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3D WindScanner lidar measurements of wind and turbulence around wind turbines, buildings and bridges

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Abstract. WindScanner is a distributed research infrastructure developed at DTU with the participation of a number of European countries. The research infrastructure consists of a mobile technically advanced facility for remote measurement of wind and turbulence in 3D. The WindScanners provide coordinated measurements of the entire wind and turbulence fields, of all three wind components scanned in 3D space. Although primarily developed for research related to on- and offshore wind turbines and wind farms, the facility is also well suited for scanning turbulent wind fields around buildings, bridges, aviation structures and of flow in urban environments. The mobile WindScanner facility enables 3D scanning of wind and turbulence fields in full scale within the atmospheric boundary layer at ranges from 10 meters to 5 (10) kilometers. Measurements of turbulent coherent structures are applied for investigation of flow pattern and dynamical loads from turbines, building structures and bridges and in relation to optimization of the location of, for example, wind farms and suspension bridges. This paper presents our achievements to date and reviews briefly the state-of-the-art of the WindScanner measurement technology with examples of uses for wind engineering applications.

1. Introduction

WindScanner is a DTU-lead European Research Infrastructure designed for 3D wind field measurements based on mobile deployable, space-scanning coordinated and time synchronized wind lidars (Figure 1).

The construction of Scanning lidars was motivated by the steadily increasing size of modern wind turbines which are today soaring hundreds of meters into the sky. Their blades sweep through areas bigger than several football fields.

Obviously, the wind field in the rotor plane can no longer be characterized from a single-point measurement but the characterization requires detailed knowledge of the dynamics of the entire 3D wind fields, over the entire rotor plane upwind and in the turbine wakes.

The vision of WindScanner is primarily to develop, establish and operate a mobile joint European distributed Research Infrastructure (RI) for experimental research in wind and turbulence for wind energy. The scope and main focus of the project is primarily the wind energy sector, however there are, as will be described below, several other uses and applications for the WindScanner wind field measurement methodology, including aeronautics, various atmospheric studies, construction and performance of buildings, bridges, street canyon flow etc.

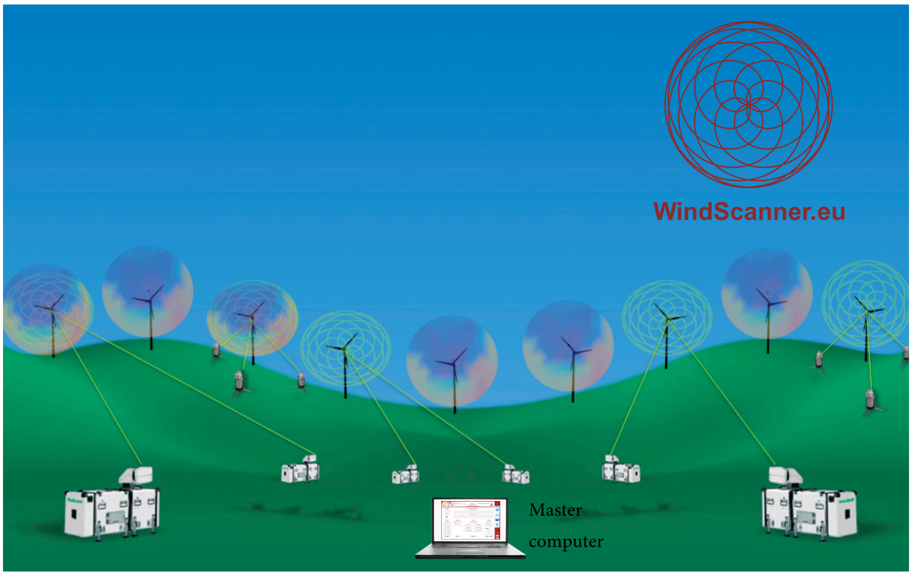


Figure 1. Inflow and wakes around turbines exposed to wind and turbulence in complex terrain are scanned in 3D space and time from WindScanners.

WindScanner.eu was admitted to the EU ESFRI Roadmap in 2010 and since then possible synergies of an enhanced collaboration with similar European RIs in other fields have been promoted.

The mission of fostering a joint European WindScanner project is: (1) Planning and coordination of WindScanner measurement activities, (2) Coordination of purchasing, commissioning, calibration and maintenance of WindScanner equipment, (3) Training and education in WindScanner operation and data analysis, (4) Development of e-science facilities for campaign design, documentation, data management and data analysis, (5) Providing access to the research data, (6) Dissemination of WindScanner opportunities and achievements to foster optimal stakeholder collaboration.

Traditionally, wind speed measurements are made using mechanical devices such as cup or sonic anemometers and wind vanes that need to be mounted at the points of interest, usually using a meteorological mast.

However, WindScanner systems are composed of several ground-based multiple trajectory-scanning and time synchronized Lidars, being remote-sensors using laser light to measure wind speed. The new technology has been successfully tested in Europe and in North America across many different topographies including hot and cold regions, flat and complex terrain sites and on- and offshore.

Today (2017) the original vision, mission, scope and identity of the WindScanner wind and turbulence measurement system based on remote sensing methodologies has been fully defined. During the last decade, the technical and scientific goals for establishing WindScanner as a mobile and joint European research infrastructure project have been achieved.

The WindScanner RI consortium consists of 10 Research Institutions from 7 member states: DTU (Denmark), IPU (Denmark), CENER (Spain), CRES (Greece), Fraunhofer IWES (Germany), ForWind (Germany), ECN (Netherlands), SINTEF (Norway), LNEG (Portugal), University of Porto (Portugal). Today, bound by a common Memorandum of Understanding (MoU) signed in Sep 2015 the aim during the on-going RIs construction phase is now to build-up national WindScanner nodes and to provide infrastructure access to users from industry and the research community.

The project involves the most significant principal RIs in Europe in the field of wind energy research and WindScanner is therefore considered today by ESFRI to provide a consolidated scientific leadership on the wind field research matter in EU.

Today, the WindScanner research infrastructure offer a new open-access and joint European research infrastructure for promoting research and innovation in atmospheric wind and turbulence via full-scale open air 3-dimensional wind field experimental investigations. Real-time measurements of the 3D wind velocity and turbulence vectors in the atmospheric boundary-layer are obtained using advanced remote sensing-based wind measurement techniques known as wind lidars.

Distributed European WindScanner nodes are being established as national/regional competence centers engaged with a planned central hub located at DTU Wind Energy regarding the continued operation, maintenance and further development, coordination of applications and training of experts to operate the WindScanner wind measurement technology.

WindScanner.eu can lead and disseminate coordinated experimental research for large European-level wind energy measurement campaigns throughout Europe.

At DTU Wind Energy in Denmark, we plan to lead and host the European central hub for coordinating access, planning operation, training and maintenance and also we disseminate detailed WindScanner instrument manufacturing plans, to assist partners to build the mobile WindScanner instruments locally.

The DTU hub will also maintain the scanners and version control software and data processing algorithms to secure data management and manage host servers, and train experts and users from research community and industry.

WindScanner is an open-access experimental facility that also serves atmospheric boundary-layer research on- and offshore, air safety, wind load measurements on buildings and bridges, 3D wind circulation field measurements in street canyons and in the urban environment, etc.

The paper addresses and reviews recent WindScanner based experimental research activities and present several WindScanner experimental setups including 3D wind field measurements from recent WindScanner measurement campaigns.

Additional information can be found on our home pages were also open-access publications and detailed descriptions can be found, cf. `www.WindScanner.dk` and `www.Windscanner.eu`.

2. The 3D scanning windscanner system

The WindScanners were originally designed for 3D wind field and turbulence measurements of the atmospheric airflow around wind turbines. To date, DTU has designed and built two different sets of multiple trajectory-coordinated synchronized WindScanners, i.e a short-range WindScanner system, consisting of three synchronized continuous-wave scanning Doppler lidars, and also a long-range WindScanner system consisting of multiple trajectory-coordinated scanning pulsed Doppler lidars.

The objectives and technical functionality specifications including technical details of the 3D wind field WindScanner facility, both the short-range and the long-range WindScanners are available in [1, 2, 3, 4].

A WindScanner system consists of two or more spatially separated scanners (short- or long-range WindScanners) that are controlled by a central master computer, cf. Figure 1.

The first generations of the short and long-range WindScanners were built at DTU Risø campus in 2007 from modified prototypes of commercially available vertical profiling ZephIR lidars and WindCube 200S lidars, respectively.

During the Danish national infrastructure development project 2009-2013 WindScanner.dk DTU with the support from partners QinetiQ (UK), later ZephIRLidars.com and Leosphere (France) developed steerable scan heads, enabling the lidars to become steerable and synchronized scanning lidars.

In addition, DTU Wind Energy developed specific data acquisition and control software for both systems [5]. Each WindScanner measure the instantaneous line-of-sight wind components along a user-defined steerable scanning trajectory.

The 3D short-range WindScanner systems are built from three continuous-wave lidars and the measurements of the line-of-sight wind components are synchronized via a master computer connected to the WindScanners via an optic fiber network. They generate high-frequency sampling of the line-of-sight wind speed (up to 400 Hz) from spectral Doppler shift measurements scanned in the atmospheric flow with variable probe length, in the range between 0.25 m at the shortest 10 m measurement range and with up to 30 m resolution at their longest measurement range (300 m).

The long-range WindScanners are beam-steered pulsed lidars and have larger but fixed probe length (minimum 30 m) [6]. Long-range WindScanners measurement frequency is typically 1 Hz. However, they can retrieve line-of-sight measurements from a large number of ranges along their line-of-sight path. The long-range WindScanner systems are synchronized with the master computer using 3G network [5].

The maximum range of the biggest, a WindCube 400S based long-range WindScanner is at present about 8 km as observed during the RUNE 2016 offshore experiment [7].

The long-range WindScanner systems are primarily intended for measurements of 2D mean flow fields over a larger area while the short-range WindScanners can measure 3D wind fields with high spatial and temporal resolution in smaller probe volumes, hence enabling scanning of atmospheric small-scale 3D turbulence structures including coherent structures.

3. 2D Windscanner measurements performed on wind turbines, buildings and bridges

Adhering to the primary objectives of the WindScanners, a detailed 3D wind field inflow study on a wind turbine was performed at DTU Risø campus in 2015, focusing on the 3D inflow velocity fields in front of a Vestas V27 turbine [8].

Furthermore, detailed inflow and wake studies were performed on a horizontal axis wind turbine in the induction zone and in the wake of a NEG 550 kW Nordtank wind turbine, also at DTU Risø Campus [9, 10].

Multiple wind lidars also find applications in civil engineering, where they, for instance, hold a potential for studies of two-point statistics of wind turbulence. The coherence is of particular interest since the spatial correlation of wind gusts are of fundamental importance for estimating the total wind load on large structures such as long-span suspensions bridges and wind turbine rotor blades. In the following, we review applications where WindScanners have been used with focus on bridges, wind breaks, urban canopies and offshore applications.

4. Inflow and wake studies around a suspension bridge (Lysefjordbrua) 2014

Two synchronized short-range WindScanner were installed on the bridge in the Lysefjord near Stavanger in Norway during a one-week intensive measurement campaign in May 2014 with the purpose to measure 2D wind field inflow and wake wind fields and coherence of the along- and across-wind velocity components as illustrated in Figures 2-5.

Wind records obtained by five sonic anemometers mounted on the West side of the bridge were used as reference data. Single- and two-point statistics of wind turbulence were studied, with special emphasis on the root-coherence and the co-coherence of turbulence. A good agreement was observed between data obtained by the sonic anemometers and the lidars.

The bridge study has evaluated the potential of the WindScanner wind lidar technology for full-scale, outdoor monitoring in wind engineering. To date, the short-range WindScanner investigation has, together with the in-situ sonic anemometer measurements on the bridge, resulted in the following publications from the Lysefjordbrua measurement campaign in 2014:

(a) (b)

Figure 2. Panel (a): the Lysefjord Bridge is a suspension bridge which was equipped with two short-range WindScanners (two red circles) in May 2014. Panel (b): one of two short-range WindScanners installed on the Lysefjord Bridge providing synchronized scanning of the inflow and wake wind field in a two-dimensional plane at the 55 m bridge deck height.

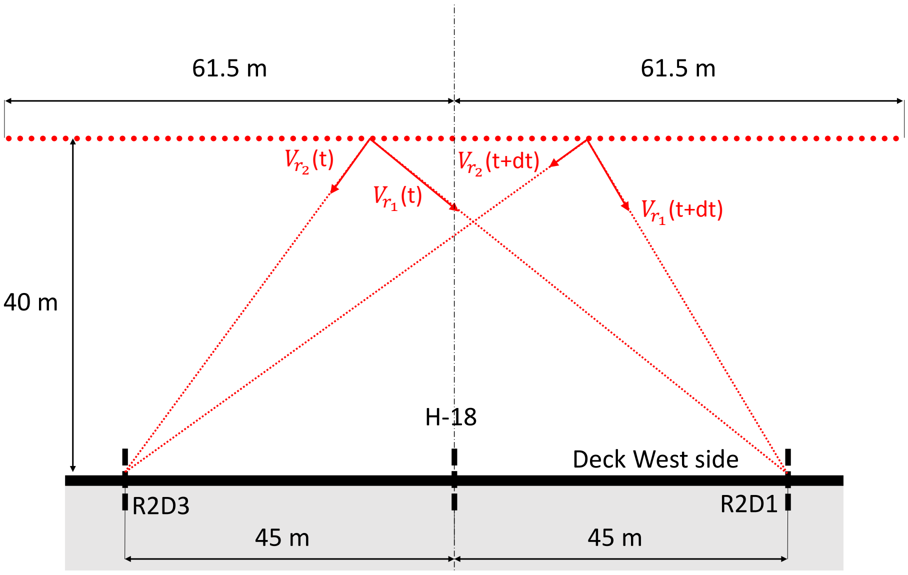


Figure 3. Top view of setup using two Short-range WindScanners at Lysefjordbrua, May 2014.

- Assessing the potential of a commercial pulsed lidar for wind characterisation at a bridge site [11]
- Application of short-range dual-Doppler lidars to evaluate the coherence of turbulence [12].
- Full-scale observation of the wake flow 40 m downstream of a suspension bridge deck [13].

Also the long-range WindScanners provide on- and offshore wind field measurements using synchronized scanning pulsed lidars as seen in Figure 5. Wind fields and wind statistics can be measured in the atmospheric boundary layer wind fields within scanning distances up to 5-8 km, of e.g.: the mean wind velocity, the velocity standard deviation, the turbulence length scales, the wind velocity component spectra and coherence [11, 14].

Recently measurements of mean flow and turbulence were performed over another wide

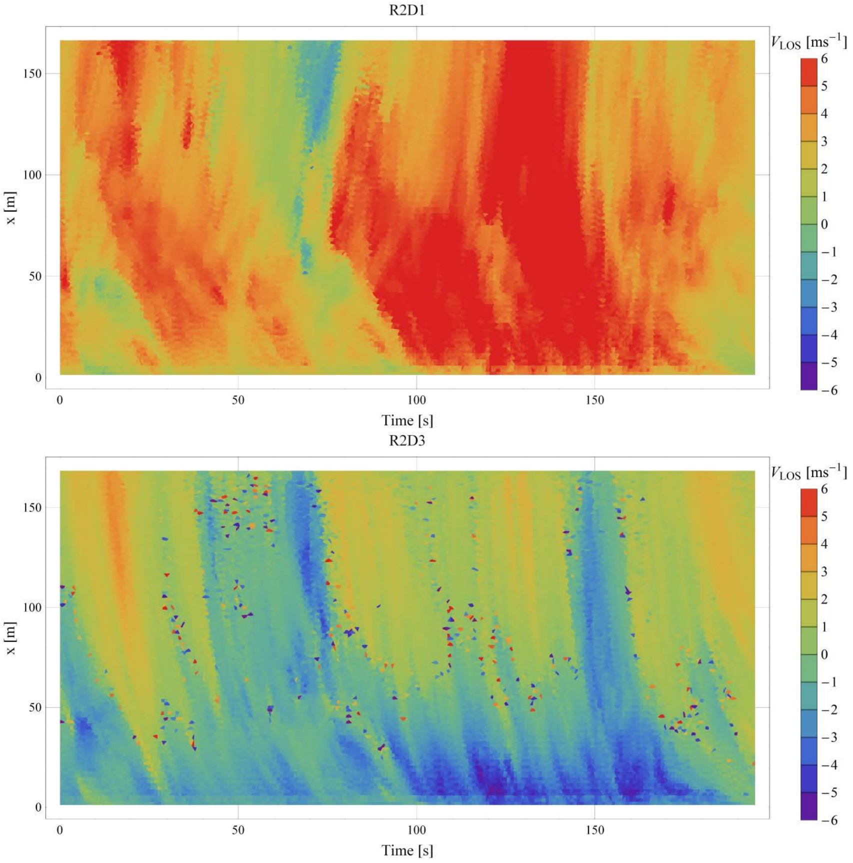


Figure 4. Coherent structures in the line-of-sight wind component measured along an upwind horizontal scan line perpendicular to the bridge by the short-range WindScanner R2D1 (top) and R2D3 (bottom) just after noon on 2014-05-22.

Figure 5. A long-range WindScanner operated by Christian Mikkelsen Research (CMR) during the 2014 Lysefjord bridge measurement campaign.

Norwegian Fjord (Bjørnafjord) using three of DTU Wind Energy developed trajectory-coordinated and synchronized long-range WindScanner lidar systems [14].

5. 3D WindScanner measurements of wakes behind a wind break fence

Short-range WindScanner based 3D wind measurements of the wake region behind a 3 m tall and 30 m long wind break was investigated experimentally in a full-scale experimental study at Risø campus in Denmark in 2015 [15]. The wake measurements were performed with three lidars scanning on a vertical plane downwind of the fence (Figures 6-7). Inflow conditions were monitored by a sonic anemometer installed in a nearby mast. In the free-stream aloft the fence the lidar measurements of the wind speed agreed well with the adjacent sonic anemometer. For near-neutral wind conditions the average inflow conditions were described by a logarithmic vertical mean wind profile.

Figure 6. The fence experimental set-up at DTU Risø campus test station, installed with three short-range WindScanner lidar instruments and a met mast.

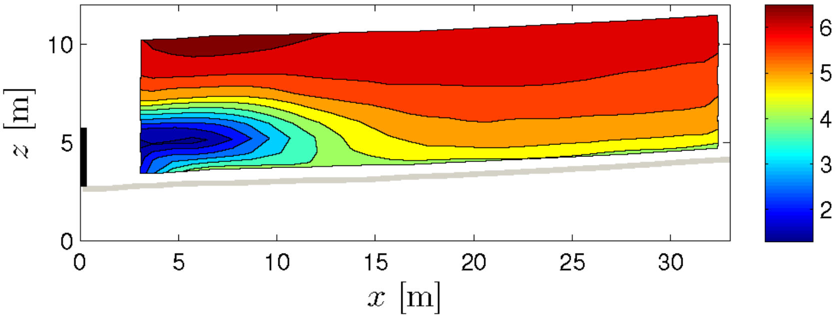


Figure 7. Example of WindScanner mean wind speed measurements of the wake behind the 3 m tall 30 m long solid wind break scanned in a vertical plane at the fence centerline during the period 10 March to 1 April 2015 when the fence was solid. Later, the fence was made porous and scanned again [15]. The grey line indicates the terrain height and the fence are 3 m tall and 30 m long. The measurements were taken in a vertical plane with wind coming almost perpendicular to the fence near the fence centerline.

Seven measurement cases were defined given the relative wind direction to the fence, the fence porosity, and the inflow conditions. The sheltering effect of the wind break was noticed to be highest below ≈ 1.46 fence heights. The sheltering effect was notably stronger during stable atmospheric conditions. For larger deviation of the mean wind direction from the direction normal to the fence, the effect of the shelter was lower.

For the case with the largest relative directions, no sheltering effect is observed in the far wake (distances $\gtrapprox 6$ fence heights downwind of the fence). Sometimes the wake could be observed at all downwind positions up to 11 fence heights downwind. Below the fence height, the porous fence has a lower impact on the flow close to the fence compared to the solid fence. Velocity profiles in the far wake converge onto each other using the self-preserving forms from two-dimensional wake analysis.

6. TrueWind 3D open air calibration stand

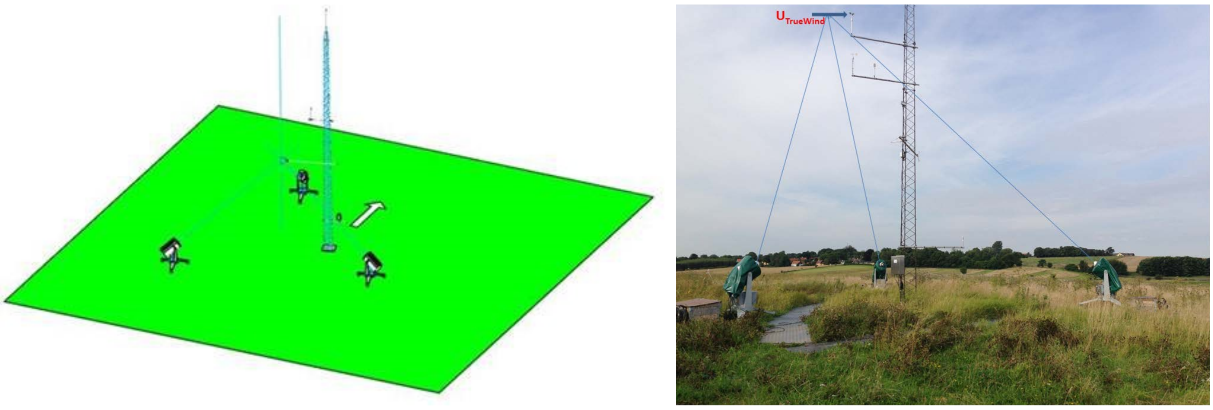
“TrueWind” is a permanent calibration facility using touchless remote sensing methodology to achieve hitherto unprecedented accuracy in wind measurements. To reduce uncertainty of anemometry in the wind energy sector TrueWind is designed to contribute to the advancement of wind metrology engineering, by:

(i) Improved cup anemometry.
(ii) Introduce coherent wind lidar measurement technology to wind tunnel measurement.
(iii) Provide accurate touchless calibrations in wind tunnels.

TrueWind aims to improve significantly the measurement accuracy of commercial cup anemometers used today in wind energy resource assessments, power performance measurements and field calibration of lidars.

Higher accuracy in wind tunnel calibrations has today already resulted from applying the TrueWind touchless remote sensing-based lidar instruments called Lidics (Figure 8). Lidics, similar to the WindScanners but without the scanning parts, measure Doppler shift in the laser radiation backscatter from aerosols via a laser beam stared and focused into a small sounding volume in the wind field.

TrueWind as a remote sensing based wind engineering calibration facility address the objectives delineated in: EU TPWIND - Wind Condition activities addressing advanced measurement



(a) (b)

Figure 8. Panel (a): Permanent TrueWind Calibration Stand at DTU Risø campus Schematic setup. panel (b): TrueWind 3D open air touchless calibrations stand for calibration of cup anemometers and other sensors Oct. 2017.

techniques including remote sensing. (`www.windplatform.eu`).

7. Scanning of wakes from scaled wind turbines in wind tunnel

Two synchronized short-range WindScanners were measuring the wakes behind scaled wind turbines installed in the boundary-layer wind tunnel at Politecnico di Milano (Figure 9) in January 2016 [16].

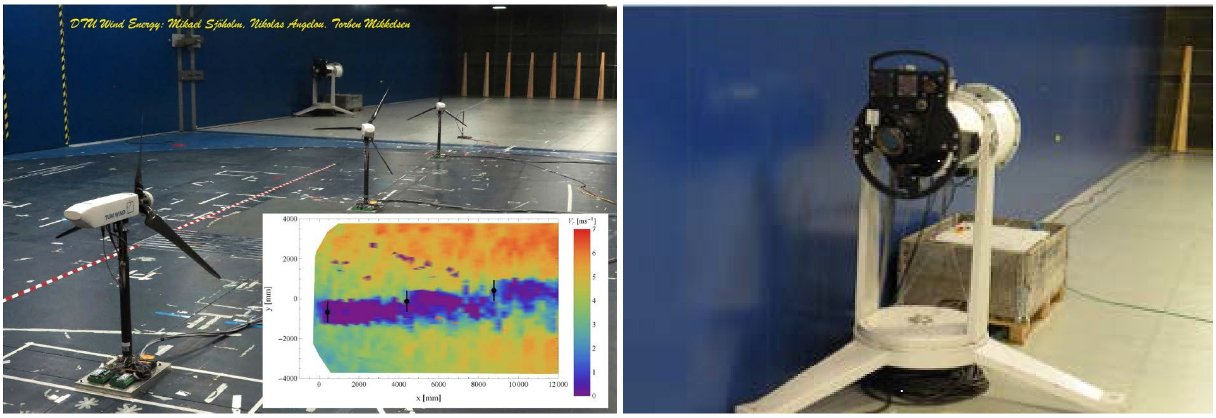
This research combines wind tunnel experiments with scaled wind turbine models and remote-sensing short-range WindScanner lidar techniques. In this measurement campaign the wind tunnel of the Polytechnic University of Milan was equipped with three wind turbine models and two short-range WindScanner lidars to demonstrate the benefits of lidar in such experimental surroundings.

The WindScanners provided 2D area scans within seconds to minutes, depending on the complexity of the scan pattern, without disturbing the flow. For the initial validation, WindScanner staring mode measurements were compared to hot wire probes commonly used in wind tunnels.

Hub height 2D horizontal area scans as well as wake profiles were measured (Figures 10-11). Compared to hot wire probes the lidars have larger measurement probe volumes and also some loss of measurements due to the moving blades, but the benefits include high flexibility in conducting both point measurements and area scans, in addition to having the benefit of providing touchless undisturbed 2D flow field measurements. The research campaign in 2016 confirmed for the first time a high potential for using short-range WindScanners for mapping of detailed high-resolution flow structures inside a wind tunnel.

The overall objective of applying WindScanners in the wind tunnel was to measure the flow field and, in particular, how the wind turbine wakes interact in case of scaled models in a boundary-layer wind tunnel.

A similar yaw control wake study using a DTU SpinnerLidar has also been investigated in a measurement campaign in 2016- 2017 behind a full-scale V27 wind turbine operated at the Sandia NL test site SWIFT [17].



(a) (b)

Figure 9. Panel (a): Wake measurements from three scaled wind turbines by two synchronized WindScanners installed in the wind tunnel at Politecnico di Milano January 2016. The inserted figure shows the mean wind field in a horizontal plane at hub height. The scaled turbines are represented by the black bars. In this figure, the turbines are not yawed. Panel (b): One of the two (R2D3) short-range WindScanners installed in the PoliMi boundary layer wind tunnel.

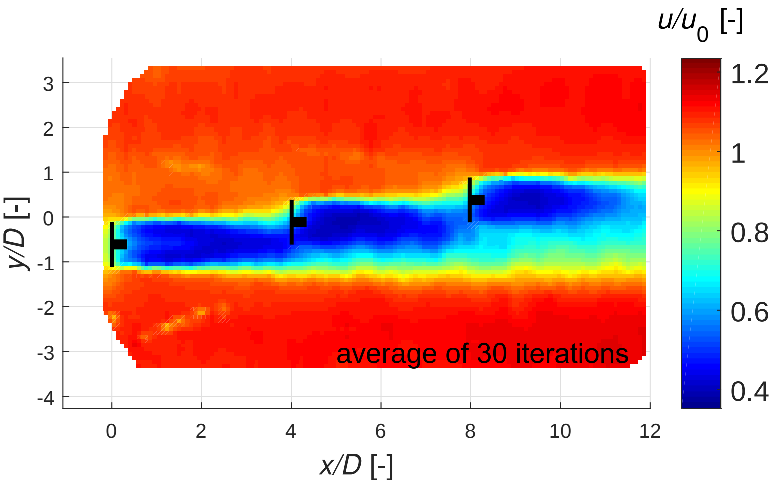


Figure 10. 2D horizontal scan of the mean wind field at the hub height showing the combined wakes from the three scaled turbines aligned without yaw from the mean wind direction.

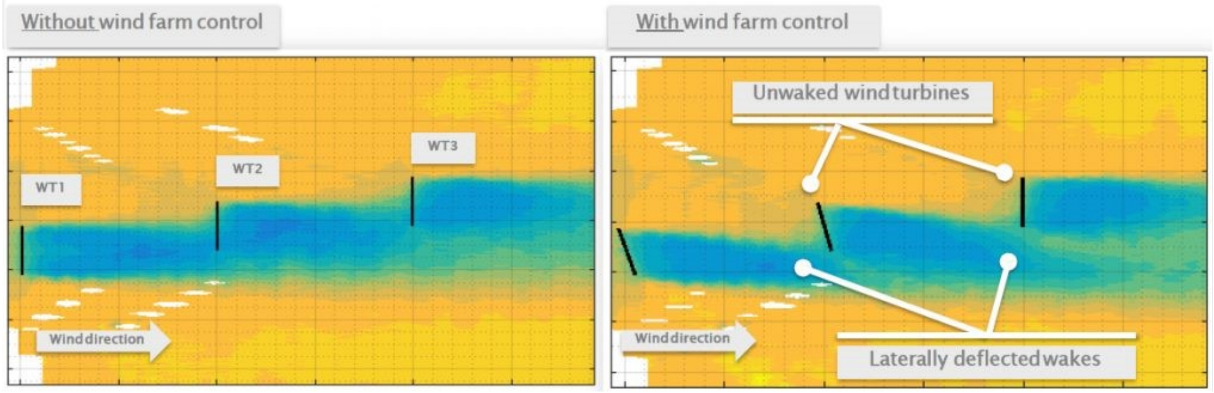


Figure 11. WindScanner measurements of controlled wake steering in the PoliMi Wind tunnel by two WindScanners. The wake field is similar to the setting in Figure 14 above; however the two forefront turbines have on purpose been yawed to steer their wakes around the 2. and 3. turbine in the row [16, 18].

8. Urban street canyon windscanner measurements

For research into detailed wind flow circulation and turbulence coherent structures in urban environment we are also planning to engage the short-range WindScanner measurement methodology with synchronized scanning in an open and full scale urban street canyon study to be conducted in collaboration with the University of Aarhus as part of Danish WindScanner node of the European WindScanner.eu research infrastructure, probably during the year 2019.

From an installation in the ground or aloft in a street canyon the WindScanners can be operated to provide instantaneous velocity measurements of the 3D wind field in a pre-defined volume section of real-life street canyons with high spatial (< 1 m) and temporal (< 1 m) resolution (Figure 12).

Such measurements will enable detailed insight into the microscale flow and transport processes, including turbulence and aerosol concentrations, which then can be visualized, quantified, analyzed and be used for model evaluation as well.

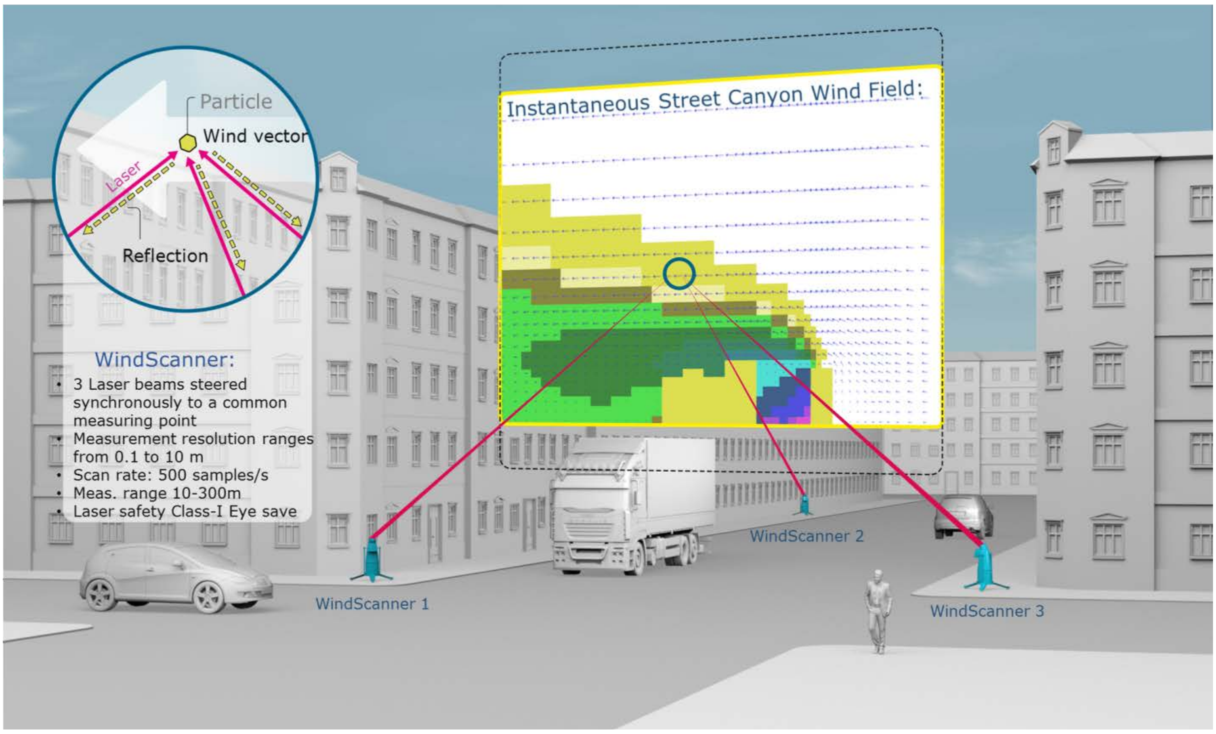


Figure 12. Design of a forthcoming Urban Street Canyon WindScanner experiment in Copenhagen. The figure illustrates how the instantaneous wind field in selected scan planes can be measured, by engaging three synchronized short-range WindScanners.

9. Measurements of inflow and wakes from WindScanners installed on wind turbines.

DTU has in parallel developed a special 2D WindScanner, a so-called SpinnerLidar, which is a single continuous wave lidar (built upon a DM ZephIR lidar) equipped with a DTU designed fixed rosette-pattern scan head, cf. Figure 13.

Installed on the nacelle or directly into the turbine spinner the SpinnerLidar can measure the incoming wind field in about 400 points per second upwind of a wind turbine distributed over a 2D circular scan plane in front of a turbine, and also for measurements of the wake characteristics behind a turbine, on- or offshore [19, 20, 17, 21].

The Danish node of the WindScanner.eu research infrastructure participated centrally in the first IRPWind open call on Joint Experiments 2016 with a joint DTU and ECN project about measurements of high-resolution full-scale wind fields scanned 60 m upwind in front of a 2.5 MW research wind turbine. The measurement campaign involved DTUs 3D WindScanner and a DTU SpinnerLidar.

The aim of the experimental activity was to establish a unique benchmark experiment for comparison of SpinnerLidar inflow measurements by at the same time operating a DTU developed high- resolution nacelle integrated 2D SpinnerLidar installed on the nacelle of the 2.5 MW N9 ECN Nordex 80 research wind turbine in concert with three ground-based profiling short range WindScanners (Figure 14). The benchmark is now available through an open-access e-science platform via the website `www.irpwind-scanflow.eu`.

An intensive measurement campaign was carried out from the 16th of December 2016 until the 20th of February 2017 comprising meteorological mast measurements, ground-based vertical profiling lidar measurements, turbine SCADA data, combined SpinnerLidar rosette scan

Figure 13. A DTU SpinnerLidar installed on the Nacelle of a Nordex 80 test turbine at the ECN test site in Holland during IRPWind ScanFlow 2016-2017 [22].

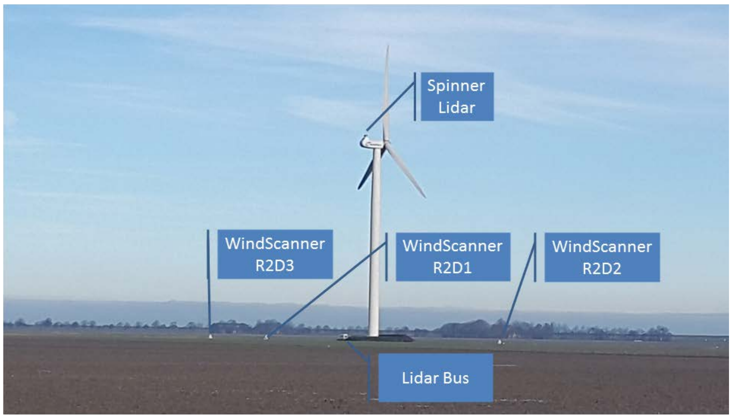


Figure 14. Experimental Setup at ECN during ScanFlow: One of the Nordex 80 tests Turbine at ECNs proving grounds were equipped with a Nacelle mounted forward-looking DTU SpinnerLidar. At the same time, three short-range WindScanners were operated on the ground for measurement of the vertical wind profile in front of the turbine at the same location where also the DTU SpinnerLidar scanned the inflow [22].

measurements and short-range WindScanner measurements.

The SpinnerLidar operated at ECN from December 16th to 28th, 2016 and from January 16th to February 16th, 2017. All other instruments except the ground-based WindScanners worked continuously. The short-range WindScanners have been measuring from mid-January 2017 to mid-February 2017 when the wind direction was appropriate, i.e. with wind coming in the sector between 185 and 245 degrees. These events occurred on January 29th, February 4th and 5th, 2017.

SpinnerLidars may also be installed on offshore turbines, either on the nacelle or on floating pontoons, cf. Figure 15, for measurement of in-situ power curves and for providing preview inflow for advanced feed-forward turbine control that enables load and tower bending reductions and thereby assist turbine operation offshore and extend the turbines lifetime.

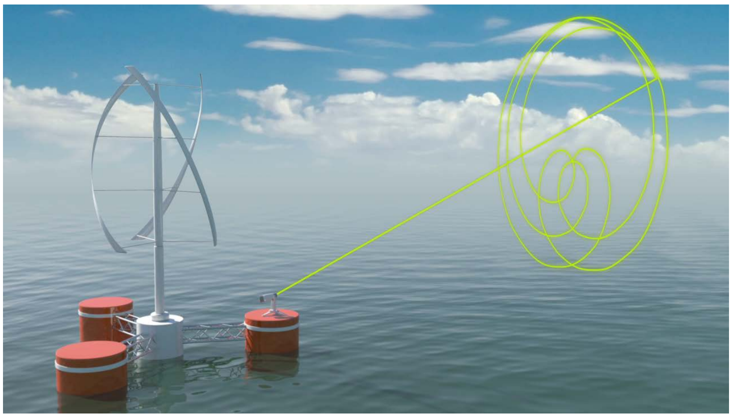


Figure 15. Offshore WindScanner concept: Rotor plane inflow scanned from of an offshore Vertical Axis Wind Turbine equipped with a DTU SpinnerLidar.

10. Conclusions

The paper has briefly reviewed the state-of-the-art of the WindScanner measurement technology with examples of uses for wind engineering applications at short measurement ranges. The technology is suitable for studying turbulent coherent structures of importance for investigation of flow patterns and dynamical loads on wind turbines, building structures and bridges and in relation to optimization of the location of, for example, wind farms and suspension bridges.

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