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Improved Air Quality Forecasting
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Visualisation of Dual Doppler Lidar data

By

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ABSTRACT

This report ISB52-08 was produced under Project 52 of the Invest to Save Scheme, or ISB. The objective of this project is to improve the ability of air quality forecasts and thus impact on the quality of life in and around urban areas.

As part of the project, the *Propagation and Remote Sensing Research Laboratory* at the University of Essex undertook a study to determine how the measured lidar data and the retrieved products can be best visualised. For this purpose a software suite, called *DAViS*, was developed, which could load lidar data and then visualise it by two-dimensional plots and on an interactive three-dimensional display. The software also allows interactive processing and display in real-time.

The report describes the DAViS software and how it can be used to visualise Lidar data and retrieved products. Examples of the visualisation produced by DAViS are also included.

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1. Introduction

As part of the ISB-52 project, the *Propagation and Remote Sensing Research Laboratory* of the *Department of Mathematical Sciences* at the University of Essex developed software to visualise the measured data and retrieved products from both Doppler lidars involved in the project. This method in which two lidars are used to sense the atmosphere is, we believe, the first such study of its kind. Whilst the two lidars are nominally identical small differences in the ldiar and different scanner mechanisms means that they save data in different formats.

Therefore the process of visualising the data required the following two steps:

- Converting the lidar data into a common data format (DML).

- Loading data in the common format and visualising the data.

The common data format, DML, was developed at the University of Essex and is described in section 2 of this document. The following section describes how the data from both lidars was converted into the single DML format. We also describe how retrieved information and output from numerical models (Met Office NAME model) can be stored. Section 4 gives an overview of the DAViS visualisation software. The structure and usage of the software is described. This section is then followed by snapshots of results of the visualisation process. The document concludes with a summary and suggestions for further work in analysing and visualising lidar data.

Lidar data

The lidar collects data along a ray of given azimuth and elevation. The data received from the lidar consists of intensity and radial velocity for a set of resolution bins along the ray. In this experiment the bins had a length of 112 m. There are a number of possible scan patterns [1]. Those used in this experiment were PPI (plan position indicator), RHI (range height indicator) and LOS (line of sight). The PPI scans include a range of azimuths at a given elevation. The RHI scans include a range of elevations at a given azimuth. The LOS data contains a time series in a fixed direction.

2. DML data format

All the pertinent information for a scan made by a lidar for each scan is distributed in several data files (e.g. One file for Doppler products and one for angles). For different scan strategies different data files are recorded. This makes it difficult to write an automatic procedure to read and process the data. To overcome this weakness a data format was needed. This format does not only have to store all recorded lidar data and its parameters, but also had to be able to store retrieved information about the observed wind field.

The result of this, is the *Doppler Markup Language* (DML) This format is based on the XML-Markup-Language which is commonly used to describe data formats in the World-Wide-Web. The format has the advantages that it is ASCII and can be edited with any standard editor under Unix or Windows.

As, DML is based on XML, this means that the first line of the DML data file has to identify the format. This is done by the line *<!DOCTYPE dml>*. XML is based on objects which start and end with a so-called tag. Tags are symbolised by < >. An object starts with a tag containing the object name and finishes with a tag where the object name has a '/' in front of it. This signals the reader that the object is finished. The whole data set itself is also an object of type "dml". This means that a minimal DML file looks like this:

> *<!DOCTYPE dml>*
> *<dml>*
> *.... list of objects ....*
> *</dml>*

The advantage of having a object-oriented format is that it is very flexible in holding different kinds of data and can be easily extended by inclusion of further objects if necessary. In the following sections the various objects which are currently defined in DML are described.

Describing the lidar site - <site>

The object *<site>* defines in the data file the site at which the lidar was positioned, and various other information about the measurement. Each DML data file should only contain one <site> definition. The information which can be stored in an *<site>* object are:

> ***<name>*** *Sets the name of the location*
> ***<time>*** *Sets the date and time of the measurement. Attributes are:*
>> ***year*** *- integer value of the year*
>> ***month*** *- integer value of the month*
>> ***day*** *- integer value of the day*
>> ***hour*** *- integer value of the hour*
>> ***minute*** *- integer value of the minute*
>> ***duration*** *- integer value giving the length of measurements in minutes*
>
> ***<position>*** *(or <location>) Sets the position in metres from a origin. Attributes are:*
>> ***x*** *- floating-point number of location in the x-axis (towards east)*
>> ***y*** *- floating-point number of location in the x-axis (towards north)*
>> ***z*** *- floating-point number of location in the z-axis (height)*

In principle, seconds can also be recorded, but it was not appropriate for this experiment, because the time data was not sufficiently precise.

Example for a description of a lidar site:

```
<site>
  <name>Malvern (QinetiQ)</name>
  <time year="2003" month="3" day="18" hour="17" minute="50" duration="13" />
  <location x="-432.0" y="2923.0" z="7.0" />
</site>
```

This example describes the site called Malvern, with giving in the brackets the owner of the lidar. The data was measured in the winter trial on the 18th of March in 2003 at 17:50 o'clock (The data of this trial is described in more detail in the MS6 report). The measurement took 13 minutes. The grid position was -432 m in the x (west→east-axis) direction and 2923 m in the y (south→north-axis) direction. The height is given as 7m (this is meant to be the difference to the height of the second lidar.)

Lidar data – <ray>

The lidar data is organised in rays. A *ray* is defined as measurements along a line for given angles in azimuth and elevation. An <dml> object can contain as many <ray> objects as needed. The definition of the object <ray> is as following:

> **<orientation>** *Set the direction in which the lidar beam is pointing. Attributes are:*
> > **elevation** *- floating point number giving the elevation angle*
> > **azimuth** *- floating point number giving the azimuth angle*
>
> **<dimension>** *Sets the date and time of the measurement. Attributes are:*
> > **beamwidth** *- integer type*
> > **binlength** *- integer type*
> > **skipbins** *- integer type*
> > **type** *– string defining the type of measurement ("ppi","rhi" or "los")*
>
> **<velocities>** *Object to hold all velocity values for a ray*
> **<intensities>** *Object to hold all intensity values for a ray*
>
> *The objects* **<velocities>** *and* **<intensities>** *have both the attribute* **number** *which gives the number of bins. Inside these objects all bin values are stored in an object called* **b***.*

Example for the description of a ray:

```
<ray>
  <orientation elevation="25.0" azimuth="2.27" />
  <dimension beamwidth="1" binlength="112" skipbins="1" type="ppi"/>
  <velocities number="2"> <b>14.814</b> <b>0.496557</b> </velocities>
  <intensities number="2"> <b>1141.36</b> <b>2877.65</b> </intensities>
</ray>
```

This example shows a ray which only consists of two bins which are measured at an elevation angle of 25 degrees and an azimuth angle of 2.27 degrees. The ray belongs to a PPI and the first bin can be skipped.

Wind information - <windvector>

Additional to lidar data, DML can also store information about wind fields. This information is wind direction and speed and is stored in an object of type <windvector>. The definition is as follows:

>   ***<position>*** *Sets the position of the wind vector in 3D. Attributes are:*
>   >   ***x*** *- floating-point number of location in the x-axis (towards east)*
>   >   ***y*** *- floating point number of location in the x-axis (towards north)*
>   >   ***z*** *- floating point number of location in the x-axis (height)*
>   ***<amplitude>*** *Sets dimension of the wind vector. Attributes are:*
>   >   ***x*** *- floating-point giving the strength of wind along the x-axis (towards east)*
>   >   ***y*** *- floating-point giving the strength of wind along the x-axis (towards north)*
>   >   ***z*** *- floating-point giving the strength of wind along the x-axis (vertical)*
>   ***<properties>*** *Object to describe various properties of the wind vector*
>   >   *Two attributes exist to describe the quality of the wind information:* ***quality*** *and* ***variance****.*

Example for the definition of a wind vector:

```
<windvector>
  <position x="34.0" y="-102.0" z="23.0" />
  <amplitude x="-2.0" y="23.0" z="7.0" />
  <properties quality="0.5" variance="0.1" />
</windvector>
```
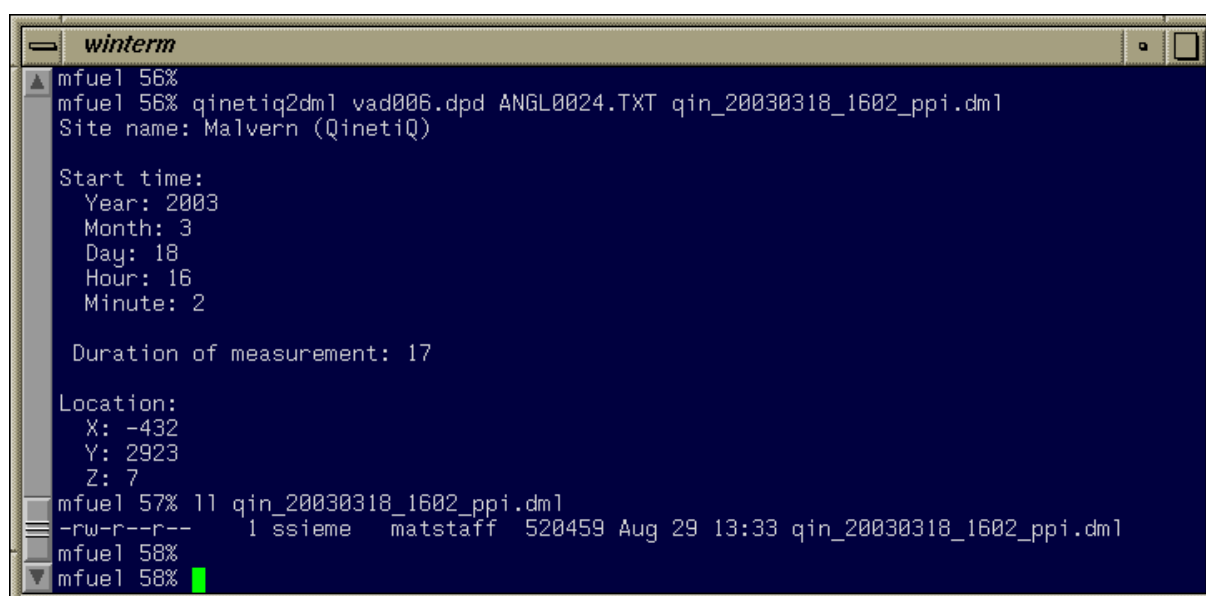
3. Software to convert lidar data

As mentioned earlier, the lidar data was recorded in various data files and some information was even noted down by hand before insertion into a relevant data file. In this format it would have been too difficult to run an automated processing. To solve this problem it was decided to convert all data into one single data format: the above described DML.

To convert the lidar data into DML format, three small programs were written. These are explained in more detail in the following. All programs are written in C++ and require user interaction to adopt to the various data sets. Not only did the formats of the lidar data change slightly during the project, but also some data sets need adjustments by hand for the angles at which the data is measured. To obtain information about how the program can be used, only the program name (without any parameters) should be typed into a console and a help text will appear (see user guide, currently under preparation).

qinetiq2dml

This program converts the lidar data recorded by the QinetiQ lidar into the DML format. As input the program needs the raw file in which the data is recorded, the angle file and a name for the DML output file. An example of a conversion is given in figure 1. In the beginning of the conversion the user is asked for the site name and the date and time of when the measurement was conducted.


```
winterm
mfuel 56%
mfuel 56% qinetiq2dml vad006.dpd ANGL0024.TXT qin_20030318_1602_ppi.dml
Site name: Malvern (QinetiQ)

Start time:
   Year: 2003
   Month: 3
   Day: 18
   Hour: 16
   Minute: 2

 Duration of measurement: 17

Location:
   X: -432
   Y: 2923
   Z: 7
mfuel 57% ll qin_20030318_1602_ppi.dml
-rw-r--r--   1 ssieme   matstaff   520459 Aug 29 13:33 qin_20030318_1602_ppi.dml
mfuel 58%
mfuel 58%
```

Figure 1: Example of converting QinetiQ lidar data into DML with *qinetiq2dml*.

salford2dml

The program to convert the lidar data from the Salford lidar is similar to the program to convert the data from the QinetiQ lidar, however there are a number of small, but important differences. Firstly the Salford lidar records the data anti-clock-wise during a VAD scan, whereas the QinetiQ lidar records it clockwise (corresponding to increasing azimuth). For Salford data, zero degree in azimuth does not correspond to the geographical north which is the case with the data from the QinetiQ lidar. The relation between zero degree in azimuth and geographical north depends on the position of the van in which the Salford lidar is located. This means that for every data set, the orientation of the van has to be known and the azimuth angles have to be accordingly corrected. This software will do this automatically if the offset angle is given by the user. The correction angles were supplied by Salford University.

Another complication was caused by the format of the angle files. Whilst the QinetiQ angle data file contains elevation **and** azimuth angles, the Salford angle files only contain the

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angles of elevation **or** azimuth angles, depending which is changing and which is constant during a scan. This means that the user has to give an additional parameter to indicate if the lidar data is a PPI, RHI or a line of sight (LOS) measurement.

name2dml

In addition to the data from both lidars, the University of Essex received model output data from the Met Office. The data was produced by the NAME model. The data was provided as a column ASCII file and this made automatic processing possible. The data described a vertical column in which variables as the wind direction, wind speed, pressure and temperature were given with height. Each file contains forecasts in steps of three hours over three days.

The conversion program takes as input the name of the file of the ASCII table. The names of the DML output files are automatically produced by the program. After start-up the user is asked for the day the forecast was produced. The program then writes the extracted wind vectors in the DML output file. If required in future, further variables could be stored and displayed by DAViS.

Transforming the lidar position

As part of the conversion of the data into DML format, the position of each lidar is converted. The conversion sets the lidar position in a place which makes it convenient for the three-dimensional graphics display to insert an underlying map of the surrounding area (taken from www.streetmap.co.uk). The maps are given by square kilometre in the National Grid. In the following the conversion of co-ordinates is given for the two most used sites at Great Malvern, where the winter trial took place, and Northolt, where the summer trial was located.

Geometry for the March 2003 trial:

Setting the origin to 378000 (east) and 242000 (north):

Lidar	Easting	Northing	DML - x	DML - y	DML - z
Salford	378 925	242 112	925	112	0
QinetiQ	378 432	244 923	432	2923	7

Geometry for the July 2003 trial:

Setting the origin to 507000 (east) and 183000 (north):

Lidar	Easting	Northing	DML - x	DML - y	DML - z
Salford	510 537	184 607	3537	1607	0
QinetiQ	509 157	185 364	2157	2364	0
Met Office Model output	509 780	184 975	2780	1975	0

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4. DAViS

The main software developed at the University of Essex is the **D**oppler **A**nalysis and **Vi**sualisation **S**oftware, in short DAViS. This software loads and processes the lidar data in order to visualise it in various ways in 2D or 3D.

Main features

The main features of DAViS are:

* Load data in the DML data format.
* Visualise lidar data in 2D as RHI and PPI.
* VAD analysis of PPI lidar data with various options.
* Interactive 3D display for lidar data (RHI and PPI) and wind information.
* Stereo graphics for the 3D display.

How to use DAViS

DAViS can be started from a text console (typing *DAViS*) or through a link on the desktop. After start-up, it opens a menu, as shown in figure 2. From this menu everything can be controlled.

To start with, the lidar data has to be loaded. This can be done from the menu by pressing "*File→Open ...*". Only lidar data in the above described DML format can be read. After the data was loaded, the Options in the menu *Data management* allows the user to see exactly which data was loaded. Figure 3 shows an example of the *Ray Explorer* in which the loaded rays are listed.

The next step is then to visualise the loaded data. In *Visualisation* of the main menu various 2D and 3D plotting options can be found. The data can be displayed as a PPI, a RHI, a VAD or on a 3D display. Figure 4 shows the dialogue to select a RHI display.

The two-dimensional displays, such as PPI, RHI and VAD all offer a basic menu on their own to close the window and to print the plot. The produced plot can be saved as a file, currently only as a bitmap file. The bitmap file can be read with the program *xv* to convert it into any other major file format.

The VAD window is divided in two parts: the upper part is plots the VAD display while the lower part gives the user various options to select the data and to visualise and to analyse it. Figure 5 shows an example of the VAD display. On the right side of the lower part the various methods to analyse a VAD can be chosen. The first two options are simple least-squares fits of sine curves, the second one has an ability to fit a velocity offset. The third and fourth methods are based on a Fourier analysis of the VAD. The first one is based on the method by Browning and Wexler (1968). [2] The last method is the fitting of straight lines over intervals of 15 degrees in azimuth to improve the detection of zero crossings and maxima.

The three-dimensional display can be chosen, as with the two-dimensional displays, from the visualisation menu. A browser window will appear, as shown in figure 6, with two smaller windows to select the scan and the variable which should be displayed. The mouse can be used to rotate the scene, by pressing the left button or the three wheels at the borders of the viewer. The menu on the right of the viewer gives the possibility to set a bookmark to a preferred view angle, to zoom in on a point, or to make a snapshot of the scene.
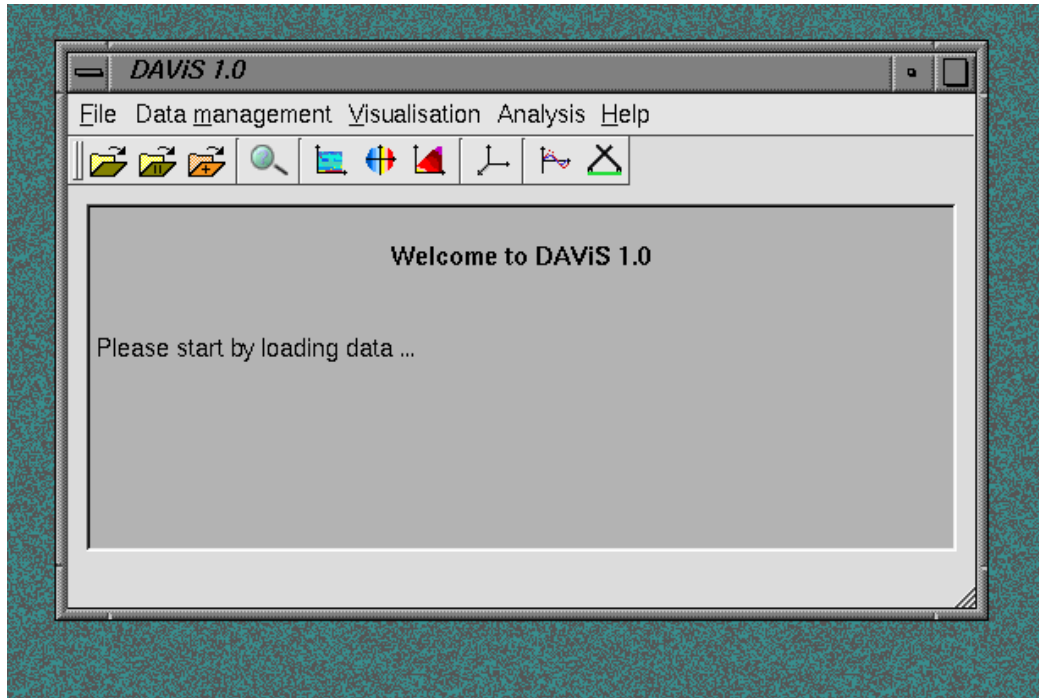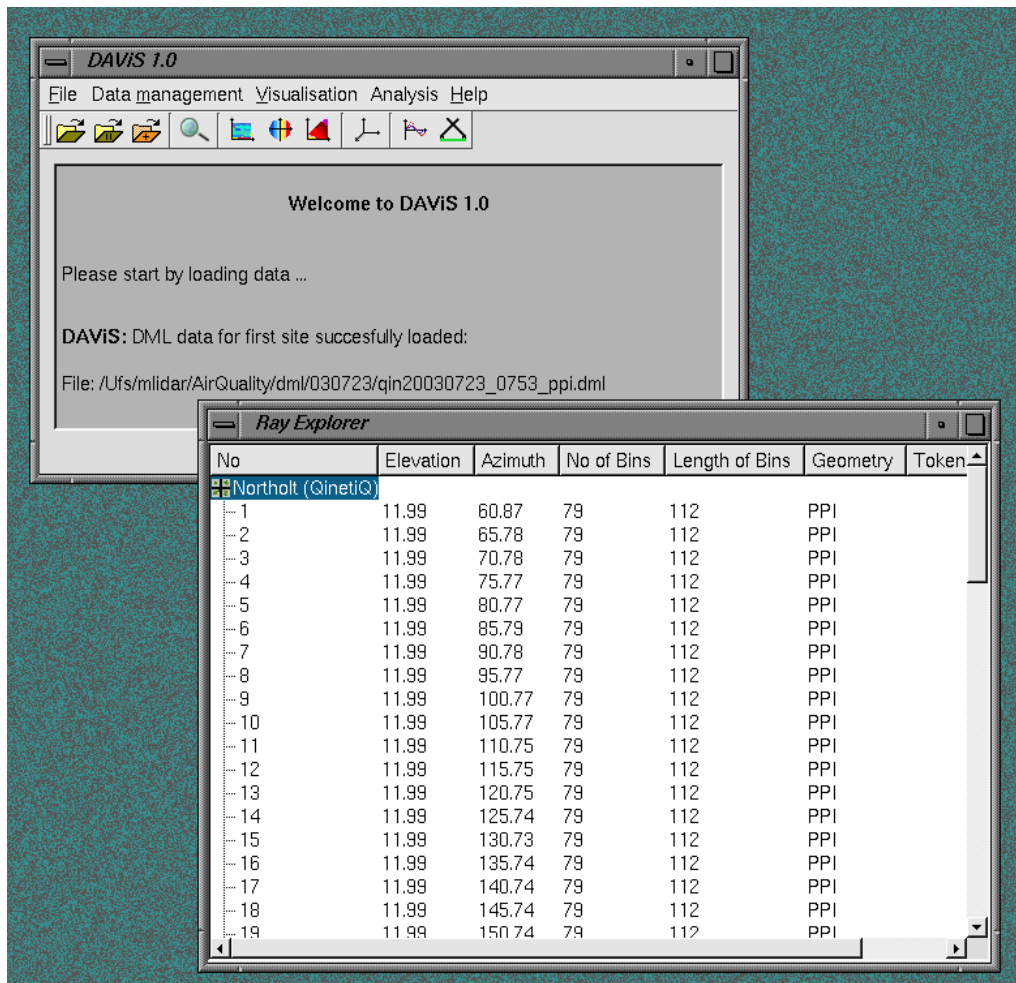
Figure 2: Main menu of DAViS.

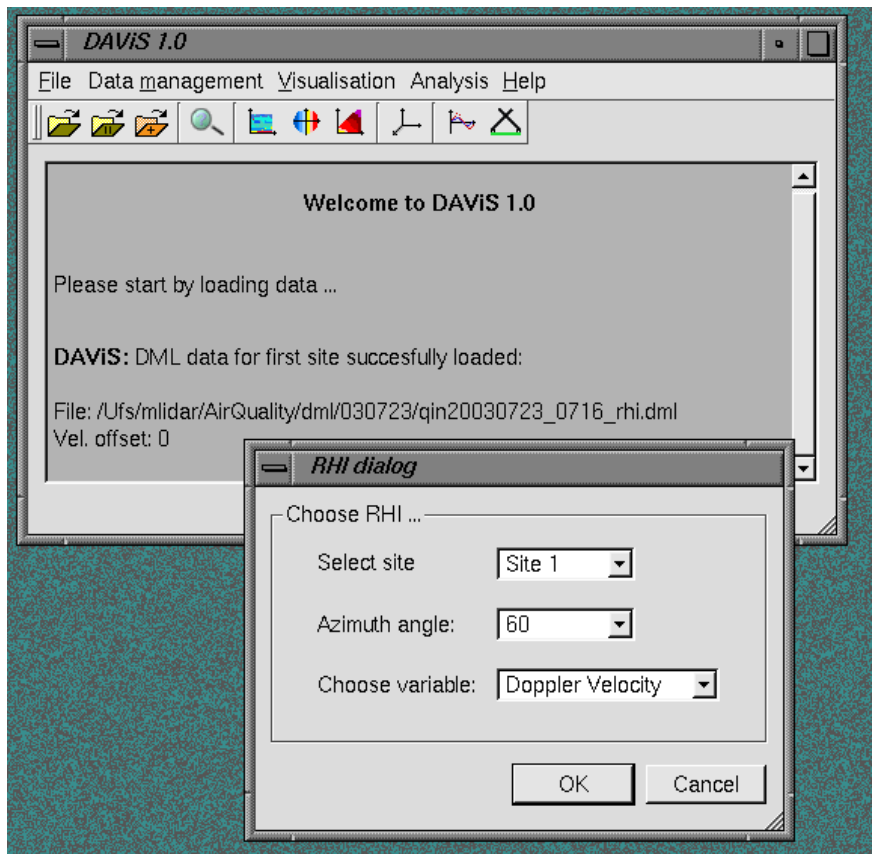Figure 3: Example of how *Ray Explorer* shows which lidar data was loaded.

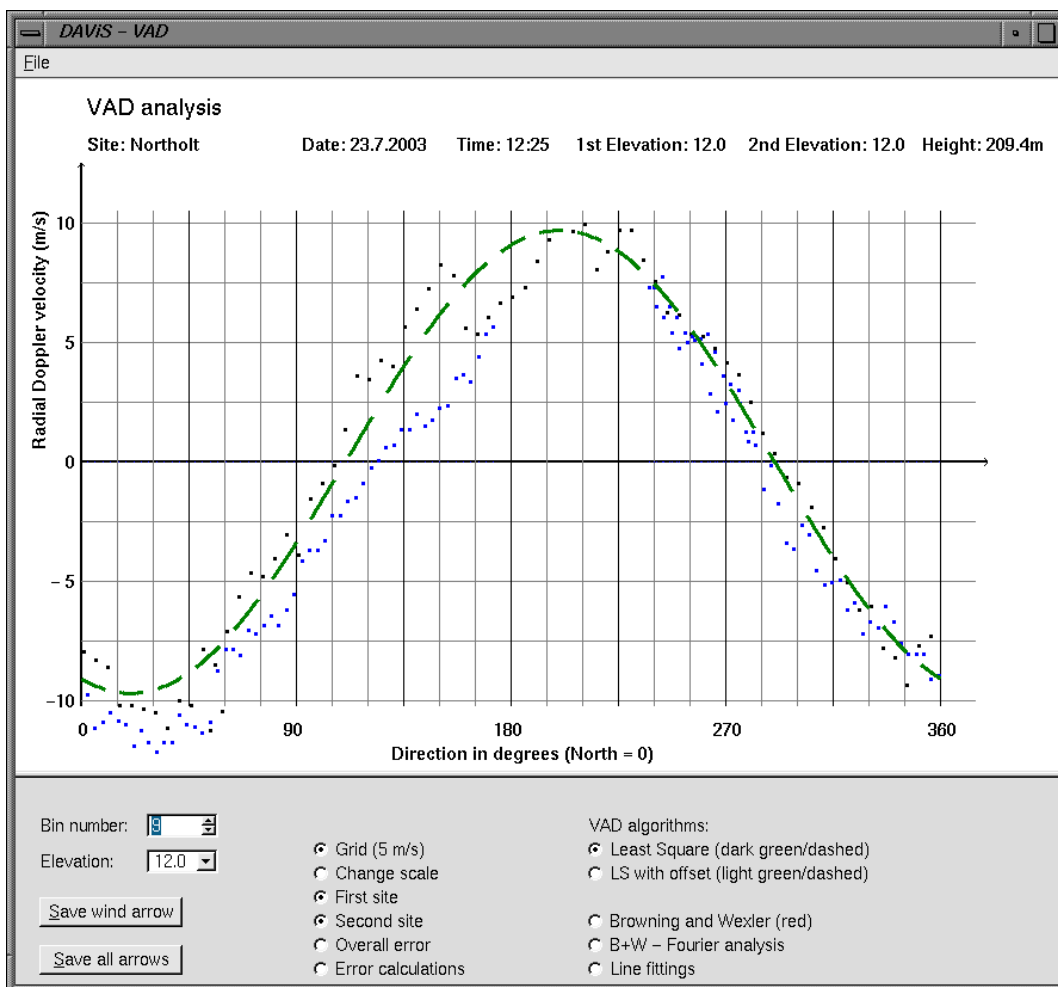Figure 4: Window to select a RHI display.

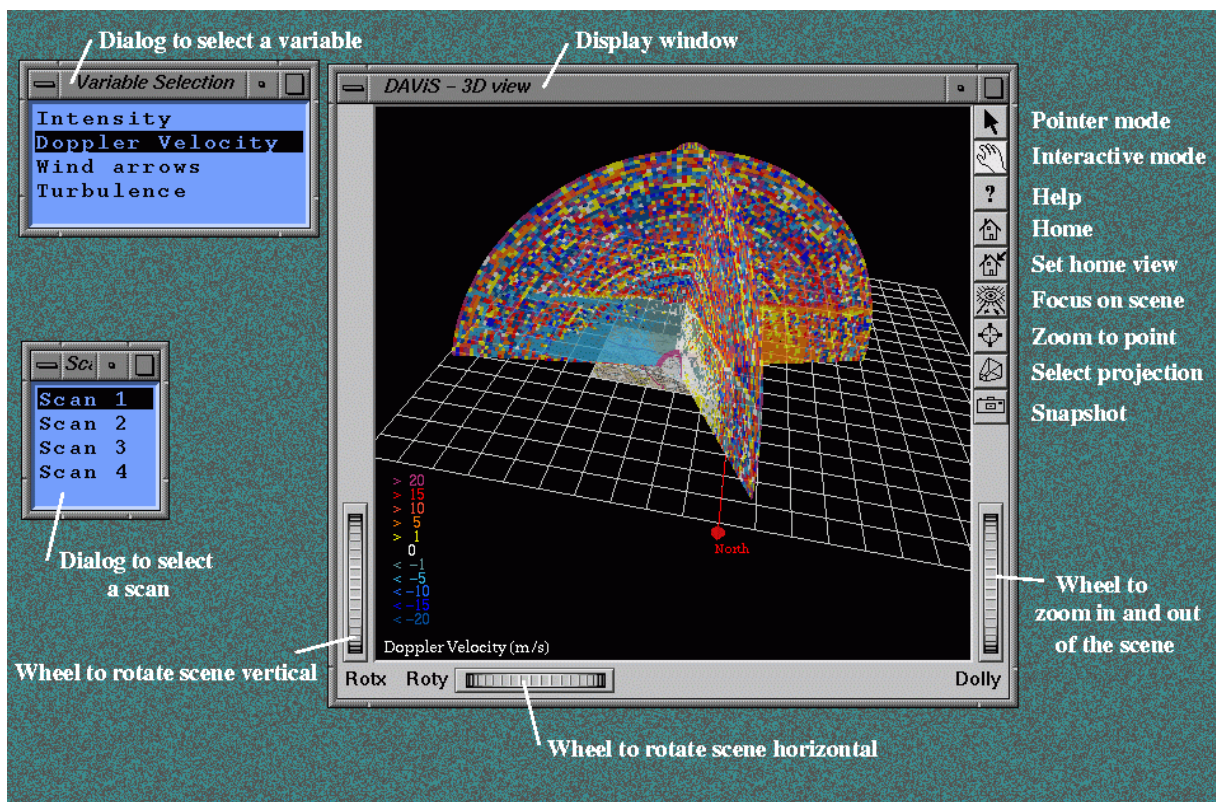Figure 5: Example of a two-dimensional display; a VAD.

Figure 6: Example of a three-dimensional display with dialogues to control the display.

Using stereo graphics

Three-dimensional displays are difficult to produce on a two-dimensional monitor screen. To make the impression more realistic stereo graphics can be used. Stereo graphics produces two different pictures, one for each eye to give the illusion of viewing an object in 3D. To use stereo graphics there are hardware as well as software requirements. Further details about the hardware are given later in this section.

In X11, as used on most Unix machines, the X-Server has to be set in stereo mode. This is necessary because the X-Server has to provide two versions of the screen display. This has to be done with caution because some hardware can break under the pressure of running at double the normal speed. To set the X-Server in stereo mode a script called *set_stereo* was written for the *mfuel* workstation, which does this automatically. As noted, stereo mode requires double the resources as in normal single mode. That is why a second script was written to set the X-Server back into the single mode. This script is called *unset_stereo*. Both scripts are located in the directory */usr/local/bin/*, which should be included in every user path.

After the set-up of the X-Server, the application has to be told to switch also in stereo mode. This is done by through a menu in the Open Inventor window. This is shown in Figure 8. The camera rotation (the difference between the two screens) has to be adjusted individually for each person. The default value of 3.0 is for most people not suitable, and a proper value lies between 1.0 and 1.2.

Warning: Before use of these glasses please be sure that all viewers are aware of the dangers of stereo viewing. People with epilepsy are especially at risk. People might not feel well observing stereo images and should be closely monitored while they use stereo graphics!

If the stereo graphics appears not to work this can be caused by a low battery in the glasses or one may have forgotten to switch on the stereo emitter.

Design of the software

DAViS is written in C++ in an object-oriented design and was developed in an Unix X11 environment. It was successfully compiled and used under SGI IRIX (version 6.5) and Linux (Kernel 2.4). To ensure and stable and fast development some third-party software packages have been used:

* SGI's *Open Inventor* with its *Motif* bindings for interactive 3D rendering.
* Trolltech's *Qt* for development of menus, File-IO-operations and 2D graphic windows.

The software was designed on a SGI graphics workstation which was specially purchased for this project. The SGI *Fuel* workstation is equipped with a 64-Bit processor for faster floating-point calculations and a V10 Graphics card which enables OpenGL accelerations and stereo graphics. The software is designed to run on other Unix platforms, but has shown slower reaction times in the interactive 3D display and the stereo graphics cannot be used.

Using the software *doxygen* an on-line documentation in HTML of the source code was produced. It enables any programmer easily to understand the code already written and to add further extensions.

Figure 7: Screen snapshot showing the 3D display and the menus to enable stereo graphics.

Hardware considerations

To fulfil the task to develop a visualisation software system there were high demands on the computer hardware used. The amount of data visualised in 3D requires a large amount of

(graphics and system) memory and processing time from the CPU and GPU to work in real-time. To manage this task a SGI Fuel graphics workstation was chosen. The advantage of this workstation is that it is optimized for real-time hardware optimized OpenGL.

The workstation was finalised with a 21 inch SONY GDM-5411 (oem SGI) Triniton Monitor. This monitor is needed to allow fast changes in repainting the screen when stereo mode is used. The information about the workstation is summarized in table 1.

To be able to use stereo graphics it was also necessary to purchase an *emitter* and special glasses. These were bought from *Stereographics*, a well-known seller for 3D hardware. The emitter, when connected to the graphics card of the workstations and sends signals to the glasses to synchronise with the monitor. This is necessary because the stereo effect is produced by painting the screen in fast consecutive order for the left and right eyes separately. The synchronisation tells the glasses when to hide or view the monitor screen to the left or right eye.

SGI Fuel Workstation "mfuel"	
Processor	600MHz MIPS R14000 (IP35 - 64 bit)
Memory (system)	1 GB
Graphics card	SGI/NVIDIA V10 - "ODYSSEY" graphics 32 MB on card graphics memory Video Output (DVI): 1280x1024 @ 96Hz Stereo Output
Monitor	21 inch SONY GDM-5411 (oem SGI) Triniton Monitor
Operating system	SGI IRIX64 Release 6.5

Table 1: Summary of mfuel's hardware configuration.

Figure 8: Picture of the SGI Fuel workstation *mfuel* in its office at Essex University.

Figure 9: Stereo hardware: the emitter (left) and the stereo glasses (right).

5. Results of visualisation

In this section, results are presented from the visualisation of lidar data with DAViS. The data used was recorded in the winter trial in March 2003 in Malvern [3] and in the summer trial in July 2003 in Northolt (London) [1] First examples of two-dimensional plots of the data are presented before examples of the three-dimensional visualisation are shown.

A small selection of the results is now presented. More detailed examples of the visualisation work are on a web page launched at the University of Essex at *http://prswww.essex.ac.uk/lidar* . The web page not only contains more snapshots of DAViS and the visualisation, but also movies from the three-dimensional display.

2D plots

The two-dimensional plots consist of PPIs, RHIs, VADs and time series of line of sight data.

The summer trial in July 2003 produced a number of interesting data sets. To start a series of measurements, PPI scans were measured to establish the mean wind direction. Figure 10 shows such a PPI of the radial Doppler velocity at 8:43 on the 23rd of July 2003. The radial velocity is in the majority positive on the bottom left (south-west) part of the PPI. On the opposite (north-east) the velocity values are mostly negative. This points to a linear wind flow which can be more closely examined with a VAD.

Figure 11 shows a corresponding VAD, produce out of the above described PPI scan. Based on the assumption that positive velocities are towards the lidar and negative ones are away from the lidar the wind flows from the south-west to the north-east.

To observe what happens in the vertical plane above the lidar a 180 degree RHI by the QinetiQ lidar is very useful. The intensity RHI for example, which is displayed in Figure 12, shows a clear layer, which could be the top of the boundary layer or clouds. The velocity RHI (Figure 13) at the same time shows also a clear signature at this layer's position.
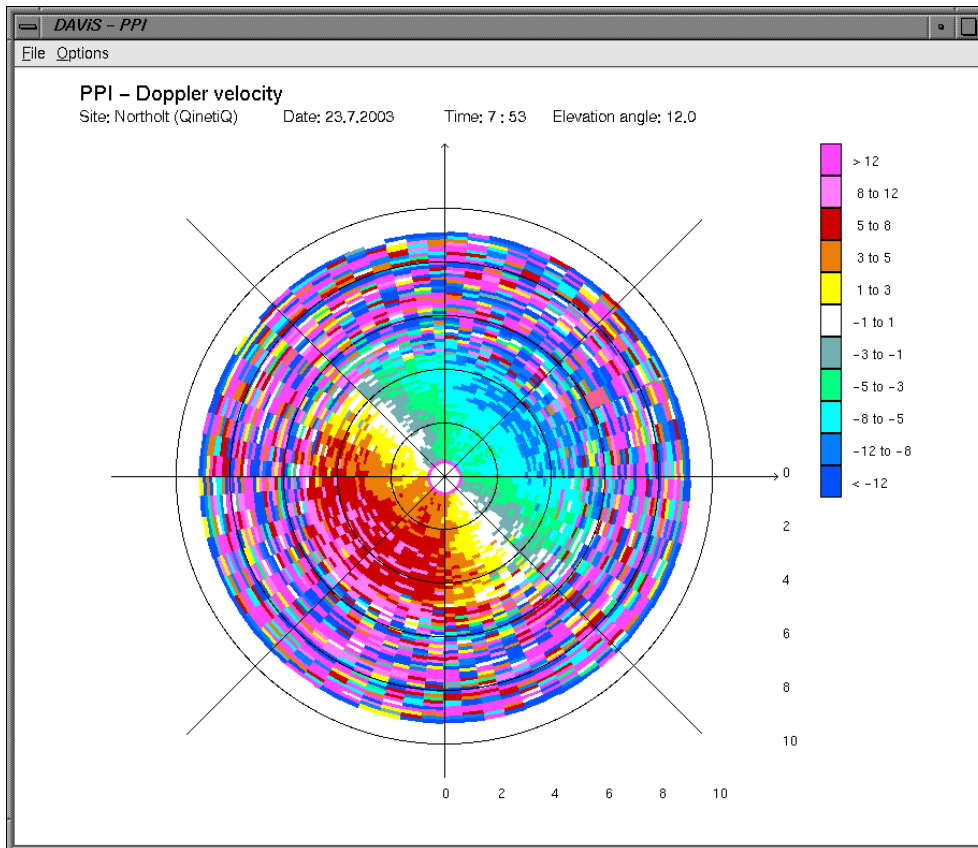
Figure 10: PPI of Doppler velocity recorded by the QinetiQ lidar on the 23th July at 7:53.
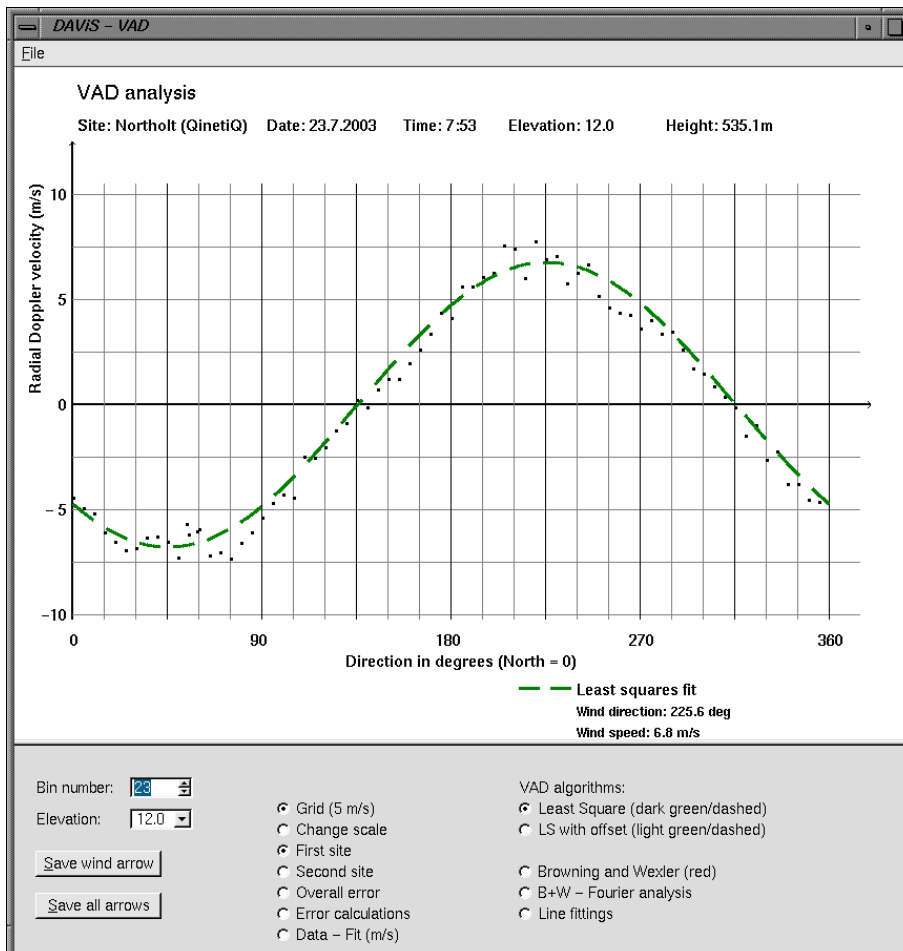

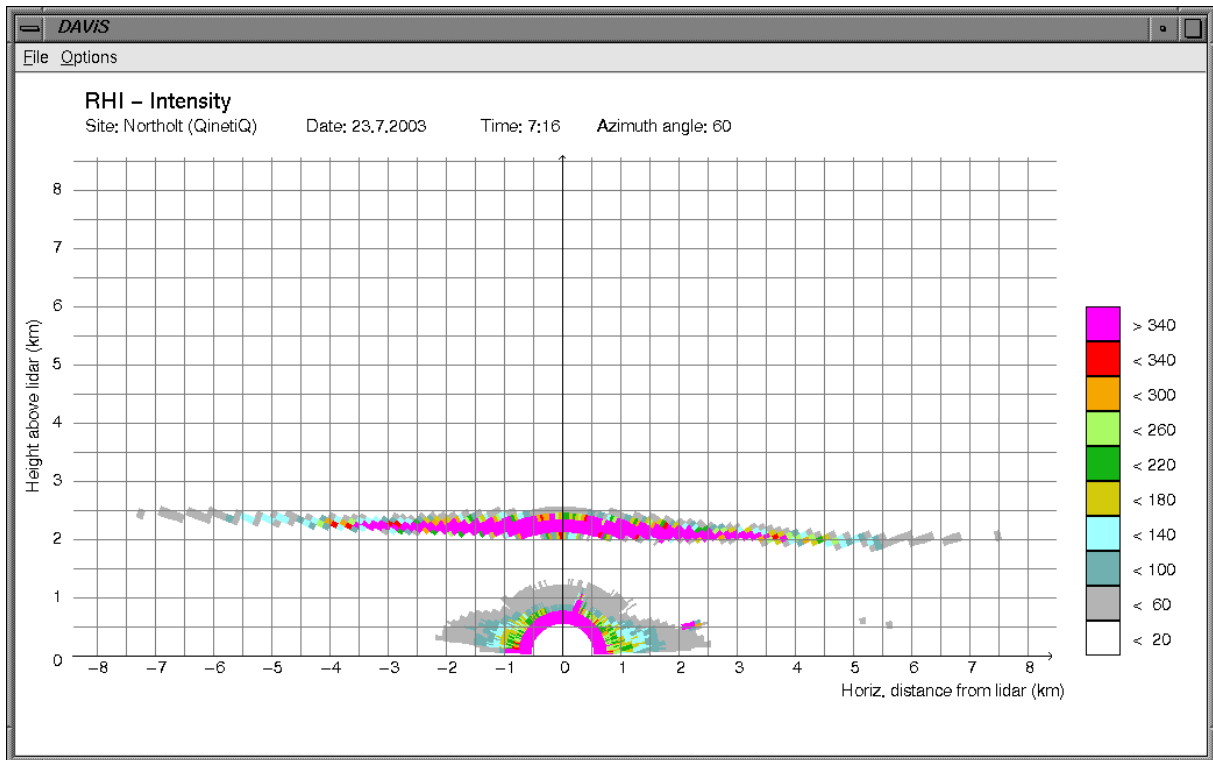Figure 11: VAD analysis of PPI data shown in figure 10.

Figure 12: Intensity RHI plot recorded by the QinetiQ lidar on the 23rd July at Northolt. A layer can be clearly seen.
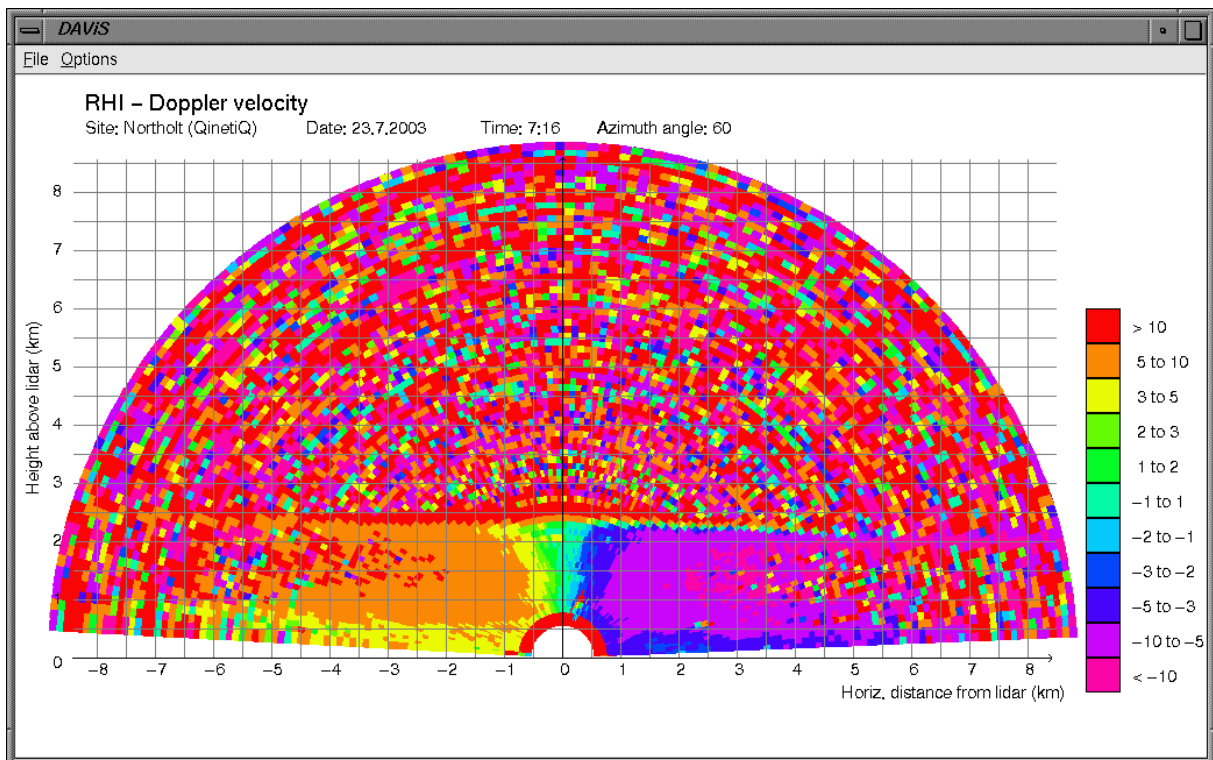

Figure 13: Radial velocity RHI of the same scan as in Fig. 10.

VAD analysis

One common method to retrieve wind information from single PPI (lidar or radar) measurements is the VAD display or method. In a VAD the radial velocities are plotted depending on the azimuth in which they are recorded. For a uniform wind flow this display should result in a sine curve, in which the maximum is related to the horizontal wind speed and the location of the maximum in azimuth gives the direction in which the horizontal wind is flowing.

Figure 13 shows an example of a VAD plot measured during the winter trials in Malvern on the 18th of March 2003. Two fits are shown. The first dark green fit is a standard least squares fit of a sine curve. This curve does not fit very well, because the radial velocity data has apparently an offset. That is why the second least squares fit, shown in light green and smaller dashes, of a sine with offset fits the VAD much better.

Figure 14: DAViS's window to display and analyse a VAD. The data shown was measured during the winter trial in Malvern on the 18th March.

Analysis of LOS data in the vertical plane

If the two lidars measure along the vertical plane which passes through the sites of the lidars, then the horizontal wind component along the plane and the vertical velocity component can, in principle, be determined using analysis derived during the project.

Figure 15 and 16 show two examples of the LOS plane analysis. Both cases were recorded during the summer trail in Northolt on the 23rd of July. On this day two series of scans were taken at which the lidar beams were directed towards each other at the same elevations. This meant that the beams intersected in the middle between the lidars.

The first case, shown in figure 15, was recorded at 17:02 and the elevation angle was 42 degrees at both lidars. That meant that the point of intersection of the beams was at about 711 metres height. On the left side the radial velocity of each lidar in bin 9 is plotted over the 10 minutes duration of the scan. On the right side the calculated vertical velocity and the horizontal wind component along the plane are plotted. Both are again plotted over the 10 minutes duration. Both calculated variables show consistency.

The second case, shown in figure 16, was recorded 24 minutes later at 17:26 with elevation angles of 14.2 degrees. This resulted at height of 206 metres in which the lidar rays intersected. While the horizontal component along the plane is still consistent, the vertical component has become noisy. This results from the lower elevation angle at which the measurements were taken. At low elevation angles the equations becomes ill-conditioned.
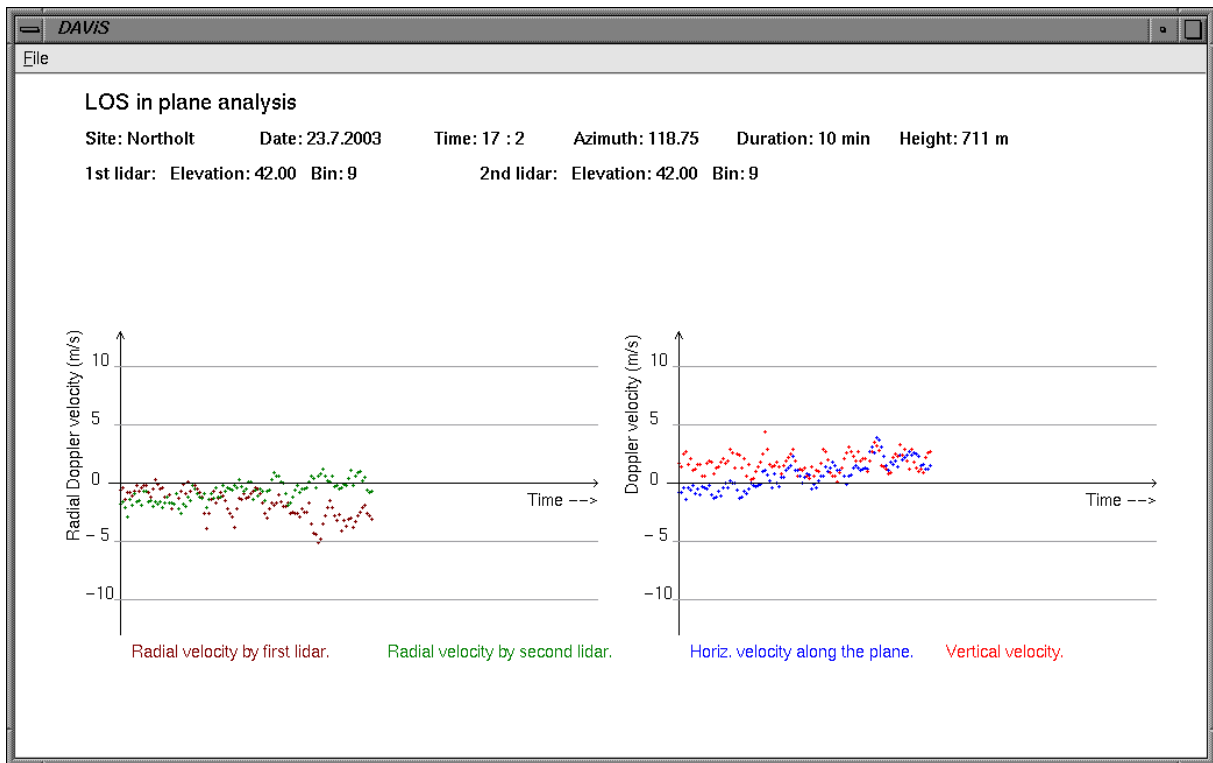
Figure 15: Result of the LOS analysis in the vertical plane at the summer trial in Northolt on data measured at 17:02 on the 23rd of July 2003 at a height of 711 metres.
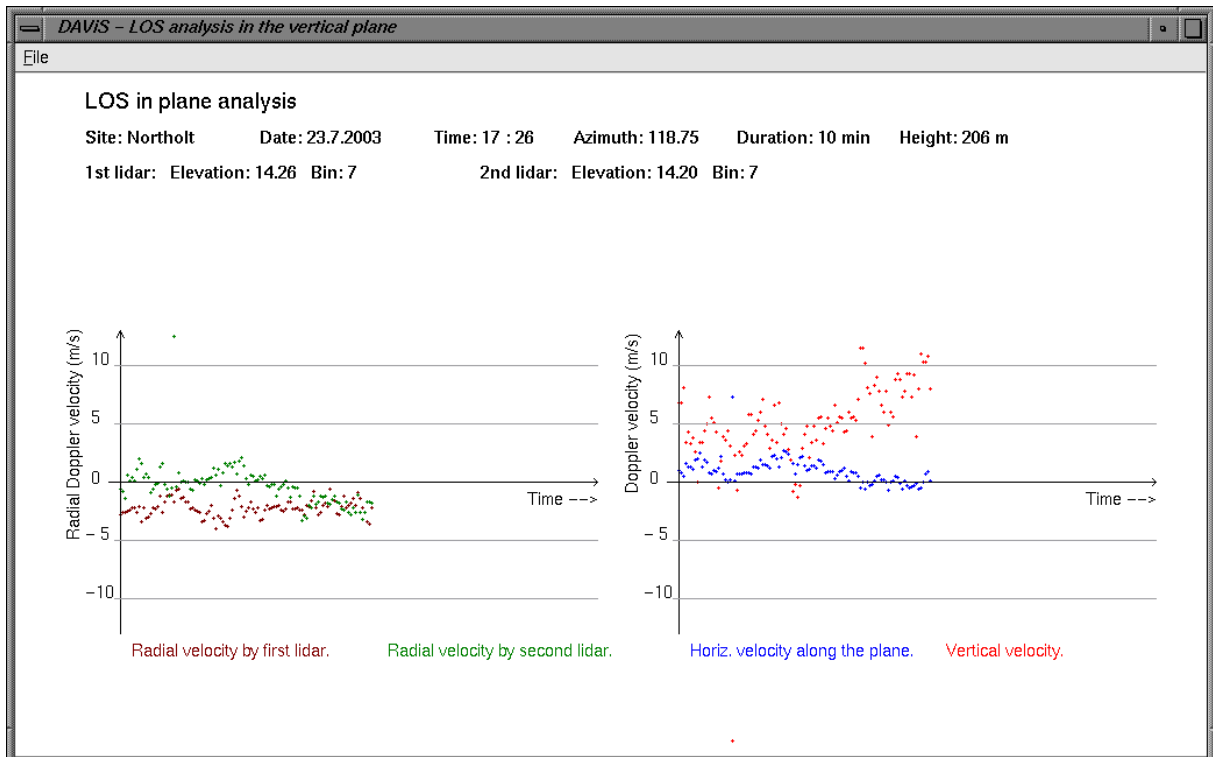

Figure 16: Result of the LOS analysis in the vertical plane at the summer trial in Northolt on data measured at 17:26 on the 23rd of July 2003 at a height of 206 metres.

3D visualisation

One of the strengths of DAViS is the three-dimensional display of data. Unfortunately it is quite difficult to present results of three-dimensional displays on flat paper or on a monitor screen. Two techniques can help to let the user see the data in 3D: movement of the scene and stereo graphics. Both techniques are implemented in DAViS.

In the following examplesvarious combinations of lidar scans are visualised to show the visualisation ability of DAViS.

QinetiQ PPI + Salford PPI

The first example (figure 17) shows two PPI measurements measured by both lidars. In the figure the observer views the scene from north to south and the full cone in the front belongs to the measurement of the QinetiQ lidar. The cone, on the right, which lacks 65 degrees in azimuth, belongs to the Salford lidar.

Both PPIs were recorded at low elevations (QinetiQ lidar: 12.0^o ; Salford lidar: 17.1^o). That is why the top of the boundary layer is not visible and the scene looks shallow. This case, however, shows how both lidars agree in the measured data, with the positive velocities (yellow and red) on the right (west) and the negative velocities (green and blue) on the left (east).

Salford RHI + Salford RHI

On the 21th of July at 14:06 and 14:38 the Salford lidar measured two RHIs in different directions. Figure 18 shows a snapshot of the resulting display.

QinetiQ RHI + Salford PPI

The second example shows an RHI, measured by the QinetiQ lidar, and a PPI, measured by the Salford lidar, combined in 3D. The data was measured at the summer trial in Northolt on the 23rd of July at 11:17.

Figure 19 shows the radial velocity data measured by both lidars. Comparison of both scans indicates, as in the last case, the velocity values agree very well with each other. Especially from the intensity display of the scan (shown in figure 20), it can also be seen, that the PPI elevation angle is too low to intersect with the top of the boundary layer which is visible in the RHI.

The RHI seems to suggest that there is a change in the top of the boundary layer. While in the west direction (left side in figure 19), there appear to be two layers high above some noise, the height of the top of the boundary in the east (in the right of the RHI in figure 19) seems to be a constant as expected.
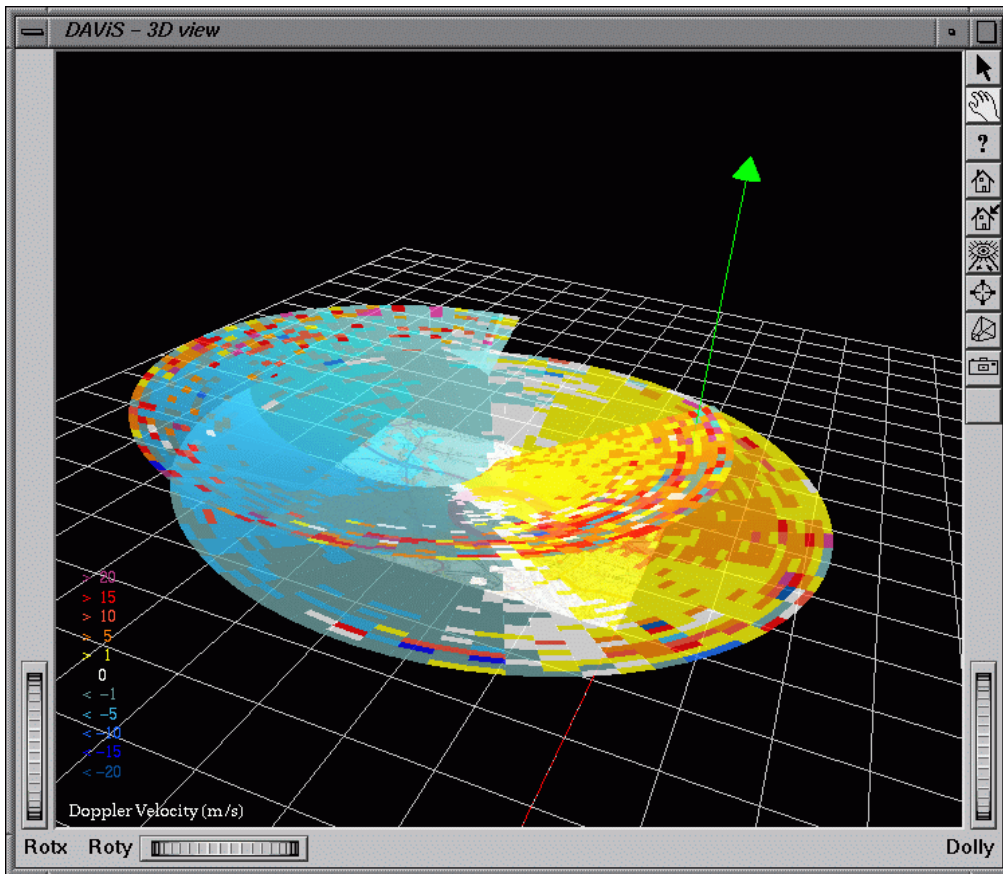
Figure 17: A 3D display of radial velocity measurements of by the QinetiQ lidar and by the Salford lidar at Northolt on the 23rd of July at 18:23.
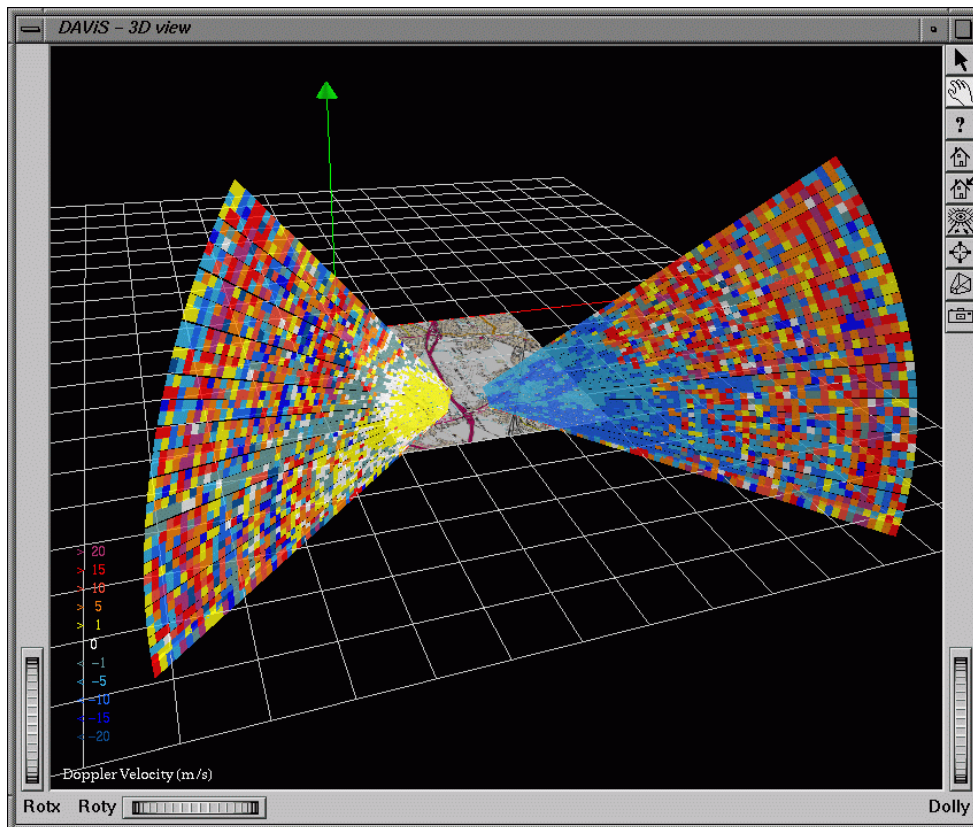

Figure 18: Two velocity RHI scans by the Salford lidar combined. The data was measured at 14:06 and 14:38 on the 21th of July.
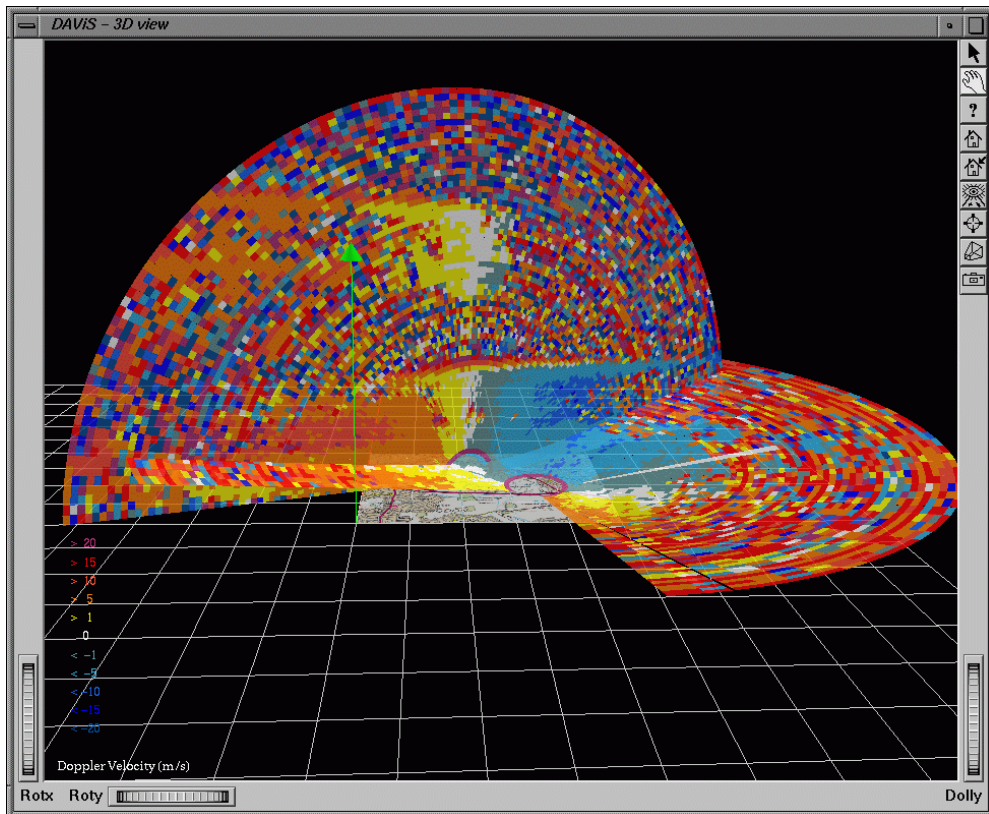
Figure 19: A 3D display of radial velocity measurements of by the QinetiQ lidar (RHI) and by the Salford lidar (PPI) at Northolt on the 23rd of July at 11:17.
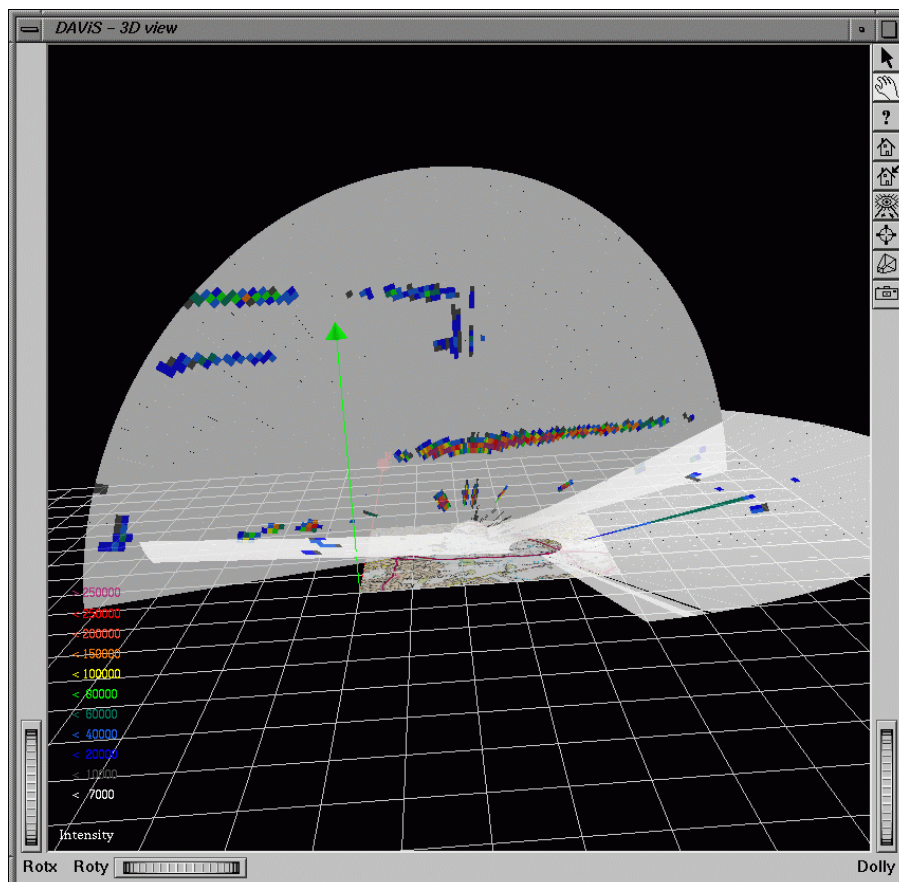

Figure 20: A 3D display of range-corrected intensity measurements of the QinetiQ lidar (RHI) and the Salford lidar (PPI) at Northolt on the 23rd of July at 11:17.

QinetiQ RHI + QinetiQ RHI

The ability of the QinetiQ lidar to measure RHI over a full 180° elevation is presented in the following case in which two RHI plots by the QinetiQ lidar are combined. Both measurements were made on the 22nd July at 17:15 and 17:29 respectively.

The visualisation of the intensity in figure 21 shows how both lidars record the same layer height, except to the south east where the layer seems to collapse in height (see right side of figure 21). The Doppler velocity pictures (figure 22) shows clearly how on one RHI (east-west) the values change from negative (blue, east) to positive (yellow-red, west), while the other RHI (north-south) shows values low in velocity near to zero (white).

QinetiQ RHI + QinetiQ PPI

The example considered, is the PPI at 16:31 and the RHI at 16:47 on the 9th of July recorded by the QinetiQ lidar. The PPI was recorded at an elevation of 40 degrees while the RHI was orientated on the east to west axis.

The high elevation angle of the PPI was rarely used during the experiment, and shows combined with the RHI the boundary layer of the lower atmosphere. The intensity display is shown in figure 23. The height of the boundary layer is not clearly visible from the RHI but is from the PPI, where a circle of higher intensity is clearly visible.

The velocity display in figure 24 shows that the RHI and PPI generally agree in the direction of the velocities.

VAD data + Model output

The main aim of the project is to compare output from forecast models and retrieved information from lidar data to see if the model can be improved.

A good opportunity to compare these types of data was on the 23rd of July around lunch time, where in short period of time (30 minutes) data is available from the model and PPI scans by both lidars.

Figure 25 shows the resulting 3D display viewing from west to east. Three columns of wind vectors can be seen. The two columns of green vectors show the results of VAD analysis on the two PPIs measured by the lidars. The front green column was measured by the QinetiQ lidar while the back column was measured by the Salford lidar. The middle column (red) is retrieved from the model output which was provided by the Met Office.

While the wind information retrieved from the VADs agree quite well with each other, the wind information from the model only agrees with them at heights beyond 1000 metres. Nearer to the ground the model shows a wind flow which differs by about 45 degree in easterly direction.
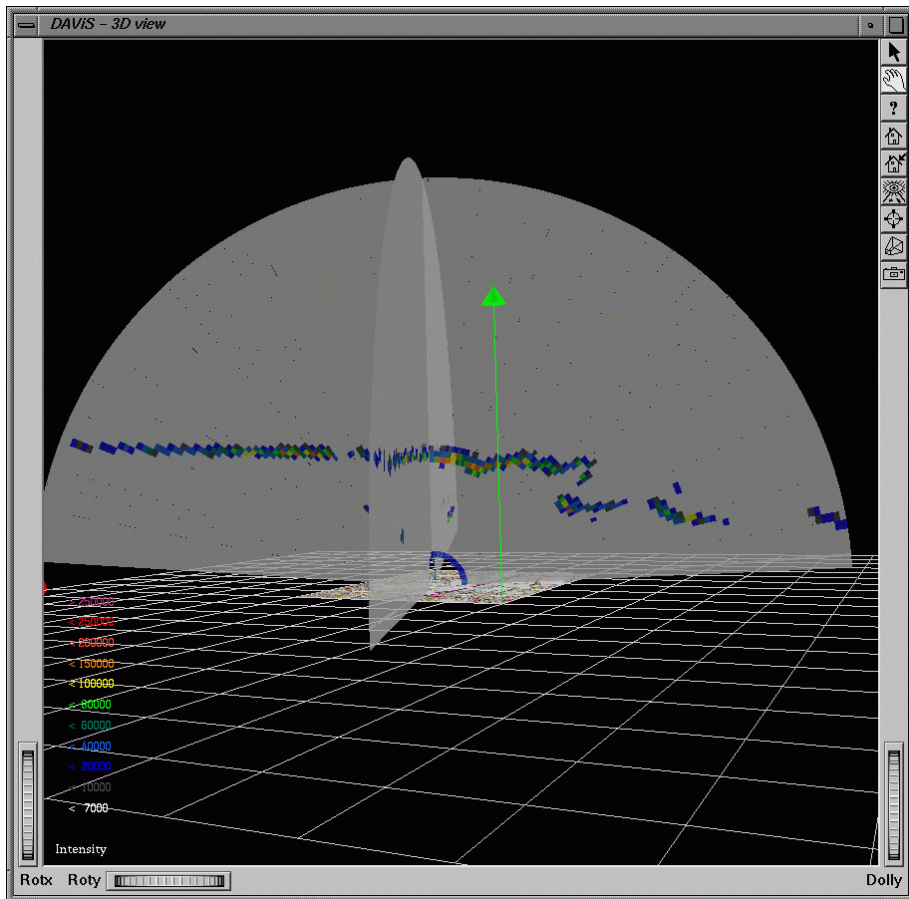
Figure 21: A 3D display of two RHIs, showing range-corrected intensity. This was measured by the QinetiQ lidar at Northolt on the 22rd of July at 17:15 and 17:29.
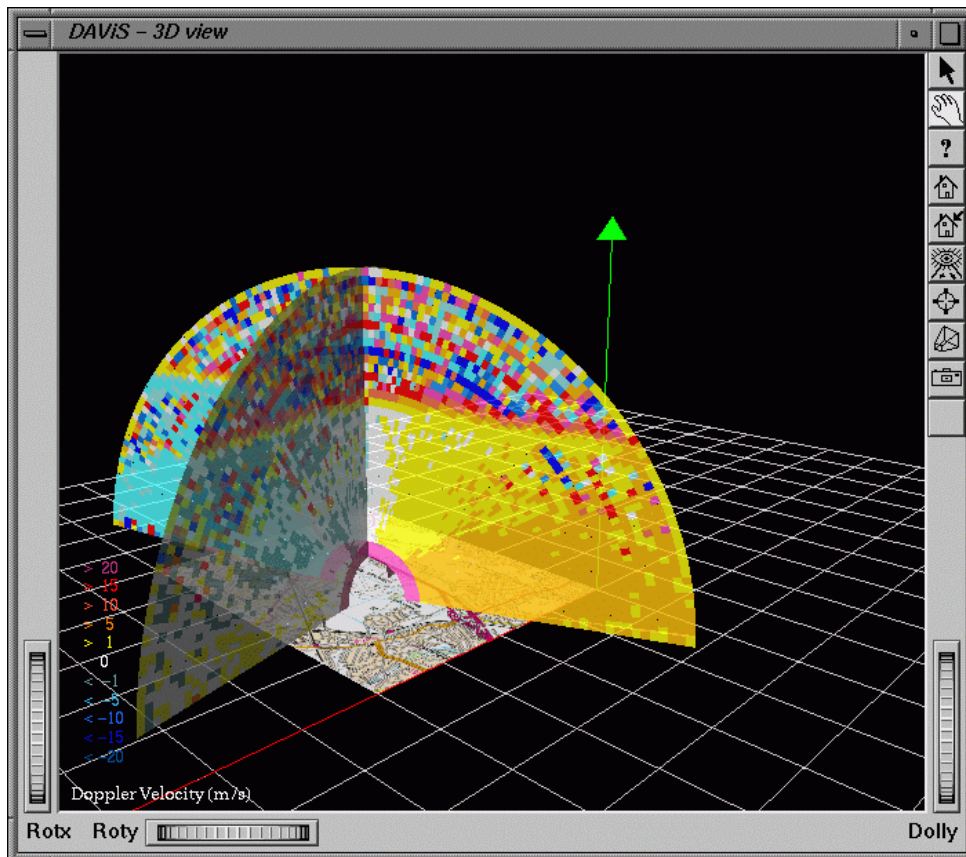

Figure 22: Another plot of two RHIs combined. This is the same data as in figure 19, but this time the radial Doppler velocity.
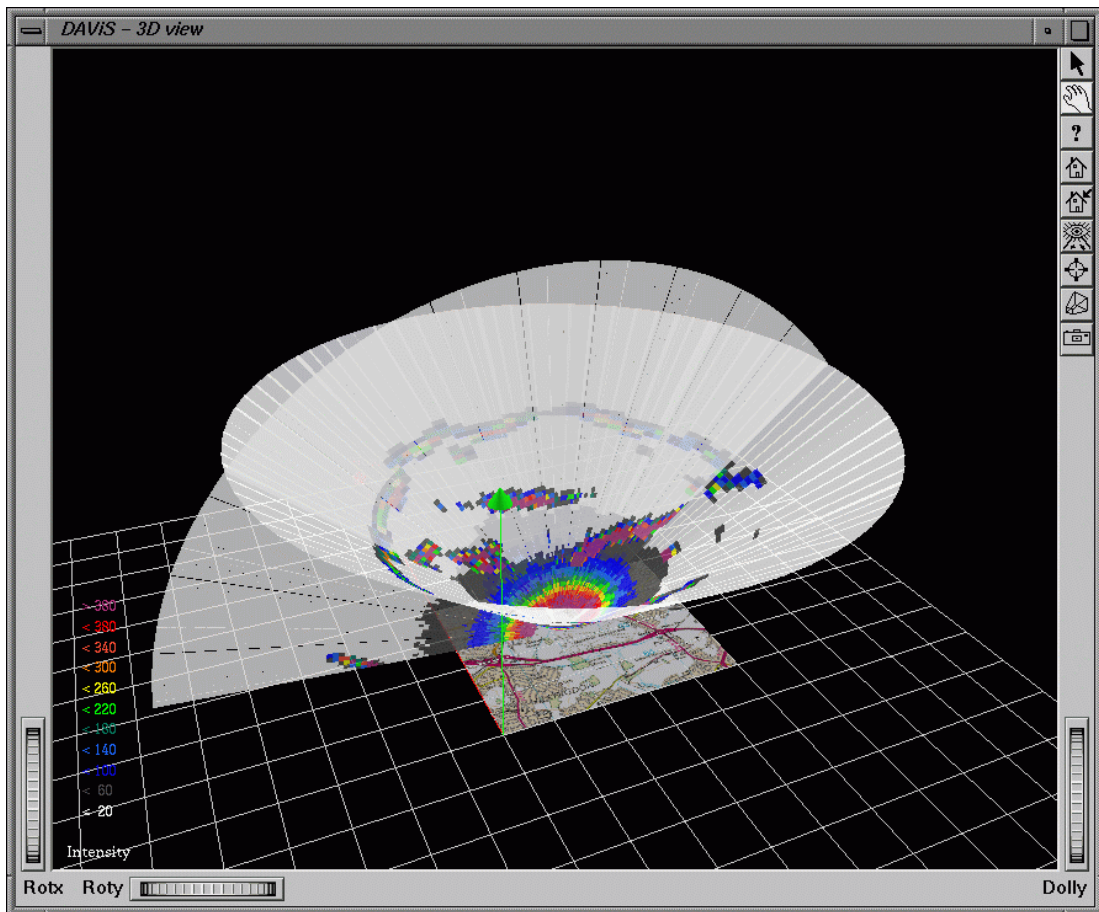
Figure 23: Intensity display of the QinetiQ lidar data measured on the 9th of July
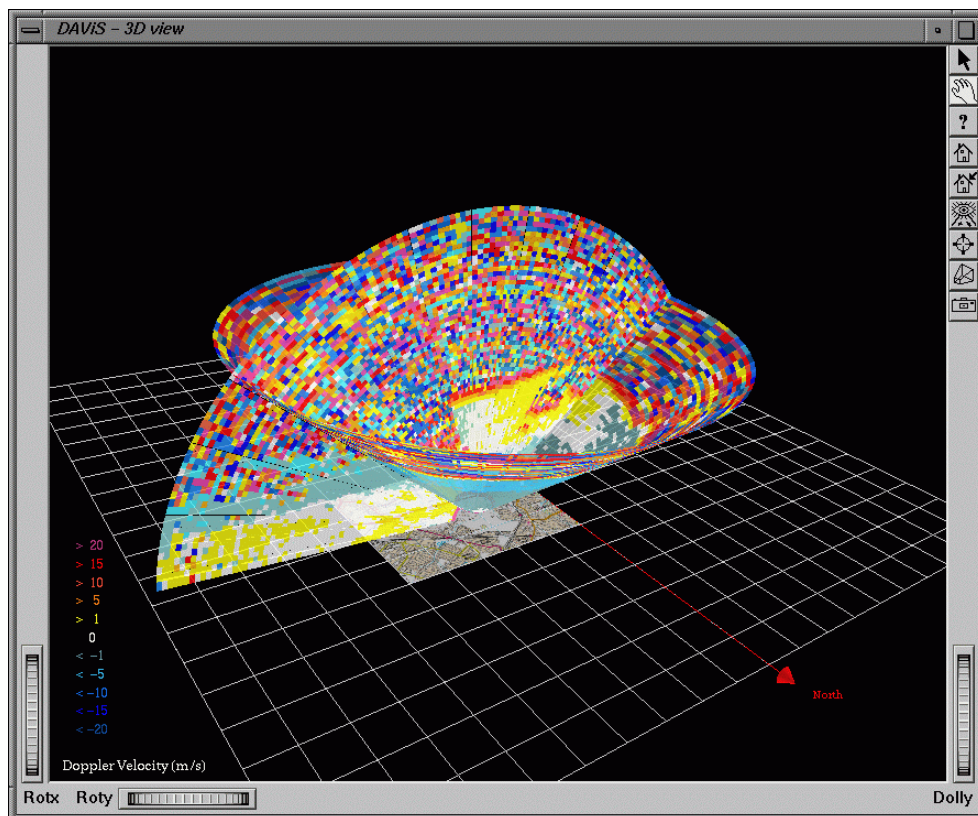at 16:31 (PPI) and at 16:47 (PPI)

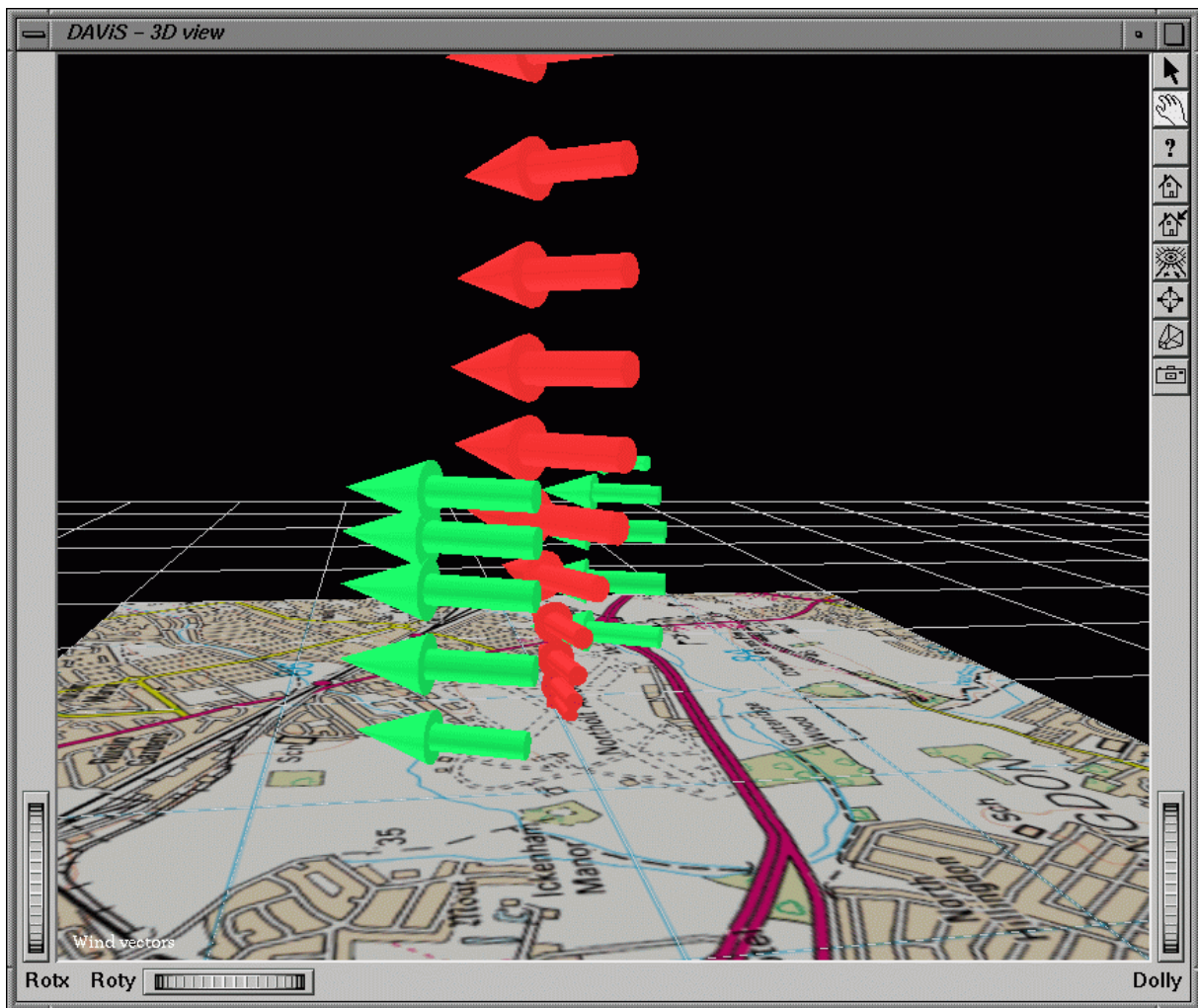Figure 24: Doppler velocity plot of the same case as in Figure 23.

Figure 25: Comparison of wind information retrieved from the model (red) and from lidar data through VADs (green) on the 23rd of July. The front green column is retrieved from data from the QinetiQ lidar (12:25), while the second green (back) column is retrieved from data measured by the Salford lidar (12:28). The model data was extracted on the eve before for 12:00.

6. Summary and further work

The software developed at the University of Essex gives the user various ways to process and visualise the lidar data and retrieved wind information.

More work than expected has gone into the conversion and organisation of the lidar data. This was partially because the data recording process at the two lidars was not fully automated and because changes in the format, in which the data was delivered to Essex, were made during the project.

The DAViS software should be easily ported to Linux to enable it to be distributed more widely. This is now possible due to the technical development of graphics hardware on PCs. We have successfully ported it to SuSE Linux on one of our PCs, but it may well not port to other versions without development.

Conclusions of the visualisation work

The work undertaken by the University of Essex group has brought these conclusions:

- If the data were recorded automatically the display and analysis of lidar data can be done in real-time.

- A three-dimensional display can give vital information to the observer how data from the two lidars relate to each other in space.

- Retrieved wind information can be also easily added to a three-dimensional display.

- Stereo graphics can improve the visual impact to the user. It enables the user to obtain a clearer picture of the scene.

- The visualisation and analysis can be combined in one software package, which, combined with a fixed common data format, makes it easy to reproduce and compare results.

- The scan strategies most interesting for the visualisation are 180 degree RHIs and PPIs at higher elevation angles. These show best the structure of the boundary layer.

Possible (future) improvements

Although the software currently fulfils all contract requirements, there is a list of features which could be added in the future:

- For a long-time measuring campaign, a 3D-profile of the terrain can be added to the 3D display to make comparison to measured and retrieved information to the ground.

- A flexible colour table could help to highlight changes in the velocity pattern more easily.

7. REFERENCES

[1] Description of the RAF Northolt ISB-52 Dual Doppler Lidar Trial. RI Young, GN Pearson, C Collier, F Davies & K Bozier. ISB52-07 August 2003

[2] The Determination of Kinematic Properties of a Wind Field using Doppler Radar. Browning and Wexler, Journal of Applied Meteorology, Vol. 7, 105-113pp, 1968

[3] Boundary Layer Measurements of Dispersion Model Parameters using Dual Doppler Lidar at Malvern, UK. F Davies, C Collier, A Holt, D Middleton, G Pearson, S Siemen, DV Willetts & RI Young. ISB52 -06 July 2003

8. ACKNOWLEDGEMENTS

9. DISCLAIMER

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