Nacelle-Based Lidar Systems

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Summary

The use of a nacelle-based Lidar system allows measuring turbine inflow and wake in a very high spatial and temporal resolution. The new measurement techniques to be developed have direct applications on- and offshore for the verification of wake models, predictive control strategies and new methods for power curve determination and load estimation.

An adaptive scanning device was developed for the standard pulsed Lidar system Windcube. This additional system has been conceived with a certain flexibility to allow different trajectories and to scan horizontally the flow field in front and behind of turbines covering the whole rotor disc. The design and construction of the device was supported by a software tool for wind turbine Lidar simulation (Schlipf et al. 2009). Based on the results of the simulation of different trajectories, requirements to the hardware and software adaptation could be defined.

Introduction

Installation of the Lidar system on the nacelle of a turbine is advantageous because in this way the Lidar yaws with the turbine and the laser beam is always orientated along the up- or downwind wind direction, depending on the application.

If the Lidar system "is looking" upwind one can measure the incoming wind for e.g. predictive turbine control, load estimation or power curve determination. If the Lidar is looking downwind it is possible to measure the turbine's wake wind and thus making the validation of wake models possible. The wind speed component of the line-of-sight vector is much higher when operating horizontally from a nacelle than from the ground.

The development of different nacelle-based Lidar systems are on the one hand commercial products (e.g. Catch the Wind, Avent Lidar) with two/three beam directions which mainly focus to support the yaw control of the turbine. On the other hands different research Lidar were developed for nacelle applications. For this reason one of the first cw-Lidar systems from QinetiQ was used for the first investigations regarding turbine control (Harris et al., 2006) and wake (Trujillo et al., 2008). Another cw- Lidar was mounted in the rotating spinner of a wind turbine (Mikkelsen et al., 2010). The Lidar system presented here is based on the pulsed Lidar device "Windcube" of Leosphere (Rettenmeier et al., 2010).

The units of the Lidar scanner

The SWE Lidar system consists of two components. The first component is the commercial "Windcube WLS-7" from Leosphere. The second part of the used system is a scanner specifically created for nacelle-based Lidar measurements.

Windcube

The "Windcube WLS 7" was developed to measure wind speed and wind direction from the ground in order to replace the conventional met masts for wind potential analyses in some areas and to support the certification process regarding power curve and load measurements in the future. The working principle of the pulsed Lidar system is described by (Cariou, Boquet, 2010),

In order to use the standard Windcube for a nacelle-based measurement campaign several adaptations had to be made. The internal deflection mirror with 45° was removed and the optical axis from the Windcube to the scanner had to be ensured. The software had to be adapted insubstantially:

- The Windcube has to be synchronized with the controller unit of the scanner so that the movement of the mirror and the measuring of the laser is synchronized.

- The ten arbitrary heights from the ground-based system have been reduced to five arbitrary focus distances in front of the Lidar system for the nacelle-based version. With a fixed focus length the scanning figure is described on a cubic surface (Fig. 1). It is possible to vary the focus length at each measurement point so that the focus plane is vertical which means a "slicing" of the wind field (Fig. 2).

- The maximum number of measurement points of a scanning pattern is limited to 49.

- The scanning modes are either "Start-Stop" or "Bang-Bang". At the Start-Stop mode the mirror stops at the measurement point, the measurements involve shooting and averaging the spectras to the line-of-sight wind speed. Afterwards the mirror moves to the next measurement point. The employment of this mode allows to average a higher number of shots which are taken into account to calculate the line-of-sight velocity. The result is a good carrier to noise ratio (CNR) and a higher maximum measurement range. In the "Bang-Bang" mode the mirror always moves, but decelerates shortly before reaching the measurement point and accelerates after passing the measurement point. In this mode the number of shots to be averaged has to be lowered. This means that the CNR is worse compared to the "Start-Stop" mode, but the movement is much faster and therefore the temporal resolution is better.
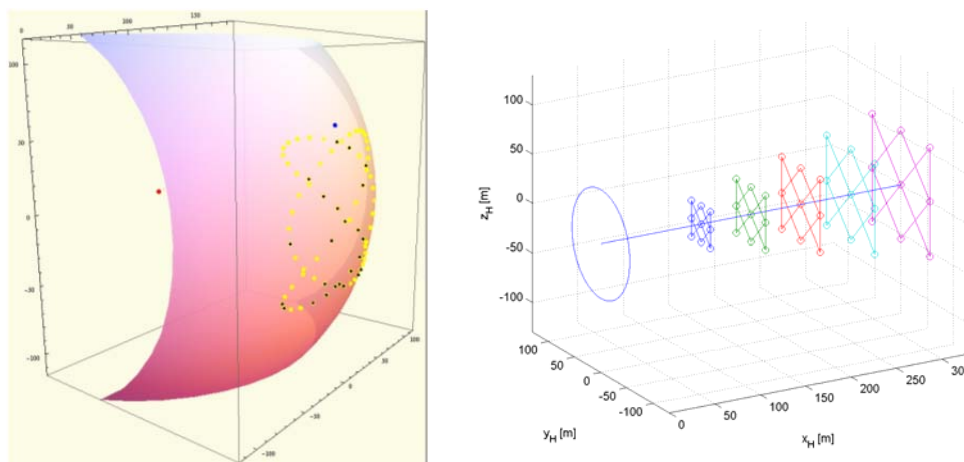

**Figure 1, 2. Measuring on a cubic shape with a fixed focus length (left)
and using variable focus length to "cut" the wind field vertically (right)**

Scanner

A scanner device with two degrees of freedom has been developed for the nacelle measurement campaigns in order to be able to position the laser beam of a standard Windcube Lidar system in any direction. The requirements for the development of the scanner system were:

- Angle of projection: 53,2°. In a distance of 1D the measurement area should cover the whole swept rotor disc.

- Flexible trajectories. Depending on the different applications, various scan patterns should be possible.

- High speed and acceleration. To get a good temporal and spatial resolution, it is neccesary that the measurements are fast and have a high repeatable accuracy.

The scanner system developed is based on a single mirror which is moved by a mechanical system with two independent rotation stages (Fig. 3). The mirror has a mechanical angle range of ±15° in the pan and tilt direction (horizontal and vertical). The motors are controlled by an external unit which is synchronized with the Windcube. The two mentioned rotation stages and the supporting structure with the transmission rods form the scanning system which was mounted in a modular way in order to simplify attachment to the standard Windcube (Fig. 4). The scanner was integrated in a second housing so that an adaptation to the original Windcube was easy and water tightness as well as structural stability could be assured. Thus, the orientation of the laser beam and the alignment of the optical axis could be guaranteed.

The mirror which deflects the beam in the original Windcube system is removed so that the laser beam goes through both casings and is deviated by the 2-DOF mirror (Fig. 5).
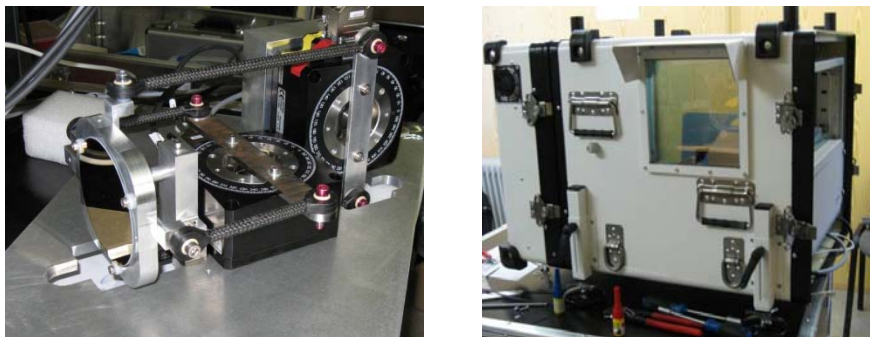

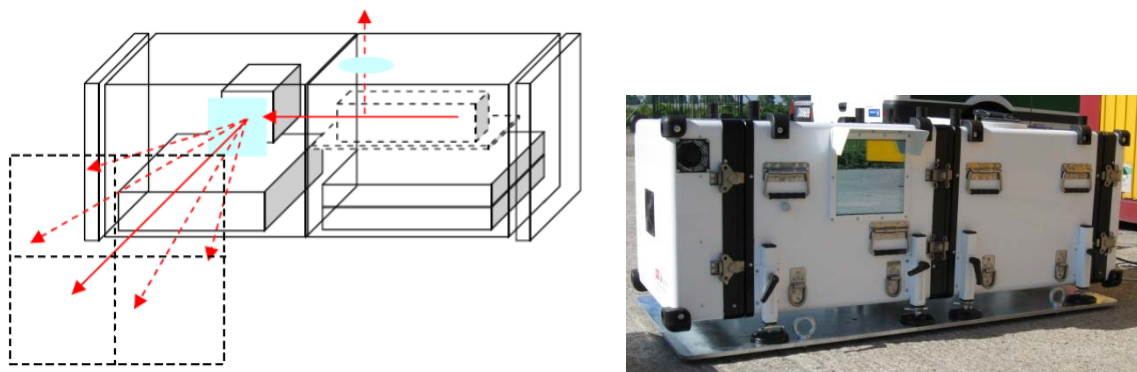**Figure 3, 4. Scanner assembly (left) and integration to a second housing (right)**

Figure 5, 6. Way of the laser beam and the optical axis (left) and the assembled system modules (right)

Scan pattern

Measuring the wind field from the nacelle of a turbine makes it possible to gather wind field information (wind speed, wind direction) in a high temporal and spatial resolution. To scan a wind field in any vertical and horizontal direction, the laser beam runs along a predetermined path and executes the measurement at predefined points. For designing a scan pattern the wind turbine simulator WITLIS was developed (Schlipf et al (2008). This software supports the development of trajectories considering the motor speed and acceleration. WITLIS scans a synthetic wind field generated with Vindsim and interpolates the measurements to a defined grid. Then the calculated wind field is compared with the synthetic one (Basterra Taramona (2008)). Some investigations were carried out in accordance with the planned application of inflow and wake measurements taking into account the maximum measurement points per focus plane. The software WITLIS is also used to post-process the measured data.

As a result of the consideration to scan as many points as possible in the shortest possible time inside a square, the trajectories based on Lissajous-figures show the best ratio of temporal and spatial resolution. A Lissajous figure can be created by superposing two harmonious waves that can be driven from the two independent rotation stages used. In mathematics, a Lissajous curve (Lissajous figure or Bowditch curve) is the graph of a system of parametric equations which describe complex harmonic motion. (Eq. 1, 2)

$$\text{Eq. (1)}$$

$$\text{Eq. (2)}$$

"This family of curves was investigated by Nathaniel Bowditch in 1815, and later in more detail by Jules Antoine Lissajous in 1857. The appearance of the figure is highly sensitive to the ratio a/b. For a ratio of 1, the figure is an ellipse, with special cases including circles ($A = B$, $\delta = \pi/2$ radians) and lines ($\delta = 0$). Another simple Lissajous figure is the parabola ($a/b = 2$, $\delta = \pi/2$). Other ratios produce more complicated curves, which are closed only if a/b is rational. The visual form of these curves is often suggestive of a three-dimensional knot, and indeed many kinds of knots, including those known as Lissajous knots, project to the plane as Lissajous figures."
[http://en.wikipedia.org/wiki/Lissajous_curve]

One of the basic trajectories used in different measurement campaigns was a Lissajous figure with a ratio of 3:4. If a Lidar scans the figure in such a way, it becomes more difficult to evaluate and recalculate a wind field from the measured points (Fig. 7). Therefore, specific measurement points have to be defined, and the figure was adapted to 7x7 measurement grid points (Fig. 8). The time needed to scan the 49 measurement points was 8.4 sec. which led to a good temporal and spatial resolution. Based on the pulsed Lidar technology, each trajectory point is measured at 5 focus planes simultaneously which even allows an interpolation between the different focus planes.
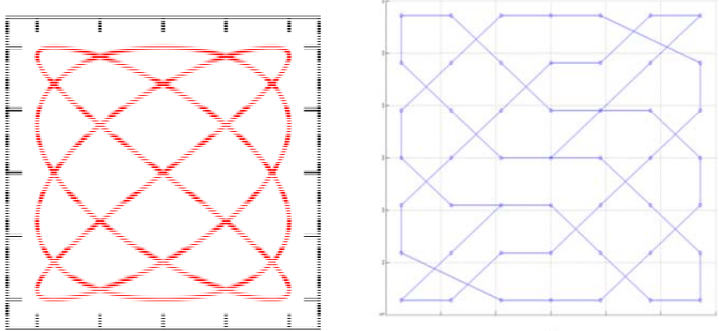

**Figure 7, 8. Lissajous figure with a frequency ratio of 3:4 (left)
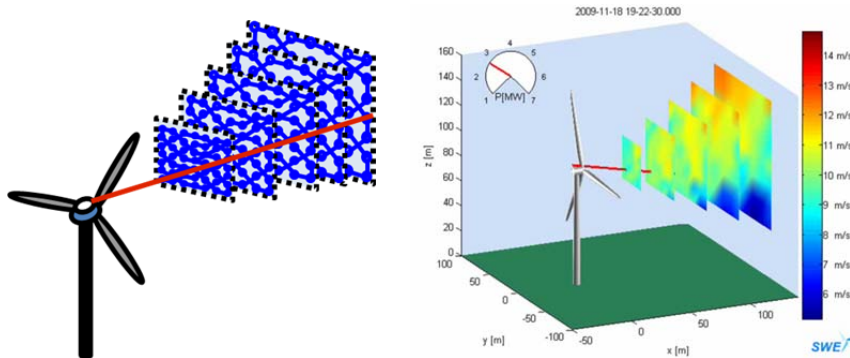and adapted to 7x7 measurement grid (right)**

Figure 9, 10. Sketch of simultaneous measurements at different distances (left) and real measured data with an interpolation within one focus plane (right)

To ensure that the scan pattern works with a high accuracy a visible red laser was used and the scan pattern was photographed with a long exposure time (Fig. 11). As a second step, the use of an infrared camera and an IR-sensitive card makes even the real eye-safe beam visible.
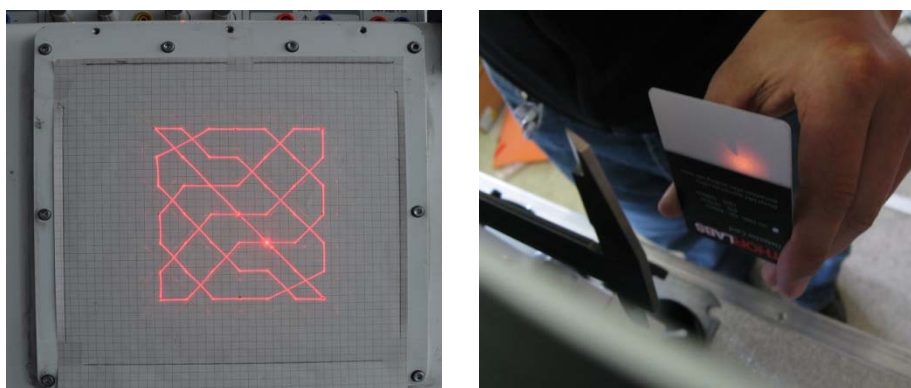

Figure 11, 12. Photo of Liss2Grid trajectory taken with long exposure time (left). Use of an IR-sensitive card for the invisible laser beam (right)

CNR

The carrier to noise ratio (**CNR**) is deemed to be as an indication of the quality of the measurement. It describes the ratio of sent photons **C** to the number of reflected photons **N** using the unit dB (Cariou, 2008).

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad -\qquad\qquad\qquad\qquad\qquad\qquad \text{Eq. (3)}$$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad -\qquad\qquad\qquad\qquad\qquad\qquad \text{Eq. (4)}$$

The CNR value of every point measurement can be used to obtain information about the quality of the line-of-sight velocity. Measurements with a bad CNR value (< -17dB) have to be ignored. There are several reasons for poor CNR values, from a dirty window/prism to the quantity and kind of the aerosols in the air. During -and directly after- a heavy rain the air is very clean and contains fewer aerosols to reflect the laser beam. Here the ratio between carriers to noise is quite bad. In offshore conditions the value of CNR is often higher due to the salty air.

If we examine nacelle-based measurements, the impact on the rotor blades causes a bad CNR signal when the system is installed behind the rotor. About 30% of the data has to be removed due to

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rotor impact. Synchronizing the scan pattern with the rotor position or scanning the pattern in the opposite direction of the rotor direction will reduce the ignored data sets. If any faults in the Lidar system occur, there is a need to know that issue especially when the output data and information is linked to the control of the turbine.

Wind field reconstruction

To reconstruct the wind speed and the wind field some assumptions have to be made. This is due to the fact that one can measure only the line-of-sight velocity along the laser beam.

Based on the assumption that the wind field is parallel to the ground, the following drawings show how the wind speed vector is mapped by the line-of-sight vector. The absolute values of the line-of-sight velocity v_{LOS} at points P_i for every focus area m and the angles of the vertical and horizontal beam deflection are needed to recalculate the wind field. By means of these angles the coordinates of the measured points (for every five focus planes) can be calculated.
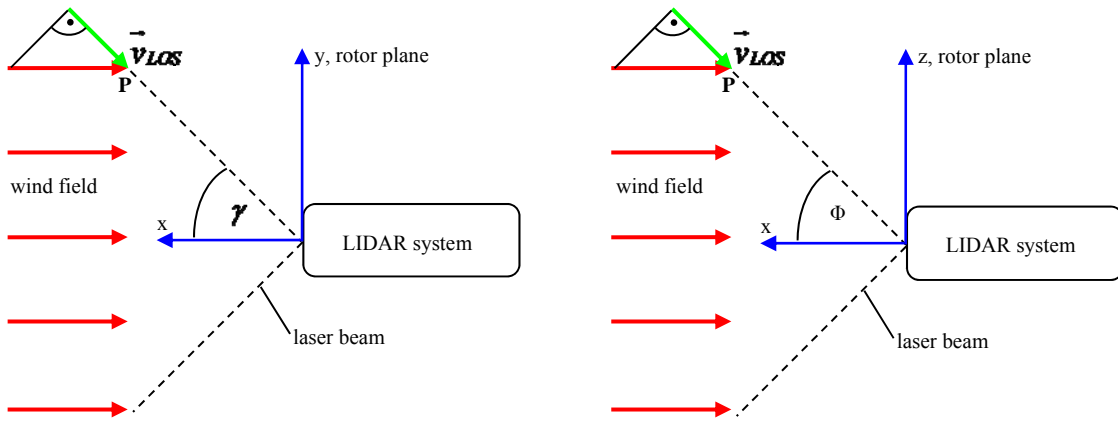

Figure 13, 14. Schematic drawing of the LiDAR coordinate system from top and lateral views (left, right)

For a Cartesian coordinate system, where the LiDAR system is the origin of the coordinate system, the coordinates of a measured point $\mathbf{P_i}$ are x_P, y_P, z_P. Using these coordinates the normal vector $\vec{n}_{LOS} = [x_n, y_n, z_n]^T$ of the laser beam can be defined as

$$x_n = \frac{x_p}{\sqrt{x_p^2 + y_p^2 + z_p^2}} \qquad \text{Eq. (5)}$$

$$y_n = \frac{y_p}{\sqrt{x_p^2 + y_p^2 + z_p^2}} \qquad \text{Eq. (6)}$$

$$z_n = \frac{z_p}{\sqrt{x_p^2 + y_p^2 + z_p^2}} \qquad \text{Eq. (7)}$$

Therefore $\left|v_{LOS,fpm,Pi}\right|$ at focus plane m and point i yields to:

$$\left|v_{LOS,fpm,Pi}\right| = u_p \cdot x_n + v_p \cdot y_n + w_p \cdot z_n \qquad \text{Eq. (8)}$$

where the wind speed coordinates at point P_i, u_P, v_P, w_p, are unknown. Assuming that a plane parallel wind field prevails, the wind speed vector can be simplified by setting the wind speed coordinate in horizontal direction v_P and the wind speed coordinate in vertical direction w_p to zero.

$$v_p = 0$$
$$w_p = 0$$

The normal wind direction vector $\vec{n}$ $_{wind\ direction}$ for a plane parallel wind field (that always inflows right-angled to the rotor area) without vertical wind component can be described as followed:

$$\vec{n}\ _{wind\ direction} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad \text{Eq. (9)}$$

The angle $cos\ \varphi$ between $\vec{n}$ $_{wind\ direction}$ and $\vec{n}$ $_{LOS}$ can be calculated

$$\cos \varphi = \frac{\vec{n}\ _{LOS}\ \vec{n}\ _{wind\ direction}}{\|\vec{n}\ _{LOS}\|\|\vec{n}\ _{wind\ direction}\|} \qquad \text{Eq. (10)}$$

The wind speed component u in x-direction, is the projection of v_{los} in the direction of $\vec{n}$ $_{wind\ direction}$. It can be calculated with the angle between the vectors.

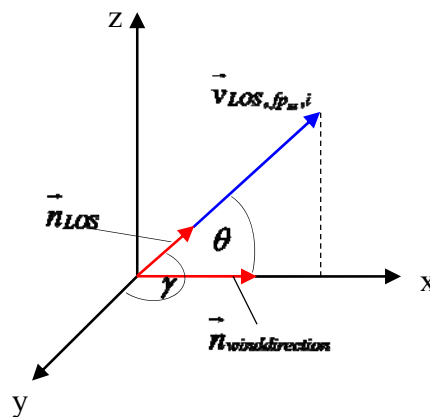$$u_{los} = \frac{v_{los}}{cos\varphi} \qquad \text{Eq. (11)}$$

Fig.15. Schematics of the normalized vectors and $\vec{v}_{LOS}$

Assuming a plane parallel wind field and no vertical wind speed component enables a reconstruction of the wind field. But what's about horizontal and vertical shear, yaw error, turbulence? Here some measurements and basic investigations still take place to understand those issues. One possibility is shows with an "Estimator" by Schlipf, 2011.

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"Visited" test sites of the SWE Scanner

Onshore test site Bremerhaven, Germany

The prototype of the AREVA Wind M5000 wind turbine was erected in December 2004 in Bremerhaven, close to the North Sea. In cooperation with DEWI (German Wind Energy Institute) and AREVA Wind the SWE started a thorough measurement program in spring 2005. In 2007 the national funded project "Development of Lidar measurement techniques for the German offshore test site" started with the objective to develop reliable and standardized remote sensing techniques for various new applications in the wind energy community and to support in a later step other RAVE (research at alpha ventus) projects at the German offshore test site "alpha ventus". Except for a FINO1 campaign, all Lidar measurements from ground and from nacelle were carried out in Bremerhaven.

The M5000 is a 5 MW wind turbine designed for offshore purposes. With a hub height of 102m and a rotor diameter of 116m the M5000 is currently one of the largest wind turbines. The cut-in wind speed is 4m/s, the rated wind speed is 12m/s and the cut-out wind speed 25m/s. The M5000 is a pitch-controlled, variable speed wind turbine with a permanent magnet generator.
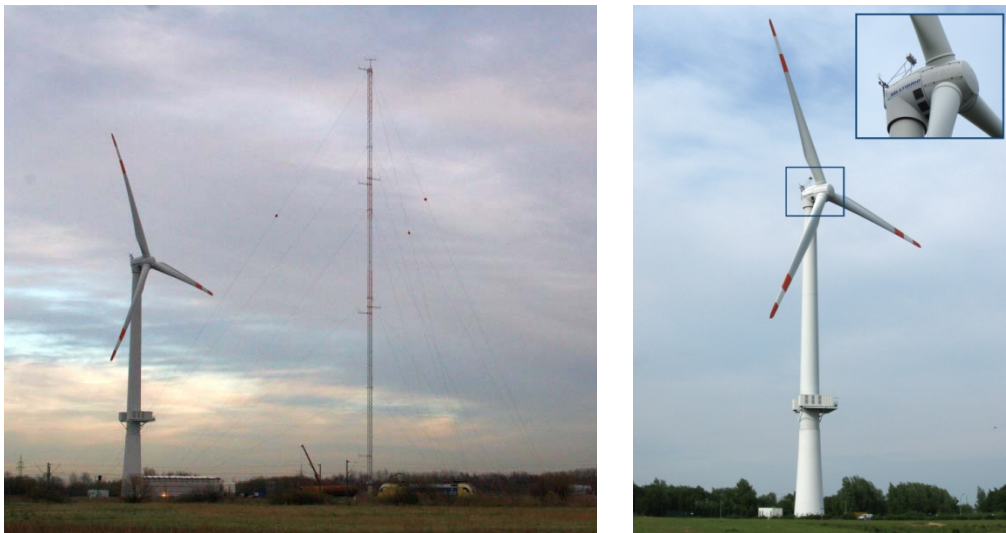
Figure 16, 17. Onshore test site with AREVA M5000 and SWE met mast (102m) (left)
Installation of the Lidar system on the nacelle of the turbine (approx. 105m AGL) (right)

Onshore test site Risø Campus - DTUWind Energy, Denmark

The measurement campaigns at this test site mainly focus on fundamental investigations concerning the minimum number of trajectory points for equivalent wind speed, turbulence measurements, horizontal/ vertical wind shear and mean wind speed accuracy compared to a cup anemometer on a met mast. The test site of DTU Wind Energy is located close to the research center on the Risø Campus (Denmark). The SWE-Lidar system was first installed on ground, tilted up with 25°and pointed towards the met mast. In a second campaign, the Lidar system was installed on a platform of a Nordtank wind tubine in about 38m height. From this platform, the Lidar system shot almost horizontally to a met mast where the laser pointed to three sonic anemometers at different heights.

**Figure 18, 19. Test site at Risø-DTU with the Nordtank and Tellus wind turbines (left).
Tilted SWE Lidar system pointing to a met mast (right)**

Onshore test site National Wind Technology Center (NWTC) – NREL, USA

The measurement campaigns at this test site mainly focus on the first test and validation of Lidar assisted control worldwide. The SWE scanner was installed on the nacelle of the two-bladed Controls Advanced Research Turbine (CART-2).

Figure 20. SWE scanner mounted on the CART-2 machine for Lidar Assisted control purposes

Offhore test site "alpha ventus"

The offshore test site "alpha ventus"[1] is located 45 km north of the island of Borkum next to the research platform "FINO 1". It comprises twelve offshore wind turbines with a total capacity of 60 MW. Six AREVA Wind M5000 turbines were installed in summer 2009, six REpower 5M turbines followed in 2010. The German Federal Environment Ministry supports "alpha ventus" with a major research funding. The RAVE[2] initiative is accompanying the construction and operation of the test site to attain a broad basis of experience and expertise for future offshore wind parks. Several research projects are currently carried out. Within the RAVE-OWEA research project two scanning Lidar systems, one installed on the nacelle of the AREVA Wind M5000 the other one on REpower 5M, measure the inflow and the wake of the turbines under offshore conditions.

Figure 21, 22. Lidar system (scanner unit and Windcube) on the top of a Repower 5M measuring the inflow

Measurement campaigns and some results

Different measurement campaigns regarding different applications such as the verification of Taylor's frozen turbulence hypothesis, validation of wake models, predictive control, load estimation and power curve determination are still on-going or have been terminated. If we look at the power curve determination and load measurements, the wind field information has to be summed up to equivalent wind speed and turbulence intensity (Klausmann, 2010), (Bischoff et al., 2010).

Equivalent wind speed

The advantage of measuring from the nacelle of a turbine is that the whole swept rotor area is covered and that horizontal and vertical wind shear can be taken into account. According to the standard, fewer sectors have to be excluded because there is no met mast in the wake of the turbine or of other obstacles. Thus measurement campaigns can be carried out in a shorter time.

To determine a power curve, the mean values as well as the standard deviation of the electric power and the average wind speed over 10 minutes are necessary. The main goal is to get a power curve including all wind field information, as well as to get a smaller standard deviation. A second goal consists in the definition of relevant trajectory points. Both methods presented here are based on the trajectory *Liss2Gridopt*. With 7x7 measuring points a variety of different methods is feasible.

[1] www.alpha-ventus.de
[2] www.rave-offshore.de

<u>Arithmetic average of all points</u>
The first method is a simple arithmetic average over all mean wind speeds of measurement points during a 10 minute period of time.

$$u_{mean} = \frac{1}{N}\sum_{i=1}^{N} v_i \qquad \text{Eq. (11)}$$

where N is the number of layers and v_i the average wind speed of trajectory layer i. The used trajectory for this example, *Liss2Gridopt*, has seven layers.
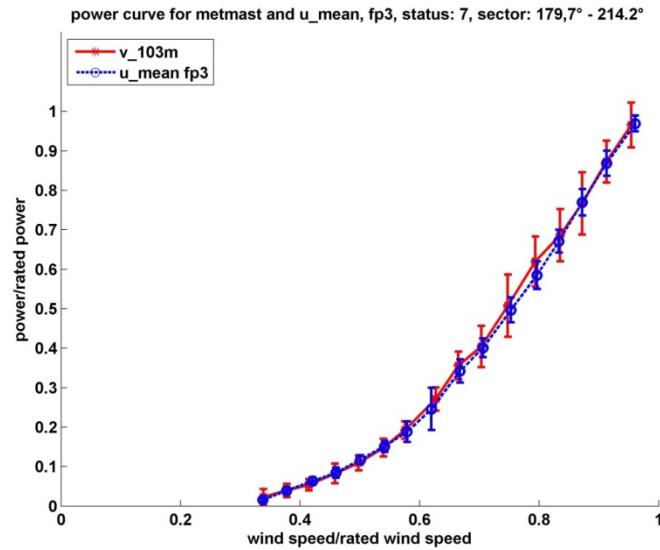

Figure 23. Power curve met mast and *u_mean* method

The curve is relatively similar to the power curve measured with a met mast and a cup anemometer according to the IEC standard. One can see that the bars of the standard deviation are significantly smaller. That means that the uncertainties in the measurements are lower and the accuracy is higher.
In another approach, five single points were picked out of the 49 measurement points (Big-Cross). Even when reducing the measurement points the standard deviation is still very small.

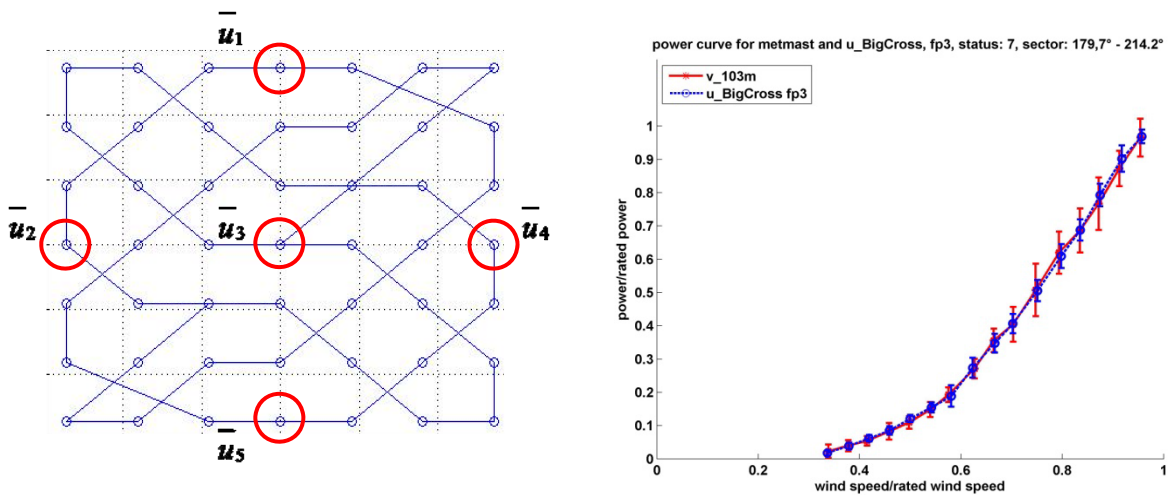$$u\_BigCross = \frac{1}{5}\sum_{i=1}^{5} \bar{u}_i \qquad \text{Eq. (12)}$$

Figure 24, 25. Five points out of 49 for the Big cross method (left) and calculated power curve (right)

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Outlook & Conclusions

The use of a LiDAR system from the nacelle offers various applications in wake wind field analysis, wind turbine control, power curve determination and load estimation. The whole swept rotor area can be taken into account, but assumptions have to be made. Nacelle-based measurement methods show a great potential on- and offshore and even in complex terrain. But there are still some investigations that have to be done concerning turbulence, vertical and horizontal shear, comparison criteria and equivalent wind speed.

Information

For other applications information can be found in the following presentations /paper

Taylors Hypothesis

Canadillas B., Schlipf D., Neumann T., Kuehnel D., *Validation of Taylors Hypothesis under offshore conditions. An experimental study using a nacelle-based two-beam Lidar*, EGU, Vienna, Austria, April 2011.

Schlipf D., Trabucchi D., Bischoff O., Hofsäß M., Mann J., Mikkelsen T., Rettenmeier A., Trujillo J.J., Kühn M., *Testing of Frozen Turbulence Hypothesis for Wind Turbine Applications with a Scanning Lidar System*, ISARS, Paris, France, Juni 2010.

Trujillo J.J., Trabucchi D., Bischoff O., Hofsäß M., Mann J., Mikkelsen T., Rettenmeier A., Schlipf D., Kühn M., *Testing of Frozen Turbulence Hypothesis forWind Turbine Applications with a Staring Lidar*, EGU, Vienna, Austria, May 2010.

Wake

Trujillo J.J., Kühn M., Bischoff O., Hofsäß M., Rettenmeier A., Schlipf D., *Validation of a Dynamic Meandering Model with Near Wake Lidar Measurements*, DEWEK, Bremen, Germany, November 2010.

Trujillo J.J., *Measurements of a multi-MW turbine near-wake using LiDAR from the nacelle*, Euromech Colloquium, Madrid, 2009

Load

Bischoff O., Anger J., Hofsäß M., Rettenmeier A., Schlipf D, Siegmeier B.. *Vertical wind shear measured with a nacelle-based Lidar system and its impact on mechanical loads*, EOW, Amsterdam, November 2011

Power curve_ground-based

Wagner R., *Accounting for the speed shear in wind turbine power performance measurement*, Risø-PhD-58(EN), ISBN 978-87-550-3816-5

Predictive Control

See contribution to this compendium by David Schlipf, SWE

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Mikkelsen T., Hansen K., Angelou N., Sjöholm M., Harris M., Hadley P., Scullion R., Ellis G., Vives G. "*LiDAR Wind Speed Measurements from a rotating spinner*, EWEC, Warsaw, Poland, April 2010.

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Acknowledgements