Improved Air Quality Forecasting
Invest to Save Report ISB52-05

Description of the first ISB-52 Dual Doppler Lidar Trial.

By

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Executive Summary ISB-52-05

This report ISB52-05 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 first time that separate lidars have been deployed with the intention to subsequently combine their observations to give an accurate description of the dynamics of wind flow was in early 2003. This was the first of the ISB-52 trials and it occurred local to the Malvern area. This report describes that trial and the data subsequently released for further analysis.

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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. In support of this it had been decided that the optimum observation technique is to stare for long periods of time along a relatively low number of pointing angles in preference to trying to cover a large number of points for a short time period. In parallel to defining the experimental technique the 10 μm Pulsed Doppler lidars of Salford University and QinetiQ had been upgraded to a performance level necessary to meet the requirements of the intended ISB-52 observations.

In early 2003 the ISB-52 Project Team where finally ready to deploy their Dual Doppler Lidars. This report describes that work, the first deployment of Dual Doppler Lidar in an experiment where the intention is to combine the lidar data to fully resolve the wind flow field.

Section 2 gives details of the trial. In section 3 a description of the trial data released for analysis is made. Section 4 presents preliminary results from the data analysis.

2 DESCRIPTION OF THE TRIAL.

The trial local to Malvern was initially undertaken as a preliminary to full deployment in West London for the first formal ISB-52 trial: the 'winter' trial. The intention was to test the Dual Lidar systems and refine the associated experimental technique prior to deploying to RAF Northolt. However as world events unfolded the ability to deploy to an operational RAF airbase came into doubt. Therefore an alternative location to RAF Northolt was required. Given the short notice it was decided that the winter phase trial would be continued local to Malvern.

The first phase of the trial had the two lidars co-located at QinetiQ Malvern. This was to enable a direct comparison of lidar data. The QinetiQ site is approximately 1.5 km to the east of the ridge of the Malvern hills. The Malvern hills are a ridge of hills approximately 13 km long orientated in the north - south direction and approximately 300 - 360 m above the surrounding terrain (425 m above mean sea level).

The second phase of the trial deployed the two lidars along an extended baseline. The second site used was the Three Counties Showground, which was approximately 3 km 9° east of south of the QinetiQ site. This second site was therefore also approximately 1.5 km east of the Malvern hill ridge. The crest of the hill at this latitude is approximately 250 - 280 m above the surrounding terrain.

The trial geometry is shown in figure 2.1. The QinetiQ lidar was located in a car park at the northern edge of the QinetiQ site. The Salford lidar was deployed in the southern car park of the Three Counties Showground. Further details of these locations are given in Table 1.1 The QinetiQ team were located at ten figure grid reference SO 78472 45036, the Salford team at SO 78925 42112, and the intersections of the beams were roughly over SO 800426 (six fig reference). Two other provisional sites where prepared but in the event not used because the ambient winds where always from the East for which the QinetiQ to Three Counties baseline was optimum.

Site Name	Location		Deployment
QinetiQ Car Park	45 1 N	78 5 W	Yes (QinetiQ Lidar)
3 Counties Car Park	42 1 N	78 9 W	Yes (Salford Lidar)
Hall Green	45 5 N	80 6 W	Not used
Malvern Common	44 3 N	77 8 W	Not used

Table 1.1 Lidar position information.

One advantage of operating local to Malvern was that it allowed the lidars to be deployed along an extended baseline of almost 3000 m. At RAF Northolt the baseline would be closer to 1800 m.

The key period for the observations was between the 13th and 19th of March 2003. As the trial progressed, the experimental technique improved and so the data released for subsequent analysis comes from the afternoons and early evenings of the 18th and 19th of March.

The weather throughout this period was typical winter anticyclonic conditions. A high pressure system was situated over central England and slight easterly winds were found at the trial site. These turned to be south easterlies during the last day of the trial. During the mornings of the trial there was persistent mist and visibility was quite low (~ 5 km). On certain days of the trial this mist did not clear at all and temperatures remained low throughout the day (8º-9ºC). On the other days the mist cleared and the afternoons were sunny and fairly warm (14º - 15ºC). Figure 2.2 and 2.3 detail Met Office synoptic charts for Western Europe at midnight for the 18th and 19th April 2003.

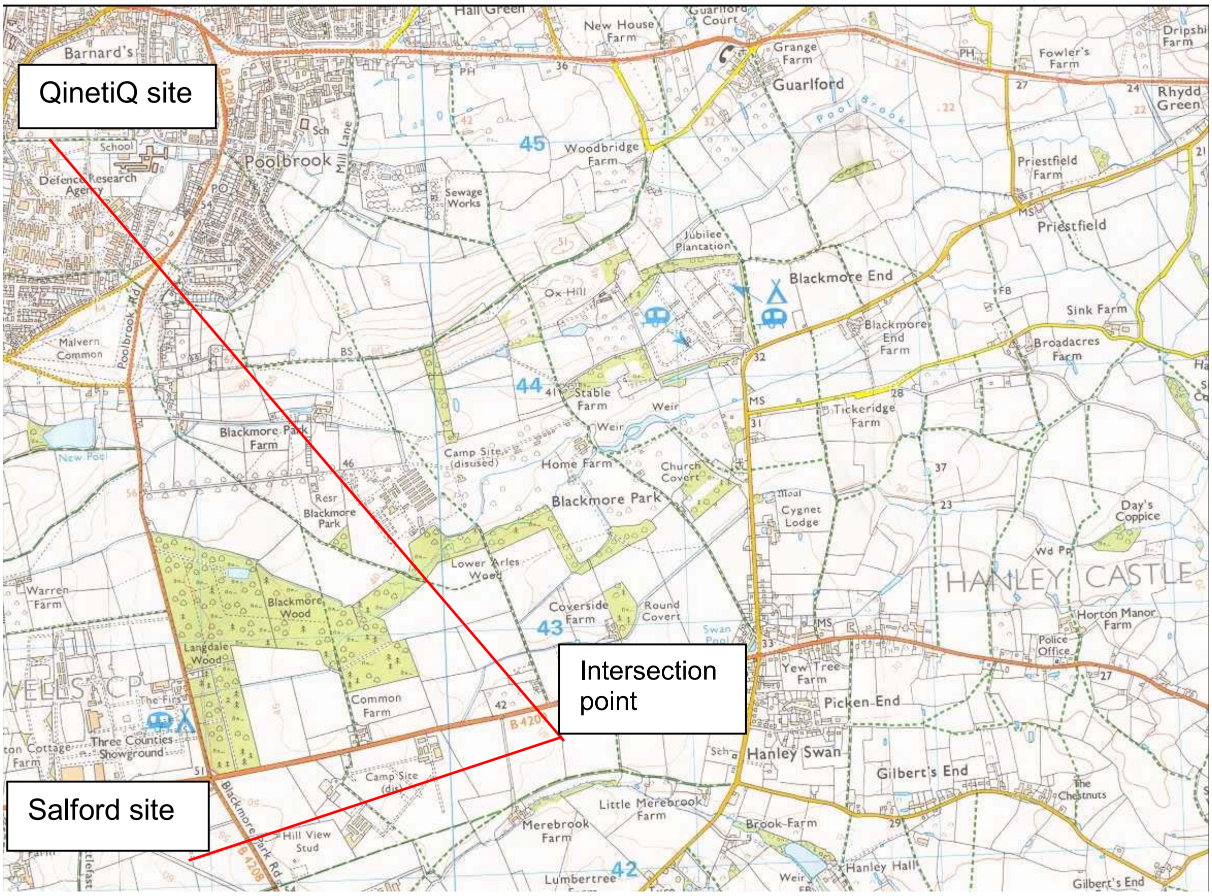

Figure 2.1 Map illustrating the trial geometry.

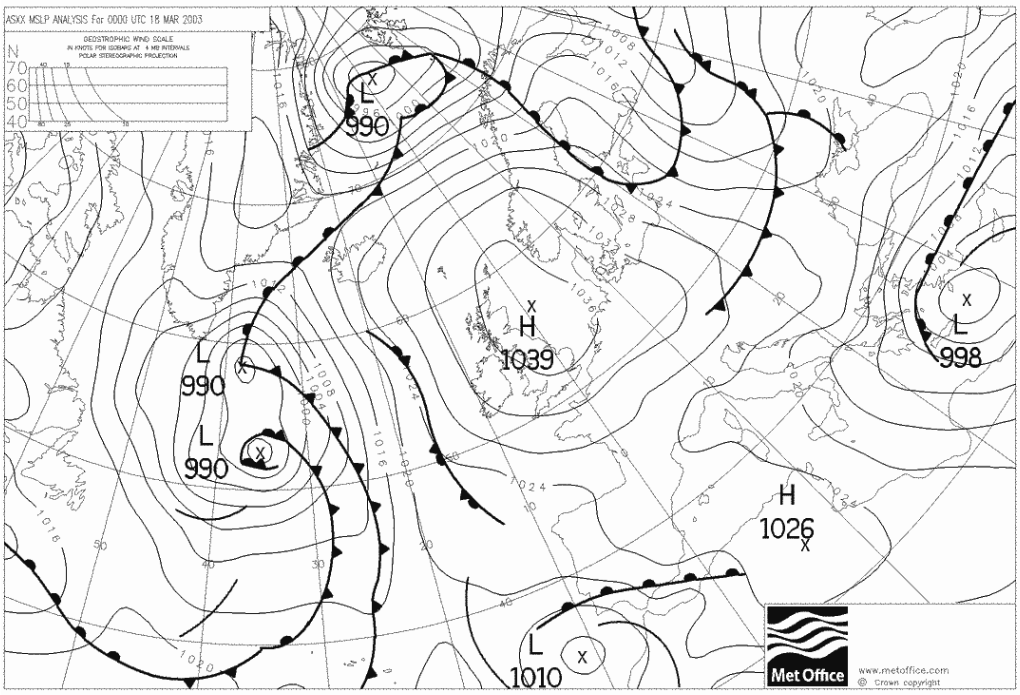

Figure 2.2 Synoptic chart for midnight 18th March 2003

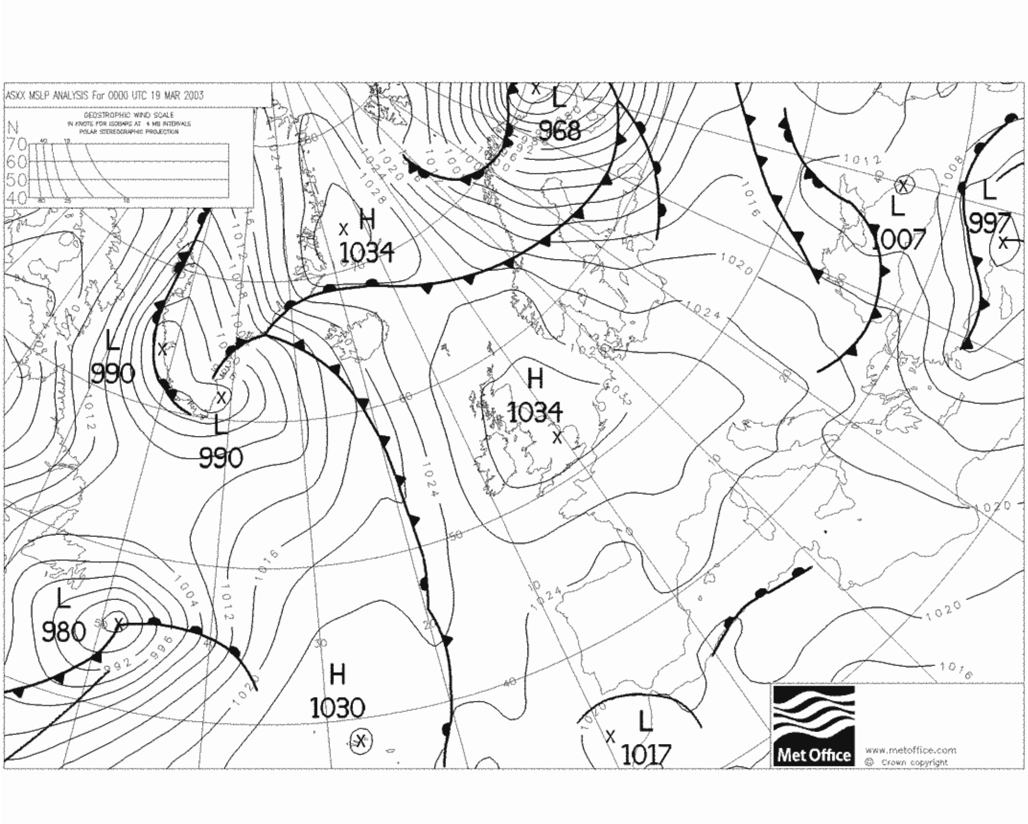

Figure 2.3 Synoptic chart for midnight 19th March 2003

The general trial scheme was for both lidars to calibrate their alignment using local land marks after the vehicles had been levelled. For calibration of bearing and elevation angles it was found convenient to use the steeples of local churches, Christ Church Malvern for the QinetiQ lidar and St Mary's Church, Hanley Swan for the Salford lidar. All data was time stamped from a GPS signal.

Once the lidar systems were calibrated a VAD was undertaken to determine the predominant wind direction. (The VAD data is also useful for comparing the results from the two lidars). Once the wind direction was identified the lidar beams were orientated to intersect over a chosen point and allowed to dwell there for a period of time. Data was typically collected in the order of between 10 and 20 minutes duration along any given line of sight. This approach corresponds to part of scan pattern 1 in reference 2. This scan pattern crosses the beams to gather unambiguous horizontal flow data at a given column. A small number of elevations were chosen with the lower limit of elevation being dictated by local buildings on the QinetiQ site and the upper limit to ensure the beams crossed at an altitude below the top of the planetary boundary layer. Figure 2.1 illustrates a typical arrangement for crossing the beams projected onto the plane of the map.

The lidars were operated in a real time data processing mode. This allowed the operator the ability to continually check that the lidar performance was satisfactory during a data collection phase. The QinetiQ lidar sampling rate was of the order of 0.2 Hz, the Salford system was 0.12 Hz. Range gates were of 112 m length unless otherwise noted.

That this trial did not measure the environment around a rural to urban interface is unfortunate. Nevertheless these results give considerable scientific merit. This includes the first use of dual Doppler lidar in this manner, extensive monitoring of the planetary boundary layer as it evolved around sunset and the provision of adequate data to demonstrate both proof of concept and be used for comparison with air quality forecasts.

3 KEY RESULTS SUBMITTED FOR FURTHER ANALYSIS.

The key data products that will be released for subsequent analysis are files containing the results of lidar observations. Tables 3.1 and 3.2 summarise the data files released, give details of the scans used and when the file was recorded. Where necessary additional information has been added as appropriate.

Table 3.1 summarises the released QinetiQ data and Table 3.2 the released Salford data. Table 3.3 gives details of the locations of where the beams crossed and the accuracy of the beam intersection.

17/03/03 Monday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	**Comments**
VAD002.dpd	16.54	17.1	0-360	25	angl0015.txt	Range gate = 112 m, Scan speed 1°/s
VAD003.dpd	17.13	117.3	0-360	25	angl0016.txt	
VAD004.dpd	17.35	17.55	0-360	25	angl0018.txt	
VAD005.dpt	18.2	18.4	0-360	25	angl0021.txt	224 m range gate used
RHI001.dpd	18.44	18.48	90	0-150	angl0022.txt	Detector blocked when elevation just passed 90°
18/03/03 Tuesday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	
VAD006.dpd	16.02	16.19	0 - 360	25	angl0024.txt	Range gate = 112 m, Scan speed 1°/s
VAD007.dpd	16.22	16.39	0 - 360	25	angl0025.txt	
VAD008.dpd	16.445	16.51	0 - 360	25	angl0026.txt	
Stare01.dpd	17.05	17.24	150	25		
Stare02.dpd	17.29	17.46	150	25		
Stare03.dpd	17.49	17.55	150	25		
Stare04.dpd	17.58	18.11	142.8	12.5		
Stare05.dpd	18.27	18.34	142.8	12.5		
Stare06.dpd	18.36	18.45	142.8	8		
VAD009.dpd	18.50	19.03	0 - 360	25	angl0027.txt	Scan speed 1°/s
19/03/03 Thursday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	**Comments**
VAD010.dpd	18.50	19.03	0 – 360	25	angl0028.txt	
Stare07.dpd	14.00	14.12	141.8	12.47		
Stare08.dpd	14.24	14.36	141.8	12.46		
Stare09.dpd	14.38	14.51	141.8	8		
Stare10.dpd	15.00	15.08	141.8	12.47		

Stare11.dpd	15.16	15.33	141.8	12.47		Continuation button pressed accidentally. First 4 lines of data need to be placed at the end of the file and times adjusted accordingly.
Stare12.dpd	15.41	15.53	153.4	3.85		
Stare13.dpd	16.21	16.27	153.35	3.85		
Stare14.dpd	16.32	16.34	153.35	3.85		

Table 3.1 Summary of QinetiQ lidar data.

13/03/03 Thursday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	**Comments**
los131.dpd	15:48	15:57	167.5	5.1		
vad131.dpd	16:31	16:39	0-295	6	vad131.dat	
vad132.dpd	16:42	16:54	0-296	25	vad132.dat	
los132.dpd	16:57	17:12	180	4.9		
17/03/03 Monday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	**Comments**
mar17los1.dpd	16:26	16:28				moved to el=13 in middle of scan
vad01mar17.dpd	17:06	17:24	0-295	25	vad01mar17.dat	
vad02mar17.dpd	17:26	17:44	0-296	25	vad02mar17.dat	
mar17los2.dpd	17:55	17:57				
vad03mar17.dpd	18:19	18:37	0-298	25	vad03mar17.dat	
vad04mar17.dpd	18:40	18:55	0-299	25	vad04mar17.dat	
18/03/03 Tuesday						
Data File	**Start Time**	**Finish Time**	**Az**	**El**	**Angle File**	**Comments**
vad181.dpd	16:33	16:44	0-295	25	vad181.dat	
los181.dpd	17:00	17:21	92.5	25		
rhi181.dpd	17:26	17:33	92.5	1.9-42	rhi181.dat	
rhi182.dpd	17:38	17:45	272.7	Feb-42	rhi182.dat	
los182.dpd	18:04	18:24				
los183.dpd	18:26	18:32	92.5	25		
los184.dpd	18:36	18:42	92.5	15.5		
vad182.dpd	18:50	19:05	0-295	25	vad182.dat	
19/03/03 Wed						
Data File	**Start**	**Finish**	**Az**	**El**	**Angle File**	**Comments**

	Time	Time				
vad191.dpd	13:33	13:52	0-295	8.9	vad191.dat	
los191.dpd	14:00	14:20	94.3	25.1		
los192.dpd	14:20	14:31	94.3	25.1		
los193.dpd	14:38	14:58	94.3	15.7		
los194.dpd	15:00	15:20	94.3	25		
los195.dpd	15:23	15:33	94.3	25		
los196.dpd	15:40	16:00	156.5	4.3		
vad192.dpd	16:04	16:16	0-295	7.7	vad192.dat	Actual run time 16.04-16.14 as scanner jammed
los197.dpd	16:20	16:41	156.5	4.3		
vad193.dpd	16:42	17:02	0-290	7	vad193.dat	
vad194.dpd	17:03	17:21	0-290	17.1	vad194.dat	
err191.dpd	17:23	17:31	94.3	3		Ints=200, Int runs=20
err192.dpd	17:31	17:36	94.3	3		Ints=1, Int runs=400
err193.dpd	17:37	17:43	94.3	3		Ints=10, Int runs=200

Table 3.2 Summary of Salford University lidar data.

In Table 3.3 sight line bearings are degrees from Grid North. Figure 3.1 shows the co-ordinate system between the two lidar stations and hence the geometry for resolving the vector analysis. The lengths to the intersection points from the Salford Lidar, L1, and from the QinetiQ lidar, L2, are ranges projected onto the ground. Height implies height above sea level. The final column in Table 3.3 gives the difference in heights between the centre of the two range gates at the point of intersection. In reference 1 it was argued that the turbulence relevant to pollution dispersal mechanisms should be isotropic over a scale of 112 m, therefore provided the twin lidar beams are not separated by a difference greater than about 112 m the beams will effectively be measuring the same phenomenon.

It should be noted that small errors in the azimuth will cause the location of intersection between the two lidar beams to move a little but do not influence the ranges greatly. Elevations are more critical in altering heights. This explains most of the height disparities.

Serial	Malvern lidar sight line				Salford lidar sight line				Difference in heights m
	Bearing from degrees grid north	L2 m	Elevation (degrees)	Height (above sea level, m)	Bearing from grid north	L1 m	Elevation (degrees)	Height (above sea level, m)	
01 to 03	148.3	3054	25	1489	74.2	1192	23.8	584	905
04 to 05	141.1	3194	13.5	832	74.2	1608.5	23.8	767	65
06	141.1	3194	8	514	74.2	1608.5	14.2	465	49
07 to 08	140.1	3161	12.5	766	72.4	1647	23.8	784	-18
09	140.1	3161	8	509	72.4	1647	14.5	484	25
10 to 11	140.1	3161	12.5	766	72.4	1647	23.8	784	-18
12 to 13	151.6	1552	3.7	167	10.2	1583	3.1	144	23

Table 3.3 Evaluation of the lidar beam crossing points.

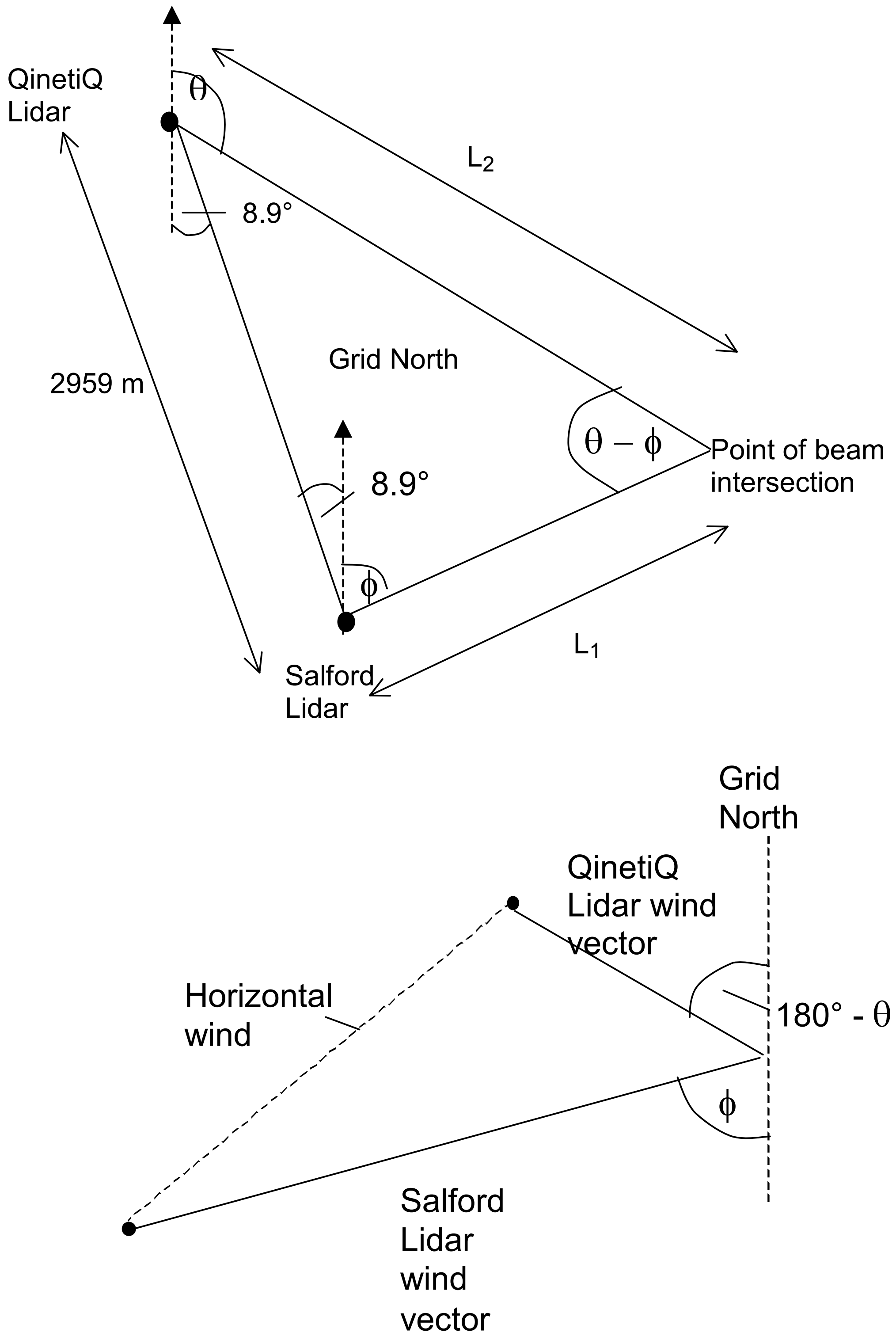

Figure 3.1 Geometry for vector analysis

4 PRELIMINARY DATA ANALYSIS
4.1 INITIAL SYSTEM ASSESSMENT.

With the two systems co-located at the QinetiQ site, an initial assessment of the performance of the two systems was carried out. During the day of the 17/03/03 data was taken simultaneously using the two lidar systems. The following figures 4.1 and 4.2 show PPI scans (azimuth scans), at an elevation angle of 23.8º, from the two systems taken at approximately the same time. The two figures show winds coming from the east-north-east direction with a magnitude of approximately 4 -5 ms^{-1}. The Salford (figure 4.1) shows a distinct cut off at range gate 18 (height = 814 m). This is a clear signature of the top of the boundary layer, since aerosol particles tend, in high atmospheric pressure situations, to be trapped within the boundary layer. Air above the top of the boundary layer gives very little return intensity. Figure 4.2 shows the data from the QinetiQ lidar. The QinetiQ lidar shows a similar signature of the wind below the top of the boundary layer, but above the top of the boundary layer (range gate 18), good velocity estimates can clearly be seen.

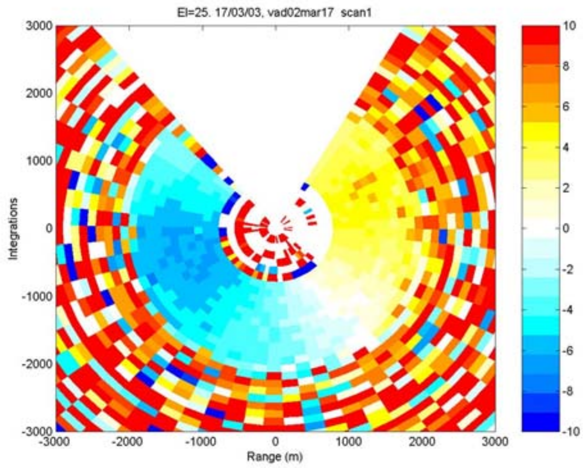

Figure 4.1: Salford lidar scan

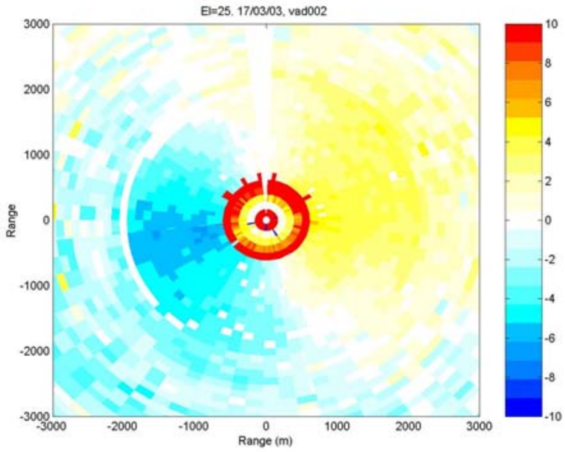

Figure 4.2: QinetiQ lidar scan

The difference in sensitivity between the two lidar scans is mainly attributed to the accuracy of alignment of optics internal to the lidar head and the quality of the surface of the external beam steering optics is also influential.

A comparison of the signal intensity for the two systems shown in figure 4.3 shows a distinct drop in the signal backscatter intensity at range gate 18.

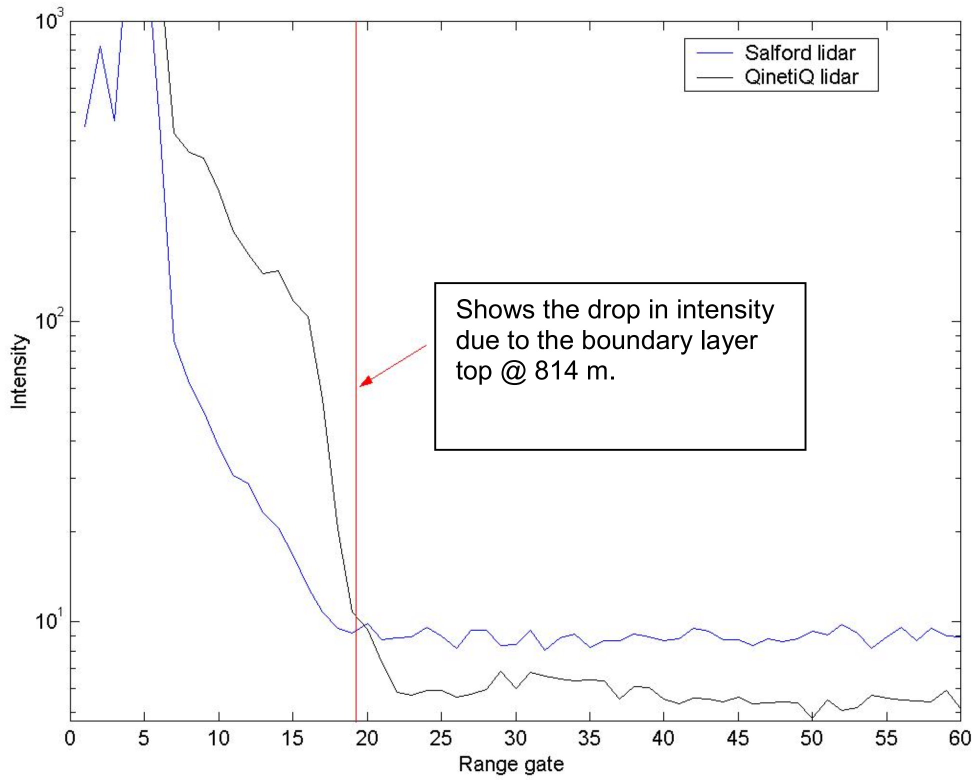

Figure 4.3 Graph comparing fall in intensity of received signal as a function of range for the two lidar systems.

During the afternoon / early evening the wind speed at the surface increased from roughly 5 ms^{-1} to 6.5 ms^{-1}. The figures 4.4 and 4.5 show the maximum wind speeds obtained from the PPI scans shown above. For this initial assessment the data are shown for the time periods that the data files were compiled. As such, although the data times for the Salford and QinetiQ system overlap the actual times and duration are not exactly the same for the two sets of data.

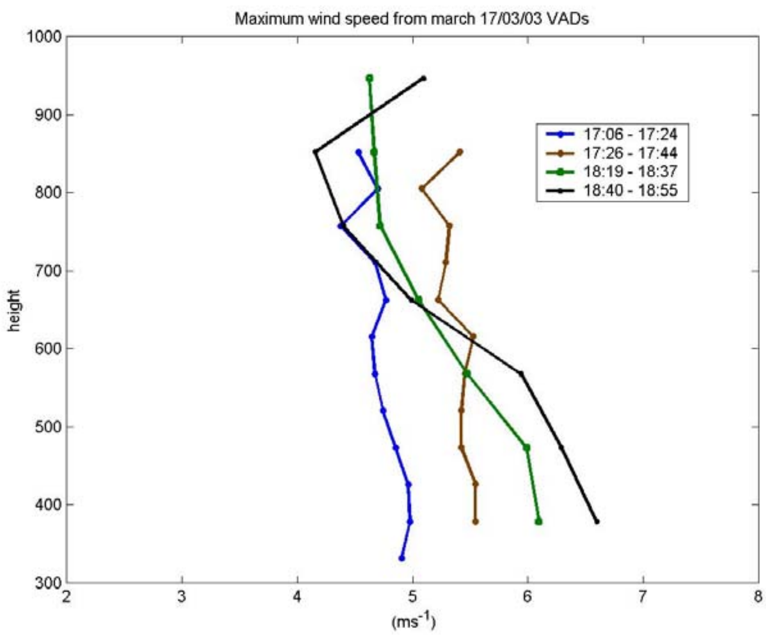

Figure 4.4: Salford lidar wind speeds derived from PPI scans

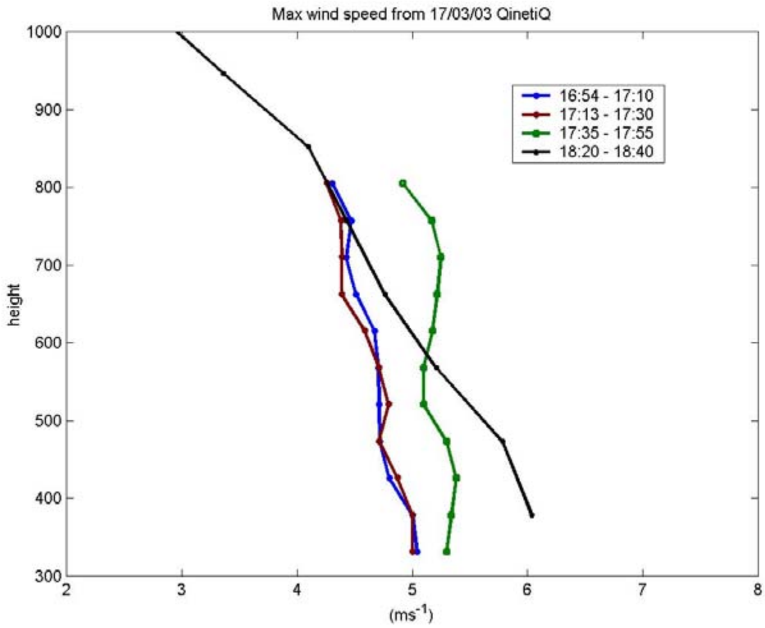

Figure 4.5 : QinetiQ lidar wind speeds derived from PPI scans

From the PPI scans we can also derive wind direction. Figures 4.6 and 4.7 show the wind directions derived from the two systems.

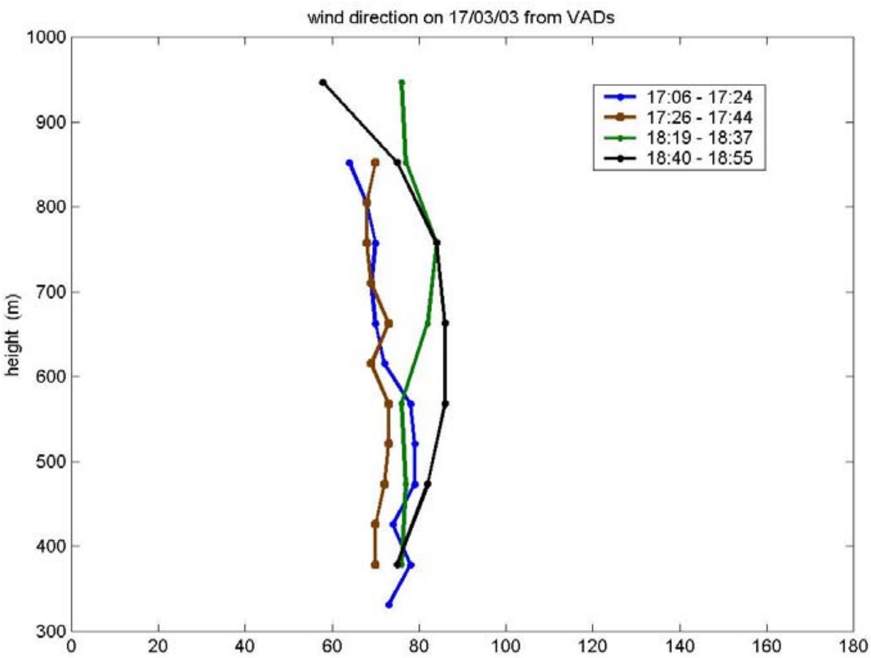

Figure 4.6: Salford wind direction data

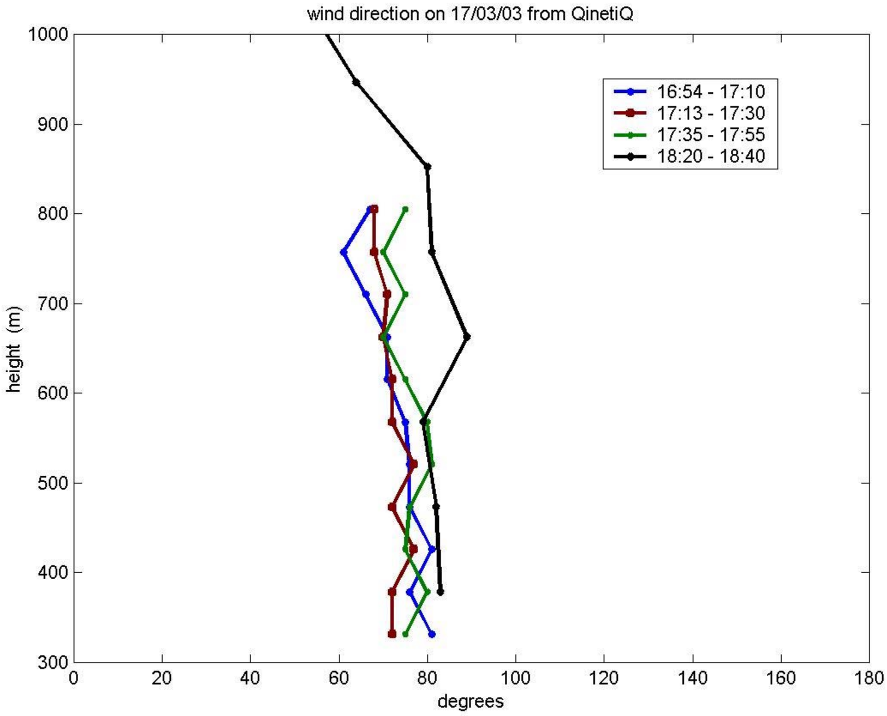

Figure 4.7: QinetiQ wind direction data

Initial examination of the wind speed and directions shown in figure 4.7 compare very well. Further analysis needs to be done to assess how similar the observations actually are and where and why they may possibly be different. Another parameter that may be obtained from this analysis is the offset. A difference between the magnitudes of the maximum and minimum can be seen in the two lidar scans (Figures 4.1 and 4.2). This difference is the offset value. The Salford lidar shows slightly lower minimum values than the QinetiQ lidar. This bias could arise from a vertical component of velocity [3] or more likely from flow distortions due to orographic effects. However lidar systems can also have a systematic bias, which is constant, that will also contribute to this offset value. The figure below shows the offset for the two systems.

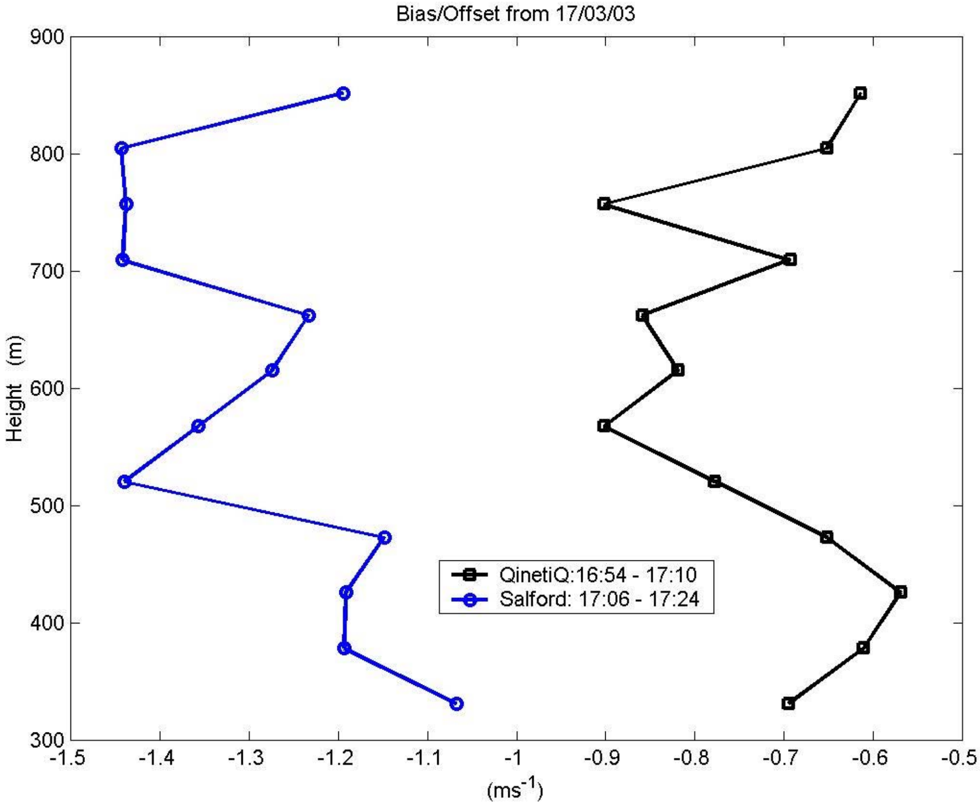

Figure 4.8: Offset value for the two lidar systems

From figure 4.8 the Salford lidar system is seen to have a larger system bias. The constant systematic bias of the QinetiQ system can be estimated to be -0.75 while for the Salford system it is approximately -1.2.

4.2 ANALYSIS OF TURBULENCE VALUES

To obtain data with a high temporal resolution the technique used is to keep the lidar beam at a fixed azimuth and elevation position. This enables us to measure the radial wind velocity along a line of sight at a rate of up to approximately 0.2 Hz.

On the 18/03/03 the Salford Lidar system was moved to the Three Counties Show ground. The wind was north - easterly at the surface turning to south - easterly at upper levels. The mist did not clear fully during the day and the maximum temperature at the site was approximately 10°C. The PPI scan in figure 4.9 shows data from the Salford lidar with the elevation set at 25°.

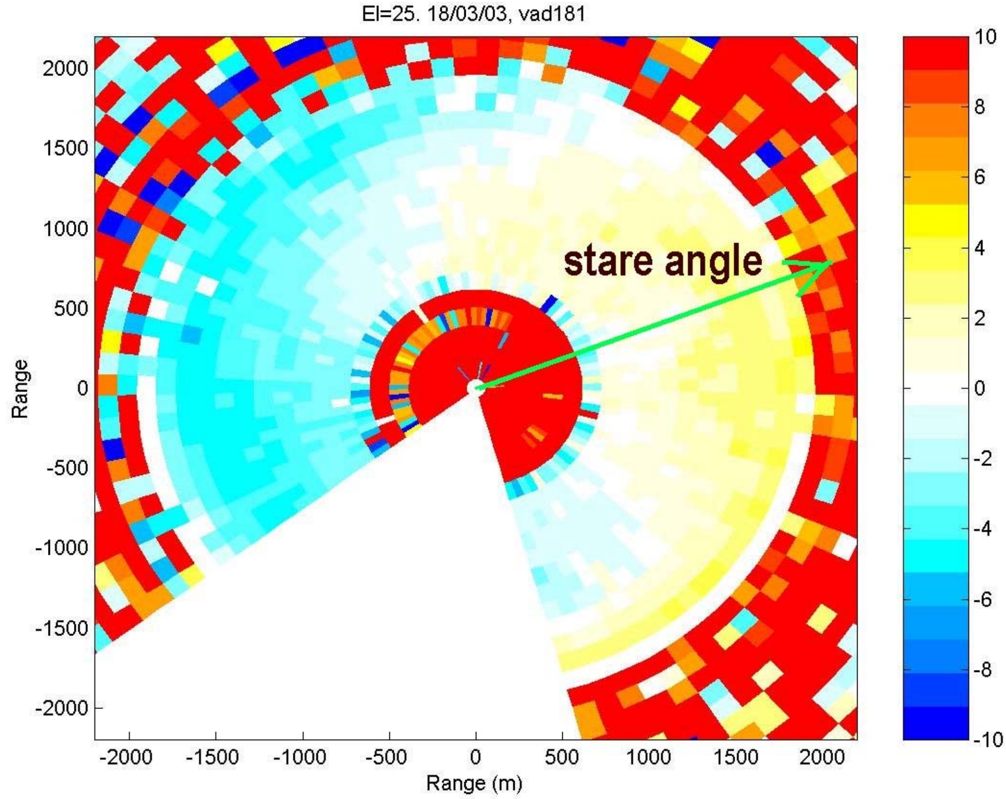

Figure 4.9: Salford lidar scan data from 18/03/03 at 16:33 - 16:44 UTC.

Line-of-sight data was then taken along the stare angle, shown in figure 4.9. It was also taken at an elevation of 23.8°. Figure 4.10 shows the line-of-sight radial wind velocity from the Salford lidar for four separate time periods against the maximum wind speed obtained from two separate PPI scans.

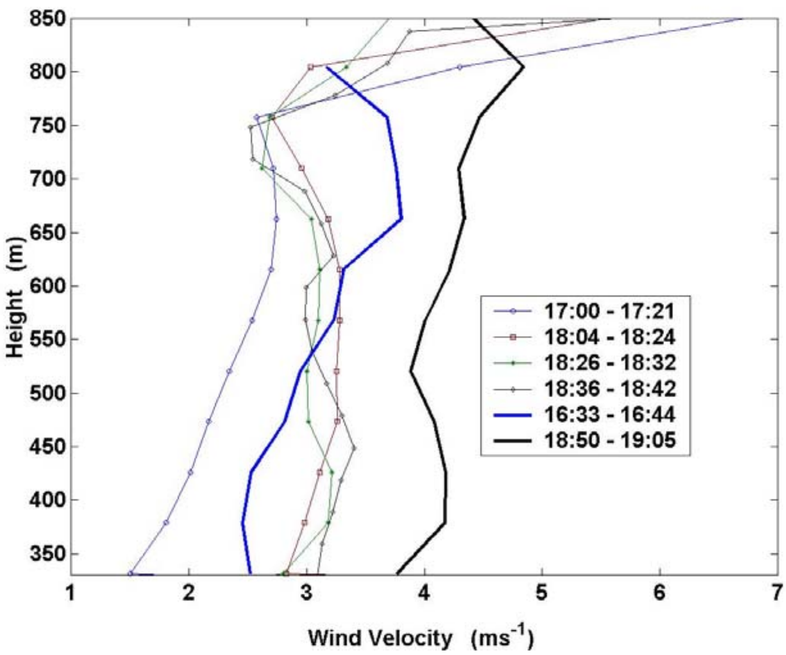

Figure 4.10 shows the line-of-sight radial wind velocity for different time periods (thin lines) against the maximum wind speeds from PPI scans (thick lines).

The winds, shown in figure 4.10, increase from approximately 1.6 ms^{-1} to 3.0 ms^{-1} during the data collection period. The two PPI scans were taken before and after the line-of-sight data. During the data collection period the wind also veers by about 30° at the surface. It is normal to assume, for homogeneous terrain and isotropic turbulence that the mean vertical component of wind velocity is zero. Under these conditions the mean horizontal component of wind, $\langle v_x(r) \rangle$, can be calculated from the radial wind velocity, $\langle v(r) \rangle = \cos\theta \langle v_x(r) \rangle$, [5]. The standard deviation for the line-of-sight radial wind velocities are shown in figure 4.11. These are shown to be approximately constant with height up to the top of the boundary layer. The increase at the boundary layer top is possibly due to bad data from the low signal-to-noise returns. The standard deviation of the radial velocity is shown to decrease throughout the time period from 0.5 ms^{-1} to approximately 3.5 ms^{-1}.

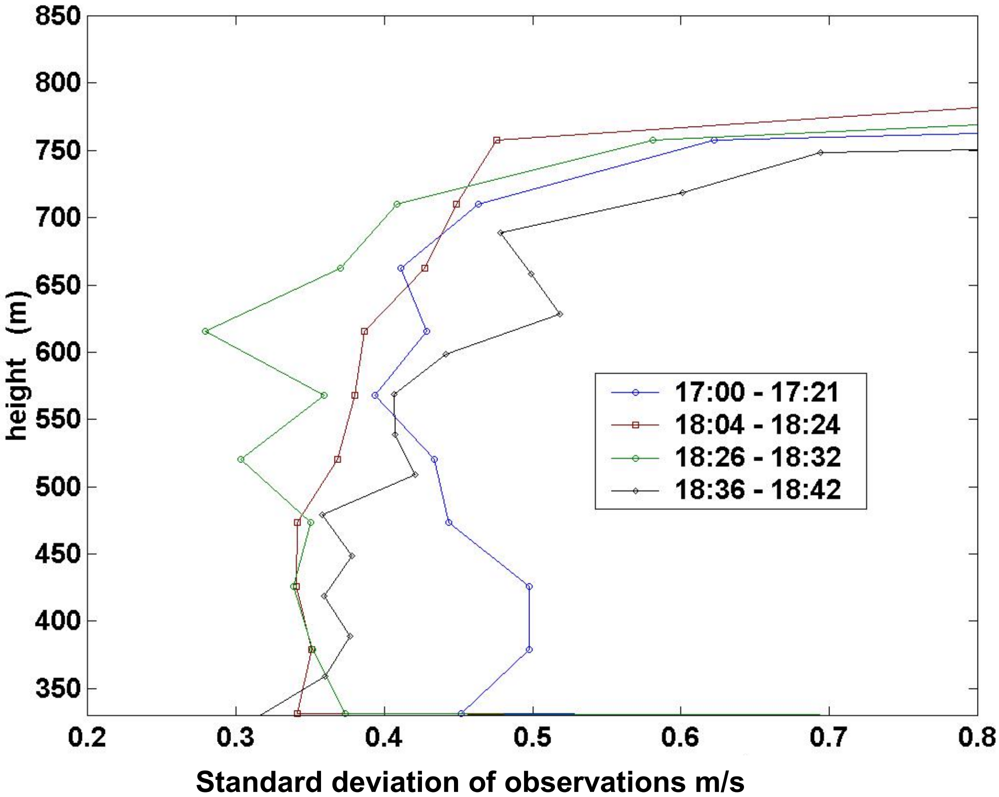

Figure 4.11: Standard deviation of the observed radial velocity on 18/03/03 using the Salford lidar system.

The estimation of retrieved radial velocity winds from a pulsed Doppler lidar system are a function of the lidar parameters, the atmospheric conditions and the velocity estimation procedure. There is thus an error on the retrieved radial velocity due to the lidar set-up and the velocity estimation procedure. The technique for estimation of this error used here is outlined in [5]. A refined version of error estimation is presented in [6].

In conclusion whilst the systems have differing sensitivities and hence ranges that they can operate to, this difference is not significant and can be adapted for during the experiment. When that is done the initial examination indicates that for the simultaneous observations of wind speed and direction there is good correlation between the two sets of results.

5 SUMMARY

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

- A description of the winter trial has been made.
- A review of the data released for subsequent analysis is given.
- A preliminary analysis of the data has been made in order to compare system performances.

The next stage of the project is to analyse the results of the winter trial. This work will consist of a full review of the data quality, followed by a conventional data analysis of single lidar data, then the derivation of the Dual Lidar data product and finally a comparison to Met Office observations and NAME model predictions.

Initial results from this analysis will appear in a technical working paper [6] concentrating upon investigation into the lidar system's bias. The results of the complete data analysis will appear in the next ISB52 milestone, MS5, due in May 2003.

5 REFERENCES

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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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