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Lidar-based Research and Innovation at DTU Wind Energy – a Review:

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Abstract. As wind turbines during the past decade have increased in size so have the challenges met by the atmospheric boundary-layer meteorologists and the wind energy society to measure and characterize the huge-volume wind fields surpassing and driving them.

At the DTU Wind Energy test site “Østerild” for huge wind turbines, the hub-height of a recently installed 8 MW Vestas V164 turbine soars 143 meters up above the ground, and its rotor of amazing 164 meters in diameter make the turbine tips flicker 225 meters into the sky.

Following the revolution in photonics-based telecommunication at the turn of the Millennium new fibre-based wind lidar technologies emerged and DTU Wind Energy, at that time embedded within Risø National Laboratory, began in collaboration with researchers from wind lidar companies to measure remote sensed wind profiles and turbulence structures within the atmospheric boundary layer with the emerging, at that time new, all-fibre-based 1.55 μ coherent detection wind lidars.

Today, ten years later, DTU Wind Energy routinely deploys ground-based vertical profilers instead of met masts for high-precision measurements of mean wind profiles and turbulence profiles. At the departments test site “Høvsøre” DTU Wind Energy also routinely calibrate and accredit wind lidar manufactures wind lidars.

Meanwhile however, new methodologies for power curve assessment based on ground-based and nacelle based lidars have also emerged. For improving the turbines power curve assessments and for advancing their control with feed-forward wind measurements experience has also been gained with wind lidars installed on turbine nacelles and integrated into the turbines rotating spinners.

A new mobile research infrastructure WindScanner.dk has also emerged at DTU Wind Energy. Wind and turbulence fields are today scanned from sets of three simultaneously in space and time synchronized scanning lidars. One set consists of three fast scanning continuous-wave based wind lidars (short-range system), and another consisting of three synchronized pulsed wind lidar systems (long-range system).

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Today, wind lidar profilers and WindScanners are routinely deployed and operated during field tests and measurement campaigns. Lidars have been installed and operated from ground, on offshore platforms, and also as scanning lidars integrated in operating turbines. As a result, wind profiles and also detailed 3D scanning of wind and turbulence fields have been achieved: 1) of the free wind aloft, 2) over complex terrain, 3) at coastal ranges with land-sea interfaces, 4) offshore, 5) in turbine inflow induction zone, and 6) of the complex and turbulent flow fields in the wakes inside wind parks.

1. Introduction

Since its early establishment in the 1960's the Department of Wind Energy, until 2007 the Wind Energy Division at Risø National Laboratory, Roskilde, Denmark, and today referred to as DTU Wind Energy, has been engaged with atmospheric boundary-layer experimental measurement activities in particular with surface and boundary-layer mean wind and turbulence quantities.

Most of the experimental investigations the department engaged in, from the early 1970's throughout the 1990's, were conveyed using quite heavy, cumbersome and expensive in-situ meteorological masts (met-masts) installations equipped with high-precision and calibrated micro-meteorological instrumentation such as cup anemometers, wind vanes acoustic sonic anemometers, and various temperature and pressure sensors. Examples are: the "Askervein Hill Project" [1], the multi met-mast based JylEX wind resource measurement campaign [2], and the densely instrumented "Bolund Experiment" where flow over a steep, three-dimensional hill was investigated [3], to mention a few.

During the 1980's and 1990's a scanning high-resolution 2D scanning aerosol-backscatter Lidar, developed in collaboration with DLR Oberpfaffenhofen. The aerosol Lidar was deployed as a tool to characterize puff and plume dispersion from point sources during many full-scale atmospheric diffusion tests (e.g. the BOREX smoke puff and smoke plume field tests [4,5]; the nuclear safety MOL'99 dual-tracer Argon-41 smoke plume dispersion field test [6]; the MADONA concentration fluctuation and puff diffusion field trials in the UK [7].

The experimental challenges addressed during the departments many micro-meteorological and boundary-layer observation activities have been to provide measurable evidence to be compared with the department's theoretical and numerical modelling activities. The overall quest has been to enhance our comprehension of the complex nature of atmospheric wind flow and turbulence phenomena's occurring within the atmospheric boundary layer and investigate the influence of different atmospheric stability characteristics, e.g. by investigating the characteristic differences between boundary-layer day and night time flow characteristics. The departments combination of experimental, theoretical, and numerical modelling activities has to data addressed, among others, wind flow terrain effects such as the influence of wind and turbulence profiles aloft complex terrain, - the influence of changes in surface roughness changes and surface heat flux changes on flow e.g. at coastal interfaces between onshore and offshore wind regimes.

The obvious advances of remote sensing-based measurement techniques to scan and probe the atmospheric boundary-layer wind and turbulence has always been an aspiring but not always technically feasible alternative to traditional in-situ met mast installations equipped with calibrated wind, temperature, humidity and pressure sensors. In the 1980's and 1990's the department's remote sensing based boundary-layer investigations was predominantly focused on developing and deploying sound-based remote sensing devices such as Sodars [8–10] and aerosol-backscatter lidars [11,12].

Prior to the turn of the Millennium, and with a history going back to the early work with wind coherent detection remote sensing pioneered by R.M. Huffaker [13], wind sensing coherent Doppler

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Lidars have been dedicated research tools built from discrete-component coherent laser-systems and open-space optical component, as for example the High-Resolution Doppler Lidar (HRDL), which still today is an agile operational pulsed long-range scanning wind lidar system developed and operated at NOAA, Boulder CO, USA [14].

At the turn of the Millennium, however, new optical all-fibre-based remote sensing technology emerged and soon became available for wind remote sensing to address the growing wind energy's scientific and wind industry needs. Here, in the aftermath of the late 1990's telecom revolution, new fibre-based coherent optical Erbium doped fibre amplifiers; so-called EDFA lasers came available as drivers for Doppler wind lidars. An all-fibre coherent Doppler wind Lidar was conceived and first demonstrated by Karlsson, Olsson, Letalick and Harris in 1999 [15]. In 2003, representatives from U.K QinetiQ who later formed ZephIR Lidar Inc. visited DTU Risø Campus and demonstrated on-site their first all-fibre continuous wave (cw) prototype of a wind lidar built on the remote sensing technology which today is the key feature in ZephIR Lidars.

At the wind turbine test station collocated at DTU Risø Campus, the department immediately challenged the new measurement opportunity and the very same day the new prototype cw wind lidar wind was directed towards a met mast equipped with a calibrated cup anemometer and wind vane at 2 m height. From a measurement range of 60 m the line-of-sight projected wind speed measured by the lidar was compared with the correspondingly projected cup anemometer wind speed, cf. Fig 1.

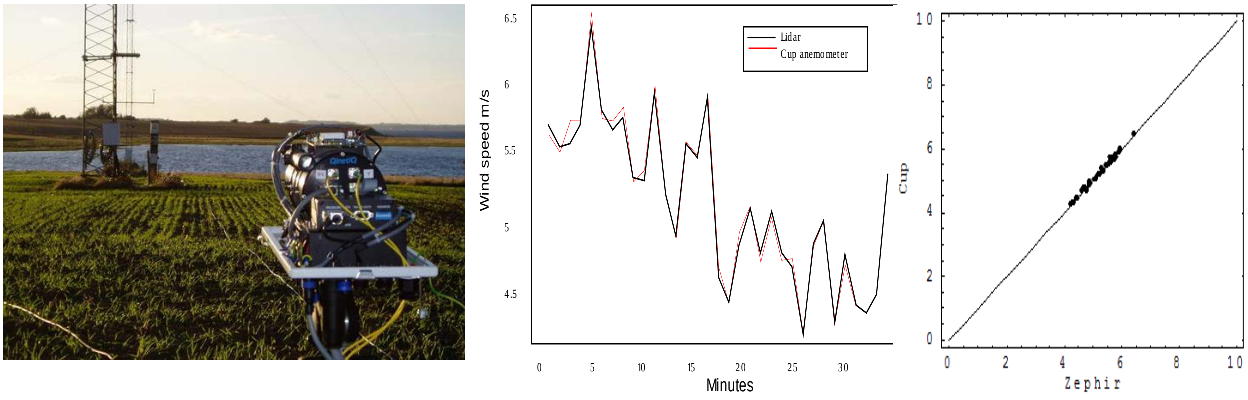

Figure 1. Left: "gray" QinetiQ all-fibre cw prototype lidar at test at Risø Campus October 14. 2003.
Middle: measured time series of the lidar and the met mast cup at 60 m range.
Right: scatter diagram between measured wind speeds from lidar vs cup anemometer.

As obviously seen by the correlation between the measured time series of wind speed from the lidar and the cup anemometer, the similarity in the wind speed measurements indeed was encouraging. The degree of correlation was superior to anything obtained previously with other wind speed remote sensing devices.

This very first all-fibre cw lidar test marked a milestone and also a turning point for the department's remote sensing-based instrument development, deployment and experimental wind energy research activity. In the 2000's there was at the same time a growing interest for measurements of the wind flow within what today among wind energy scientists has become known as the so-called "rotor layer" of the atmospheric boundary layer, that is, heights ranging between 20 m and, say 200 m, corresponding to the rotor operating height within the boundary-layer of the past decades wind turbines. Today, as already noted, the department operates turbines with tip heights reaching 225 meters into the atmospheric boundary-layer (cf. the Vestas V164 test turbine operated at DTU Wind Energy test site Østerild.

Along with the new wind lidar technology also new remote sensing opportunities for wind and turbulence measurement emerged. In retrospect, there was back in 2003 as there is still today, grooving needs for experimental investigations and this can now in many cases be facilitated by substituting tall met masts with wind remote sensing wind devises. Before 2020 turbine heights is anticipated to reach 250 meters. The new wind lidar remote sensing technology has spurred a learning process for wind energy scientists and industry during the past decade. New applications like wind lidar-based forecasting, wind lidar-based power curve assessment methods and wind lidar-based feed-forward turbine control strategies have emerged.

Also more effective methods for achieving previously defined measurement objectives and previously designed measurement campaigns is now possible, which for practical reasons and poor accuracy have not previously been technologically feasible without today's 1.55µ based wind lidar measurement technology.

Now with rotor diameters continuing to increase, as do deployment of turbines in complex terrain, knowledge of the site-specific characteristics of the wind fields beyond just mean speed and direction at hub height becomes important. Today, nacelle-mounted lidars are being recognized as a tool with potential for assessing accurate power curves, understanding wind flow characteristics, and controlling turbines. Also, measurements of turbine inflow operating under influence of wind shear, wind veer, inhomogeneous turbulence levels, low-level jets, inflow over complex terrain, and operation in wakes from other turbines are all examples of flow conditions that today can be measured, investigated and characterized by the new wind lidar-based measurement methodologies.

At DTU Wind Energy, the recently established research infrastructure operating scanning synchronized lidar systems, and referred to as "WindScanners" (Cf. the Danish research infrastructure national node: windscanner.dk and the forthcoming joint European research infrastructure facility: windscanner.eu) have been developed, commissioned, and is now in operation to reveal a wealth of such information.

In Section 2 the departments remote sensing instrument development, configuration and functional specification characteristics are described, grouped into: 1) single staring lidars, 2) single Velocity Azimuth Display (VAD) mode scanning lidars, and 3) Lidar systems equipped with steerable scan heads for three-dimensional space and time synchronized scanning (WindScanners). In section 3 then follows a listing with references to the experimental measurement activities and results obtained at DTU Wind Energy with partners during the past decade.

2. Wind Lidars and WindScanners acquired and built by DTU Wind Energy

During the past decade DTU Wind Energy has acquired, built and deployed the following sets of Doppler wind lidar systems:

Table1. Wind lidars at DTU Wind Energy 2004 - 2014

a.	Two QinetiQ prototype continuous Wave Scanning Lidars
b.	Three continuous wave ZephIR lidar (two Z150; one Z300)
c.	One ZephIR DM integrated with a DTU Wind Energy/IPU developed 2D fixed pattern scan head
d.	Three pulsed Leosphere WindCube WLS7
e.	One Leosphere pulsed tall profiling WindCube WLS70
f.	Three modified ZephIR Z150 integrated in short-range WindScanners equipped with steerable prism-based scan heads and operated as synchronized short-range WindScanners
g.	Three Leosphere type WLS 200 pulsed long-range lidars equipped with DTU Wind Energy/ IPU developed full-sky scan heads (WLS 200S prototype systems).

The wind lidars a) – e) have all been acquired as early prototypes in close collaboration with the lidar manufactures QinetiQ, ZephIR and Leosphere. The wind lidars for the WindScanners f) – g) have been jointly developed with the lidar manufactures and combined with DTU Wind Energy and IPU designed beam steering short and long-range scan heads, respectively.

2.1 *Wind Lidar System Development – Lidars, Scanners and Data Acquisition Systems*

2.1.1 Single Staring Lidars
The departments first wind lidar purchase was a white-painted copy of QinetiQ's gray prototype continuous wave "ZephIR" lidar. By removing its built-in 30 degree VAD prism wedge scanner used to deflect its scanning probing beam in a circular scan pattern 30 degrees from the telescopes pointing direction, the prototype lidar could as shown in Figure 1 be stared at a fixed pointing direction. Operated in starring mode, the cw lidars spectral transfer function could then be experimentally investigated by joint cross-correlation measurement techniques between lidar and sonic anemometer measurements co-located within the lidars sampling volume[16].

Also, the departments first acquired pulsed lidar system, a WindCube WLS7 VAD profiler, has operated in horizontal staring mode from the top of the DTU Risø Campus' 125 met mast and provided measurements for experimental evaluation of analytical and numerical tensor models for lidar-measured fine structure turbulence[17]. This first pulsed lidar was also used to measure spectral coherence in the inertial subrange turbulence [18]. It also provided measurements of the spectral coherence between spatially separated range gates, from which the applicability within Taylor's frozen turbulence hypothesis within the inertial subrange of turbulence could be assessed [19].

2.1.2 Single Lidar - VAD based scanning
With the assumption of homogeneous and stationary wind flow, all three wind components of the mean wind velocity vector can be measured by the so-called VAD (Velocity Azimuth and Display) scanning strategy as introduced by Browning and Wexler(1968) [20]. Today, the 360 degree VAD scanning methodology has found widespread application for ground-based wind energy assessment lidars, such as the cw-based ZephIR lidar (Zephirlidar.com, UK), the pulsed Wind Cube's (Leosphere, Fr), and the Galion lidar (SgurrEnergy, UK). From azimuth-scan about Zenith of the aloft wind field, both cw-based and pulsed lidars can estimate the vertical mean wind speed and direction profiles from a ground-based location, up to 150 - 200 meters height for the cw-based, and up to the top of the aerosol-containing boundary-layer with the pulsed lidars.

2.1.3 Three-dimensional Wind Velocity Scanning Lidar Systems - WindScanners
Two different types of 3D wind and turbulence wind velocity scanning lidar systems have been designed, developed and inaugurated as operational research infrastructures at DTU Wind Energy during the period 2007-2014.

The purpose has been to establishment a new research infrastructure for wind energy research via an experimental tool for atmospheric boundary-layer wind and turbulence research, and to provide open access research infrastructure support for wind energy and wind industry scientific and technological developments:

1. A short-range WindScanner system, consisting of three time and beam position scanning synchronized continuous wave (cw) wind lidars, and
2. A long-range WindScanner system, consisting of three time and beam position scanning synchronized pulsed-lidar wind lidar systems.

The two different sets of 3D wind vector synchronized WindScanner systems have been designed and built to provide high-resolution three-dimensional (3D) velocity vector scanning of remote sensed wind fields at complementary ranges:

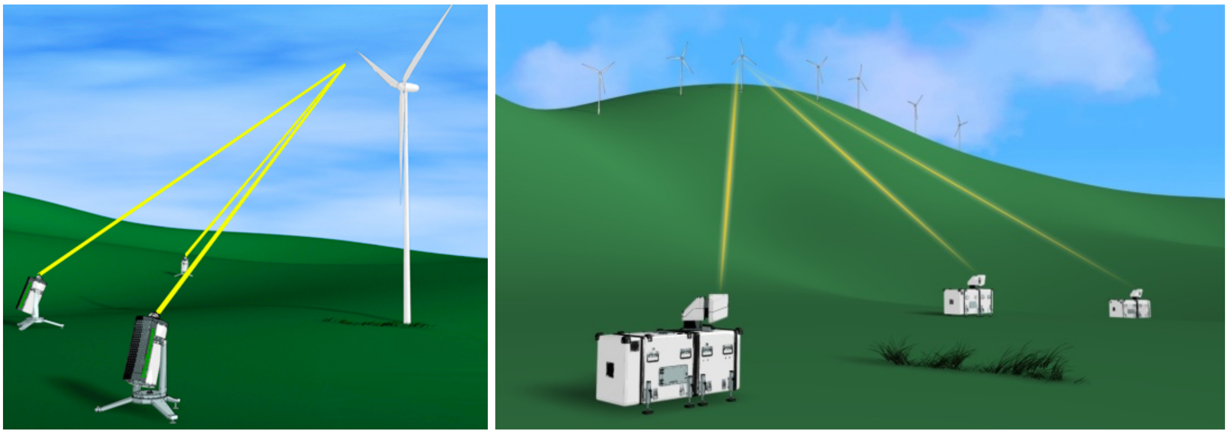

Figure 2. WindSscanner.dk: Synchronized three-dimensional scanning high-resolution wind velocity vector scanners. Left: Three short-range (10-150 m) WindScanners oriented to measure the three wind components of the wind vector at a common point in front of an operating turbine. Right: Three long-range (0.1-6 km) WindScanners in operated in bean-intersected synchronized scanning mode.

The WindScanner.dk activity set out in 2009 to exploit the new and handy telecom fibre-based wind lidars for the demanding research requirements for wind scanning for wind energy. The development of reliable and fast vector scanning wind lidars was spurred by the wind energy society's need for extended wind condition assessment studies. However, a single coherent wind lidar measures only the 3D wind velocity vector's projection along a single wind lidars line-of-sight (LOS) beam pointing direction. A variety of scanning and retrieval strategies therefore exists for single-lidar, for dual-Doppler lidar, and for triple-lidar wind vector measurements:

2.1.4 Multiple Lidars - 3D wind vector scanning and retrieval

By combining space and time synchronized LOS-measurements from three simultaneously operated wind lidars equipped with synchronized steerable-beam scanners, true 3D wind velocity and turbulence measurements have become attainable for boundary-layer research and for wind energy industry applications from the new research infrastructure WindScanner.dk.

During its development, factors influencing remote sensing-based wind measurements, measurement availability and representativeness have been key issues:

1. The data acquisition time required per wind measurement depends on the wind lidars signal-to-noise ratio, which, in addition to the number of backscattering natural aerosols within the probed boundary-layer, for a continuous wave (cw) lidar system depends on lasers continuously transmitted power [Watt]; whereas for the pulsed lidar systems the maximum achievable measurement range depend on the total energy [Joule] per pulse, the number of pulses transmitted, and on the wind lidars effective aperture size [21].

2. The spatial representativeness of the wind measurement is determined by the lidars effective sampling or "sounding" volume. Both for the cw and the pulsed lidars the spatial weighting function has the shape of a thin elongated "pencil" shaped measurement volumes. In the transverse directions the probe volume is confined by the laser beams transverse confinement, ranging from a few millimeters to a few centimeters depending on range. For the cw lidars, the

effective along-the-beam "Line-Of-Sight" sounding length is determined by the cw-lidars Gaussian beams focal properties, which in length along the beam turn is determined by the cw lidars effective aperture size. The effective "sounding length" defined by the half-width "full width half maximum" (FWHM) measure of the LOS spatial averaging distribution is for a cw lidar like ZephIR about 12 m at the 100 m measurement range. For a pulsed wind lidar the wind measurement effective sounding length is in contrast determined by the pulse width and shape of the transmitted energy pulse convoluted by the width of its range gate sample function [22], the pulsed lidars effective sounding length is typical 30 m or 60 m depending on the lasers pulse length and the acquisition time applied per sample, and hence the lidars spatial sampling length are much bigger than e.g. the sounding path within a sonic anemometer (0.1-0.2 m).

2.1.5 3D Scanning Lidars

Detailed wind and turbulence measurements in the rotor-layer requires, due to the three-dimensionality (3D) nature of wind being a three-dimensional wind vector, three linearly independent simultaneous measurements of the wind velocity vector from within the same sounding volume.

That is, three simultaneous measurements are required for determination of each of the three wind components measured in a non-degenerated coordinate system, cf. the measurement configurations shown in Figure 2. A conceptual design of a full "triple-lidar" based time and space synchronized wind vector scanning system was suggested by the department in 2008 [23] and has since then been referred to as "the 3D WindScanner research infrastructure".

The departments first 3D wind velocity vector measurement was obtained from three simultaneously operated wind lidars in staring mode pointed towards a three-axes sonic anemometer installed in a met mast at Høvsøre. At that time the steerable scan heads were not developed yet. The lidar vs sonic 3D wind measurements were intercompared and presented in 2009 [24] .

Today DTU Wind Energy has so far developed two different time and scape synchronized data acquisition systems including multiple axes based agile beam-steering motion control and corresponding scanning programs that operate, steer, sample and store the all three wind components from both short-range and long-range WindScanners, cf. Table 2.

Table 2: WindScanner.dk - Systems Specifications

WindScanners:

- 3D velocity scanning short-range system: the short-range WindScanner system consisting of three space and time synchronized continuous wave (built from three ZephIR type Z150 lidars)
- 3D velocity scanning long-range system: the long-range WindScanner system consisting of three synchronized pulsed lidars (built from three Leosphere type WLS200S lidars)
- 2D rotor plane scanning SpinnerLidar for turbine-integrated measurements of power curves and for real-time feed-forward control (built from a modified ZephIR Type Z300DM dual mode lidar

Data Acquisition and Synchronization Software:

Short-range:	Real-time synchronization (Delta-Tau): three-lidar LOS speeds and 9-axes motion control
Long-range:	*i)* Master Control (MCS); *ii)* Client Control (CCS), *iii)* Communication Protocol
SpinnerLidar:	On-the-fly real time data processing for turbine control (NI-CRio)

Spatial and Temporal resolution:

Short-range:	LOS FWHM: 12 m @ 100 m range - 500 LOS speed samples/s
Long-range:	LOS FWHM: 30m (all ranges) @ 200 ns sampling period. Rep rate: ~1 Hz
SpinnerLidar:	LOS FWHM: 12 m @ 100 m range - 400 LOS speed samples/s per full 2D rotor scan

3. Wind Lidar Achieved Measurements, Analysis Data Interpretation and Results

The last section presents an overview with references to published achievements obtained with the departments wind lidar activities during the last decade:

Following DTU Wind Energy acquired the first prototype wind lidars; the department began to investigate the influence of the lidars special sounding volumes on the measured wind fields.

Coherent lidars rely on radiation intensity in the transmitted beams to defining their measurement volumes, coherent wind lidars are as such special and different from other wind-measurement devise used previously within boundary-layer meteorology research, such as cup anemometers and sonic anemometers.

For modeling purpose the coherent lidars sounding probe can be mathematically represented as a LOS weighting function of size 10 to 30 meters [22]. Also, to investigate wind lidars wind data representativeness during low signal-to noise conditions the applied data retrieval procedures have been investigated [25]. On-going research is continuously addressing new ways to improve the wind speed retrieval from noisy measurements with low wind speed [26].

3.1 Single Staring lidar

The department has in particular addressed the effects of the lidars elongated probe volume on measured turbulence. The lidars spectral transfer functions have been determined by measurements of the turbulence with a single pulsed lidar beam, pointed into the mean wind direction at a fixed angle to the mean wind direction, and then compared lidar measured turbulence with turbulence spectra obtained from a co-located sonic anemometer in DTU Risø Campus' 125 m met mast [18,22,27].

The department has also measured the effective radial measurement resolution of a continuous wave staring lidar by determining its measurements cross-correlation with a sonic anemometer [16]. By invoking of an analytical fine structure tensor model the department has investigated the spectral coherence between range gates along the Line-of-Sight (LOS) of a pulsed lidar beam [17]. From top of the 125 m met-mast on-site at DTU Risø campus, a pulsed WLS7 lidar with the prism scanner removed was operated in staring mode and pointed horizontally into the wind while measurements were made on the approaching turbulence between 20 m separated range gates. These measurements were used to experimentally investigate the validity and limitations in applying "Taylors frozen turbulence hypothesis" [19].

Again, after removing the built-in prism wedge scanner in a WLS70 the pulsed long-range lidar was stared vertically to observed the vertical variance profile of the vertical turbulence component σ_w [m/s] over Høvsøre as part of the departments "Tall Wind Profile" measurement activity. These vertical turbulence profile measurement were first analyzed in connection with the thesis work of M. A. Gürpinar (2011) [28] and later used for a LES model vs. measurement in 2012 [29]. In Figure 3 two vertical turbulence measurements from two different days of are presented: day 14.02.2011 represent the evolution of the vertical profile of turbulence during a neutral-stable atmospheric period while the second day, 06.05 201, present profiles from a day with much more dramatic evolution in the turbulence representative for a highly convective day. It is seen that the turbulence profiler lidar measures two very distinct vertical turbulence structures these two days, representative of a neutral-stable boundary-layer, and a convective boundary layer, respectively.

Small lidar telescopes, so-called "Lidic's", that is small DTU/IPU designed 1" all-fibre fed cw lidar telescopes, have been developed and manufactured for wind turbine blade integration and for wind tunnel diagnostics. Lidic's have been installed and their measurements compared with standard in-situ precision instrumentation in a wind tunnel[30].

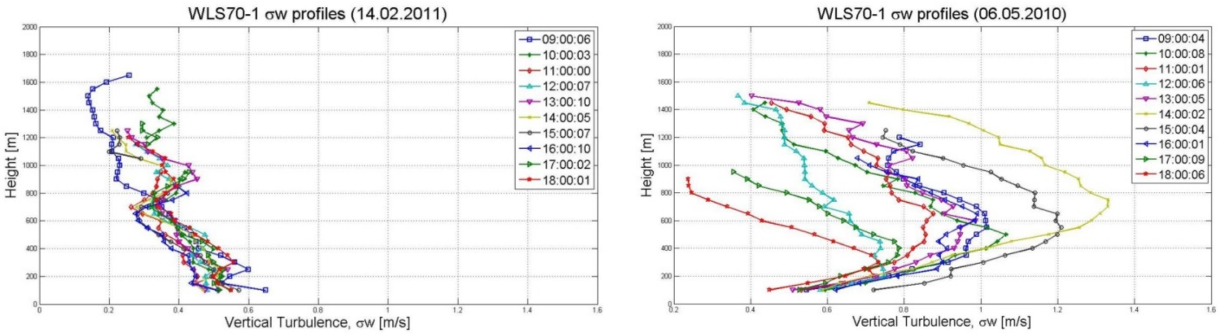

Figure 3. Vertical profiles of the vertical turbulence component σ_w as function of height above DTU test site Høvsøre. Left: evolution during a neutral-stable stratified (winter) day. Right: evolution during a highly convective (summer) day.

Two 1” Lidic’s, each with preset focus range of 5 meters, were installed and their beams were crossed from each side of a 40 m turbine blade. The dual Lidic’s were operated during test measurements of the inflow speed and angle-of-attack in front of the leading edge on a 2.3 MW test turbine[31]. A new methodology to infer, not only the total variance, but the entire pdf of the along-beam turbulence, have also been demonstrated to be attainable from fast sampled cw lidar data [32].

3.2 Single Scanning Lidar

The department measured wake deficit and turbulence behind a 95 kW Tellus on-site test from a simple 2D scanner built from the “white” QinetiQ prototype cw lidar. The lidar telescope with a build-in wedge scanner was modified and installed on a mechanical pan- and-tilt head, and the lidar was then installed as a 2D wake scanner measuring from the aft balcony of an on-site test turbine [33,34].

3.3 Single Scanning Lidar operated in “VAD scanning mode”

By adding a rotating prism, a so-called wedge scanner, on top a starring wind lidar, it becomes a “Velocity Azimuth Display” (VAD) scanning lidar. Pointed vertically, the lidar receive information of all three wind component from different pointing directions at a given measurement height. A VAD scanning lidar can also be mounted horizontally on the nacelle and in this way give information about the upwind inflow or downwind wake. The departments first VAD lidar investigation dates back to 2006 [35]. The department subsequently investigated the effect of performing VAD scanning on measured turbulence [36], see also below. The department soon after began to evaluate the VAD Lidars up against the met mast at Høvsøre [37] . Today the lidar test facility at Høvsøre operates under Danish DANAK accreditation. VAD scanning lidars have also been deployed into complex terrain to measure wind profiles and their measurements have been corrected for inhomogeneity in the aloft wind field [38–40], and over forest [41,42].

Several experimental wind condition and wind energy assessment studies with VAD vertical scanning mean wind profilers have been performed and reported from both on- and offshore installations. The departments offshore wind lidar profiling began early with vertical measurements of the wind profile from a cw lidar installed on the Horns Rev-I’s transformer operated during 2007- 2008 and reported in 2009 [43,44]. Also offshore wind resource has been extensively measured with VAD scanning lidars from distributed offshore platforms located in the North Sea (NorseWind.eu) [45].

Tall wind profiles, up to 600 m height or more, have been measured and their corresponding climatological Weibull mean and shape distribution fitted. The measured mean and shape parameters has been assessed as function of height from year-long lidar profile observations of horizontal wind speed profiles over rural coastal (Høvsøre) and inland at a suburban site in the outskirts of Hamburg, Germany [46] . From these Tall-wind lidar measurements the atmospheric boundary-layer wind climate during a 1-year measurement campaign at Høvsøre has been investigated [47]. The tall profile measurements have also provided an experimental basis for intercomparison with numerical weather prediction modelling in the coastal boundary layer at Høvsøre [48].

Ground-based VAD scanning vertical wind profile lidars have early been suggested as a replacement for tall reference met masts used today for accurate wind turbine power curve assessments [49]. From ground-based vertical wind profile measurements of the wind shear, a hub-height "rotor equivalent" wind speed has been proposed and this methodology is now widely accepted within the wind energy society [50,51]. Also the boundary-layer height has been measured using VAD wind lidar measurements in conjunction with simultaneous met mast and ceilometer observations [52]. A recent investigation have intercompared and addressed wind lidar performance at a flat (Høvsøre, Denmark) and at a complex wind site (Alaiz, Spain) [53].

3.4 Turbulence assessed from VAD scanning Lidars

Several of the VAD scanning lidar-based activities listed above have also addressed direct measurement of turbulence from a single VAD scanning lidar.

Being a vector consisting of three wind components a fundamental challenge is that it takes three independent and simultaneous lidar LOS wind measurements within the same probe volume to extract the three wind components of the instantaneous wind velocity vector. The departments 3D WindScanners have consequently been designed to do exactly that, but several investigations to measure turbulence with a single lidar have been the subject of research on the assumption of local homogeneity, some even with good success:

A first attempt to measure turbulence suggested compensating for the volume filtering effects of measured turbulence. For a cw wind lidar a model of the filtering effects of the huge VAD scanned volume has included in the assessment of the lidar measured variances[54]. Another investigating dealt with measurement of the surface layer shear stress u_* from differences in the lidar measured variances upwind and downwind respectively of the line-of-sight radial wind speeds observed by a VAD scanning lidar [55].

The difficulties, however, of measuring the three turbulence wind component by VAD scanning cw and pulsed lidars was addressed by Sathe et al. in 2011 in a study where lidar measurements were intercompared with profile measurements of all three turbulence components as measured by sonic anemometers in the 120 m Høvsøre met mast [56]. Also the issue of measuring turbulent spectra via a pulsed VAD scanning lidar has been addressed [57]. Sathe and Mann (2012) have revealed that it in principle always requires a total of six simultaneous and linear independent radial LOS measurements from a single ground-based lidar to resolve all six components of the (u, v, w) co-variance matrix while assuming homogeneous and stationary turbulence [58]. Several other methods have been developed and investigated over the years by other researchers besides DTU Wind Energy determine the vertical profile of mean wind speed and turbulence from VAD scanning, for a recent review of the different methodologies cf. Sathe and Mann 2013 [59].

3.5 Multiple Synchronized Scanning Lidars "WindScanners"

The conceptual idea to operating three simultaneous beam-steered space and time synchronized wind lidars to measure the full 3D wind vectors aloft, the so-called "WindScanner" concept, was conceived and presented by the department in 2008 [60]. As already mentioned the multiple-beam crossing wind velocity measurement concept was demonstrated in 2008 [24]. Today the departments wind lidars, both the cw-based and the pulsed systems are now equipped with motion controlled prism-based and mirror-based steerable beam scanners, hence the lidars are referenced to as “short-range” and long-range” WindScanners, respectively.

The first WindScanner measurement results obtained with the short-range WindScanners were obtained by scanning the wind flow over a small building located inside the DTU Risø campus and was published in 2012 [61]. In the fall of 2011 the department measured a two-dimensional mean and turbulent wind field by scanning wind and turbulence in a two-dimensional vertical plane normal to a small hill near the Risø peninsula (Bolund Experiment) with the first of the three now operational short-range WindScanners (R2D1) [62]. With the mobile facility, several additional WindScanner.dk-based wind scanning field measurement campaigns have now been performed; one particular outstanding effort has been the characterization of 3D downwash footprint underneath a low-hovering Norwegian rescue helicopter in Sola Airport, Stavanger, Norway [63,64].

The department has also improved direction sensing at low wind speed in the continuous wave WindScanners by applying a new hybrid optical in-phase and quadrature detection methodology [26]. The long-range lidars multiple-beam synchronized beam steering methodology was been developed in collaboration with ForWind University of Oldenburg and the long-range scanners syncronisatin and pointing accuracy has been investigated by simulation, and by CNR backscatter measurements from hard targets [65,66]. A recent study addresses optimal scanning patterns for reducing the measurement uncertainty by scanning at coastal ranges with two crossing lidars beams [67] .

3.6 Lidar Measurements from Wind Turbines of Upwind Inflow and Downwind Wakes

The department has also been engaged with the development and testing of lidars for installation on turbine nacelles [68] and integration of forward-looking lidar scanners directly into the turbines rotating spinners [69]. Measurements of wake deficit behind a 95 kW “Tellus” wind turbine was performed already in 2006[33]. In collaboration with ZephIR Lidar DTU Wind Energy developed and tested an upwind full-rotor plane scanning SpinnerLidar in 2009 [70]. The turbine integration showed that lidars installed or integrated in the turbine spinners has potential to serve and to enhance several purposed ranging from power curve measurements, turbine yaw control, to detection and assist mitigation of the effects of wind shear and wind veer and extreme gust events. Credible power curve measurements have also been demonstrated with lidar measurements taken directly from the nacelle [71,72]. New low cost wind lidar concepts for wind turbine power curve measurements and control are being tested [73]. Upwind measurements of the inflow such as wind shear, wind veer, turbulent gusts, wake inflow ramp-up etc. with the purpose to assist the controllers to mitigate loads and improve yaw [74] and energy capture [70].

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References

[1] Taylor P A and Teunissen H W 1987 The Askervein Hill project: Overview and background data *Boundary-Layer Meteorol.* **39** 15–39

[2] Sempreviva A M, Larsen S E, Mortensen N G and Troen I 1990 Response of neutral boundary layers to changes of roughness *Boundary-Layer Meteorol.* **50** 205–25

[3] Berg J, Mann J, Bechmann A, Courtney M S and Jørgensen H E 2011 The Bolund Experiment, Part I: Flow Over a Steep, Three-Dimensional Hill *Boundary-Layer Meteorol.* **141** 219–43

[4] Jørgensen H E, Mikkelsen T and Pécseli H L 2010 Concentration Fluctuations in Smoke Plumes Released Near the Ground *Boundary-Layer Meteorol.* **137** 345–72

[5] Mikkelsen T, Ejsing Jørgensen H, Nielsen M and Ott S 2002 Similarity scaling of surface-released smoke plumes *Boundary-Layer Meteorol.* **105** 483–505

[6] Rojas-Palma C, Aage H K, Astrup P, Bargholz K, Drews M, Jørgensen H E, Korsbech U, Lauritzen B, Mikkelsen T, Thykier-Nielsen S and Ammel R Van 2004 Experimental evaluation of gamma fluence-rate predictions from Argon-41 releases to the atmosphere over a nuclear research reactor site *Radiat.Prot.Dosim.* **108** 161–8

[7] Cionco R M, aufm Kampe W, Biltoft C, Byers J H, Collins C G, Higgs T J, Hin A R T, Johansson P E, Jones C D, Ejsing Jørgensen H, Kimber J F, Mikkelsen T, Nyren K, Ride D J, Robson R, Santabarbara J M, Streicher J, Thykier-Nielsen S, Raden H van and Weber H 1999 An overview of MADONA: A multinational field study of high-resolution meteorology and diffusion over complex terrain *Am. Meteorol. Soc.* **80** 5–19

[8] Mikkelsen T, Jørgensen H E and Kristensen L 2007 *The Bistatic Sodar "Heimdall "*, Risø-R-1424 (Roskilde: Risø National Laboratory)

[9] Bradley S and Mikkelsen T 2011 SODAR remote sensing *Int. Sustain. Energy Rev.* **5** 38–41

[10] Bradley S, von Hünerbein S and Mikkelsen T 2012 A bistatic sodar for precision wind profiling in complex terrain *J. Atmos. Ocean. Technol.* **29** 1052–61

[11] Ejsing Jørgensen H and Mikkelsen T 1993 Lidar measurements of plume statistics *Boundary-Layer Meteorol.* **62** 361–78

[12] Ejsing Jørgensen H, Mikkelsen T, Streicher J, Herrmann H, Werner C and Lyck E 1997 Lidar calibration experiments *Appl. Phys. B-Lasers Opt.* **64** 355–61

[13] Hall F F, Huffaker R M, Hardesty R M, Jackson M E, Lawrence T R, Post M J, Richter R A, Weber B F and Hall, Jr. F F 1984 Wind measurement accuracy of the NOAA pulsed infrared Doppler lidar. *Appl. Opt.* **23** 2503

[14] Banta R M, Pichugina Y L, Kelley N D, Hardesty R M and Brewer W A 2013 Wind Energy Meteorology: Insight into Wind Properties in the Turbine-Rotor Layer of the Atmosphere from High-Resolution Doppler Lidar *Bull. Am. Meteorol. Soc.* **94** 883–902

[15] Karlsson C J, Olsson F Å A, Letalick D and Harris M 2000 All-Fiber Multifunction Continuous-Wave Coherent Laser Radar at 1.55 num for Range, Speed, Vibration, and Wind Measurements. *Appl. Opt.* **39** 3716–26

[16] Angelou N, Mann J, Sjöholm M and Courtney M 2012 Direct measurement of the spectral transfer function of a laser based anemometer. *Rev. Sci. Instrum.* **83** 033111

[17] Kristensen L, Kirkegaard P and Mikkelsen T 2011 *Determining the Velocity Fine Structure by a Laser Anemometer with Fixed Orientation* vol Risø-R-1762(EN); DTU Wind Energy; DTU Risø Campus; Technical University of Denmark

[18] Kristensen L, Kirkegaard P, Mann J, Mikkelsen T, Nielsen M and Sjöholm M 2010 *Spectral Coherence along a Lidar Anemometer Beam* Risø-R-1744(EN) DTU Wind Energy; DTU Risø Campus; Technical University of Denmark

[19] Sjöholm M, Kapp S, Kristensen L and Mikkelsen T 2011 Experimental evaluation of a model for the influence of coherent wind lidars on their remote measurements of atmospheric boundary-layer turbulence ed U N Singh and G Pappalardo *Proc. SPIE* **8182** 818210–818210–7

[20] Browning K A and Wexler R. 1968 The determination of kinematic properties of a wind field using Doppler radar *J. Appl. Meteorol.* **7** 105–13

[21] Sonnenschein C and Horrigan F A 1971 Signal-to-Noise Relationships for Coaxial Systems that Heterodyne Backscatter from the Atmosphere. *Appl. Opt.* **10** 1600–4

[22] Mikkelsen T 2009 On mean wind and turbulence profile measurements from ground-based wind lidars: limitations in time and space resolution with continuous wave and pulsed lidar systems - a review (proceedings) *EWEC 2009* (EWEA - The European Wind Energy Association) p 10

[23] Mikkelsen T, Mann J and Courtney M 2008 Wind Scanner: A full-scale Laser Facility for Wind and Turbulence Measurements around large Wind Turbines *EWEC 2008* (Brussels: EWEA - The European Wind Energy Association) p 10

[24] Mann J, Cariou J-P-P P, Courtney M S, Parmentier R R R, Mikkelsen T, Wagner R, Lindelöw P J P P J P, Sjöholm M, Enevoldsen K, Lindeløw P J P and Sjøholm M 2009 Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer *Meteorol. Zeitschrift* **18** 135–40

[25] Angelou N, Abari F F, Mann J, Mikkelsen T and Sjöholm M 2012 Challenges in noise removal from Doppler spectra acquired by a continuous-wave lidar *26th International Laser Radar Conference* p 4

[26] Pedersen A T, Abari C F, Mann J and Mikkelsen T 2014 Theoretical and experimental signal-to-noise ratio assessment in new direction sensing continuous-wave Doppler lidar *Torque 2014* (Copenhagen: IOP Publishing)

[27] Sjöholm M, Mikkelsen T, Mann J, Enevoldsen K and Courtney 2008 Time series analysis of continuous-wave coherent Doppler Lidar wind measurements *IOP Conf. Ser. Earth Environ. Sci.* **1** U411–U416

[28] Gürpinar M A 2011 *Estimating Atmospheric Boundary Layer Height from Vertical SigmaW Profiles and Parameterization of Vertical Variances – by LIDARs at Høvsøre*

[29] Pedersen J G, Kelly M, Gryning S-E, Floors R, Batchvarova E and Peña A. 2012 Comparison of Large Eddy Simulations of a convective boundary layer with wind LIDAR measurements *Adv. Sci. Res.* **8** 83–6

[30] Pedersen A T, Montes B F, Pedersen J E, Harris M and Mikkelsen T 2012 Demonstration of short-range wind lidar in a high-performance wind tunnel *EWEA 2012 Copenhagen* ed ewea (EWEA - The European Wind Energy Association) p 6

[31] Pedersen A T, Sjöholm M, Angelou N, Mikkelsen T, Montes B F, Engholm Pedersen J, Slinger C and Harris M 2013 Full-Scale Field Test of a Blade-Integrated Dual-Telescope Wind Lidar *EWEA 2012 Copenhagen* (Copenhagen: EWEA - The European Wind Energy Association) Poster

[32] Branlard E S P, Pedersen A T, Mann J, Angelou N, Fischer A, Mikkelsen T, Harris M, Slinger C and Montes B F 2013 Retrieving wind statistics from average spectrum of continuous-wave lidar *Atmos. Meas. Tech. Discuss.* **6** 1943–77

[33] Trujillo J-J, Bingöl F, Larsen G C, Mann J and Kühn M 2011 Light detection and ranging measurements of wake dynamics. Part II: two-dimensional scanning *Wind Energy* **14** 61–75

[34] Bingöl F, Mann J and Larsen G C 2010 Light detection and ranging measurements of wake dynamics. Part I: one-dimensional scanning *Wind Energy* **13** 51–61

[35] Smith D A, Harris M, Coffey A S and Park T 2006 Wind Test Site in Høvsøre 87–93

[36] Kristensen L, Kirkegaard P and Mikkelsen T 2012 *Determining the Velocity Fine Structure by a Laser Anemometer in VAD operation* vol E-0008(EN) (Roskilde: DTU Wind Energy)

[37] Courtney M, Wagner R and Lindelöw P 2008 Testing and comparison of lidars for profile and turbulence measurements in wind energy *IOP Conf. Ser. Earth Environ. Sci.* **1** 012021

[38] Bingöl F, Mann J and Foussekis D 2008 LiDAR error estimation with WAsP engineering *IOP Conf. Ser. Earth Environ. Sci.* **1** 012058

[39] Bingöl F 2009 *Risø-PhD-Report* PhD 52(EN) (Risø DTU, Roskilde, Denmark)

[40] Bingöl F, Mann J and Foussekis D 2009 Conically scanning lidar error in complex terrain *Meteorol. Zeitschrift* **18** 189–95

[41] Mann J, Dellwik E, Bingöl F and Rathmann O 2007 Laser measurements of flow over a forest *J. Phys. Conf. Ser.* **75** 012057

[42] Dellwik E, Mann J and Bingöl F 2010 Flow tilt angles near forest edges – Part 2: Lidar anemometry *Biogeosciences* **7** 1759–68

[43] Hasager C B, Gryning S, Courtney M, Antoniou I, Peña A and Mikkelsen T 2014 Offshore Wind Profiling Using Light Detection and Ranging Measurements *Wind Energy* **12** 105–24

[44] Peña A, Gryning S-E and Hasager C B 2008 Measurements and Modelling of the Wind Speed Profile in the Marine Atmospheric Boundary Layer *Boundary-Layer Meteorol.* **129** 479–95

[45] Hasager C, Stein D, Courtney M, Peña A, Mikkelsen T, Stickland M and Oldroyd A 2013 Hub Height Ocean Winds over the North Sea Observed by the NORSEWInD Lidar Array: Measuring Techniques, Quality Control and Data Management *Remote Sens.* **5** 4280–303

[46] Gryning S-E, Batchvarova E, Floors R, Peña A, Brümmer B, Hahmann A N and Mikkelsen T 2013 Long-Term Profiles of Wind and Weibull Distribution Parameters up to 600 m in a Rural Coastal and an Inland Suburban Area *Boundary-Layer Meteorol.* **150** 167–84

[47] Peña A, Floors R and Gryning S-E 2013 The Høvsøre Tall Wind-Profile Experiment: A Description of Wind Profile Observations in the Atmospheric Boundary Layer *Boundary-Layer Meteorol.* **150** 69–89

[48] Floors R, Vincent C L, Gryning S-E, Peña a. and Batchvarova E 2013 The Wind Profile in the Coastal Boundary Layer: Wind Lidar Measurements and Numerical Modelling *Boundary-Layer Meteorol.* **147** 469–491

[49] Wagner R, Courtney M and Wagner A R 2009 *Multi-MW wind turbine power curve measurements using remote sensing instruments – the first Høvsøre campaign, Risø-R-1*679(EN)

[50] Wagner R, Antoniou I, Pedersen S M, Courtney M S and Jørgensen H E 2009 The influence of the wind speed profile on wind turbine performance measurements *Wind Energy* **12** 348–62

[51] Wagner R, Courtney M, Gottschall J and Lindelöw-Marsden P 2011 Accounting for the speed shear in wind turbine power performance measurement *Wind Energy* **14** 993–1004

[52] Peña A, Gryning S-E and Hahmann A N 2013 Observations of the atmospheric boundary layer height under marine upstream flow conditions at a coastal site *J. Geophys. Res. Atmos.* **118** 1924–40

[53] Sanz Rodrigo J, Borbón Guillén F, Gómez Arranz P, Courtney M S, Wagner R and Dupont E 2013 Multi-site testing and evaluation of remote sensing instruments for wind energy applications *Renew. Energy* **53** 200–210

[54] Wagner R, Mikkelsen T, Courtney M and Wagner A R 2009 *Investigation of turbulence measurements with a continuous wave, conically scanning LiDAR*, Risø-R-1682(EN)

[55] Mann J, Peña A, Bingöl F, Wagner R and Courtney M S 2010 Lidar Scanning of Momentum Flux in and above the Atmospheric Surface Layer *J. Atmos. Ocean. Technol.* **27** 959–76

[56] Sathe A, Mann J, Gottschall J and Courtney M S 2011 Can Wind Lidars Measure Turbulence? *J. Atmos. Ocean. Technol.* **28** 853–68

[57] Sathe A and Mann J 2012 Measurement of turbulence spectra using scanning pulsed wind lidars *J. Geophys. Res.* **117** D01201

[58] Sathe A and Mann J 2012 Turbulence measurements using six lidar beams *ISARS 2012* (Boulder) pp 302–305

[59] Sathe a. and Mann J 2013 A review of turbulence measurements using ground-based wind lidars *Atmos. Meas. Tech.* **6** 3147–3167

[60] Mikkelsen T, Mann J, Courtney M M and Sjöholm M 2008 Windscanner: 3-D wind and turbulence measurements from three steerable doppler lidars *IOP Conference Series: Earth and Environmental Science* vol 1 (Institute of Physics Publishing Ltd) pp U148–U156

[61] Sjöholm M, Angelou N, Hansen K H, Mann J and Mikkelsen T 2012 First measurements by the DTU Wind Energy Short-range WindScanner *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition; Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition* (EWEA - The European Wind Energy Association)

[62] Mann J, Angelou N, Sjöholm M and Mikkelsen T 2012 Laser scanning of a recirculation zone on the Bolund escarpment *16th International Symposium of the Advancement of Boundary-Layer Remote Sensing* (Boulder) pp 19–22

[63] Sjöholm M, Angelou N, Hansen P, Hansen K H and Mikkelsen T 2012 Helicopter downwash measured by continuous-wave Doppler lidars with agile beam steering Analysis procedure *16th International Symposium of the Advancement of Boundary-Layer Remote Sensing* p 4

[64] Sjöholm M, Angelou N, Hansen P, Hansen K H, Mikkelsen T, Haga S, Silgjerd J A and Starsmore N 2014 Two-dimensional rotorcraft downwash flow field measurements by lidar-based windscanners with agile beam steering *J. Atmos. Ocean. Technol.* **31** 930 – 937

[65] Vasiljevic N, Courtney M, Wagner R, Mann J and Mikkelsen T 2011 A windscanner simulator *EWEA 2011, Marseilles, Fr,* Poster

[66] Vasiljevic N, Lea G, Courtney M, Mann J and Mikkelsen T 2013 The long-range WindScanner system - how to synchronously intersect multiple laser beams ed N Vasiljevic, G Lea, M Courtney, J Mann and T Mikkelsen *EWEA 2013, Vienna, Austria*

[67] Courtney M, Wagner R, Murthy R K and Boquet M 2014 Optimized lidar scanning patterns for reduced project uncertainty *EWEA 2014* PO. ID 121

[68] Courtney M 2013 *Calibrating nacelle lidars*, DTU Wind Energy report E-0020, DTU Risø Campus

[69] Mikkelsen T, Angelou N, Hansen K, Sjöholm M, Harris M, Slinger C, Hadley P, Scullion R, Ellis G and Vives G 2013 A spinner-integrated wind lidar for enhanced wind turbine control *Wind Energy* **16** 625–643

[70] Sjöholm M, Angelou N, Mikkelsen T, Pedersen A T, Kapp S, Harris M and Slinger C 2014 Two-dimensional structures in wind turbine inflow studied by a spinner-mounted lidar, ISARS 2014; Auckland, Nz.

[71] Wagner R, Pedersen T F, Courtney M, Antoniou I, Davoust S and Rivera R L 2013 Power curve measurement with a nacelle mounted lidar *Wind Energy, doi: 10.1002/we.1643*

[72] Medley J, Barker W, Harris M, Pitter M, Slinger C, Mikkelsen T and Sjöholm M 2013 Evaluation of wind flow with a nacelle-mounted, continuous wave wind lidar *EWEA 2014* ed EWEA (Barcelona: EWEA - The European Wind Energy Association)

[73] Sjöholm M, Dellwik E, Hu Q, Mann J, Pedersen C and Rodrigo P J 2014 Field test of an all-semiconductor laser-based coherent continuous-wave doppler lidar for wind energy applications Turbine Industry - Challenges *ISARS 2014*

[74] Kragh K A, Hansen M H and Mikkelsen T 2013 Precision and shortcomings of yaw error estimation using spinner-based light detection and ranging *Wind Energy* **16** 353–66