WINDSCANNER.DK

A New Danish Mobile Remote Sensing-based Infrastructure
for
Wind Energy and Turbulence Research:

Design, Establishment and Operation 2009-2014

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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 the huge volume wind fields surrounding and driving them. At the DTU Wind Energy test site for huge turbines, Østerild, the hub height of a newly installed 8 MW Vestas V164 turbine reach 143 meters up above the ground, and the turbine rotor of amazing 164 meters in diameter, makes its blade tips soar 225 meters into the sky.

Experimental facilities are needed for research in wind and turbulence fields impacting on, and generating wakes from, such huge wind turbines, on and offshore.

This report documents the state-of-the-art by end 2014 regarding the built and establishment of the new Danish national research infrastructure entirely based on new remote sensing innovation achievements with coherent detection lidars and scanning synchronized WindScanners.

The WindScanner.dk research infrastructure was admitted to the European EU ESFRI Road Map for future renewable Energy research European Research Infrastructures in 2010 and also to the 2011 established Danish road map for research infrastructure, cf. the active Home Pages:

   I.   *"WINDSCANNER.DK - a new Mobile Facility for Wind Energy and Turbulence Research" (www.windscanner.dk/)*

   II.   *"WINDSCANNER -the European WindScanner Facility" (www.windscanner.eu)*

1. Introduction

In 2009 DTU Wind Energy was granted 25 M DKK by the Danish National Research Council to support the design, establishing and initiating the operation of a new Danish national research infrastructure WindScanner.dk

The research infrastructure (RI) was proposed to enhance research and technological development in collaboration with research institutes and industry within the field of renewable wind energy in Denmark.

Today, by end 2014, the new research infrastructure have been designed and established in the Wind Energy Department at DTU Risø Campus where it now has begun to service the wind energy research society and the wind energy industry via its operation.

This paper summarizes the new RI's technological development during the five year period 2009-2014 as well as and the first uses of the new infrastructure for wind energy research.

Historical background: Since its early establishment the DTU Wind Energy, formerly the Wind Energy Division at Risø National Laboratory, Roskilde, Denmark, have engaged in atmospheric boundary-layer experimental research based on experimental activities, in particular with focus on measurements of surface and boundary-layer wind and turbulence quantities.

Most of the experimental investigations the wind energy Department engaged in during the 70'ties throughout the 90'ties were conveyed using at times quite heavy, cumbersome and also expensive in-situ erected meteorological masts 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 Askervain wind flow over a "Gaussian" hill experiment [1], the multi-met mast based JylEX wind resource measurement campaign [2], and the densely instrumented "flow over escarpment" Bolund hill field test [3].

During the 80'and 90'ties a high-resolution scanning aerosol backscatter Lidar was developed in the department's micro-meteorological test and measurement section. The scanning aerosol Lidar was a useful tool to characterize puff and plume dispersion from various sources during several 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], and the MADONA concentration fluctuation and puff diffusion field trials in the UK [7].

The scientific challenges addressed in by the experimental activities are to provide experimental evidence on which theoretical and numerical modelling activities based on CFD can be evaluated. The overall goal with our experimental activities, and with WindScanner in particular, is to enhancement our common comprehension of the complex nature of atmospheric wind flow and turbulence phenomena's in the atmospheric boundary-layer and to understand how this is influenced by different atmospheric stability characteristics, e.g. by investigating the characteristic differences between boundary-layer day and night time flow characteristics. The departments combined experimental and CFD modelling activities also address wind flow in combination with terrain effects such as the influence of wind and turbulence profiles aloft complex terrain, and the study of flow influence from changes in surface roughness changes and surface heat flux changes at they occur e.g. at coastal interfaces between onshore and offshore wind regimes.

Today, with wind lidars and WindScanners at hand, the attractiveness and obvious advances of remote sensing-based meteorological measurement techniques has indeed become aspiring for scanning and probing fields in two and three dimension space of wind and turbulence in the the atmospheric boundary-layer.

Previously however, and to some extend still today, entirely remote sensing-based measurement techniques are not always a technical feasible alternative to in-situ meteorological mast (met mast) installations equipped with calibrated wind, turbulence temperature, humidity and pressure sensors.

Back in the 80'ties and 90'ties the experimental field studies addressing wind and turbulence measurements mainly involved in-situ installation tall met masts, and the Wind Energy Department's remote sensing investigations were back then predominantly limited to the developing and deploying sound-based remote sensing devices, such as Sodars [8] [9] [10] and aerosol-backscatter lidars [11] [12].

Prior to the turn of the Millennium, and with a history going back to the first work with wind coherent detection remote sensing pioneered by e.g. Mike Hardesty and Milton Huffaker [13], wind sensing coherent Doppler Lidars have been dedicate research tools build from discrete coherent laser systems and open-space optical component, as e.g. the High-Resolution Doppler Lidar (HRDL) which today is still an agile operational pulsed long-range Lidar system developed and operated by NOAA, Boulder CO, USA [14].

At the turn of the Millennium, however, new optical fibre-based remote sensing technology emerged and soon became available for wind remote sensing instrumentation to serve the growing wind energy's scientific and wind industry needs. In the slipstream of the 90'ties telecom revolution, new fibre-based coherent optical erbium doped fibre amplifiers; so-called EDFA lasers came available as drivers for Doppler wind lidars. The first all-fibre coherent Doppler wind Lidar was conceived and demonstrated by Karlsson, Olsson, Letalick and Harris in 1999 [15]. In October 2003, representatives from QinetiQ UK, who later formed ZephIR Lidar Inc., visited DTU Risø Campus and demonstrated their first continuous wave (cw) prototype Lidar; build on the all-fibre technology. The prototype wind lidar soon after became the remote sensing key component within ZephIR Lidars.

Measurement of wind using remote sensing wind lidars:

A single coherent detection-based wind Lidar measures only the projection along the laser beam of the 3D wind velocity vector assessed remotely by the Lidar in the Lidar's probe volume, namely the projection of the 3D wind vector projected along the laser beam's line-of-sight direction, v_{los}. This wind speed is then in turn determined from the measured Doppler shift in frequency of the laser radiation that is backscattered from the ever-present sub-micron aerosols submerged in the atmospheric boundary layer flow

$$v_{los} = -½ \, \lambda \, \Delta f_{Doppler}$$

Here, λ is the wavelength of the laser and $\Delta f_{Doppler}$ is the measured Doppler shift relative to the transmitted laser frequency.

At DTU Wind Energy, Risø Campus, we took the opportunity the same day to intercompare the prototype cw lidars wind speed measurement with an on-site cup anemometer and wind vane measurements installed at 2 m height in a met mast located 60 m away, Cf. Fig 1.
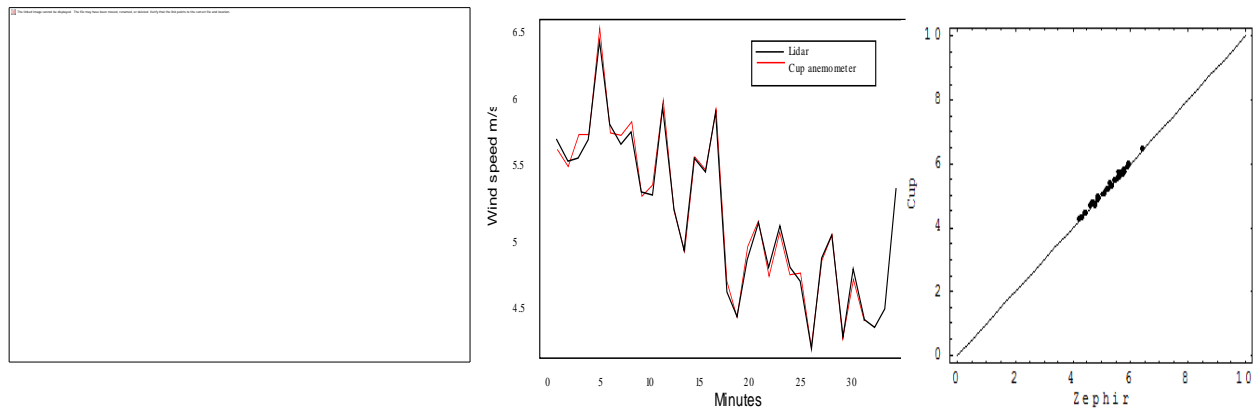
Figure 1. Left: "gray" QinetiQ all-fibre cw prototype lidar at test at Risø Campus October 2003.
Middle: measured time series of the lidar and the met mast cup at 60 m range.
Right: scatter diagram between measured wind speeds from lidar vs cup anemometer.

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 was indeed encouraging. The degree of correlation was superior to anything obtained previously with other wind speed remote sensing devises.

That very first all-fibre cw Lidar test back in October 2003 marked a milestone and also a turning point for the DTU wind energy's remote sensing based instrument development, deployment and wind energy research activity. In the 00'ties there was also a growing interest for measurements of the wind flow within the so-called "rotor layer" of the atmospheric boundary layer, that is, at heights ranging between 20 meters and, say 200 meters height, corresponding to the rotor operating height within the boundary-layer of the past decades wind turbines. Today already we operate with rotor tip heights of 220 meters (test turbine Vestas V164 installed and operated at DTU Wind Energy- Østerild, where we also at the same time are preparing for wind measurements of wind flow at heights up to 250 meters before year 2020.

With the new technology also new remote sensing opportunities for wind and turbulence measurement emerged for DTU Wind Energy. In retrospect, there was already back in October 2003, as there is today, a continuous need for experimental investigations by replacements of the tall met masts with wind remote sensing wind sensors. The emergent new wind lidar remote sensing technology has led to a learning process for wind energy scientists and industry during the past decade. New applications like wind lidar based forecasting, wind lidar based turbine power curve measurements and wind lidar based feed-forward turbine control has emerged, as has more effective methods to achieve already defined measurement objectives and previous designed measurement campaigns that for practical reasons were not possible beforehand.

Now that rotor diameters continue to increase, as does the deployment of turbines in complex terrain, knowledge of the specific characteristics of the incident wind field 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 power curves, understanding wind flow characteristics, and controlling turbines. Also, measurements of detailed turbine inflow influenced by wind shear, wind veer, inhomogeneous turbulence levels, low-level jets, inflow over complex terrain, and measurements for turbines operation in wakes from other turbines are all examples of flow conditions that today can be measured, investigated and characterized by wind lidar measurements. Another example of wind lidar application is turbine controller improvements based on feed-forward wind measurements and for calculation of the rotor-equivalent power curves from wind measurements from lidars installed in the turbine spinner or on the nacelle.

At DTU, the multi-lidar scanning synchronized lidar systems, referred to as "WindScanner" (Cf. the research infrastructures Danish national node: windscanner.dk; and the corresponding Joint European research infrastructure facility: windscanner.eu) have been designed and a prototype constructed, and is now in operational at DTU Wind Energy Risø Campus to reveal a wealth of wind field information.

2. Wind Lidars and Scanners - acquired and built - continuous wave and pulsed lidar systems

In total, the new Danish WindScanner.dk Research Infrastructure established at DTU Wind Energy possesses, maintains and operates the following sets of all-fibre, coherent detecting based Doppler wind lidar systems:

Table1. Wind lidar inventory at DTU Wind Energy Ultimo 2014.

a.   Two QinetiQ prototype continuous Wave Scanning Lidars
b.   Three continuous wave ZephIR lidar (Unit 2- Type Z150, Unit107 Type Z150,one Z 300)
c.   One ZephIR DM integrated with a DTU Wind Energy/IPU developed 2D fixed pattern scan head
d.   Three pulsed Leosphere WindCube's Type WLS7
e.   One Leosphere WindCube type WLS70
f.   Three modified ZephIR Type 150 integrated into short-range WindScanners equipped with 3" optics telescope and with 3" scanning steerable prism-based scan heads operated synchronized in space and time as a 3D scanning, 3D velocity vector measuring short-range WindScanners
g.   Three Prototype Leosphere WLS 200S pulsed space and time synchronized lidar systems all equipped with DTU Wind Energy/ IPU developed full-sky 4" double mirror-based scan heads.

The wind lidars in Table 1 have all been built and modified to scanning lidars in close collaboration with the lidar manufactures QinetiQ, ZephIR and Leosphere. In particular, both the set of 3 short-range and also the three long-range wind lidars for the WindScanner research facility were custom designed and further developed for integration with the DTU Wind Energy and IPU designed scan heads capable of steering the focused beams.

Table 2 Key technical specifications of the two sets of three space and time synchronized short-range and long-range scanners developed during WindScanner.dk 2009-2014.Further technical specification details are contained in Appendix I.

WindScanner.dk: Short- and Long-range WindScanners:		
Technical Specifications	3 x Short-range (SRWS) V1.0	3 x Long-range (LRWS) WLS 200S
Laser type	Continuous wave (cw)	Pulsed

Steerable scanners	Prism based	Mirror based head
Range [m]	10 - 200	50 - 8000
Aperture size [inch]	3" optics	4" optics
Max. LOS sampling rate [s^{-1}]	500	10
Probe lengths FWHM [m]	0.125 – 50 (range dependent)	30 - 60 (user selective)
Dual axis scanner head	Double-prism based	Triple-mirror based
Backlash [°]	< 0.1	< 0.05
Mechanical rotation	Belt driven	Worm gear driven
Rotation	Endless	Endless
Sky coverage [sr]	π (Semi hemisphere) Cone angle +/- 120 °	2π (Full hemisphere) Cone angle +/- 180 °
Max Rot speed [° s^{-1}]	2880	50
Weight [Kg]	120	150

2.1 *Wind Lidar System Development – Lidars, Scanners and Data Acquisition Systems*
We will divide the wind lidar description up in the following categories: 1) single Staring lidars, 2) stand-alone (single) scanning lidars, and 3) 3D time and space synchronized scanning lidar systems.

2.1.1 Single Staring Lidars
Our first Lidar purchase was a QinetiQ Prototype QinetiQ "ZephIR" lidar. By removing its build-in 30 degree prism wedge scanner that is used to deflect its scanning probing beam in a circular scan pattern 30 degrees from the telescopes pointing direction, the prototype lidar could stare in a fixed pointing direction.

2.1.2 Single Lidar - VAD based scanning
With the assumption of homogeneous and stationary wind flow, the three mean wind components of the wind velocity vector can be measured by the so-called VAD (Velocity Azimuth and Display) scanning strategy as introduced by Browning and Wexler(1968) [16]. Today, the 360 degree VAD scanning methodology has found widespread application for ground-based wind energy assessment instruments, such as the cw-based ZephIR lidar from Zephirlidar.com (UK), the pulsed WindCube's (Leosphere, Fr), and the Galion lidar from SgurrEnergy, UK. From single 360 degree azimuth-scans of the aloft wind field, cw-based lidars can estimate the vertical wind profiles from ground up to heights 150 - 200 meters, whereas the pulsed VAD scanning wind lidar have proven capable of measuring profiles up to the top of the boundary-layer, 1200 - 1600 m above ground.

2.1.3 3D Scanning lidar systems -3D WindScanners
Two different types of 3D wind and turbulence wind velocity scanning lidar systems have been developed at DTU Wind Energy during the period 2007-2013 for the purpose of establishment of a new research tools for atmospheric boundary-layer and wind energy research, with the purpose to provide research infrastructure support for wind energy and wind industry technological development:

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

   The different sets of 3D wind vector synchronized WindScanner systems have been built to provide high-resolution three-dimensional (3D) velocity vector scanning of remote sensed wind fields:
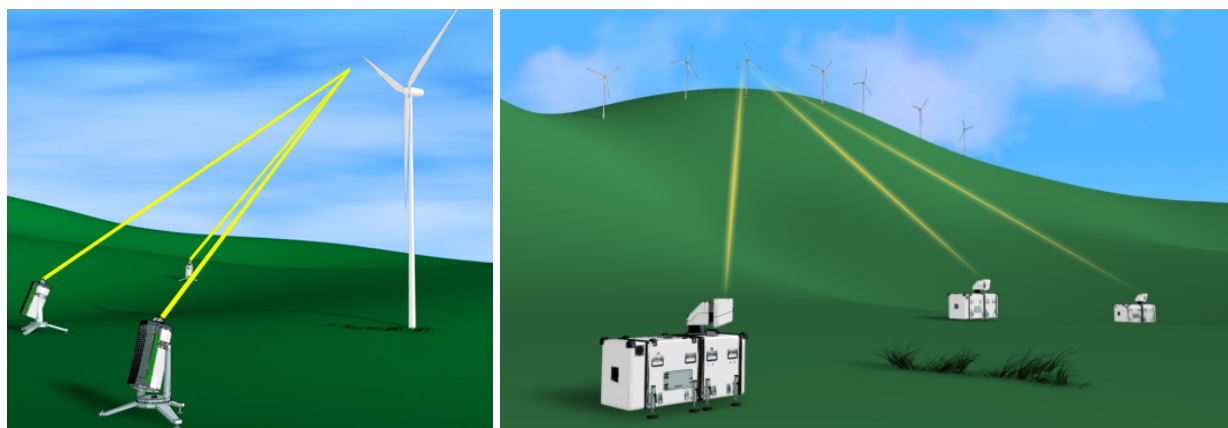
Figure 2. WindSscanner.dk: 3 Dimensional high-resolution wind velocity vector scanners. Left: Three short-range (10-150 m) 3D WindScanners. Right: Three long-range (0.1-6 km) WindScanners.

Aimed at experimental full-scale atmospheric rotor -layer research in wind flow and turbulence the two WindScanner systems have been conceived and manufactured by DTU Wind Energy with mechanical design assistance from IPU, Lyngby, to be operated as time and space synchronized scanning wind Lidar's.

The remote sensing based wind vector scanning measurement technology is disseminated in collaboration with leading wind energy research centers in Europe, assisted by the European Strategic Forum for Research Infrastructure, ESFRI. WindScanner was admitted on the ESFRI Road Map in 2010 for progressing towards a new joint European research infrastructure, to be inaugurated by 2016 (WindScanner.eu). When fully operational the European WindScanner facility, RI WindScanner.eu, is envisioned to offer open access collaboration with all wind energy engaged atmospheric boundary-layer researchers and experimentalists, including the wind energy industry throughout Europe and Overseas.

WindScanner.dk, the WindScanner RI's Danish national node, set out in year 2009 to exploit the new and handy telecom fibre-based wind lidars emerging after the turn of the Millennium. The development of reliable and fast vector scanning wind lidars was spurred by the wind energy society and its need for accurate ground-level based wind resource assessment. However, a coherent wind lidar measures only the 3D wind velocity vector projection along the lidars beam pointing direction. A variety of scanning and retrieval strategies therefore exists for single-lidar, and for dual-Doppler lidar, and for triple-lidar wind vector measurements:

2.1.4 Multiple Lidars - 3D wind vector scanning and retrieval
By combining of today's reliable and sturdy continuous and pulsed wind lidars based 1.55 μ telecom component fibre technology developed for the wind energy market over the past decade, with special-designed synchronized steerable-beam scanners, 3D wind and turbulence scanning lidar systems are now becoming available to researchers and industry for boundary-layer researchers and for wind energy industry applications. This is facilitated via the new Danish open access research infrastructure facility, now established at DTU Wind Energy, Risø campus: WindScanner.dk.

During its development, we have adhered to the following three factors characterizing the measurement availability and data accuracy acquired by wind remote sensing methodologies

1. For wind lidars, the data acquisition time required per wind measurement depends on the wind lidars signal-to-noise ratio (SNR), which, in addition to the number of backscattering natural aerosols within the boundary-layer. For the continuous wave (cw) short-range wind lidar systems the SNR scales with the cw lasers continuously transmitted power [Watt]; whereas for pulsed lidar systems the maximum achievable measurement range depend on the energy [Joule] transmitted per pulse and, at the longest ranges, also on the telescope aperture size. The system consisting of three long-range scanners have for this reason in collaboration with Leosphere been designed with 4" optics apertures, and corresponding mirror-based full-sky steerable scan heads.

2. The spatial representativeness of the lidars wind measurement is given by the lidars effective sampling or "sounding" volume. Both for the cw and the pulsed lidars the sampling volumes consists of thin elongated "pencil-shaped" wind speed sounding volumes. In the transverse directions the probe volumes are well confined by the laser beams transverse confinement, ranging from a few millimeters to a few centimeters depending on range. In the line of sight direction, however, it is different. For the cw lidars, the effective along-beam sounding length is determined by the lidars beams optical focus depth, which, in turn, is determined by the cw lidars aperture size. A typical sounding probe length for our cw lidars are approximately 13 m

at 100 m focus distance (range). For a pulsed wind lidar the wind measurement effective sounding length is determined by the pulse shape of the transmitted pulse in combination with the width of the pulsed lidars range gates, our pulsed lidars effective sounding length is typical 30 m or 60 m depending on max range. Both for the cw and the pulsed lidars the effective sampling volume is therefore much larger in the line-of sight direction than the sounding path within our commonly used i-situ met mast mounted sonic anemometer (0.1-0.2 m).

3. A single wind lidar, cw or pulsed, can only measure one component, that is, the projection along the lidars line-of-sight of the full 3D wind velocity vector. It is for this reason we have designed, manufactured and now operational inaugurated, two sets of scanning wind lidar systems, each set consisting of three space and time synchronized wind lidars, for the WindScanner.dk research infrastructure.

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 3D vector, three independent measurements of the wind velocity from within the same sounding volume by three wind lidars, one for determination of each of the three wind components in a non-degenerated orthogonal coordinate system, se Figure 3. A conceptual design of a full "triple-lidar" based time and space synchronized wind vector scanning system was first suggested in 2008 [17] and has since then been referred to as "WindScanners".

Our first 3D wind vector measurements obtained with three simultaneously beam-crossing wind lidars were recorded with three lidars pointing towards the instrumentation on a tall meteorological mast quipped with three-axes sonic anemometers and the wind vector measurements were intercompared and presented already in 2009 [18] .

During WindScanner.dk we have developed time- and scape synchronized data acquisition systems including agile beam steering drives and scanning programs that operate, steer, ample and store the acquired wind components with both types of WindScanners, cf. Table 2

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Table 2: RI WindScanner.dk wind lidar inventory at DTU Wind Energy – December 2014

Scanning Lidars - WindScanners:
- 3D scanning system: Short-Range WindScanners:
  DTU Possession: 3 of synchronized (space and time) short-range
- 3D scanning system: Long-Range WindScanners:
  DTU Possession: 3 of synchronized (space and time) 3 of Synchronized (in space and time) WLS200S
  Upwind 2D rotor plane SpinnerLidar for equivalent rotor plane power curve measurements and for real-time feed-forward control. DTU Possession: 1 of.

Operation and Synchronisation Software:

Long-range:	a) Master Control Software (MCS); b) Client Control Software (CCS) w/ Leosphere, c) Communication Protocol (in collaboration w/ Uni Oldenburg ForWind).
Short-range:	Delta-Tau MCS - real time synchronization and 500 Samples/ s data acquisition
SpinnerLidar:	Real-time inflow data processing for turbine control

3D Short-range WindScanners

The short-range WindScanner lidar system (see Fig. 2) can measure the wind fields in the induction zona and in the wakes behind operating turbines.

Each of the three short-range WindScanner system consists of three synchronized continuous-wave lidars developed by ZephIR Lidar, and equipped with a DTU Wind Energy invented dual-axis prism scanning systems capable of orienting the beams line-of-sight within a 60 degrees scanning cone adjustable center axis [11, 12]. Two independent motion controllers are used to orient the beam while a third focus motor is used to control the focus distance of the lidars at ranges between 10 m and 200 m. The short-range WindScanners are capable of sampling the wind speed at 400 Hz, but a sample rate of 100 Hz is used for this campaign. All three WindScanner lidars can be synchronized to scan the same pattern in space simultaneously allowing for line-of-sight measurements from three unique directions, and therefore the ability to solve for the three wind speed components.

Rather than measuring the line-of-sight velocities at precisely the point where the lidars are focused, there will probe volume or sounding volume averaging will occurs along the beam.

The cw lidar's range weighting function describes the weighting applied to the radial velocities along the beam as a function of the range r . For a continuous-wave lidar with an effective aperture size[1] α_0 is operated in the near-field range of the telescope, $R \ll k\alpha_o^2$, where $k = 2\pi/\lambda$, the lidars line-of-sight weighting function can to a good approximation be approximated as Lorentzian distribution [19].

$$\varphi(R) = \frac{1}{\pi}\frac{Z_R}{Z_R^2 + R^2} \tag{1.1}$$

The focus depth expressed in terms of the Rayleigh length, $Z_R(R) == \frac{\lambda R^2}{\pi\alpha_0^2}$, increases with the square of the measurement range. For the three 3" ZephIR Type 150 lidar telescopes in question, having an effective aperture sizes of $\alpha_0 = 28 \text{ mm}$, the resulting full-width-at-half-maximum width $\left(FWHM = 2Z_R\right)$ has been experimentally confirmed to closely approach the theoretical diffraction limit prediction, $FWHM \simeq 0.0013R^2$, where R is the range from the lidar to the focus point. At 100 meters range, the 3" ZephIR telescope's effective FWHM probe length has been experimentally determined to be close to 13 meters, Angelou et al. [14].

At every time sample, a Doppler velocity spectrum is provided by each lidar. Each Doppler spectrum is formed by computing the discrete Fourier transform of the backscattered light and contains 255 frequency bins, where the width of each frequency bin represents a velocity change of 0.153 m/s. Many 255-bin Doppler spectra are averaged together during the sampling period to reduce noise; for longer sampling periods, noise suppression is higher. Because of range weighting, the Doppler spectrum contains energy at frequencies corresponding to all of the velocities detected along the beam, weighted by the line-of-sight sounding weighting function. After subtracting the mean background noise spectrum and only considering frequency bins containing energy in excess of 5 standard

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[1] α_0 is defined as the radius on the aperture where the laser radiation intensity in the telescope has diminished to a factor e^{-2} of its central peak value.

deviations of the remaining noise or [14], a single value of the line-of-sight velocity detected by the lidar is estimated. For example, the velocity bin containing the maximum amount of energy or the velocity representing the centroid of the Doppler spectrum could be used to estimate the line-of-sight velocity. Due to the sensitivity of these approaches to spurious noise in the spectra, however, the more robust approach of identifying the velocity representing the median value of the energy in the Doppler spectrum is used. More information about estimating the line-of-sight velocity from a Doppler spectrum is provided in Angelou et al. [14].

The short-range WindScanner system is usually set up in the field so that the longitudinal x axis is aligned with the mean wind direction, y is defined as the transverse or lateral direction, and z is the vertical direction. The longitudinal (u), transverse (v), and vertical (w) wind components correspond to the x, y, and z directions, respectively. To follow the convention that lidar measurements when pointing into the wind direction are detected as positive line-of-sight velocities

Once the line-of-sight velocities for the three lidars focusing at the same point in space are known, the measurements are used to estimate the orthogonal *u, v,* and *w* wind components of interest. This estimation is achieved by solving the inverse detection problem, that is, to find the *u, v,* and *w* components that would have produced the three line-of-sight measurements.

In reality, due to range-weighting, the line-of-sight measurements are only approximations of the true Line-of-sight (v_{los}) velocities at the focus point. However, by ignoring the range-weighting effect in (1.1), the u, v and w components at the common focus point can be solved for using:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = -\begin{pmatrix} l_{x,1} & l_{y,1} & l_{z,1} \\ l_{x,2} & l_{y,2} & l_{z,2} \\ l_{x,3} & l_{y,3} & l_{z,3} \end{pmatrix}^{-1} \begin{bmatrix} v_{los,1} \\ v_{los,2} \\ v_{los,3} \end{bmatrix} \qquad (1.2)$$

where $\begin{bmatrix} l_{x,i}, l_{y,i}, l_{z,i} \end{bmatrix}$ and $v_{los,i}$ are the beam direction unit vector and measured line-of-sight velocity, respectively, for lidar i . It is desirable to choose lidar positions and scan patterns that result in a well-conditioned matrix in (1.2) to minimize the sensitivity of the u, v and w component estimates to errors in the line-of-sight measurements and beam direction vectors.

1D WindScanner measurements -The first WindScanner R2D1

The short-range WindScanners are designed and constructed by the Wind Energy department of the Danish Technical University in collaboration with the Danish Institute of Produktudvikling (IPU, Lyngby), ZephIR Lidar (UK) and (Heason Technology Limited).

It's two main components consists of a directional sensing modified version of a commercial ZephIR Z150 wind lidar (Kindler et al 2007; Smith et al 2006) and a fast-scanning scanner head (Mikkelsen et al 2011).[20,21]

The scanner head consists of two top-mounted rotating prisms, of 30° deflection angle each, the orientation of which can be controlled independently, to steer the Lidar's focused beam within a 2D scanning cone with a full opening angle of 120◦.

The design of the focus mechanism allows a minimum focusing distance of approximately 8 m. The instrument has been calibrated in order to achieve a pointing accuracy of $0.1°$ during scanning. The lidar is continuous wave (cw), coherent Doppler lidar first described in Karlsson et al (2000). The measurement technique is described in Sjöholm et al (2014) and the data filtering and processing is described in Angelou et al. (2012). The produced
laser Doppler spectra contain information about the almost instantaneous (2.5 ms averaged) wind speed projections along the lidar beam averaged in space over the lidars sounding probe length (Angelou et al 2012).

The probe length of a cw lidar is determined by the width of the line-of-sight intensity profile of the focused transmitted laser light energy, the intensity profile peaks almost symmetrically around the WindScanner CW lidars set measurement range (i.e. focus point).

To a good approximation, the los intensity profile of a cw lidar follows a Lorentzian distribution weighting function (Sonnenschein and Horrigan 1971).

The theoretically expected probe lengths defined from the intensity profiles full width half maximum (FWHM) have been calculated based on the properties of the 3" optical components of the instrument, and have also been experimentally evaluated using hard target return. The probe length increases with distance squared. At 100 m focus range the FWHM probe length is 12 m.

The WindScanner CW lidar system samples 200,000 time series of 5 microsecond length in time per second and produces correspondingly 200,000 real-time spectra of the line-of Sight projected wind speed per second. Prior the post process the spectra are averaged together in order to reduce the noise.

During measurement in a standard atmosphere aerosol loaded environment, typically 500 to 4000 Doppler spectra are averaged in real time. The number of useful noise-reduced wind speed measurement that are time stamped and streamed to data logger are correspondingly between 400 and 50 spectral resolved Line-of-sight wind speed measurements per second. The lower Carrier-to-Noise limit with + 2 standard deviation threshold is typically – 30 dB.

The resulting spectra offer the possibility of measuring radial wind speeds between 0.3 ms^{-1} and 18 ms^{-1}, with a Doppler spectral speed resolution of 0.15 ms^{-1}.

The optoelectronic design of the first three short range WindScanner instruments, R2D1; R2D2 and R2D3 all includes an optical acoustic modulator (AOM) that with a shift frequency of 27 MHz that allows distinction of the direction of the detected line-of-sight (LOS) wind speeds.

3. Scanning Wind Lidar Systems – Measurements, Data Interpretation and Analysis
At first, once we acquired the first wind lidars, we started to investigate the physical properties of the special sounding volumes tie lidars uses to probe the atmosphere wind field. Due to coherent lidars required high radiation intensity used to defining their measurement volumes, wind lidars are special and different from any previous wind measurement instrument used within boundary-layer meteorology such as cup anemometers and sonic anemometers. This is caused by the way the lidars probe the wind. Wind Lidars have extremely huge aspect ratios between their probe volumes dimension in the beam pointing direction, and its two cross beam dimensions. Mathematically, we say that the lidars probe the atmosphere along a single line of sight, with an along-beam weighting function of the order of 10 to 30 meters. To manage the lidars basic data interpretation features also the wind lidars signal-to noise relations ships have been investigated [22].

Our research has also addressed new ways to improve the wind speed retrieval from noisy measurements with low wind speeds. During the development of the fourth short-range WindScanner, vers 1.2 for the University of Western Ontario wind dome "WindEEE", the AOM system was replaced by an all-fibre optical hybrid In-phase and Quadrature (IQ) detection scheme [23]. The new IQ detection invention developed during the development of the Windscanner.dk infrastructure will now allow forthcoming generations of WindScanner systems to be able to detect low speed including direction sensing at speeds limited only by the data acquisition arbitrarily selective length of time series to generate the Doppler spectra. For the three first ZephIR-based WindScanner systems, R2D1; R2D2 and R2D3, each with a 5 µs sampling time controlled by the ZephIR's, the lowest FFT bin is at 0.15 m/s. With the new IQ system installed in WindScanner vers 1.2, the lower frequency bin in the Doppler spectrum can now be set arbitrarily low by increasing the length of the per spectrum set sampling time.

3.1 Single Staring lidar
Then we investigated the effects om measured turbulence by measuring the wind field with a single pulsed lidar beam, pointed into the mean wind direction at a fixed angle to the mean wind direction [24] [25] [26].

We measured the effective radial measurement resolution of a continuous wave staring lidar by investigating the lidar cross-correlations with a sonic anemometer [19]. By invoking a spectral tensor model we also investigated the spectral coherence between two range gates along a pulsed lidar's beam [27]. From top of the 123 m on-site DTU Risø campus met mast a pulsed WLS7 lidar with the prism scanner removed was pointed horizontally and measured the decay in approaching turbulence eddies between fixed range gates, in order to experimentally investigate the validity of the Taylors Frozen Turbulence Hypothesis [28].

Again, after first removing the build-in prism scanner in our WLS70 we stared the lidar vertically and observed the vertical variance profiles of the vertical turbulence component σ_w [m/s]. The lidar a Leosphere WLS70 was installed at Høvsøre as part of the Danish "Tall Wind Profile" project. The measurement were first analyzed in connection with the thesis work of M. A. Gürpinar (2011) [29] and later used for LES model intercomparison as presented at the 11 EMS annual meeting in 2012 [30]. In Figure 3 two distinct different days of lidar measurements are presented: day 14.02.2011 represent the evolution in turbulence during a neutral-stable atmospheric evolution while the second day 06.05 2010 present the much more dramatic evolution in the turbulence representative for a highly convective day. It is seen that the lidar measures two distinct vertical turbulence structures these two days, representative of a neutral-stable boundary-layer, and a convective boundary layer, respectively.
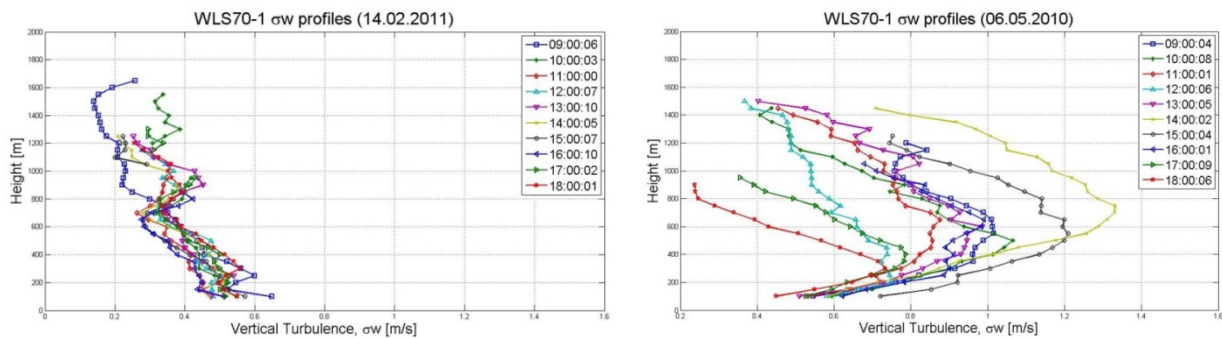
Figure 3. *Vertical profiles of the vertical turbulence component* σ_w *as function of height above DTU test site Høvsøre. Left: evolution during a neutral-stable stratified (winter) day. Right: evolution during a highly convective (summer) day.*

A small "Lidic", that is a DTU/IPU designed 1" cw lidar telescope developed for blade integration and wind tunnel diagnostics was developed and mounted together with standard in-situ instrumentation in a wind tunnel. A methodology to infer not only the variance, but the entire pdf of the along-beam turbulence from fast sampled lidar data have been demonstrated [31].

3.2 Single Scanning Lidar
We investigated wake flow and turbulence behind a Tellus turbine by integrating a simple wedge scanner on our first QinetiQ prototype cw lidar, mounted the lidar on a mechanical pan- and-tilt head, and installed the resulting wake scanner on the aft balcony of an on-site Tellus turbine [32,33].

3.3 Single Scanning Lidar operated in "VAD scanning mode"
By adding a rotating prism on top the starring wind lidar becomes a "Velocity Azimuth Display" VAD scanning lidar. Pointed vertically, the lidar will retrieve information of all three wind component 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. Our first VAD lidar investigation goes back to 2006 [34]. We later investigated the effect on measured turbulence by VAD scanning [35], see also below. We soon began to evaluate the VAD Lidars against our calibrated met mast at Høvsøre [36] . Today our Høvsøre lidar test facility has been approved as Danish accredited DANAK calibration facility. VAD scanning lidars have also been deployed in complex terrain to measure wind profiles if corrected for inhomogeneity in the aloft wind field [37] [38] [39], and over forest [40] [41]. Several experimental wind condition and wind energy assessment studies have been made on and offshore over the years with cw and pulsed VAD vertical scanning profilers: 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 during 2007- 2008 and was reported in 2009 [42] [43]. The offshore wind resource has been extensively measured with VAD scanning lidars from offshore platforms located in the North Sea (NorseWind.eu) [44].

Tall wind profiles, up to 600 m height, have been measured and their Weibull speed distribution parameters as function of height has been assessed from year-long lidar profile observations of horizontal wind speed profiles over rural coastal (Høvsøre) and inland suburb (near Hamburg) areas [45] . Also the entire ABL wind climate form a 1-year measurement campaign at Høvsøre has been investigated [46]. The tall profile measurements have also provided an experimental basis for intercomparison with numerical weather prediction modelling in the coastal boundary layer at Høvsøre [47].

Ground-based VAD scanning vertical wind profile lidars has early suggested as a replacement for tall met towers for wind turbine power curve assessment [48]. From ground-based vertical wind profile measurements of the wind shear, a hub-height rotor equivalent wind speed has been defined is now widely accepted within the wind energy society [49] [50]. Also the boundary-layer height has been measured by VAD wind lidar measurements in conjunction with simultaneous met mast and ceilometer observations [51]. A recent investigation addresses wind lidar performance a flat (Høvsøre, Denmark) and a complex (Alaiz, Spain) wind site [52].

3.4 Turbulence assessed from VAD scanning Lidars
Several of the above listed VAD scanning lidar based activities has also addressed the issue of direct measurement of turbulence with a single (VAD) scanning lidar.

Being a vector consisting of three wind components the fundamental problem with measuring the wind velocity components for assessing the three components of the turbulence is that it takes three independent lidars line-of-sight wind velocity projected measurements on the same probe volume to extract all three wind components of the wind velocity vector simultaneously. Our 3D WindScanners are 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 success.

A first attempt to measure turbulence suggested compensating for the volume filtering effects of measured turbulence. For a cw lidar a model of the filtering effects of the huge VAD scanned volume has included in the assessment of the lidar measured variances [53]. Another investigating dealt with measurement of the surface layer shear stress u_* from differences in the lidar measured variances upwind and downwind the line-of-sight radial wind speeds observed by a VAD scanning lidar [54].

The fundamental problem of measuring the three turbulence wind component by VAD scanning cw and pulsed lidars has been addressed by Sathe et al. in 2011 and lidar measurements are compared with profile measurements of all three turbulence components measured in the 120 m Høvsøre met mast [55]. Also the issue of measuring turbulent spectra via a pulsed VAD scanning lidar has been addressed [56]. It has been shown by Sathe and Mann (2012) [57] that it takes six simultaneous and independent radial beam projection measurements with a single lidar of the wind field to resolve all six components of the (u, v, w) co-variance matrix under the assumption of homogeneous turbulence. Several other methods have been developed and investigated over the years by other researchers outside DTU to 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 [58].

3.5 Multiple Synchronized Scanning Lidars "WindScanners"
The conceptual idea of 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 DTU Wind Energy back in 2008 [59]. The multiple beam crossing wind velocity measurement concept was demonstrated in 2008 with 3 staring wind lidar measurements intercepting near a sonic measurements in a reference mast at DTU Wind Energy's test site Høvsøre [18]. Today our lidars, bot the cw based and the pulsed systems are all equipped with steerable- beam scanners and the scanning lidars are therefore referred to as the "short and long-range WindScanners".

We recently tested the three short-range WindScanners wind vector measurement accuracy by direction crossing the three WindScanner beams into the gab of a high precision sonic anemometer and were here by the WindScanners able to detect flow distortion in the gab caused by the Sonic's support structure [60]. Our first WindScanner measurement results with the continuous wave short-range WindScanners obtained in the surroundings around the DTU Risø campus was published in

2012 [61]. In the fall of 2011 we scanned the first 2D mean and turbulent wind fields within a two-dimensional vertical plane over a small hill (Bolund) with our first operational short-range WindScanner (R2D1) [62]. Several other WindScanner based field tests have meanwhile been undertaken; the most involving was the 2011-2013 Norwegian All Weather Search and Rescue (NAWSARH) 3D downwash measurement program on low hovering rescue helicopters [63].

Recently we have successfully improved the continuous wave WindScanners direction sensing and also their low wind speed detection limit by utilizing a new hybrid optical in-phase and quadrature detection devise   [23]. For the long-range lidars multiple-beam synchronized beam steering methodology was developed in collaboration with ForWind University of Oldenburg and investigated by simulation and by CNR backscatter measurements from hard targets [64,65] . A recent study has addressed optimal scanning patterns for reducing the measurement uncertainty by scanning at coastal ranges with two crossing lidars beams [66] .

3.6 Lidar Measurements from Wind Turbines of Upwind Inflow and Downwind Wakes
At DTU Wind Energy today we are busy engaged with development and testing of lidars for installation on turbine nacelles [67] and integration in the rotating spinners [68]. The first measurements of wake behind a Tellus wind turbine was performed already back in 2006. [32]. In collaboration with ZephIR Lidar DTU Wind Energy has developed and tested an upwind full-rotor plane scanning SpinnerLidar [69]. Lidars installed or integrated in the turbines serve different proposes 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 been performed directly from the nacelle [70] [71]. New low cost wind lidar concepts for wind turbine power curve measurements and control are being tested [72].

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 [73] and energy capture [69].

Summary: The new Windscanner.dk research infrastructures design, its remote sensing operation principles and its technical description documentation have been documented.

Also the facility's initial full scale operation with up to three Syncronized scanners at the Wind Energy Department at DTU Risø campus and abroad, as well as a listening of the WindScanner.dk facility's first references to published results from field trials in Denmark and in Europe has been described.

Further details on results obtained with the windscanner.dk research facility including also many other remote sensing-based research activities based on lidar remote sniping at DTU Wind Energy achieved during the past decade can be found in Mikkelsen 2014 [74].

WindScanner.dk based Wind Field Measurements 2011-2014

The first measurements outside the laboratory with the new short-range WindScanner R2D1 took place at DTU Risø campus in 2011. With a single WndScanner, the wnd field aloft a snall hut at Risø Campus was scanned and showed increased wind speed above the hut.

Later, in December 2011, two syncronized wndscanners were deployed at Sola Airfield in Norway to characterize the downwash underneath a hoveing Sea King risque helicopter. This was a pre-trial to what later became a bigger international intercomparison of downwash under neath several otherer resque helicopters.

In 2012 the R2D1 windscanner was installed manually and deployed for measurements of the wnd flow aloft and in romt of the escarpmemt to the west on the Bolund Hill, situated just 1 km north of Risø campus. The purpose was to charactetize and to supplement previous met-mast based wind measurements at Bolund. On October 10, when the wind direction was predicted to be westerly, a single windscanner (R2D1) was manually carried to, set up and deployed at Bolund hill in a few hours. Detailed wind characteristica inclusng turbulence was succesfully achiewed during a few hours of measurements.

In 2013 the first WindScanner based wake measurements were performed at Risø Campus in the row of test turbines. The DTU Wind Enegy's 550 kW NEG Nordtank test turbine was equipped with simultaneous forward and backward loking windscanner lidars for inflow and wake measurement from the nacelle, ans an ajacent turbine (Tellus) was installed with a prototype scanner. The purpose was to investigate the effect og wake-wake interaction og the two turbines wakes, when the wind direction made the Tessus turbine wake impinge upon the Nordtank wake.

Also in 2013, now with three syncronized and short-range WindSanners operational, the first 3D Wind Velocity measyrements were intercompared with corresponding wind measurements from tall met masts.

In may 2013 the 3D operatonal WindScanner facilty was operated in the scaled wid farm at ECN, Holland.

During the summer 2013, we revisited Sola airfield for obtaining reference Helicopter downwash measurements with three scanners and later the same year the mobile WindScanner facility was touring Europe while wisiting air fields and measuring downwash from warious helicopters in the UK and in Southern France.

In 2013 also toe long-range Windscanners were sucecsfully syncronized in space and time, and deployed in a first long-range field trial at the DTU test site for large wind turbines at Høvsøre, Jutland. Measurements of inflow and wake flow behinf the test site was obtained to distances +/- 5 km from the test site. Among other stings the long-range WindScanner PPI-scan measurements revealed facinating «radar» plots of the surrounding wind flow that included visible wakes from the test site's operating wind turbines.

For turbulence, the three short-range WindScanners were set up to cross beams at 90 m height over DTU Risø Campus, and their 3D turbulence measurements at that height was compared with a sonic anemometer in the DTU Risøe Campuss 123 m tall met mast.

In 2014, the first real 3D Inflow induction zone measurements took place at DTU Risø campus around the V27 test turbine. Horizontal plane at hub height and vertical plane scans of the inflow in the induction zone revealed 3D characteristics of the 3D flow in the turbines induction zone.

Later the same year, in connection with a new Danish power curve performance project (UniTTE) both the short-range and also the long range set of 3 Syncronized WindScanners were engaged in measurements of 3D inflow and wake from DTU Risø Campus installed NKT 550 Nordtank test

turbine. Also the WindScanner facility's 2D upwind rotor plane scanning SpinnerLidar was operated at the same time, from an installation on top of the turbine nacelle.

In May 2014, during a one-week measurement campaign in collaboration with Norwegian NORCOWA partners at the University of Stavanger, two synchronized short-range WindScanners were deployed during an intensive measurement campaign on a large suspension bridge over Lysefjord in Norway. The purpose was to measure turbulence characteristics including power spectra, spatial correlation and crosswind coherence functions at a distance 60 m in front of the bridge deck.

Also the set of three synchronized long-range WindScanners were deployed in a so-called "Pre-RUNE" field test at Høvsøre, where inter comparison of wind offshore wind speed and direction measurements from different lidar scanning configurations were interrogated.

During summer 2014 the synchronization software developed for the three Danish long-range WindScanners were shared with the three similar long-range WindScanners belonging to University of Oldenburg in a joint common field test with six synchronized long-range Wind lidars at Röderseberg near Kassel in Germany.

Also in 2014,the special 2D SpinnerLidar was installed for control feed-forward testing on the CART3 test turbine at NREL, Colorado USA.

In the beginning of 2015 the three short-range WindScanners were engaged via the EU MARINET infrastructure coordination program to measure full-scale 3D wind velocity wake flow scanned in horizontal and vertical planes around and behind the 2.3 MW Nenuphar Vertical Axis Wind Turbine (VAWT) installed for test runs at the Nenuphar onshore test site near Fos-sur-Mer in Southern France.

Finally, to assist improvements of CFD predictions the downwind lee effects and extent behind a simple wind break is being investigated by deployment of the three short-range WindScanner in a field test near the shore line at DTU Risø campus.

Windscanner.dk engaging field test activities 2011-2015:

2011
1) First 2D Wind field measurements of mean flow over a small hut @ DTU Risø Campus. [61]
2) First Pre-NAWSARH full scale field test at Sola Airport, Stavanger, Norway. Sea King Helicopter downwash measurements using two syncronized short-range WindScanners (Horizontal plane and vertical plane scanning.

2012
3) First short-range high-resolution wind and turbulence measurementsin front and over the Bolund hill located north of DTU Risø Campus in Roslikde fjord.[62,75]

2013
4) Simultaneous Spinner Lidar inflow forward & WindScanner R2D1 backward Wake measurements from WT NKT 550 Nordtank;Marchefaux et al. 2015 [76]
5) Short-range 100 Hz WindScanner.dk measurements vs. 3D sonic at 90 m height.
6) Scaled Wind Farm @ ECN 3D short range inflow/wake
7) Three HAWSARH Helicopter downwash measurements: 1) Norway; 2) UK and 3) France. [77][78]
8) Two syncronized Long-range WindScanners performing PPI scanning at 6 km range @ Høvsøre 2013.
9) Lidar Turbulence: High-resolution wind velocity measurements with three short-range wind Lidar @ Risø campus test site [79].

2014
10) 3D Inflow induction zone measurements around a V27 test turbine located at DTU Risø Campus. Work in collaboration with Colorado University and National Renewable Energy laboratory; Colorado USA. [80].
11) Assessment of wind conditions at a fjord inlet by complementary use of sonic anemometers and lidars, Norway May 2015[81,82].
12) Long-range WindScanner Pre-RUNE experiment, April-May 2014 [66].
13) Long-range WindScanner Kassel Campaign w/ six synchronized long-range scanners. June-July 2014 [83] . Röderseberg Kassel 2014: Long-range WindScanner Field Test.
14) 3D inflow and wake measurements on the NKT 550 Nordtank test turbine @ DTU Risø Campus, July - October 2014 (UniTTE).
15) SpinnerLidar installed and test operated at NREL CAT3 Turbine for lidar assisted feed-forward Control (INNWIND.EU).

2015
16) MARINET EU Infrastructure Support: Nenuphar offshore VAWT; Fos-sur-Mer Marseilles 2015
17) IEA Task 27 Lee Belt and Small House wakes 2015

Acknowledgements

Appendix-I: WindScanner.dk Scanning Lidars - Technical Specifications:

1. Short-range WindScanners (Scanning continuous wave lidars)

Figure 1. Left: First Short-range WindScanner at DTU Risø Workshop 2010; Middle: Inaugurating the first of three Short-range WindScanners, R2D1 vers. 1.0, Risø DTU 2011; Right: Improved Short-range WindScanner vers. 1.2 Sep 2014).

WindScanner.dk - Short-Range CW Lidar based Proto-type: Design Specifications:		
Type of Wind LIDARs: CW	*Modified ZephIR's from QinetiQ, Malvern, UK- Polarization maintaining, heterodyned*	
Range R[m] of operation	*10 m < R < 200 m*	
Telescope focal length f_0	*0.24m (ZephIR Unit 2)*	***0.28m (WindScanner ZephIR_Stretch)***
Lens: 3" aperture; a_0 $(I_{a0}/I_0 = e^{-2})$	*0.020 m*	*0.28 m*
Minimum waist d_0	*0.00493 m @ R= 100 m*	*0.00352 m @ R = 100 m*
Rayleigh length @ focus-limited sounding range: $FWHM_{@100m}=2 Z_{R @100m}$ [2,3]	*$Z_R \sim 0.001234 R^2$ FWHM = 24.68 m*	*$Z_R \sim 0.000630 R^2$ $FWHM_{100m} \sim 12.6$ m; $FWHM_{200m} = 50.4$ m*
Two-axis Scan Heads for focused laser beam steering in 2-D [4]:		
Scan range per axis	*Two-axis two 30° prisms: +/- 30 degrees per axis (+/- 60 degree total)*	
2-D solid angle subtended	*One full (π) solid angle [one Steradian]*	
Moment of inertia per axis	*< 0.03 [kg m^2]*	
Scan bandwidth	*~10 Hz with closed-loop full deflections (+/- 60 degrees)*	
Motion Controller AC motor type AKM44G (9 pc.)		
Torque: Peak[5]/rated max torque	*16.5/(20.2) [Nm]*	
Max power	*320 V DC @ 20 Amp; Rated power 1000 Watt*	
Focus control bandwidth	*>> 10 Hz Heason Ltd. UK nano-position linear actuators max driving force ~ 4 N*	
Wind speed acquisition rate: PM CW modified ZephIR wind lidar:		

[2] Ref Sonnenschein;& Horrigan (1971).

[3] Ref I. N. Smalikho, (1995), On measurements of the dissipation rate of the turbulent energy with a CW Doppler Lidar Atmospheric Oceanic Opt. Vol. 8 No.9.

[4] Patent WO 2009/155924 A1; Risø DTU (2008).

[5] Limited by controller (20 Amps)

CW lidars internal power spectra acquisition rate	*200.000 FFT's per second*
Signal-to-Noise ratio S/N	*Acceptable S/N ratios (> 5) achievable by ensemble averaging of ~ 400 power spectra per wind measurement with a standard aerosol contaminated atmospheric surface layer*
Maximum wind speed acquisition rate via 1. moment estimation of ensemble averaged Doppler spectra	*500 per second per CW Lidar (from sampling rate 200.000 s^{-1} /400 averages => 500 samples s^{-1} Doppler wind measurements per CW lidar per second).*

2. Long-range WindScanners (Scanning Pulsed lidars)
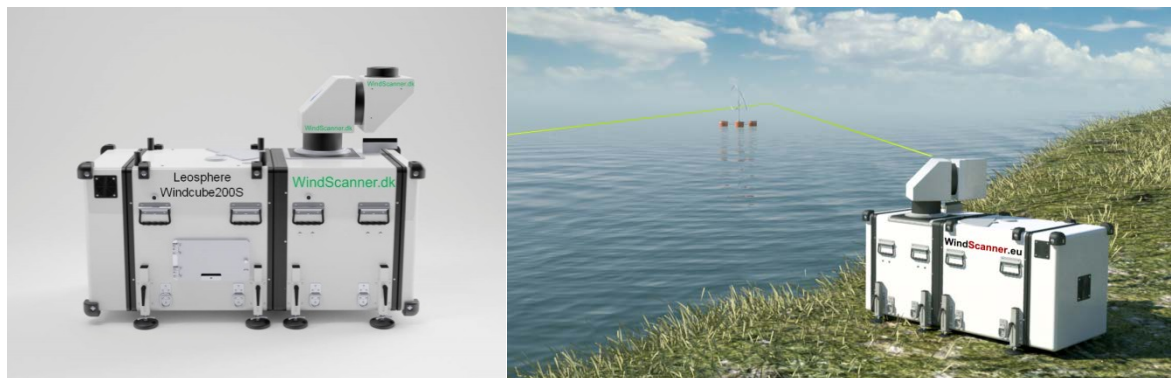
LONG RANGE SCANNER, (detailed specifications)

Performances
Windcube200S

PERFORMANCES	WINDCUBE200S
Maximum Lidar signal acquisition range	15,000 m
Wind measurement range (on aerosol - within boundary layer) (1)	Typical scenarii (depending on range gate width and accumulation time): - 100m to 10,000m - 100m to 6,500m - 50m to 2,500 m
Averaging time	1s to 10s
Range gate width	20 - 50 - 100m selectable
Number of programmable gates	120, 240
Radial wind speed accuracy	0.2 m/s below 1,500m ; 0.3 m/s above
Cloud detection	15,000m
SCANNER	
Azimuthal scanning	0° to 360°
Zenithal scanning	-10° to 190°
Angular resolution (azimuthal-zenithal)	0.5°
Maximum rotation speed	0.5-1-2-3-4°/s when acquiring data
Scanner position refreshment	1Hz to 800Hz

Technical Specifications
Windcube200S

| ELECTRICAL	
Power supply	110-240V AC / 27V DC / 50-60 Hz
Power consumption	750 W to 1,500 W in DC
ENVIRONMENTAL	
Temperature range	-15°C to +40°C
Relative humidity	from 10 to 100%
Environmental protection	IP65 - waterproof and dustproof
OPTICS & ELECTRONICS	
Laser wavelength	Pulsed laser at 1.54 μm
Eyesafety	IEC/EN 60825-1 compliant / ANSI ZI36.1-2007 compliant
DIMENSIONS	
Size (mm)	1570 x 680 x 1000 mm
Weight	180 kg
DATA	
Operating system	Windows 7 OEM 64 bits
Data format	ASCII & BUFR

IPU

The Future: Towards a Danish Road Map hosted WindScanner.eu ESFRI HUB:

Further Sensors and Research Infrastructure Developments:

From WindScanner.dk (2009-2014) towards a WindScanner.eu ESFRI Hub (2015 – ff.)
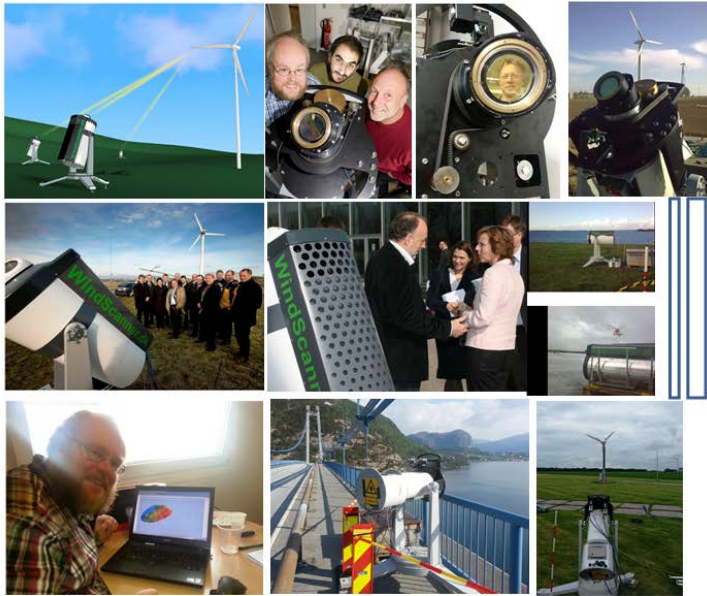
Activities at DTU Wind Energy during **WindScanner.dk** (2009-2014)
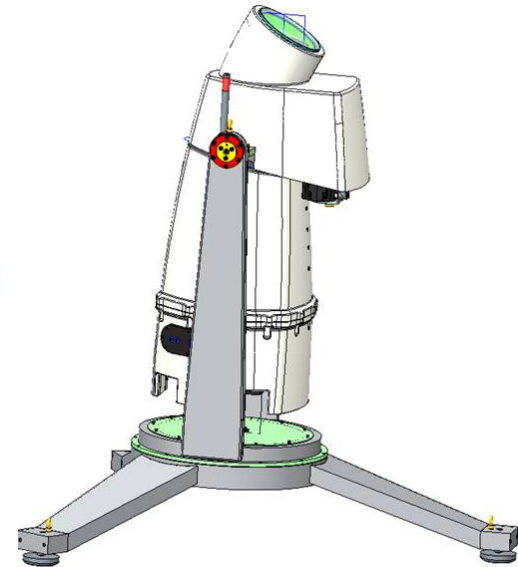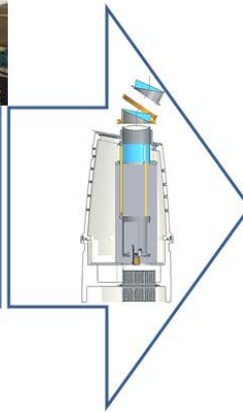
Recent development during the ongoing PP **WindScanner.eu** WP3 program (2012-2015):

New design Short-range WindScanner 2.0 [6" - 300 m range]

WindScanner.dk GPS time Syncronized Long-Range WindScanners in operation at Röderseberg near Kassel 2014.

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, Kristensen L and Jørgensen H E 2007 *The Bistatic Sodar Heimdall'', You blow, I listen* vol Risø- R-14 (Ris° 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]   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

[17]   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

[18]   Mann J, Cariou J-P-P P, Courtney M S, Parmentier R R R, Mikkelsen T, Wagner R, Lindelöw P P J P P J P, Sjöholm M, Enevoldsen K, Lindeløw P J P and Sjøholm M 2008 Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer *Meteorol. Zeitschrift* **18** 135–40

[19]   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

[20]   Mikkelsen T, Kristensen L, Dellwik E and Mann J 2013 A Single laser All-fibre Based optical Sensor and Switching System and method for Measureing Velocity in Atmospheric Air Flow Patent WO 2013/092746 A1 43

[21]   Mikkelsen T, Mann J and Nielsen M 2009 Rotating Prism Scanning Device and Method for Scanning Patent EP 2 304 489 B1; WO 2009/155924 **1** 1–21

[22]   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

[23]   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* vol 524 (Copenhagen: IOP Publishing) p 012004

[24]   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** U411–6

[25]   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

[26]   Kristensen L, Kirkegaard P and Mikkelsen T 2011 *Determining the Velocity Fine Structure by a Laser Anemometer with Fixed Orientation* vol Risø-R-rep (Roskilde: Danmarks Tekniske Universitet, Ris° Nationallaboratoriet for Bµredygtig Energi)

[27]   Kristensen L, Kirkegaard P, Mann J, Mikkelsen T, Nielsen M and Sjöholm M 2010 *Spectral Coherence along a Lidar Anemometer Beam* vol RR-1744 (Roskilde)

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

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

[30]   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

[31]   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

[32]   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

[33]   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

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

[35]   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)

[36]   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

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

[38]   Bingöl F 2009 *Risø-PhD-Report* vol PhD 52(EN) (Roslikde)

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

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

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

[42]   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

[43]   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

[44]   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

[45]   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

[46]   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

[47]   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** 469–91

[48]   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-Report*
        vol 1679

[49]   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

[50]   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

[51]   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

[52]   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** 200–10

[53]   Wagner R, Mikkelsen T, Courtney M and Wagner A R 2009 *Investigation of turbulence
        measurements with a continuous wave, conically scanning LiDAR* vol 1682

[54]   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

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

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

[57]   Sathe A and Mann J 2012 Turbulence measurements using six lidar beams *ISARS 2012* (Boulder) pp 302–5

[58]   Sathe a. and Mann J 2013 A review of turbulence measurements using ground-based wind lidars *Atmos. Meas. Tech.* **6** 3147–67

[59]   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 U148–56

[60]   Dellwik E, Mann J, Angelou N, Simley E, Sjöholm M and Mikkelsen T 2014 Can coherent continuous-wave Doppler lidars be utilized for in-situ instrument calibration？ *17. ISARS* (Auckland) pp 1–43

[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]   Vasiljevic N, Courtney M, Wagner R, Mann J and Mikkelsen T 2011 A windscanner simulator *EWEA 2011* vol 10 (Marseilles, Fr)

[65]   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* **In: Procee**

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

[67]   Courtney M 2013 *Calibrating nacelle lidars* (Lybgby)

[68]   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** 625–43

[69]   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

[70]   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* n/a – n/a

[71]   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)

[72]   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*

[73]   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

[74]   Mikkelsen T 2014 Lidar-based Research and Innovation at DTU Wind Energy – a Review *J. Phys. Conf. Ser.* **524** 012007

[75]   Mann J, Angelou N, Sjöholm M, Mikkelsen T, Hansen K H, Cavar D and Berg J 2014 Laser scanning of a recirculation zone on the Bolund escarpment *J. Phys. Conf. Ser.* **555** 012066

[76]   Machefaux E, Larsen G, Troldborg N, Hansen K, Angelou N, Mikkelsen T and Mann J 2015 Investigation of wake interaction • Provide high resolution measurements of wake interaction *To Appear Wind Energy*

[77]   Sjøholm M, Pedersen A T, Angelou N, Foroughi Abari F, Mikkelsen T, Harris M, Slinger C and Kapp S 2013 Full two-dimensional rotor plane inflow measurements by a spinner-integrated wind lidar *EWEA 2013*

[78]   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** 939–937

[79]   Dooren M and Kraft M 2014 Analysis of a 100 Hz time series of wind speed measured by three short range cw-LiDAR WindScanners

[80]   Simley E, Angelou N, Mikkelsen T, Sj M, Mann J and Pao L Y Characterization of wind velocities in the upstream induction zone of a wind turbine using scanning continuous-wave lidars *J. Sustain. Renew. Energy (AIP JRSE)* **1** 1–18

[81]   Jakobsen J B, Cheynet E, Snæbjörnsson J, Mikkelsen T, Sjöholm M, Hansen P, Svardal B, Kumer V and Reuder J 2015 Application of lidars for assessment of wind conditions on a bridge site *ICWE14 June 21 - 26 2015* (Porto Alegre - Brazil) pp 20–3

[82]   Jakobsen J B, Cheynet E, Snæbjörnsson J, Mikkelsen T, Sjöholm M, Angelou N, Hansen P, Mann J, Svardal B, Kumer V and Reuder J 2015 Assessment of wind conditions at a fjord inlet by complementary use of sonic anemometers and lidars *12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015* vol 00 (www.elsevier.com/locate/procedia)

[83]   Vasiljevics N 2014 *A time-space synchronization of coherent Doppler scanning lidars for 3D measurements of wind fields DTU Wind Energy - DTU Wind Energy PhD-0027 (EN)* (Roskilde: DTU Wind Energy).