Lidar Remote Sensing

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Abstract

Our experimental research for wind energy focuses at the moment on new remote sensing based measurement technologies to be deployed in future site-specific wind condition measurements and for real-time turbine-integrated wind condition monitoring and control.

Developments in 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 and hence diminishing signal-to-noise ratios (SNR) with increasing distance to the measurement volume.

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 matched performance wind lidar measurement was obtained with a wind lidar in the calibrated wind tunnel belonging to LM Wind Power, Kolding Denmark.

The laser beam from a 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 and successfully measured wind speeds from 5m/s to 75 m/s with an averaged difference of just 0.4% for a sustained period of time and across all measured speeds (see Fig. 1).

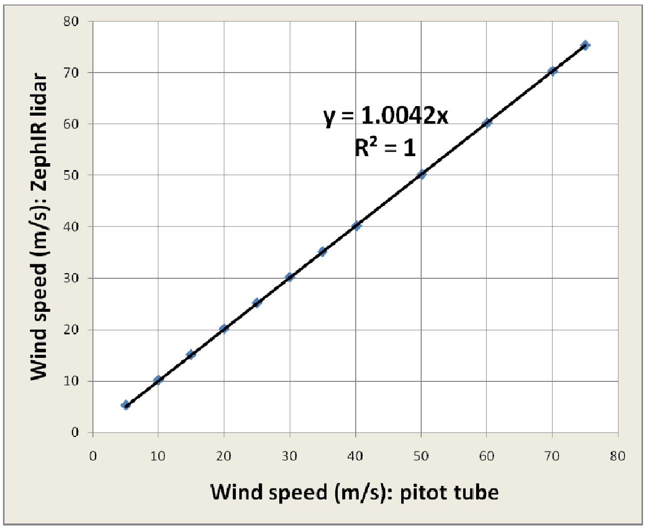


Figure 1 WindTunnel mached performance testing of LIDAR

These new calibrated wind tunnel measurements conclusively shows 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. Its final report was published here in March 2011 (www.upwind.eu).

Subtask "WP6" on remote sensing was motivated by the continuous growth in wind turbine size, which makes mast-borne conventional wind 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, such LIDARs based on this "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, but recently, they have extended their range 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 Wind lidars, and without depending on masts, power curve measurements can today be performed on very large wind turbines. The best LIDARs investigated measured wind speeds with an 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's "equivalent wind speed" concept and allowing the use of remote sensing to measure wind profiles.

- With relatively low power consumption, LIDARS can provide profile measurements over the entire rotor plane that can be used for resource assessment over flat terrain. (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 vertical wind profile scanning 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 reduction results from the large measurement volumes involved with fixed-inclination, azimuth scanning, wind profiling LIDAR's.

The effective measurement volume for LIDARs typically exceeds 100 meters in horizontal dimension (length scale). 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 VAD 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 correctly, unless we introduce supporting measurements from a met-mast instrument or introduce additional assumptions about the turbulence.

New Wind Energy Research Infrastructures build from LIDARs: "WindScanners"

At Risø DTU, we are heading the establishment of a new Research Infrastructure (RI) for LIDAR-wind and turbulence measurements based around large turbines on 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 WindScanners 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, cf. 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 spring 2011 ("Six-beam" 3D turbulence profiling experiment, and "Small hut wind wake flow and turbulence visualization").

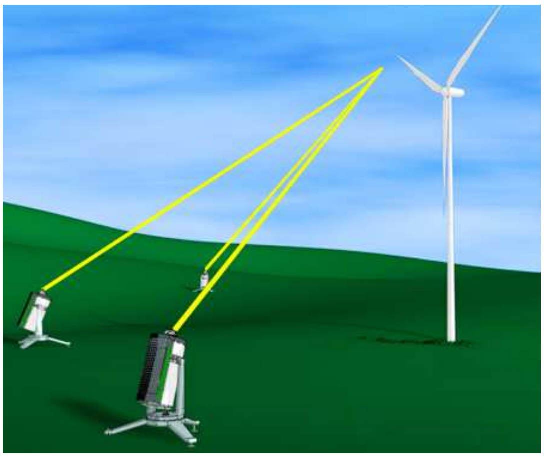


Figure2a: 3D Short-range WindScanners at work (concept)

Figure 2b: 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. cf. 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 from Leosphere as 2D beam-steerable wind profilers (Windcube200S), with 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.

Figure 3a: 3D Long-range WindScanners at work (concept)

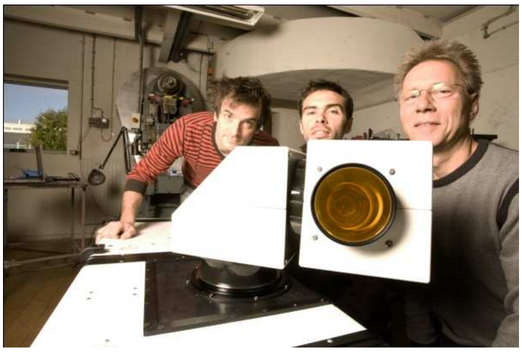


Figure 3b: 2D scan head for long-range WindScanner during Lab test at Risø DTU.

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 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-min sampling period of 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 turbines 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] and 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 Ø, 59 m hub height 2.3 MW Vestas NM80 turbine (Mikkelsen et al. [6]). This, to our knowledge first wind LIDAR integrated in a rotating spinner, provided us with unimpeded views and detailed measurements of the approaching wind fields from 100 meters distances in front of the rotor plane, cf. Fig 4 (b and c).

A n Lidar based devices for turbine mounting have since emerged, including, among others: “ControlZephIR” (Natural Power); “Vindicator” (Catch the Wind, Ltd.) and “Wind Iris” (Avent Lidar Technology).

Accordingly, researchers, engineers and manufacturers working with remote sensing for wind energy have now all been challenged to demonstrate, in traceable scientific experiments, that wind turbines actually can make practical use of upwind looking LIDARs 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 at the moment engaged in designing and constructing a first 2D “cone-filling” upwind scanning wind lidar, intended for forecasting of entire rotor plane wind fields, to be combined with enhanced feed-forward control, see Fig.4 a-d.

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

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].

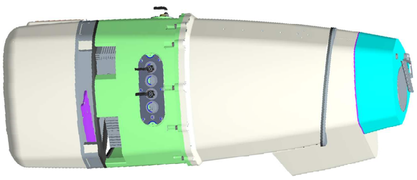
The Future

So apparently from the above, its clear that we already came a long way with LIDAR remote sensing during the past decade, and that development and deployment within wind energy now progresses fast.

We expect soon to see many new applications and activities around LIDAR remote sensing to become disseminated within experimental meteorology and hence also within wind condition assessment, resource assessment, and active wt control.

So in the future to come look out for LIDARS everywhere - , they will soon become integral part on many turbines, both on new ones as OEM equipment, and also retrofitted, on many existing turbines, we believe….

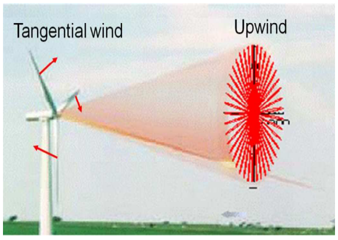
2D Scanning Spinner Lidar



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 (a:top left).

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 2D scan pattern probing the wind field upwind in 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)).

References

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[2] Wagner R., Courtney M., Gottschall J., Lindelöw–Marsden P. Accounting for the wind speed shear in wind turbine power performance measurement.(Submitted to Wind Energy).

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[5] Harris M., D .J. Bryce, A. S. Coffey, D. A. Smith, J. Birkemeyer, U. Knopf, “Advance measurement of gusts by laser anemometry”, J Wind Eng. 95, 1637-1647 (2007).

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[i] The Danish National Advanced Technology Foundation’s (DNATF) Project: “HTF nr. 049-2009-3 - Integration of Wind LIDAR’s In Wind Turbines for Improved Productivity and Control”