SafeWind

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Abstract: This Deliverable of the SafeWind project presents the state of the art in ground based remote sensing technologies (sodar and lidar) related to wind energy. Sodar is found to be a well-established technology that is capable of providing useful wind resource estimates. Due to the low temporal resolution of sodar, this technology is unable to observe short-term extreme events relevant to wind turbine loading and survival. Lidar has higher absolute accuracy, higher temporal resolution and lower intrinsic measurement noise. Lidars can be used for wind resource measurements and to provide meaningful observations of short term extreme events such as gusts and extreme wind shear. However, more knowledge is required about how the spatial sampling of a lidar modifies observed extreme events in comparison with those measured by conventional point sensors such as cup and sonic anemometers. Lidars possess sufficient accuracy to be used for stand-alone power curve measurements if and when the relevant international standards can be modified to permit the use of remote sensing instruments. However both types of remote sensing technologies rely on an assumption of homogeneous flow over the sampling volume and this condition is violated in complex terrain, resulting in significant measurement errors. A possible remedy is to use flow modeling to estimate and correct for the complex terrain induced errors. Several possible uses are found for remote sensing in wind power forecasting, including the prediction of short scale extreme events using nacelle mounted lidars to the use of data assimilation from networks of remote sensors to improve forecasting accuracy.

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Contents

1. Introduction

Wind resource assessment and power curve verification are crucial measurement disciplines in the wind industry. Both require accurate wind speed registration and both require or benefit from measurement at the hub-height. As wind turbines get higher, so too does the attraction of ground based profilers, capable of measuring horizontal wind speeds remotely at heights up to or beyond that of the upper blade tip. In many environments, for example offshore or in complex terrain, the cost of high meteorological towers is considerable.

Sodars have been available for many years [17]. These are remote sensing devices that utilize the Doppler shift of sound waves in order to measure wind speed profiles. Due to the diffraction of sound and the relatively low speed of sound waves, the accuracy of sodars is inherently limited. Lidars sense the Doppler shift of light, backscattered from entrained aerosols. Laser beams do not bend in air due to the wind and light travels very fast, allowing averaging of many more spectra in the same time period and consequently much lower noise. As a consequence, the potential accuracy of lidars is significantly higher and they may in due course successfully replace cup anemometers for many duties in the wind industry.

A modern generation of lidar profilers, designed specifically for wind energy applications, began to emerge in 2006. These systems borrow heavily from the telecommunications industry, using optical fibre terminated standard components in order to reduce costs and increase robustness. At the start of 2009 there are two well established products on the market and a number of new competitors are appearing.

In this report we will give a summary of the technological status of both sodars and lidars, indicating how these technologies are being employed in the wind industry. We will comment on the instrument's ability to measure short term extreme events and provide some thoughts on how remote sensing could contribute to improving forecasting accuracy, the central theme of the SafeWind project.

2. Sodar state of the art

2.1 Measurement principle

A SODAR (SOund Detection and Ranging) measures the vertical profile of wind using the principle of acoustic backscattering. Acoustic pulses are emitted and directed into the atmosphere, where a small fraction of the emitted energy is scattered by small-scale fluctuations of the refractive index of air. The spatial scales of these fluctuations which are the most efficient for the scattering are of the same order as half wave-length of the acoustic pulses (about 10 cm).

Fluctuations in refractive index are produced by turbulence especially in wind shear layers, inversion layers, or thermal plumes in a convective boundary layer. The scattered power can be related to the temperature and velocity structure functions. However, for a monostatic SODAR, in which the transmitter and receiver are combined in the same antenna, the scatter angle is 180°, and the intensity of the received signal is only sensible to temperature fluctuations.

The Doppler shift due to the transport of the turbulent fluctuations by the wind is directly proportional to the radial wind velocity along the beam axis. The 3 components of wind vector can be determined by combining the radial velocities measured along at least 3 directions. The vertical profile of these components can be obtained by dividing the time series in small blocks, each one being related to a discrete layer in the atmosphere considering the time the pulse needs to propagate from the antenna to this layer and back to the antenna.

2.2 Different technologies

The first commercially available SODARs consisted of three-axis monostatic system, with three parabolic antennas included in large enclosures. Today, phased-array SODARs are generally used, as they are far smaller and of more flexible use. A unique antenna includes an array of vertically pointing acoustic transducers. Different directions of emission are obtained by phase delayed driving of the rows and columns. With the phased array technology, it is possible to emit more than the 3 required beams, which allows an increase of the signal-to-noise ratio without sacrificing the vertical resolution, cross checking among wind components, or choosing the paths least disturbed by the environment. Currently the number of emitted beams varies from 3 to 9 depending on the manufacturer. Generally (but not always), one of the beams is vertical, with the advantage of a direct determination of the vertical velocity and its standard deviation, and the other beams are tilted with an angle ranging between 15° and 30°. It should be noticed that some recent SODARs like AQ500 are not phased-array and still used 3 parabolic antennas.

Nearly all commercial SODARs are monostatic, because they are easy to install and require a small area. However, the advantages of monostatic and bistatic (in which transmitter and receiver are separated) configurations are still discussed among researchers and manufacturers. Monostatic SODARs are only sensitive to temperature fluctuations and show generally a decrease of the signal-to-noise ratio in near-neutral layers (especially during the morning and evening transitions, and in the mixed layer), whereas bistatic SODARs can receive signals induced by wind velocity fluctuations. Moreover, the measurement of monostatic systems relies on the assumption of horizontal homogeneity of the flow, as it combines measurements at three separate locations in space. The bistatic configuration allows a determination of the wind vector components at the same point, which is especially interesting

in complex terrain. However, the bistatic system seems to be more sensitive to ground clutter [6].

Figure 1 An Aeronvironment sodar (left) and an AQ500 sodar (right) at the Høvsøre Test Station, Denmark.

Another important parameter of the SODAR is the frequency of the emitted pulses. This frequency has a strong effect on the maximum altitude reached, as the molecular absorption by air increases rapidly with the frequency. The average height range is typically of 200 to 300 m for SODARs emitting around 4000 Hz, and 600 to 1000 m around 2000 Hz. On the other hand, high frequencies provide a reduced response to ambient noise [7], increased vertical resolution and smaller beam width. SODARs which emit in the high frequencies are the most appropriate for wind energy applications, which do not require measurements higher than 200m.

Several commercial SODARs use a multi-frequency emission (with up to 9 or 10 frequencies), which allows a significant increase of the signal-to-noise ratio. Srinivasa Rao et al. [15] observed (at about 2000 Hz) an increase in height coverage of 30% and a better consistency in the wind estimate with the multi-frequency emission compared to a single-frequency operation.

Two major drawbacks of acoustic remote sensing are the sensitivity to the ambient noise and the fixed echoes. Background noise can be generated by different activities in the vicinity but also by the interaction of the wind with obstacles, especially with trees, and with the edges of the SODAR system itself. Thus, SODARs are limited in the measurement of high wind speed. In order to reduce the influence of background noise, most of the SODARs are used with an

enclosure, which has also the advantage to reduce the noise pollution generated by the SODAR disturbing the nearby resident or working populations. In general, the higher the enclosure, the more sensitive the system to small signal levels [5]. The fixed echoes result from the interaction of the secondary lobes (or side lobes) of the antenna beam patterns with structures and objects in the surrounding of the instrument. Fixed echoes can influence strongly the signal processing as the backscattered signal intensity from these objects is very high compared to the signal due to the temperature fluctuations. In the most frequent case of not moving objects, fixed echoes tend to bias the measured wind speed towards lower values. Different methods are used by the manufacturer to reduce fixed echoes, including enclosure, modification of the beam patterns (reduction of the side lobes but with a widening of the main lobe), identification of contaminated measurements (based on the analysis of the echo history over several hours or days, or on the comparison between several beams) and correction or invalidation by the software.

SODAR measurements are also affected by rain, especially because of the noise of the droplets when they impact the instrument. Thus, the availability rate and the height coverage are reduced in these conditions, although this performance degradation varies strongly from one SODAR design to another.

The possibility for the user to fix the parameters of emission of a commercial SODAR is very different from one manufacturer to another. In most cases, the user can only choose basic parameters like vertical resolution and maximum height. However, in some systems, it is possible to define a pulse sequence with a selection of beams and frequencies which can be adapted in function to suit the characteristics of the site. This is especially useful for difficult sites for which the use of the standard parameters of emission may not give the best possible data availability and quality.

2.3 Measurements quality

As a remote sensing instrument cannot be operated in a wind tunnel, the only way for estimating the quality of its data is to compare them on site with other wind and turbulence measurements which are considered as the “reference”. This reference is provided by in-situ measurements, instrumented masts up to 200 m height, and radio-soundings for higher levels. However, there are some well-known reasons to be careful in the analysis of these comparisons, especially the different averaging characteristics (volume measurement for SODAR and point measurement for mast or radio-sounding), and the distance between the sounded volumes. This last point is especially critical for the SODAR in complex terrain, as it is necessary to operate it at a minimum distance from the mast in order to reduce the fixed echoes.

Wind speed

A large number of comparisons between SODARs and masts were made during the last three decades. Coulter and Kallistratova [5] provided a summary of the comparisons presented at the ISARS (International Society for Acoustic Remote Sensing of the Atmosphere and Oceans and Associated Techniques) conferences between 1981 and 2002. Correlation coefficient for wind speed ranges between 0.94 and 0.97. Mellinghoff and Albers [13] reported a systematic underestimation of about 10% by an Aero Vironment AV4000 SODAR compared to cup anemometers. Antoniou et al. [1] presented in the framework of the EU-funded WISE project a simultaneous comparison of 3 SODARs (AV4000, Scintec SFAS, and Metek PCS2000-64) in

flat terrain with high met masts (Figure 2). Wind speed data have been filtered especially to eliminate some unrealistic values obtained during rainy events. The slope of the regression line (mast measurements vs. SODAR measurements) for height between 40 and 116 m was about 0.86-0.87 for one SODAR, 0.96-0.99 for the second one, and 1.02-1.03 for the third one. These relatively large differences of behaviour have also been observed by Dupont et al. [9] during another comparison (AV4000, Remtech PA0, Scintec SFAS) in flat terrain with sonic and cup anemometers for height between 40 and 80 m. The correlation coefficient at 80 m varied between 0.90 and 0.98, the slope of the regression line (SODAR vs mast) at the same level ranged between 0.96 and 1.04, with bias between –0.42 m/s and 0.09 m/s. In this case the scores have been calculated without any user filtering of the data. It appeared clearly from the scattering diagrams that for two of the SODARs, the manufacturer software was efficient enough to eliminate erroneous data, while for the third one an additional filtering was necessary. It is interesting to note that the best SODAR during this campaign was the only one which combined a multi-frequency operation, with more than 3 beams, and a large enclosure. This SODAR showed also a better ability to measure strong winds (up to 18 m/s at 80 m which was the highest wind speed measured by the anemometers during the campaign) and in rainy situations, both in terms of data availability and data quality. . Finally, Antoniou et al. [1] showed a comparison between a AQ500 SODAR (which uses 3 parabolic dishes instead of a phased array antenna) and cup anemometers with a very good correlation coefficient (0.99) and a regression slope of about 0.95.

In the final report of WISE project [8], attempts to calibrate the SODAR at hub height against a cup anemometer mounted at 40 m are reported. This kind of calibration improves the accuracy of SODAR measurements compared to an instrumented mast only if the regression slope remains roughly constant with height. Another calibration method based on a transponder system is currently developed in the framework of the EU-funded UPWIND project [2]. This method consists in simulating the effect of given atmospheric conditions on an acoustic pulse and then to compare the SODAR and the simulated signals.

Wind Direction

The wind direction measured by SODAR is generally in very good agreement with vane or sonic measurements, with a higher degree of homogeneity of the results for different SODARs than for wind speed. The comparisons reported in [5] show correlation coefficients better than those obtained for wind speed (0.97 to 0.98). In [1], the regression lines SODARs / vanes obtained for the 3 compared sodars are quite similar, with a slope of about 0.98 and a constant lower than 8°. In [9], biases between the 3 compared sodars and sonic anemometers do not exceed 7°, which is of the same order of magnitude than the uncertainty in the alignment of the instruments. The standard deviations are a bit more variable, ranging at hub height from 5° to 17°. The best results were obtained with the SODAR which also provided the best measurements of wind speed.

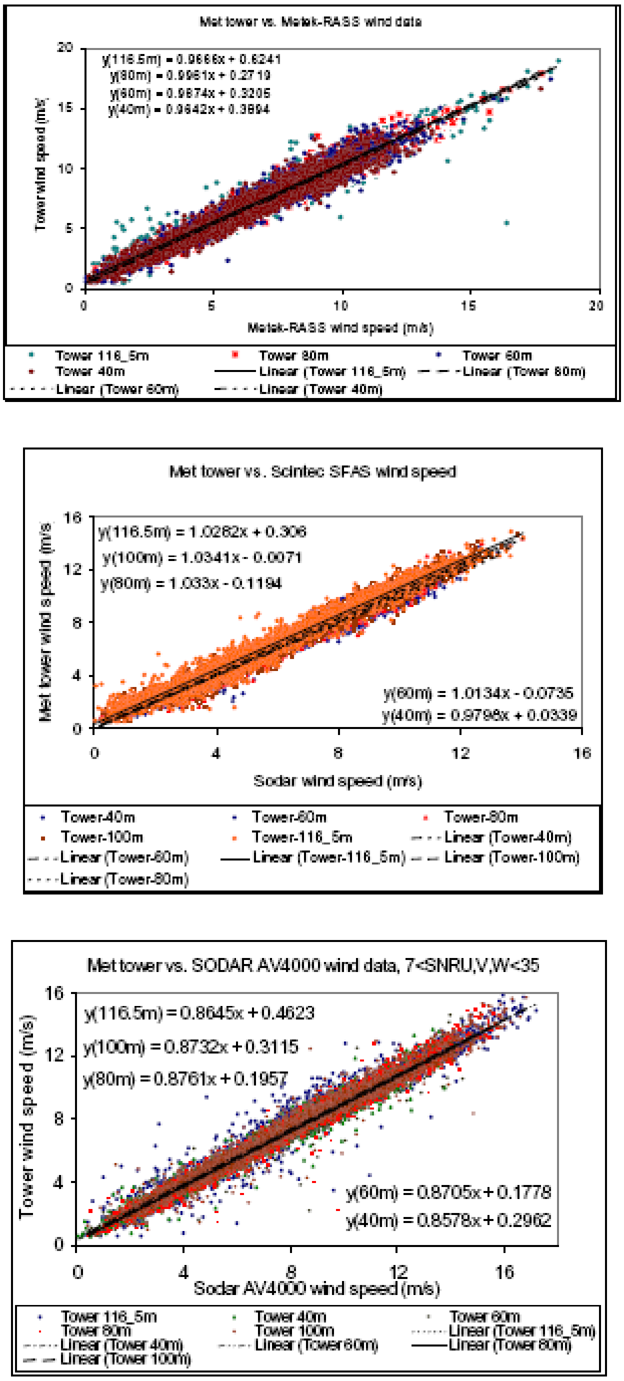

Figure 2 Comparison between wind speed measured by the Metek RASS sodar, the Scintec SFAS sodar, the AeroVironment AV4000 sodar, and cup anemometers, on the test site of RISOE [1].

2.4 Sodar measurements in complex terrain

Monostatic SODARs combine radial velocity measurements following at least 3 directions. Thus, an assumption of horizontal homogeneity of the flow is needed, on spatial scales of about some tens of meters. In complex terrain, the topography induces scale in-homogeneities which invalidate this assumption.

Bradley [3] estimates the wind speed error generated by these in-homogeneities using an analytic potential flow model for different configurations on hills. He found typical errors of 5 to 20%, depending on the hill shape and the beams orientation. Largest errors occur when the SODAR is placed at the ridge. In this case, the speed is systematically underestimated. The vertical profile of the correlation coefficient between winds measured by different combinations on the same 5-beam SODAR exhibits a maximum at the height at which the time needed for air to travel from one beam to another is equal to the time between acoustic pulses [4].

As most of the inter-comparison between SODARs and instrumented masts have been performed in flat terrain, few results are available in complex terrain. Mellinghoff et al. [12] presented comparisons between an AeroVironment 4000 SODAR and cup anemometers on two complex sites. On the first one, a good agreement was found, whereas a sodar underestimation of about 10% was observed on the second one. Dupont et al. [10] found a global underestimation of 12% with a Scintec SFAS SODAR on a complex terrain of southern France, with a strong directional dependency, as the ratio between SODAR and sonic anemometer wind speeds was found to vary between 0.80 for a wind sector corresponding to high terrain slope, and values close to 1 for wind sectors corresponding to low steepness.

Future works are planned to correct the remote sensing data in complex terrain using CFD numerical simulations, for example in the framework of the EU-funded project WAUDIT.

2.5 Turbulence and extreme events as observed by sodars

On site measurements of turbulence are generally expressed in terms of horizontal turbulence intensity (ratio between standard deviation and mean value of the horizontal wind speed), probably because it is the only turbulent variable that can be measured by cup anemometers. However, the vertical component of the turbulent kinetic energy is probably also important to characterize the loads on wind turbines.

The standard deviations of the three wind components (σ_u, σ_v, σ_w respectively) can be measured with a SODAR. Coulter and Kallistratova [5] mentioned that the correlation coefficients obtained for σ_w in the comparisons with anemometers are globally reasonable (generally higher than 0.8), but are rather poor for the horizontal components. There are two main reasons to explain this behaviour. The first one is the separation in space and time of radial velocities used to measure the horizontal components, whereas the vertical component is most of the time directly measured. The second reason lies in the error in subtraction of vertical velocity from radial velocities.

SODAR measurements of w are generally found underestimated compared to sonic anemometers values. The main reason is the difference of spatial and time scales which are taken into account by both instruments. A sonic anemometer integrates almost the entire spectrum of time scales, whereas the SODAR cuts the higher frequencies because of the time needed to perform a complete antennas cycle. Moreover, a SODAR cannot take into account correctly the turbulent scales smaller than the volume of measurement. For example, Thomas and Vogt [16] found a regression slope of 0.63 (with a constant of 0.1 m/s) for a Remtech SODAR, and Dupont et al. [10] found a regression slope of 0.54 (with a constant of 0.18 m/s) for a Scintec SODAR (Figure 3).

For the same reason, measuring extreme gusts seems difficult with a SODAR, as the minimum time needed for a correct measurement of the horizontal wind speed cannot be less than about 1 minute. Measuring wind speeds higher than about 20 m/s on this time scale is even more difficult because of the poor signal-to-noise ratio.

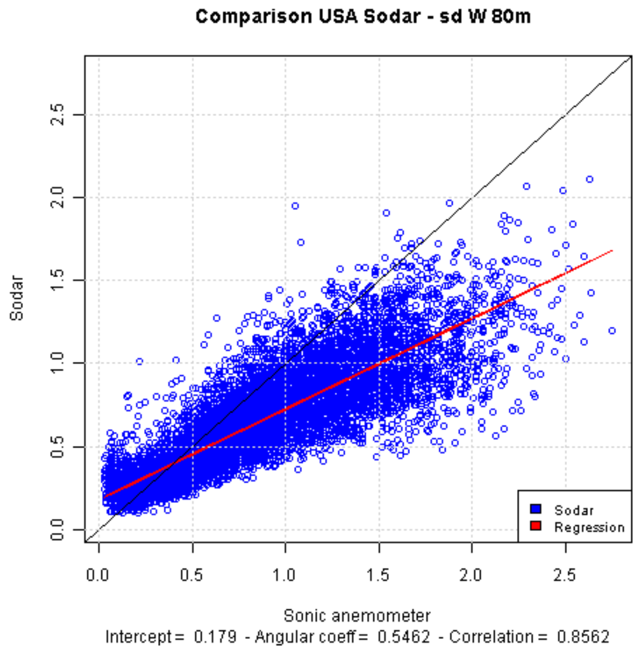

Figure 3 Comparison between standard deviation of vertical velocity measured by a Scintec SFAS sodar and a Metek USA-1 sonic anemometer, on a complex terrain of South of France [10].

3. Lidar state of the art

3.1 Principle of operation of lidar profilers

A lidar profiler performs the same task as a sodar – it measures the vertical profile of the horizontal wind speed. Lidars emit a beam of coherent laser light. Backscattered light from suspended aerosols illuminated by the beam is Doppler shifted since the aerosols are convected in the wind. A good assumption (only really violated in rain) is that the aerosols move at the wind speed. Hence the Doppler shift will be directly proportional to the projection of the wind speed vector along the laser beam. By pointing the laser beam in different directions whilst assuming the flow to be horizontally homogeneous, it is possible to determine the horizontal wind speed and direction.

The task of determining the very small Doppler shift is performed using the technique of coherent detection. By mixing the returning backscatter with a copy of the un-shifted laser light (the sø-called ‘local oscillator’) a beating signal is obtained at the difference frequency. The mixed signal is detected by a photo diode, the resulting electrical signal is digitally sampled and using an FFT, the power spectrum is obtained. By repeating this process several thousand times and aggregating the power spectra, the inherent noise is suppressed sufficiently to enable the Doppler frequency to be determined.

3.2 Commercially available lidars

Already established on the market for lidar profilers are both the QinetiQ/Natural Power ZephIR and the Leosphere Windcube. These two radically different designs are described in some detail and compared in [18].

Briefly, the ZephIR is a continuous wave (cw) lidar that uses a variable focus to interrogate successive heights. Each height is conically scanned for one or three seconds, after which the horizontal speed is recovered from the set of radial speeds obtained for the different azimuth directions. Up to five heights are scanned successively. ZephIRs have been commercially available since 2006 and it is estimated that well over 50 units are in operation.

In contrast, the Windcube is a pulsed laser, discriminating between heights or, more correctly, height ranges, by use of the arrival time of the backscatter in relation to the start of the pulse. This technique, familiar from sodar technology, is known as range-gating. Radial wind speeds for all the required heights are obtained simultaneously. The laser beam does not scan continuously. Instead radial speeds are acquired successively for four perpendicular directions, a complete cycle taking between 4 and 5 seconds. A new horizontal speed for each height is calculated on each rotation step, using one new and three old radial speed values. Windcubes have been commercially available since the start of 2008. About 50 units are already in operation.

At least two new lidar systems intended for the wind energy industry have been announced. That most obviously competing for the ground-based profile market is the Sgurr Energy Galion [19]. Like the Windcube, this is a pulsed lidar. Whilst the Windcube has a simple rotating prism to steer and incline the laser beam, the Galion uses a novel 2 degree of freedom scanner head. This geometry can reproduce the so-called velocity azimuth display (vad) scanning patterns of the Windcube (but here permitting a variable cone angle) but also has the flexibility to perform terrain scanning and irregular scanning patterns that are claimed by the manufacturer to be beneficial in complex terrain. The Vindicator is also a pulsed lidar system. It has three fixed angles, designed for forward looking measurements from a wind turbine nacelle. In this sense it is not optimized for ground based upwards looking measurements and it is likely that the geometry will yield less accurate horizontal speeds when measuring from the ground. The only available test results show considerable scatter when compared to a cup anemometer.

Figure 4 The Leosphere Windcube lidar (left) and the QinetiQ/Natural Power ZephIR lidar (right) at the Høvsøre Test Station.

3.3 Lidar testing

Lidar testing has many purposes. To start with it is important to assess the performance of new designs. This gives important feedback to the lidar manufacturer, spurring improvements. At a later stage it becomes necessary to formally document the performance of specific lidars. This will become increasingly more important as lidars are used more frequently for resource assessment. At the current level of lidar development there are still significant differences between nominally identical lidar systems. These differences are due to both to component tolerance variation (e.g. the exact angle of the prism) but also often to degradation or sub-optimal performance of particular components.

Lidars can not be accepted as substitutes for cup anemometers unless we can verify their accuracy using calibrated and traceable instruments. Traceable reference instruments alone are not enough – these cup anemometers must be mounted on a tower and the lidar being tested must be placed in the vicinity of the same tower. It is essential to examine all the possible error sources that can arise from these juxtapositions. Fortunately as lidars improve in quality, the clearer signals help to reveal the more subtle details. This is well illustrated in Figure 5 where it is possible to see both the influence of the mast on the cup anemometer and also the influence of the mast wakes on the lidar measurements. In order to mitigate the errors it is possible (and necessary) to derive corrections for the cup anemometers that take into account the effect of the mast and booms. Lidar testing inherently requires measurements at several different heights and this precludes the simple and most accurate solution of using a top-mounted cup

anemometer only. For lidars with few, fixed beam directions such as the Windcube and Galion, it is possible to choose wind sectors where the lidar beams are unaffected by the mast wakes. Lindelöw [22] has made a thorough analysis of these issues for the Høvsøre test site.

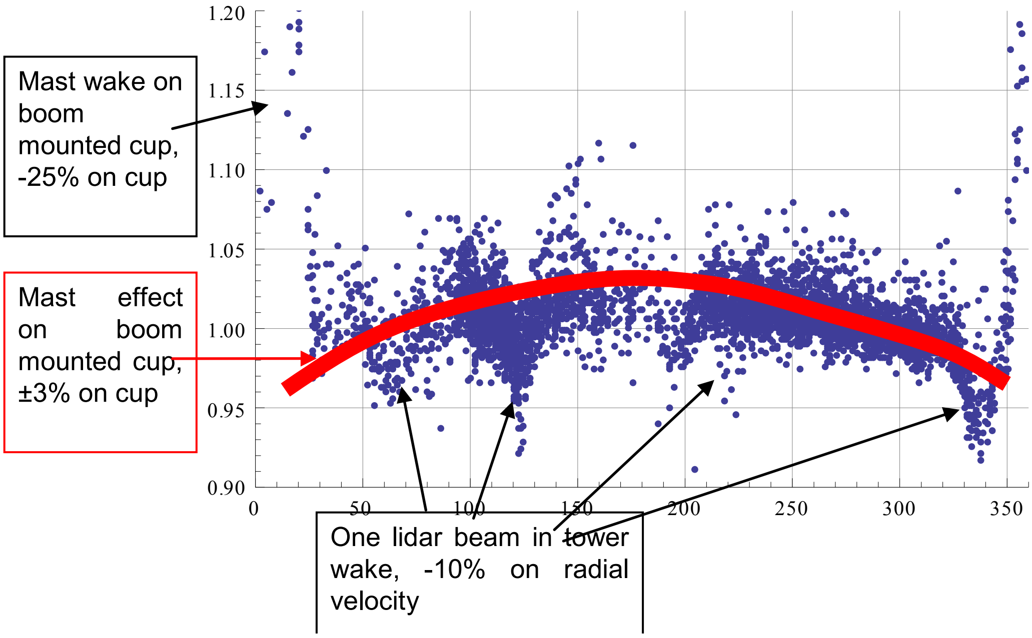

Figure 5 Lidar speed normalised by cup anemometer speed (y axis) as a function of wind direction (x axis). An example showing both the mast effect on the cup and effect of the mast wakes on the lidar beams.

3.4 The accuracy of contemporary lidars

Here we will attempt to place the accuracy of the best available lidars in relation to the accepted standard – the cup anemometer, here implicitly meaning a Class 1 cup anemometer calibrated to the Measnet standard. For legal reasons, we are currently unable to comment on the accuracy of cw lidars. Although we have recently commenced testing of the Galion lidar, we do not yet have sufficient data to support a rigorous conclusion. Therefore we restrict our comments to measurements made with Windcube lidars at the Høvsøre Test Station [20].
Wind speeds reported by the Windcubes are highly repeatable and have exceptionally low scatter for a remote sensing device. It is usual for the Windcube wind speed to be within +/- 1.5% of the cup anemometer speed (for a regression forced through zero) and the r^2 value can often exceed 0.995. A linear regression between lidar and cup anemometer data is shown in *Figure 6*
for a dataset where periods of low wind speed, ice affected cup anemometers, rain and high wind veer have been removed. Using a 2-parametric regression [22] it is possible to estimate the altitude error made by the lidar (an example is shown in Figure 7). This is typically less than 5m.
In an analysis of the error propagation in an annual energy production estimation (AEP) [23] it was shown that the current precision of a Windcube lidar would lead to an error in the AEP prediction of between 2.5% for a coastal site (characterised by low shear and high wind speed) and 6.5% at an inland site (characterised by high shear and medium wind speed). In

comparison, using a perfect cup anemometer but with a vertical extrapolation from 60m to 100m using WaSP gave an error of between -8.5% for the coastal site and +6% for the inland site.
Although the current level of lidar precision generally gives a reduction in the AEP uncertainty in comparison to vertically extrapolated mast measurements, it seems to be desirable to further improve both the lidar precision and our ability to verify this. In the medium term, we believe it is realistic is to be able to verify a precision of 1% and an altitude error of less than 3m. A higher precision than this will probably be difficult to document using mast-mounted cup anemometers that themselves have combined calibration and mast/boom uncertainties already approaching 1%.

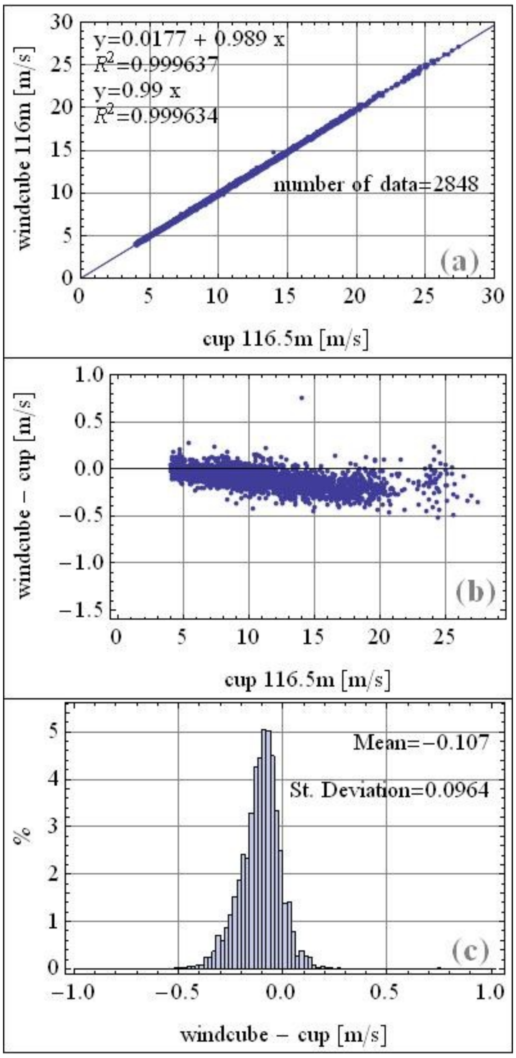

Figure 6 Comparison of wind speed measurements at 116m between the Windcube lidar and the cup anemometer. In all figures, data were selected within the wind sectors which are not affected by mast or turbine wakes. Periods with low wind speed, ice affected cup anemometers, rain and high wind veer were filtered out. (a): Regressions (firstly with an offset and secondly forced through zero); (b): Difference between wind speed measured by the LiDAR and by the cup anemometer at hub height as a function of (cup) wind speed; (c): Distribution of the difference between the wind speed measured by the LiDAR and the cup anemometer.

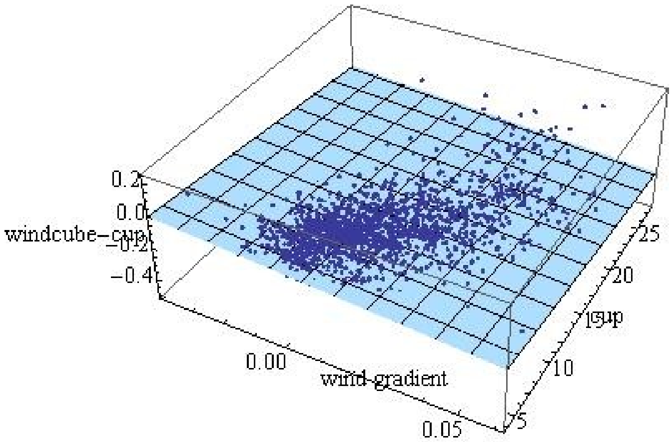

Figure 7 A two-parametric linear regression showing lidar error as a function of wind speed and wind shear. This method can separate speed and shear dependant errors.

3.5 Complex terrain

Many, perhaps a majority of lidars are purchased in order to make measurements in complex terrain, where the cost and difficulty of raising masts can be avoided. Unfortunately, lidar profilers extract the horizontal wind from a set of inclined, radial speeds under the assumption that the flow is homogeneous over the entire measuring volume. Whilst this works satisfactorily for flat terrain, it is clearly untrue in flows with significant curvature such as at the top of a hill. Changes in the upstream and downstream values of the vertical speed are incorrectly interpreted as decreased horizontal speed (for a convex flow). The errors can approach 10% in the terrain complexity experienced for wind energy projects. Foussekis [24] shows recent measurements from three different lidar configurations in complex terrain.

It was widely believed that a smaller cone angle would mitigate the effects of the inhomogeneous flow. This is not true, particularly for the case of a uniformly varying vertical speed over the measuring volume. Bingöl [25] shows that the error on the horizontal speed is independent of the cone angle. This is confirmed by the measurements of Foussekis [24] who used Windcubes with both 15 and 30 degree cone angles.

One approach is to use a flow model to estimate the error made by the lidar in a given terrain [28]. The idea here is for a given direction to calculate the orthogonal components of the flow at the measuring points of the lidar. By projecting all three components along the radial directions of the lidar, it is possible to simulate the 'horizontal' speed that would be obtained from the lidar and relate it to a modelled horizontal speed above the lidar location or at an adjacent mast. Initial measurements show some measure of success for this method but of course it is limited by the flow model's ability in the given terrain.

3.6 Wind direction

In addition to wind speed, wind direction is also reported by the lidars. Figure 8 shows a comparison of wind directions measured by a wind vane and reported by two different lidars. The data are simultaneous and are taken from measurements at the Høvsøre Test Station. All data are for a 100m sensing height. Significant differences in measuring performance can be seen between the two systems. The pulsed Windcube (the orange-brown points) performs a very robust wind direction measurement with little scatter and a slope of 1.00 when correlated to

the wind vane data. For the continuous wave ZephIR system (the blue points), the scatter is much more considerable. A peculiarity of the ZephIR design is that (due to monodyne detection) there is an 180˚ ambiguity in the direction of the sensed wind speed. This ambiguity is usually correctly resolved by comparing the sensed wind speed with a value obtained from a sensor on the top of the instrument. However in strong wind direction shear, the possibility remains that the incorrect direction is chosen and we can see occurrences of this in the dataset. A few of the ten minute data points reported by the ZephIR are exactly 180˚ offset, indicating a ten minute period in which all the directions were incorrectly assigned. If only a fraction of the wind speeds in a ten minute period are incorrect, the error will be less but still considerable and points of this nature are also evident.

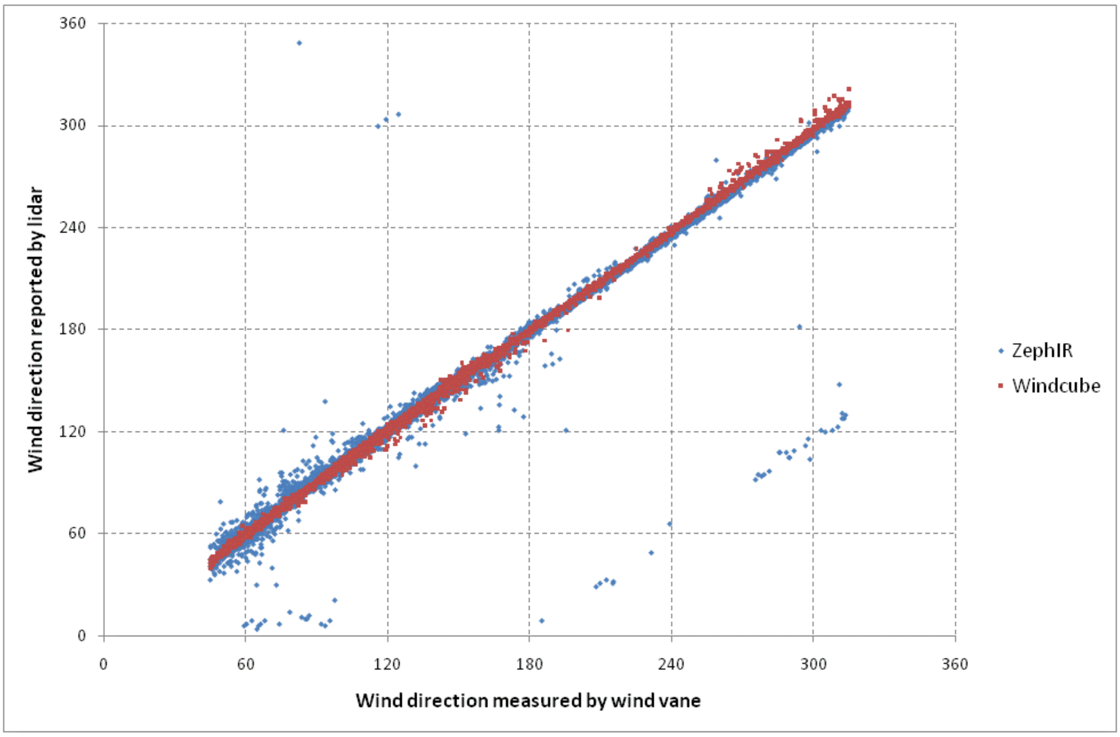

Figure 8 Wind directions reported by two lidar types compared to a wind vane measurement. The data are from the Høvsøre site, sensed at 100m.

Lidars are particularly well suited to the measurement on wind direction shear since the measurements at different heights all have a common absolute reference (the ground orientation of the instrument). Wind direction shear measurements from point sensors (wind vanes or sonic anemometers) are often difficult to analyse since each individual sensor will have an absolute orientation that is only practically possible to determine with an accuracy of a few degrees.

3.7 Turbulence

An important question to answer is how to relate the turbulence measured by a lidar to the turbulence that would have been measured by a cup anemometer at the same position. Since the lidar measures over a volume whilst the cup measures at a point, intuitively the two values will not be the same. We would anticipate some attenuation due to the volume averaging as shown in Figure 9. Wagner [26] describes a simple model for the turbulence seen by a conically scanning, cw lidar. Disregarding the effects of the vertical turbulence, the model indeed confirms

that with a 30 degree cone angle we can expect the lidar to observe about 80% of the wind speed standard deviation that would be obtained from a cup anemometer reading. The attenuation is shown to be mostly due to the scanning in the horizontal plane with a secondary contribution due to the attenuation along the length of the laser beam. Experimental results from flat terrain (for example Figure 10

Figure 10) generally support the model although considerable scatter is observed in the cup/lidar turbulence ratio.

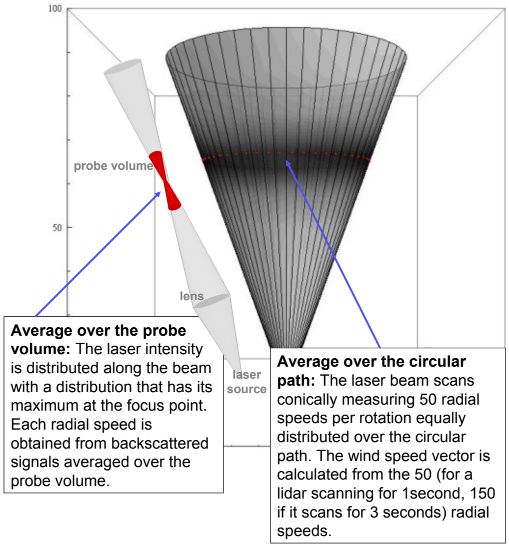

Figure 9 Averaging mechanisms inherent in a cw conically scanning LiDAR

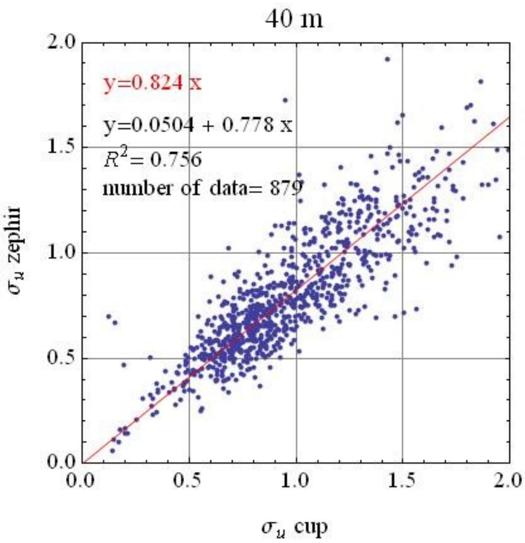

Figure 10 Regression between 10 minutes horizontal wind speed standard deviation measured by a cw conically scanning LiDAR and a cup anemometer.

Recent measurement results in complex terrain [24] show that the real world is more complicated than the simple model. Firstly, a Windcube lidar with a 30 degree cone angle measuring in complex terrain observed almost the same turbulence as an adjacent cup anemometer. A second Windcube measuring at the same location but with a 15 degree cone angle observed a 15% higher standard deviation than the cup anemometer. There are two immediate conclusions to be drawn here: Firstly the ratio of standard deviation between a cup anemometer and a lidar observation apparently depends on the terrain type, probably because the ratio between the vertical and horizontal turbulence will be different. The apparently higher 'horizontal' turbulence seen by the lidar in complex terrain is actually contamination from more vertical turbulence. This suspicion is supported by the second observation; that a different cup/lidar turbulence ratio will be observed with different cone angles. In a recent unpublished presentation (Upwind wp6 meeting, CRES Athens, March 9-10 2009) Mann has explained this effect and shown that the ratio is indeed a function of the cone angle, diverging as the angle approaches zero.
In summary we know that the horizontal turbulence reported by the lidar will be attenuated due to the spatial averaging. To a first approximation, the attenuation is roughly constant with height since both the turbulent length scale and the scanning area increases with height. We are also beginning to understand that the turbulence reported by the lidar is actually a true mix of both the horizontal and vertical turbulence. What we actually observe will depend on the true ratio of horizontal to vertical turbulence (which varies with terrain type and atmospheric stability), on the cone angle of the lidar and on how much the various components are attenuated by the volume averaging.

3.8 Extreme events as observed by lidars

Lidars are much better suited than sodars for measuring short term extreme events, for two main reasons. Firstly lidars report reliable wind speeds at the rate of about $1s^{-1}$, about two orders of magnitude faster than sodars. Secondly lidars can measure in high wind speeds without problem whereas sodars can not, for the reasons we saw in section 2.5.

In much the same way that horizontal turbulence is attenuated, we can expect small scale gusts observed by the lidars to be modified by the volumetric averaging of the lidar and also by the contamination from the small scale vertical turbulence. First when the horizontal scale of the structures significantly exceeds the diameter of the lidar scanning pattern will we expect to see a closer agreement between extreme speeds measured by lidars and in-situ sensors.

Since lidars are able to measure profiles (of both speed and direction), they are obviously able to detect extreme shear events that would require a complete mast and sensor array using in-situ instrumentation. Shear events covering the entire rotor disc can be detected even for large multi-MW size wind turbines from a single, ground-based sensor.

Due to the major differences in the scanning patterns of the cw and pulsed lidars, we can expect to see significant differences between the lidar designs in the way extreme events are observed. Probably the pulsed lidars, reporting all heights simultaneously, will observe shear events with higher fidelity than possible with the cw lidars, since these can be up to 18s on completing a complete cycle of measuring heights. Conversely, cw lidars scan a horizontal plane significantly faster than is possible with pulsed lidars. Hence cw lidars are probably better able to smaller scale gust type events than pulsed lidars.

3.9 Bankability

As most lidars are purchased in connection with wind energy project development, an important question is whether lidar wind resource data can be accepted by the commercial banks on the same footing as cup anemometer data – is lidar data bankable? Here we are in a sense fortunate that there is no formal standard for resource assessment and therefore the 'rules' are much less rigid than for power performance verification. This gives the freedom (and requirement) for projects and their supporting wind measurements to be assessed on a case-by-case basis. It is our belief that well documented lidar measurements in flat terrain should be similar in precision to cup anemometer measurements and that, as we saw above, the avoidance of vertical extrapolation can in fact reduce the overall AEP estimate uncertainty.

Our advice is to make early contact to the banker's consultant – the organization who will perform a 'due diligence' analysis on the measurement project. By a process of lidar verification against a well documented measurement mast before and preferably also after the measurement campaign, it should be possible to assess the accuracy of the lidar measurements. It is also clear that a code of practice for this process is required.

In complex terrain it is often the turbulence levels rather than the wind resource that is most critical to determine. As indicated above, with our current level of understanding we can only make qualitative rather than quantitative statements about the relationship between the turbulence intensity measured by a cup anemometer and a lidar. This is a research area that should be given high priority.

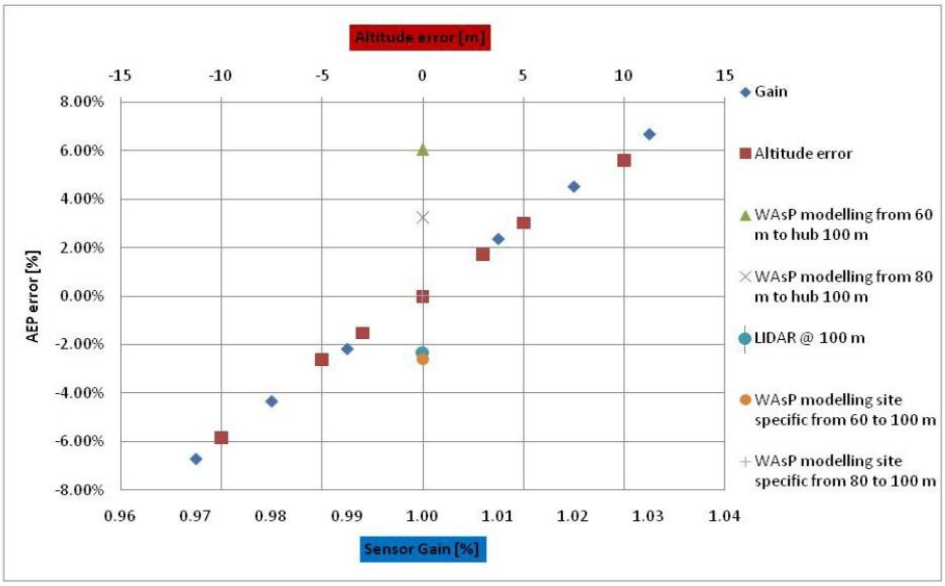

Figure 11 AEP prediction results for a 100 m hub-height, 2 MW turbine in a flat land site. Blue diamonds indicate the errors due to sensor gain, red squares the influence from altitude errors. The light blue circle is the result from the lidar measurements while cross and plus sign is a WAsP model result from a measurement at 80 m and the orange circle and green triangle is the WAsP result from 60 m, explained in a following chapter.

3.10 Better power curves with lidars?

Power curve measurement is also a 'classic' wind measurement discipline where lidars can participate. There are two good reasons for using a lidar; firstly replacing tall and costly meteorological towers by ground (or nacelle) based lidars, secondly using the lidar to measure the complete profile over the entire rotor height in an attempt to mitigate the effects on the power curve of large speed variations over the rotor disc. Wagner [29] has shown with simulations that profile measurements combined to an equivalent wind speed should reduce the scatter in a power curve.

An initial measurement campaign [27] shows that for wind speed profiles close to ideal, the power curve obtained from the equivalent wind speed is close to the conventional version using a hub-height cup anemometer. The measurements did show that the accuracy of the lidar measurement needs to be high at all rotor heights if the equivalent wind speed method is to be able to reduce the power curve uncertainty. Noisy measurements at just one height will very easily add more scatter to the power curve than the equivalent speed method can normally remove.

Currently, a possible revision of the IEC16400-12-1 power curve standard is under consideration. One possible change is to allow the use of profile measurements with a remote sensing device as a supplement to a conventional mast measurement. Work is being carried out in order to define a classification of such a remote sensing device and how its verification should be performed.

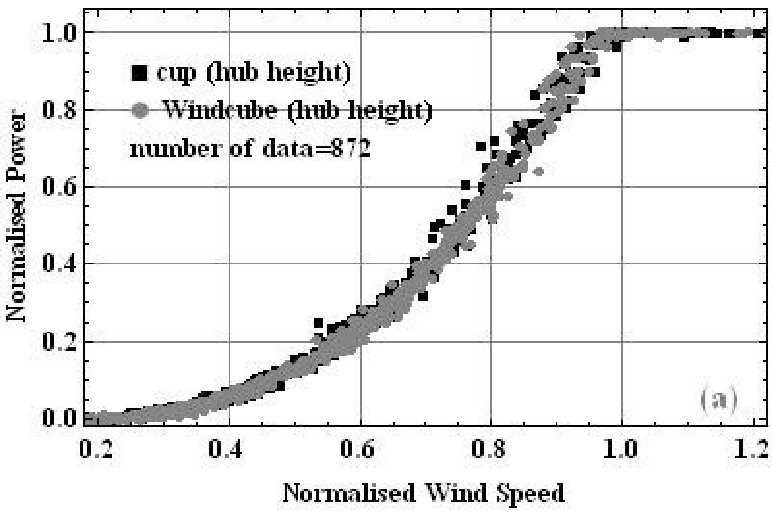

Figure 12 Power curve scatter plot of a multi-megawatt wind turbine obtained with wind speed measurements at hub height with a cup anemometer and a lidar

4. Possible remote sensing contributions to forecasting improvement

Remote sensing can be used for wind power forecasting applications in different horizons and/or scales: as on-site instrumentation for the monitoring of local turbulence-driven wind conditions or as an off-site system to support Numerical Weather Prediction (NWP) systems through data assimilation in the forecasting of regional winds.

In the very short term range, say from 1 to 10s, a spinner-based lidar can be used to forecast the upcoming wind conditions several seconds ahead. This is practically achieved by placing the lidar in the hub of the wind turbine and scanning the area in front of the wind turbine so as to measure the wind speed as seen by the rotor. This real time forecasting capability allows improved control of the wind turbine and the wind farm enhancing efficiency and safety.

In the short to medium term, from some hours to one day, remote sensing can be used to improve the performance of NWP systems by data assimilation. This could be feasible in the case of areas with very large wind power penetration through the installation of a grid of remote sensing instruments that can feed a NWP model to get a more reliable analysis of the regional winds of the area of interest. A remote sensing grid can also be used to provide warnings of the passage of fronts to wind farms situated some minutes/hours downstream in the direction of the storm.

In connection with its standard application in wind assessment activities, remote sensing instruments can be used prior to the operational phase of a wind farm in order to calibrate the wind conditions at each wind turbine position. This can be particularly important in complex terrain, where the wind flow can change rapidly from one wind turbine position to another. Traditional site calibration is a technique that aims at assessing the wind speed at each wind turbine hub height based on site-to-site wind speed correlations between a reference and a temporary mast. Similarly, power curve performance tests are conducted to assess the relation between wind speed and wind power at the particular conditions of the site. The higher level of portability of remote sensing instruments is a logical advantage in substituting costly 70-100m masts. The information obtained from the site calibration, together with the wind turbine power curve, can be used for the generation of an historical database of wind farm production virtual time series. These historic records are typically used by wind power forecasting systems for training (tuning of model parameters) at the start-up phase of the operation of a wind farm, when real production measurements are not available or come with low quality.

5. Conclusions

Much progress has been achieved in the SODAR technology since its first use in the seventies, especially in the antenna, the processing of Doppler signals, the efficiency in the extraction of echo signals from ambient noise and ground clutter and in the elimination of outliers. A very good level of accuracy is now reached for wind speed and direction measurements. New improvements are expected in the next years especially to better eliminate ground clutter, better operate in rain, and to allow shorter averaging times. The development of bistatic SODARs is also considered as a way to improve the measurements accuracy in complex terrain.
Sodars are well established technologically. Commercial systems have been available for many years although only recently have systems been designed specifically for wind energy applications. Due to the relatively long wave length of sound beams and the relatively low speed of sound, the accuracy of sodars will never be comparable to in-situ anemometry. For physical reasons also, the data rate available from a sodar will always be low (< 1 min^{-1}) and this coupled with their unavailability in high wind speeds make them inappropriate for detecting short scale extreme events. However, sodars can contribute to document (at a much lower price than lidars) the mean wind vertical profile (with the associated wind shear), and its variability in time and space.

Since the wavelength of light is very small and the speed of sound very high, the potential accuracy of lidars is high and will ultimately match that of in-situ anemometry.
Lidars are beginning to play a significant role in wind energy. Currently there are two well established lidar profilers on the market and several new models are appearing. It is probable that as quality and reliability improve the market size will increase markedly resulting in a reduction in price.

Improvements in lidars require us to be ever more precise in our testing. At the same time, the lower measurement noise of pulsed lidars helps to reveal the subtle details of mast and wake effects. It is now important to consider both the effect of the mast on the cup anemometers and the effect of the mast wakes on the lidar measurements. We estimate that the best pulsed lidars now measure to within 1.5% of a traceable cup anemometer with an altitude error of less than 5m.

In complex terrain, the inhomogeneity of the flow, in particular changes over the measuring volume in the vertical wind speed, can cause errors of up to 10% in the horizontal wind speed reported by the lidar. These errors can be estimated by the use of 3D flow models.
Turbulence, in particular the standard deviation of the horizontal speed, will be observed differently by a lidar than by a cup anemometer. This is partly due to the volume averaging but also because all 3 turbulence components are actually sensed by the lidar to different degrees, depending on the scanning geometry. On a flat site with a 30 degree cone angle, a conically scanning lidar will typically report between 80 and 90% of the standard deviation measured by a cup anemometer.

Due to a relatively high data rate, lidars can detect short term extreme events although the various lidar scanning patterns will each modify how such events are observed. This is a major subject for our future work in the SafeWind remote sensing work package.
In terms of the broader aims of the SafeWind project, improving forecasting accuracy, remote sensing can play several roles. Nacelle mounted lidars could be used to predict sudden and extreme changes in wind speed and direction – e.g. the arrival of a Bora wind. This could aid extreme load alleviation and also have important dispatching advantages. At the very short term, lidars can also detect gusts and shear events in front of the turbine and if the information is made available to the turbine controller, change blade pitch angles accordingly. Again, significant load alleviation can be achieved.

Networks of remote sensing devices could provide wind profile information for data assimilation, thereby improving NWP systems. As lidar performance improves and prices fall, this could be an economically attractive option.

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