

## EVALUATION OF A NEW AUTONOMOUS DOPPLER LIDAR SYSTEM DURING THE HELSINKI INTERNATIONAL TESTBED FIELD CAMPAIGN

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### 1. INTRODUCTION

The Helsinki Testbed is a mesoscale observation network, a collaboration between the Finnish Meteorological Institute (FMI), Vaisala meteorological measurement company together with other public, private and academic partners (Dabberdt et al, 2005). The testbed provides the opportunity for measuring, studying and predicting atmospheric processes and applications, which seeks to enable and promote testing of new measurement systems. The testbed measurement area is located in and around Helsinki, Finland and is operational between January 2005 and September 2007.

The testbed provided the opportunity for the University of Salford to test their new autonomous Doppler lidar system and gain access to complimentary observations which will be used to evaluate the lidar system's capabilities and performance. This conference paper describes the new University of Salford autonomous Doppler lidar system and demonstrates the measurement accuracy and capabilities of the system.

### 2. DOPPLER LIDAR SYSTEM

A new Doppler lidar system has been developed to meet the requirements of unattended and autonomous operation. The University of Salford specification required a Doppler lidar system capable of providing high temporal (0.1 – 1.0 second) and spatial resolution (length scales of order 30 m) measurements of the wind velocity and backscatter within the atmospheric boundary layer.

The system was required to be portable and rugged and capable of being used for field work and long term measurements. Eye safety and a minimum range of approximately 50 m were required in order to facilitate measurements in the urban environment.

The Salford Autonomous Lidar System (SALiS), operating at an eye-safe, near infrared wavelength of 1.5 microns, employs novel optical technology and the design approach has led to a new type of eye-safe Doppler lidar (class 1 or 1M) providing a high level of performance and exhibiting exceptional stability. The system has a modular design arranged in three separate units; the optical base unit, the weather-proof monostatic antenna and the signal processing and data acquisition unit. Figure 1 shows the lidar system base unit with the antenna situated on the top of the base unit. The base unit has approximate dimensions 0.56 m x 0.54 m x 0.18 m and contains the optical source, interferometer, receiver and electronics. The system operates with low power consumption and is air cooled. The weather-proof antenna is attached to the base unit via an umbilical. The antenna can be deployed permanently outside whilst the base unit and data acquisition system are housed within a laboratory environment. Some lidar system parameters are provided in table 1. The signal processing has been developed with a view to providing a high level of flexibility with respect to the data acquisition parameters. Measurements are shown in real-time and users are able to set parameters such as the length of the range gate, maximum range, number of pulses accumulated for each measurement and the spectral resolution of the Doppler measurements. The lidar system may also be monitored and controlled with data transfer via remote access software where a network connection is available. The lidar system also has the capability to perform diagnostic tests in order to monitor and log the status of the system.

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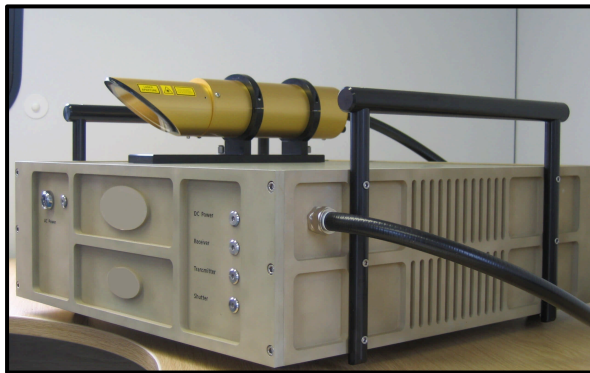


Figure 1: The image shows the lidar base unit with the antenna positioned on top.

Parameter	Value
Operating wavelength	1.5 microns
Pulse repetition frequency	20 kHz
Energy per pulse	10 $\mu$ J
Pulse duration	150 ns
Beam divergence	50 $\mu$ rad
Range gate	Variable: 20 – 60 m
Minimum range	30 m
Maximum range	7 km
Temporal resolution	0.1 – 30 s

Table 1: Autonomous Doppler lidar system parameters

### 3. HELSINKI TESTBED SETUP

The University of Salford autonomous Doppler lidar system was installed at Malmi airport, Helsinki, Finland during August 2006. The station is situated at latitude  $60.25^\circ$  and longitude  $25.05^\circ$  at a height of 15 m above sea level, approximately 10 km from the Helsinki city centre and 6 km from the sea. Figure 2 shows the network of observation stations in the domain of the Helsinki testbed along with the larger area domain with nearby radiosonde sounding stations. Table 2 lists the measurement sites according to the symbols given in figure 2. Other instruments sited at the Malmi measurement site included a Doppler sodar, a Vaisala LAP-3000 lower atmosphere wind profiler with RASS capability, a Vaisala CL31 ceilometer and an automatic weather station. Details on the Helsinki Testbed project including participating instruments can be found at [www.fmi.fi/testbed](http://www.fmi.fi/testbed).

The lidar system operated continuously from 09:00 UTC on 7<sup>th</sup> August 2006 until 09:00 UTC on 21<sup>st</sup> September. During this time period the lidar

generally operated with a fixed vertical beam, providing vertical velocity, normalised intensity and atmospheric backscatter measurements within the atmospheric boundary layer. The system was also operated with the antenna fixed off zenith to provide line of sight radial velocity measurements for comparison with the UHF wind profiler operating in range imaging mode (RIM) configuration. In this paper only measurements which were taken with a fixed vertical beam are considered.

### 4. LIDAR MEASUREMENTS

During August 2006 there were several bad air quality incidents in and around Helsinki, some which were partially due to forest fires in Western Russia, near St. Petersburg. On 21<sup>st</sup> August 2006 poor air quality was recorded by air quality monitoring stations in and around the Helsinki region.

Figures 3 and 4 show the atmospheric backscatter and vertical velocity measurements from the lidar data for two hour time periods on 21<sup>st</sup> August 2006. The temporal resolution of the time series in figures 3 and 4 is 3.2 seconds with a range gate of 30 m and a minimum range of 30 m. Figure 3 contains an hour time series of lidar measurements taken between 12:00 – 12:59 UTC. Figure 3a shows a time series of the log of the atmospheric backscatter with the corresponding vertical velocities shown in figure 3b. For both images in figure 3, the vertical axis shows the height above ground level and the horizontal axis shows the time period. The lidar was providing good measurements up to approximately 600 m above ground level. The signal then falls below the noise level and no useful velocity or backscatter measurements are obtained above this height. It can be seen in the atmospheric backscatter data that at approximately 12:25 UTC there is strong increase in the atmospheric backscatter signal, which implies more aerosol and particulates in the atmosphere. Convective cells can be seen in the vertical velocity time series, where negative (green – blue coloured) velocities indicate downward motion and positive (green – red coloured) velocities indicate upward motion. Individual thermals can be seen as the mechanism for lofting the aerosol laden air within the atmospheric boundary layer. It can be seen that the down draughts contain the cleaner air between the up draughts.

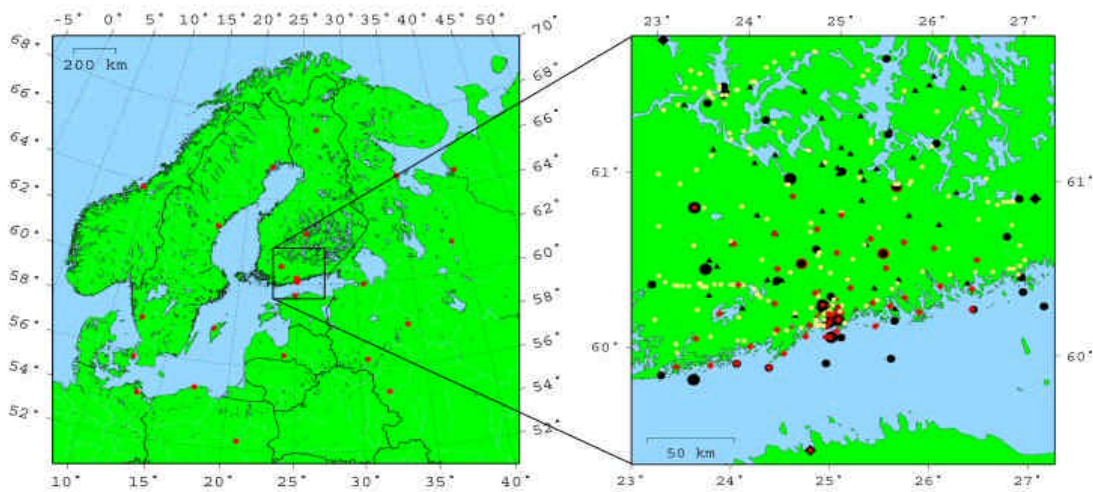


Figure 2: Observing sites in the domain of the Helsinki Testbed (right) and larger area model domain with nearby radiosonde sounding stations (left). Image courtesy of the Helsinki testbed website ([www.fmi.fi/testbed](http://www.fmi.fi/testbed)).

No of instruments	Sites in Helsinki Testbed domain	Symbol
46	FMI weather stations	●
34	FMI precipitation stations	▲
13	Off-line temperature loggers in Greater Helsinki area	▲
8	Weather transmitters in Greater Helsinki area	▲
191	Road weather station	●
<b>292</b>	<b>Total no. of surface weather stations</b>	
42	Pairs of weather transmitters on masts	◆
5	Optical backscatter profilers (new ceilometers)	●
6	FMI ceilometers	●
4	C-band Doppler radars	◆
1	Dual polarization Doppler radar	◆
4	RAOB sounding stations	●
1	UHF wind profiler	▲
-	Total lightning network	-

Table 2: Observing sites in relation to the images shown in figure 2. Information courtesy of the Helsinki testbed website ([www.fmi.fi/testbed](http://www.fmi.fi/testbed)).

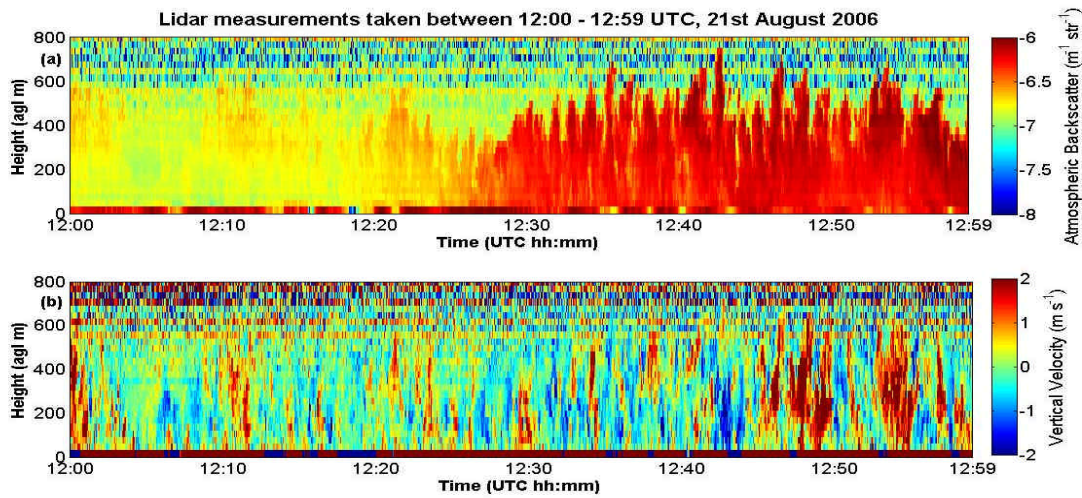


Figure 3: Time series of lidar atmospheric backscatter and vertical velocity measurements taken on 21<sup>st</sup> August, 12:00 – 12:59 UTC. The log of the atmospheric backscatter is shown in figure 3a with the vertical velocity data from the lidar shown in figure 3b. The vertical axis shows height above ground level (m) and the horizontal axis is time (UTC).

The mean wind speed during the measurement period 12:00 – 12:59 UTC was  $3.9 \text{ m s}^{-1}$ , with a wind direction of  $114^\circ$  and an average temperature of  $22.8^\circ\text{C}$ . The average vertical velocity measured with the lidar during the time period was  $0.09 \text{ m s}^{-1} \pm 0.83 \text{ m s}^{-1}$ . The vertical velocity value has been calculated using data from range gates where the signal is above the noise level. The increase in the atmospheric backscatter continues until approximately 14:20

UTC where a reduction in the backscatter signal is observed in the lidar data. An increase is again seen in the lidar data from 16:20 – 20:20 UTC. The second increase in the atmospheric backscatter coincides with a change in the wind direction from  $110^\circ - 60^\circ - 90^\circ$  during the time period 16:20 – 18:00 UTC. Figure 4 contains an hour time series of lidar measurements taken between 20:00 – 20:59 UTC on 21<sup>st</sup> August 2006.

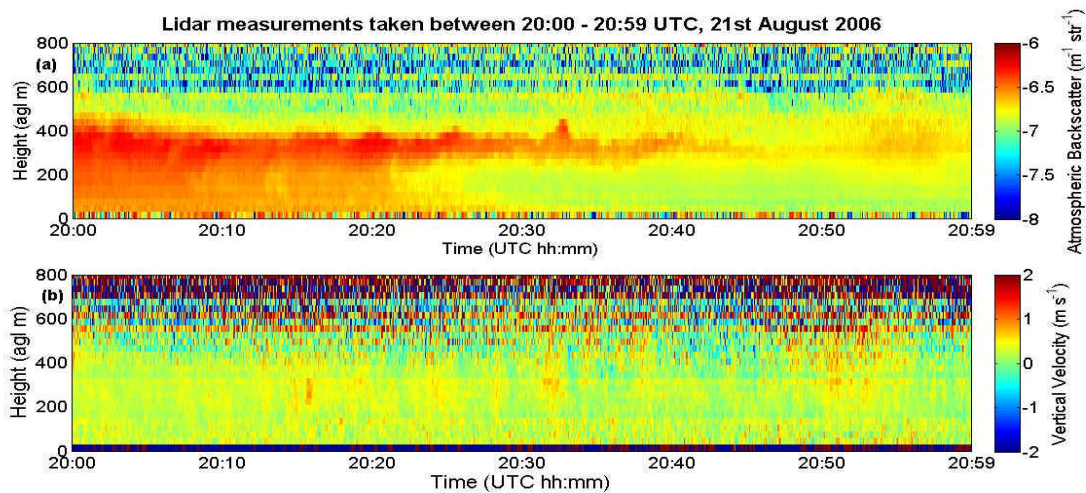


Figure 4: Time series of lidar atmospheric backscatter and vertical velocity measurements taken on 21<sup>st</sup> August, 20:00 – 20:59 UTC. The log of the atmospheric backscatter is shown in figure 4a with the vertical data from the lidar shown in figure 4b. The vertical axis shows height above ground level (m) and the horizontal axis is time (UTC).

Figure 4a shows a time series of the log of the atmospheric backscatter with the corresponding vertical velocities shown in figure 4b. The axes and vertical velocity properties are the same as in figure 3. It can be seen from figure 4a that there is a stronger backscatter signal until around 20:20 UTC which then decays leaving a strong scattering layer visible at around 400 m. The average vertical velocity during the time period 20:00 – 20:59 UTC was  $0.24 \text{ m s}^{-1} \pm 0.26 \text{ m s}^{-1}$  with a mean wind speed of  $1.08 \text{ m s}^{-1}$ , and average temperature of  $18.4 \text{ }^\circ\text{C}$ .

## 5. ERROR ANALYSIS OF LIDAR RADIAL VELOCITY DATA

The estimation error in the retrieved radial velocities for a Doppler lidar is a function of the lidar parameters, the atmospheric conditions and velocity estimation procedure. It is therefore important to know what the combined effect of the lidar parameters and the velocity estimate algorithm is when attempting to measure the atmosphere using pulsed Doppler lidar. Drobinski *et al* (2000) defined the radial velocity,  $V_r(r,t)$  at a range  $r$  and time  $t$  as measured by a pulsed Doppler lidar as the sum of an effective wind velocity,  $V_m(r,t)$  and an error  $e(r,t)$ :

$$V_r(r,t) = V_m(r,t) + e(r,t) \quad (1)$$

The magnitude of the random error in the Doppler velocity estimates can be determined from radial velocity data using the velocity spectrum, the velocity covariance and velocity differencing (Frehlich, 2001). For multiple pulse measurements the wind variability over the measurement volume determines the performance of the velocity measurements. An important parameter is the total measurement time and the transverse motion of the atmosphere during velocity measurement. In the error analysis presented, the covariance and differencing methods have been used to calculate the error in the radial velocity estimates. The magnitude of the uncorrelated estimate error has been calculated using unbiased covariance estimates. This method requires a well defined discontinuity of the covariance at zero lag. The algorithm produces useful estimates in low turbulence. The velocity differencing method is based on the difference between each pair of even and odd numbered velocity estimates,  $\Delta V(r,t)$  and on the consistency of the data. The variance of the difference time series can then be used to calculate the variance of the estimation error:

$$s_e^2(r, N) = \frac{s_{\Delta V}^2}{4} \quad (2)$$

where  $N$  is the number of velocity estimates in the time series. Frehlich showed that the velocity differencing method has the best performance with the smallest estimation error. The estimation error in the radial velocity has been calculated for vertical velocity measurements between 19:00 UTC and 21:00 UTC on 23<sup>rd</sup> August 2006 with the assumption that the measurements were made during stable conditions. The automatic weather station at the Malmi site measured the average wind speed during the measurement period as  $0.68 \text{ m s}^{-1}$  with an average air temperature of  $16.9 \text{ }^\circ\text{C}$  and a relative humidity of 67 %. The wind direction was from the northeast to easterly sector during the first hour turning more northerly during the second hour of measurements. From the measurements, four 10 minute data sets have been used to estimate the error in the radial velocity measurements. The lidar antenna was in a fixed vertical position during the measurements with the maximum range set at 1275 m. To estimate the performance of the lidar system, the number of pulses accumulated was varied.

Figure 5 shows the estimation error versus range, which for a vertical beam is equivalent to height, for the four different data sets. The estimation error was calculated using the velocity differencing method as given in Frehlich (2001). The estimation error is dependent the signal to noise ratio (SNR) which is dependent range, atmospheric attenuation and backscatter intensity. Where the signal falls below the noise level the error in the radial velocity increases as the velocity estimates are not valid and the error estimation algorithm fails to produce meaningful results. Information on the number of pulse accumulations for each set of line of sight radial velocity estimates, the dwell time of the measurements, number of data points used to calculate the estimation error at each height bin and the height range over which good velocity estimates were obtained, are given in table 3. It can be seen from table 3 and figure 5 that the higher number of pulses accumulations the further out in range good velocity estimates were retrieved, which is due to the increase in the returning backscattered signal. There is a trade off between the maximum range to which good velocity estimates can be obtained and the dwell time for the measurements. For turbulence measurements the dwell time requirements are for several seconds or less.

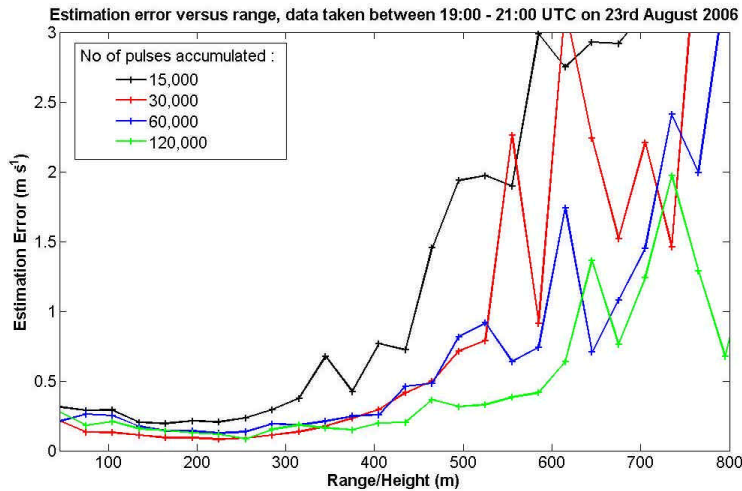


Figure 5: The estimation error calculated for each height range for the four different data sets using the velocity differencing method. The estimation error increases significantly where the signal falls below the noise level. Further information on each data set is given in table 3.

No of pulses	Temporal resolution (s)	No of estimates	Measurement range (m)	Average velocity (m s <sup>-1</sup> )	Average estimation error (m s <sup>-1</sup> )	
					Differencing	Covariance
15,000	1.6	357	45 – 435	0.10	0.37	0.36
30,000	3.2	174	45 – 525	-0.17	0.25	0.57
60,000	6.3	87	45 – 585	0.00	0.35	0.49
120,000	12.6	44	45 – 615	-0.02	0.24	0.32

Table 3: Estimation errors calculated using the velocity covariance and velocity differencing method for different number of pulse accumulations for 10 minutes of data.

## 6. CONCLUSIONS

An autonomous Doppler lidar system was deployed at Malmi airport, Helsinki as part of the international Helsinki Testbed project. The lidar system operated continuously for a period of 49 days with minimum user intervention. A total of 1052 hours of vertical measurements and 75 hours off zenith measurements were collected during the testbed, with the off zenith measurements being used for comparison with the Vaisala wind profiler operating in RIM configuration. The lidar system was monitored, controlled and data were downloaded via simple remote access software via an internet connection.

Two time series of atmospheric backscatter and vertical velocity data are shown for measurements

made on 21<sup>st</sup> August 2006 during an episode of poor air quality in the Helsinki region. The images in figures 3 and 4 show the ability of the lidar to measure small temporal and spatial changes in the atmospheric backscatter and wind field within the atmospheric boundary layer. Correlating the atmospheric backscatter data with the vertical velocity data shows the turbulent mechanisms that are responsible for transporting aerosol within the lower atmosphere. Comparison of the lidar measurements with the nearby Vaisala ceilometer will provide a means of testing the performance and ability of the lidar system to capture small scale features within the boundary layer. Useful intercomparisons will also be made with the UHF wind profiler and Doppler sodar.

The error in the radial velocity estimates have been calculated for the vertical velocity measurements. The errors calculated using the covariance method were found to be generally larger than those calculated using the velocity differencing method. In normal lidar operation, the radial velocity values are calculated by accumulating 30,000 pulses. For the 10 minute time period where 30,000 pulses were accumulated with a measurement temporal resolution of 3.2 seconds the average vertical velocity was  $-0.17 \text{ m s}^{-1}$  and the average error is  $0.25 \text{ m s}^{-1}$  (differencing method). From lidar data gathered at the Helsinki testbed with 30,000 pulse accumulations and where the signal to noise has been higher than the data used in section 5, estimation errors have been calculated that are less than  $0.1 \text{ m s}^{-1}$ . The analysis of the atmospheric backscatter and radial velocity data collected during the Helsinki testbed is ongoing.

## 11. FUTURE RESEARCH

The lidar system will be installed for long term measurements at SUBERB, Salford University Urban and Built Environment Research Base, which is situated on the edge of the Greater Manchester conurbation, approximately 10 km south west of Manchester city centre, UK. One of SUBERB's objectives is to make long term measurements of the turbulence, temperature and moisture structure of the atmospheric boundary layer within the urban environment with a variety of remote sensing instruments. Research will focus on observations over the Greater Manchester conurbation and the rural-urban interface with a view to achieving a better understanding of the effects of urban areas on the local meteorology and of the boundary layer development over the urban and rural interface.

## 12. ACKNOWLEDGEMENTS

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## 13. REFERENCES

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