Remote Sensing of Wind

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1. Ground-Based Remote Sensing for Today's Wind Energy Research

Wind turbines are being installed at an ever increasing rate today, on and offshore, in hilly and forested areas and in complex mountainous s terrain. At the same, as the wind turbines become bigger and bigger, they reach higher and higher into the atmosphere but also into hitherto unknown wind and turbulence regimes.

The traditional method for accredited measurements for wind energy is to mount calibrated cup anemometers on tall met masts. But as turbines grow in height correspondingly high meteorology masts and instrumentation becomes more and more cumbersome and expensive. Costs for installation of tall instrumented met towers increase approximately with mast height to the third power and licensing permits can be time consuming to obtain.

With hub heights above 100 meters and rotor planes nowadays reaching diameters of 120m or more on today's 5 MW turbines the wind speed distribution over the rotor planes will no longer be representatively measured from a single hub height measurement point, but will also require a multi-height measurement strategy with measurements ranging in heights between 50-200 meters, for the purpose of capturing the wind distribution simultaneous over the entire wind turbine rotor.

1.1. Wind Remote Sensing (RS) methodologies:

A simple way to remotely determine the wind speed is by observe marked cloud drift aloft from the ground on a sunny day.

More quantitative and accurate remote sensing measurement techniques for wind energy applications include nowadays sound and light wave propagation and backscatter detection based instruments such as SODAR, LIDAR and Satellite-based sea surface wave scatterometry.

Today's quest within RS research for wind energy is to find useful replacement alternatives for expensive and cumbersome meteorology mast erection and installations.

However, accuracy is of particular importance for site and resource assessments irrespectively of terrain, on or offshore, , and measurement errors much in excess of 1% cannot be tolerated neither by banks nor by project developers, as 1% uncertainty in mean wind speed results in 3 % uncertainty in mean wind power.

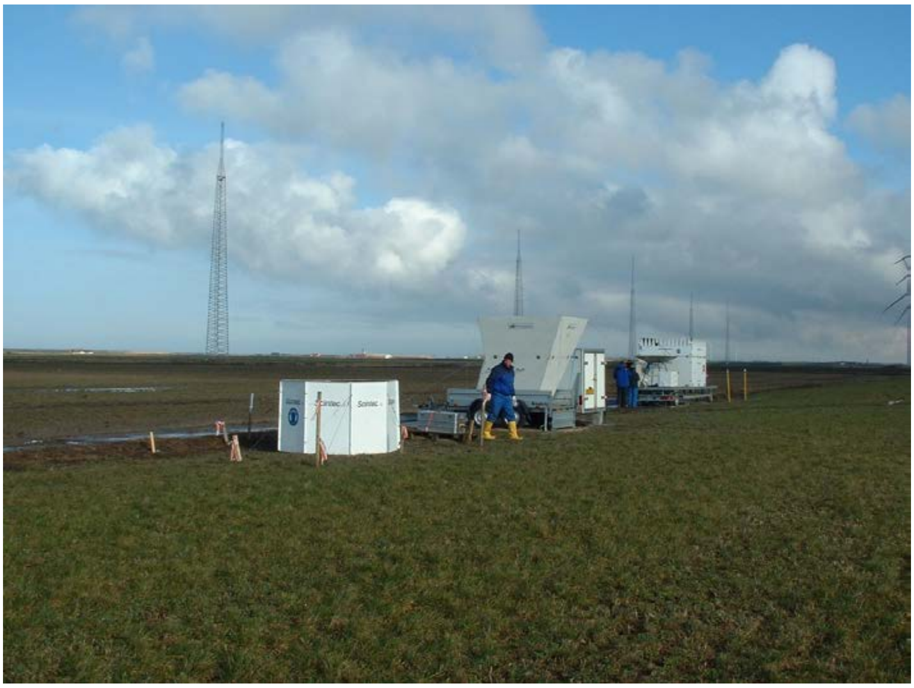

Figure 1 Commercial available SODARs being inter-compared at the Danish Høvsøre test site during the WISE 2004 experiment: An array of SODARS (and one LIDAR) during inter-comparison and testing against the tall met towers (up to 168 meter above ground) equipped with calibrated cup anemometers at several heights. Venue: The Test station for large wind turbines, Høvsøre, Denmark.

Part I: Remote Sensing of Wind by Sound (SODARS):

SODAR is based on probing the atmosphere by sound propagation, LIDAR (Light Detection and Ranging) is based on probing the atmosphere by electromagnetic radiation (microwaves or laser light) and satellite remote sensing is based on microwave scatterometry on the sea surface and Synthetic Aperture Radar (SAR) methods.

The first two (SODAR and LIDAR) are direct measurements of wind speed based on Doppler shift whereas the satellite scatterometry are based on proxy-empirical calibration methods.

In this, the first of two articles on remote sensing and wind energy, a description of the background and the state of the art re SODAR is addressed. In a forthcoming issue, the corresponding development and application LIDAR remote sensing technology will be addressed.

Wind turbines operate within the so-called atmospheric boundary layer, which is characterized by relatively high turbulence levels. Turbulence is here created from the strong wind shear due to the proximity of the Earth’s surface. The wind speed at the ground is always zero, both on and offshore!

SODAR (SOund Detection And Ranging) is a remote sensing methodology for measurements of the wind speed and direction aloft at various heights in the atmosphere.

SODAR's are ground-based instruments that transmit a sequence of short bursts of sound waves at audible frequencies (2000-4000 Hz) upward in three different inclined directions into the atmosphere.

The SODAR measurement technology was well established and in operational use for decades by now, starting in the 1980' ties where they served environmental protection issues and has been extensively applied to atmospheric research for environmental protection air pollution prediction measures well before the present burst in wind energy research and application.

In Germany for example, SODARS have been commissioned on several nuclear installations to replaced tall meteorological towers and serve now as operational monitoring devises of the local wind speed, direction and atmospheric stability.

As the sound waves from a SODAR propagate forward a small fraction of the transmitted sound energy is scattered and reflected in all directions from temperature differences and turbulence in the atmosphere.

A very small fraction of this scattered energy reaches back into the SODAR's detector, which in principle is a directional-sensitive microphone.

The height at which the wind speed is measurement is usually determined by the time delay in the backscatter from the transmitted pulse. Under standard atmospheric conditions with sound propagation speed of about 340 m/s backscatter from a SODAR measurement at 170 meters height above the ground will reach back into the detector after 1 s delay time.

The wind speed component in the transmitted beam direction is subsequently determined from the Doppler shift observed as frequency difference between the transmitted frequency and the frequency of the received backscattered sound wave.

By combining the measured wind speed components obtained in this way from three differently inclined sound path directions, e.g. from one vertical and two inclined sound paths, the three-dimensional wind vector including wind speed and direction and tilt can be measured by SODAR from preset heights from the ground and up to the limit determined by the SODARS lowest acceptable Carrier-to-Noise (C/N) ratios.

The above description is for a mono-static system, where transmitter and receivers are co-located on the ground. But alternative configurations, e.g. in the form of so-called bi-static SODAR configurations exists as well, where the transmitter and receivers are separated e.g. 100-200 meters on the ground.

Bi-static configurations have significant S/N-ratio advantages over mono-static configurations for wind energy applications. Received backscatter in a bi-static configuration is not limited to direct (180 degree) backscatter from temperature (density) fluctuations only, but enables also backscatter contributions from the atmospheric turbulence. And the higher the wind speed the more turbulence…

As a consequence significant improvements of the C/N- ratios can be obtained from a so-called "bi-static configuration", in which the transmitter and the receiver are separated from one another on the ground.

This becomes in particular relevant during strong wind situations, where the background noise level increases with the wind speed.

A particular configuration considered for wind energy applications is therefore the bi-static Continuous Wave (CW) SODAR configuration. Alternatively to the range gating in a pulsed system, the range to the wind speed measurement in a CW system can be determined by well-defined overlapping transmission and receiving antenna functions. At Risø DTU we have build and investigated such a SODAR system for wind energy applications.

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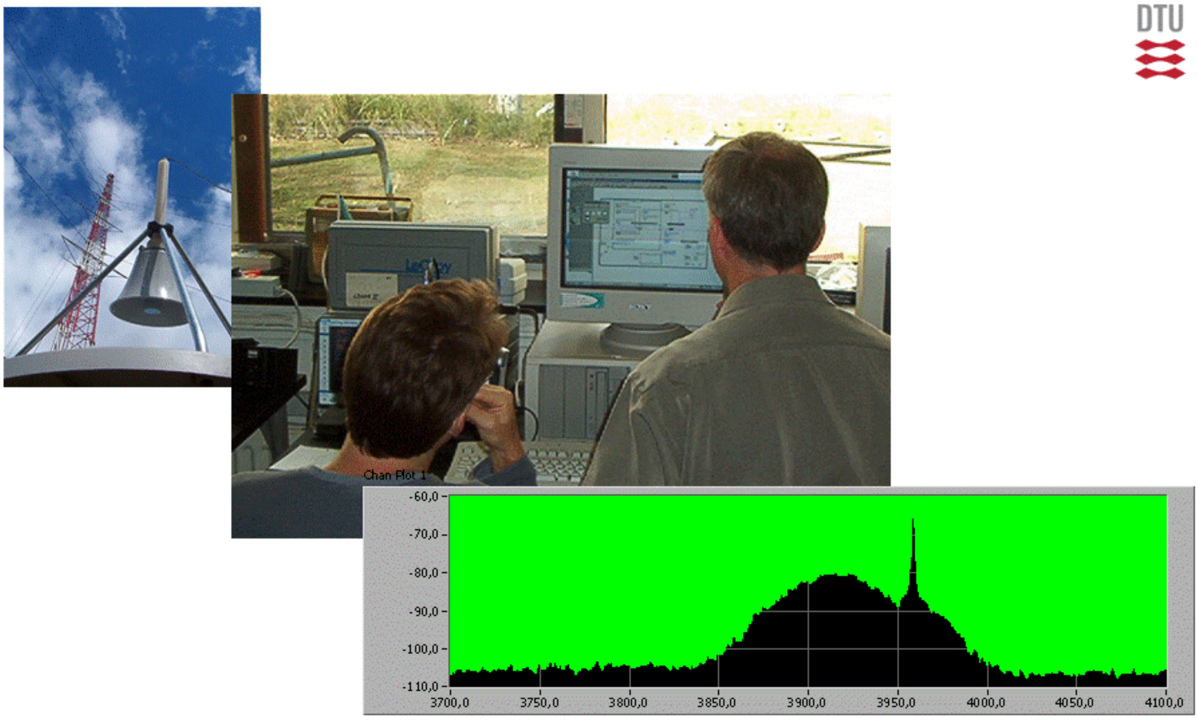

Figure 2:

Calibration, laboratory work, and real-time Doppler spectrum obtained at Risø DTU with the experimental bi-static CW SODAR "Heimdall" (from Mikkelsen et al. (2007): Researchers at Risø DTU under testing of the Heimdall bi-static SODAR designed particular at Risø DTU to address acoustic remote sensing for wind energy research.

Upper panel: Shows a combined acoustic horn and parabola antenna for high-yield (+30 dB gain) backscatter receiving of sound waves.

Middle panel: shows two researchers in the Risø DTU Laboratory while testing of the bi-static SODAR.

Lower panel: shows a real-time obtainable continuous Doppler spectrum Heimdall bi-static SODAR from wind measurements at the 60 meter level above Risø DTU.

4. Remote sensing applications within Wind Energy

Remote sensed wind speed measurements are needed to supplement and extend tall met mast measurements, on and offshore, and within research to evaluate various wind flow models and wind atlases for a number of purposes, including:

1. Wind resource assessments
2. Wind park development projects
3. Power curve measurements
4. Bankability
5. Wind model and wind resource (wind atlas) uncertainty evaluation.

The common denominator in most of these issues is high accuracy, and with a demand for reproducible certainty to more than 99% of what can be achieved with a corresponding calibrated cup anemometer. A significant source for uncertainty with RS instrumentation relative to a cup anemometer, and for SODARS in particular, is the remote instruments relative big measurement volumes. A SODAR measuring the wind speed from say 100 meters height probes a total sampling volume of more than 1000 m^3 whereas a cup anemometer essentially is essentially a point measurement device in this connection. In addition the SODAR measured wind components are displaced in space and time, which makes the interpretation of measured turbulence by a SODAR impaired. In addition the huge sampling volumes will be putting restrictions on measurements in non-uniform flow regimes such as found near forest edges on offshore platforms, and over hilly or complex terrain.

SODARS remote sensing is also in demand for direct turbine control integration, wind power optimization and turbine mounted gust warning systems, but here the demand on accuracy and reliability is correspondingly high.

Today, SODARS are typically used to measure 10-min averaged vertical profiles in the height interval between, say 20 and 200 meters above the ground, of the following quantities:

- Mean wind speed,
- Mean wind directions (including azimuth and tilt)
- Turbulence (all three wind components: longitudinal, transverse and vertical).

Albeit significant inherent scatter persists in SODAR measured mean wind speed and direction data average mean wind speed compare relatively well (in most cases to within +/- 3 %) to that of a corresponding cup anemometer measured wind speed, cf. the slopes of the scatter plots in Fig. 3.

However, the correlation coefficients between SODAR and cup anemometer data is, depending on measurement height and atmospheric stability, relative poor as compared to a cup-to cup anemometer correlation ,where the two cups are separated by ~100 m (typically less than 0.95) and reflects, among other issues, that a mono-static SODAR measure the wind speed over a huge volume whereas the cup anemometer represents a point measurement. In addition, increased scatter will occur as a result of beam-bending due to the relative big s wind speed relative to the propagation speed of the sound pulses. Also notable is that SODARS are capable able to make only a single 3D vector speed measurement about once per 6 - 10 seconds. A slow sampling rate also makes the mean prediction of a 10-min averaged quantity uncertain, due to limited independent sampling counts. In his note “Statistical analysis of poor sample statistics”, Kristensen (2010) have shown that “counting “uncertainty in terms of relative “standard deviation of the sample variance” in a small sample can give rise to a ~10% relative uncertainty when averaged quantities are drawn from a set of only 100 independent samples).

It is also seen from the SODAR vs. cup anemometer data in Fig.3 that difficulties with the C/N ratio can occur when wind speeds exceeds approximately 15 ms^{-1}, which by the way is a nominal wind speed for a wind turbine. This is due to high background noise and the loss of backscatter in neutrally stratified high wind speed regions.

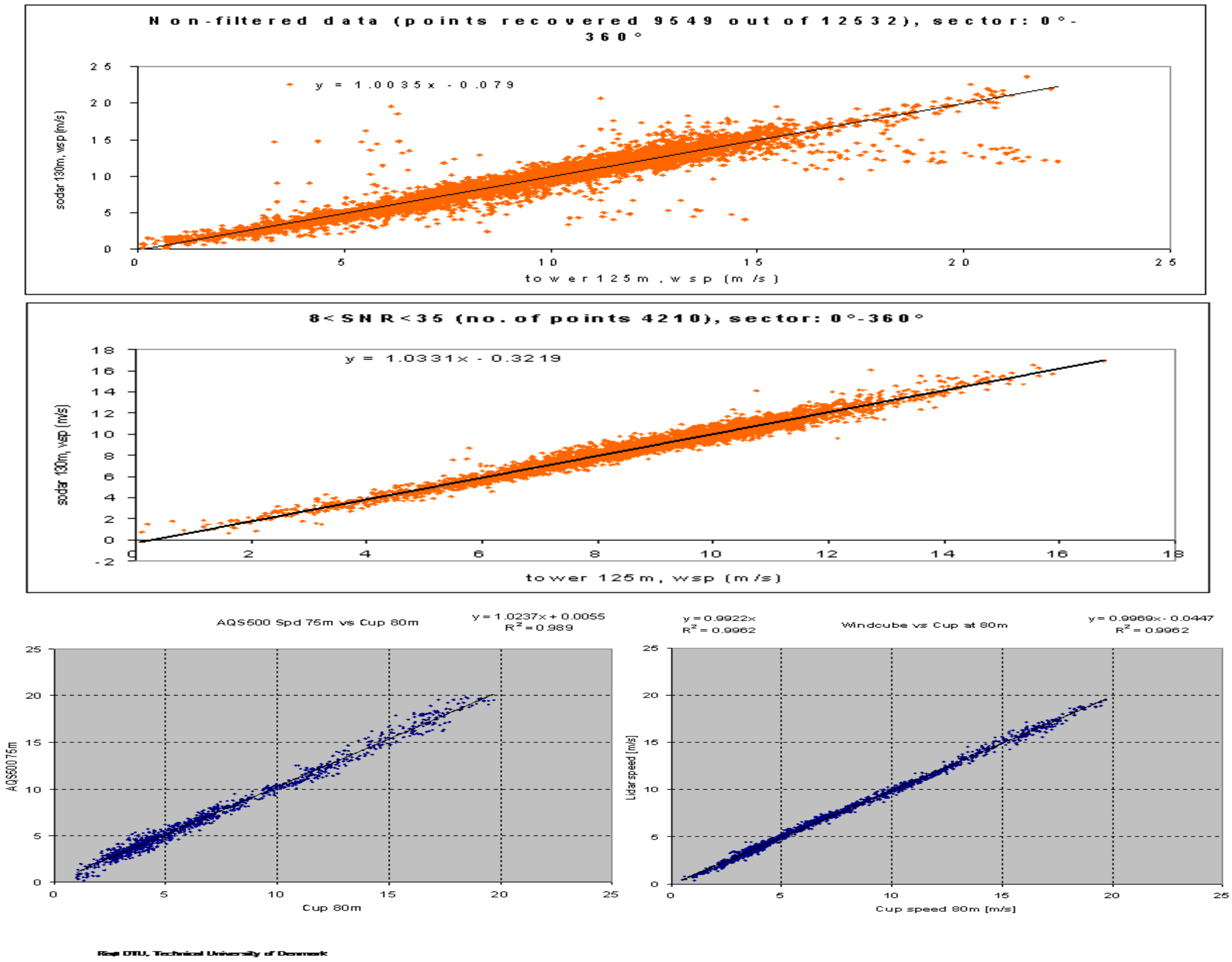

Figure 3 Example of scatter plots from SODAR vs. cup anemometer data.

The upper graph presents unscreened SODAR wind speed data plotted against corresponding high-quality cup anemometer data measured by the Risø DTU met tower at the 125 meter level. A data availability corresponding to 76% (9549 10-min averaged wind speeds) was obtained during this particular SODAR vs.cup anemometer inter-comparison test of almost three month duration (12532 10-min periods.

The middle data graph shows the same data set after screening of the SODAR data for high Signal-to Noise ratios. The scatter is significantly reduced, but so is also the data availability which with only 4210 data points has been reduced to almost 34%.

The bottom panel shows (left) simultaneous measured SODAR vs. cup scatter plot @ 75 m height (0.989) and (right) LIDAR vs. the same cup for the same data period. The LIDAR measurements @ 80 m are seen to exhibit less scatter and high correlation coefficient (0.996).

Recently relative good agreements over forested areas have nevertheless been seen (< 1% discrepancy) between SODAR and cup anemometer mean turbulence intensity has been reported by Gustavsson (2008).

However, turbulence intensity, which is the stream wise turbulence component relative to the mean wind speed, is in a 10-min averaged quantity dominated, particularly in forested areas, by the most energy containing eddies, which in this case will be larger than the SODAR's sampling volumes and therefore be well represented in the statistics. However, the smaller scales including turbulent eddies with wind gusts must be anticipated to be present also on the scales smaller than a mono-static ground based SODAR will be able to capture.

While SODARs appears to be able to measure accurately both the mean winds speed and the turbulence intensities at a turbines hub height it was found more difficult to use a SODAR for accurate measurements over the entire rotor plane due to low C/N, cf. Ref. Wagner et al. (2008).

There exists several SODAR manufactures on the wind remote sensing marked today including for example Remtech, Atmospheric Systems Corporation (formerly Aerovironment), Metek, Scintec , Second Wind Inc. and Swedish AQ System to mention the most dominant. All but one base their SODAR technology on mono-static phased array antenna configurations except AQ System SODARs which are build on three solid dish parabolas offering a somewhat bigger antenna directivity (12 degree opening angle) . However, only a couple of today's SODAR manufacturers address today directly the high accuracy demanding wind energy market.

The EU WISE project (M. de Noord, 2005) addressed and evaluated commercial SODARS for wind energy and concluded then that neither of the commercial SODARS were particularly close to be able to substituting standard measuring masts. In conclusion the WISE project stated that general purpose commercial SODARS were unreliable, especially in case of bad weather or high background noise

5. Recent developments

A few improvements seem to have emerged since 2005. Particularly for the few SODARS that addresses the wind energy marked. Replacement of the phased arrays by parabola dish seems to have contributed to the SODARS overall C/N performance. Also better and improved signal processing is apparently applied today. However, it is my personal belief that we won't see any significant quantum leap in SODAR performance until SODARS for wind energy applications are build on bi-static configurations. Research and development along these lines are in progress, and researchers and test engineers at Risø DTU are looking forward to see and to test possible future bi-static configured SODARS especially designed to meet the high accuracy demands set within wind energy remote sensing.

Table 1: Pros & Cons re SODAR's :

Pros:

- Portable
- Build on well developed and well-proven audio-frequency "low tech" technology.
- SODARS are relatively cheap (priced down to some 25% of a corresponding Wind LIDAR).
- Low power consumption (One solar powered version uses less than 10 Watt).
- Sound backscatter: Relatively high yield (backscattered power at the detector of the order of 10^{-10} Watts.

Cons:

- Low duty cycle (1 pulse transmitted every 3 seconds, and up to 6-10 s lapse times before all three wind components have been sampled).
- Limited by low S/N- ratio at: 1) high wind speed conditions, 2) during neutrally stratified conditions.
- Prone to solid reflections from the surroundings (including wind turbines),
- Prone to high background environmental noise.
- Low wavelength/aperture ratio (1:10) results in undefined broad antenna beams.
- Prone to beam bending with wind speed of the order of 5 % or higher of the speed of sound.
- Huge measurement and sample volumes.
- Signal processing limited by pulsed SODARS relative long data acquisition times (sampling time per pulse of the order of 1 s).

Table 2: Accuracy with SODARS during Neutral Conditions:

- Slope mean wind speed vs. calibrated cup anemometers: +/- 3%
- Correlation coefficients [@ 125 m height, neutral stratification] : 0.9 - 0.95
- Mean turbulence intensity[@ 80 m height]: < 1% error

6. SODAR Remote Sensing Update 2012:

SODAR remote sensing for wind energy

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ABSTRACT

Remote sensing by LIDARs and SODARs is now ubiquitous in the wind energy industry, but both these technologies are still rapidly changing. What accuracy and reliability can today be expected from SODAR wind measurements? Is there traceable evidence for performance? Environmental factors, turbulent fluctuations and non-uniform terrain all affect the wind speed uncertainty. So site-to-site variations for SODAR-mast comparisons can be large. We discuss these factors, and also new developments, including the "vertical column SODAR" (or "bi-static SODAR"), which should reduce measurement uncertainty.

KEYWORDS

SODARs; remote sensing of wind; errors in wind measurement; spatial separation of sampling volumes; turbulent fluctuations of wind; cup-SODAR inter-comparisons; winds in complex terrain; vertical column SODAR; bistatic SODAR.

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1. INTRODUCTION

There are currently two technologies being used for wind farm site evaluations and for installed turbine monitoring. The first is point measurements on a vertical mast and the second is winds remotely sensed from an instrument placed on the ground. Of the mast instruments, cup anemometers are the standard, but sonic anemometers are in wide use. The remote sensing instruments are LIDARs (based on laser energy reflections back to the instrument from atmospheric particles) and SODARs (based on acoustic energy reflections back to the instrument from turbulent fluctuations). LIDARs and SODARs share some geometric and signal processing features, and are both challenged by diminishing reflected power and hence diminishing signal-to-noise ratio (SNR) with increasing height of their wind speed measurement volume.

A FP6 EU Program, WISE, reported in 2004 on the state of the art at that time for the use of SODARs in wind energy applications [1]. The conclusions were broadly that SODARs provided a number of advantages compared with mast installations but were not a direct replacement because of significant differences in estimated wind speeds. It was recommended that a small mast installation be used alongside a SODAR. A successor EU program, UpWind, in particular Work Package 6 on Remote Sensing, researched improvements, particularly wind energy LIDARs which had emerged toward the end of WISE. Considerable effort in UpWind has gone into mast-LIDAR inter-comparisons, with the result that, with careful field setup and data filtering, remarkable correlations can be consistently obtained between LIDAR winds and mast installation winds. Nevertheless, for wind energy assessment studies, the final project report still recommends use of an accompanying small mast [2].

Based on the results reported from UpWind for inter-comparisons between remote sensing and mast installations, SODARs do not appear to be giving as close an agreement with mast measurements as do LIDARs [3]. Fig. 1 shows a typical result of an inter-comparison between a Scintec SODAR and mast instruments at 60 m height at the Risø DTU test site for large wind turbines at Høvsøre in western Denmark during WISE, where the coefficient of determination (often simply called the 'correlation') for wind speed was $R^2 = 0.987$.

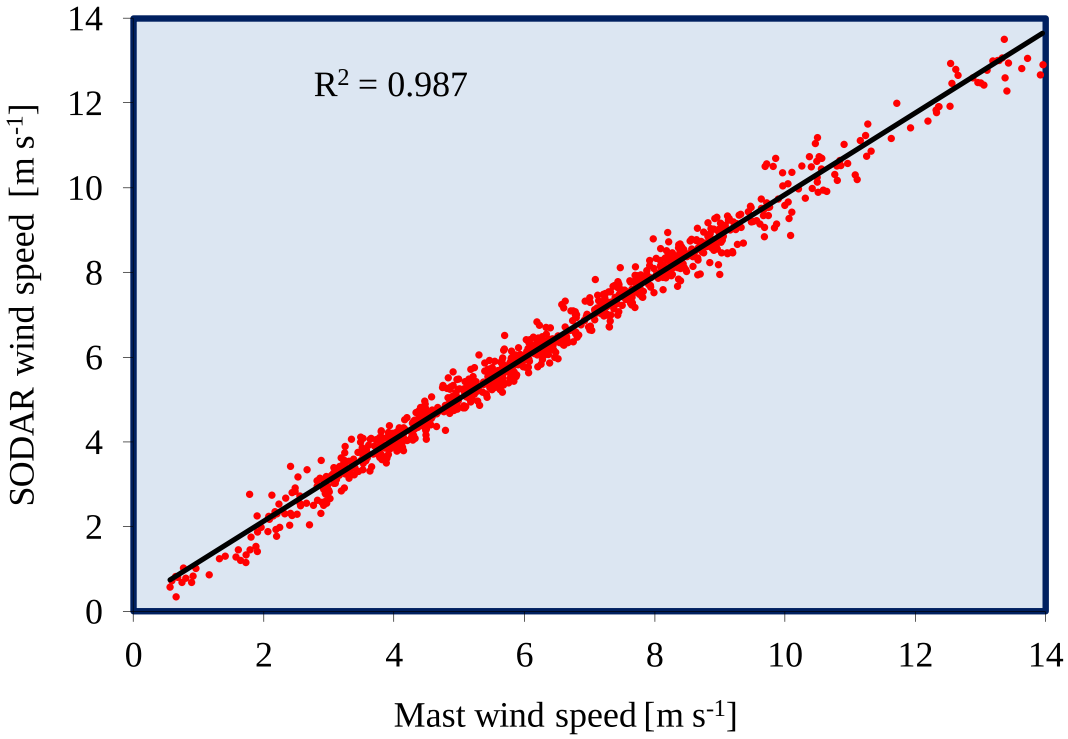

Figure 1. A typical scatter plot of SODAR remotely sensed 60 m wind and cup anemometers on a mast.

Bradley [4] gives a comprehensive description of SODAR technology and Mikkelsen [5] gives a brief overview. Throughout the UpWind project, SODAR technology has improved, and there has been the appearance of SODAR manufacturers developing expressly for the wind energy market, and offering autonomous units powered by solar panels (Fig. 2). Additionally, there have been developments in the way in which inter-comparisons between remote sensing instruments and mast installations are treated, and new insights into how differences between estimated winds can arise, particularly in complex terrain.

2. CORRELATION BETWEEN MAST AND REMOTE INSTRUMENTS

The quality of remote sensing instruments is generally judged by performing an inter-comparison experiment such as PIE [6]. In an inter-comparison, wind speed and direction are measured at several heights by cup anemometers (and/or sonic anemometers) on a mast together with measurements by a remote sensing instrument where a number of sampling volumes are centered around the same heights as the mast measurements. Differences between winds measured by mast sensors and remote sensors can arise from a number of causes, including

- The difference between wind-run or scalar (cup-type) and vector component (remote-type) measurements
- Sampling over spatially distributed volumes
- Sampling for each wind estimate spread over time
- Remote sensing in the presence of background noise.

Figure 2. Four of the SODARs designed primarily for wind energy applications. Second Wind Triton SODAR (upper left), AQSystem AQ500 SODAR (upper right), Metek PCS.2000-24/LP (lower left), and ASC 4000i (lower right).

Except in the case of complex terrain, these differences are essentially random instead of systematic and, except for background noise, the differences are due to turbulent fluctuations in wind speed being sensed differently by the mast sensors and the remote sensors. Ultimately, if the following conditions are satisfied

- the site is uniform,
- turbulence intensity is very low,
- background noise is minimal, and
- wind speeds are widely distributed,

then a very high R^2 should be achieved by any good quality remote sensing instrument, since the inherent limitations of the instrument are being reached. This explains why it is possible to get very high R^2 values in some inter-comparisons, while much lower values are obtained in others. One of the features of the efforts in UpWind to demonstrate the quality of remote sensing, has been filtering the wind data to remove occasions when there are background influences such as fog, or low SNR, and when there is not low shear and low turbulence.

The outstanding results obtained for LIDARs in UpWind show that these remote sensing instruments can approach very closely to the wind speeds measured by high quality cup anemometers under these 'laboratory' conditions. Regrettably, the same attention has not been paid to demonstrating the quality of remote sensing by SODARs by removing occasions in which background influences increase mast-SODAR differences. This makes it quite difficult to compare different remote sensing technologies. Ideally, a LIDAR and a SODAR would be placed at the same location (the same distance from a well-instrumented mast) and the identical filtering of the wind data applied to both. This contrasts with the usual situation of a SODAR being placed 80 m or more away from a mast, whereas LIDAR-mast inter-comparisons generally have the LIDAR within a few meters of the mast. For a short period during an inter-comparison at Myres Hill in Scotland, a ZephIR LIDAR and an AQ500 SODAR were co-located. No statistically significant differences between the two instruments were found, although this co-located inter-comparison was too short in duration and also at a moderately complex site, so it is difficult to make strong conclusions [7].

Statistical analysis shows that 1- R^2 is a measure of the ratio of the variance between mast and remotely sensed winds, to the overall variance of the wind speeds during the inter-comparison. What this means is that, for a wind regime having a typical Weibull shape factor of 2, a measured $R^2 = 0.995$ is the equivalent of a root-mean-square (rms) mast-remote difference of 4% of the mean wind speed. Similarly, $R^2 = 0.985$ is equivalent to a 6% difference. This range of R^2 is typical of that currently reported for LIDARs and SODARs under controlled inter-comparison conditions [2]. In less idealized field conditions, R^2 for SODAR-mast comparisons are more typically between 0.97 and 0.98, corresponding to rms differences of 9% to 7%.

3. DEPLOYING MODERN SODARS

SODARs have relatively low power requirements and so are now typically solar-powered for wind energy applications. For example, Second Wind quote the power consumption of the Triton SODAR as only 7W. A SODAR may also include locating hardware such as an integrated digital compass, a 2-axis inclinometer, and/or GPS location, making field deployment very low effort, as well as providing a check on the instrument integrity at a site susceptible to, for example, vandalism or large changes in ground softness. Transmission of data from the field site to the user's office is generally available via GSM modem.

In the past, reflections from rain have been a problem for SODARs during heavy rain. This problem has largely been solved by application of software detection and rain reflection removal schemes. However, data availability at the higher height ranges may be affected by acoustic noise on the antenna from heavy rain or from high winds.

SODARs measure wind by detecting the change in pitch, or frequency, of the sound reflected from moving turbulence [4]. This is done in practice by converting the microphone voltage signal received from each height range into a Doppler frequency spectrum, which shows how much reflected power is received at each acoustic frequency. Depending on the site, a SODAR can also receive reflections from fixed non-atmospheric objects. This ‘fixed echo’ effect produces a second Doppler spectrum peak centered on zero Doppler shift. If the wind speed is relatively low, then the two spectral peaks can overlap and an incorrect lower estimate of the wind speed is obtained from the composite peak. This is not generally a problem for SODARs providing the spurious zero-Doppler peak is of smaller magnitude than the required atmospheric reflection peak. Unfortunately, this often is not the case if a SODAR is placed close to a mast or close to trees or buildings. Most SODAR manufacturers will give some guidance on the orientation of the SODAR so that the fixed object falls between two of the SODAR beams, rather than in line with a beam. Similarly, guidance is often given on how far away the SODAR should be placed from a fixed object of a given height. Best practice guidelines will generally include something like “Locate the SODAR a lateral distance of 1 –2 times the vertical height of the nearest structure or obstruction”.

4. SODARS IN COMPLEX TERRAIN

It is now well-established that remote sensing instruments exhibit large errors in wind speed estimation in complex terrain [8][9][10]. Fig. 3 is from the only analytic model available [10].

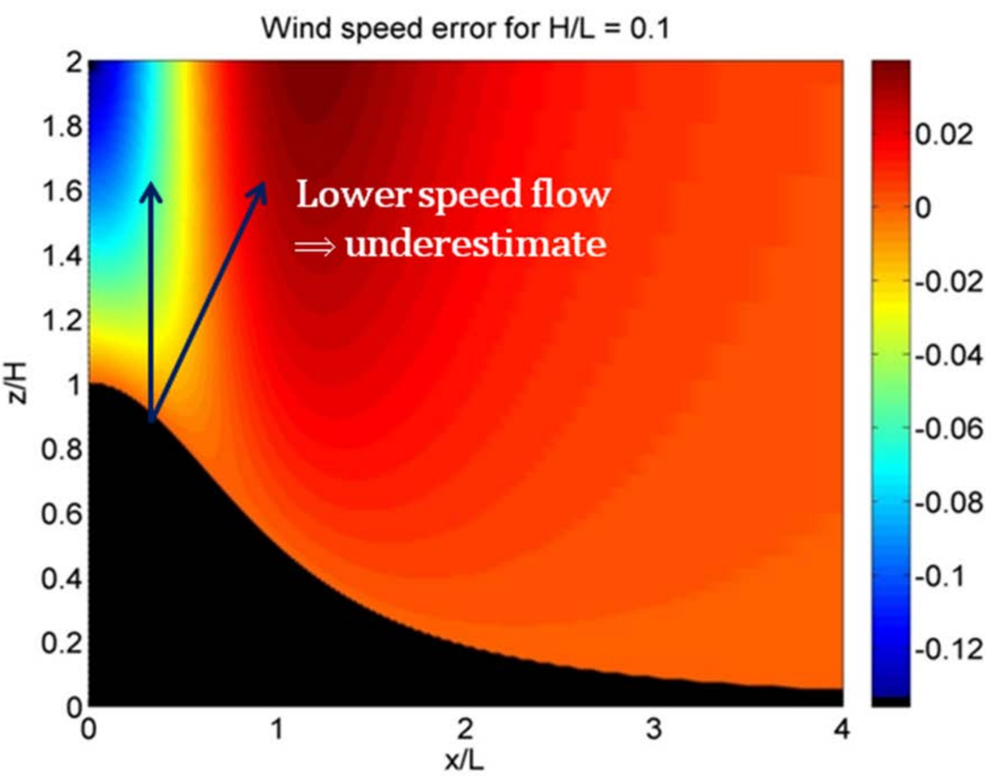

Figure 3. The fractional error in remotely sensed wind speed for flow over a hill defined by a height-to-half-width ratio of 0.1. The error is shown vs height, in hill height units, and vs lateral position of the instrument, in hill half-width units.

The speed-up of flow over the hill crest means that a mast placed at the top of the hill will measure higher winds than a remote sensing LIDAR or SODAR, since these instruments perform some of their measurements in volumes to the side of the hill peak where the wind speed is lower. In this case remote sensing produces an under-estimation in wind speed. Similarly, an instrument mounted half-way up the hill slope may do some of its measurements in a higher wind speed regime closer to the crest, thereby giving an over-estimation of wind speed.

Fig. 4 shows complex terrain errors measured with a ZephIR LIDAR and an AQ500 SODAR at Myres Hill in Scotland [7], and by a Metek PCS.2000-24/LP SODAR at a much more complex hill site at Turitea in New Zealand (adapted from [8][11]). These errors are characterized by their increasing with height, and there is no clear statistical difference between the LIDAR and SODAR errors. The Turitea data are also compared with various flow models. The simple bell hill model compares well with the industry-standard WindSim and the complex CFD OpenFoam model [11].

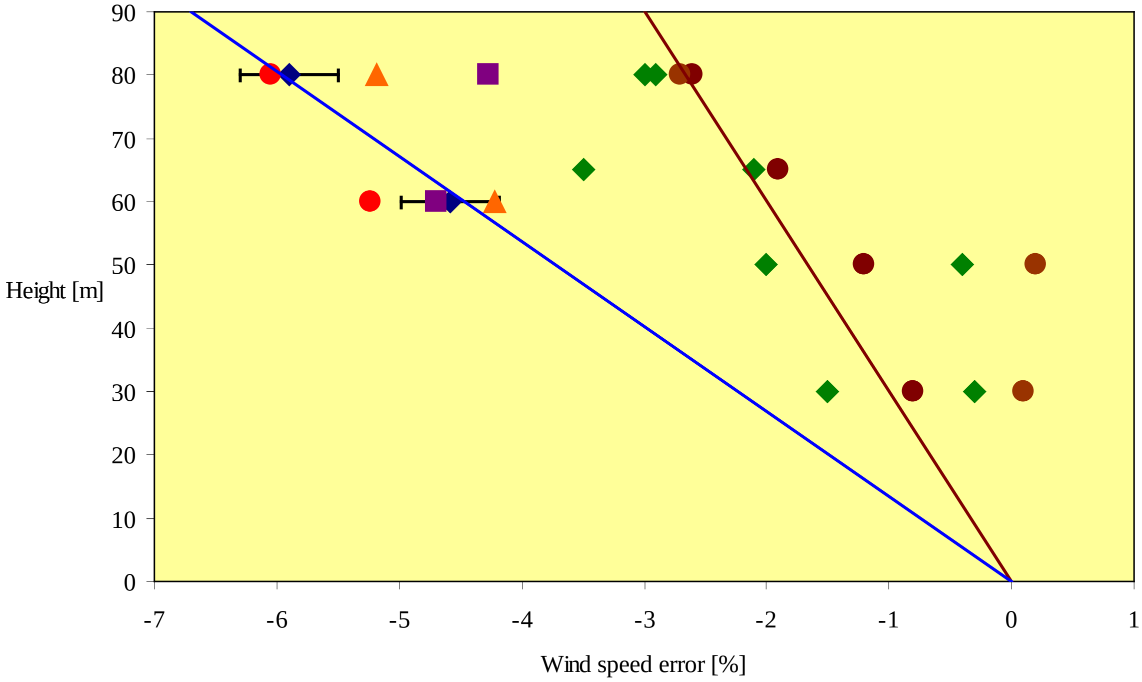

Figure 4. Complex terrain errors measured at Myres Hill for a LIDAR (green diamonds) and a SODAR (brown circles), and SODAR measurements at Turitea (blue diamonds). Also shown are predictions for Turitea from the bell-hill model (orange triangles), WindSim (purple squares), and OpenFOAM (red circles). The straight lines show the approximate linear trend with height for errors in moderately complex terrain (Myres Hill) and very complex terrain (Turitea).

5. A VERTICAL COLUMN SODAR

The conventional design for SODAR beams, shown in the left hand side of Fig. 5, gives rise to all the discrepancies discussed above, except for differences due to mast-SODAR separation. However, there is another configuration [12-14], often called "bi-static", although we prefer the much more descriptive term "vertical column SODAR", shown on the right of Fig. 5. The prototype designed under UpWind comprises a transmitter sending a sound pulse vertically, and two receivers which each electronically scan up the column in which the acoustic pulse propagates. There is a third receiver facing upward co-located with the transmitter. So all the reflected Doppler signals originate from the same volume at any instant, and this reflecting volume moves upward at the speed of sound (like a conventional radar). There are many advantages, including

- Simultaneous sampling of a common volume in a vertical (mast-like) column
- Larger reflected signal (because of the scattering geometry)
- Larger Doppler shift, and so lower sensitivity to fixed echoes
- No complex terrain effect

Because of the beam geometry, this system may also be able to be located close to a mast, and a better comparison made between acoustic remote sensing and mast sensors. It is expected that the scanning receivers will ultimately be available as an "add-on" option to commercial SODARs, giving the benefit of being able to operate as a conventional SODAR simultaneously with the vertical column mode.

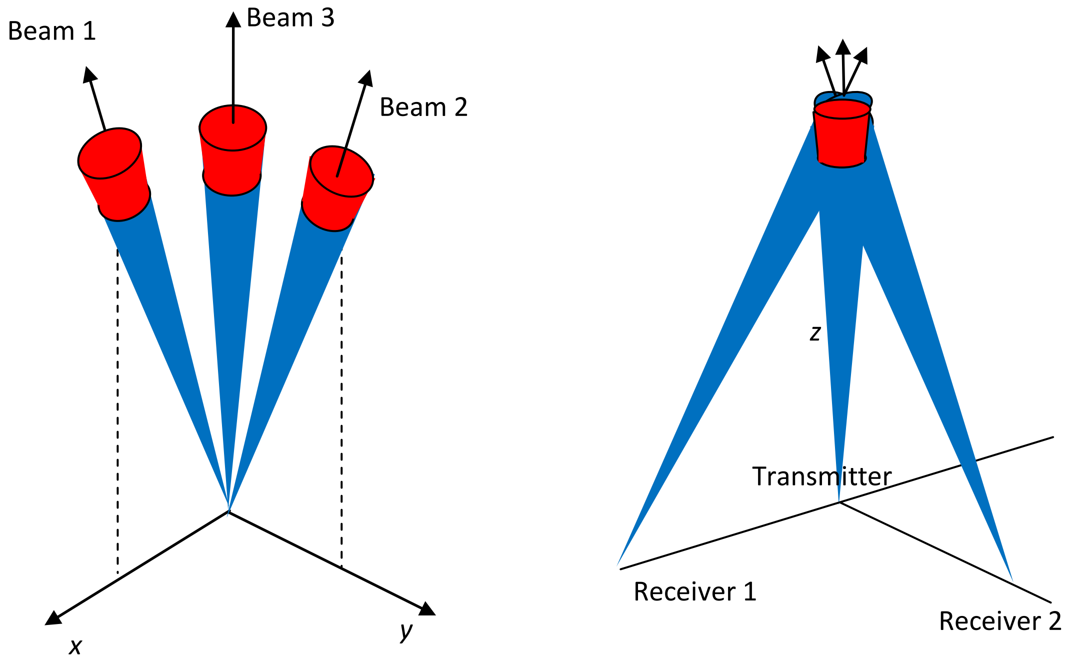

Figure 5. The conventional SODAR design (left) showing the sampling volume separation, and the vertical column configuration (right).

6. CONCLUSIONS

Today's SODARs are relatively inexpensive and very readily deployed at wind energy sites. Most manufacturers produce solar-powered options. Current experience being reported by SODAR users is very positive, with relatively little or no maintenance time. Care does need to be taken though with regard to: 1) acoustic reflections from nearby tall objects; 2) measurements from heights above, say 100 meters, where the SNR can be small, and 3) with SODAR measurements obtained during high-wind speed (and hence noisy) conditions, particular during near-neutrally stratified atmospheric conditions, where also the acoustic backscatter coefficients are small.

All current remote sensing instruments produce winds with errors in complex terrain. The errors become larger for a steeper hill or for measuring further above the ground. These errors can be estimated from flow models, and actual field measurements suggest a relatively simple model (which can be run on a laptop in a few seconds) gives predictions comparable to much more complex models. But there appears to still be more work required to demonstrate that the combination of *in situ* remote sensing measurements and flow models can robustly produce wind data of the required accuracy.

Both the turbulence-related random fluctuations and the complex terrain errors can potentially be removed by use of a vertical column geometry. This geometry also has other advantages, but it does have the disadvantage of having to distribute three sensors on the ground instead of one. However, since the extra receiver antennas have very low power requirements they could be compact and autonomous.

On a uniform terrain site, differences between a SODAR and a mast-mounted cup anemometer will arise due to turbulent fluctuations and wind components being measured in different spaces, as well as to variable background noise. Such differences can be minimized by selecting the environment and selectively filtering the data for periods of low fluctuations. There is real difficulty therefore in answering the question: How good is a SODAR? Most *field use*, away from an idealized test environment, appears to produce SODAR-mast rms differences greater than the 0.1 m s^{-1} or less typically quoted by SODAR manufacturers. However, in these real environments it is likely that much of the difference arises from the mast sensors and the SODAR actually measuring in different spaces.

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Part II: Remote Sensing of Wind by Light (LIDAR's):

2.1 Introduction to LIDAR's

We next address atmospheric remote sensing of wind featuring light-scatter based wind LIDAR's.

The motivation and demand in the wind energy market for wind LIDARs are similar to those of wind SODARs. At a continuously increasing rate today wind turbines are being installed on, offshore, in hilly and forested areas, and even in complex or mountainous terrain. At the same time, as the turbines gets bigger and more powerful, they also reach higher and higher into the atmospheric flow, and thereby also into hitherto unknown wind and turbulence regimes – on as well as offshore.

The industry's traditional method for performing accredited and traceable measurements of power performance is to mount a single accurately calibrated cup anemometer at hub height two to four rotor diameters upwind in front of the turbines on a tall meteorological mast. IEC 61400-12-1 describes the accepted standard for power performance verification (power curve measurement) and prescribes measurements of power production correlated with wind speed measurements from a cup anemometer located at hub height in front of the wind turbine 2-4 rotor diameters upstream.

With turbines becoming bigger correspondingly high meteorology masts equipped with wind speed instrumentation becomes progressing more cumbersome and expensive to install, especially in mountainous and complex terrain. As wind turbines rotor planes reaches 120 meters in diameter or more it is evident that the incoming wind field over the entire rotor planes is not measured representatively from a single cup anemometer mounted at hub height.

Accurate measurements of the inflow to today's huge wind turbines will require multi-point multi-height wind measurements within the entire rotor plane, to characterize the wind speed and wind shear over the entire rotor plane. Research activities addressing detailed rotor plane inflow and wakes is ongoing at Risø DTU in connection with the establishment of new research infrastructure based on wind LIDARs, cf. the updated web pages at Windscanner.dk including recent references for more details (Mikkelsen et al., 2008)

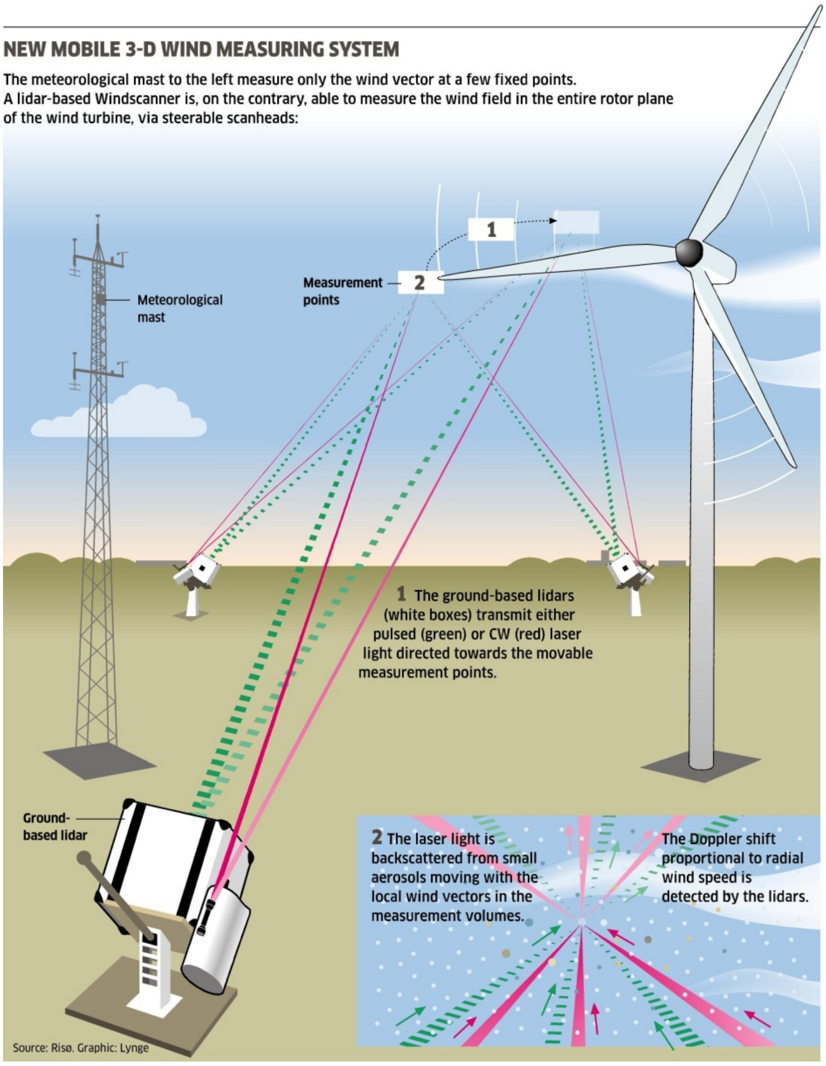

Figure 4 Windcanners in operation – CW and pulsed wind LIDARs engaged in measurements of the wind and turbulence fields around a spinning wind turbine (See Windscanner.dk for more details).

2.2 Wind Remote Sensing (RS) methodologies:

Remote sensing measurement methodologies for wind energy applications are today commercially available and encompass various measurement techniques that include sound based SODARs, laser based LIDARs and satellite borne scatterometry. The application range for wind measurements are also plentiful, and encompass for example:

i) Wind turbine power performance verification

Establishment of new remote sensing based measurement standards for the replacement of in-situ reference meteorological masts. Work within the IEC is at the moment aiming at establishment of a new international IEC-standard for remote sensed wind measurements, as e.g. obtained by LIDARs, for power curve measurements.

ii) Wind energy resource measurements

The global wind resources are now being mapped globally on shore, off shore, over hilly and in mountainous terrain etc. Here also, high accuracy is of uttermost importance for accurate site and resource assessments. Measurement errors in excess of 1% are unacceptable by project developers and investment banks.

iii) Wind turbine control

Remote sensing LIDAR instruments that are directly integrated into the wind turbines hub or spinner or even into the blades are also seen as a forthcoming remote sensing measurement technology that can help improve the wind turbines power performance and possibly also diminish fatigue wear from extreme gusts and wind shear via active steering the wind turbines individual blade pitch or, to come one day maybe, its trailing edge flaps.

Researchers at Risø DTU National Laboratory for Sustainable Energy have during decades now followed and contributed to the development of improved instrumentation for remote sensing of wind. Starting out already in the 60'ties with more general boundary-layer meteorological investigations of flow and diffusion our present research and experimental developments within the meteorology and test and measurement programs at Risø DTU has recently become more and more directed towards applications within wind energy.

This article addresses wind LIDARs and LIDAR-based wind profilers, their measurement principles, their measurement performances, and also their possible future integration within wind turbines themselves.

3. Wind LIDAR's

Measuring wind with a wind LIDAR means to probe the atmospheric flow from the ground by use of light beams.

LIDAR stands for: "LIght Detection And Ranging". A wind LIDAR is wind measurement devise able to detect the Doppler shifts in backscattered light. The Doppler shift is proportional to the wind speed in the beam direction in the wind LIDARS adjustable measurement volumes.

LIDARs, like SODARs, provide a ground-based remote sensing measurement methodology for measuring the winds at various ranges, angles and heights aloft.

Wind LIDARs work by transmitting electromagnetic radiation (light) from a laser with a well-defined wavelength in the near infrared band around 1.5 micron. They detect a small frequency shift in the very weak backscattered light, a Doppler shift that results from the backscattering of light from the many small aerosols suspended and moving with the air aloft.

From a meteorological point of view wind turbine are "obstacles" within the lowest part of the atmospheric boundary layer, that is, the part of the atmosphere best characterize by high wind shear, strong wind veers, and with the highest levels of turbulence.

A wind profiler is a ground-based wind LIDAR transmitting a continuous beam or a sequence of pulsed radiation in three or more different inclined directions. A wind profiler determines the radial wind speeds in multiple directions above its position on the ground. It does so also by determining the Doppler shifts in the detected backscattered radiation along each beam direction. Wind LIDARs, like SODARs, therefore have both transmitting and receiving antennas, which most wind profilers today combine into a single optical telescope. The three-dimensional wind vector as function of height by measuring the radial wind speeds in three or more beam directions above the LIDAR. In practice, the transmitting and receiving radiation are combined in a single telescope and the beam is then steered in different directions via a rotating wedges or turning mirrors.

Wind LIDARS in the marked for vertical mean and turbulence profile measurements are available based on two different measurement principles:

a) ***Continuous Wave (CW) LIDARS***

b) ***Pulsed LIDARS***

Several wind LIDARs addressing the wind energy market is commercial available today. CW-based wind LIDARS are manufactured by Natural Powers (ZephIR) and OPDI Technologies & DTU Fotonik (WINDAR) while Coherent Technologies Inc. (Wind tracer), Leosphere (WindCube), CatchtheWindInc (Vindicator) and Sgurr Energy (Galion) manufacture pulsed LIDARs for the time being.

The technology imbedded in today's CW and pulsed wind LIDAR systems have been spurred from the telecommunication 1.5 micron fiber and laser technology revolution in the '90'ties. There are however, some principally differences between CW and pulsed LIDARS temporal and spatial resolution, properties that have influence on the different LIDAR types ability to measure and resolve the mean wind and turbulence characteristics of the atmospheric boundary layer wind field.

The CW LIDAR focus a continuous transmitted laser beam at a preset measurement height and there determines, also continuously, the Doppler shift in the detected backscatter also from that particular height. When wind measurements from more than a single height are required, the CW LIDAR adjusts its telescope to focus on the next measurement height. The measurement ranges (measurement heights) as well as the spatial resolution of a CW LIDAR measurement is controlled by the focal properties of the telescope. The shorter the measurement distance, and the bigger the aperture (lens), the better defined is a CW LIDARS range definition and its radial measurement confinement. A CW LIDAR resolves the wind profile along its beam in a similar manner as a photographer controls the focal depth in a big sport or bird telescope.

Figure 5 Two CW wind LIDARs belonging to the Windscanner.dk research facility being inter-compared and tested up against the tall meteorological masts at Høvsøre, Risø DTU.

The focal depth of any telescope, however, increases proportional to the square of the distance to the focus or measurement point. This optical property limits a CW LIDAR build with e.g. standard 3”optics to measurement heights below, say 150 meters.

A pulsed LIDAR on the other hand transmits a sequence of many short pulses, typical 30 m in effective length, and then it detects the Doppler shift in the backscattered light from each pulse as they propagate with the speed of light.

While a CW LIDAR measure from one height at a time a pulsed LIDAR measures wind speeds from several range-gated distances simultaneously, typically at up to 10 range gates at a time.

The pulsed LIDARs spatial resolution, in contrast to the CW LIDAR, is independent of the measurement range. The pulse width and the distance the pulse travels while the LIDAR samples the detected backscatter control its resolution. The spatial resolution in the beam direction obtainable with the 1.5-micron wavelength pulsed LIDARs in the marked today are of the order of 30 to 40 meters.

In addition, while a CW LIDARs upper measurement distance is limited progressing unconfined measurement volume at long distances, a pulsed LIDARs maximum measurement range is limited by deteriorating signal-to noise ratios in measurements from far distances (height).

Moreover, while a CW LIDAR equipped with a 1 Watt 1.5 micron eye-safe laser has been tested able to sample and process up to 500 wind speed measurements per second, a corresponding powered pulsed LIDAR can handle only 2-4 wind speed samples per second. Each of these samples, however, then on the contrary contain wind speeds from up to 10 range gates (ranges) measured simultaneously.

CW vs. pulsed LIDARS

Overall, CW LIDAR features high spatial resolution in the near range and very fast data acquisition rates, features that are well suitable for turbulence measurements. Today's commercial available CW LIDAR profilers measure radial wind speeds at ranges up to ~ 200 m and wind vectors at heights up to 150 m.

The pulsed LIDAR configuration on the other hand features lower but always constant spatial resolution properties (30- 40 m) at all ranges. They are also inherently slower in their data acquisition rate, but then they measure wind speeds at multiple heights simultaneously, and they hold also potential for reaching longer ranges (heights) than corresponding powered CW LIDARs. At the test site in Høvsøre Risø DTU, commercial available pulsed wind LIDAR profiles have regularly measured the wind vector profiles up to 300 meters height.

Wind Profiling

A wind "profiler" measures 10-min averaged quantities of the vertical wind speed profile, the vertical direction profile, and the vertical turbulence profiles, by combining a series of radial measured wind speed components from several, and at least three, different beam directions, into a three-dimensional wind vector. CW-based wind LIDARS, like e.g. the ZephIR, measure the vertical wind profile at five consecutive heights, selectable in the range from, say 10 to 150 meters height Pulsed LIDARs, like e.g. the WindCube or the Galion, measure correspondingly the vertical wind profile simultaneously at several (of the order of 10) heights, in the height interval from 40 to ~300 meters, the upper bound depending on the amount of aerosols in the air.

Figure 6: CW wind LIDARs (ZephIR's) under testning at Høvsøre, Risø DTU.

Figure 7: Pulsed wind LIDARs (six WLS7 WindCube's) and one Galion (far back) during testing at Høvsøre

True for all wind profilers in the wind energy market, however, CW and pulsed LIDARs irrespectively, is that they rely during combining measured radial wind speeds into a single wind vector on the assumption that the flow over the wind LIDAR is strictly **homogeneous**. Homogeneous wind flow means that the air stream is unaffected and not influenced by hills, valleys, other wind turbine wakes, or near-by buildings within their volume of air scanned above the LIDARs.

For this reason, neither LIDAR nor SODAR based wind profilers will be able measure correctly over sites located in hilly or complex terrain where the wind field is affected by the near-presence of hills or upwind turbines. Easily, up to ~10 % measurement errors can be observed between wind speeds measured by a LIDAR and a mast-mounted cup anemometer co-located to take wind profile measurements from the on top of a hill. Research is therefore ongoing in order to correct wind LIDAR based profile measurements for flow distortion e.g. induced by terrain effects (Bingöl et al., 2008).

LIDAR Accuracy

Inherently, LIDARS can remotely measure the wind speeds aloft with much higher accuracy than a SODAR. This is due to the nature of light, which propagates ~ 1 million times faster than a sound pulse, and because a LIDARs antenna aperture size compared to the wavelength, i.e. "Lens diameter-to- wavelength ratio" in a LIDAR is about 1.000 times bigger than practically obtainable with a SODAR. This result in superior beam control and also in much higher data sampling rates with LIDAR technology compared to SODAR.

At Risø DTU's test site at Høvsøre, testing and calibration of wind LIDAR is now daily routine and is performed by inter-comparing and correlating LIDAR-measured wind speeds with wind speeds from calibrated cup anemometers in our 119-meter freely exposed tall reference meteorological mast.

During “fair weather conditions”, 10-min averaged wind speeds from LIDARs and the cups are in-situ intercompared and correlated. Linear regression coefficients with both CW and pulsed LIDARs could be obtained in the range of ~ 0.99-1.00, and correlation coefficients as high as ~0.99 (Wagner and Courtney, 2009).

“Fair weather” means here that LIDAR data are screened for periods with rain, fog, mist and low-hanging clouds and mist layers. Usually this only removes a few per cent of the data. All LIDARs, CW and pulsed included, rely during determination of the wind speed from Doppler shift measurements on the assumption that the aerosols in the measurement volumes are homogeneously distributed and follow the mean wind flow.

SODARs for that matter, can under ideal conditions perform almost similar well with respect to mean wind speed (linear regression coefficients as high as ~ 0.99 has been reported above). The observed scatter, however, as compared to a LIDAR, is bigger. Correlation coefficients observed while testing of SODARs at Risø DTU’s 125 meter tall MET-mast at wind energy relevant neutrally stratified strong wind conditions (>10ms$^{-1)}$ has so far not been observed to exceed the 0.90 level.

4. Wind LIDAR applications for Wind Energy

Wind LIDAR manufactures today address the marked for replacement of tall reference meteorology mast installations at the moment required for accredited and bankable wind resource measurements and for ground-based wind turbine performance measurements. LIDAR manufactures also offer their wind LIDARS as instruments for evaluation of model-based wind resource estimation, on and offshore (numerical wind atlases).

Wind LIDARs in the market today offer the wind energy industry with remote sensing instruments, for:

- Wind speed, wind direction and turbulence profiling.
- Wind resource assessments, on and offshore.
- Wind turbine performance testing (power curves).
- Wind resource assessment via horizontal scanning over complex terrain.

Further developments

Furthermore, new and improved wind LIDAR data and measurement technologies are under development for RS-based power performance measurements from the ground but also directly from the wind turbines. A conically scanning wind LIDAR (Control-ZephIR) have during the summer 2009 been tested in a operating NM80 2.3 MW wind turbine located at Tjæreborg Enge, Denmark with the purpose to investigate the use of wind LIDARs integrated directly into the wind turbine hubs, blades or spinners. The intention is to improve the wind turbines performance by use of upstream approaching wind speed measurements from inside the turbines rotor plane as an active input to the wind turbines active control systems. Wind LIDARs for turbine yaw control is already nowadays on the market (Vindicator) and new and smaller wind LIDARS are in the near-future envisioned to become integrated as “standard” on wind turbines to provide upstream lead time wind data to the turbines control system, e.g. for:

- Enhanced wind turbine YAW control.
- Lead-time control for individual pitch control.
- Protection against fatigue from extreme wind shear and wind gusts.
- Prolonging the wind turbines longevity.
- Improving the wind turbine productivity.

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Lidar Remote Sensing Update (2012)

By Torben Mikkelsen and Stuart Bradley

Introduction

Research on wind measurement for wind energy currently focuses on new remote sensing technologies for site-specific wind measurements and for real-time turbine-integrated monitoring and control. Wind measurement methodologies are progressing from point measurements, obtained from in-situ instruments mounted on vertical masts, towards wind profiles and entire wind fields retrieved from remote sensing instruments placed on the ground or integrated within the turbines themselves. However, mast mounted in-situ instruments are still used for reference measurements (cup anemometers are the standard, but also sonic anemometers are in wide use).

The remote sensing instruments used for wind energy today are lidars (based on laser energy reflections back to the instrument from atmospheric particles) and sodars (based on acoustic energy reflections back to the instrument from turbulent fluctuations). Lidars and sodars share many common geometric and signal processing features, and both are challenged by large sampling volumes and/or diminishing reflected power with increasing distance to the measurement volume. Nevertheless, extremely high accuracies are now possible, particularly from lidars, and many exciting possibilities are opening up.

In this, our second review article this year on remote sensing (see [1]), we now report on recent and planned lidar remote sensing R&D activities in connection with wind energy.

Proof of Lidar Wind Measurement Concept

Recently, in June 2011, a hitherto unparalleled demonstration of wind lidar performance was obtained in the calibrated wind tunnel belonging to LM Wind Power, Kolding Denmark.

The laser beam from renewable energy consultancy Natural Power’s continuous wave ZephIR 300 wind lidar was re-directed via a small fibre-fed telescope into LM Wind Power’s calibrated wind tunnel in Denmark. Wind speeds from 5m/s to 75 m/s were measured by the lidar and a calibrated pitot, with an averaged difference of just 0.4% (see Fig. 1).

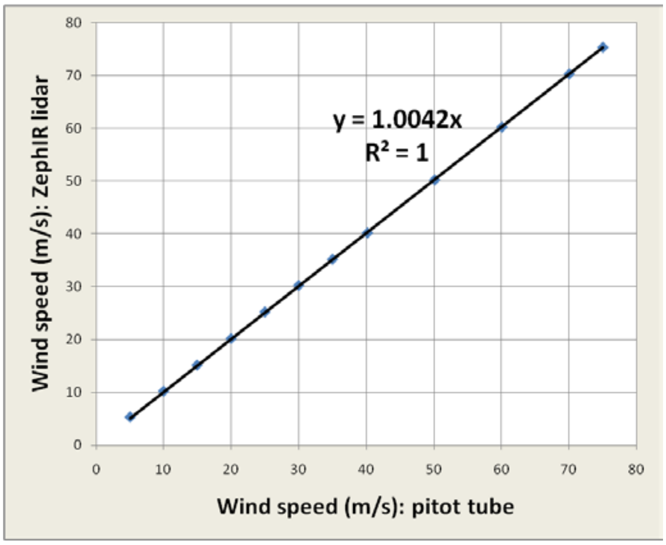


Figure 8 WindTunnel mached performance testing of lidar

These new calibrated wind tunnel measurements conclusively show that a wind lidar is capable of making high accuracy wind measurements.

Latest Results from EU Upwind WP6 Remote Sensing Group:

UpWind was a European Commission funded project that ran from 2006 to 2011. UpWind's overall aim was to look towards the future design of very large wind turbines (5-10MW) for onshore and offshore. The final report was published in March 2011 (www.upwind.eu).

Sub-task "WP6" on remote sensing was motivated by the continuous growth in wind turbine size, which makes mast-mounted conventional wind instrument installations for reference measurements more and more costly and cumbersome. The work package looked at testing, improving and developing remote sensing methodologies for more accurate wind profiling, for wind condition assessment, for resource assessments, and for better wind turbine control.

Wind Lidars

Lidars measure the wind speed at remote distances by transmission of coherent laser light that, when backscattered from aerosols (dust) suspended in the air flow, becomes Doppler-shifted (changes color) proportional to the speed of the aerosol. Since the aerosol moves with the air, the lidar records the speed of the air flow in the measurement volume.

Over the past decade, lidars based on the "coherent detection" principle have appeared on the wind energy market. At first, they were designed to perform wind measurements over height ranges relevant to wind turbine applications. More recently their range has been extended so they can measure wind profiles even to the top of the atmospheric boundary layer (1-2 km), and enable wind resource mapping from a single ground-based installation out to 5-10 km distance.

Today, lidars designed for direct wind turbine integration and control are under development and testing, and one day soon we might see the first wind lidars being integrated directly into the rotating blades.

New IEC Standards based on Remote Sensing?

Questions addressed during UpWind WP6 included: "Can remote sensing techniques replace conventional towers with the precision required by the IEC standards" and "How is it best to exploit the measurement flexibility offered by remote sensing?" Our conclusions from the remote sensing work package were:

- Using lidars, and without depending on masts, power curve measurements can today be performed on very large wind turbines. The best lidars, of those investigated, measured wind speeds with accuracy close to that of cup anemometers.

- For very large turbines, however, wind shear should be taken into consideration in power curve measurements. A so-called "equivalent wind speed method" (Wagner et al. [2]) was developed to improve power curve repeatability. Work is ongoing to amend IEC 61400-12-1 to account for the effect of shear, based on Wagner et al.'s "equivalent wind speed" concept and allowing the use of remote sensing to measure wind profiles.

- Lidars can provide profile measurements over the entire rotor plane, that can then be used for resource assessment over flat terrain. Power consumption is relatively low: today's new 2nd generation wind lidars use significantly less than 100 Watt.

- Wind speed assessment from lidars operating in complex terrain will require corrections that are now in principle well understood and that can be predicted if the local flow deflections can be modeled reasonably well.

Progress with LIDAR for Wind Energy Research

Turbulence Measurements using LIDARs:

At potential wind energy sites, turbulence intensity is also an important quantity to assess in addition to the local wind energy content. Lidar testing during UPWind has shown that, even when the mean wind speed is highly correlated to a reference cup anemometer measurement, the standard deviations in wind speed seen by ground-based wind lidars reveal typically only 60-80 % of the corresponding turbulence intensity measured by a mast-mounted cup anemometer.

During UpWind we examined lidar measured turbulence theoretically and experimentally. The cause for the lidar under-estimation results from the large measurement volumes involved with fixed-inclination, azimuth scanning lidars.

The effective measurement volume for lidars typically exceeds 100 meters in horizontal dimension. For comparison, a cup anemometer's effective measurement scale is only about one meter. To correctly interpret lidar measured turbulence, we found it necessary to account for both the inter-correlations between the wind measurements in different (azimuth) directions and the filtering effects of the radially probing laser beams themselves.

A simple filter model based on length scales was developed, as well as a more rigorous spectral tensor-based model. These models were developed to understand and possibly correct for lidar-filtered turbulence. Both models have then been intercompared to turbulence measurements [3], [4]. We find however, that the ratio between lidar and cup anemometer turbulence intensity varied markedly both with height and atmospheric stability.

The majority of the ground-based wind lidar manufacturers today, design with fixed inclination azimuth-scanning beams. For this configuration, however, we concluded that it will not be possible to directly measure the turbulence intensities as to achieve rigorous agreement with conventional anemometry, unless we introduce supporting measurements from a mast instrument or introduce additional assumptions about the turbulence.

“WindScanner” Research Infrastructure

At Risø DTU, we are heading the establishment of a new Research Infrastructure (RI) for lidar wind and turbulence measurements based around large turbines onshore and offshore. The activity is called “WindScanner”.

With 7 partners from the European Energy Research Alliance (EERA), WindScanner joined in 2010 the European infrastructure ESFRI RI Roadmap to boost the use of remote sensing for wind energy nationally, regionally, and throughout Europe.

Our aim with WindScanner is to develop and jointly disseminate the use of mobile WindScanner lidars for detailed 3D wind scanning and mapping of the wind and turbulence structures around today’s huge wind turbines, to deploy portable WindScanners on and offshore for regional measurement of wind conditions and energy assessment, and also to help develop and test new small wind lidars integrated into wind turbines for wind turbine control.

WindScanners, both for short-range and for long-range applications, have recently been constructed in connection with the establishment of a first new Danish national research infrastructure based on remote sensing of wind (see www.windscanner.dk).

Short-range (10 - 250 m) WindScanners

Three short-range wind scanners, built from modified continuous wave ZephIR wind lidars, have been constructed to date. The short-range WindScanners are each equipped with individual two-axis prism-based, beam-steerable scan heads, invented, designed and manufactured by Risø DTU in close collaboration with Natural Power and a Danish industrial design company IPU (DK).

Test work is progressing, in our laboratory and in the fields around Risø DTU, to calibrate and performance-test these new short range WindScanners. The first outdoor wind and turbulence studies have been performed in the spring of 2011 (“Six-beam” 3D turbulence profiling experiment, and “Small hut wind wake flow and turbulence visualization”).

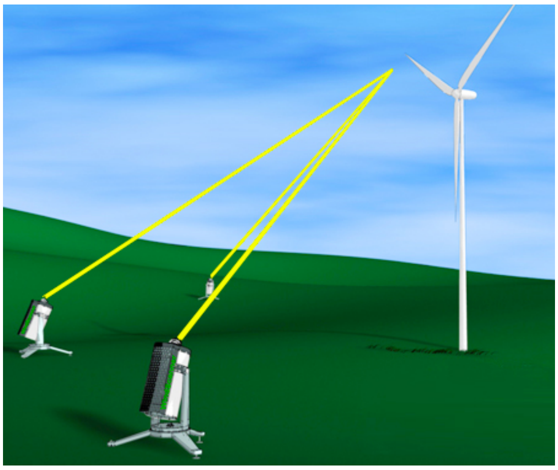


Figure2a: 3D Short-range WindScanners at work (concept)

Figure 9b: A Short-Range WindScanner (R2D1) during field test at Risø DTU

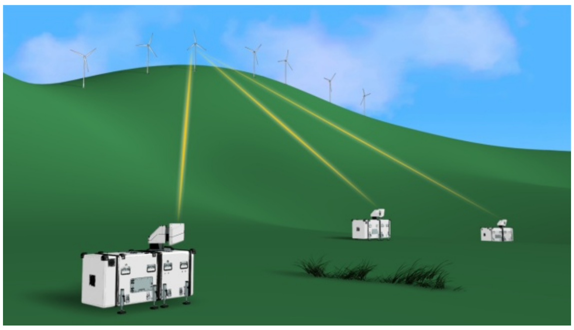
Figure 2c: 2D Steerable scan head on top of short-range WindScanner.

Long-range (0.1 – 6 Km) WindScanners

In addition, in collaboration with the French lidar manufacturer Leosphere, IPU and Risø DTU have also engaged in the design and manufacturing of three new two-axis mirror-based steerable scan heads, and integrated them with three WindCube200 lidars to power WindScanners for long-range applications (Fig. 3). Testing of hardware and software for jointly steering and controlling these long-range wind scanners is in progress in collaboration with Leosphere.

The long-range WindScanners have since become available commercially from Leosphere as 2D beam-steerable wind profilers (Windcube200S), with a nominal measurement range during typical atmospheric conditions out to 6000 m.

The first field testing of the long-range WindScanners took place at Nice airport and Marseilles airport in France during April-May this year.



WindScanners at work (concept)

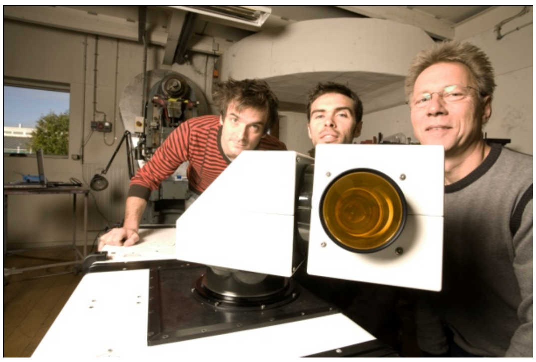


Figure 3a: 3D Long-range

Figure 3b: Engineers from Leosphere and IPU behind the scan head on a long-range WindScanner during Lab test at Risø DTU.

Turbine Integrated Lidars for Steering and Control

Wind turbines are often placed in areas where powerful winds are common and, if they are not optimally trimmed and aligned into the gales, they can be exposed to excess loads or even be destroyed.

By use of lidars mounted on the nacelle, or integrated into the spinner or the blades, it is now possible to obtain pre-vision and forecasting of the incoming wind gusts and shear.

Detailed monitoring of the upwind inflow conditions, in combination with new (to be developed) active feed-forward control, opens up many new possibilities for minimizing the loads and increasing the efficiency and hence the life-time of turbines and wind farms.

Several time scales for the wind measurements and the corresponding systems will be involved. The typical 10-minute sampling period of wind data for wind surveys may be adequate for controlling the turbines yaw. But this time scale is not short enough to characterize the impact of local turbulence on the turbine performance.

Wind gusts detected 100-200 meters upwind typically impact the turbine rotor on a 10 s scale, timely enough to feather or pitch the blades. The turbine rpm is another variable that can be adjusted to prevent damage on that time scale. Blades provided with active trailing edge flaps require wind data acquired at even shorter (sub-second) time scales.

A first turbine-mounted lidar capability was achieved in a proof-of-principle experiment in 2003, in which a prototype ZephIR lidar was placed on the nacelle of a Nordex N90 turbine [5]. This experiment demonstrated the feasibility of wind speed measurements at ranges up to 200 m in front of the turbine.

In 2009, a continuous wave (CW) conically-scanning wind lidar (ZephIR) was installed in the spinner of a large 80 m diameter, 59 m hub height, 2.3 MW Vestas NM80 turbine (Mikkelsen et al. [6]). This, the first wind lidar integrated in a rotating spinner, provided us with unimpeded views and detailed measurements of the approaching wind fields from 100 m distance in front of the rotor plane (Figs. 4b and 4c).

Several wind lidars for turbine mounting have recently emerged, including, among others: “ControlZephIR” (Natural Power); “Vindicator” (Catch the Wind, Ltd.) and “Wind Iris” (AventLidar Technology).

At the Risø DTU Test Centre for Large Wind Turbines (Høvsøre), power curve performance measurements have been performed on turbine-mounted lidars. For instance, in 2011 it was demonstrated that power curves based on a turbine-mounted prototype of the “Wind Iris” lidar exhibited less scatter than power curves based on a standard met-mast, cf. Wagner et al. 2011 [7].

The challenge now for researchers, engineers and manufacturers working with remote sensing for wind energy, is to show, in traceable scientific experiments, that wind turbines actually can make practical use of upwind looking lidars for power curve measurements and for improving control strategies, and to optimize performance and minimize the loads.

2D Upwind Scanning Spinner-integrated Lidar for Control:

In collaboration with Natural Power (UK) and IPU (DK), Risø DTU is currently engaged in designing and constructing a first 2D "cone-filling" upwind scanning wind lidar. This instrument is intended for forecasting of entire rotor plane wind fields, to be combined with enhanced feed-forward control (see Figs.4 a-d).

The new 2D "cone-filling" spinner lidar is realized by combining a standard conically-scanning ControlZephIR, based on a ZephIR 300 with different system software and mechanical housing configurations to allow the unit to be either spinner or nacelle mounted. This spinner lidar is equipped with a fixed cone-filling scan pattern version of the scan head earlier developed for the short-range WindScanners at Risø DTU, cf. the blue top in Fig. 5a (top left) and the cone-filling scan pattern in Fig. 5d (bottom right).

In collaboration with Dong Energy, LM Wind Power (DK), Natural Power (UK), NKT photonics DK, IPU (DK) and Risø DTU, the new 2D spinner lidar will be tested again in the 2.3 MW NM80 turbine situated at Tjæreborg Enge, as part of an ongoing Danish National Advanced Technology Foundation (DNATF) supported project: "Integration of Wind LIDARs in Wind Turbines for Improved Productivity and Control"[i].

The Future

It is clear from the scope of the above descriptions that lidar remote sensing has come a long way during the past decade, and that development and deployment for wind energy is now progressing very rapidly.

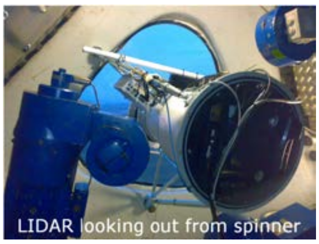
We expect soon to see many new applications and activities around lidar remote sensing, not just within wind condition assessment, resource assessment, and active control, but also more widely in meteorological boundary layer studies.

So in the future lidars are going to be evident in many areas. They will soon become an integral part on many turbines, both on new ones as OEM equipment, and also retrofitted, on many existing turbines, as well as progressively appearing as endemic in other fields.

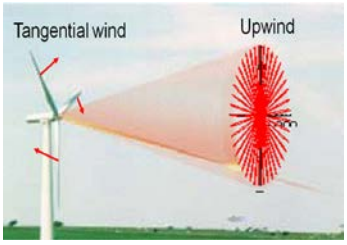
2D Scanning Spinner Lidar

2D Spinner Lidar

Prototype ZephIR in NM80 Spinner



Prototype testing in a MN80 2.3 MW WT



2D Upwind scanning concept

Figure 4 a-d:

2D upwind Spinner lidar for spinner integration build from a standard conically scanning Control ZephIR equipped with a Risø DTU 2D scan head (top left(a)).

Prototype spinner lidar testing in Dong Energy's NM80 test turbine at Tjæreborg Enge 2009 (top right (b) and bottom left(c)).

Visualization of a cone-filling scan pattern probing the wind field in front of the rotor plane. Shown also are three small lidar telescopes integrated into the turbine blades and fed via optical fibers from a ControlZephIR installed in the rotating spinner (bottom right (d)).

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