable it to visualise (after conversion to the DML format) the measured data and to show the retrieved wind information.

In addition to its primary role for 3D visualisation, the software will be able to produce 2D views of the data. An example is shown in Figure 3.3 which shows an RHI (vertical plane – constant azimuth, changing elevation angle) produced from Salford lidar data.

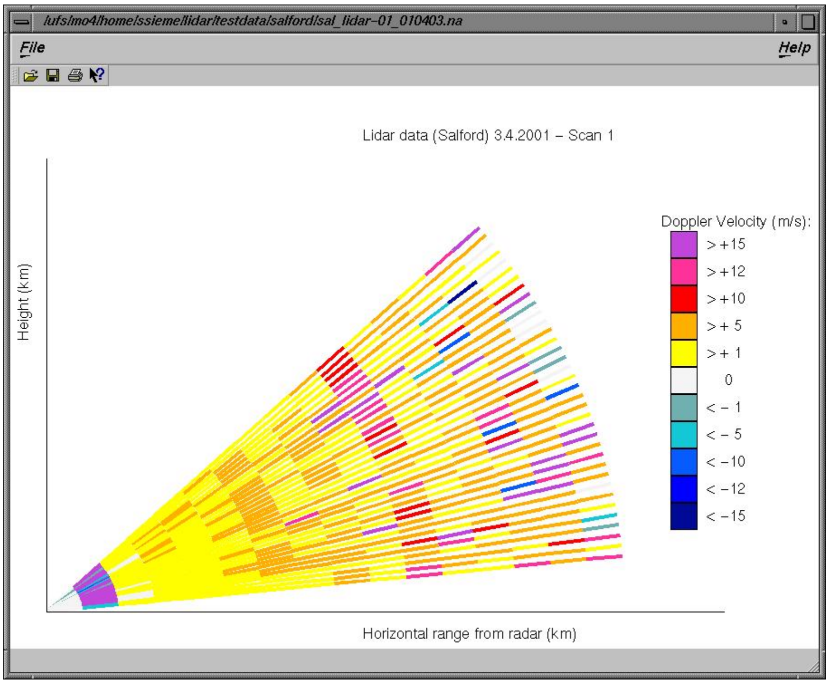

Figure 3.3: RHI showing data recorded by the Salford lidar.

Data format

A requirement of the project was that the raw lidar data and the retrieved wind information should be stored in a (human) readable data format. One possible format is the BADC (British Atmospheric Data Format); however this format is ill suited for input to a computer program.

A new data format has therefore been developed. This format is based on XML (Extensible Markup Language). The DML (DAViS Markup Language) format can contain two different types of objects: rays (effectively expressed in polar co-ordinates) and wind vectors (effectively in Cartesian co-ordinates). The DML format is still under development and will be described in a separate document.

The data format is already supported by the Doppler data simulator program, which was developed by the author in an earlier project (see Figure 3.2). The Doppler simulator currently can only produce data from one site, but this is being developed to provide the data for two sites. Further details will be provided in the MS4 report.

As an indication of what is achievable the following example is cited. In this example data from 10 range gates along the lidar beam's line of sight are obtained at different elevations from two different lidar positions. The colour coding indicates the strength of the wind speed at each range gate. The corresponding rays intersect and the three "retrieved" wind vectors are included in the data set. Figure 3.4 shows a visualisation of the resulting data. The vertical blue arrow shows the z-axis through the centre of the co-ordinate system with the lidar positions represented by the red spheres at x = -30 and x = 30.

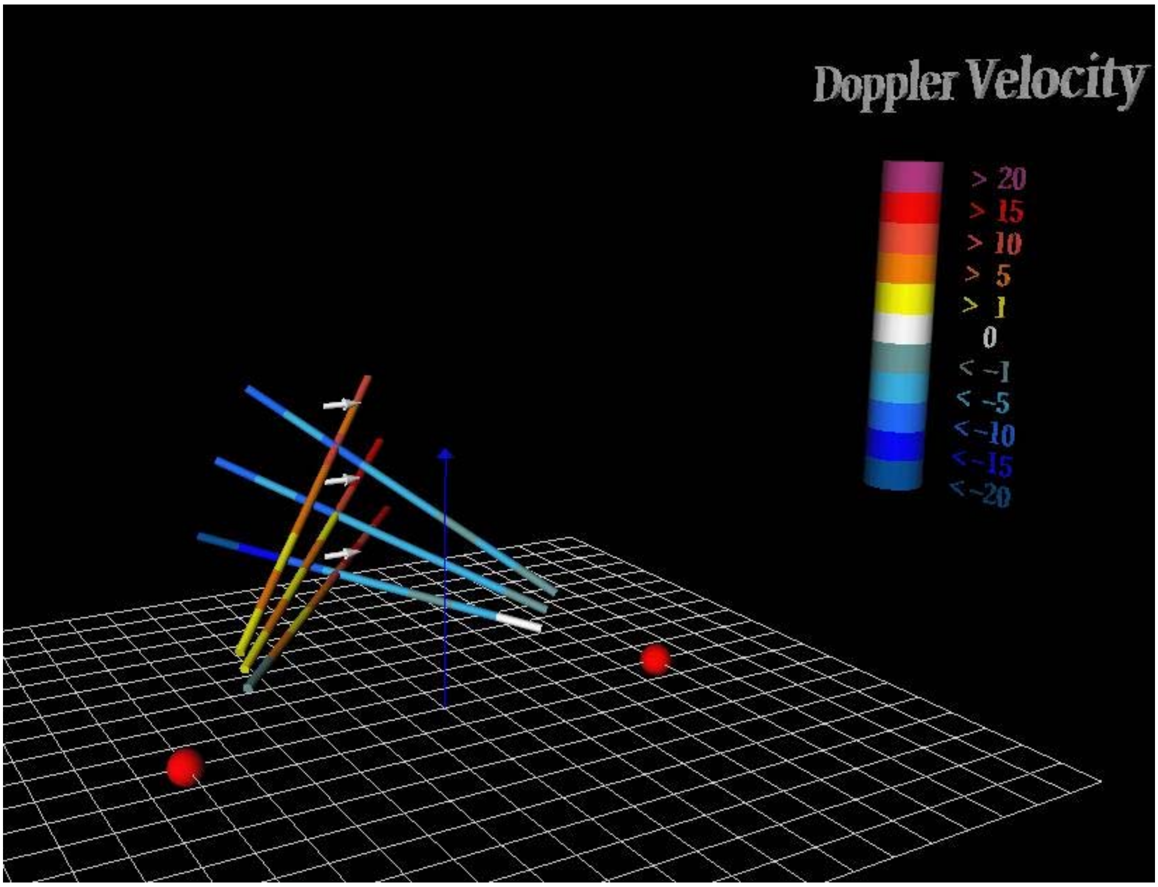

Figure 3.4: Visualisation of the example data set shown in the listing above.

Figures 3.2 and 3.4 are single examples of what are, in fact, dynamic displays that can be controlled by the viewer. Rotating the point of view of the 3D object results in greater insights. An idea of the possibilities is provided by the animation available to view at http://prswww.essex.ac.uk. (Then follow the Air Quality links).

Further work

Further development of the current program

Even though the software is able to visualise three-dimensional lidar data and wind-field information, there are a number of enhancements still to be made. The following improvements are envisaged:

- Addition of a time stamp to each data item

- Implementation of a time engine to permit animation
- Improved layout with interactive menus (allowing, for example, the revision of the colour tables) and information about scales and variables (so that, for example, pointing the mouse on a object can show information about that object).
- Implementation of vertically-sliced and horizontally-sliced 2D displays
- Addition of features allowing the expression of further wind features (beside direction and magnitude) and an indication of the dispersion of pollutants in the air
- Introduction of an interactive menu for the 3D display (to change variable type, timing and view)
- Improved graphics including transparency and a more informative colour scheme
- Increased visualisation speed through more efficient coding

Requirements for the visualisation of various scan strategies

An important feature of the software will be to visualise products that will be retrieved from various scan strategies. Different scan patterns give different patterns of three-dimensional information. One strategy concentrates on detailed information concerning a column of air (measured by two orthogonal RHIs) whereas another would provide information over a hemisphere.

Without additional assumptions, scan patterns based on two measurements can only give (at most) 2D components of the wind vectors. It will be important that the resulting 3D display makes this apparent.

Development of supporting software

Further to these changes in the visualisation software another small conversion program should be written to convert the raw lidar data to the DML data format. This program can be written in PERL or ANSI C/C++ so as to enable its use on UNIX and Windows machines. If any data is written in DML format it can be immediately visualised by DAViS.

4 SUMMARY

This report is the third milestone in the ISB Urban lidar project. The contents of the report are summarised below:

- The key parameters to be measured during the ISB52 trials have been identified. They are the structure of the Planetary Boundary Layer and turbulence.

- Two complementary sets of scanning patterns have been developed to ensure a meaningful set of observations for these phenomena are made.

- The intention is to gain a better understanding of the dynamics of wind flow for the urban environment rather than gather data to be fed directly into forecasts.

- Currently it is not possible to quantify the likely improvements to the accuracy of future forecasting of pollution dispersal through the incorporation of new knowledge derived from the lidar observations. However it is well known that all models contain assumptions developed for the rural environment that become erroneous when applied to describe conditions within the urban environment.

- A set of visualisation tools has been developed to assist in the interpretation of the twin lidar data. The mean features to be visualised are the mean wind flow in terms of direction and strength, turbulence and the structure of the PBL.

- It is intended to present the data in the following formats: Visualising rays of lidar data and wind vectors in 3D, production of a 2D snapshot of a 3D display and animations of time series.

The next stage of the project is to survey the likely trials sites and then combine the results of that survey with the findings of this report to fully define the experimental procedure for use in the imminent trials. The definition of the experimental procedure will appear in the next ISB52 milestone, MS4, due in Sep 2002.

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6 GLOSSARY

PBL Planetary Boundary Layer

RHI Range Height Indicator

PRF Pulse Repetition Frequency

PPI Plan Position Indicator

VAD Velocity Azimuth Display

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8 DISCLAIMER

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7	Dr R I Young	PD115, QinetiQ Malvern
8-11	Dr D Middleton	Met Office, London
12	Prof C Collier	Salford University
13	Dr F Davies	Salford University
14	Dr K Bozier	Salford University
15	Prof A Holt	Essex University
16	Dr G Upton	Essex University
17	Dr S Siemen	Essex University
18	Project File	PD115, QinetiQ Malvern
19-23	Spares	PD115, QinetiQ Malvern