

WindScanner.eu - a new Remote Sensing Research Infrastructure for On- and Offshore Wind Energy

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ABSTRACT

A new remote sensing based research infrastructure for atmospheric boundary-layer wind and turbulence measurements named WindScanner have during the past three years been in its early phase of development at DTU Wind Energy in Denmark.

During the forthcoming three years the technology will be disseminated throughout Europe to pilot European wind energy research centers. The new research infrastructure will become an open source infrastructure that also invites collaboration with wind energy related atmospheric scientists and wind energy industry overseas.

Recent achievements with 3D WindScanners and spin-off innovation activity are described. The Danish WindScanner.dk research facility is build from new and fast-scanning remote sensing equipment spurred from achievements within fiber optics and telecommunication technologies. At the same time the wind energy society has demanded excessive 3D wind flow and ever taller wind profile measurements for the wind energy resource assessment studies on- and off shore of the future.

Today, hub heights on +5 MW wind turbines exceed the 100 m mark. At the Danish DTU test site Østerild testing is ongoing with a Siemens turbine with hub height 120 meters and a rotor diameter of 154 meters; hence its blade tips reaches almost 200 meters into the sky. The wind speed profiles over the rotor planes are consequently no longer representatively measured by a single cup anemometer at hub height from a nearby met-mast; power curve assessment as well as turbine control call for multi-height multi point measurement strategies of wind speed and wind shear within the turbines entire rotor plane.

The development of our new remote sensing-based WindScanner.dk facility as well as the first measurement results obtained to date are here presented, including a first wind lidar measurement of turbulence in complex terrain within an internal boundary layer developing behind an escarpment. Also measurements of wind speed and direction profiles, including turbulence, have been acquired from remote sensing to heights above 1.5 km above the ground.

Keywords: wind energy; wind conditions; turbulence measurements; 3D remote sensing; wind fields; scanning; wind lidars.

1. WINDSCANNER.EU - THE EUROPEAN WINDSCANNER FACILITY

1.1 Introduction

The “WindScanner Facility” is a distributed Research Infrastructure facility (RI) that was first conceived at DTU Wind Energy during 2009-2012 and which will next be established throughout Europe, following a preparatory phase in 2012-2015.

The European WindScanner facility will be designed for pan-European dissemination and construction ultimo 2015 and will start operation in 2016. WindScanner is a unique new innovative remote sensing-based research facility capable of providing new fundamental knowledge about the detailed three-dimensional atmospheric wind flow and turbulence around huge wind turbines. This knowledge will, we believe, result in more efficient, stronger, smarter and lighter wind turbines in the future.

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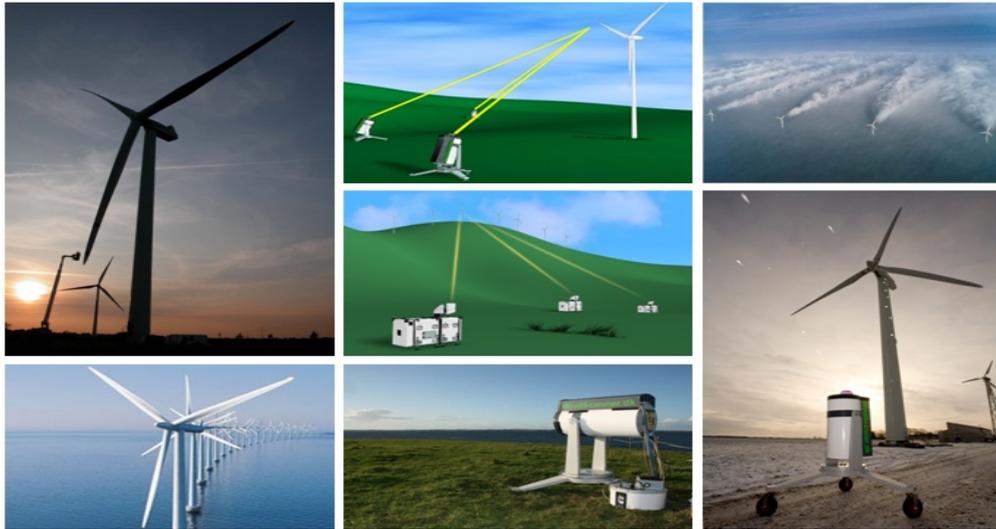


Figure 1: The DTU Wind Energy Department is presently engaged with the development and testing of short-range (10-200 m) and long-range (100 - 5000 m) 3D scanning wind lidar systems for detailed surface and PBL research on- and offshore.
www.windscanner.dk

The now starting European dissemination of the facility, WindScanner.eu, will be designed and prepared during its Preparation Phase (PP) in fulfillment of the requirements of a European center of excellence embedded within organizations and research partners from leading European Energy Research Alliance (EERA) research institutions, education and innovation organizations.

1.2 Concept and objectives: WindScanner.eu - The European WindScanner Facility

The European Strategy Forum on Research Infrastructures (ESFRI) has as mission to coordinate top-class European research infrastructures. The ESFRI roadmap registers the need for joint European research infrastructures over the next 10-20 years. Following the EU's 2009 call for proposals within the area of sustainable energy, RI WindScanner.eu was adopted in the official EU ESFRI's roadmap in November 2010.

The role of the now starting WindScanner.eu preparatory phase (PP) 2012-2015 is to provide catalytic and leveraging support towards the construction of the facility, in order to bring the project to the level of legal, organizational, technical and financial maturity required to establish and operate the facility by 2016 onwards. The operational European WindScanner Facility – once established - will become a truly European distributed and mobile Research Infrastructure (RI) that integrate and upgrade already existing major wind energy and wind turbine test centers and test sites in Europe. The new RI will ensure coordination and upgrading of the European wind Energy research facilities with state-of-the-art WindScanner equipment that we believe will be instrumental for Europe in retaining its competitiveness within wind energy. The European added value, scientific and technological quality, and the impact for innovation in Europe were previously acknowledged by the inclusion of the WindScanner Facility in the 2010 update of the ESFRI Roadmap for Europe's forthcoming RIs. The new WindScanner RI will enhance technology development and lead to new scientific and innovative opportunities and thereby contribute to the realization of the European Research Area.

The overall concept of the new WindScanner PP project can be summarized as a coordinated and joint European further development and dissemination of the already established Danish [WindScanner.dk](http://www.windscanner.dk) facility in a network between distributed WindScanner research and demonstration nodes embedded within leading European energy research organizations. The participants are all partners of the European Energy Research Alliance (EERA) and the WindScanner vision is to develop a European RI that underpins the EERA Joint Programme on Wind Energy. The establishment of the facility requires an unprecedented joint effort with highly dedicated trained personnel and mobile wind profilers and remote sensing based WindScanner instrumentation. This is a technical and economically substantial task that requires a Pan-European approach including hardware, user-programmes, joint research and innovation activities, data exchange, and joint training and exchange programmes for scientific-technical staff of the various nodes.

1.3 Structure of WindScanner.eu

The structure of the WindScanner.eu RI facility - once established in 2016 - will include the following elements:

- Anticipated 6-8 new partner nodes equipped with new and WindScanner PP-designed and constructed WindScanners deployed to existing or newly planned test facilities all over Europe, reflecting the objective of maximizing innovation impacts and the need to distribute the facility for different climate conditions and terrains.
- A coordinated experimental research programme for large European-level concerted wind energy measurement campaigns based on key contributions from WindScanners. This leads to the creation of a comprehensive database of wind data from potential wind energy sites, which is instrumental for researchers, modelers, wind turbine manufacturers and wind energy developers. Indeed, these all need to acquire detailed and site-specific information on wind condition (3D wind and turbulence measurements) from on- and offshore prior to turbines are designed, selected and installed. Based on this new information, modeling of local flow conditions will be improved; wind turbines efficiency will be optimized, and life time extended while costs of wind energy being reduced.
- The establishment of a central “WindScanner.eu hub” with functionality to disseminate and service the instrumentation, handle the data flow and data management, hosting servers, hosting of websites, administrative office, training of technicians and researchers who will operate the WindScanners, training of users, etc. The [WindScanner.eu](#) central hub will be established at DTU Wind Energy, located at DTU Risø Campus, in Denmark.

An operational WindScanner.eu RI will underpin and enable the EERA Joint Programming on Wind Energy and, among others, its research activities on remote sensing based mapping of regional wind resources and local wind conditions etc.

The European WindScanner Facility will be coordinated by DTU Wind Energy - Technical University of Denmark with 10 partners from 6 European Countries (Denmark, Germany, Greece, the Netherlands, Norway and Portugal). The projects' PP started on 1 October 2012 and ends ultimo 2015.

As a new EU FP7 supported activity the WindScanner.eu PP Project will develop a detailed technical design and budget, and look into different financing models and prepare and initiate discussions with the EERA partners and EU Member States. The exact nature of each of the nodes in the RI will need to be identified and analyzed. At national level, WindScanner.eu is already included on the Danish Roadmap for Research Infrastructures 2011 onwards.

Different Governance structure models will be investigated in the ESFRI PP project. The facility will be distributed to 6-7 nodes throughout Europe in line with the ESFRI definition.

The biggest challenge during the preparation phase will inevitably be to secure the necessary national funding for the constructing phase 2016 for establishment of the proposed new 6-7 national nodes and the running cost of the WindScanner facility at the European nodes. Several other issues like choice of governance model, handling of IRP, and open access will also be challenging, but the WindScanner PP project has been designed to deal with this.

The choice of site for hosting the WindScanner facilities is not an issue due to the RI's distributed nature. The European WindScanner will be distributed, so all interested and committed countries have the possibility to create a national node. The design and location still needs to be specified nationally and between the partners. If not mitigated some technical housing difficulties is foreseen regarding national WindScanner installations or buildings at the nodal host facilities. The WindScanner.eu's central office and technological repository and distribution centre will be established at the Wind Energy Department at DTU, Denmark.

Major development and technical problems are not foreseen during the construction phase because already the prototype system WindScanner.dk exists and is pre-operational (Sep 2012). Some minor technical innovations are still envisioned, e.g. regarding range resolution, but they will be addressed in the PP project.

During the next 3 years, workshops arranged by e.g. EU ESFRI for exchange of experience of similar PP projects are envisioned. Also ESFRI's support is particularly important in establishing organizational and legal issues. As a newcomer to the ESFRI family the WindScanner RI facility is very open and interested in collaborating with similar, distributed facilities already existing in PP phase or in operation.

2. THE DANISH NATIONAL RESEARCH INFRASTRUCTURE WINDSCANNER.DK

Today, one of the scientific quests for wind energy research is to measure and understand the three-dimensional and time varying wind field as it passes through and interacts with the huge rotor of a modern wind turbine. Using traditional wind measurement devices such as anemometers mounted on meteorological masts, it is practically impossible to acquire the full three-dimensional (3D) wind information in a huge rotor plane. Our present comprehension of the turbulent wind flow and its interaction with large scale wind turbines is correspondingly still today limited.

2.1 Wind Remote Sensing Measurement Technology

Following the telecom revolution at the turn of the Millennium, new and small all-fibre based remote wind sensing devices, so-called wind lidars, emerged on the wind energy scene. During the last decade scientists and engineers have turned this measurement technology into the benefit for wind energy remote sensing research. At DTU Wind Energy the methodology behind multi-lidar based and coordinated beam steered WindScanners was earlier developed [1].

Due to their 3D remote sensing wind measurement methodology integrated with controllable scanning systems, WindScanners can today provide detailed full-scale 3D real atmospheric wind and turbulence measurements with lower uncertainty than achievable by down scaled wind tunnel testing or computer modeling [2; 3;4].

Scientifically, the objective for the new European WindScanner Facility is to establish and jointly operate a new pan-European WindScanners facility for wind and turbulence measurements in relation to wind energy research and development. In addition WindScanner.eu will, through joint data analysis and data management, enable detailed 3D wind scanning and mapping of the flow structures within and around today's huge individual wind turbines, turbine arrays, on- and offshore, for local assessment of wind conditions and wind resources. In addition, the Consortium beneficiaries trust the WindScanner Facility will continue to spur new innovative products and remote sensing methodologies developed and operated for integration with wind turbines for enhanced wind turbine steering and control.

The wind measurement methodology exploits recent advances from technological developments within laser-based remote sensing wind measurement techniques (wind lidars combined with beam-steerable scanners). Prototype WindScanners, both for short-range and for long-range applications, have already been designed and the first prototypes have been constructed in connection with the build-up and establishment of a first new Danish national RI based on remote sensing of wind (Cf. www.windscanner.dk). DTU Wind Energy in Denmark, in bilateral collaboration with ForWind OL Oldenburg, has already during 2009-2011 worked on the establishment of new national RIs for remote sensing-based wind, flow and turbulence measurements around large operating wind turbines installed onshore and offshore. In Denmark, the national infrastructure activity is called "WindScanner.dk", in Germany it is referred to as "Multi-Lidar".

RI Windscanner.dk set out in 2009 as a Danish national infrastructure project with the aim to design and apply remote sensing of wind within a research infrastructure able to provide detailed and high spatial and temporal resolution measurements of wind and turbulence around large turbines on- and offshore, based on new and hitherto unprecedented remote sensing wind detection technology (wind lidars).

For joint European infrastructure development within ESFRI RI, mobile wind scanners for three dimensional measurements of wind and turbulence structures have to date therefore been developed and constructed as part of WindScanner.dk. Today, at DTU Wind Energy, we possess and operate via a joint beam steering control system three short-range (<250 m) and three long-range (<5 km) wind scanners.

Also specific WindScanner systems are developed for integration and installation on wind turbines for improved turbine management, control and operation of wind turbines [5; 6]; see also below spin-off innovation products.

As mentioned above WindScanner.dk started in 2009 and it is now entering its full operational phase by servicing wind energy research projects and wind industry. The project will come to an end during 2013, but the activity as a research facility will be continued within the just started (October 1 2012) windscanner.eu infrastructure preparation phase.

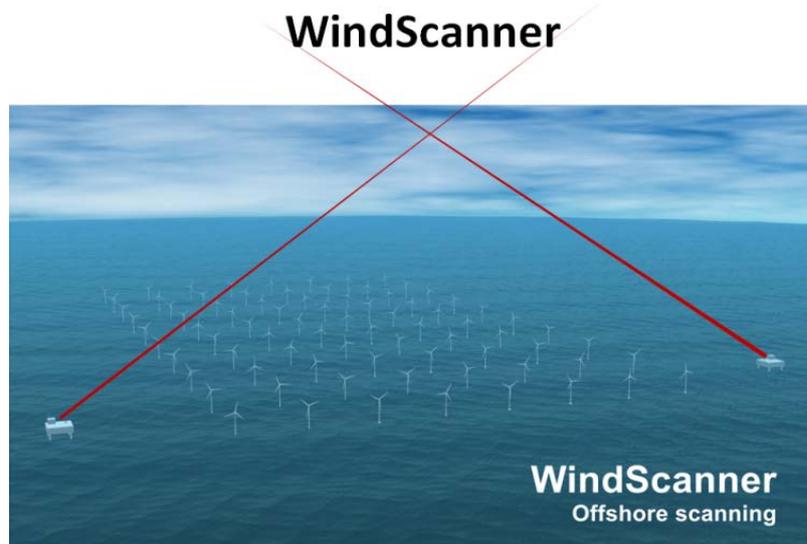


Figure 2: Two long-range WindScanners in operation offshore (concept).

The design, build, test and construction of the first three short-range WindScanners able to scan using three independent steerable continuous wave lidar beams were developed and tested during 2010-2011, and from 2011 applied to several full-scale measurement campaigns at the Danish RI WindScanner.dk infrastructure at DTU Wind Energy in Denmark.

In parallel with the short-range WindScanner.dk development and testing, DTU Wind Energy in 2011 together with the Danish SME technology consultant IPU and the French lidar manufacturer Leosphere engaged in the development of a pulsed long-range three-axis WindScanner system. Each long-range WindScanner is equipped with a two-axis mirror-based steerable scan head integrated with a new-designed and range-enhanced power full WindCube200 pulsed wind lidar, with a measurement range under normal conditions of up to 6 - 10 km, see Fig.4. Development and testing of hardware and software for jointly steering and controlling these long-range wind scanners is also already in progress in collaboration between the partners DTU Wind, ForWind Uni Oldenburg and Leosphere.

Long-range WindScanners have also been deployed by Leosphere for other applications such as air port safety and measurements of meteorological boundary-layer structures including low level jets. The long-range prototypes have furthermore been introduced in the market as a standalone wind scanner available from Leosphere as full-sky beam-steerable wind profiler (Windcube200S). Figure 2 shows an artist's view of offshore wind scanning by two long-range wind lidars.

Although the technological development in the commercial market has opened up new ways of measuring the wind conditions and turbulent flow, significant efforts and R&D development work still need to be performed within the new WindScanner PP project in order to integrate the new remote sensing instruments in the European WindScanner Facility for true 3D scanning.

Technologically, wind lidar remote sensing has come a long way already during the past decade. Development, integration and deployment of wind Lidar technology is now progressing very rapidly within the wind energy society, cf. for example the many lidar papers presented during the EWEA 2012 International conference on Wind Energy held in Copenhagen 16-19 April 2012.

Today wind Lidars, reliable as they have become, do hold huge technological potential to become integral parts in wind energy research and development. We believe that WindScanner spurred remote sensing spin-off products are soon to become integral parts on the huge turbines of tomorrow, both as new ones and as OEM equipment for integration and possibly also retrofitted on many existing turbines, either permanently for enhanced operation or for in-situ adjustments and trimming, as well as progressively appearing as endemic in other fields [5].

Lead by stimulus from the our upcoming PP WindScanner.eu facility, the wind energy society and industry will soon, we believe, see many new applications and activities spurred from recent progress within lidar remote sensing, not just

within wind condition assessment, resource assessment, and active control, but also more widely in meteorological boundary layer field studies of e.g. low level jets, boundary-layer height determination, etc.

It is therefore to be expected that the joint efforts and resources to be generated and mobilized with the establishment of the new European WindScanner.eu RI facility will continue to spur innovation and improved wind turbine design and new pre-vision based control strategies, for the benefit of wind turbine manufacturers, including a large group of SME suppliers to the wind power industry. Moreover, we envision that the forthcoming new WindScanner.eu Facility will represent a paradigm shift and a significant upgrade and supplement to the existing wind tunnel-based wind turbine testing facilities, and thus provide lasting advantages to the forthcoming European and worldwide wind energy research and development.

2.2 Short-range WindScanners

To date DTU Wind Energy operates three short-range wind scanners, built upon three modified continuous wave ZephIR wind lidars provided by Natural Power U.K. All three short-range WindScanners have been equipped with three individual dual-axis steerable 2D prism-based scan heads, designed by IPU and manufactured from a DTU Wind Energy pending patent. Work is ongoing at DTU Wind Energy and surroundings to calibrate and test the capabilities of the performance of these new short range wind scanners. The first wind and turbulence study with short-range wind scanners was performed during the spring 2011: “Six-beam” 3D turbulence profiling experiment, and “Small hut wind wake flow and turbulence visualization study”. Also a complex terrain flow over an escarpment at Bolund and a helicopter downwash wake measurement experiment was conducted with the short-range WindScanners in 2011 [2; 3; 4], see also Table 1.

2.3 Long-range WindScanners

With Leosphere, DTU Wind Energy has to date designed and manufactured three long-range wind scanner systems, built upon long-range wind LIDAR (type WLS70/WindCube upgraded to WLS200 (6- 10 km range) and in cooperation with the industrial design firm IPU DTU have designed, manufactured and integrated 2D mirror-based steerable scan heads. Software for management of long-range wind scanners is being developed. The first tests of the new long-range wind scanner was undertaken in Airports at Nice and Marseilles in France in April-May 2011, and is now continuing also at DTU Wind Energy in collaboration Leosphere, IPU and Uni Oldenburg.



Figure 3. Left: Short-range prism-based half-sky (π Sr) scanhead jointly developed by DTU Wind Energy IPU - Natural Power. Right: WindScanner R2D1.

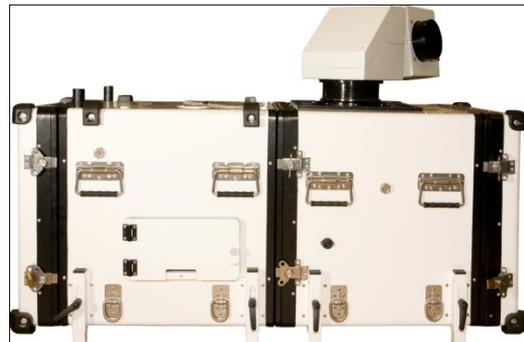


Figure 4. Long-range WindScanner (build from Leosphere WLS200 and equipped with a full-sky (2π Sr) - DTU Wind Energy – IPU- Leosphere jointly developed two-axis mirror-based scan head.

A single WindScanner can produce detailed maps of wind conditions at a wind farm covering several square kilometers. Developed by Risø DTU, the WindScanner consists of high-tech laser systems. It is a sophisticated research facility for studying wind and turbulence in connection with leading-edge research into wind energy, and can be packed into an ordinary van and taken wherever needed. The Risø WindScanner will, in collaboration with six European Energy Research Alliance (EERA) partners, be made available to EU’s sustainable energy research laboratories and companies via the European research infrastructures.

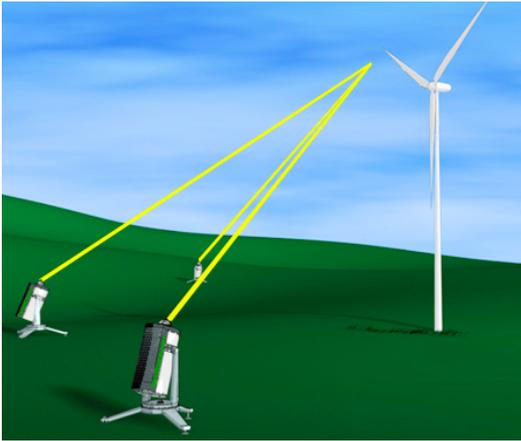


Figure 5. 3D Short-range (10-300 m) wind vector WindScanners at work (concept)



Figure 6. 3D Long-range (0.1-10 km) wind vector WindScanners at work (Concept)

Because wind is a three-dimensional quantity, three simultaneous measurements of the wind vector's three components are required to determine a given wind velocity vector at any point in space.

2.4 WindScanner.dk based measurement campaigns performed during 2011 - 2012

Wind field and turbulence measurement campaigns based on short and long--range WindScanners in 2011 and continued in 2012:

Table 1. WindScanner.dk measurement campaigns completed 2011 through Sep. 2012:	
Short-Range Task 2011.1 R2D1 (May 2011).	Six-beam 3D turbulence profiling experiment
Short-Range Task 2011.2 September R2D1 (Oct. 2011).	Small hut wind wake flow and turbulence visualization, and Bolund Hill internal boundary-layer recirculation zone wind flow study. The WindScanner team performed a 2D measurement of inflow over hill Bolund. Results were published at EWEA 2012 and at the biannual remote sensing conference ISARS 2012 in June in Boulder, USA and in Torque 2012, in Germany: Sjöholm et al. 2012 WindScanner.dk @ first measurements Mann et al. 2012 WindScanner.dk @ Bolund
Short-Range Task 2011.3 R2D1 & R2D2 (Dec. 2011).	Helicopter Downwash A full-scale 2D scanning measurement campaign performed with two simultaneously operated short-range WindScanner systems measured detailed down wash from a hovering rescue helicopter. Helicopter downwash from a hovering helicopter presented at ISARS Boulder 2012. Sjöholm et al. 2012 WindScanner.dk @ helicopter downwash
Short-Range task 2012.1 R2D1 (Feb. – May 2012)	DTU Risø Campus joint Neg-Micon 550 KW and V27 2D Wake measurements with R2D1 from rear of Neg-Micon 550 KW turbine

	nacelle.
Short-Range task 2012.2 R2D3 (June-August 2012)	Six beam covariance measurements of turbulence with R2D3 at DTU Risø Campus up against campus Risø permanent 123 meter Met-mast equipped with 3axis sonic anemometers.
Long-range task 2012.1 WLS200S Unit #2 & WLS200S Unit #3 (September 2012)	Laser beam steering resolution and repeatability testing (Long-range Unit #2 and #3).3X WLS200S long-range Wind lidars: To date we have in collaboration with industry partners Leosphere (F) and IPU (DK) designed and build three mirror-based full sky scan heads and integrated them with three long range pulsed wind lidars type WLS200 (Range 5 - 6 km). At DTU Wind Energy and we are presently operating with test tracking scan patterns when operated individual and in concert and we are testing their beam pointing stability, repeatability and scan pattern resolutions up against their design criteria's which are < 0.5 mRad.
Short-Range task 2012.4 R2D1&R2D2&R2D3	Windscanner.dk: 3D: Testing of all three short range WindScanners beam steered in concert (common steering of the three beams) at DTU Wind Energy in preparation of our first full 3D scan measurement campaign planned in October 2012.
WindScanner.dk scheduled measurement campaigns Oct. 2012 through 2013	
Short-Range X3 R2D1 & R2D2 & R2D3 October 2012	Three-dimensional wind vector test measurements with three short-range WindScanners - intercomparison with instruments (3D sonics) installed at 60 m and at 125 m height in the Campus Risø 125 m tall met tower.
Short-Range R2D1 & R2D2 & R2D3 Risø Campus NM550 Tjæreborg Enge -NM80 Wind Farm 2013 Spring	Dong Energy - 3D wind vector wake scanning experiments Site: Risø Campus and Tjæreborg Enge Collaboration with Dong Energy and AAU/ DTU regarding extreme wind load generated fatigue and load assessment on turbines in operation.
Short-range Wind Turbine Wake Measurements	DTU Risø Campus Neg-Micon 550 KW test turbine 2D Wake measurements with joint R2D1 from rear of turbine nacelle and "Scanning gray prototype". Continued from spring 2012
Short-range wind scanning of flow over escarpments	Collaboration with Oxford University, Department of Zoology, U.K. re studies of bird's aviation maneuvering performances during changing and turbulent wind flow environments.
3 X Short-range WindScanners	WindEEE Dome wind tunnel studies in collaboration with Canada Western University
3 X Short-range Wind Scanners	Texas Tech: Wakes in small scale V27 Wind Farm
Long-Range WLS200S Unit #1 & WLS200S Unit #2 & WLS200S Unit #3	Italian Research Council: Wind flow study within a coastal wind regime – 3D wind scanning and wind field experiment. Southern Italy, June 2013.

3. WINDSCANNER.EU CONSORTIUM AND PARTICIPANTS

3.1 WindScanner.eu Consortium

The partners in the new WindScanner.eu Preparatory Phase project are: DTU Wind (Denmark), Fraunhofer IWES (Germany), ECN (the Netherlands), ForWind (Germany), CENER (Spain), SINTEF (Norway), LNEG (Portugal), University of Porto (Portugal) and CRES (Greece). The project will be coordinated by DTU Wind Energy as hub.

Below is a short description of the existing and/or planned test facilities under consideration to be hosts of the various nodes in the WINDSCANNER.EU Facility, their variation regarding climate zones (subtropical to arctic, ocean to continental) and terrain types (e.g. open land, forest, hilly and mountainous, coastal and offshore).

Table 2. The European WindScanner.eu Facility: Design Features

1. The new PP WindScanner.eu project is an EERA embraced joint program on wind energy RI development sponsored by national research councils, Ministries, and the European Commission
2. WindScanners, being combinations of short or long-range devices can produce detailed maps of wind conditions in the wake of a single wind turbine or within an entire wind farm covering several square kilometers
3. WindScanners consist of high-tech laser systems for wind and turbulence measurements in connection with leading-edge research into wind energy
4. WindScanner will be available to EU sustainable energy research laboratories and companies
5. A new portable and distributed RI for wind energy research in the field
6. Available to EU sustainable energy research laboratories
7. The new PP WindScanner.eu research infrastructure development project is initiated in an EU FP7 supported and ESFRI road map assisted collaboration between seven European Energy Research Alliance (EERA) participants.
8. PP WindScanner.eu is an EERA joint program on wind energy RI development by
 - CENER (Spain)
 - CRES (Greece)
 - ECN (The Netherlands)
 - ForWind (Germany)
 - Fraunhofer IWES (Germany)
 - IPU (Denmark)
 - LNEG (Portugal)
 - SINTEF (Norway)
 - UPorto (Portugal)
9. Knowledge and experience with remote sensing scanned wind field measurements in 3dimensions disseminated via the EERA participants
10. WindScanner based lidars and their control software is to be jointly developed and scanning wind lidars are to be deployed regionally throughout Europe and beyond.
11. Wind lidars will be designed and constructed as handy and easy-deployable units transportable via ordinary vans for installation and operation wherever needed.

Table 3. WindScanner.eu: Nodes Regional wind clima and terrain features

1	Denmark	DTU Wind	Flat terrain wind turbine test station and offshore wind parks. Horns Rev I & II
2	Spain	CENER	Inland mountain wind turbine test station Wind tunnel test and measurements

3	The Netherlands	ECN	Full-scale research wind farm, scale research wind farm, offshore site with large turbines and offshore Met-masts
4	Greece	CRES	Coastal complex terrain
5	Germany	Fraunhofer IWES ForWind OL	Test site in forested hilly terrain, onshore sites with large (5 MW) turbines, offshore wind park Alpha Ventus, offshore test sites FINO 1-3 BARD1 and Baltic1 offshore wind farms Wind tunnel tests and measurements
6	Norway	SINTEF	Onshore test sites and deepwater offshore floating technology
7	Portugal	LNEG/INETI UPorto	Offshore and Highly complex terrains with high turbulence, intense stratification and strong complex mountain-valley breeze circulations

4. WINDSCANNER.DK GENERATED INNOVATION AND SPIN-OFF:

Wind turbines are preferably installed in areas where powerful winds are common and, if they are not optimally trimmed and aligned into the site-specific gales, they can be exposed to excess loads or even be destroyed.

By use of wind turbine integrated lidar products spurred from the ongoing WindScanner development and designed for mounting on the wind turbine nacelle, on top of the hub, integrated directly into the spinner, or even inside or outside on the blades, wind lidar innovation products have already today made it practically possible to obtain pre-vision and hence forecasting of the incoming wind gusts and shear.

Detailed monitoring of the upwind inflow conditions, in combination with new (under development) advanced feed-forward controllers, therefore opens for many new remote sensing devices as means to minimizing the loads and increasing the efficiency and hence the life-time of turbines and wind farms.

In 2009, a first Spinner mounted upwind scanning wind lidar was developed and tested spurred from the Danish national WindScanner.dk RI facility [6]. The first spinner-integrated wind lidar in form of a continuous wave (CW) conically-scanning ZephIR wind lidar was installed and operated remotely in the spinner of a large 80 m diameter, 59 m hub height, 2.3 MW Vestas NM80 turbine by DTU Wind Energy in collaboration with the company Natural Power. This, the World-first wind lidar integration in a rotating spinner, has now provided our research community with unimpeded previews and detailed measurements of the approaching wind fields from 100 m distance in front of the rotor plane [7].

4.1 SpinnerLidar

The existing Danish WindScanner.dk RI facility have already today spurred several new innovative ideas and remote sensing based products for wind energy research and development, and also for enhanced wind turbine control. E.g. new products developed and operated as wind lidars for direct integration in or on wind turbines for enhanced wind turbine steering and control is one example.

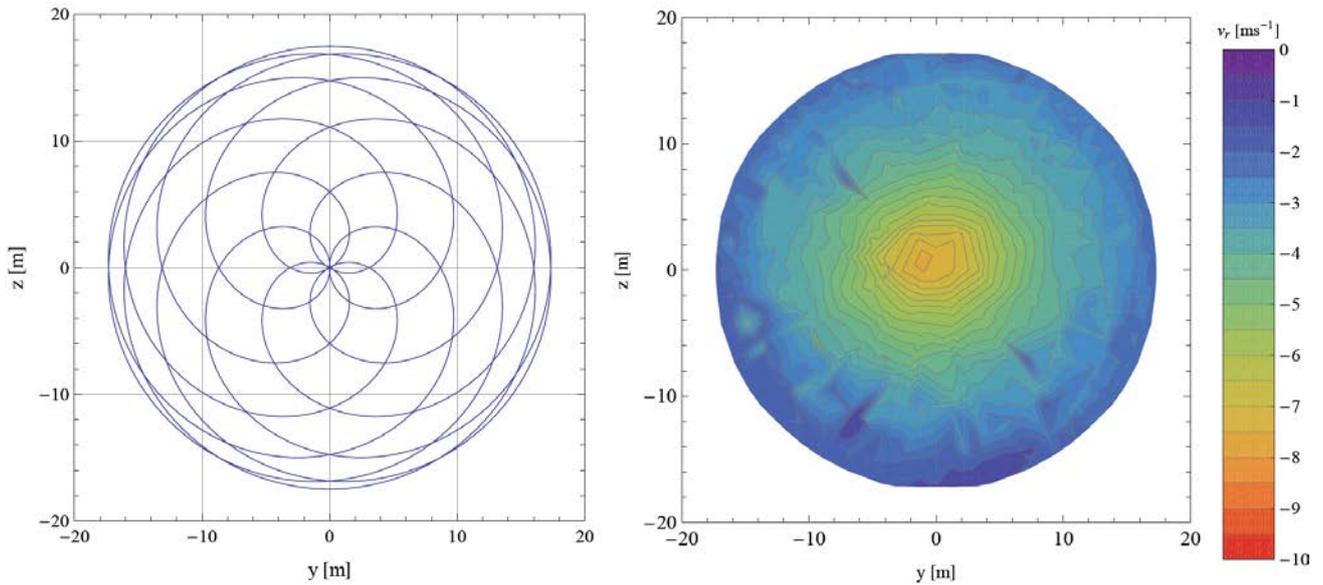


Figure 7. Example of a WindScanner (R2D1) wake scans measured downwind in the wake from the aft of the nacelle of a 38 meter tall NM 550 (38 m rotor diameter) test wind turbine installed at DTU Risø Campus. The applied scan pattern (left) where the laser beam is swept with a maximum deviation of +/- 60 degree in the two crosswind directions, subtend a solid angle of one Steradian (π). Simultaneously, up to 400 measurement points (left) was retrieved from the scanned wake area over time intervals as small as one second. The 5-min mean averaged wake deficit measured with a constant 20 meter focus distance is shown in the figure to the right.



Figure 8

First SpinnerLidar on display at EWEA 2012 in Copenhagen.

SpinnerLidar is a specific designed 2D “rotor scanning wind lidar for upwind inflow prevision and downwind wake measurements.

The 2D SpinnerLidar consist of a DTU Wind Energy invented and IPU designed two-axis prism-based scan head integrated on top of a new slim-design Control-ZephIR provided by Natural Power, U.K.

In joint bilateral collaboration with Natural Power (UK) and IPU (DK), DTU Wind Energy and ForWind, Uni-Oldenburg scientists in 2012 engaged in designing and construction of a fixed 2D “cone-filling” scan pattern for upwind scanning wind lidar, see Figure 7 and 8. This is one example of a WindScanner.dk derived innovation product, possibly with some market potential, because it provides prevision and hence lead time of rotor plane inflow for enhanced steering and control of the turbines. This new 2D scanning wind lidar is intended for forecasting of the entire rotor plane wind fields, to be combined and integrated with enhanced feed-forward control systems to be developed. In July – September 2012 the shown 2D cone-filling SpinnerLidar was installed and tested in the 2.3 MW NM80 test turbine at Tjæreborg Enge in western Denmark.

4.2 Rotor plane inflow measurements by a 2D scanning Spinner-integrated wind lidar:

The potential for wind turbine load reduction and also enhanced power performance optimization via advanced control strategies is today an active area within the wind energy load and control research community.

In particular, feed-forward control using upwind inflow measurements by lidar (light detection and ranging) remote sensing instruments has attracted an increasing interest during the last couple of years. So far the reported inflow measurements have been obtained from select measurement directions or on a circle in front of the turbine, which is not optimal in a complex inflow such as in the wakes of other turbines.

A specific 2D cone –filling laser beam scanner was developed by DTU Wind Energy Department within the Danish advanced Technology Program (HTF) in collaboration with IPU, Denmark and Natural Power, U.K. in order to achieve full two-dimensional radial inflow measurements. The 2D scan head, cf. Figure 8, is consequently based on two co-rotating prisms that each deviate the beam by 15 degrees. The resulting 2D scan pattern is space filling with a full opening angle of 30 degrees on an upwind spherical surface, cf. Figure 7.

The scanner design has sprung off the similar 2D steerable scan head on the three short-range WindScanners “R2D1; R2D2 and R2D3” earlier developed by the same group. However, for the SpinnerLidar only a single drive is required due to a fixed gearing between the two prism axes in order to achieve a reliable and space-filling scan pattern implementation for turbine control applications.

During the test and measurement period July 13 through September 2012 we successfully installed and tested this new proof-of-concept SpinnerLidar scanner in a full-scale field campaign, where the SpinnerLidar scanned upwind from its position inside the rotating spinner of the operating NM80 turbine with 59 m hub height and 80 m rotor diameter, cf. the first ever measurements presented in Figure 9.

The scan head was powered by an integrated slim-design Control-ZephIR 300 lidar modified to stream measured Doppler spectra at a rate selectable between 50 and 500 Doppler measurements per second. The scan time corresponding to a full completion of two-dimensional radial inflow with 400 measurement points distributed over the translated rotor plane is presently performed during a two-second time interval. The measurement positions are determined from the instantaneous positions of the two rotating wedge-shaped optical prisms and the instantaneous angular position of the instrument of the turbine spinner as measured by a SpinnerLidar integrated accelerometer.

Turbine parameters as well as wind measurements at a nearby met mast were logged and root-bending moments in the blades have been acquired by an optical fiber-based strain measurement system installed by Bosch GmbH, Stuttgart.

The two-dimensional upwind radial wind speed scanning of inflow in the entire rotor plane now invites research and investigations as to which properties in the (e.g.: shear, veer, gusts, wakes etc.) is the most important phenomenon to be extracted, and it also opens discussions on how this information might best be used in future advanced feed-forward wind turbine control algorithms on and offshore, over flat areas or in complex terrain etc.



Figure 9.

Dr. Sjöholm DTU Wind Energy presents the first-ever SpinnerLidar 2D scanned inflow measured 100 m upwind in the rotor plane of an operating NM80 80 m Ø 2.3 MW test turbine belonging to Danish Dong Energy.

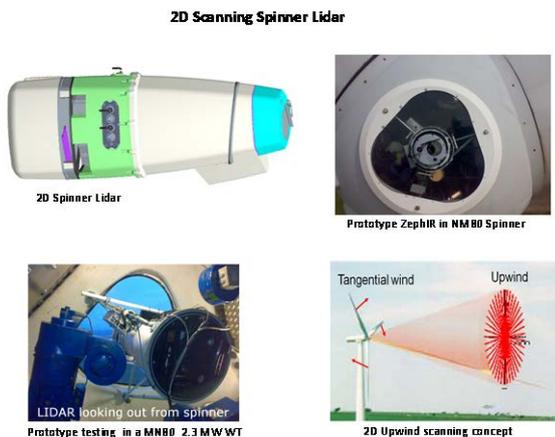
The colored “flying pancake” presents the SpinnerLidars grid interpolated measured inflow by use of the same scan pattern shown in Figure 3.

The highest wind speed (red colored part is measured near the top of the rotor plane while and lowest inflow (blue part represents measured inflow near the bottom of the 80 m Ø rotor plane.

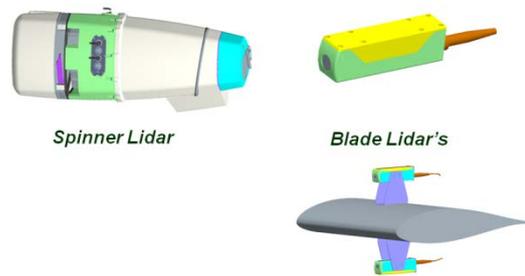
The 2D inflow was scanned during a 8 s scanning period.

Further new remote sensing wind measurement methodologies and test equipment is also envisioned to be developed within the newly started PP WindScanner.eu research facility build up in a similar way. The spin-off is envisioned to spur new product innovation and spin off products that can be foreseen to impact on European wind energy manufactures and SME supplier’s forthcoming competitive wind energy products.

For instance, we envision that the joint WindScanner.eu collaboration will boost European entrepreneurship in wind energy through remote sensing-based enhanced wind turbine control; reducing blade fatigue and turbine wear, and even maybe provide enhanced power.



WindScanner Design and Innovation Process: Spinner Lidar and Blade-integrated Lidar's (LIDIC's)



WindScanner Components - Aesthetics design

IPU

Figure 10

Spinner lidar with a innovative patented 2D scan head

Small fiber-fed telescopes (LIDIC's) for blade integration.



**Figure 11. Left: SpinnerLidar during installation in Dong Energy's NM80 Test Turbine at Tjæreborg Enge (July 2012)
Right: NM80 2.3 MW Test Turbine at Tjæreborg Enge, Jutland, Denmark owned by Dong Energy.**

4.3 Blade-integrated wind lidars

Two small all fibre-fed lidar telescope units with 1" optics were mounted on either side of one blade of a Vestas NM80 turbine 15 m from the spinner and driven via all-fibre optical cables from a new design slim pod ZephIR 300 continuous-wave Doppler lidar from Natural Power, UK

The ZephIR lidar was installed in the tip of the spinner of the turbine, where it also measured inflow via a dual-prism scanning devise, cf. the description above. The twin blade-mounted telescopes focused beams crossed 5 m in front of the telescopes on the blades cord extension line.



Figure 12.

Two small all-fibre fed lidar-telescopes (Lidic's) mounted both sides of the NM80 Tjæreborg Test turbine blade #1 at 15 m from the root.

By mounting the Lidic's so that their focused laser beams cross 4 – 5 m in front of the leading edge of the rotating blade the small telescopes can measure the true air speed approaching the leading edge and also determine the instantaneous angle of attach (AoA).

The first Twin-Lidic inflow measurements from a rotating LM38.5 m blade were obtained in collaboration with LM Wind Power, Natural Power and NKT Photonics sampled during the Tjæreborg 2012 HTF wind lidar integration test trials as part of the demonstration phase of a HTF Wind Lidar integration project with a sampling rate rates of 20 samples per second.

The Lidic beams crossed at an angle of 10 degrees which enabled measurements of the blades Angle-of-Attack (AoA) as well as the wind speed relative to the moving blade. Via an optical switch installed inside the turbine spinner, each of the two telescopes line-of-sight wind speeds could be measured alternately from the two telescopes at a switching rate of 20 Hz. The wind speed during operation ranges between 25 and 30 m/s at the measurement point.

The blade-mounted all-fibre twin-telescope lidar system was installed and tested successfully during the summer of 2012 in the NM80 2.3 MW test turbine owned by Dong Energy and situated at Tjæreborg Enge in Western Jutland; see Figure 12. The twin-telescope blade integration measurement campaign lasted from July 13 through August 19 2012.

The SpinnerLidar in the turbine spinner also recorded the raw Doppler wind spectra and the wind speed and AoA estimation is currently being processed using software developed specifically for the twin blade-mounted lidars.

The measurements we believe represents the first successful wind speed measurements from a dual lidar telescope installed on a rotating blade of a full-scale 2.3 MW operating wind turbine allows a direct measurement of the blade's AOA demonstrating its potential use in future advanced control systems

4.4 Wind Energy Remote Sensing-spurred Potential for Market Grow

Some envisioned applications of the described development and spin-off innovating could for instance include:

1. Spinner Lidars for wind turbine nacelle or spinner-hub integration for enhanced steering and control based on prevision,
2. Small telescopes (Lidic's) for direct integration into wind turbine blades or for measurement of the 3D wind velocity vector in a small measurement volume in wind tunnels,
3. WindScanner.dk developed long-range WindScanners have today already reached the market from the long-range WindScanner.dk joint development of the mirror-based steerable scan heads for long-range wind lidars, a product that today is marketed by the French lidar manufacturer Leosphere. This scanner addresses the market for wind energy resource measurements, and for airport safety (detection of micro-bursts and air plane vortex detection), etc.

To further illustrate the innovation potential and spin-off activities that results from our wind lidar-based remote sensing based R&D, we will below provide a few examples based on initiatives already taken off in the field. During the past 3 years, the following spin-off products have emerged from the ongoing Danish national Windscanner.dk:

- i. Short-range wind lidar with a DTU patented 2-D prism-based beam-steerable scan heads.
- ii. Long-range pulsed wind lidar with flat-mirror steerable scan heads
- iii. Wind turbine spinner-lidar: Integrateable upwind looking 2-D cone filling wind scanner
- iv. Lidic's: Small wind turbine in-blade installable all-fibre fed telescopes for enhanced wind turbine steering and controls.

The SpinnerLidar iii) has also been introduced commercially, spurred by WindScanner industrial collaboration spin-off product developed in collaboration with Renewable energy consultant Natural Power, Malvern, UK, www.yourwindlidar.com/control-zephyr. In 2010, also the WindScanner.dk long-range wind lidars equipped with 2D flat-mirror-based steerable scan heads was designed, proto-type developed and manufactured in collaboration with the French wind lidar manufacturing company Leosphere and IPU; Lyngby, DK. In 2011 Leosphere introduced this long-range WindScanner as product WLS200S, cf. www.leosphere.com.

The scanner have been installed and tested at two major French airports for real-time wake detection with the purpose to enhanced airport aviation capacity and safety and also WLS200S is today an attractive research instrument for wind profile and turbulence measurements within the entire atmospheric boundary layer research cf. Leosphere's home pages for details.

5. WINDSCANNER EUROPEAN AND GLOBAL OPEN ACCESS COLLABORATION

Today's societal energy supply challenge lies at a European rather than a national or local scale. The present European renewable energy supply challenges go beyond resources available at the national and regional levels.

Since the impacts of the PP WindScanner project will be transnational and existing national mechanisms are unable to support WindScanner.eu, it is welcome that joint resources have been secured at the European level for the realization of the PP WindScanner.eu project objectives.

In addition, the new WindScanner.eu research facility to emerge underpins the strategic research needs towards 2020 and beyond, in order to achieve the targets for Wind Energy deployment as set out in the SET Plan.

The establishment of the facility equally implies forthcoming partial "Europeanization" of our existing national RI WindScanner.dk infrastructure with the distributed RI implementation of regional nodes.

Through the new joint-European WindScanner consortium, it will also be possible to promote the European industry as a whole by developing exchange between database repositories, which can provide researchers and industry with samples and access to specific wind and turbulence data sampled from Europe's many different wind climate regimes on- and offshore.

Furthermore, the new WindScanner.eu research facility also witnesses an outspoken interest from trans Atlantic and pan-global collaboration partners as clearly expressed during the European Commission under Danish leadership hosted ECRI 2012 infrastructure Conference held in Copenhagen in March 2012.

The WindScanner.eu research infrastructure will continue to build upon already existing and proven national research activities. In Denmark, the starting point will be taken within the already established national WindScanner.dk facility, which has now entered into its testing and first operation phase.

Testing involves full-scale turbine inflow and wake measurements at the test sites for large wind turbines (Høvsøre and Østerild) and international collaboration is continued with joint research programmes developed and conducted with partners at the NREL research Laboratory for renewable energy research in Colorado and at Sandia in New Mexico.

Further collaboration is planned with the EERA partner German ForWind - for offshore testing e.g. at Krieger's Flag, and bilaterally for wind turbine control - and with several other EERA partners national research facilities (CENER, CRES, SINTEF, ECN, UPorto, LNEG, etc.).

6. CONCLUSION

New remote sensing wind measurement instrumentation, new methodologies and new test equipment is envisioned to be developed within the newly started PP WindScanner.eu research facility preparatory phase 2012-2015.

Remote sensing equipment development is also envisioned to spur new product innovation and spin off products that can be foreseen to impact on European wind energy manufactures and SME supplier's forthcoming competitive wind energy products.

It is therefore anticipated that also the new joint WindScanner.eu European WindScanner facility infrastructure development and collaboration will continue to boost European entrepreneurship in wind energy through remote sensing-based enhanced wind turbine control; reducing blade fatigue and turbine wear, and even maybe provide longer lasting wind turbines with enhanced power capture.

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