COMMERCIAL LIDAR PROFILERS FOR WIND ENERGY. A COMPARATIVE GUIDE.

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Summary

Lidar profilers have the potential, perhaps within a decade, of becoming an important tool for measuring wind speed. One ground based, portable instrument can eliminate the need for expensive measuring towers whilst providing an accurate and detailed picture of the wind profile. Two commercial lidar systems are currently available. Although based on the same fundamental principle, the two implementations are radically different in their means of discriminating measuring height. Depending on the application each design will have its strengths and weaknesses. The object of this paper is to illuminate the two contrasting and in many ways complimentary designs.

1. Introduction

Wind measurements are fundamental to the wind energy industry. No wind project can be started before the available wind resource has been documented and the case for a successful return on the investment has been scrutinized and accepted. Wind turbine power performance testing (measuring electrical energy as a function of wind speed) is usually an important element in the acceptance and delivery process, often with hard cash at stake.

For both wind resource and power performance testing, the mast-mounted cup anemometer is the dominant and only formally accepted sensor for wind speed. This robust, simple and accurate instrument has served the industry well. However, the rapid increase in wind turbine size over the past few years has exposed the cup anemometer's Achilles heal – the mast structure needed to locate the cup anemometer at the hub-height of the wind turbine. With typical hub-heights now often exceeding both 80 and 90m, traditional mast-mounted cup anemometry has become an expensive and logistically complex affair. At the same time, the current practice of basing power performance measurements on a single, hub-height wind speed measurement becomes intuitively more and more suspect for such huge rotor swept areas. Recent numerical studies [1] indicate that the correlation between measured electrical power and wind speed increases significantly if the wind speed is based on a weighted average of the wind speed profile over the entire rotor rather than on a single point measurement. Here, remote sensing is set to play a major role.

An alternative to mast-mounted anemometry is ground-based remote sensing systems. Sodar systems have been available for many years and have achieved some acceptance within the wind energy community, especially in North America. The measurement accuracy of sodar systems can not match that of cup anemometry and unless high acoustical powers are used, their availability falls in high wind speeds. A hybrid system comprising a moderately tall mast (say 40m) and a relatively low power (30-100W electrical) sodar has many attractive features - the high absolute accuracy and high availability of the cup anemometer complements the less accurate but highly relevant vertical resolution obtained from the sodar.

Until recently, making wind speed measurement using lidars was prohibitively expensive and essentially limited to the aerospace domain [2]. Suitable lasers were costly, large and required elaborate cooling systems. The optical systems were built on traditional optical-benches and were inherently difficult to keep aligned. In addition it was difficult to obtain a sufficient acquisition rate while keeping these early systems eye-safe and they were therefore unsuitable for unmanned operation. All these limitations were swept aside by the emergence of coherent lasers at wavelengths compliant with fiber optic components (so-called ‘fiber lasers’). Lidar systems can now be built using components compliant with stringent telecommunication quality standards. These are available off-the-shelf and are connected together by standard terminated optical fibers. The lasers consume relatively low electrical power and do not require elaborate cooling systems. Since precise alignment is no longer generally an issue, robust portable systems can be realized. Eye-safety concerns can also be overcome since the majority of fiber lasers emit at the eye-safe wavelength of 1.5µm.

Since light can be much more precisely focused and spreads in the atmosphere much less than sound, lidar systems have an inherently higher accuracy and higher signal to noise ratio than a sodar. They have the potential to replace mast measurements and in time, to perform with comparable accuracy to cup anemometers.

Two commercial lidar systems are now available. Both systems have been extensively tested both in prototype and production forms, by Risø DTU at the Høvsøre Test Station in Jutland, Denmark [3]. It is our belief that the insight gained in this testing has played a significant role in the development of these systems. It is also our hope that the Høvsøre facility can continue to contribute to the development of lidar profilers and in particular, to their acceptance within the wind energy community. The aim of this paper is to describe, contrast and compare these two commercial profilers.

2. Commercial lidar profilers

2.1. The QinetiQ ZephIR

After several prototype versions, one of which had previously been tested at Høvsøre [4], the English company QinetiQ presented the first commercial lidar profiler at the beginning of 2006. Known as the ‘ZephIR’, this is a continuous wave system with height discrimination achieved by varying focus. Five different sensing heights can be chosen. Each height is scanned for 3 seconds before the lidar re-focuses to the next height in the sequence. Figure 1 shows a ZephIR on test at the Høvsøre test facility.

The laser light is emitted through a constantly rotating prism giving a deflection of 30° from the vertical and making one complete rotation per second. Backscattered light mixed with the local oscillator is sampled at 100MHz. The unit is able to transform blocks of 512 time series scans to power spectra in real time. The 200000 spectra per second are block-averaged 4000 at a time to give highly noise-suppressed Doppler shifted spectra at 50Hz. A centroid method is used to obtain the frequency of the ‘peak’, the radial speed (i.e. in the laser beam direction) being directly proportional to this frequency. Thus 50 radial velocities, one for every 360°/50=7.2° are available from each rotation.

Unlike pulsed systems, constant-wave lidar systems do not inherently ‘know’ the height from which backscatter is being received. We are obliged to assume (or rather, hope for) a sensibly flat vertical profile of aerosol concentration, in which case the backscattered energy is from the focused volume, weighted according to the appropriate Lorentzian function centered at the focus distance [5]. The obtained radial wind speed distribution in this case is dominated by the signal from the set focus distance.

The assumption of vertical aerosol homogeneity unfortunately fails completely in the fairly common case of low level clouds (under 1500m). Here, the relatively huge backscatter from the cloud base can be detected even though the cloud is far above the focus distance. The resulting Doppler spectrum has two peaks – one corresponding to the radial speed at the focused height and a second corresponding to the (usually) higher speed of the cloud base. Unless corrected for, this will introduce a bias to the wind speed measurement. For this reason, the ZephIR has a cloud-correction algorithm. An extra three second scan at 300m is inserted into the height cycle. The spectra measured at 300m are used in an attempt to remove the influence of the clouds at the desired measuring heights.

Since the ZephIR does not apply a frequency offset to the Doppler shift, it is not possible to determine the direction of the radial velocities. This fact introduces an ambiguity in the polarity of the parameter pair wind direction and vertical velocity. For this reason, the ZephIR independently senses the wind direction using a sensor mounted on a short mast fixed to the top of the lidar. Assuming that the lowest remotely-sensed wind direction will be closest to the directly-sensed value immediately above the lidar, the ambiguity is resolved for the direction and hence also for the vertical speed.

Figure 1 A ZephIR lidar on test 40m from the meteorological mast at Høvsøre.

2.2. The Leosphere Windcube

With the recent (December 2006) introduction of the French company Leosphere's 'Windcube', there are now two contrasting lidar profilers on the market. The Windcube, shown in Figure 2, is a pulsed lidar with a fixed focus. Like the ZephIR, it has a 30° prism to deflect the beam from the vertical but here the prism does not rotate continuously. Instead, the prism holds still whilst the lidar sends a stream of pulses (5000-10000) in a given direction, recording the backscatter in a number of range gates (fixed time delays) triggered by the end of each pulse. Having sent the required number of pulses, the prism rotates to the next azimuth angle to be scanned, each separated by 90°. A full rotation takes about 6 seconds.

During the rotation and before the next stream of pulses can be sent, the recorded data are processed. For each range gate, the time series from each pulse are Fourier transformed to power spectra which are block-averaged. Due to the short recording duration (200 ns), the resulting spectra have poor frequency resolution. Instead of using a centroid to obtain the frequency of the peak, Leosphere have developed a mathematical model [6] including the most important parameters affecting the shape of the expected Doppler spectrum. This model is fitted to each block-averaged power spectrum in order to obtain the Doppler shift to a much higher resolution than could otherwise be expected. At each direction step, the Windcube combines the four most recent radial speeds at each height in order to obtain the horizontal and vertical speed and wind direction.

In contrast to the ZephIR, the Windcube uses an acousto-optic modulator (AOM) to add a precise frequency offset to the local oscillator which is mixed to and beats with the returning Doppler shifted backscatter. Backscatter from a fixed target, introducing no Doppler shift, appears shifted in the resulting power spectrum. Thus the polarity of the radial velocity is available and there is no ambiguity regarding the wind direction.

Figure 2 Four Leosphere Windcubes on simultaneous test at the base of the meteorological mast at Høvsøre.

3. Strengths and weaknesses

In this section we will discuss the relative merits of the two lidar profilers, with respect to a number of different aspects. It is not our intention to make a recommendation, but rather to present the differences as we see them.

3.1. Height resolution

Here the two systems have fundamentally different properties. The ZephIR is a variable-focus, continuous wave system and as such, the vertical probe length is determined by the depth of the focus volume. More specifically this can be defined as the FWHM (Full Width Half Maximum) of the Lorentzian function defining the collection efficiency. This increases quadratically with sensing range. When measuring at low heights, the probe length is only a few decimeters. At 100m height, it is about 20m whilst at 150m it is close to 50m.

For the Windcube, the vertical measuring depth depends on the pulse length and is constant with sensing range. By considering the contribution to the measured spectral density from different parts of the range gate, Lindelöw [7] has shown that the effective probe length is somewhat less than previously thought. For the standard Windcube parameters, the FWHM of the weighting function is about 18m.

Beneath approximately 100m, the ZephIR has the smaller probe length. Above this height, the Windcube has the edge and at heights of over 150m, only the Windcube can perform sensible measurements.

3.2. Low speeds

The most significant noise source in coherent lidar is known as RIN (Relative Intensity Noise) and is caused by rapid variations in the emitted power. RIN is typically 'pink' noise, meaning that it falls off with increasing frequency. It is so severe as to essentially blind the lidar to Doppler shifts occurring at the low frequency end of the spectrum. For the ZephIR system, this affects Doppler shifts related to low wind speeds. As the actual wind speed falls below about 4 m/s, the wind speed measured becomes increasingly positively biased. This is because more and more of the low frequency side of the peak in the spectrum falls into the region that has been blanked in order to prevent corruption by the RIN noise.

In contrast, the Windcube effectively shifts the range of radial speeds affected by RIN to large negative values, corresponding to implausible wind speeds. Thus the Windcube can faithfully measure in complete wind-still.

3.3. Clouds

As mentioned in section 2.1, the ZephIR is sensitive to backscatter from low level clouds. When it became clear that this would be an important issue, a Vaisala ceilometer was added to the Høvsøre instrumentation. This instrument is commonly used, especially at airports, to measure the height of the cloud base. The cloud base data from the instrument are available in the database and can be used to classify lidar results according to cloud conditions. A number of important results have been achieved.

Firstly it was confirmed that the ZephIR running without the cloud correction algorithm applied, was indeed sensitive to cloud backscatter. In addition, the degree of corruption varied between different ZephIR units. It is suspected that greater photo-detector sensitivity gives a greater sensitivity to unwanted cloud base backscatter. Small differences in the optics system may also cause differences in the collection efficiency at long range.

Secondly, we determined that using the internal cloud correction algorithm did reduce the sensitivity to cloud. However, the cost of this was general negative biasing (2-4%) of the data in conditions where clouds were not present. More disturbingly, the standard deviation of the horizontal speed normalized by that measured from the cup anemometer, increased with the cloud correction algorithm active. We interpret this increase as an indication of noise introduced by the cloud correction algorithm.

Recently we have been working with QinetiQ on an improvement to the cloud-correction algorithm. Two additional heights are inserted into the measuring cycle, 800m (instead of the previous 300m) and 38m. One major improvement is that the cloud correction is now conditional, being turned on and off according to the relative backscatter at these heights. A second improvement is that with the 800m cloud detection height (essentially a collimated beam), the spectral densities are very low (and very broad) unless cloud is present. This aids the discrimination process and helps to prevent the corruption of the lower level Doppler spectra that was previously experienced in cloud-free conditions. A further finesse is that only a proportion of the cloud level spectrum is subtracted from the lower level, this depending on the backscatter ratios between the highest and lowest levels. Having tested the new algorithm with several periods of previously recorded raw data, we are currently testing an embedded version of the new algorithm in a production ZephIR at Høvsøre.

In comparison to the ZephIR, clouds play only a minor role in the performance of the Windcube. Since this is a pulsed system with the backscatter collected in finite range-gates, only clouds actually present in the measuring range will have any affect. This can be considered as a discontinuity in the aerosol concentration within the measuring volume and the wind speed at the step will dominate the Doppler spectrum. Probably more significant is how mist and clouds affect the available measuring heights. Very low cloud will cause significant propagation losses and the highest measuring height may be quite restricted. On the other hand, light clouds at say 250m can increase the backscatter from these heights without extinguishing the beam and this can help the lidar to reach higher heights than would otherwise be available.

3.4. Heights - number, ranges and synchronicity

Since the Windcube is a pulsed system, the radial velocity at all heights are effectively measured simultaneously. Wind vectors at as many heights as required are produced every 1.5 s. Usually between 10 and 15 simultaneous heights are used. The lower limit of height is around 40m, the upper depends on the background aerosol level. In clean (e.g. mountain) air it may be impossible to measure regularly over 150m. At other locations the background aerosol may be significantly higher and sensible measurements can be made over a greater height range, if required. At Høvsøre, it is possible to measure up to 300m with availability of about 50%, up to 200m with 75% availability and up to 100m with 95% availability.

The ZephIR is more restricted in the number of heights that can be chosen – no more than 5. Measuring heights are scanned each 3 s at a time, with some extra time required for re-focusing between heights. A typical cycle takes about 18 s to complete. Thus at any one height, a 3 s average is available once in every 18 s period. There will be a minimum of slightly more than 3 s between measurements at consecutive heights. This has some implications for studies involving determining instantaneous wind shear or other form of extreme analysis. Heights can be chosen from 10m and above. The upper limit is largely determined by the quadratically increasing vertical probe length. At the height of 150m, the probe length is about 50m and it is usually not advisable to measure any higher than this.

3.5. Complex terrain

Both instruments rely on the assumption of horizontally homogeneous flow. In complex terrain this assumption is violated, increasingly so as the terrain complexity increases. This is not an issue that can be tested at Høvsøre but indications from other sites indicate that errors of 5-10% in the mean speed are not uncommon. With the standard configuration, both lidar profilers use the same 30 degree cone angle. The error for both systems will be similar at a given location.

An option for the Windcube is for the user to replace the standard 30° prism with one of 15°. This will reduce the error due the flow complexity (actually the curvature of the flow) but at the cost of reduced resolution of the horizontal speed. Almost certainly, this is a sensible choice for complex terrain measurements.

3.6. Ease of installation

One of the major advantages of lidar profilers in comparison with conventional measurement masts is that the lidar systems are easily and quickly deployed. Whilst this is true for both the ZephIR and the Windcube, installation of the latter is much simpler. The ZephIR is constructed as three ‘pods’ (battery, electronics and optics), mounted one on top of the other. The assembled lidar is far too large and heavy to be moved more then a short distance so any redeployment requires a disassembly and a subsequent assembly operation at the new site. For skilled operators, each operation can easily be accomplished within one hour but there are a large number of bolts and cables to manipulate with. In adverse weather conditions, this is not a particularly amusing experience!

In contrast, the Windcube is one rectangular box with a convenient handle in each corner. Deployment is accomplished by lifting it to the required position, applying power and connecting a computer. Levelling is achieved by adjusting the legs of the Windcube until the tilt and roll indicated by the Windcube software is close to zero.

3.7. User interface

Very different approaches have been taken to the user interface and to the means of removing data from the systems. The ZephIR uses the internal processing board for all processing and data storage. In order to connect with this system, it is necessary to connect using a pc running a client program. The connection can be made using either an Ethernet or a wireless (GSM/GPRS) radio link. Using the client program, it is possible to log into the ZephIR and perform a variety of tasks – configuration, data extraction and status monitoring being the most important. Both the Ethernet and wireless links are slow and only 10 minute statistics can be sensibly downloaded in this way. Data are stored in the ZephIR on a removable compact flash card. This is an alternative method for removing the data and is especially useful if it is required to store the raw Doppler spectra or the processed 3 second data. A third possibility is to have a pc permanently attached to the ZephIR and use the data streaming facility in the pc client program to store continuously, raw Doppler spectra on the pc's hard disk. In our experience, this requires a local, almost direct (e.g. one switch) Ethernet connection between the pc and ZephIR in order to work reliably.

All the processing in the Windcube is carried out using an internal Windows pc. This is accessed over an Ethernet connection by using the Window's 'Remote Desktop' facility. Data are stored on an internal hard disk. This is accessible over the network through an FTP server running on the Windcube pc. Also provided is a utility for periodically sending 10 minute statistics as e-mail. Network connection can be realised in remote locations by using an internal GSM wireless modem. The choice of architecture and operating system means that newer data transfer protocols, e.g. 3G wireless network, can easily be implemented.

3.8. How well they measure

At Høvsøre we have tested over 10 different lidar systems, a mix of ZephIRs and Windcubes. Whilst it would be inappropriate to give individual results, we are able to give an indication of the range of the test results. Here it is important to emphasize that a lidar profiler measures over a volume with both vertical and horizontal extent and this can never be the same as a point measurement on a mast, as given by a cup anemometer. Discrepancies between the point and the lidar measurements are not necessarily because the lidar is wrong, but because it measures in a different way that we are not yet fully able to interpret. Conceivably, the volume averaged lidar measurement may be more appropriate for wind energy applications than the traditional point measurement.

Comparing cup anemometer and lidar measurements, we have various measures of the 'error'. Traditional linear regressions of measured lidar and cup speeds give a slope and, if not forced through the origin, an offset (figure 3). Whilst there are statistical tests for the uncertainty of the offset, our more pragmatic approach is to perform the regression in both ways. An offset of more than a few centimeters is almost certainly an indication that there are other error sources that are not purely or linearly wind speed dependent – for example, a wind shear dependency. Comparing slopes is usually only meaningful for the regression performed with an offset forced to zero. Here typical values are between 0.98 and 1.01 and for the 10 systems tested, we have seen values in the range 0.95 to 1.02.

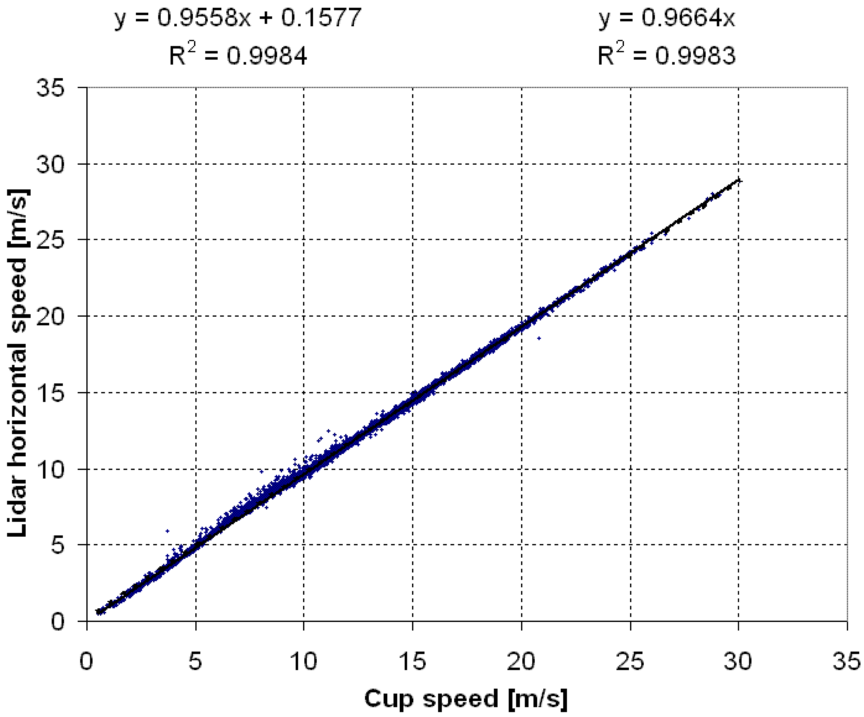

Figure 3 Example of a linear regression of lidar speed on cup anemometer speed. The example shown is for a Windcube measuring at 116m with the cup anemometer at this height as the reference. Results for regressions with and without an offset are shown at the top of the figure. The rather low value of the slope is partly attributable to an error in the effective cone angle of the Windcube. A correction to this has since added 1.5% to the slope.

Another way of characterizing the discrepancy between the cup anemometer and the lidar (at a given height) is to calculate the mean and standard deviation of the 'error' (difference in cup and lidar speed). Here typical values are 0.20 m/s for the standard deviation and mean discrepancies in the range -0.2 to 0.2 m/s. Whilst these figures are typical, the actual values will depend on the distribution on the wind speeds during the test campaign.

We are not able to identify the lidar that performs best in respect of measurement accuracy. Both the Windcube and the ZephIR are comparable and, in our opinion, perform remarkably well for remote sensing instruments.

4. Conclusions

Lidar profilers are beginning to play a role in the wind energy industry. We believe that these instruments can play a major role in replacing traditional measurement masts and providing detailed wind speed profiles for use in more accurate and repeatable power performance testing.

Two commercial lidar profilers are now available, the constant wave, variable-focus Qinetiq ZephIR and the pulsed Leosphere Windcube. At the Høvsøre facility in Denmark, Risø DTU has been testing a number of examples of both these systems. Both lidars measure to a higher degree of accuracy and with higher availability than we have previously seen from ground based remote sensing systems.

The main differences between the ZephIR and the Windcube have been presented. Probably most significant is how the ZephIR's vertical probe length increases with the square of the height but for the Windcube remains constant. This makes the ZephIR clearly better suited for measurements beneath about 80m and the Windcube clearly better suited for measurements above about 130m. In conditions where low cloud and mist are not uncommon, the Windcube has a significant advantage in that it is not affected by backscatter from the clouds.

Testing at Høvsøre has, we believe, played a significant role in the development of both the ZephIR and Windcube. Several minor defects have been detected and much feedback regarding both the physical and software design has been given. In particular, both the deficiencies of and the improvements to the ZephIR's cloud-correction algorithm have been based on the analysis of data measured at Høvsøre.

5. Acknowledgements

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ZephIR is a trademark of QinetiQ Ltd., UK. Windcube is a trademark of Leosphere, France.

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