INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

IEA R&D Wind Task 11 - Topical Expert Meeting #78

"Field Test Instrumentation and Measurement Best Practices"

October 7 – 8, 2014, Lubbock, TX USA

Organized by: **The National Wind Institute - Texas Tech University**

Scientific Co-ordination: Félix Avia Aranda

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TEXAS TECH UNIVERSITY – National Wind Institute

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For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Austria, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Carballeira Wind Farm - Spain

Two Subtasks
The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on "Social Acceptance of Wind Energy Projects", "Wind Integration Studies" and. "Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment".

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation
Since these activities were initiated in 1978, more than 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Risø National Laboratory
Republic of China	Chinese Wind Energy Association (CWEA)
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Umwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	KEMCO (Korea Energy Management Corporation)
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten – Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

CONTENTS

PRESENTATIONS

1. INTRODUCTORY NOTE

Background

The underperformance of wind plants stemming from complexities in the wind resource remains an active area of interest within the wind R&D community. In order to improve wind plant performance and to develop the next-generation of analysis tools that will facilitate better design and operation of wind farms, it is critical to better understand the physics driving system level energy production and fatigue loads. Variations in the atmospheric boundary layer (stability, turbulence, etc.), terrain effects, and vertical wake structures all have a considerable impact on the performance and loads experienced by downstream turbines.

In order to better understand these phenomena, measurements taken at utility-scale wind plants can shed light on the underlying physics, which in turn can be used to inform and improve wind flow models.

Specific measurements of interest include the atmospheric boundary layer profile, inflow conditions into the wind plant, wake evolution within wind plants, rotor loading profiles, and energy production at individual turbines.

It is quite difficult, however, to extract good quality data from field test campaigns at full-scale wind plants due to inherent randomness in inflow conditions and the high costs of instrumentation sufficient to resolve wind flow conditions appropriately. The combination of incredibly complex, random quantities of interest with instrumentation that is not necessarily up to the task of taking measurements at the appropriate fidelity results in a high level of measurement uncertainty and limits the capability of scientists to exploit the data for the validation of models and simulations.

Topics to be addressed

Towards the goal of improving the value of future utility-scale wind plant experimental campaigns, the objectives of this TEM are:

1. Provide an overview of utility-scale field campaigns carried out to date, along with a description of strengths and limitations

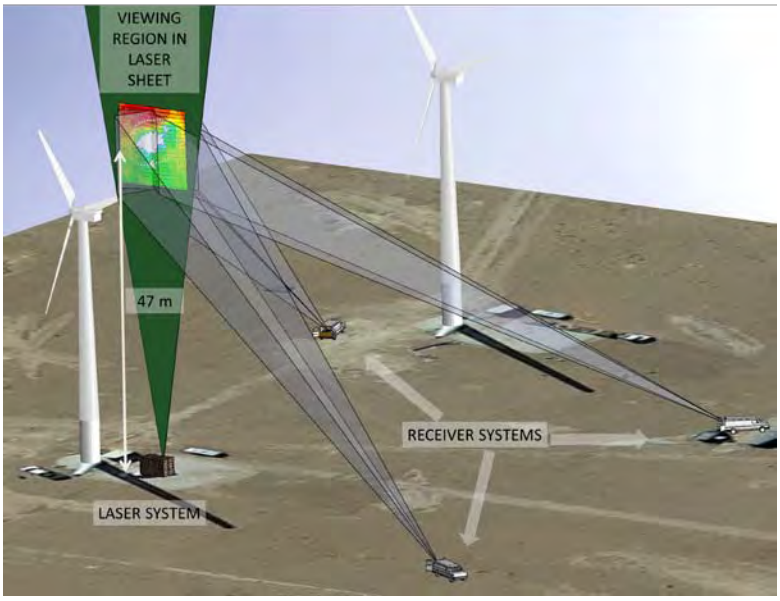
2. Establish the state-of-the-art in field instrumentation technologies and limitations that must be overcome in future campaigns

3. Establish best practices and lessons learned from previous campaigns that should serve as the baseline for future campaigns

4. Develop requirements for comprehensive future field campaigns and provide a thorough overview of the gaps and challenges, data needs, etc.

5. Establish best practices for using scaled and/or controlled testing to complement utility-scale tests

At the event an overview will also presented of innovative wind plant testing capabilities in the US, including the Texas Tech University Ka-Band Radar, Sandia Wake Imaging System, and DOE/Sandia Scaled Wind Farm Technology Facility.



Sandia Wake Imaging System

Scaled Wind Farm Technology Facility

Intended Audience

Participants will typically represent the following types of entities:

- Universities and research organizations
- Manufacturers of wind turbines
- Power companies and wind turbine developers
- Certification institutes and consultants
- Government representatives

The national members invited potential participants from research institutions, universities, manufacturers of wind turbines, power companies, developers, certification institutes, consultants, government representative and any other organizations willing to present proposals, studies, achievements, lessons learned, etc., and to participate in the discussions.
Each participant is expected to give a short presentation of their experiences in the field. The presentations can be on any topic that is in line with this Introductory Note. Each presentation is allocated 15-30 minutes, including questions and a discussion. However, the length of time available is somewhat dependent on the number of presentations to be given.

Expected Outcomes

One of the goals of the meeting will be to gather existing knowledge on the subject and come up with suggestions and recommendations on how to proceed with future developments. Based on the above, a document will be compiled, containing:

- Presentations by participants
- A compilation of the most recent information on the topic
- Main conclusions reached in the discussion session
- Definitions IEA Wind RD&D’s future role in this issue

2. AGENDA

Tuesday 7th October

>09:00 **Registration**. Collection of presentations

>09:20 **Introduction by Host**
Dr. Daan Liang, Interim Director of the National Wind Institute at Texas Tech University, USA

>09:40 **Recognition of Participants**

>09:45 **Introduction by Task 11 Operating Agent.**
Felix Avia, Operating Agent Task 11 IEAWind R&D

>10:10 **US DOE Field Measurement Activities and the Wake Forecasting and Improvement Projects"**
Mr. Joel Cline, Department of Energy, USA

●10:30 Coffee Break

1st Session Individual Presentations (11:00-13:00)

>11:00 **Resource Assessment Standards & Best Practices**
Mr. Jason Fields, NREL National Wind Technology Center

>11:30 **The ECN experience in field test campaigns**
Dr. Wagenaar Jan Willem, ECN, The Netherlands

>12:00 **Development of a Platform for Wind Energy Research in Germany**
Alexander Goermann, DLR German Aerospace Center, Germany

>12:30 **Meteorological and acoustic instrumentation of Germany's Platform for Wind Energy Research (DFWind)**
Dr. Thomas Gerz, DLR, Institute of Atmospheric Physics, Germany

●13:00 Lunch

2nd Session Individual Presentations (14:30-16:00)

>14:30 **SWiFT Facility Instrumentation – What are we missing?**
Dr. Jonathan R. White, Sandia National Laboratories, USA

>15:00 **Development of the Wake Imaging System**
Dr. Thomas Herges, Sandia National Laboratories, USA

>15:30 **Measuring Wind Plant Complex Flows using Research Radar**
Dr. John Schroeder, Brian Hirth and Jerry Guynes, Texas Tech University

●16:00 Coffee Break

3rd Session Individual Presentations (16:30-18:00)

>16:30 **Achievements, Status and Prospects of the DTU Long Range Windscanner System**
Mr. Michael Courtney, DTU Wind Energy, Denmark

>17:00 **Nacelle mounted LIDAR – are we looking the wrong direction?**
Dr. Andrew Swift, Texas Tech University, USA

●18:00 End of the Tuesday meeting

●19:00 Informal dinner at the Texas Tech Club across the street from the Overton.

Wednesday 8th October

4th Session Individual Presentations (9:00-10:30)

>09:00 **Dynamic multi-lidar campaigns for offshore wind farm flow measurements**
Mr. Beck Hauke, ForWind – University of Oldenburg, Germany

>09:30 **Impacts of stable stratification on turbine inflow and wake characteristics: Lessons from the Crop/Wind-Energy Experiments (CWEX)**
Dr. Daniel A. Rajewski, Iowa State University, USA

>10:00 **Lidar observations of wind turbine wakes in an onshore wind farm**
Julie K Lundquist, University of Colorado at Boulder, USA (presented by Dr. Daniel A. Rajewski)

●***10:30 Coffee Break***

5th Session Individual Presentations (11:00-12:30)

>11:00 **Visualizing Wind Farm Wake Losses using SCADA Data**
Dr. Carsten H. Westergaard, Texas Tech University, USA

>11:30 **Planning a wind energy test site in complex terrain based on experiences in instrumentation and measurements**
Andreas Rettenmeier, WindForS, Germany

>12:00 **Wind tunnel experiments for model validation**
Dr. Scott Schreck, NREL, USA

●***13:00 Lunch***

>14:00 **End of the meeting**

• ***14:00-16:00 Optional tour:***

Visit the Texas University Wind Facilities (Ka-Band Radar)

3. LIST OF PARTICIPANTS

The meeting was attended by 19 participants from 5 countries. Table 1 lists the participants and their affiliations.

	Title	Family Name	Last Name	Job Center	Country	E-mail
1	Mr.	Joel	Cline	Department of Energy (DOE)	**USA**	Joel.Cline@ee.doe.gov
2	Dr.	Mike	Courtney	DTU Wind Energy	**DENMARK**	mike@dtu.dk
3	Mr.	Jason	Fields	NREL National Wind Technology Center	**USA**	Jason.fields@nrel.gov
4	Dr.	Thomas	Gerz	German Aerospace Center, DLR, Institute of Atmospheric Physics	**Germany**	thomas.gerz@dlr.de
5	Mr.	Alexander	Goermann	German Aerospace Center, DLR, Institute of Atmospheric Physics	**Germany**	Alexander.goermann@dlr.de
6	Mr.	Beck	Hauke	ForWind – University of Oldenburg	**Germany**	hauke.beck@uni-oldenburg.de
7	Dr.	Thomas	Herges	Sandia National Laboratories	**USA**	therges@sandia.gov
8	Dr.	Daan	Liang	National Wind Institute, Texas Tech University	**USA**	daan.liang@ttu.edu
9	Dr.	Daniel A.	Rajewski	Iowa State University	**USA**	drajewsk@iastate.edu
10	Mr.	Andreas	Rettenmeier	WindForS	**Germany**	rettenmeier@windfors.de
11	Dr.	John	Schroeder	Texas Tech University	**USA**	John.schroeder@ttu.edu
12	Dr.	Schreck	Scott	NREL's National Wind Technology Center	**USA**	scott.schreck@nrel.gov
13	Dr.	Andrew	Swift	Texas Tech University	**USA**	andy.swift@ttu.edu
14	Mr.	Jeroen	van Dam	NREL National Wind Technology Center	**USA**	Jeroen.van.dam@nrel.gov
15	Dr.	Jan Willem	Wagenaar	ECN	**The Netherlands**	j.wagenaar@ecn.nl
16	Dr.	Carsten H.	Westergaard	Texas Tech University	**USA**	carsten.westergaard@ttu.edu
17	Dr.	Jonathan R.	White	Sandia National Laboratories	**USA**	jonwhit@sandia.gov
18	Ms.	Anna Thomas	Young	Texas Tech University	**USA**	anna.t.young@ttu.edu
19	Mr.	Felix	Avia	CENER (Operating Agent Task 11)	**Spain**	favia@cener.com

The International Energy Agency Implementing Agreement for
Co-operation in the Research, Development, and Deployment of Wind Energy Systems
www.ieawind.org

4. SUMMARY

The primary goal of the meeting was to give the participants a good overview of the challenges encountered when taking measurements at research facilities and at utility-scale wind plants. Measured data are crucial for model validation as well as for the development of the next-generation of analysis tools that will facilitate better design and operation of wind farms.

During the two days meeting a total of 17 presentations were presented by the participants, covering the addressed topics and providing an overview of strengths and limitations. After each presentation, the floor was opened and general discussions took place among the participants.

Extensive and detailed information were presented on the different ongoing projects in the existing research infrastructures and projects in USA, German, Danish and Netherlands, like SWiFT, CWEX, Wind Scanner.eu, RAVE, etc.

Several issues that should serve as the baseline for future campaigns were analysed and discussed. The following challenges were identified:

- More coordination of the research projects
- Necessity of large Databases. Requirement for harmonization of the Databases
- Share of the existing databases. Access to the existing databases
- Development of methodologies and procedures to analyse the large measurement data available in the Databases
- How to apply the information obtained from the measurements to the improvement of the Wind Turbine control and the Wind Farm control

a) Conclusions and Future Actions under the Umbrella of IEA Wind

The main part of the discussion was focused on the analysis and interest in establishing a new IEA Wind task on elaboration of best practices from previous campaigns that should serve as the baseline for future campaigns.

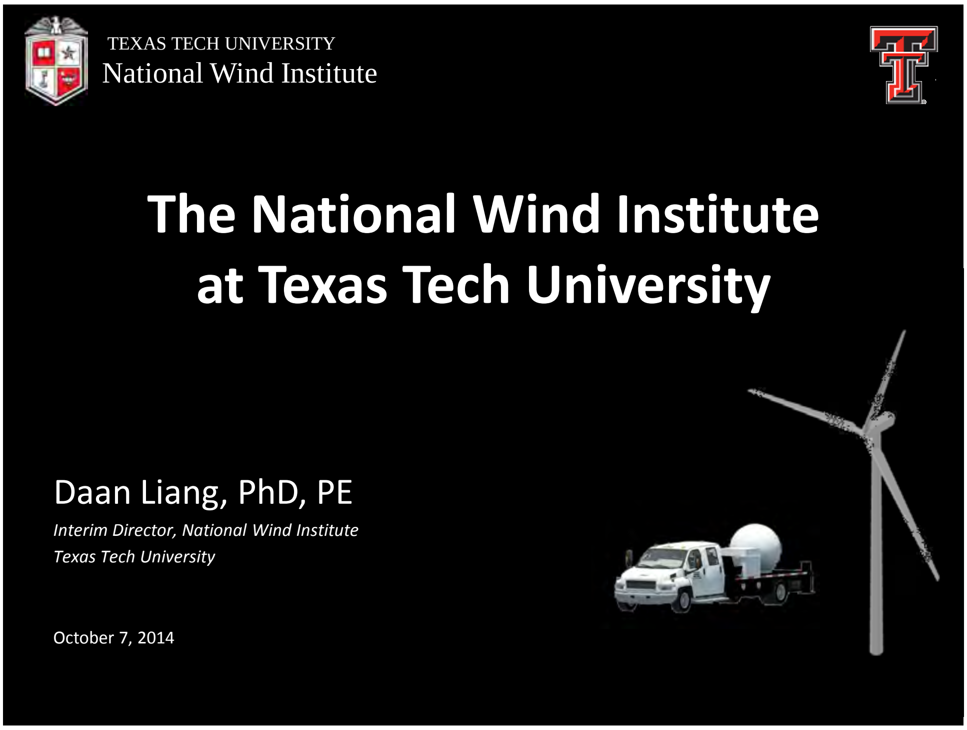
Michael Courtney (DTU) and Andreas Rettenmeir (WindFors) informed on the activities ongoing on IEAWind Task 32 on “Wind lidar systems for Wind Energy deployment”.

The aim of IEA Wind Annex 32 is to address the very fast development of wind lidar technologies and their applicability for more accurate measurement of wind characteristics, relevant for a more reliable deployment of wind power systems. The purpose is to bring together the present actors in the research community and industry to create synergies in the many R&D activities already on-going in this very promising and new measurement technology.

The main objective of this IEA Wind Task is the publication of, experimentally tested, recommended practices for wind lidar measurements. This should build up based on the joint experience of the participants. The recommendations will be benchmarked with measured data collected at various meteorological and lidar operational conditions. The selected data are mutually shared by the participants.

The expected outcome is the formulation of guidelines and expert reports dealing with the evaluation of performance of different systems applied in different selected areas. The planned IEA Recommended Practices (RP) are supposed to complement recent documents available in regards to other applications of wind lidar systems including the IEC 61400-12-1 Annex L on power curve measurement.

PRESENTATIONS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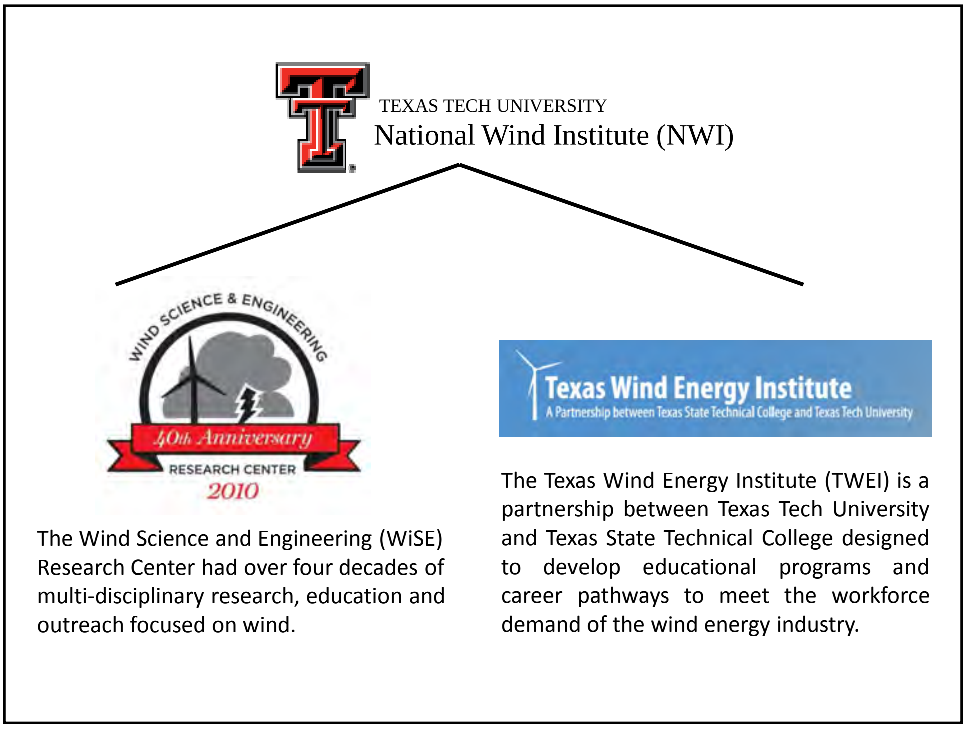
National Wind Institute
The National Wind Institute
at Texas Tech University
Daan Liang, PhD, PE
Interim Director, National Wind Institute
Texas Tech University
October 7, 2014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National Wind Institute (NWI)
WIND SCIENCE & ENGINEERING
40th Anniversary
RESEARCH CENTER
2010
Texas Wind Energy Institute
A Partnership between Texas State Technical College and Texas Tech University
The Wind Science and Engineering (WiSE) Research Center had over four decades of multi-disciplinary research, education and outreach focused on wind.
The Texas Wind Energy Institute (TWEI) is a partnership between Texas Tech University and Texas State Technical College designed to develop educational programs and career pathways to meet the workforce demand of the wind energy industry.

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National Wind Institute

NWI Establishment

- Purpose: The National Wind Institute (NWI) is intended to serve as an intellectual hub for interdisciplinary and transdisciplinary *research, commercialization and education* related to wind science, wind energy, wind engineering and wind hazard mitigation. The institute will serve faculty affiliates, students and external partners involved in these activates and other peripheral areas of interest.
- Commitment: NWI represents a significant university commitment to interdisciplinary wind research.
- Consolidation: A single campus wind organization provides one point of contact and reduces external confusion.

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National Wind Institute

Educational and Workforce Activities

- Multidisciplinary PhD in Wind Science and Engineering (2007); 15 Majors
- Multidisciplinary BS in Wind Energy (2011); 170 Undergraduate Majors
  - 120 credit hour degree
  - 9 graduates in first class, December 2012
  - 6 Wind Energy Program instructors
- Wind Energy Course Enrollments up 400% over the last three years
  - 35% of enrollments are by distance education students
- Wind Energy Graduate Program
  - Two tracks offered for the WE Graduate Certificates – Managerial and Technical
  - Graduate course enrollments are typically Graduate Certificate and PhD students
  - Wind Energy Master's program being developed
- Wind Energy Workforce Activities
  - Working with industry on tailored education/training programs
  - Professional development WE courses offered on-line for Continuing Education credits
  - Curriculum Licensing opportunities in development

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Wind Hazard Mitigation

- Wind Loads on Low-Rise Buildings
- Remote Sensing of Windstorm Damage
- Development and Testing of In-Resident Storm Shelters
- Estimating Wind and Water Damage in Hurricanes
- Performance Evaluation of Essential Facilities
- Wind Flow Characteristics and Wind Speed Profiles found in landfalling Hurricanes
- Tornado Formation and Dynamics
- Models for Measuring Regional Economic Resilience to Hurricanes

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Scaled Wind Farm Technology (SWiFT) Facility

- Partnership with DOE, Sandia National Laboratories, Group NIRE and Vestas
- Planning started in early 2011, construction started December 2012
- Located at Reese Technology Center on the TTU 67-acres
- Research scale turbines - Vestas V-27 (300 kW)
    - Cost-efficient size/research can be directly scaled to larger sizes.
    - Variable speed/variable pitch
    - 13 m blade length, 30 m tower height

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Next Generation Wind Energy Research @ NWI

- Create a ***national center for wind turbine research, testing and certification***
  - Expand prototype wind turbine deployments at Reese Technology Center
- Continue to help in the effort to develop ***"smart" wind farms***
  - Complete and expand the SWiFT facility
  - Develop Reese Technology Center into the most observed volume of atmosphere in the world
- Expand ***grid integration*** related work
  - Integrate ensemble based numerical weather production, wind farm monitoring and controls, and monitoring of the electrical grid to move towards enhancing penetration of wind energy onto the grid
- Continue to add new technologies (generation, storage and even loads) and create a Reese Technology Center ***micro-grid*** to foster research and certification, provide a cyber security testing grounds
- Expand integrated ***wind-water desalination*** activities at Reese Technology Center
  - Build upon the Seminole demonstration project which is about to come online

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Wind Forecasting Improvement Projects

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

IEA Task 11 Topical Expert Meeting #78 - Field Test Instrumentation and Measurement Best Practices

Lubbock, Texas

October 7, 2014

Joel Cline

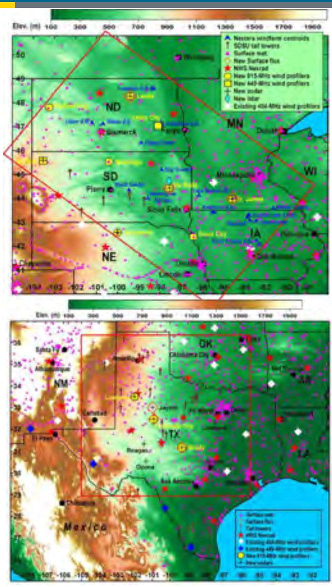
Team Lead
Resource Characterization
Wind and Water Power Technologies Office

Wind Forecasting Improvement Project (WFIP 1.0)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objectives:

- Examined impact of improved initial conditions (observations from the surface to slightly above the swept area)
- Used rapidly refreshed models with high resolution – models were WRF based
- Focused on 0 to 6 hr forecasts – examined ramp forecasts
- DOE and NOAA partnered with two private sector groups to study two geographic regions:
  - Northern Study Domain: Windlogics
  - Southern Study Domain: AWS Truepower



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Wind Forecasting Improvement Project (WFIP 1.0)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Experimental Design: Instrumentation

- Collected and assimilated observations from:
  - 12 wind profiling radars
  - 12 sodars
  - 3 lidars
  - Proprietary tall towers (184 locations)
  - Wind turbine nacelle anemometers (411 locations)
  - 6 surface flux stations
  - 71 surface met stations

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Hourly Updated NOAA NWP Models

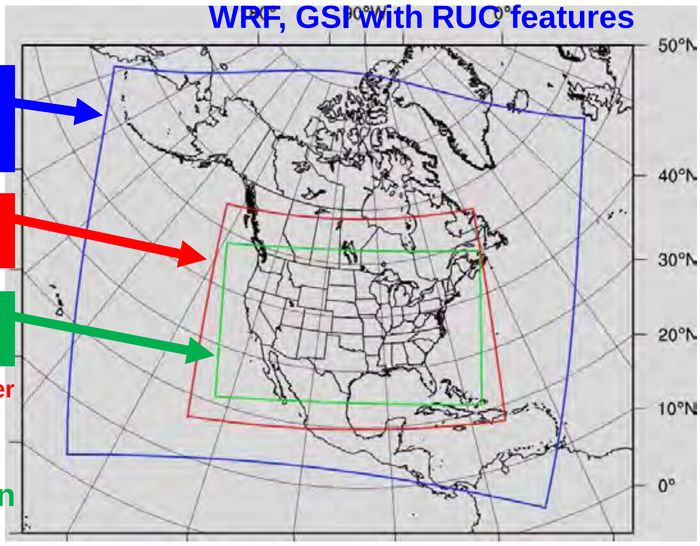
Rapid Refresh (RAP) replaces RUC at NCEP in 2012

WRF, GSI with RUC features

13km Rapid Refresh (RAP) (mesoscale)

13km RUC (mesoscale)

3km HRRR (storm-scale)



RUC – current oper Model, new 18h fcst every hour

High-Resolution Rapid Refresh

Experimental 3km nest inside RAP, new 15-h fcst every hour

4

Wind Forecasting Improvement Project (WFIP 1.0)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Differences in Study Domains:

- Southern Study Area (SSA) had a more concentrated area of turbines
- Northern Study Area (NSA) had a more dispersed area of turbines
- After restricting domains to remove outlier observation sites, greater improvement found with more restricted domains (i.e. SSA showed greater improvement)
- Assimilation of sites with low density of observations (NSA) yields a smaller improvement than sites with a high density of observations (SSA)

Two study areas with more restricted domains shown by the green rectangle in the NSA and green circle in the SSA. (Courtesy: NOAA)

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Wind Forecasting Improvement Project (WFIP 1.0)

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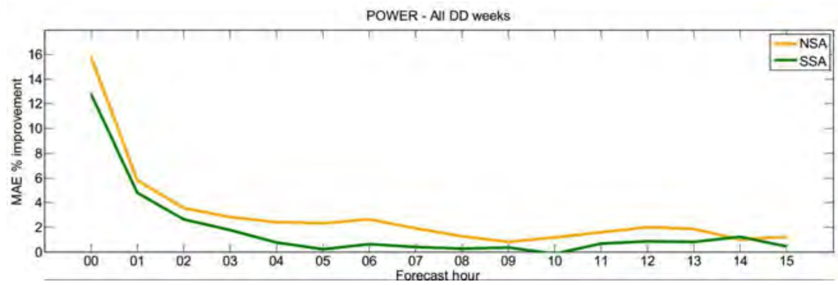
Forecast Skill Improvement Results:

- Power forecast skill improvement greatest at forecast hour 1 and remained until the last forecast hour (up to 15) in both domains
- Models showed greater forecast skill for longer duration ramp events with improvements up to 10% after assimilating additional WFIP observations
- Ability to improve wind forecasting in regions of flat terrain lead toward improving wind forecasting in regions of complex terrain



Mean Absolute Error (MAE) percent improvement for power for the Northern Study Area (orange) and Southern Study Area (green) for all 55 Data Denial (DD) episode days (Courtesy: NOAA)

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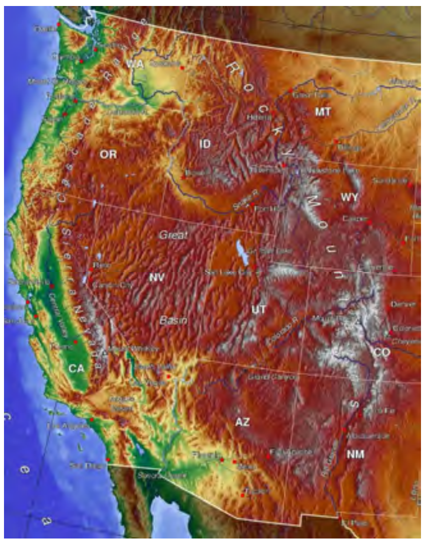
Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objectives:

- Research physical phenomena, processes, and atmospheric properties in a study area (approximately 800 by 800 km) with complex terrain that drive changes in wind speeds within the planetary boundary layer (PBL) of the atmosphere.
- Develop new or improved Weather Research and Forecasting (WRF)-based schemes or basic modeling theories used in foundational forecasting models.
- Improve short-term (0-15 hour) wind forecasts, with possible positive implications for day-ahead, by improving foundational weather models.



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Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

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Physical Processes of Interest:

- Temperature and moisture profiles of the atmosphere, at a minimum, through the depth of the turbine rotor (approximately 200 meters) and deeper, if possible, to capture a more complete profile of certain phenomena (e.g. low-level jet, full depth of sea breezes)
- Low-level jets
- Mountain drainage winds
- Other boundaries such as fronts, outflow, and wakes
- Surface flux measurements from which atmospheric stability parameters can be derived
- Pressure measurements
- Land-sea breezes
- Turbulence
- Snow and soil moisture

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Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

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Instrumentation:

- Table (right) lists a suite of Government Furnished Equipment (GFE) available from DOE and its partners
- DOE anticipates data from three new wind profiling radars being placed along the Pacific Coast to be available during the latter portion of the field campaign
- Two floating lidar buoys may also be available
- Awardee will also provide additional instrumentation or sensors

Observational Equipment/Instrumentation		Number Available	Notes
Wind Profiling Radars	915-MHz	4	At least 2 WPRs will be provided for the project
Lidars	Scanning	2	
	Doppler	1	Available for at least 2 four-week periods
	Vertical Profiling	3	1 ZephIR 300, 2 Wind Cube v2
Sodars	Vertical Profiling	6	1 Scintec sodar
Radiometers		3	1 Net (Kipp & Zonen) 1 Albedometer, 1 Net Radiometer, and 1 IRT 1 ECOR Flux module
Anemometers	Sonic	13	1 CSAT3 3-D (Campbell Scientific)
	Cup	3	
Sensors	Temperature/RH	3	1 Vaisala, At least 2 from ANL
	CO_2/H_2O	2	1 EC150 infrared gas analyzer (Campbell Scientific)
	Soil heat flux plates	4	
	Soil temperature probes	3	
	Soil moisture probes	3	
	Energy Balance Bowen Ratio system	1	
Hygrometers	Krypton	1	
	Infrared	1	
Tipping Rain Gauge		1	
Surface Weather Stations		10	Campbell Scientific Measures surface wind speed, direction, temperature pressure, and RH
3-m tall towers		2	
Wind Vane Direction		1	
Wind Bird (combined speed and direction)		1	

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Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

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Motivation:

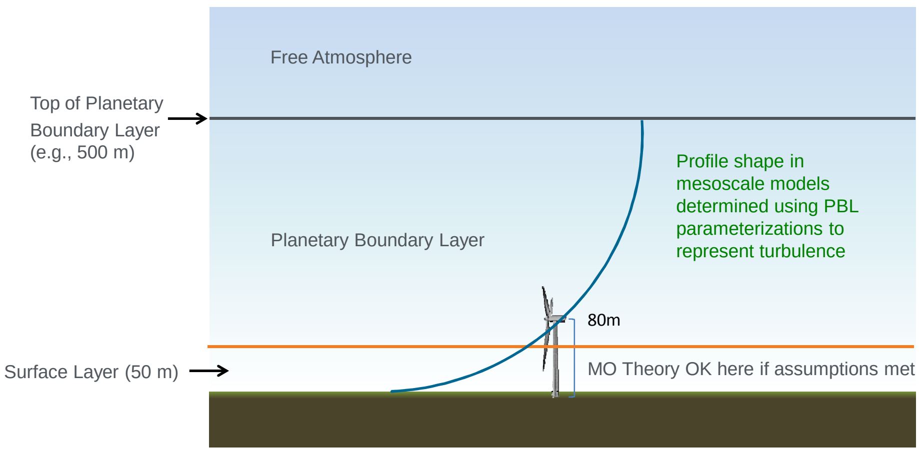
- Wind plant power losses due to forecasts errors/wake losses around 30%
- Current model parameterizations do not fully account for complex terrain
  - Planetary Boundary Layer (PBL) parameterizations in mesoscale models assume dominance by vertical gradients, do not effectively account for sub-grid steep slopes
  - Monin-Obukhov Similarity Theory used for surface exchange in models and scaling up of low-level wind observations
    - Fundamentally rests on statistically stationary, horizontally homogeneous conditions (i.e., noon on a sunny day in Kansas or Wangara)
    - Valid in lowest 10% of PBL (which is sometimes lower than hub height, especially at night)
  - A wide array of approaches can be used to represent the winds between the surface layer and top of the boundary layer
  - Parameterizations often adjusted (tuned) to get agreement with observations
- Uncertainties arising from parameterization assumptions have not generally been determined from observations in complex terrain
- WFIP 2 will aim to improve the understanding of the physics which can be used to improve the underlying theory for PBL schemes in models to address complex terrain conditions relevant to the wind industry

11 | Energy Efficiency & Renewable Energy eere.energy.gov

Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Motivation:



12 | Energy Efficiency & Renewable Energy eere.energy.gov

Wind Forecasting Improvement Project in Complex Terrain (WFIP 2)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Budget Periods (up to 39 months):

- **Budget Period 1:** Planning integration and acquiring land easements (up to 9 months)
- **Budget Period 2:** Field campaign (up to 18 months)
- **Budget Period 3:** Data analysis and model improvement (up to 12 months)

Project Team:

- The awardee will include involvement or support from one or more electric power system Balancing Authorities (BA)
- The awardee may also include wind plant operators, owners, developers, and manufacturers; wind forecasters; weather service providers; wind measurement instrument suppliers; regional academia; and others
- NOAA and the National Labs (ANL, LLNL, NREL, PNNL) will be funded to provide government-owned observational equipment and technical services to the awardee throughout the project

13 | Energy Efficiency & Renewable Energy eere.energy.gov

Three Offshore Wind Demonstration Projects Selected

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- In May 2014, DOE selected three Offshore Wind Advanced Technology Demonstration Projects each eligible for up to $46.7 million in additional funding over four years
  - **Dominion Virginia Power – Virginia Offshore Wind Technology Advancement Project (VOWTAP)**
    - Two 6-MW turbines 26 miles off the coast of Virginia Beach, VA
    - Twisted jacket foundation
  - **Fishermen's Energy Atlantic City Windfarm**
    - Five 5-MW turbines ~3 miles off the coast of Atlantic City, NJ
    - Twisted jacket foundation
  - **Principle Power Windfloat**
    - Five 6-MW turbines ~18 miles off the coast of Coos Bay, OR
    - Semi-submersible floating foundation

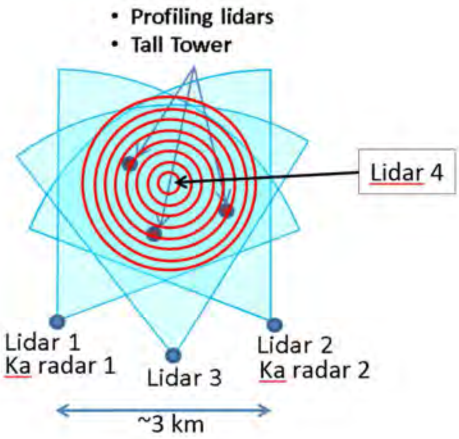
14 | Energy Efficiency & Renewable Energy eere.energy.gov

Lidar Shootout/A2e PBL Instrument Assessment Study

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objectives:

- The goal of this study is to evaluate the capability and accuracy of remote sensing instrumentation at producing 3D PBL wind fields and temperature profiles.
- This information will be used to help determine optimal control strategies for wind plant design and operation.



15 | Energy Efficiency & Renewable Energy   eere.energy.gov

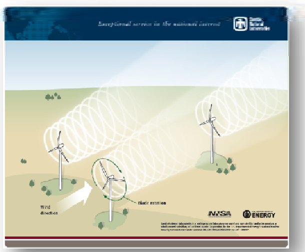
SWiFT Facility, Lubbock, Texas

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

SWiFT exists to:

- Reduce turbine-turbine interaction and wind plant underperformance
- Develop advanced wind turbine rotors
- Public open-source to advance simulation abilities

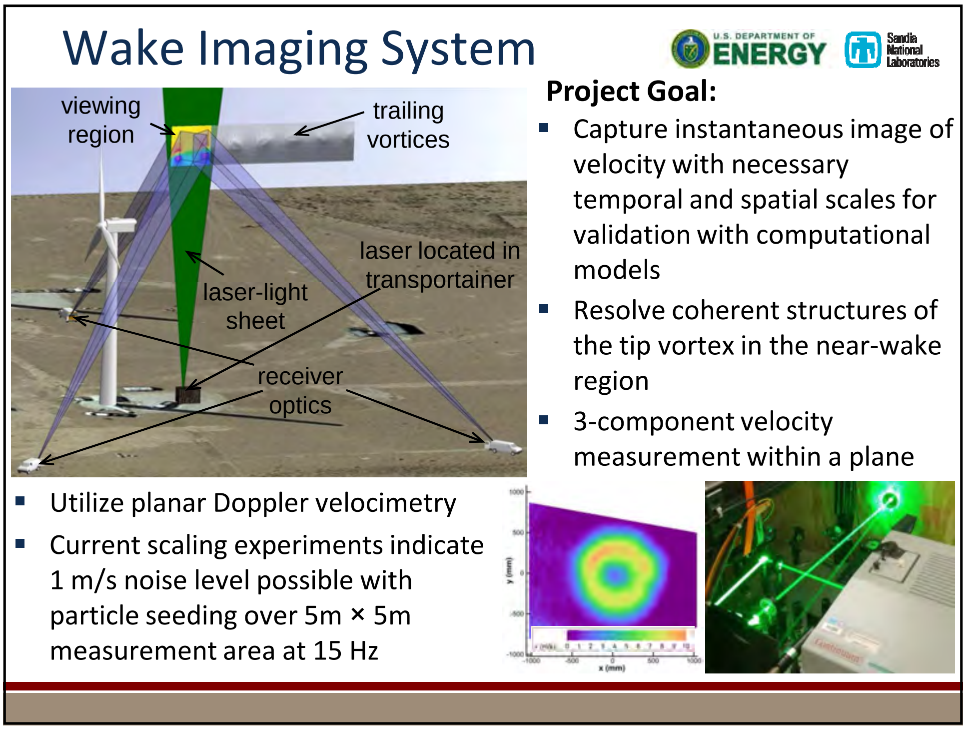
U.S. DEPARTMENT OF ENERGY · TEXAS TECH UNIVERSITY · Vestas. Wind. It means the world to us.™ · NREL

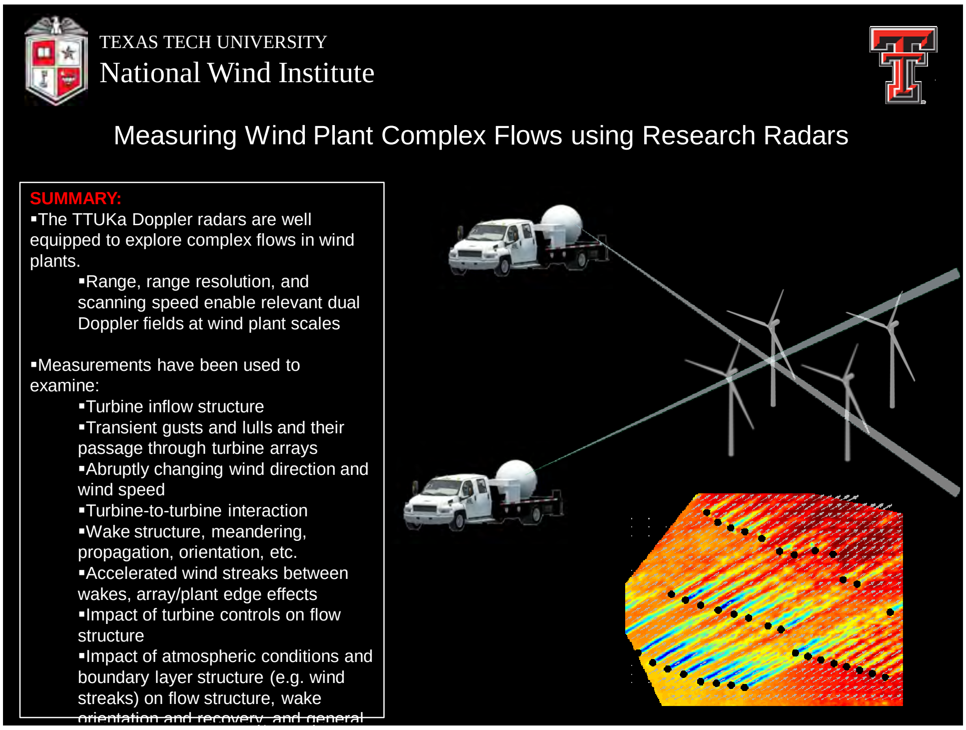


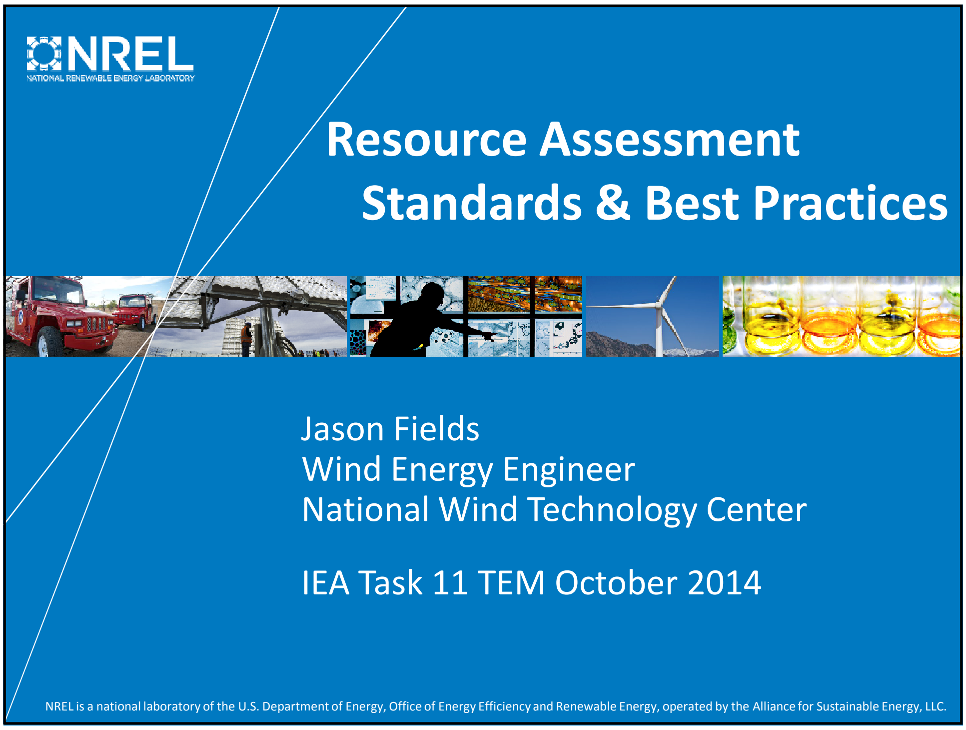
Facilities:

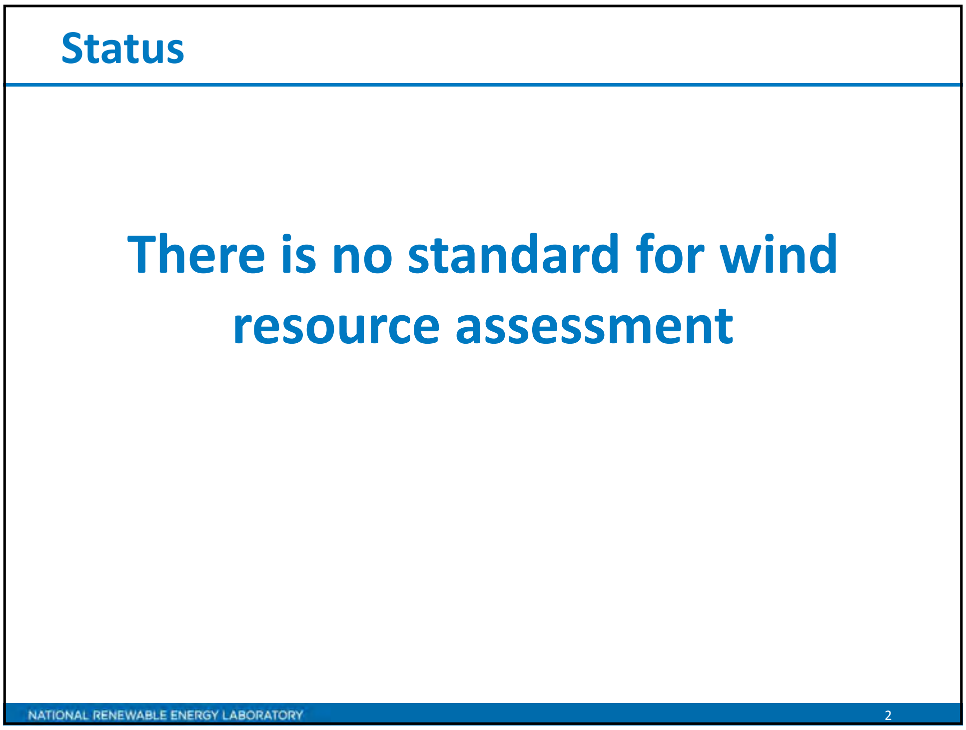
- Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

16 | Energy Efficiency & Renewable Energy   Official Use Only   eere.energy.gov


Wake Imaging System
U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
viewing region
trailing vortices
laser located in transportainer
laser-light sheet
receiver optics
Project Goal:
▪ Capture instantaneous image of velocity with necessary temporal and spatial scales for validation with computational models
▪ Resolve coherent structures of the tip vortex in the near-wake region
▪ 3-component velocity measurement within a plane
▪ Utilize planar Doppler velocimetry
▪ Current scaling experiments indicate 1 m/s noise level possible with particle seeding over 5m × 5m measurement area at 15 Hz


TEXAS TECH UNIVERSITY
National Wind Institute
Measuring Wind Plant Complex Flows using Research Radars
SUMMARY:
▪The TTUKa Doppler radars are well equipped to explore complex flows in wind plants.
▪Range, range resolution, and scanning speed enable relevant dual Doppler fields at wind plant scales
▪Measurements have been used to examine:
▪Turbine inflow structure
▪Transient gusts and lulls and their passage through turbine arrays
▪Abruptly changing wind direction and wind speed
▪Turbine-to-turbine interaction
▪Wake structure, meandering, propagation, orientation, etc.
▪Accelerated wind streaks between wakes, array/plant edge effects
▪Impact of turbine controls on flow structure
▪Impact of atmospheric conditions and boundary layer structure (e.g. wind streaks) on flow structure, wake


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Resource Assessment
Standards & Best Practices
Jason Fields
Wind Energy Engineer
National Wind Technology Center
IEA Task 11 TEM October 2014
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.


Status
There is no standard for wind resource assessment
NATIONAL RENEWABLE ENERGY LABORATORY
2

Status

Do we need one?

NATIONAL RENEWABLE ENERGY LABORATORY 3

Status

Do we need one?

Photo Credit: Harness Energy

NATIONAL RENEWABLE ENERGY LABORATORY 4

Foundational Work

Existing related standards & best practices

- IEC 61400-1,3 Wind Turbine: Design Requirements
- IEC 61400-12-1 Power Performance Testing
- IEC 61400-26 Availability: Technical Specification
- MEASNET "Evaluation of site specific winds"

Other documents/collaborations

- Consortium Loss & Uncertainty definitions
- Wind Resource Assessment: A Practical Guide to Developing a Wind Project
- IEA Wind Task 32 Remote Sensing
- IEA Wind Task 31 Windbench and Wakebench
- IEA Task 11 75th meeting on complex terrain
- AWEA WRA working group
- Power Curve Working Group

NATIONAL RENEWABLE ENERGY LABORATORY 5

But wait there is a standard

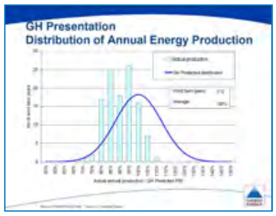
IEC 61400-15
"Assessment of Wind Resource, Energy Yield and Site Suitability input conditions for wind power plants"

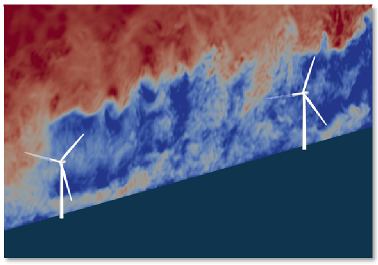
- **NP ratified almost unanimously Summer 2013**
- **Member selection Fall, Winter 2013**
- **Kickoff meeting- Feb 2014 @ NWTC**

NATIONAL RENEWABLE ENERGY LABORATORY 6

What are they doing?

- **Measurements**
- **Data Analysis**
- **Site Suitability**
- **Modeling**
    - o Flow model
    - o Wake model
- **AEP Estimation & Reporting**
- **Loss & Uncertainty Quantification**





NATIONAL RENEWABLE ENERGY LABORATORY 7

Who is it?

Official Breakdown

Country	Panel Members
Germany	6
US	7
Spain	4
Denmark	4
Japan	4
France	3
Great Britain	4
Italy	2
Sweden	1
Korea	1
Total	**36**

Geographic coverage, 10 countries and 3 continents

NATIONAL RENEWABLE ENERGY LABORATORY 8

Who is it?

Official Breakdown

Sector	Panel Members
Consulting	10
Developer/Owner	7
Research/ Certification Body	5
Turbine OEM	9
Equipment OEM	2
Industry Group	3
Total	**36**

NATIONAL RENEWABLE ENERGY LABORATORY 9

Official scope language

- **Definition, measurement, and prediction of the long-term meteorological and wind flow characteristics at the site**
- **Integration of the long-term meteorological and wind flow characteristics with wind turbine and balance of plant characteristics to predict net energy yield**
- **Characterizing environmental extremes and other relevant plant design drivers**
- **Assessing the uncertainty associated with each of these steps**
- **Addressing documentation and reporting requirements to help ensure the traceability of the assessment processes**

NATIONAL RENEWABLE ENERGY LABORATORY 10

Official scope language

- Definition, measurement, and prediction of the long-term meteorological and wind flow characteristics at the site
- Integration of the long-term meteorological and wind flow characteristics with wind turbine and balance of plant characteristics to predict net energy yield
- Characterizing environmental extremes and other relevant plant design drivers
- Assessing the uncertainty associated with each of these steps
- Addressing documentation and reporting requirements to help ensure the traceability of the assessment processes

NATIONAL RENEWABLE ENERGY LABORATORY 11

IEC 61400-15 timeline

- Committee Draft: September 2015
- Committee Draft for Vote: September 2016
- Final Draft International Standard: May 2017
- International Standard: September 2018

NATIONAL RENEWABLE ENERGY LABORATORY 12

Current Progress

- **2 Meetings held**
- **3rd Meeting Nov 2014 @ DNV-GL(UK)**
- **2 subgroups created**
  - Uncertainty
  - Site Suitability
- **Draft language started**
- **US Mirror committee formation**

NATIONAL RENEWABLE ENERGY LABORATORY 13

How to get involved

- **US Mirror committee**
  - Matt Filippelli(AWS Truepower) taking lead
- **Other countries may still have spots**
- **Official group liasons**
  - Martin Strack MEASNET
  - IEA Tasks?

NATIONAL RENEWABLE ENERGY LABORATORY 14

Contact Information

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Secretary IEC 61400-15
NREL-National Wind Technology Center
Jason.fields@nrel.gov
303-384-7150
http://www.nrel.gov/wind/

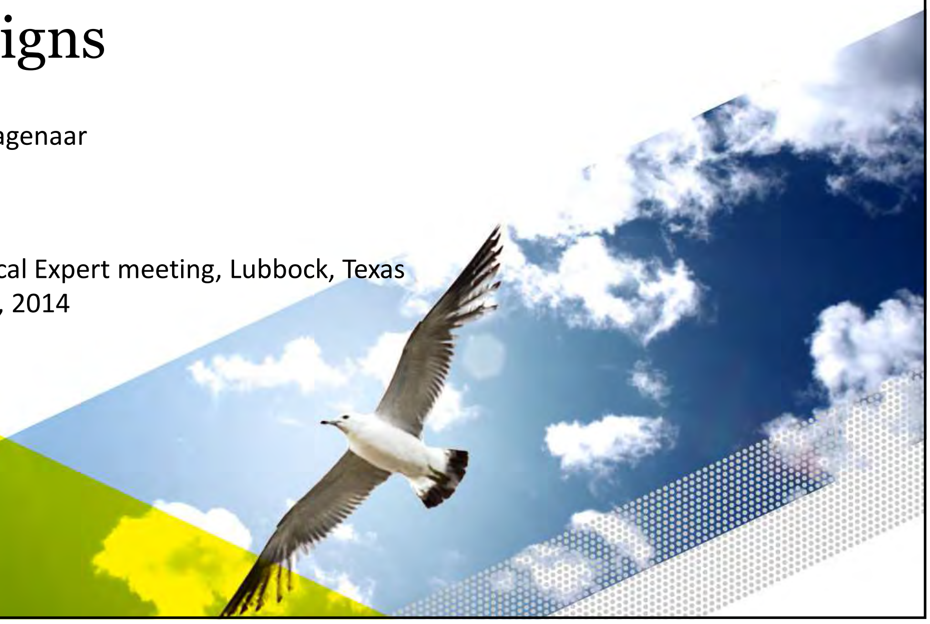
NATIONAL RENEWABLE ENERGY LABORATORY 15

ECN
Your energy. Our passion.

The ECN experience in field test campaigns

Jan Willem Wagenaar

IEA Wind Topical Expert meeting, Lubbock, Texas
October 7 & 8, 2014



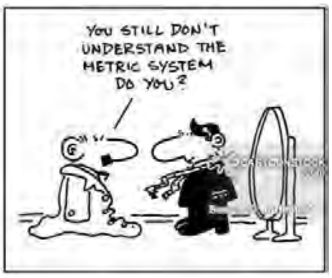
www.ecn.nl

ECN

Overview

- Overview campaigns; strength/limitations
- State of the Art tech; limitations to overcome
- Best practices and lessons learned
- Requirements future campaigns; gaps/challenges/data
- Scaled test best practices

- Introduction to ECN
- Test facilities
- Typical Campaigns & Set-up
- Examples
- Future campaigns
- Conclusions (link)



ECN

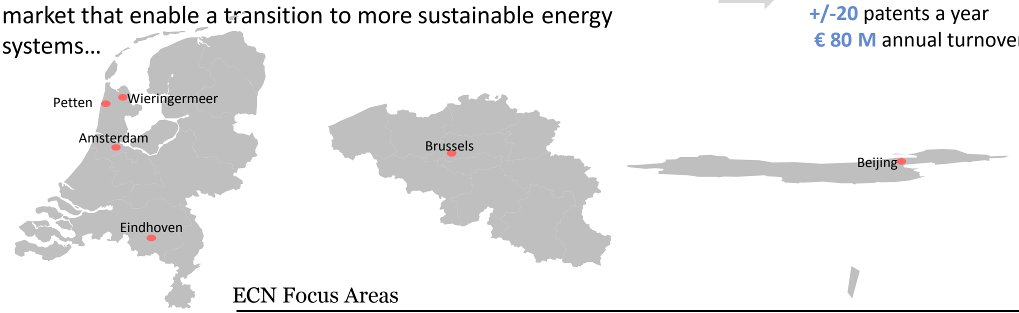
Introduction to ECN

ECN

ECN at a glance

Mission:
…To develop knowledge and technologies with and for the market that enable a transition to more sustainable energy systems…

Founded in 1955
600 Employees
+/-20 patents a year
€ 80 M annual turnover



ECN Focus Areas

Solar energy | Biomass | Policy studies | Energy efficiency | Wind energy | Environment & energy engineering

ECN acts as a bridge between science and corporate innovation

ECN

Science ⟷ Industrial partners

Fundamental Research → Applied Research → Industrial Development

What we do

- Problem Solving
- Technology development
- Studies & Policy Support

How we work with partners

- Consultancy & Services
- Contract R&D
- Tech development & Transfer
- Joint Industry Projects

Vision 2016

ECN Wind Energy as world leader institute on:

Innovative Solutions for Offshore Wind Power Plants

- Reduce cost of energy
- Innovative products and solutions
- Differentiating factor is our world leading facilities & in-depth know how
- State of the art wind farm services

J.W. Wagenaar 10-10-2014

ECN

Test Site Facilities

ECN

Test site EWTW

ECN Wind turbine Test station Wieringermeer

- On shore
- Near lake IJsselmeer
- Flat, agricultural terrain
- About 35km from ECN

- Mean ws: 8.3m/s (@100m)
- Mean wd: South West
- Mean TI: 8.1% (@80m)

ECN

ECN Test Site (EWTW)

ECN Wind turbine Test station Wieringermeer

- Prototype turbines and masts
- Research turbines and mast
- Scaled wind farm (†)
- Measurement pavilion

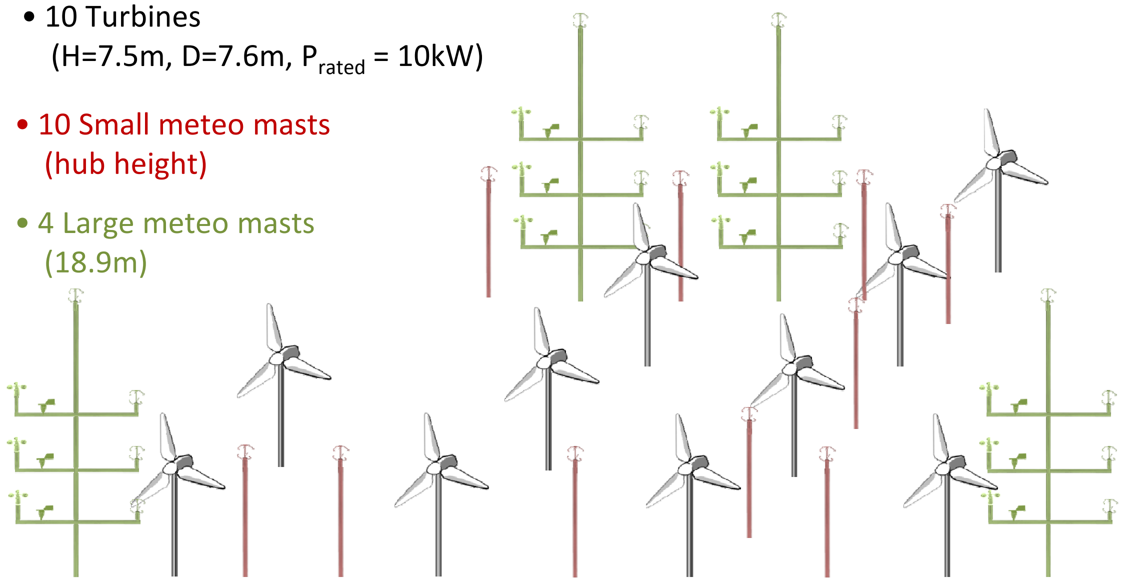
ECN

Research & Prototype turbines

- Full scale research turbines and mast
  - 5 Nordex turbines
    - 2.5MW
    - 80m
  - 1 meteorological mast
    - 52m (HH-0.7R)
    - 80m (HH)
    - 108m (HH+0.7R)
- Prototype turbines (6)
  - GE (2), Siemens (2), XEMC Darwind, Alstom
  - 4 meteorological masts
  - Rated power 2MW-5MW
  - Rotor diameter 100m-120m
  - Hub height 80m-100m

ECN's Scaled Wind Farm (†)

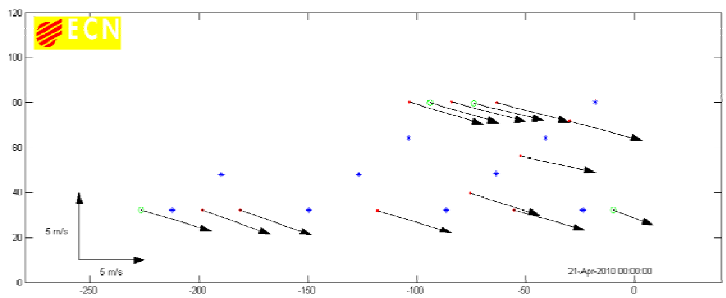
- 10 Turbines
  (H=7.5m, D=7.6m, P_{rated} = 10kW)
- 10 Small meteo masts
  (hub height)
- 4 Large meteo masts
  (18.9m)



ECN's Scaled Wind Farm (†)

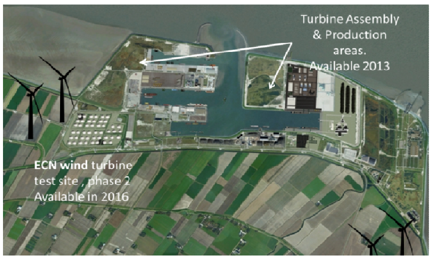
Lessons learned

- Scaling effects (obviously)
- Robust, representative turbines
- Identical
- Design & Control



ECN's new testing & assembly facilities

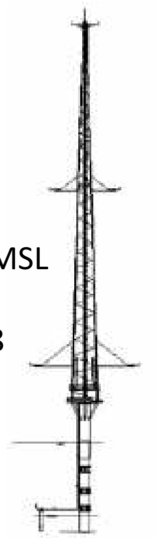
- Dedicated test site for large offshore turbines
- Reinforced quaysides
- Direct access to the Seaport harbour, for easy logistics.
- Good storage & assembly areas
- Excellent access to other windfarms in Europe both on and offshore
- Easy access for all part & component suppliers

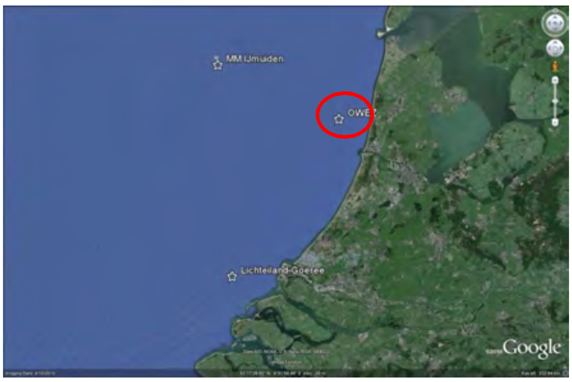


Offshore measurements

- **MM OWEZ**
- MM IJmuiden
- Lichteiland Goeree

- 36 Vestas V90, 3MW
- Hub height: 70m above MSL
- 18 – 20 km off the coast
- Met mast near T7 and T8



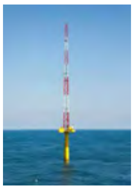


Offshore measurements

- MM OWEZ
- **MM IJmuiden**
- Lichteiland Goeree

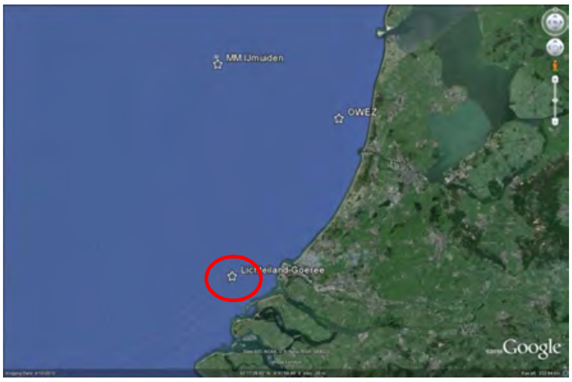
Meteorological mast IJmuiden (FLOW/RWE/ECN)

- Offshore, 75 km from IJmuiden
- Largest distance form coast in Europe at construction
- 100 heigh, 26m deep
- Measurements from 30m on at 4 heights
- Zephir LiDAR inside mast
- Triaxys Wave bouy



Offshore measurements

- MM OWEZ
- MM IJmuiden
- **Lichteiland Goeree**



'Lichteiland' (Lighthouse platform) Goeree

- About 30km from shore
- KNMI measurement station
- Windcube V2 LiDAR (planned)

ECN

Typical Campaigns & Set-up (Best practices)

ECN

Typical measurement campaigns

ECN is ISO 17025 certified for measurements on:

- Power performance
  - IEC 61400-12-1
  - MEASNET
- Mechanical loads
  - IEC 61400-13
- /Acoustic noise
  - IEC 61400-11
- Meteorological measurements
  - LiDAR/SoDAR validation
  - Offshore campaigns
- Research/dedicated campaigns

TESTING RvA L 324

Accreditation/Standardization:

- Management system
- Quality system
- Working procedures
- …

Typical structure and activities

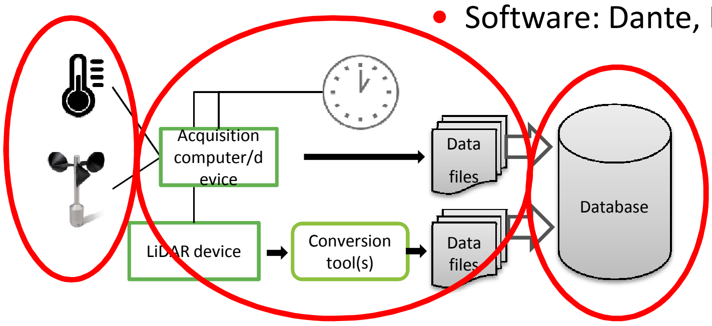
Structure:
- Phase 1: Measurement plan
- Phase 2: Prep instrumentation
- Phase 3: Instrumentation
- Phase 4: Data acq & database
- Phase 5: Instrumentation report
- Phase 6: Measurements
- Phase 7: Final reporting
- Phase 8: Dismantling
- Project Management

Activities:
- Reservation/ordering
- Calibration
  - Outside, lab, in-situ
- Instrumentation/Signal check
- Data acq & Database set-up
  - Safe and secure/Access management
- Periodic validation & reporting
  - Validation: Automated, manual
  - Reporting: Availability
- Dismantling, retrieval, storage
  - Recalibration

Typical aspects

Instrumentation
- Sensor: ID, specs, etc
- Calibration/Recalibration
- Mounting
- Uncertainty
- Instr management

Data acquisition
- Module: ID, specs, etc
- Calibration/Recalibration
- Uncertainty
- Hardware: Dante Modules, CRIO (NI)
- Software: Dante, Daisy



Data base
- Safe storage
- Stored procedures
- Access based on roles: Analyst, …
- WDMS4 (WindScanner.eu)

Analysis
- Description of dataset
- Description of methodology (standardized procedures)
- Results
- Review/Authorisation

ECN

Examples

ECN

LAWINE and WindScanner

LAWINE:

- **Aim**: Technology and services are developed to use LiDAR systems in offshore wind power plants to significantly reduce the cost of energy.
- Partners: ECN, Avent Lidar Technology, TU Delft, XEMC Darwind

TKI WIND OP ZEE

WindScanner.eu

- **Aim**: This prepatory phase project has the objective to construct the distributed, mobile and pan- European WindScanner research facility
- **Partners**: CENER, CRES, DTU, ECN, ForWind, Fraunhofer, LNEG/Ineti, Sintef, UPorto

SEVENTH FRAMEWORK PROGRAMME

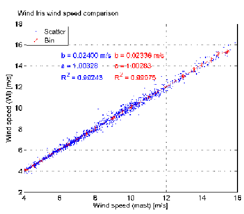
ECN

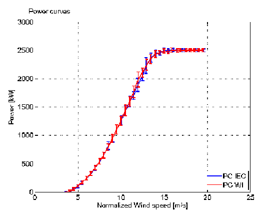
Overview

ECN

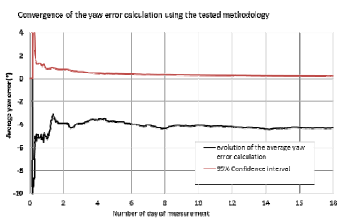
Results: 2 beam nacelle LiDAR

- Power performance
  - ➢ Very well wind speed comparison with mast (2.5D, undisturbed sector)
  - ➢ Very well power curve + uncertainties comparison

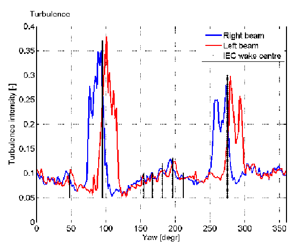




- Yaw misalignment
  - ➢ -3.6º (0.5º) offset determined in 7 days with accuracy of 95%

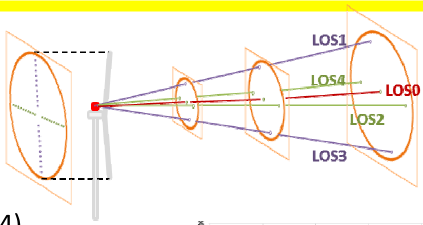


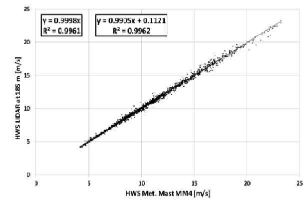
- TI
  - ➢ Wake identification
  - ➢ Good comparison with mast

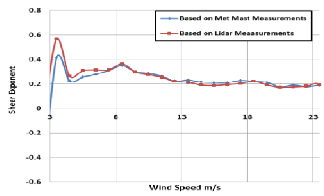


Results: 5 beam nacelle LiDAR

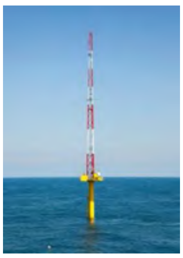
- Availability
  - 99.67%
- Wind speed comparison
  - 2 beam configuration (LOS2 & LOS4)
  - LiDAR@185m vs MM@383m
  - a = 0.9998, R^2 = 0.9961
- Wind shear
  - 2 beam configuration (LOS0 & LOS3)
  - LiDAR@185m vs MM@383m





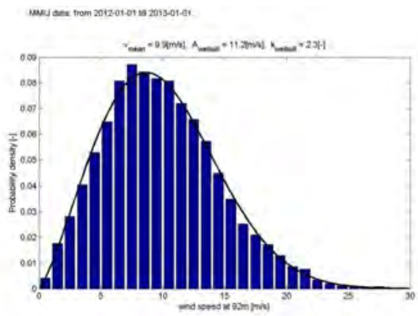


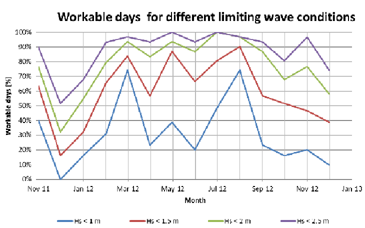
Offshore meteorological mast IJmuiden

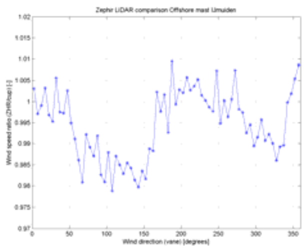


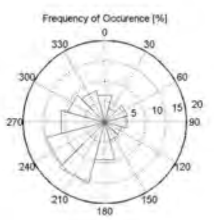
Application

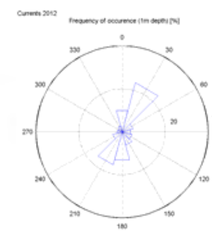
- Offshore wind resource assessment
- Floating LiDAR kalibration
- OWA / Carbon Trust











ECN

Future campaigns & Requirements

ECN

Future campaigns and Requirements

Future campaigns

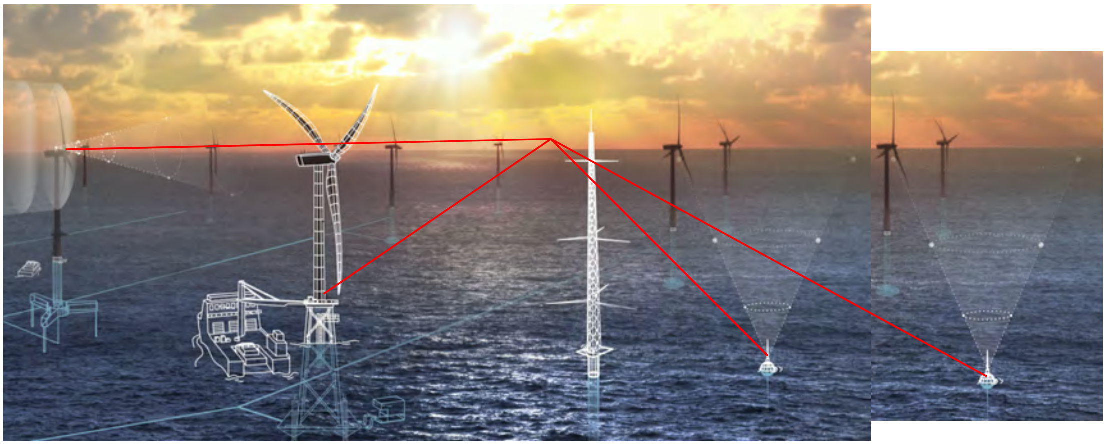
- Remote sensing
  - Nacelle based
  - Floating
  - Scanning
  - WindScanner:
    - Scaled Wind Farm/Kassel
- Offshore
  - Substructures
  - Scour
  - Inspections
- Other …

Requirements

- General
  - Do you know what you're measuring?
  - How to interpret data?
- Remote sensing
  - Exact positioning
  - Synchronization
  - Large amount of data
  - …
- Offshore
  - Robust/Offshore conditions
  - Installation
  - Translation measurements to analysis
  - …

ECN

Future sketch



ECN

Conclusions

- Overview campaigns; strength/limitations ★
  - Test sites
  - Typical campaigns and set-up
  - Best practice
- State of the Art tech; limitations to overcome ★
  - Ongoing campaigns
- Best practices and lessons learned ★
  - See before
- Requirements future campaigns; gaps/challenges/data ★
  - Future campaigns
- Scaled test best practices ★
  - ECN Scaled Wind Farm facility

Thank you for your attention

Questions?

ECN

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Development of the German Platform for Research on Wind Energy

Institute of Flight Systems
German Aerospace Center
Alexander Görmann

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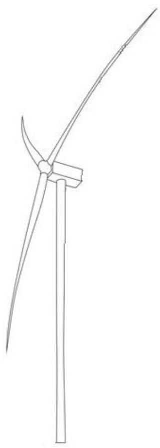
Outlook

- Fact and political conditions in Germany
- Who is the DLR
- Institute of Flight Systems
- Development of the German Research Platform
- Meteorological and Acoustic Instrumentation



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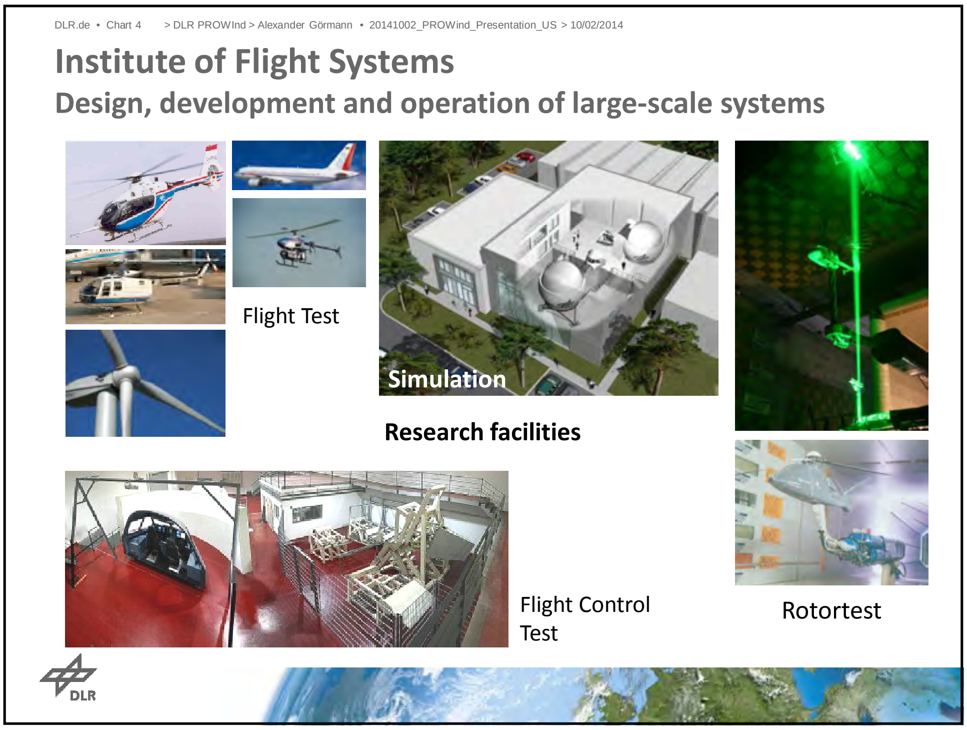
Who is the German Aerospace Center
• Aeronautics
• Space
• Transport
• Energy
• Safety
• Space Admistration
Stade
Hamburg
Neustrelitz
Bremen
Trauen
Berlin
Braunschweig
Göttingen
Jülich
Köln
Bonn
Lampoldshausen
Stuttgart
Augsburg
Oberpfaffenhofen
Weilheim
More than 8000 employees
at 16 locations in Germany
DLR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Institute of Flight Systems
Design, development and operation of large-scale systems
Flight Test
Simulation
Research facilities
Flight Control
Test
Rotortest
DLR

Flying helicopter simulator ACT/FHS

EC 135

FHS-System Simulator

Experimental System

FHS-Ground Station

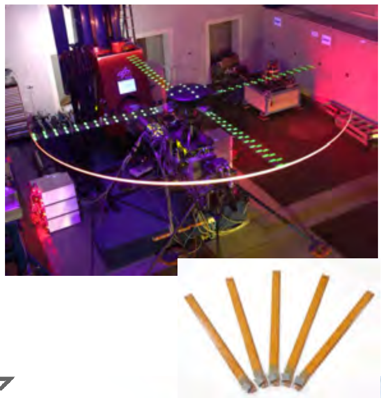
Active rotor control

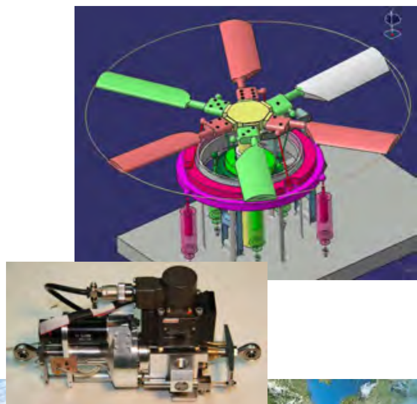
Active Twist

- New functions for noise and high speed performance

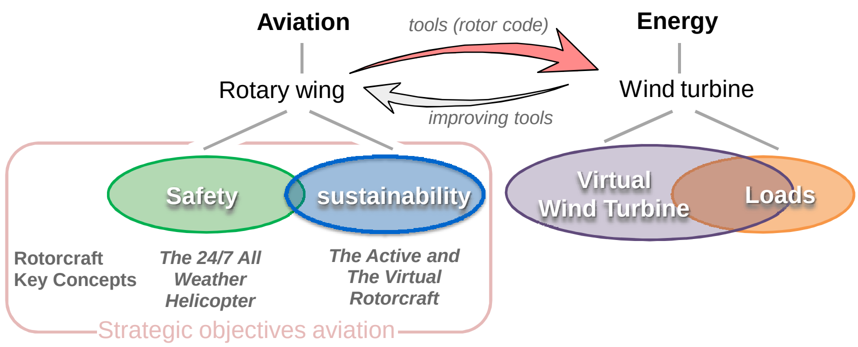
Multi-Swashplate System

- Full IBC functionality with actuators in fixed system
- System integration for rotor test rig





Transfer of Concepts



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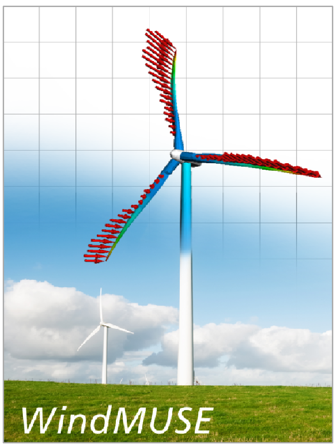
Modeling of a wind turbine

Objektives

Transfer of methods, models, and tools from aerospace to wind energy enabling a holistic simulation of wind turbines

- Project WindMUSE:
  - Fast simulation of structure and aerodynamic interaction
  - Simulation of drivetrain, generator, gear and brake
  - Pitch and Yaw controllers
  - Realtime simulation
- **Stratagic objective:** simulation of windfarms with energy network integration and stability

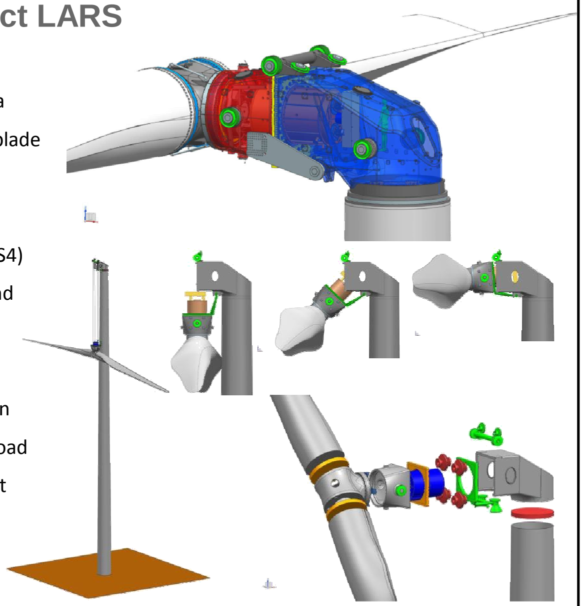


Wind Turbine in Multidisciplinary Simulation Environment

DLR

Load Reduction Project LARS

- Industrial request for development of a controller for load reduction of a two-blade rotor
- Tasks & Concepts
  - Extantion of the DLR rotor code (S4) for the dynamic simulation of wind turbines
  - linking S4 with SIMPACK
  - Research of aeroelastic interaction
  - Development of a controller for load reduction by use of active hub tilt funktion
  - Validation of the system



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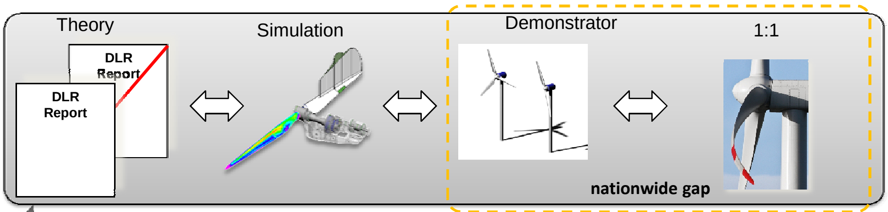
Why do we need a test site?

Existing test infrastructure in Germany

Frauenhofer IWES Rotorblade Testing Facility | Frauenhofer IWES Dynamic Nacelle Testing Laboratory | DLR High Performance Computing Cluster | DLR Aero-Acoustic Low-Speed Wind Tunnel

What we need for an holistic understanding of the entire system?



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Test site

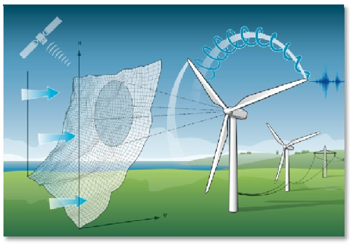
Research objektives

- Reduction of loads to develop lighter and cheaper wind turbines
- Less noise
- Early detection of damages within the drive train for more safety
- Better wind turbine modeling
- Better understanding of the interaction of wind turbines

Test site components

- 2 Turbines: ~100m rotor diameter (2,5MW)
- 1 Turbine: ~50m rotor diameter
- meteorological instrumentation
  - stationary masts
  - wind, weather, noise
  - mobile LIDAR
- Control building
- Repair and assembling hall

⇒ Reducing ‚Cost of Energy'



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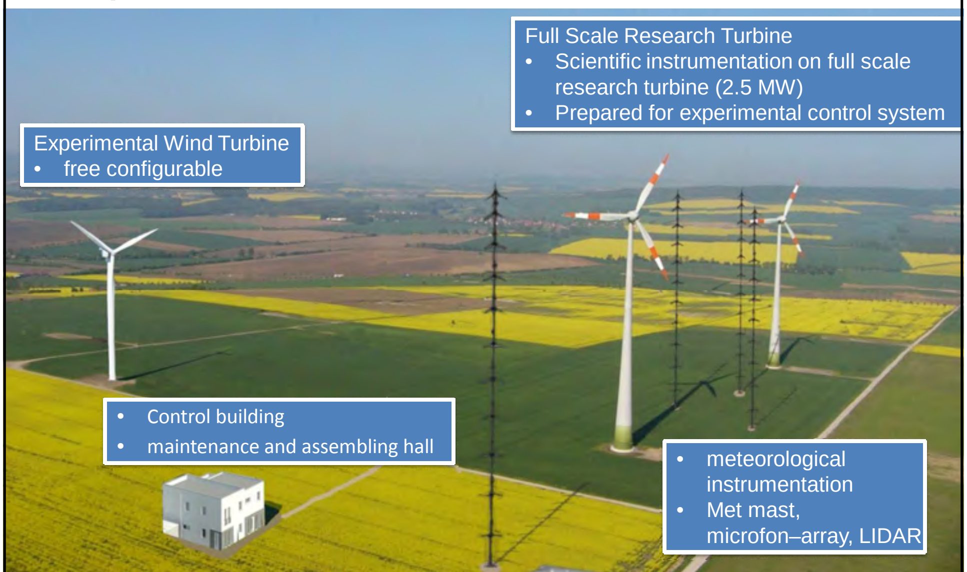
Components of the Test site



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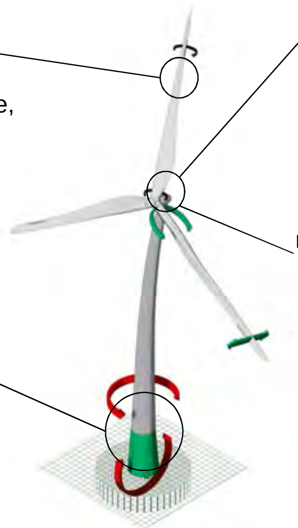
Turbine instrumentation – key points

rotorblades

- System identification
- Temperature, moisture, strain, torsion, fibre bragg, acceleration, pressure!



Experimental Control System

- Implementation a APS (Advanced Protection System) in the standard controller environment

nacelle condition

- Condition monitoring
- rotation speed, rotation angle, temperature, strain, vibrations

tower and fundation

- Strain, accelation, pressure

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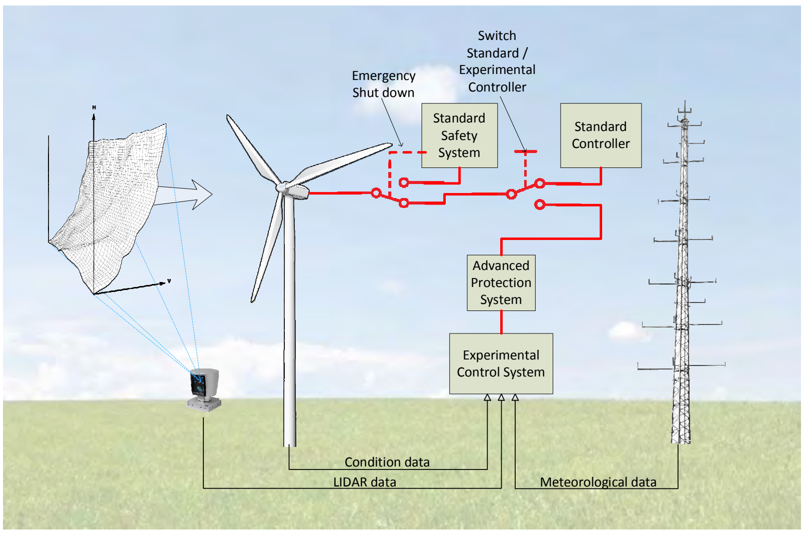
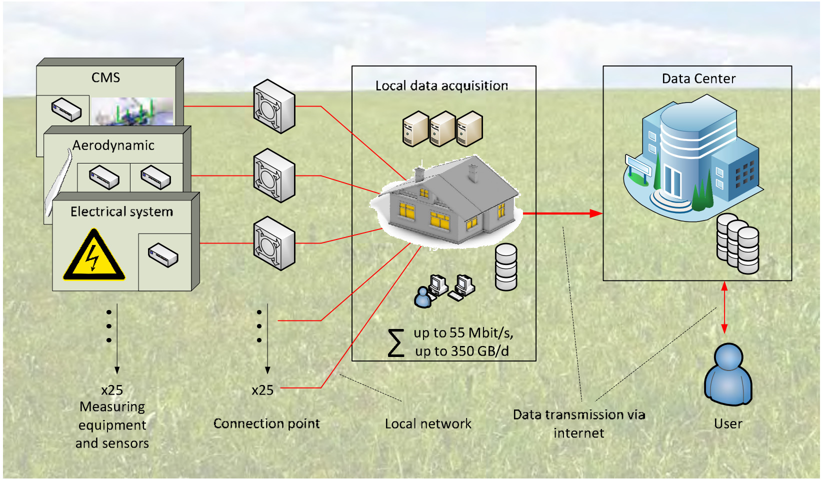
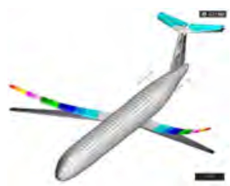
Experimental Control System



Data acquisition system



Rotorblade Instrumentation



Acceleration

sensing of the operational conditions of the oscillating system for aeroelastic

Load monitoring

Evaluation of load cases with strain measurement during the operation

Structural health monitoring

condition monitoring for reduktion of maintenance cost

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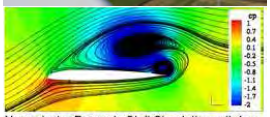
Rotorblade Instrumentation

Temperature and moisture measurement

For monitoring of operating conditions and calibration of sensors

Aerodynamc measurements

pressure measurement at the blades for research of blade aerodynamics



Numerische Dynamic Stall Simulation mit dem DLR-TAU Code

Development of a sensor network

research on eletromagnetic tolerance and lightning protection

Quelle: Energy20.net

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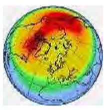
Interdisciplinary partnership teamwork



Institute of Atmospheric Physics

Institute of Flight Systems

Institute of composite structures

Institute of Aerodynamics

Research Platform

Institute of Aeroelasticty

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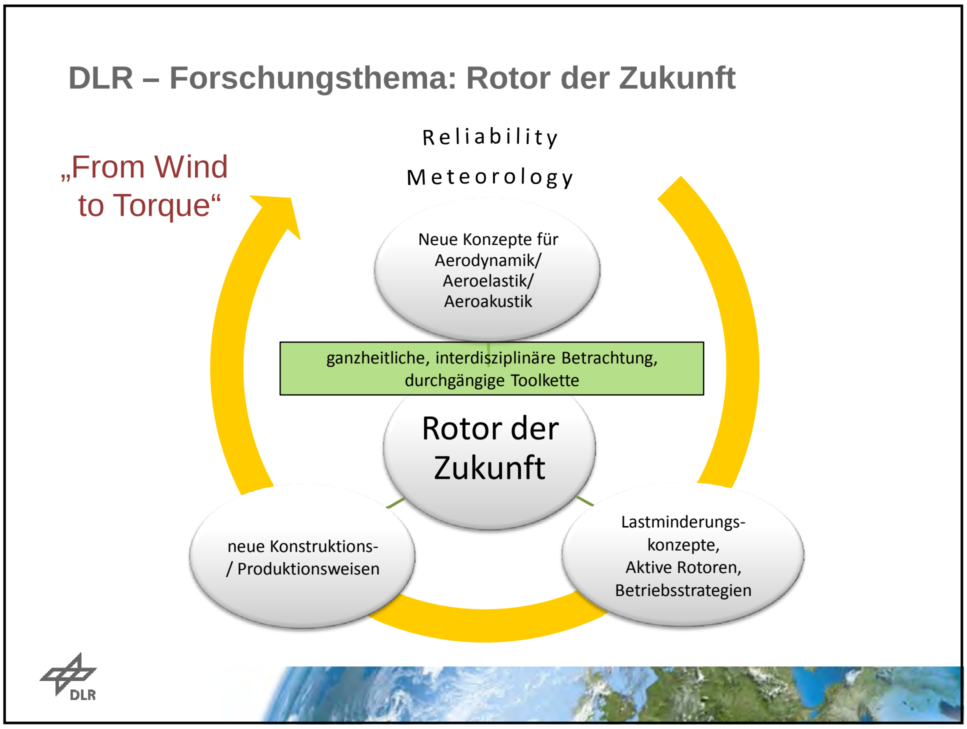
DLR – Forschungsthema: Rotor der Zukunft
„From Wind to Torque"
Reliability
Meteorology
Neue Konzepte für Aerodynamik/ Aeroelastik/ Aeroakustik
ganzheitliche, interdisziplinäre Betrachtung, durchgängige Toolkette
Rotor der Zukunft
neue Konstruktions- / Produktionsweisen
Lastminderungs-konzepte, Aktive Rotoren, Betriebsstrategien
DLR

International Energy Agency (IEA) R&D Wind Task XI

Topical Expert Meeting #78 on

"Field Test Instrumentation and Measurement Best Practises"

7th – 8th October 2014 at USA's National Wind Institute, Texas Tech University, Lubbock, TX

Wind Energy in Germany

Facts, political conditions and DLR's role

Alexander Görmann & Thomas Gerz
German Aerospace Center DLR
Institutes of Flight Technology and Atmospheric Physics
Braunschweig and Oberpfaffenhofen, Germany

Wissen für Morgen

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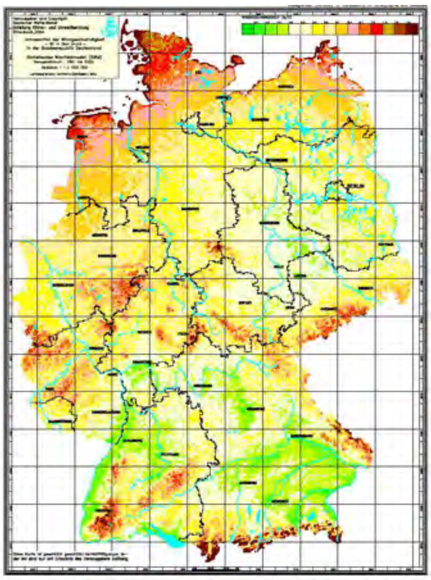
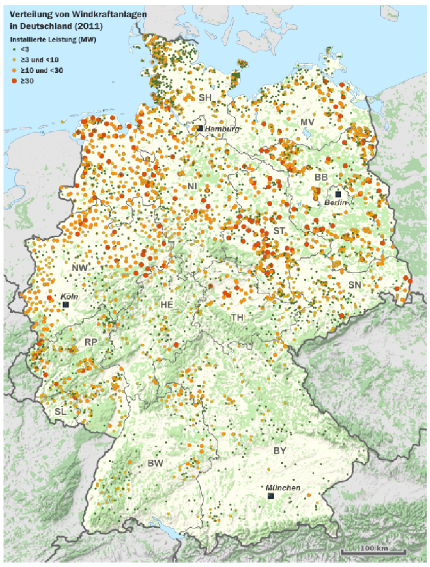
Wind Energy in Germany





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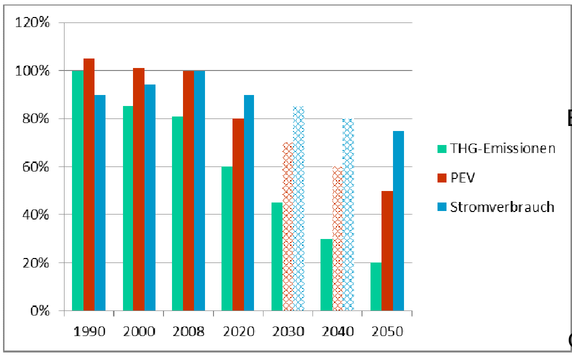
Wind Energy in Germany

political context („Energiewende“)

Germany has defined a bundle of goals:



GHG/THG -80%
PEC/PEV -50%
Electricity consumption -25%
Electricity from RE 80%
Total energy from RE 60%

until 2050 referred to 1990

GHG/THG = green-house gases
PEC/PEV = Primary energy consumption
RE = renewable energy

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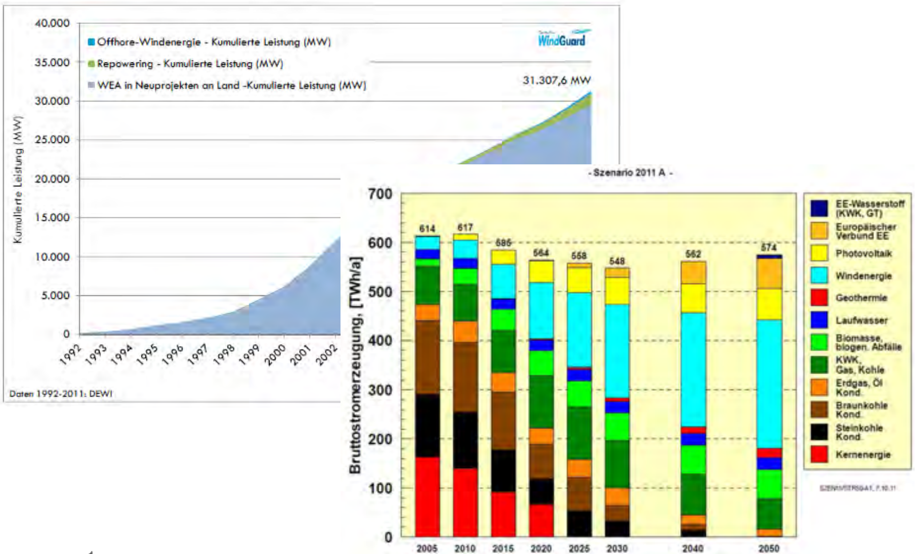
Wind Energy in Germany



Wind Energy in Germany
political context („Energiewende“)

Goal for research:
Reduce Levelized Eneregy Costs (€/kWh) of all RE techniques, in particular for wind and solar energy (high potential)

Consequences of different kind for research:

- …
- Development of cheap and long living storage media (stationary and mobile)
- Energy management in a system with many fluctuating sources
- …
- Reduce maintenance costs / increase life time of wind turbines
- Explore wind characteristics over hilly and complex terrain
- Improve wind short-term forecast and nowcast capabilities
- …

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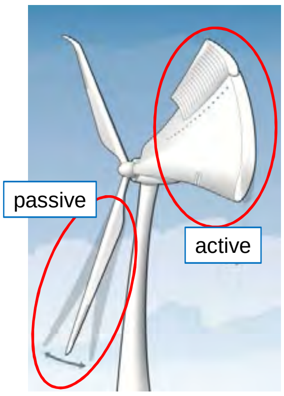
Challenges and Key Questions

Challenges:
- Increase power output and lifetime
- Increase of unit size
- System approach required

Key Questions:
- Technologies for large efficient turbines
- Reduce costs & environ. footprint



Smart Rotors

Aerospace Technologies

Quantity	Factor	Approach
Power	$V^3 * R^2$	Wind, Turbl. nowcasting
Aerodynamic forces	R^2	Load alleviation
Noise	u_{tip}^5	Noise reduction
Weight	R^3	Lightweight design
Weight stress scaling	R	High tensile materials

➡ Up-scaling faces structural limits
Breakthrough technologies required

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Development of a Platform for Wind Energy Research in Germany: DFWind

- Combined effort of DLR, wind energy research institutes of Universities in Oldenburg, Bremen, Hannover (ForWind) and the Fraunhofer Institute of Wind Energy and Energy System Technology (IWES)
- Establishment of a German Research Alliance for Wind Energy (FVWE)

DLR's Focus on „Innovative Rotor"

- New concepts for aerodynamics and active rotors
- Lightweight construction & new fabrication technology
- Meteorology & noise
- Systemic treatment and modelling

DLR

International Energy Agency (IEA) R&D Wind Task XI

Topical Expert Meeting #78 on

"Field Test Instrumentation and Measurement Best Practises"

7th – 8th October 2014 at USA's National Wind Institute, Texas Tech University, Lubbock, TX

Meteorological and Acoustic Instrumentation of Germany's Platform for Wind Energy Research

Thomas Gerz
German Aerospace Center DLR
Institute of Atmospheric Physics
Oberpfaffenhofen, Germany

Wissen für Morgen

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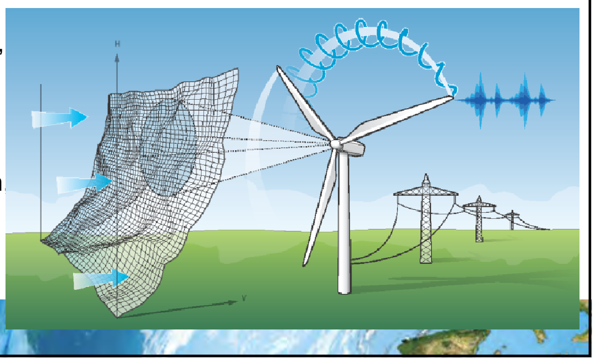
Meteorological and acoustic instrumentation at DFWind

Motivation:

- Being able to determine the meteorological parameters on temporal and spatial scales relevant for wind turbines
- Being able to assess the turbine noise immission
- in atmospheric boundary layer flows over homogeneous and complex terrain

Goal:

- Definition of measurement objectives and strategies
- Specification, selection and installation of a meteorological and acoustic measurement system
- to obtain wind, turbulence, thermal stratification, radiation balance and cloud cover
- as well as sound emission, propagation and immission



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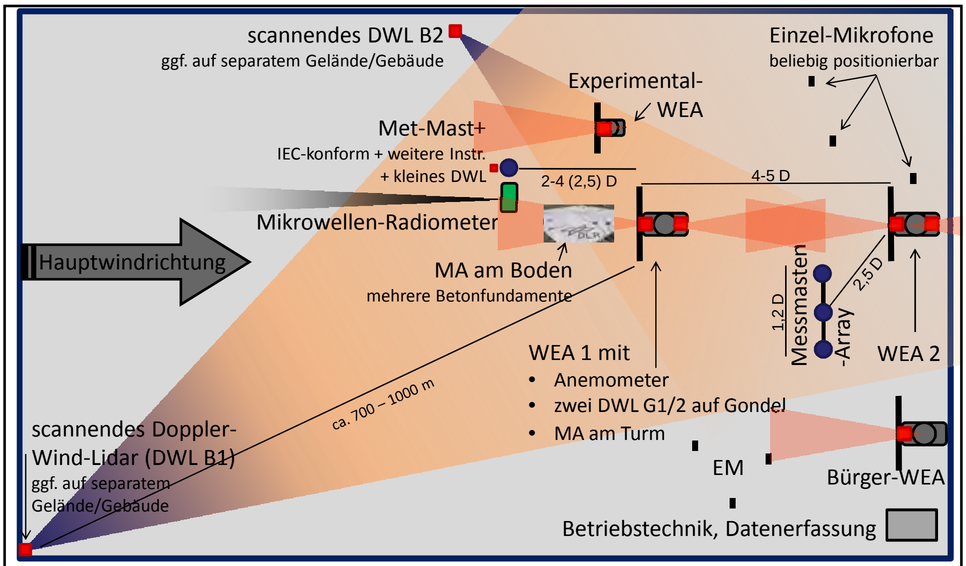

Possible layout of .meteorological and acoustic measurement devices in relation to the 3 (+1) wind turbines and main wind direction in a generic DFWind test field. DWL: Doppler-Wind-Lidar (B Ground, G Gondel), MA: microphon-Array, EM: single microphones, WEA: Wind turbine

Forschungsverbund Windenergie

A result from GROWIAN

J. Peinke, University of Oldenburg

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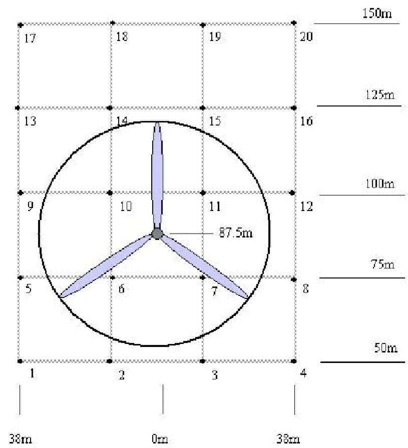
wind field, *J. Peinke, ForWind, 2012*

measuring system



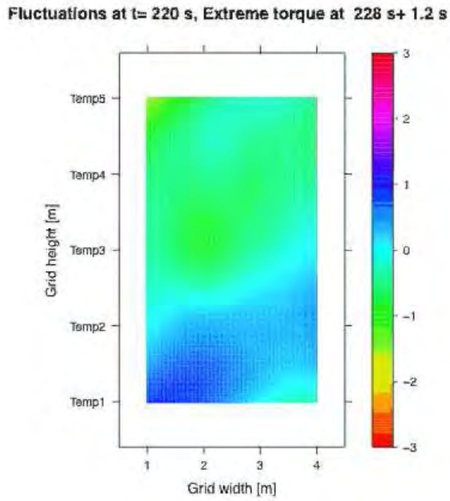
Erice 2012

wind field,

J. Peinke, ForWind, 2012

What happens in reality ?

wind fluctuations in 15 s



Erice 2012

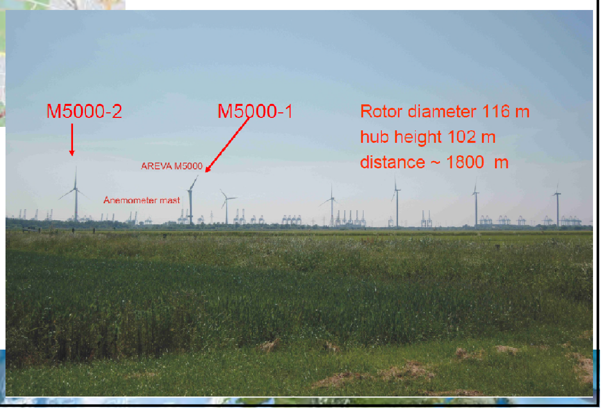
Previous Research Topics at DLR

RAVE Project

Käsler et al., 2010: ***Wake measurements of a multi-MW wind turbine with coherent long-range pulsed Doppler wind lidar.*** **JTECHA**

Lidar wind measurements before and behind an AREVA M5000 turbine

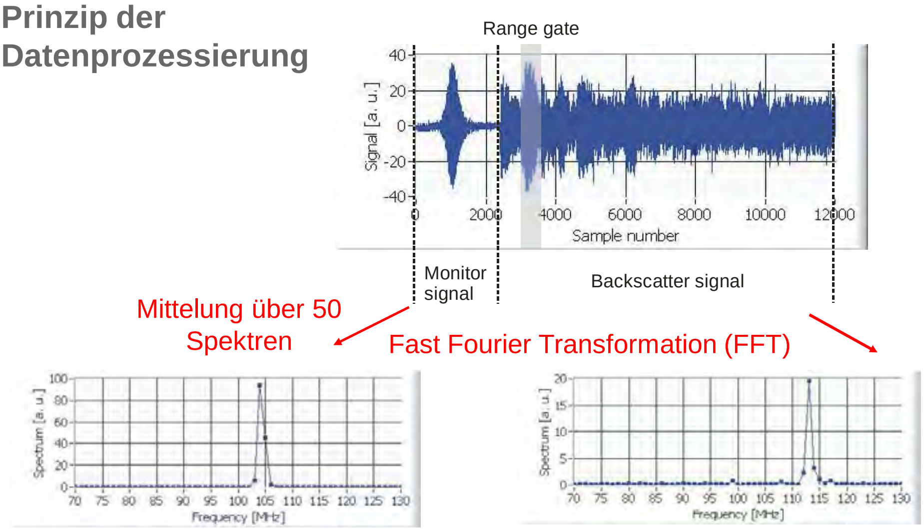
Käsler, Rahm, Simmet



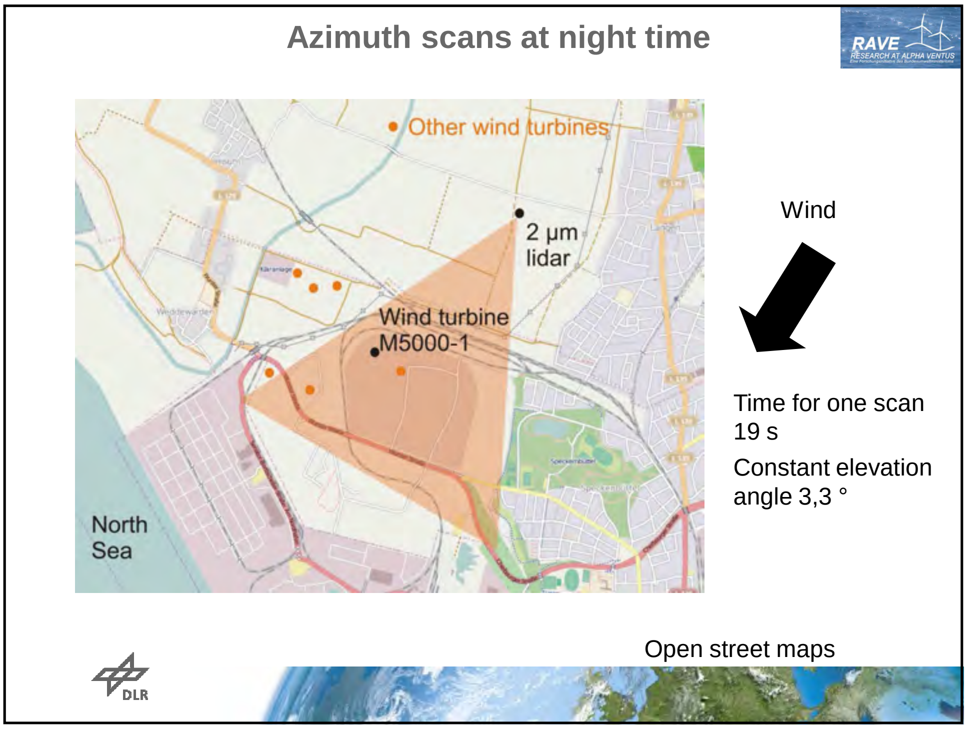
Verwendetes Messsystem: Kohärentes Doppler-Windlidar

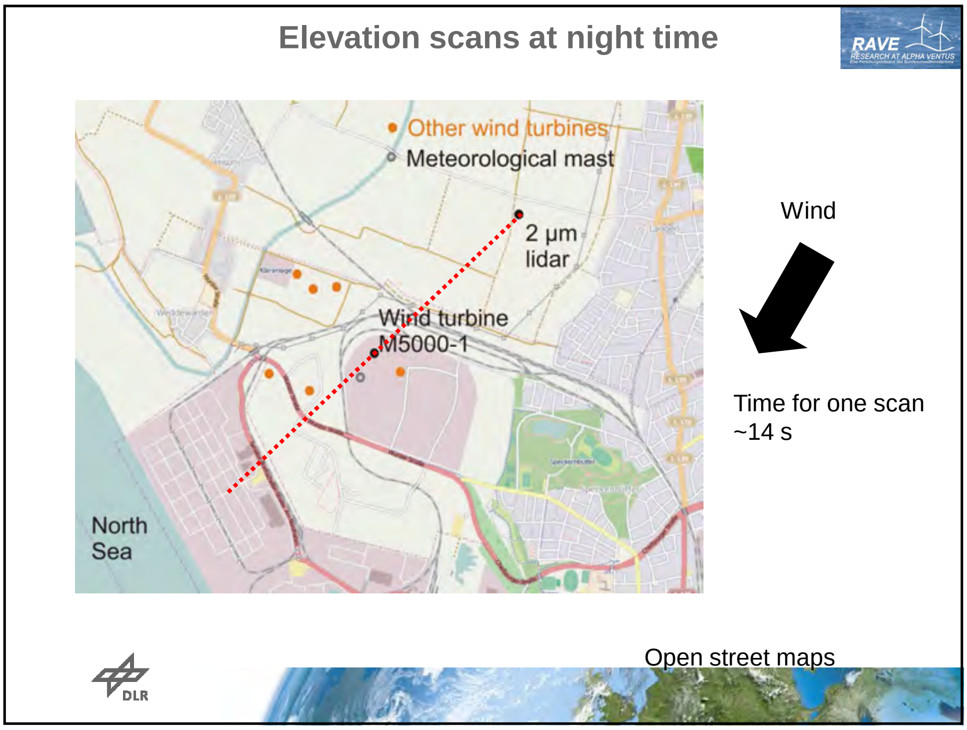
-Tm:LuAG laser
-Wellenlänge: 2.022 µm
-Pulswiederholungsrate: 500 Hz
-Pulsenergie: 1.5 mJ
-Pulslänge (FWHM):
0.5 µs ≙ 75 m
-Apertur des Teleskops: 10 cm
-Doppel-Keil-Scanner mit variabler Scangeschwindigkeit
-Maximaler Messbereich:
500 m - ≥ 10 km
Für Messungen hier:
500 m - 3 km

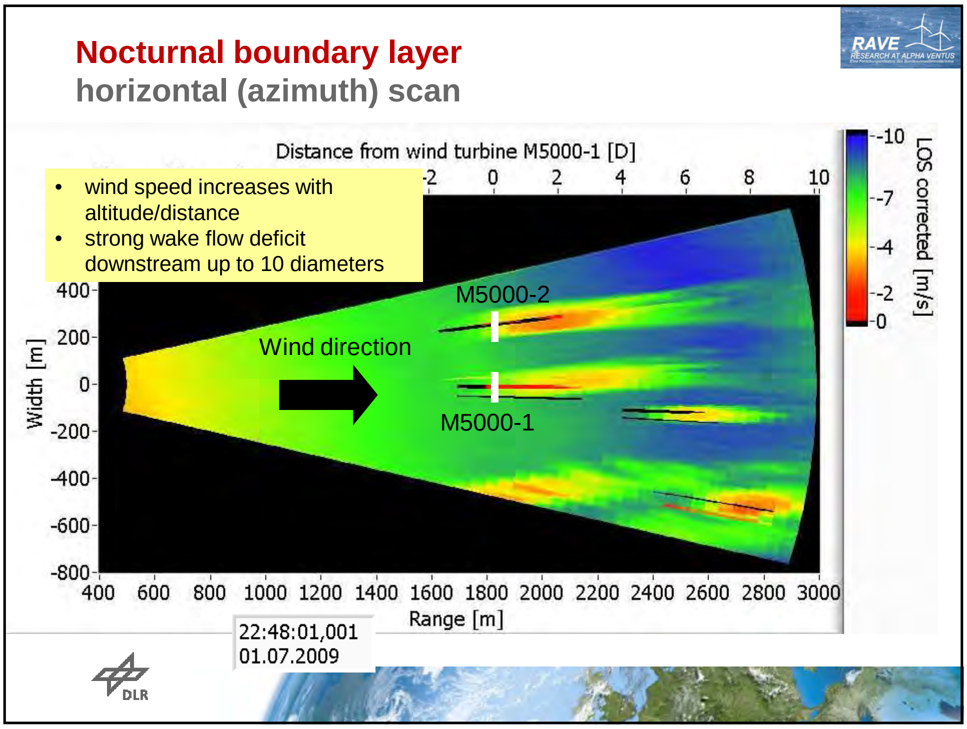
Prinzip der Datenprozessierung

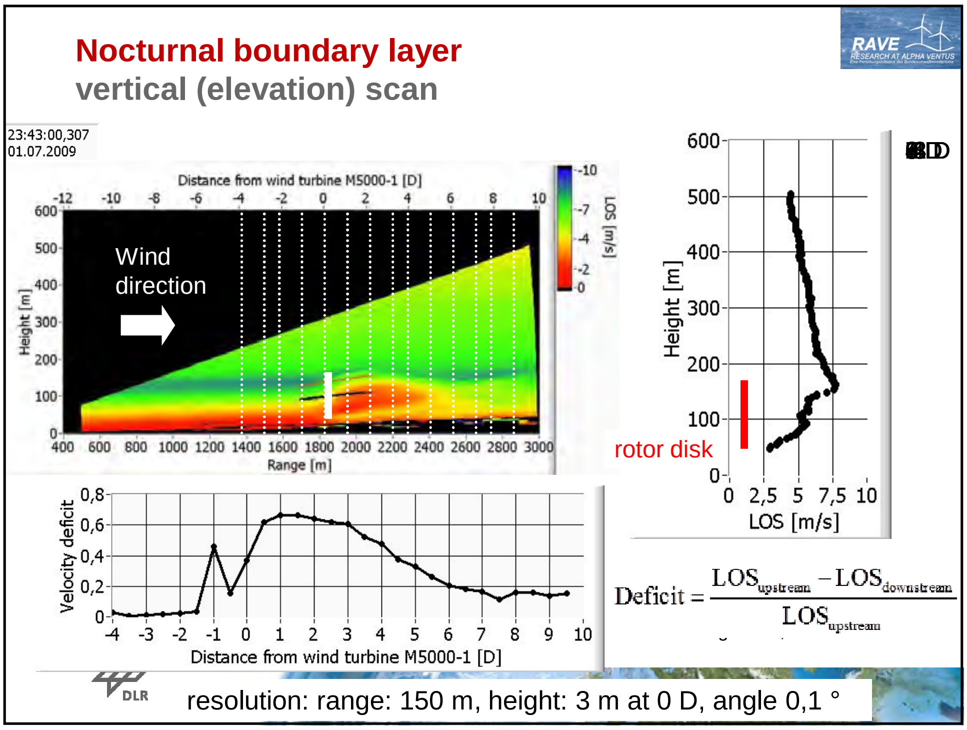


➡ Dopplerverschiebung ➡ Windgeschwindigkeit in Strahlrichtung
line of sight direction, LOS

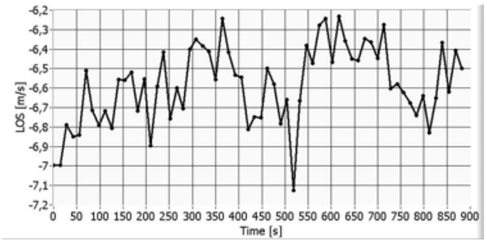

Azimuth scans at night time
RAVE
RESEARCH AT ALPHA VENTUS
Other wind turbines
2 µm
lidar
Wind turbine
M5000-1
North
Sea
Wind
Time for one scan
19 s
Constant elevation
angle 3,3 °
Open street maps
DLR


Elevation scans at night time
RAVE
RESEARCH AT ALPHA VENTUS
Other wind turbines
Meteorological mast
2 µm
lidar
Wind turbine
M5000-1
North
Sea
Wind
Time for one scan
~14 s
Open street maps
DLR


Nocturnal boundary layer
horizontal (azimuth) scan
RAVE
RESEARCH AT ALPHA VENTUS
Distance from wind turbine M5000-1 [D]
• wind speed increases with altitude/distance
• strong wake flow deficit downstream up to 10 diameters
M5000-2
Wind direction
M5000-1
Width [m]
Range [m]
LOS corrected [m/s]
22:48:01,001
01.07.2009
DLR

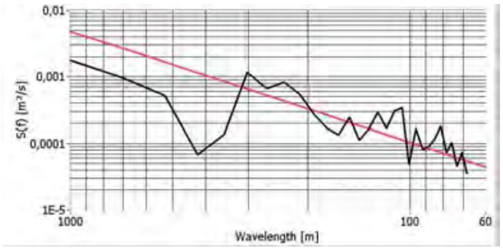

Nocturnal boundary layer
vertical (elevation) scan
RAVE
RESEARCH AT ALPHA VENTUS
23:43:00,307
01.07.2009
Distance from wind turbine M5000-1 [D]
Wind
direction
Height [m]
Range [m]
LOS [m/s]
rotor disk
Height [m]
LOS [m/s]
Velocity deficit
Distance from wind turbine M5000-1 [D]
Deficit = (LOS_upstream − LOS_downstream) / LOS_upstream
DLR
resolution: range: 150 m, height: 3 m at 0 D, angle 0,1 °

Time series and Power density spectra

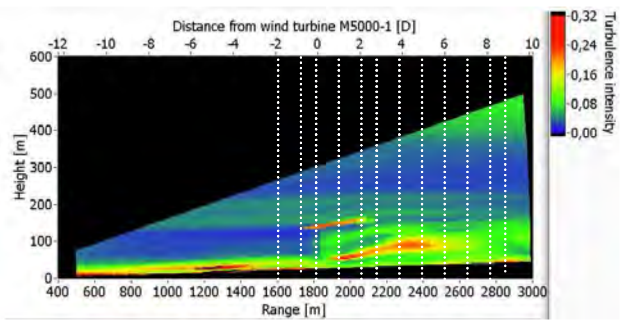


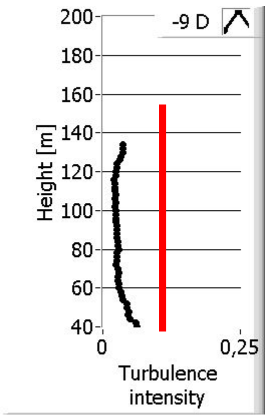
Fourier transformation

Time series LOS(t), dt=14 s, 64 values



Turbulence intensity as fct of distance to turbine

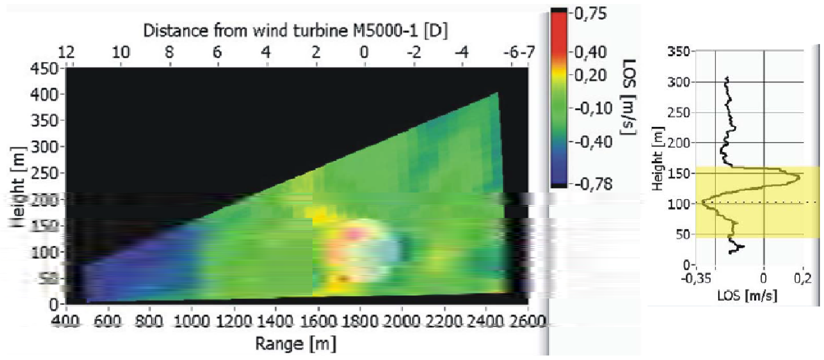




Rotor disc

Schumann, Käsler

Swirl measured with Doppler wind lidar line of sight (LOS) perpendicular to wind direction

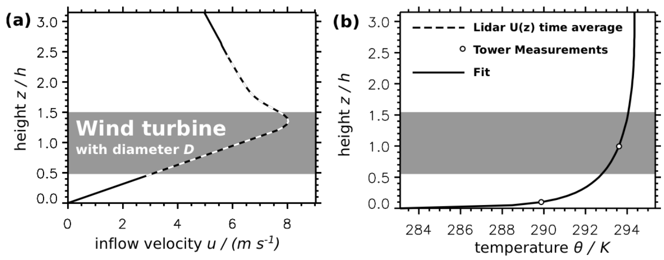


DLR

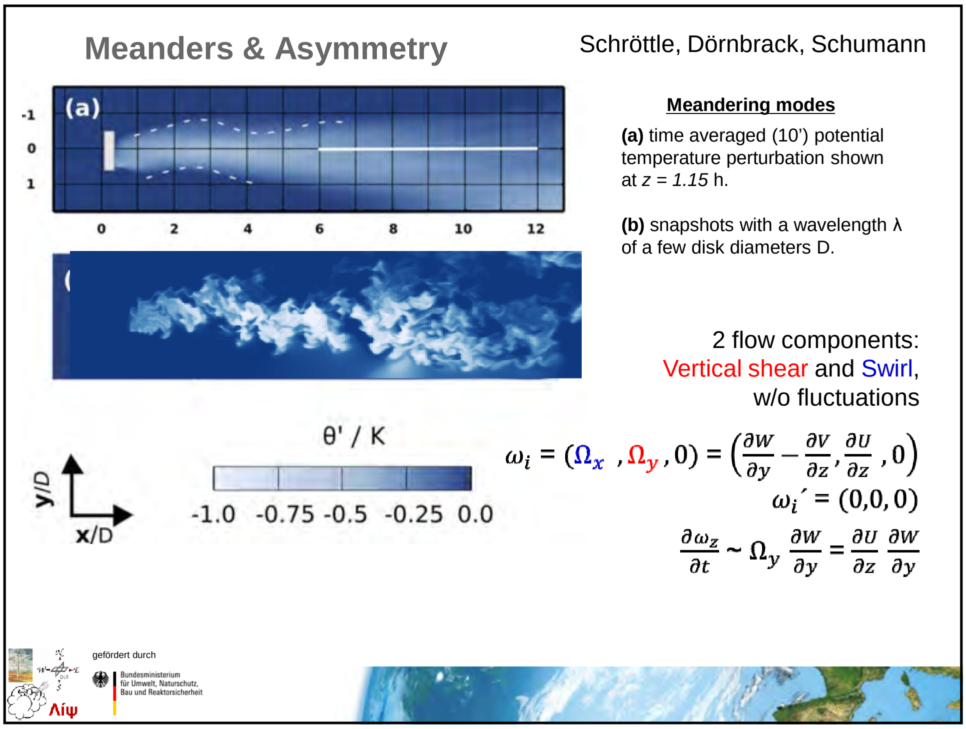
Schröttle, Dörnbrack

LES of the measured flow

iv) Inflow Conditions *(Heimann, D., Käsler, Y., and G. Groß 2011)*



gefördert durch
Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit


Meanders & Asymmetry
Schröttle, Dörnbrack, Schumann
(a)
-1
0
1
0
2
4
6
8
10
12
Meandering modes
(a) time averaged (10') potential temperature perturbation shown at z = 1.15 h.
(b) snapshots with a wavelength λ of a few disk diameters D.
2 flow components:
Vertical shear and Swirl,
w/o fluctuations
θ' / K
-1.0 -0.75 -0.5 -0.25 0.0
y/D
x/D
$\omega_i = (\Omega_x, \Omega_y, 0) = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}, \frac{\partial u}{\partial z}, 0\right)$
$\omega_i' = (0,0,0)$
$\frac{\partial \omega_z}{\partial t} \sim \Omega_y \frac{\partial w}{\partial y} = \frac{\partial u}{\partial z}\frac{\partial w}{\partial y}$
gefördert durch
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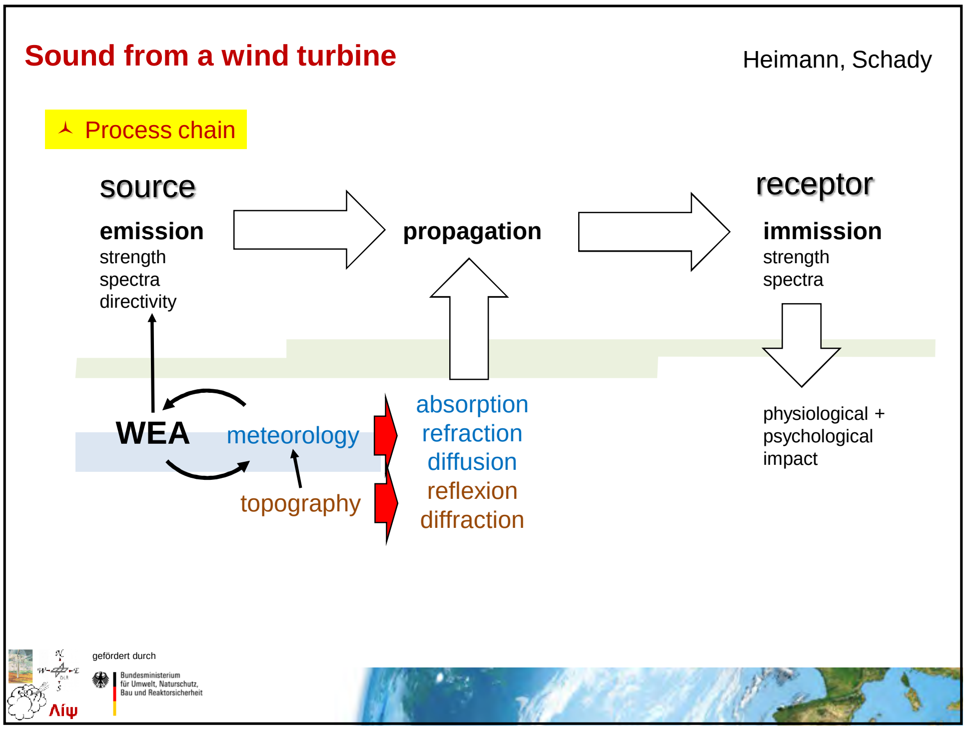
Sound from a wind turbine
Heimann, Schady
Process chain
source
emission
strength
spectra
directivity
propagation
receptor
immission
strength
spectra
WEA
meteorology
topography
absorption
refraction
diffusion
reflexion
diffraction
physiological +
psychological
impact
gefördert durch
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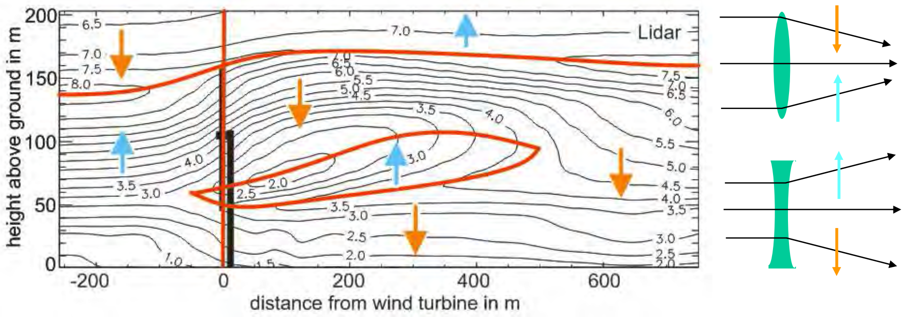
Sound from a wind turbine

Heimann, Schady

- Impact of turbine wake flow



wake flow = system of acoustical lenses

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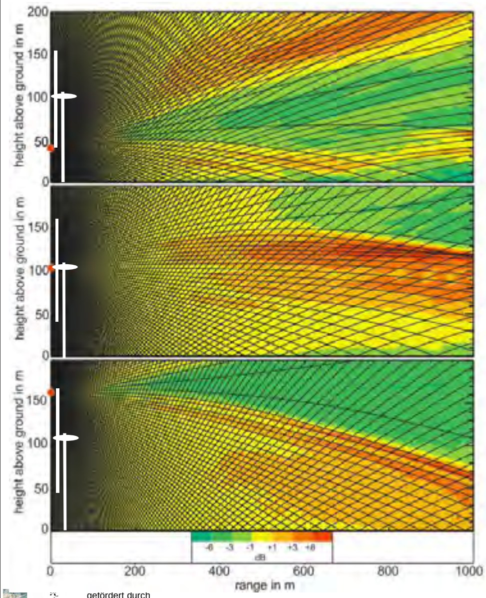
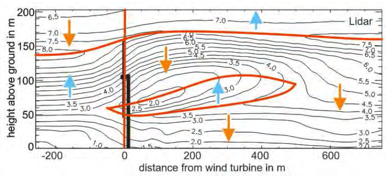
Sound from a wind turbine

Heimann, Schady



2D-simulation (sound particle model)
sound level in dB
relative to propagation
in isothermal, calm atmosphere

meteo data:
Lidar elevation scan
temperature profil (mast)



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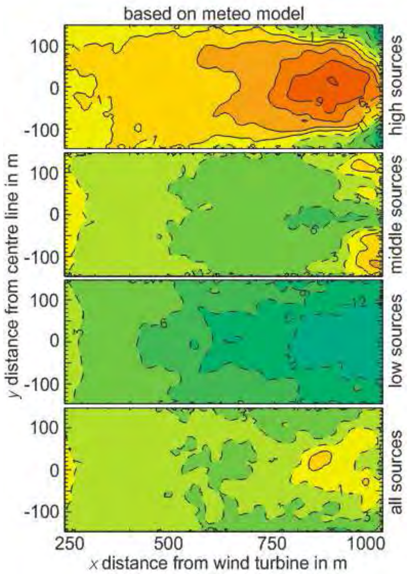
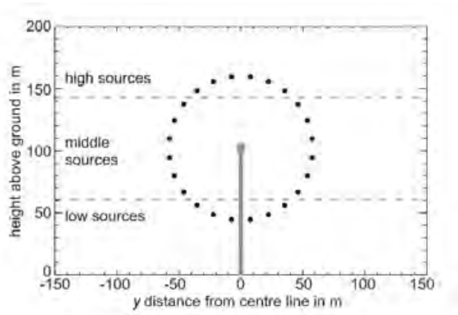
Sound from a wind turbine

Heimann, Schady



3D-simulation
meteo data:
mesoscale model



gefördert durch
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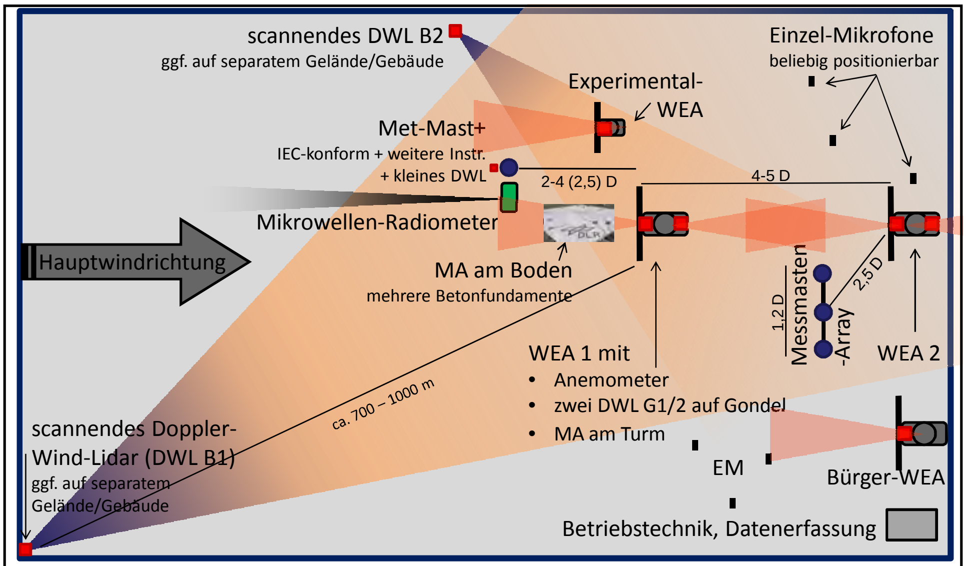
Summary

- Setting-up a wind energy research platform in Germany : DFWind
- Site assessment is in full move
- Proposal for instrumentation of DFWind is submitted to the Federal Ministry of Economy and Energy



Possible layout of .meteorological and acoustic measurement devices in relation to the 3 (+1) wind turbines and main wind direction in a generic DFWind test field. DWL: Doppler-Wind-Lidar (B Ground, G Gondel), MA: microphon-Array, EM: single microphones, WEA: Wind turbine

Forschungsverbund Windenergie

DOE / SNL Scaled Wind Farm Technology (*SWiFT*) Facility Overview

swift.sandia.gov

Jonathan White

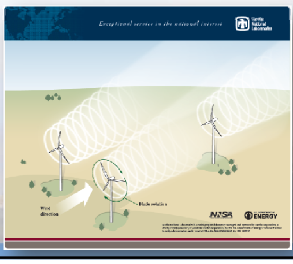
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

SWiFT Facility

SWiFT exists to:

- **Reduce turbine-turbine interaction and wind plant underperformance**
- **Develop advanced wind turbine rotors**
- **Public open-source to advance simulation capabilities**



Facilities:

- **Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite**
- **Two heavily instrumented inflow anemometer towers**
- **Site-wide time-synchronized data collection**

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Outline

- **What is the SWiFT Facility?**
- What research projects use SWiFT?
- What is the future of SWiFT?

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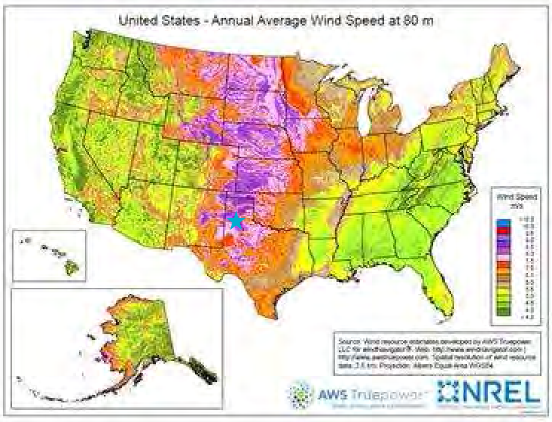
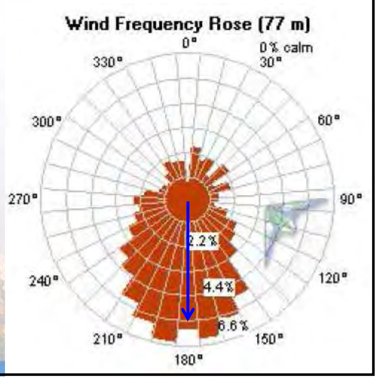
Location, Location, … Location

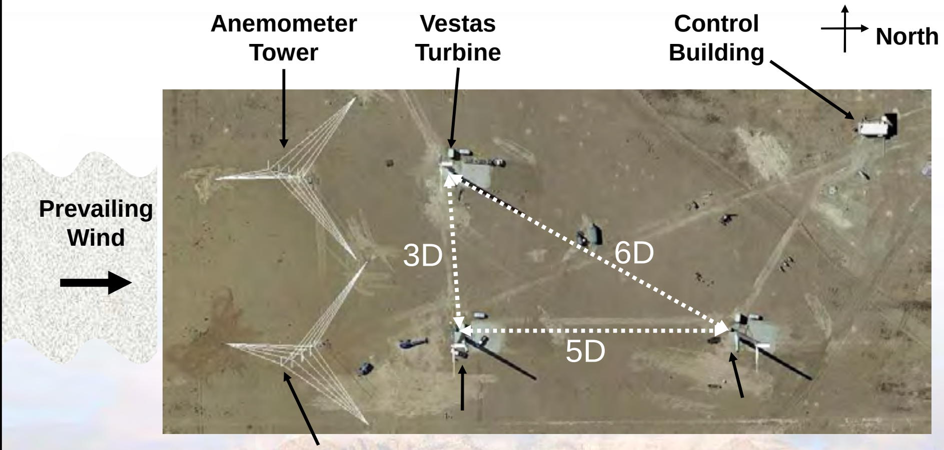


- **7.5 m/s at 50 m, Class 5 Wind Site!**
- **Consistent South Wind, 180.5°Average**



TEXAS TECH
UNIVERSITY

SWiFT Layout



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SWiFT Wind Turbines

Hardware

- Collective Pitch System
- 300 kW Variable Speed Generator
- AC-DC-AC Full Scale Convertor
- National Instruments controllers
- Complete turbine / rotor state instrumentation
- Fiber Optic blade sensing system

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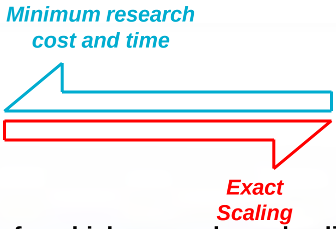
Why this size?

Research-Scale



Megawatt-Scale

- **A cost-efficient size for which research can be directly scaled to larger, more costly and time-consuming sizes.**
- **Requirements:**
  - Operation at Reynolds Number (scaling parameter) between 10^6 and 10^7
  - Tip speeds approaching 80 m/s for acoustics and large rotor projects
  - Variable-speed variable-pitch operation
  - Minimal cost and time associated with research operations
  - Highly reliable turbine
  - Minimal restrictions on publication and intellectual property

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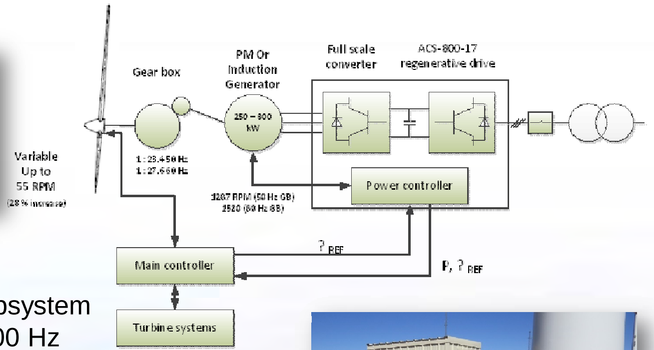
SWiFT Wind Turbines

Control Software



- Open Source Code
- Modularized by Subsystem
- EtherCAT up to 1000 Hz
- All DAQ signals available for control
- Running on NI Veristand
- Parameterized Variable Speed and Torque Controller
- Maintains all original safety systems and alarms

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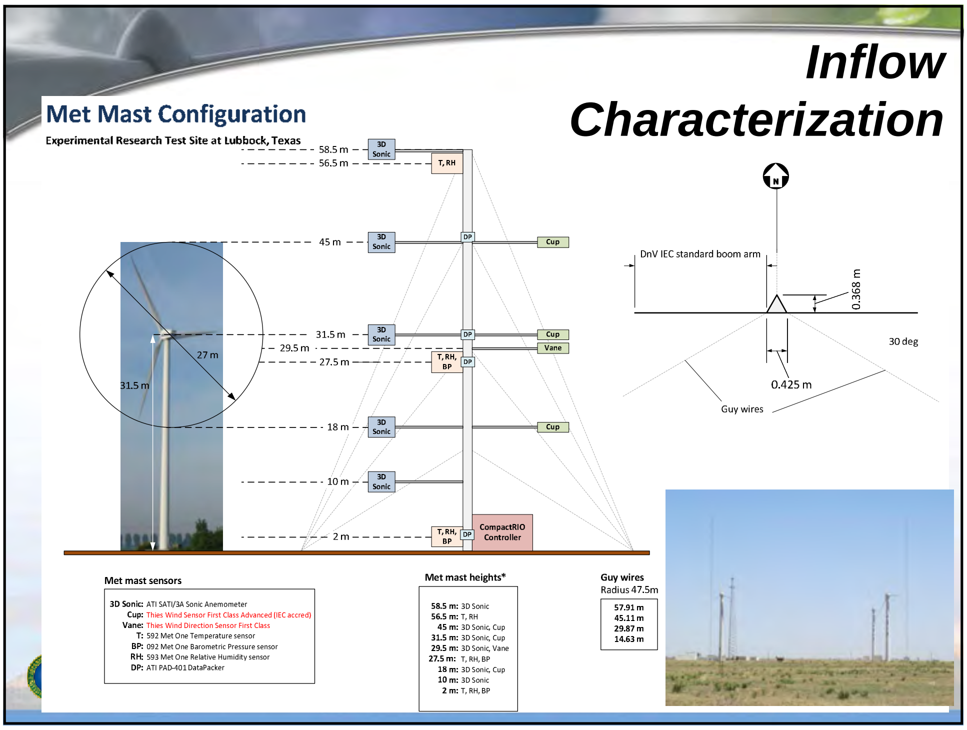
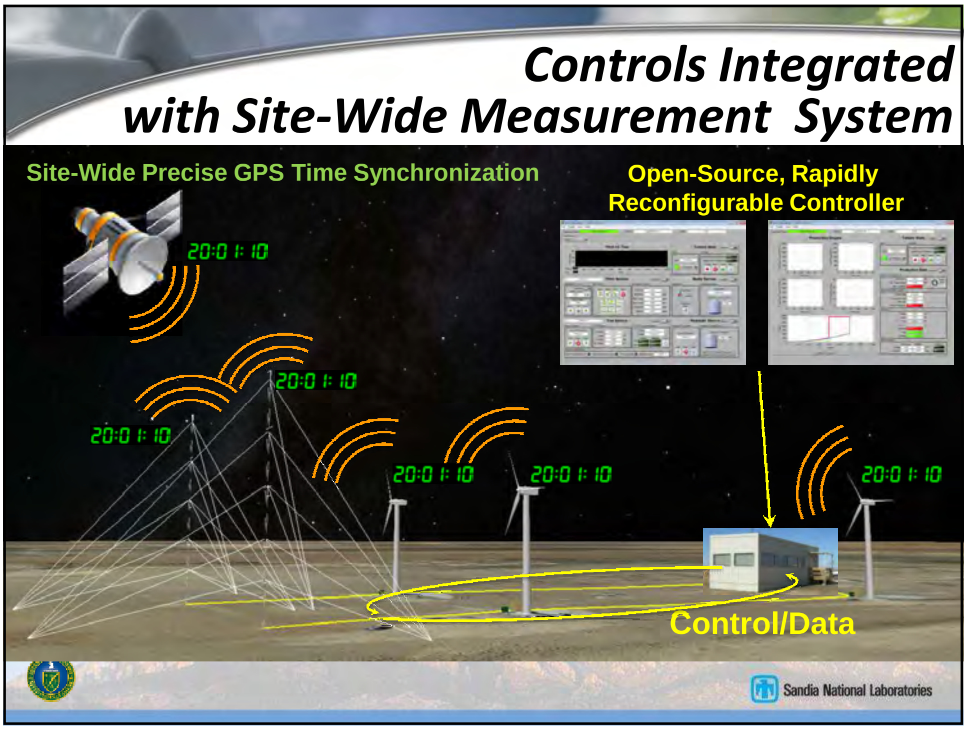
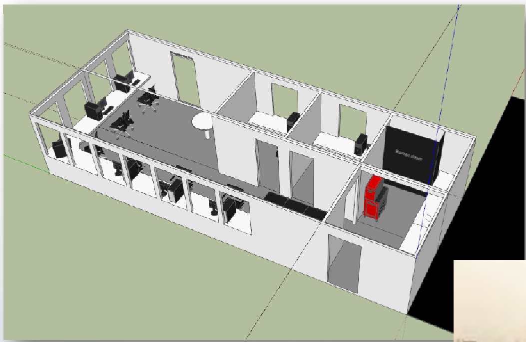

Inflow Characterization
Met Mast Configuration
Experimental Research Test Site at Lubbock, Texas
58.5 m
56.5 m
45 m
31.5 m
29.5 m
27.5 m
18 m
10 m
2 m
27 m
31.5 m
3D Sonic
T, RH
DP
Cup
Vane
T, RH, BP
CompactRIO Controller
DnV IEC standard boom arm
0.368 m
30 deg
0.425 m
Guy wires
Met mast sensors
3D Sonic: ATI SATI/3A Sonic Anemometer
Cup: Thies Wind Sensor First Class Advanced (IEC accred)
Vane: Thies Wind Direction Sensor First Class
T: 592 Met One Temperature sensor
BP: 092 Met One Barometric Pressure sensor
RH: 593 Met One Relative Humidity sensor
DP: ATI PAD-401 DataPacker
Met mast heights*
58.5 m: 3D Sonic
56.5 m: T, RH
45 m: 3D Sonic, Cup
31.5 m: 3D Sonic, Cup
29.5 m: 3D Sonic, Vane
27.5 m: T, RH, BP
18 m: 3D Sonic, Cup
10 m: 3D Sonic
2 m: T, RH, BP
Guy wires
Radius 47.5m
57.91 m
45.11 m
29.87 m
14.63 m


Controls Integrated with Site-Wide Measurement System
Site-Wide Precise GPS Time Synchronization
Open-Source, Rapidly Reconfigurable Controller
20:01:10
Control/Data
Sandia National Laboratories

Control Building

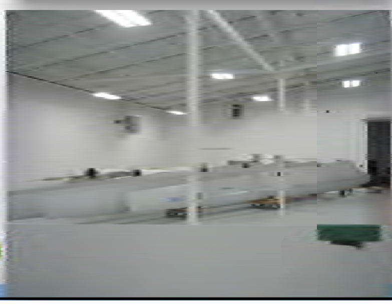


- Central control and operations
- 700 sq. ft. with 2 temporary offices for proprietary work
- Electrical troubleshooting lab

Sandia National Laboratories

Experimental Preparation Lab

- 4,500 sq. ft. environmentally controlled high-bay experimental rotor preparation
- 1,000 sq. ft. machine shop



Outline

- What is the SWiFT Facility?
- **What research projects use SWiFT?**
- What is the future of SWiFT?

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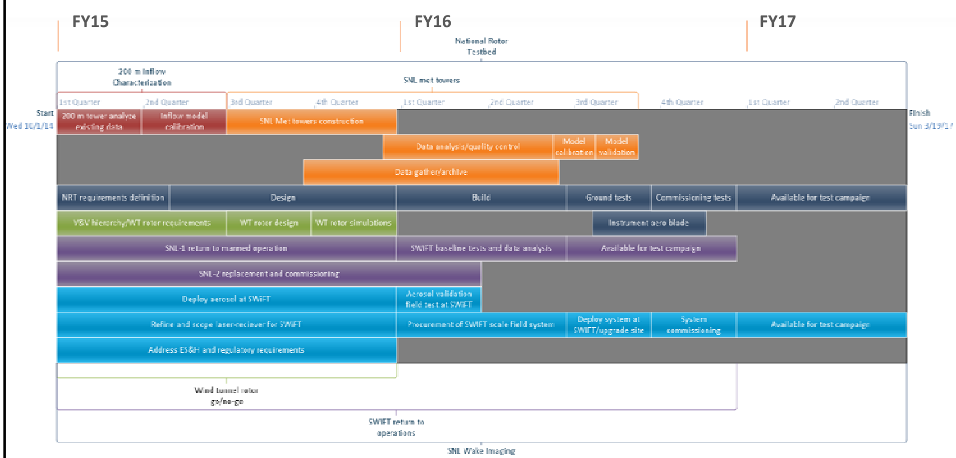
Integrated timeline



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SWiFT Baselining

- Detailed analysis of fundamental turbine-turbine interaction
- Calibration and verification of public open-source wind turbine / plant model
- Data quality analysis and troubleshooting

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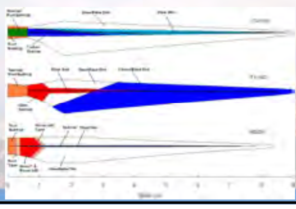
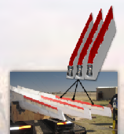
National Rotor Testbed

- The National Rotor Testbed is a rotor innovation to enable technology acceleration
- Baseline blades represent functionally scaled-down aerodynamics and structural dynamics of a modern megawatt-scale rotor
- Baseline blade design is public and open
- Enables research in: wake interactions, aero-acoustics, inboard aerodynamics, controls, aeroelastic dynamics





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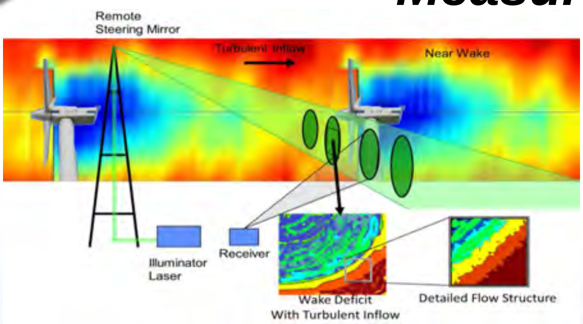
Wake Imaging Measurement System



- Capture detailed 3-D flow structures that convect downwind
- High spatial resolution: 16,000 data points per sample
- Imaging allows for fast scanning sufficient to capture sub-rotor scale turbulent flow structures
- Enables direct comparison with high-fidelity and engineering level models

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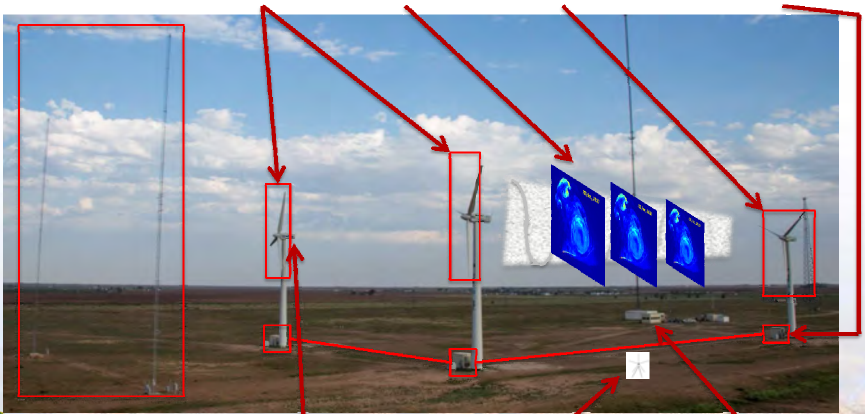
DOE Atmosphere to Electrons Support

- Change focus to Wind Plant Optimization



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Outline

- What is the SWiFT Facility?
- What research projects use SWiFT?
- **What is the future of SWiFT?**

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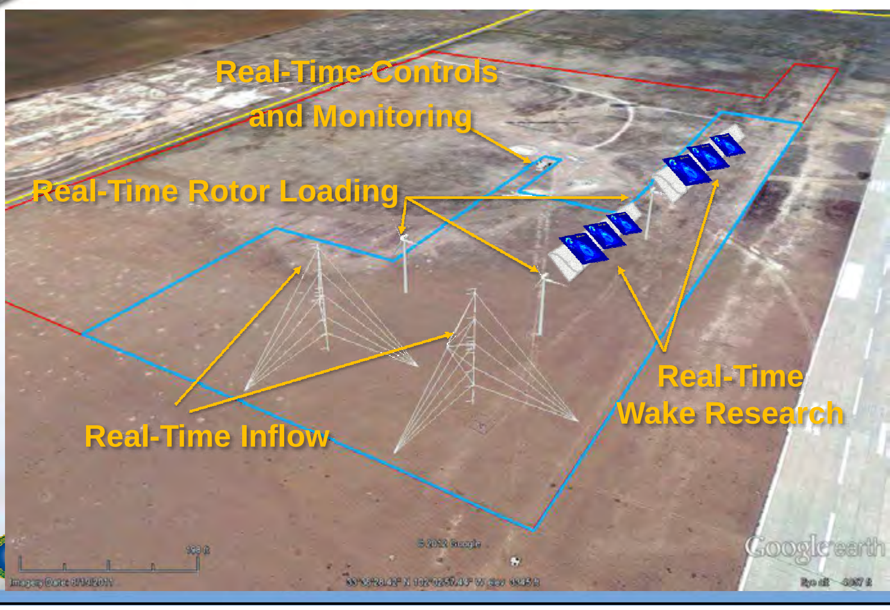
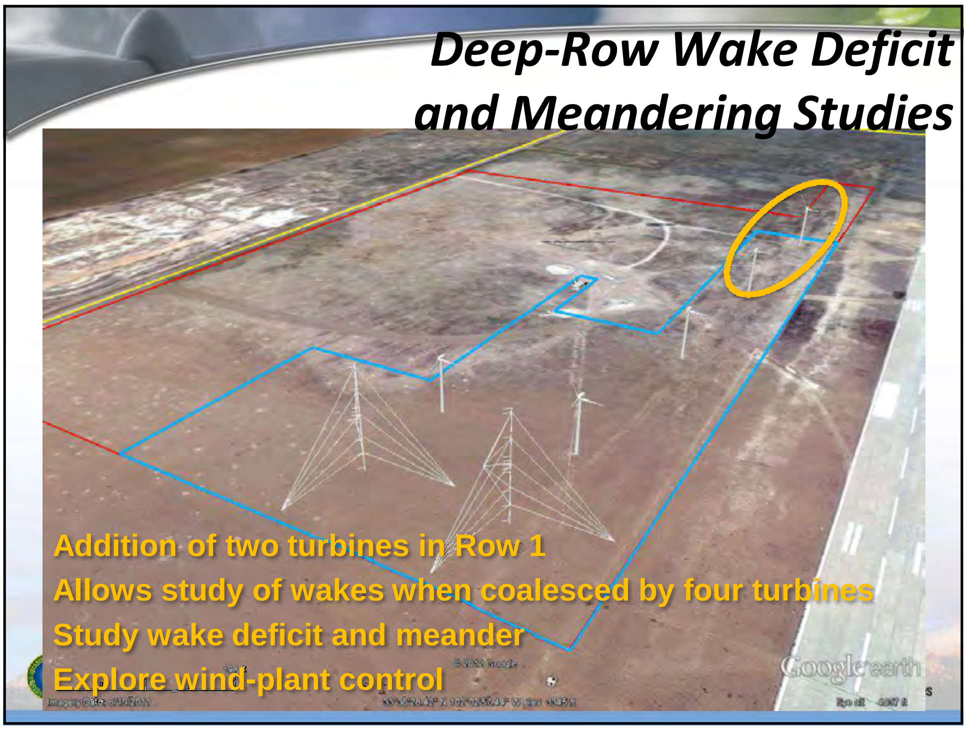
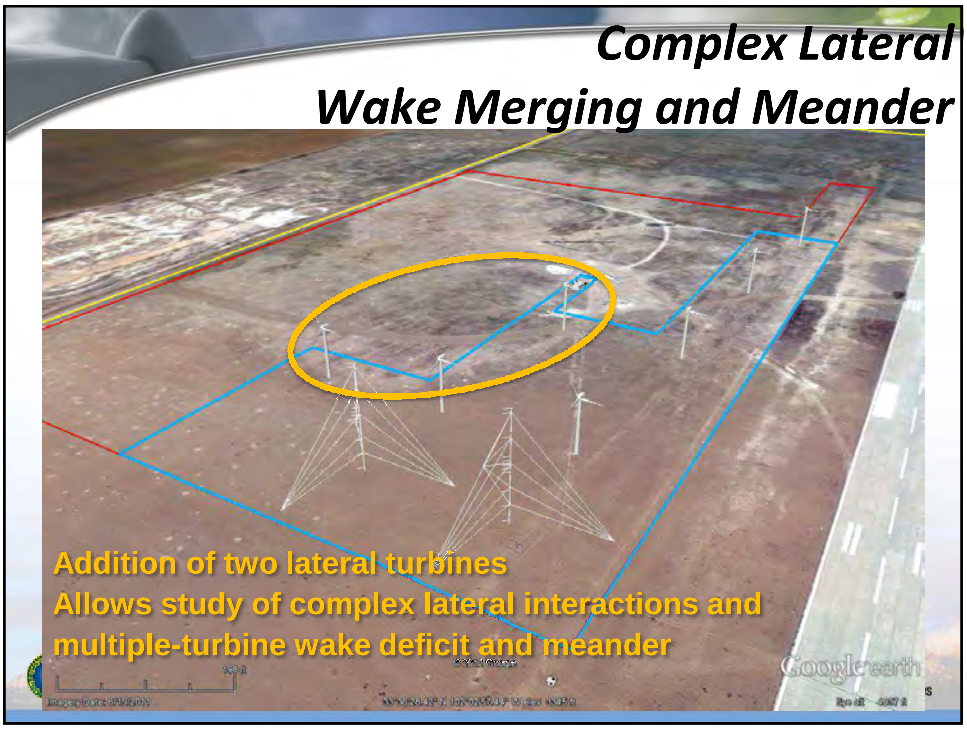
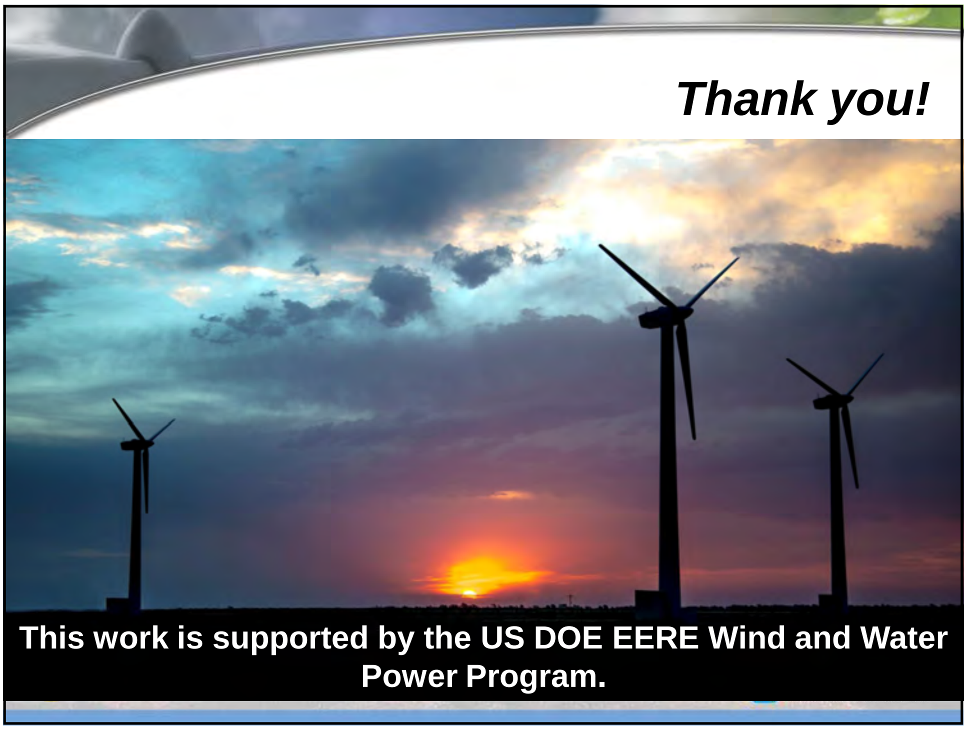
Basic Turbine to Turbine Interaction




Deep-Row Wake Deficit
and Meandering Studies
Addition of two turbines in Row 1
Allows study of wakes when coalesced by four turbines
Study wake deficit and meander
Explore wind-plant control
Google earth


Complex Lateral
Wake Merging and Meander
Addition of two lateral turbines
Allows study of complex lateral interactions and
multiple-turbine wake deficit and meander
Google earth


Thank you!
This work is supported by the US DOE EERE Wind and Water Power Program.

Exceptional service in the national interest

Sandia National Laboratories

Development of the Wake Imaging System

Funded by DOE Wind and Water Energy Technologies Office

Presenter: Tommy Herges

10/7/2014

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

Sandia National Laboratories

- Project Purpose and Objectives
- Planar Doppler Velocimetry Theory
- Notional Field System Deployed at SWiFT facility
- Scaled Sensitivity Experiments (Sprung Test)
  - Velocity Image Results
  - Noise Equivalent Velocity
- Implications for Deployment at SWiFT facility

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Purpose & Objectives

Project Goal: Capture instantaneous velocity images to resolve coherent turbulent structures in the wind turbine wake region

Impact of Project: Innovative instrumentation will enable the validation of research codes and design tools used to optimize wind plant performance.

Success Criteria and Overall Objective

- Near wake investigation in the near term
- Success criteria is a process determined by computational validation requirements
- Final system will be trade-off between required scale (both spatial and temporal), velocity noise, and cost
- Complement existing measurement capabilities such as lidar and radar

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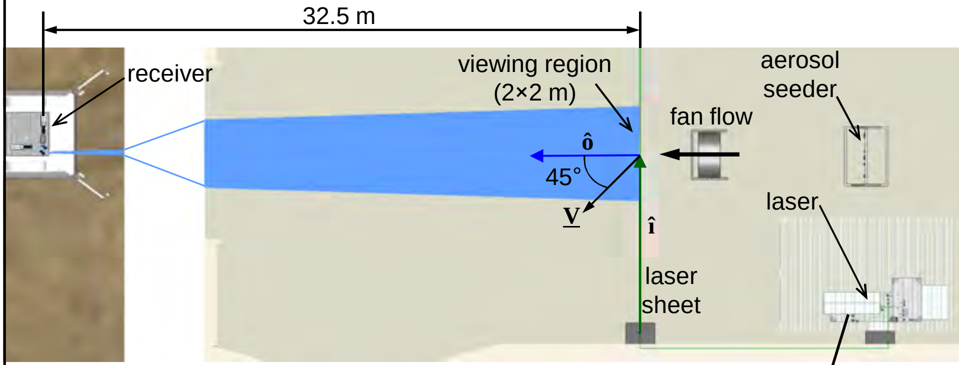
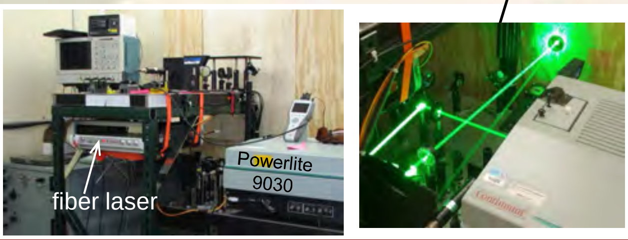
Planar Doppler Velocimetry



Doppler frequency shift equation:

$$\Delta f_D = \frac{1}{\lambda}(\hat{o} - \hat{\imath}) \cdot \underline{V}$$



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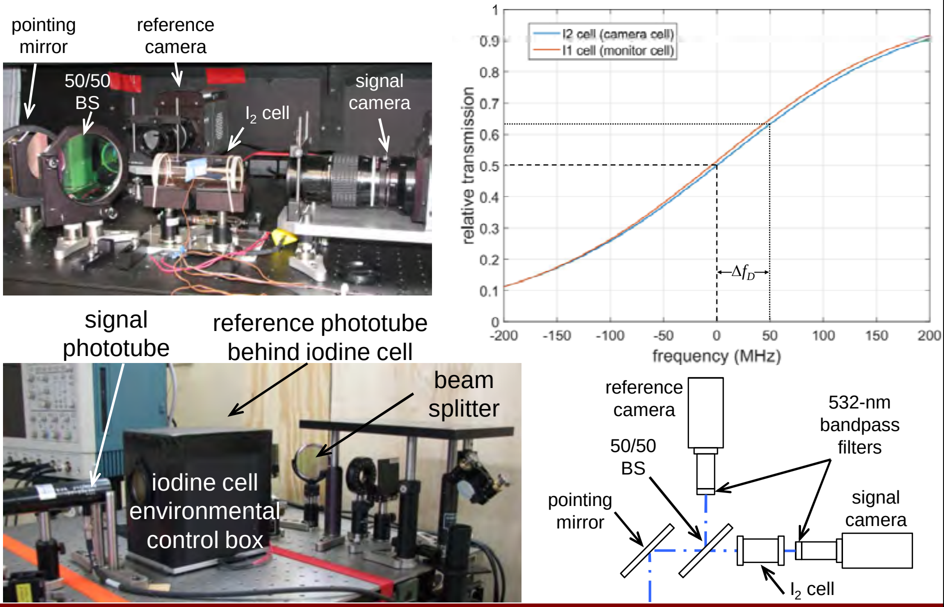
Absorption Profile



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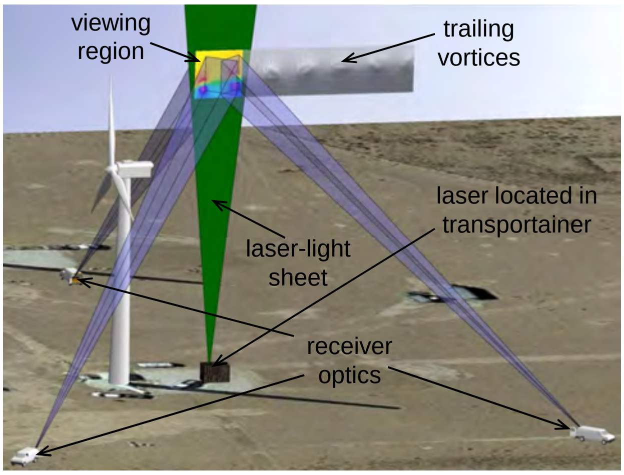
Notional Field System



- Focus on tip vortex region in the near wake
- 5m × 5m measurement area acquired at 15 Hz
- Number of velocity components set by number of receivers

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Project Arc

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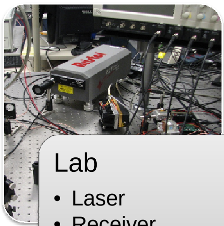
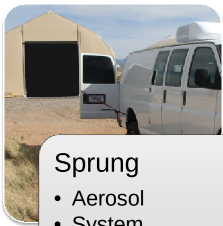
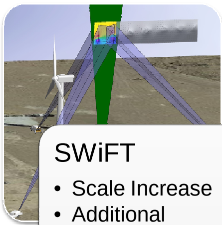


Lab
- Laser
- Receiver
- Iodine Cell
- Image Processing
- 15 cm × 15 cm



Sprung
- Aerosol
- System Sensitivity
- Measurement Uncertainty
- 2 m × 2 m



SWiFT
- Scale Increase
- Additional Velocity Components
- Outdoor Aerosol System
- 5 m × 5 m

Risk reduction approach:
- Demonstrate simplest possible system
- Address make-or-break components
- Identify and resolve safety and health issues early
- Leverage deep expertise, equipment, and facilities at Sandia to save time and money

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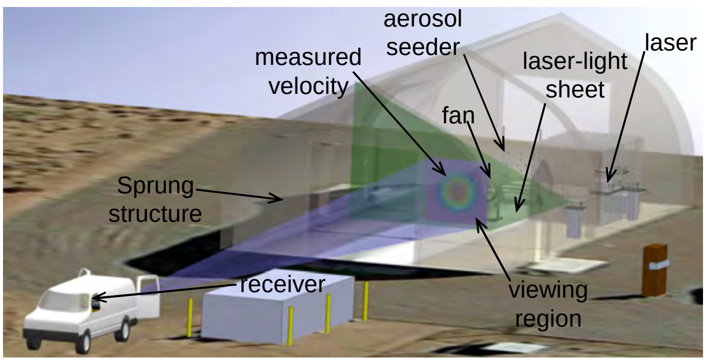
Sprung Scaling Experiment

Sandia National Laboratories

- Intermediate scale to integrate system components at more cost effective scale than possible at SWiFT facility
- Demonstrate successful imaging of velocity field
- Determine system sensitivity and development pathways for major system components



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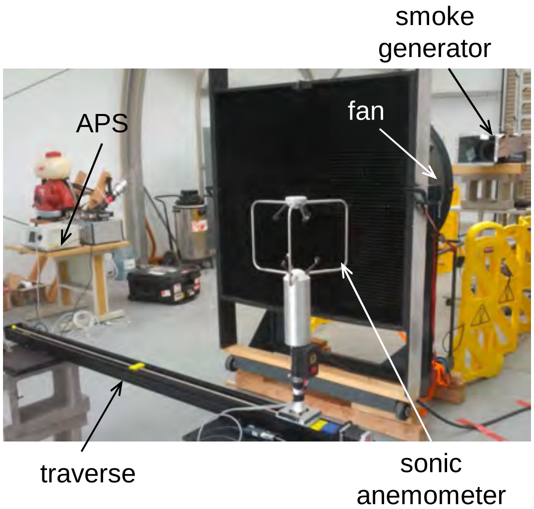
Experimental Configuration



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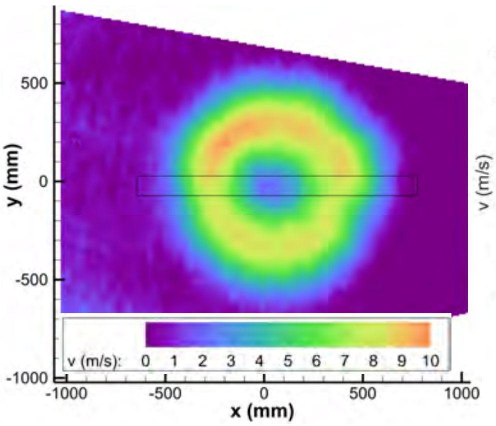
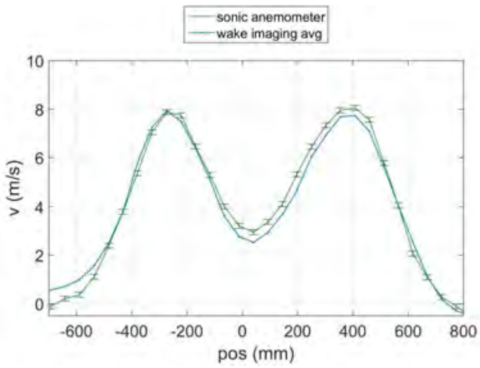
Velocity Measurement Comparison





- Independent sonic anemometer data compares well
- Velocity image processed to match sonic anemometer spatial resolution
- Velocity bias exists between different wake imaging system data sets

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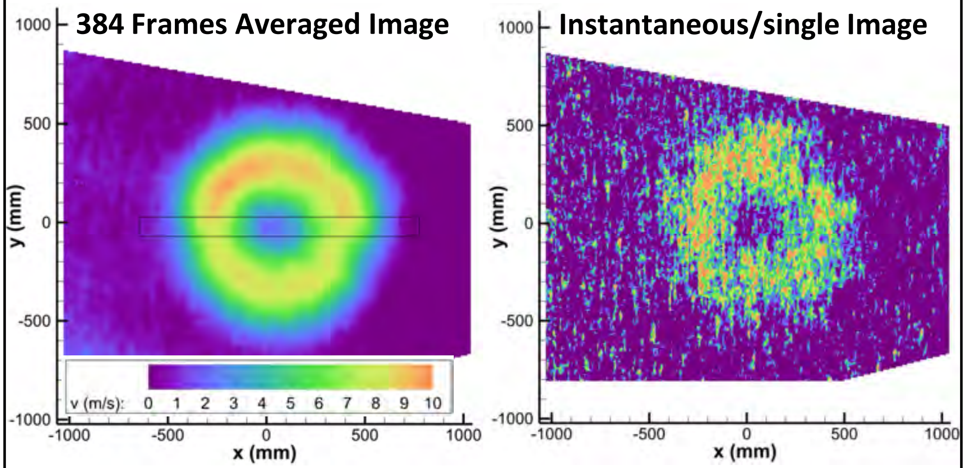
Velocity Images



- 2 m ×2 m viewing area, velocity component at 45^o to fan axis
- Increased velocity annulus created by 3 ft diameter fan
- Instantaneous image ± 3 m/s velocity noise.
- Shot noise limited measurement, depends on number of photons at receiver

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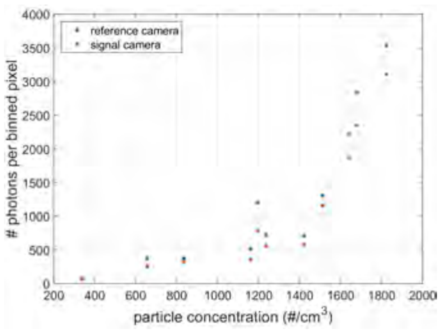
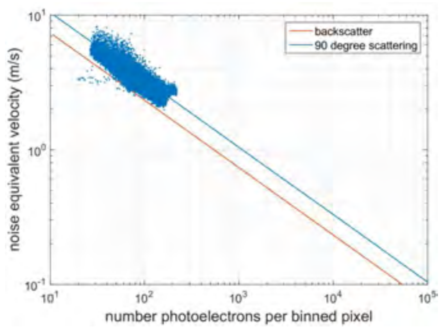
Sensitivity Results and Implications

- Particle scattering efficiency at receiver determined by varying concentration without fan flow present
- Particle size distribution and concentration measured with APS
- Noise equivalent velocity represents the minimum resolvable velocity variation
- Predicting signal levels involves multivariate trade-space: laser pulse energy, particle density and size distribution, range, aperture diameter, receiver binning





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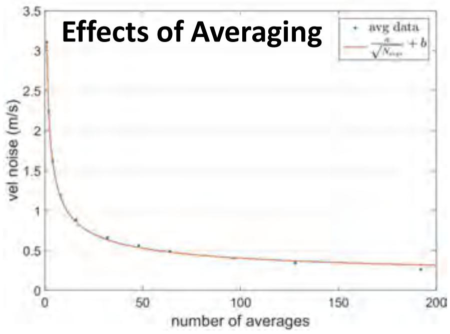
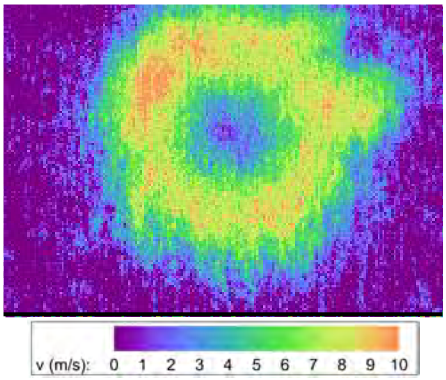
Reducing Noise for SWiFT Deployment

Sandia National Laboratories

- Increase energy per laser pulse
- Receiver binning (increased signal with reduced spatial resolution)
- Higher particulate concentration
- Larger receiver aperture
- Improved post-processing techniques
  - Averaging
  - Filtering



Post-Processed Instantaneous Images



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Notional Field System

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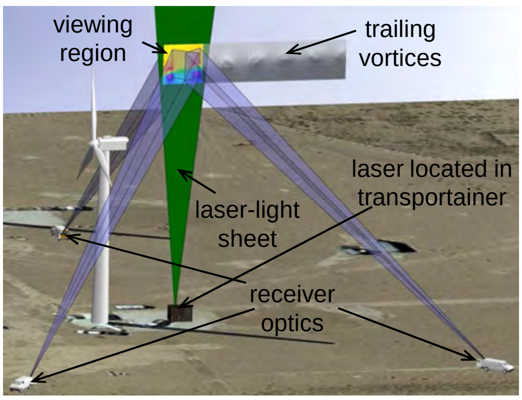
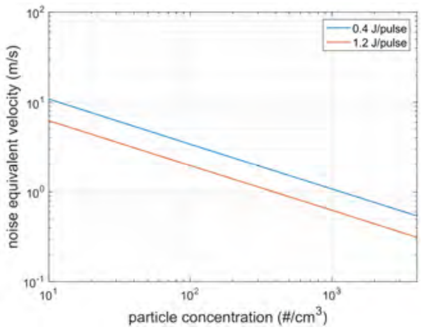


Projected Velocity Noise



- 1 m/s noise level possible assuming 5m × 5m measurement area with similar laser, increased receiver aperture, and aerosol concentration achieved during Sprung testing
- Possible to adjust configuration in trade-off space for computational validation requirements, noise limits, and system cost

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Remaining Tasks

Safety and Primary Stakeholders:

- Sandia National Laboratories
  - ES&H paperwork waiting for final system configuration
- FAA
  - Package prepared to submit to FAA
  - Have permission from Reese to submit to FAA
- DOE
  - NEPA finalized

Project Plan:

- FY15
  - Develop and test aerosol system at SWiFT facility
  - Define system specifications for deployment
  - Budget initial field deployable system
- FY16
  - Deploy the Wake Imaging System at the SWiFT facility

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Back-Up Slides

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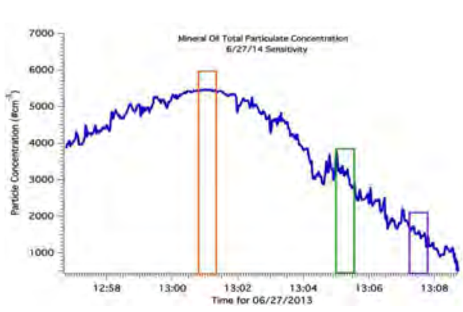
Particle Concentration



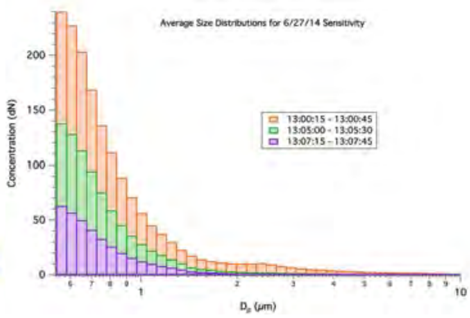
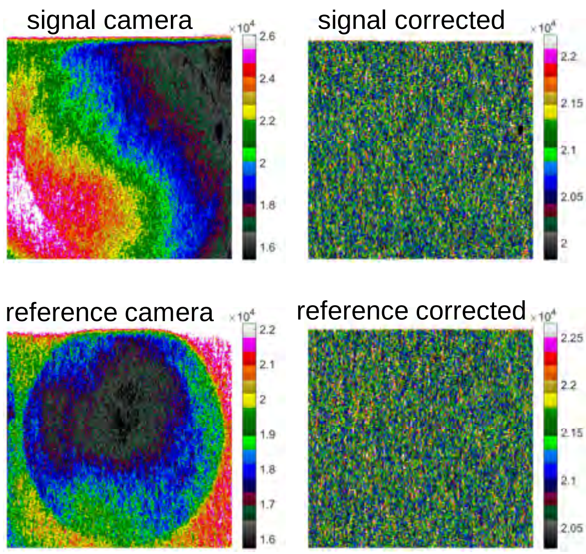


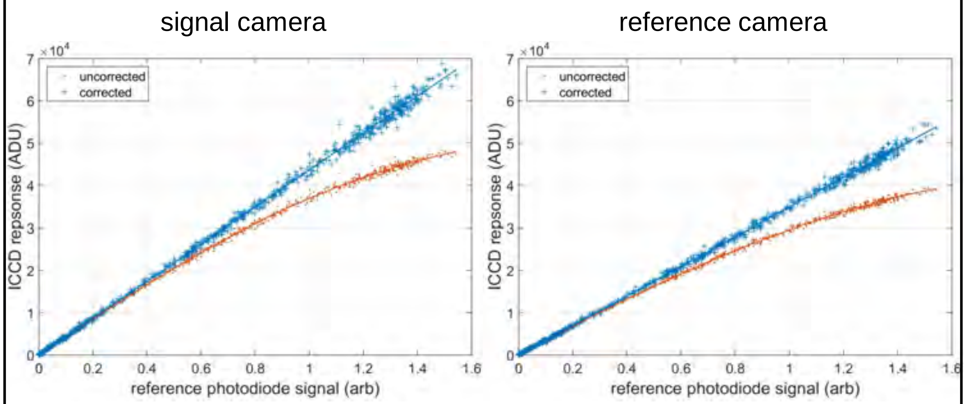
Image Flatfielding



- Each ICCD camera has spatially non-uniform response to light
- Non-linear response over large dynamic range
- Result: each ICCD camera must be calibrated over a variety of illumination levels
- Spatially uniform light source was provided using an integrating sphere

Image Flatfielding

Sandia National Laboratories



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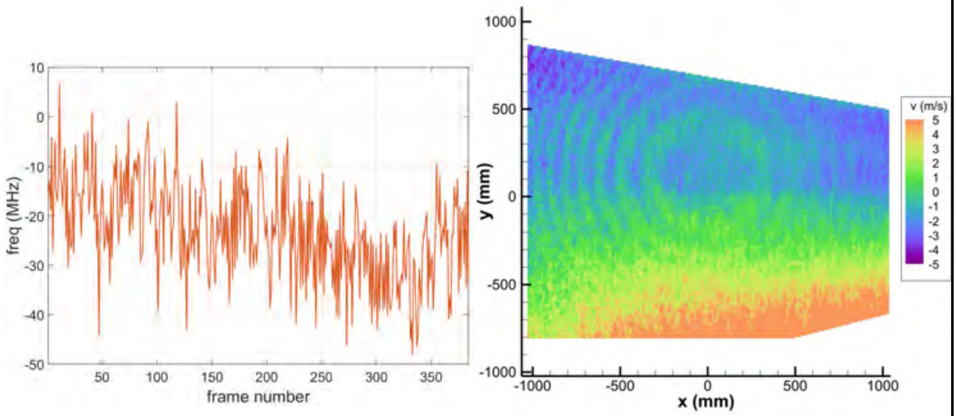
Frequency Correction

Sandia National Laboratories



- Spatial frequency variation through laser cross section of 120 MHz
- Results in velocity variation of ± 5 m/s
- Must zero out spatial frequency variation using target with zero Doppler shift
- Track fluctuating laser pulse frequency

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Velocity Noise

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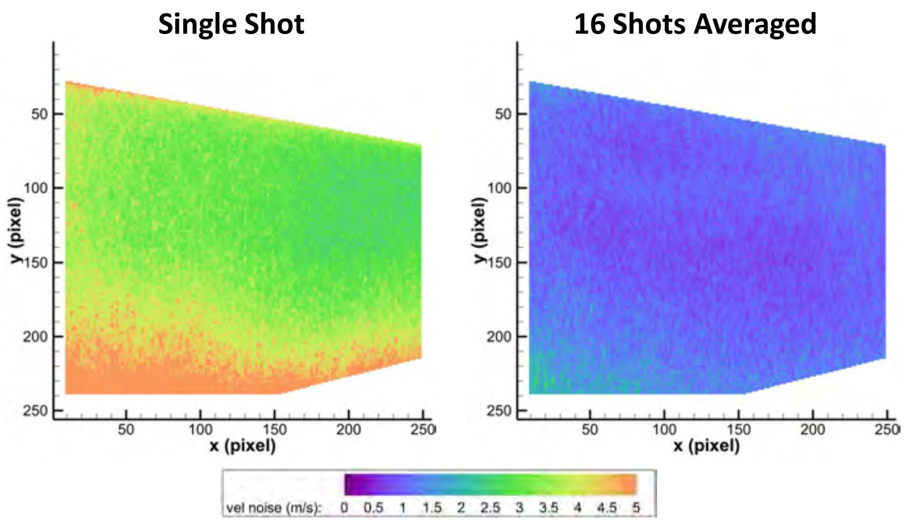

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Effects of Averaging

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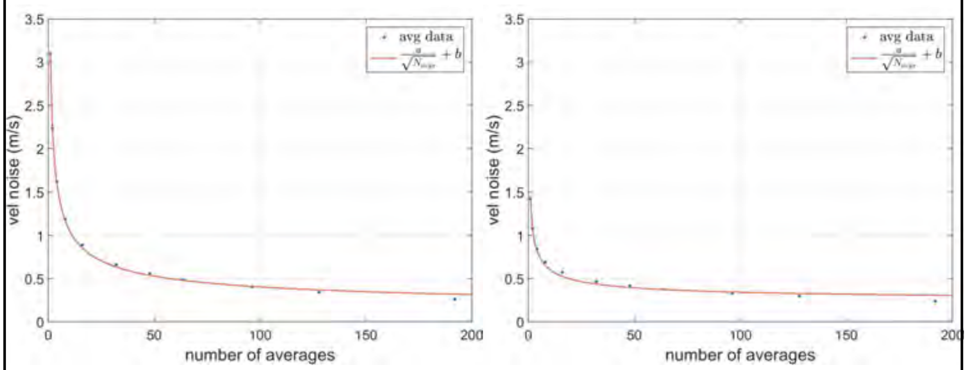

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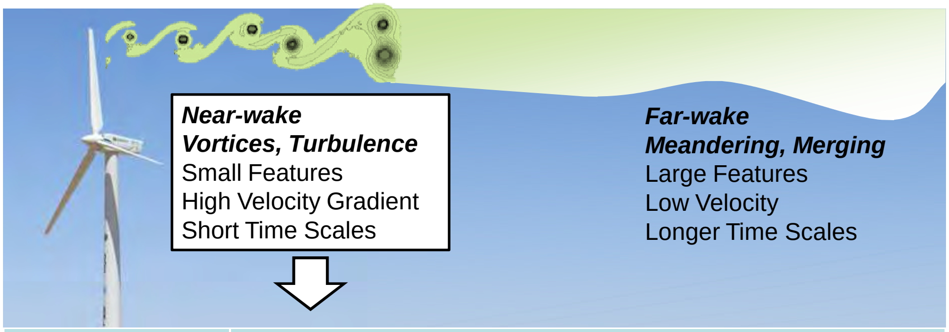
Project Arc



Existing Systems	Challenges in Near-wake field testing
Particle Image Velocimetry (PIV)	**Small field of view** due to particle size and camera resolution relation. Particle release outdoors an **EH&S challenge**.
Scanning LIDAR	**Time resolution** of scanning point measurements is insufficient to capture coherent flow structures

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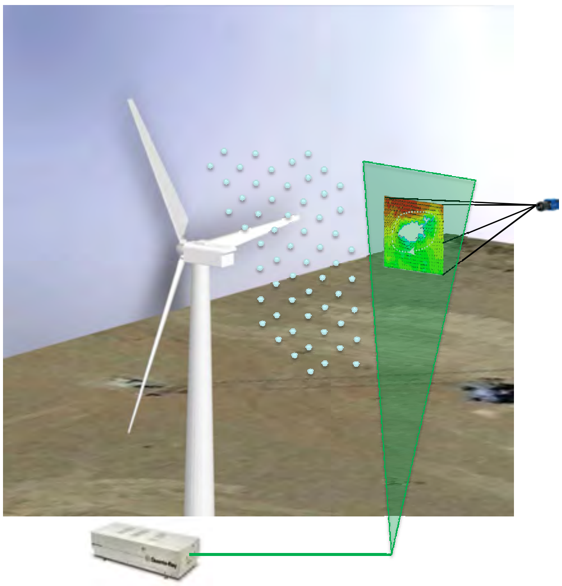
PIV System Requirements



Limiting factor for PIV:

- Light scattered from particles
- Increased laser power/seeding diameter

Drawbacks:

- Very high-powered laser
- Large seeding particles (worse flow tracking)
- Shorter working distance for camera (camera positioned near viewing region)
- Slower data sampling

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National Wind Institute

Measuring Wind Plant Complex Flows using Research Radars

John L. Schroeder[1], Jerry Guynes[2], Brian Hirth[2]
[1]Professor of Atmospheric Science
[2]Research Faculty, National Wind Institute
Texas Tech University

IEA TEM #78 – Field Test Instrumentation and Measurement
Texas Tech University
October 7, 2014

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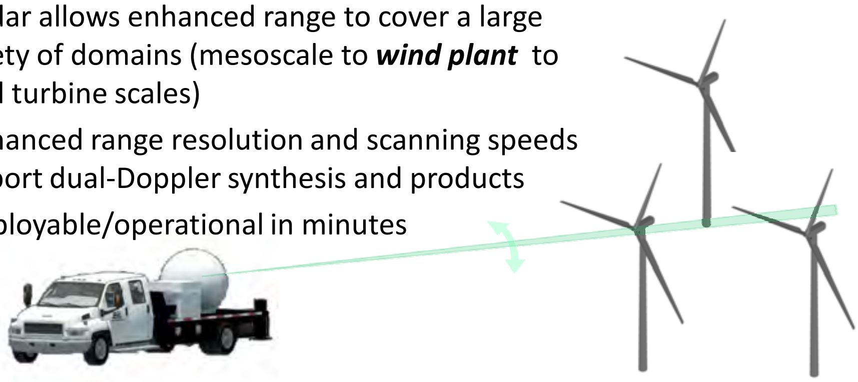
Using Radar Technology to Measure Complex Flows

- Remote sensing allows for the efficient and non intrusive measurement of wind flow
- Radar allows enhanced range to cover a large variety of domains (mesoscale to ***wind plant*** to wind turbine scales)
- Enhanced range resolution and scanning speeds support dual-Doppler synthesis and products
- Deployable/operational in minutes



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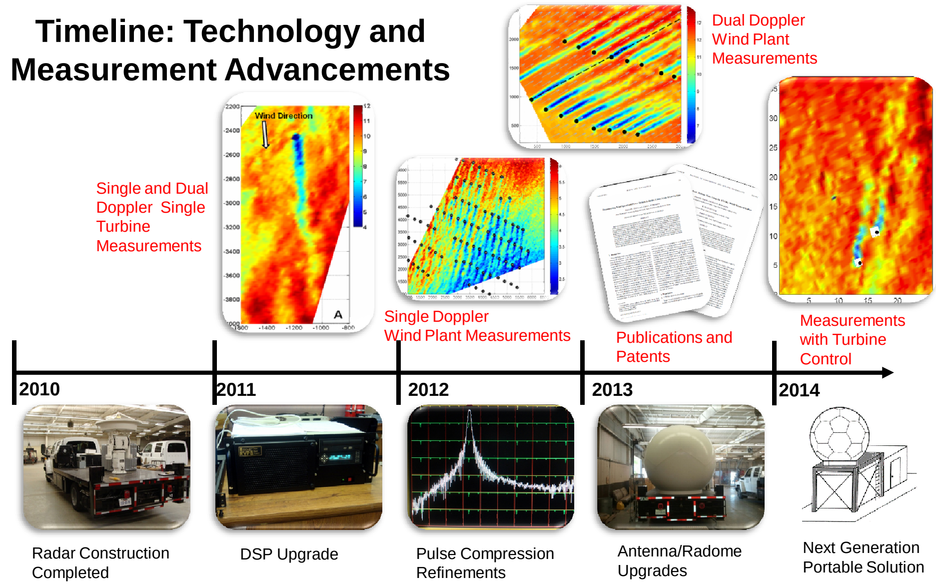
Timeline: Technology and Measurement Advancements



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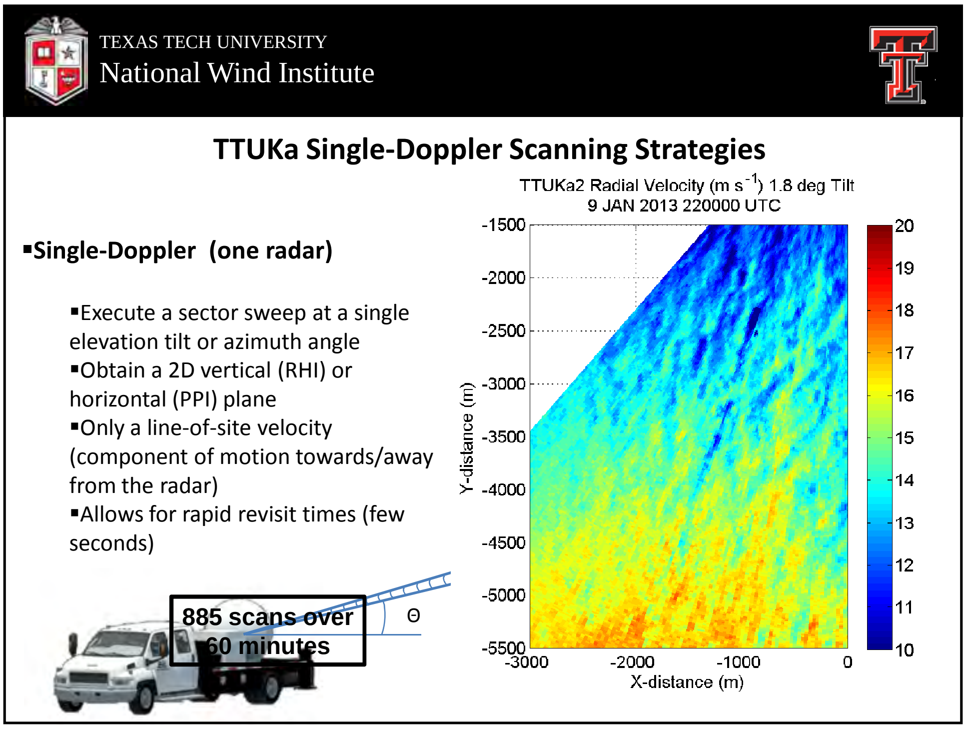
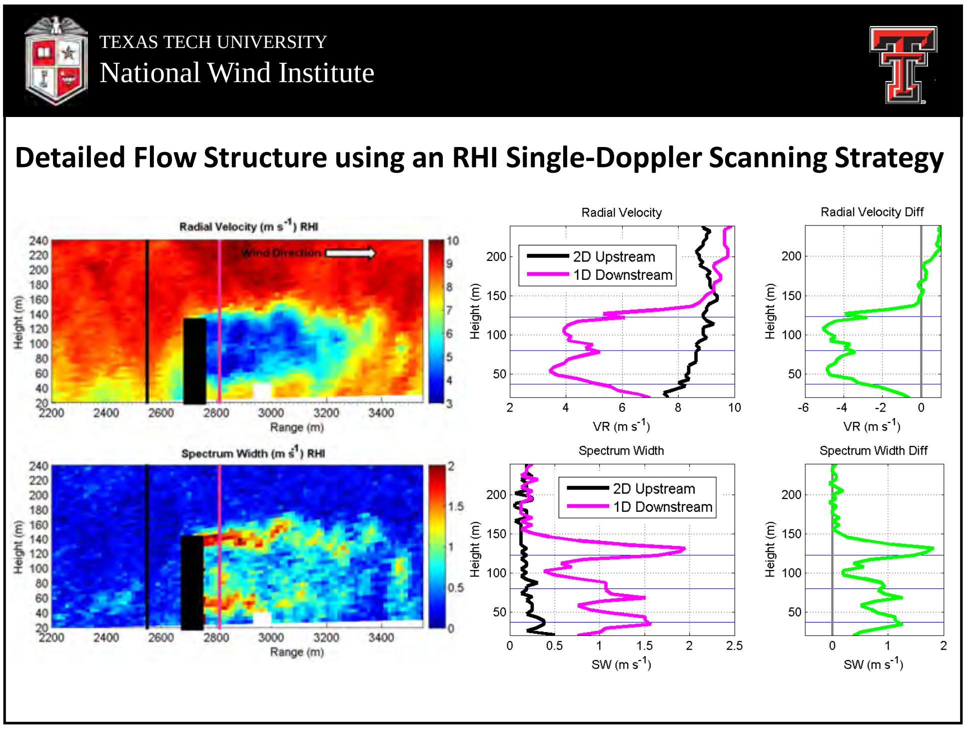
TTUKa Mobile Research Radar Technical Specifications

Parameter	Specifications
Peak Transmit Power	212.5 W
Transmit Frequency	35 GHz
Wavelength	8.6 mm
Antenna Diameter	1.83 m
Half-Power Beamwidth	0.33°
dBZ_0	-38.5 dBZ
Pulse Length	12.5, 20, 30 µs
Range Gate Spacing	9 m
Pulse Repitition Frequency	5000-15000 Hz
Operational Range	10-30 km
Azimuthal (PPI) Resolution	0.352°
Elevation (RHI) Resolution	0.1°
Pointing Accuracy	0.05°
Velocity Accuracy	0.03 m s^{-1}
Horizontal Scan Speed	30° s^{-1}
Vertical Scan Speed	6° s^{-1}

- Fully coherent traveling wave tube amplifier allowing non-linear pulse-compression frequency modulation.
- Combines the high energy of a long pulse width with the high-resolution of a short pulse width.


TEXAS TECH UNIVERSITY
National Wind Institute
TTUKa Single-Doppler Scanning Strategies
▪Single-Doppler (one radar)
▪Execute a sector sweep at a single elevation tilt or azimuth angle
▪Obtain a 2D vertical (RHI) or horizontal (PPI) plane
▪Only a line-of-site velocity (component of motion towards/away from the radar)
▪Allows for rapid revisit times (few seconds)
885 scans over 60 minutes
Θ
TTUKa2 Radial Velocity (m s-1) 1.8 deg Tilt
9 JAN 2013 220000 UTC
Y-distance (m)
X-distance (m)


TEXAS TECH UNIVERSITY
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Detailed Flow Structure using an RHI Single-Doppler Scanning Strategy
Radial Velocity (m s-1) RHI
Wind Direction
Height (m)
Range (m)
Spectrum Width (m s-1) RHI
Radial Velocity
2D Upstream
1D Downstream
VR (m s-1)
Radial Velocity Diff
Spectrum Width
SW (m s-1)
Spectrum Width Diff

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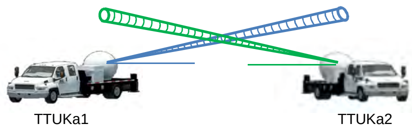
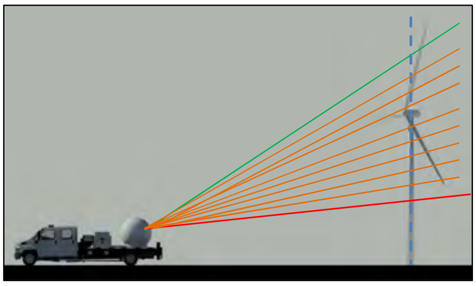
TTUKa Dual-Doppler Scanning Strategies

- **Dual-Doppler (multiple radars)**
  - Synchronize the scanning from multiple radars/look angles
  - Combine multiple tilts (elevation angles) across an azimuthal sector
  - Create 3D volumes
  - Synthesis the data to resolve the full horizontal wind vector
  - Requires slower revisit times (tens of seconds)





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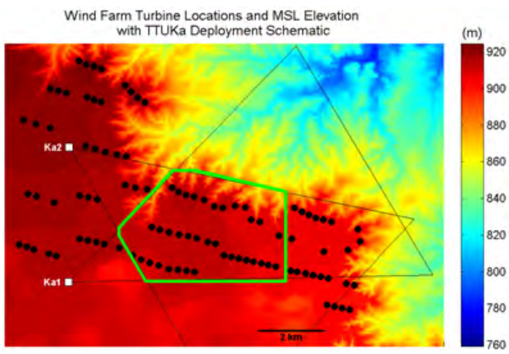
National Wind Institute

Using Dual-Doppler Techniques to Explore an Operational Wind Farm

- *Deployment Details:*
  - June 6, 2012
  - Turbine hub height = 80 m
  - Rotor diameter = 77 m
  - Elevation angles = 0.2-3.0° (15)
  - **Coordinated dual-Doppler scanning**
  - 50° PPI sector volumes
  - Pulse length 20 µs, PRF=12,000 Hz
  - Range to turbines = ~2.1-7.0 km
  - Revisit time = ~60 s
  - **36 turbines within the DD domain**



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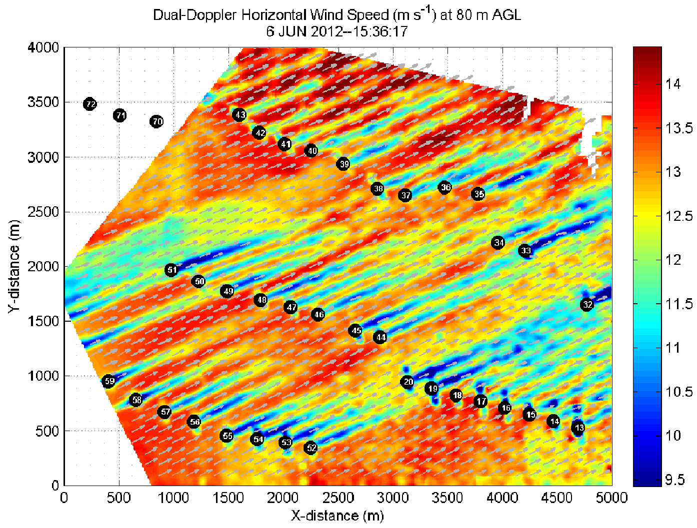
Using Dual-Doppler Techniques to Explore an Operational Wind Farm

109 volumes over 106 minutes



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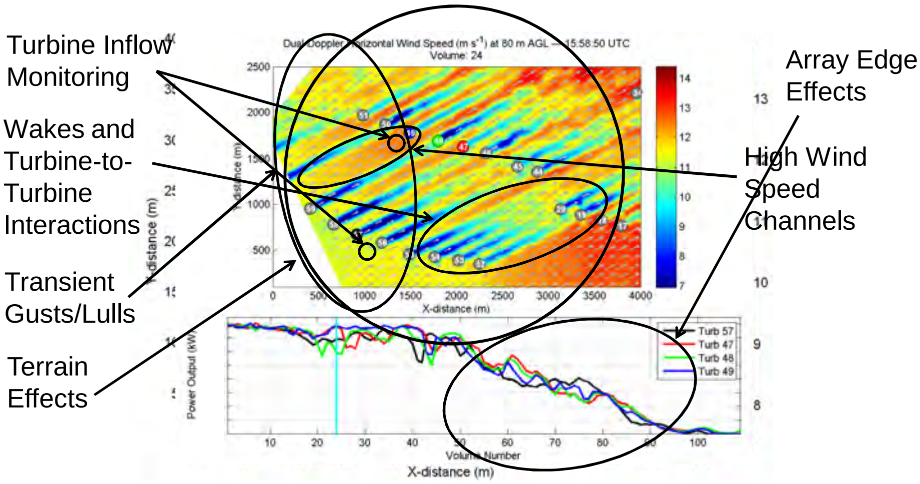
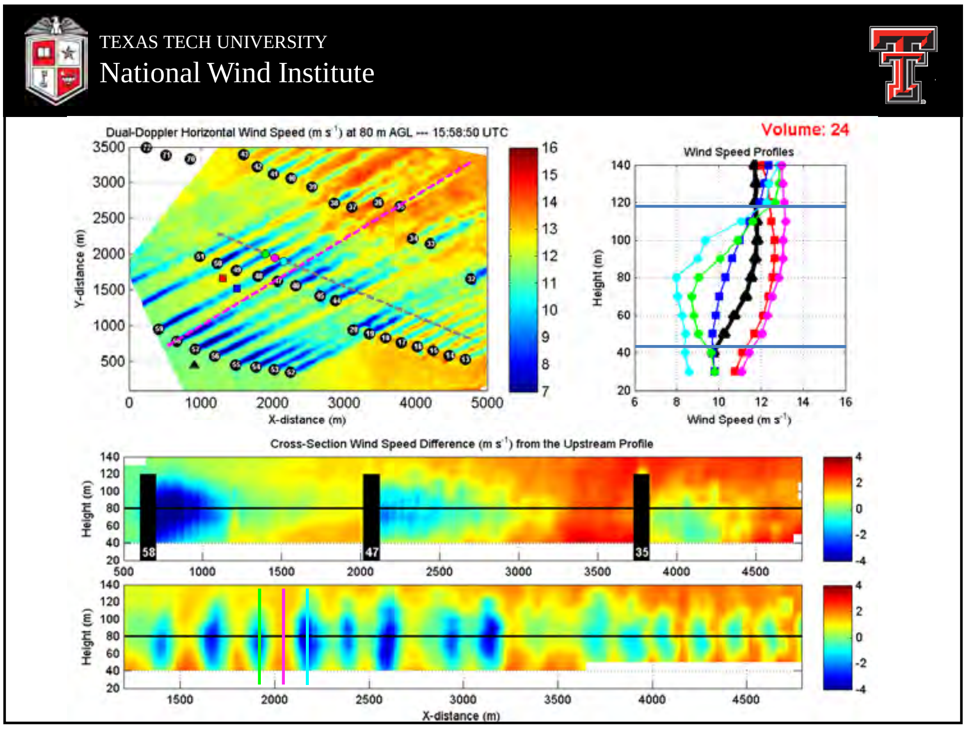
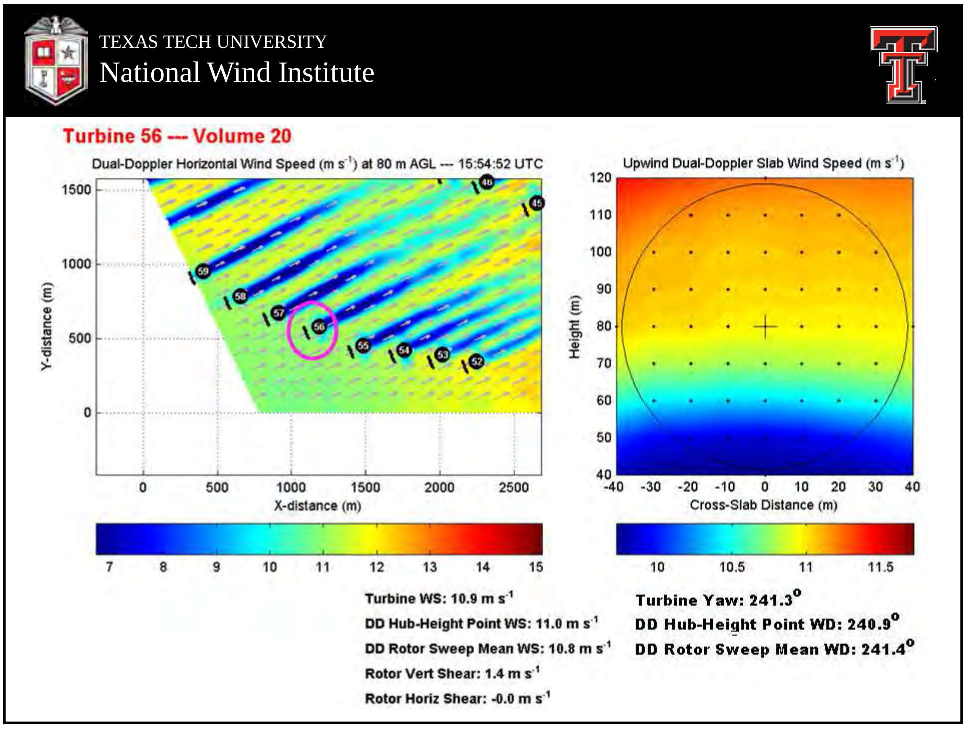
Using Dual-Doppler Techniques to Explore an Operational Wind Farm




TEXAS TECH UNIVERSITY
National Wind Institute
Dual-Doppler Horizontal Wind Speed (m s-1) at 80 m AGL --- 15:58:50 UTC
Volume: 24
Wind Speed Profiles
Y-distance (m)
X-distance (m)
Height (m)
Wind Speed (m s-1)
Cross-Section Wind Speed Difference (m s-1) from the Upstream Profile
X-distance (m)


TEXAS TECH UNIVERSITY
National Wind Institute
Turbine 56 --- Volume 20
Dual-Doppler Horizontal Wind Speed (m s-1) at 80 m AGL --- 15:54:52 UTC
Upwind Dual-Doppler Slab Wind Speed (m s-1)
Y-distance (m)
X-distance (m)
Height (m)
Cross-Slab Distance (m)
Turbine WS: 10.9 m s-1
DD Hub-Height Point WS: 11.0 m s-1
DD Rotor Sweep Mean WS: 10.8 m s-1
Rotor Vert Shear: 1.4 m s-1
Rotor Horiz Shear: -0.0 m s-1
Turbine Yaw: 241.3°
DD Hub-Height Point WD: 240.9°
DD Rotor Sweep Mean WD: 241.4°

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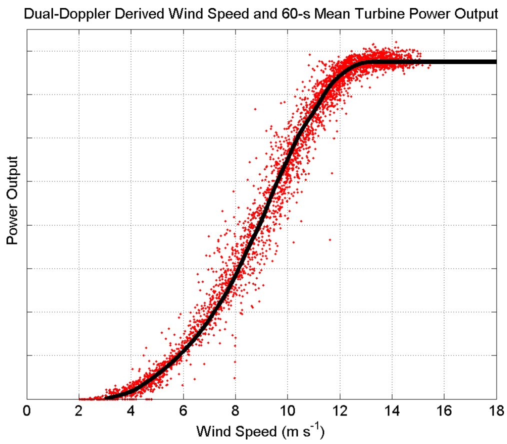
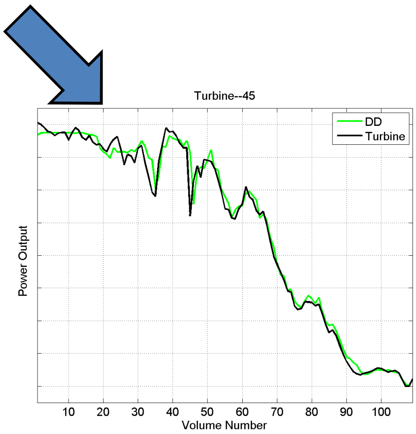
National Wind Institute

Using Dual-Doppler Techniques to Explore an Operational Wind Farm



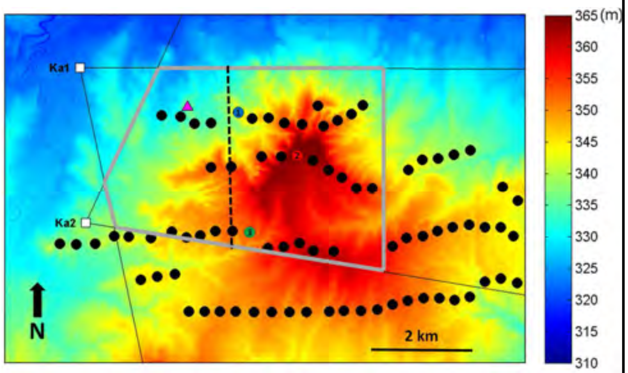


Dual-Doppler Derived Power Output and 60-sec Mean Turbine Power Output

TEXAS TECH UNIVERSITY
National Wind Institute

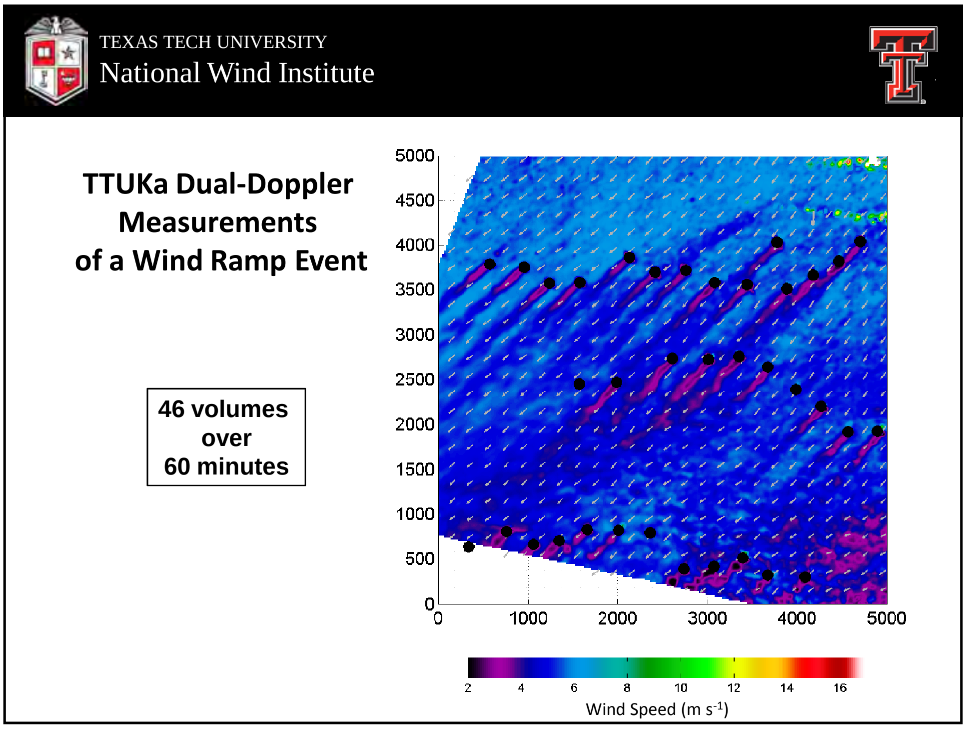
TTUKa Dual-Doppler Measurements of a Wind Ramp Event

- *Deployment Details:*
  - November 21, 2013
  - Turbine hub height = 80 m
  - Rotor diameter = 77 m
  - Elevation angles = 0.3(0.4)-3.3(3.4)° (16)
  - **Coordinated dual-Doppler scanning**
  - 80° PPI sector volumes
  - Pulse length 20 µs, PRF=12,000 Hz
  - Range to turbines = ~2.0-8.0 km
  - Revisit time = ~80 s
  - **FRONTAL PASSAGE FROM NORTH TO SOUTH**
  - **Study Carried out at Enel Green Power's Chisholm View Wind Project**

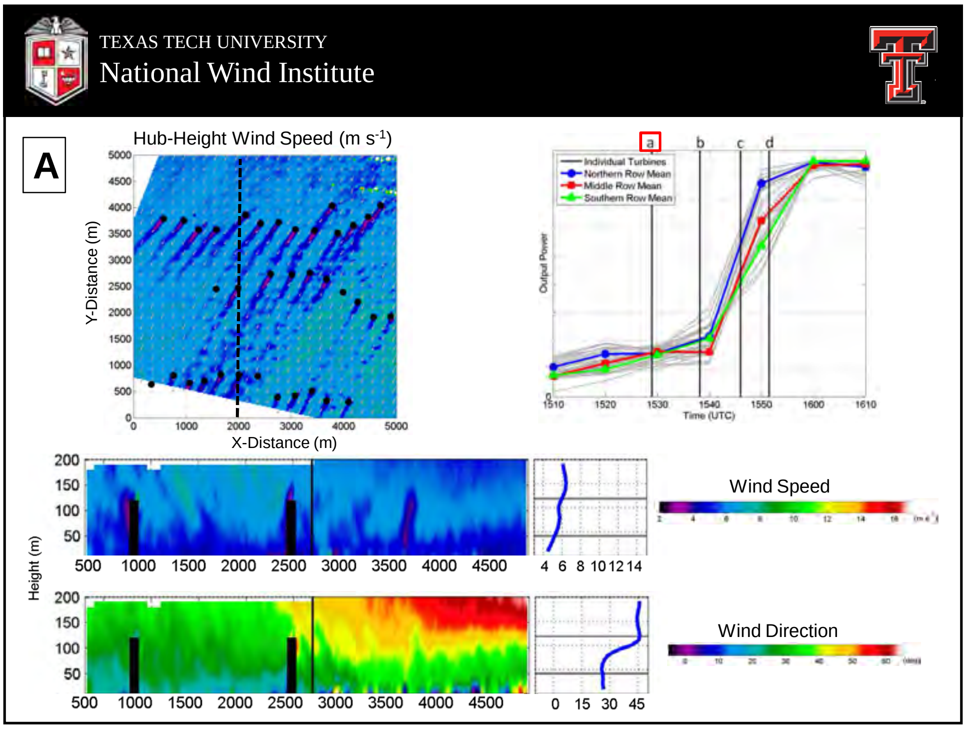


Enel Green Power

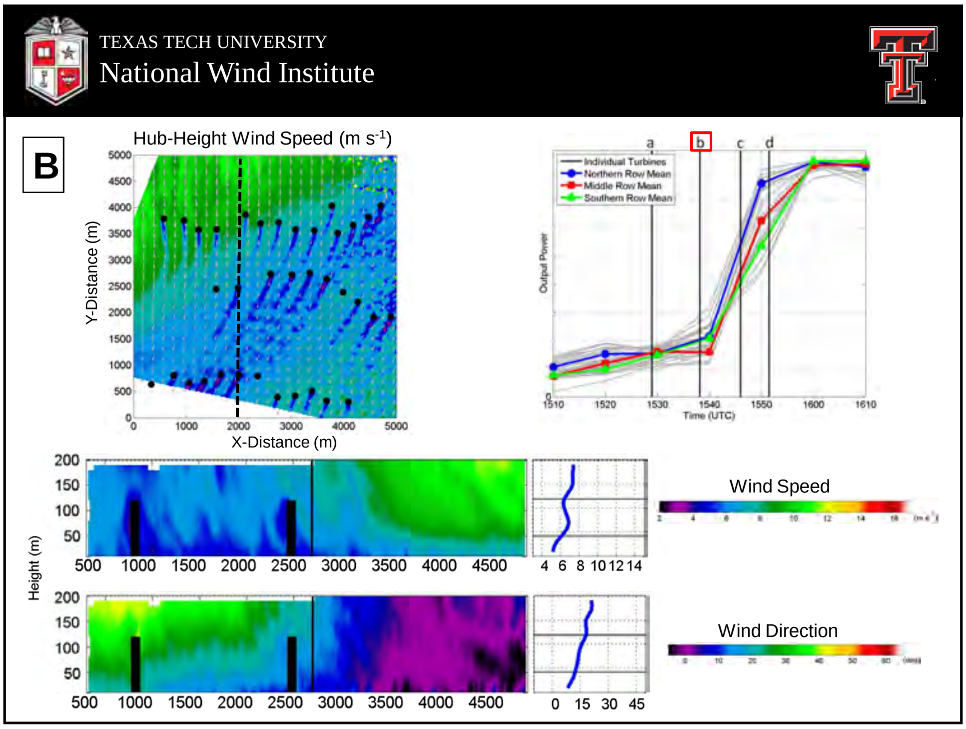
TRADEWIND ENERGY
At the heart of power

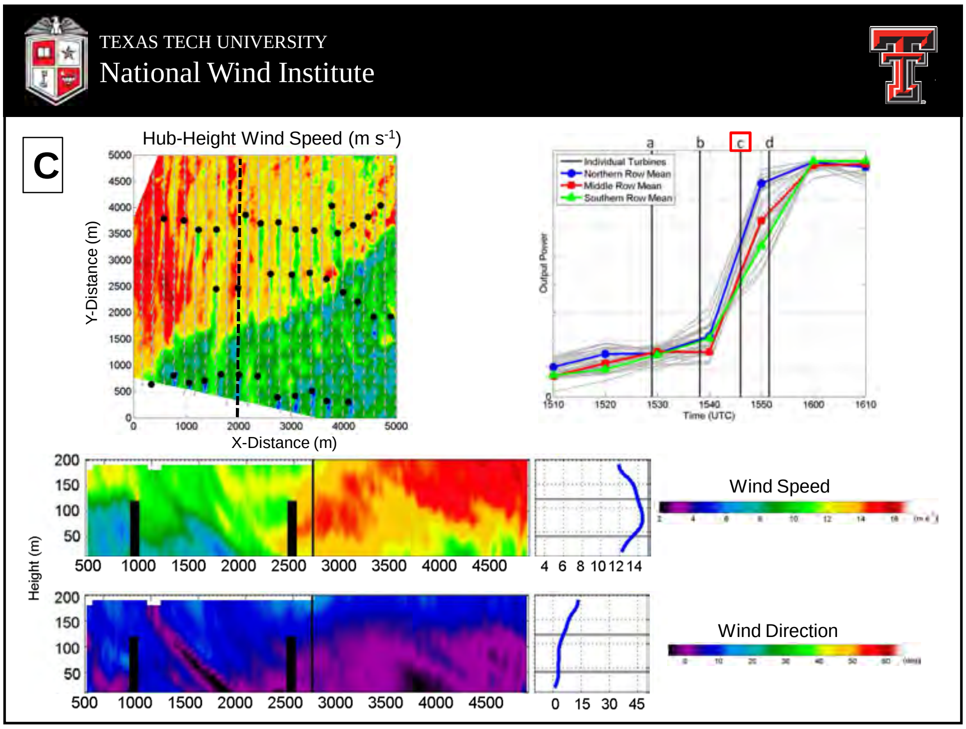


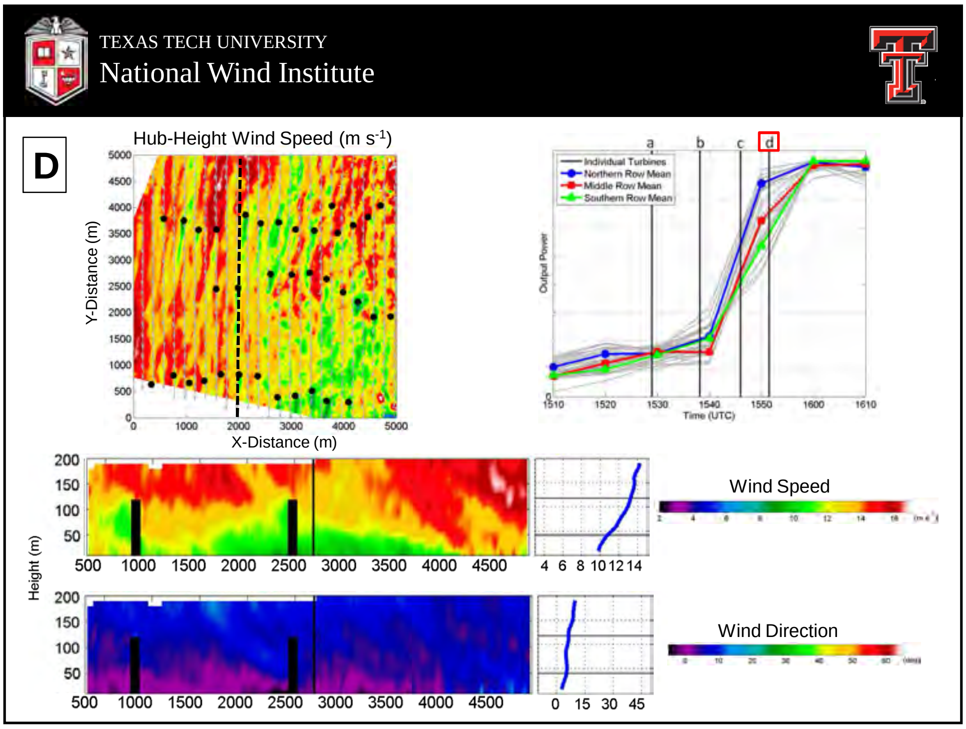
TEXAS TECH UNIVERSITY
National Wind Institute
TTUKa Dual-Doppler Measurements of a Wind Ramp Event
46 volumes over 60 minutes
Wind Speed (m s-1)



TEXAS TECH UNIVERSITY
National Wind Institute
A
Hub-Height Wind Speed (m s-1)
Y-Distance (m)
X-Distance (m)
Output Power
Time (UTC)
Individual Turbines
Northern Row Mean
Middle Row Mean
Southern Row Mean
Height (m)
Wind Speed
Wind Direction


TEXAS TECH UNIVERSITY
National Wind Institute
B
Hub-Height Wind Speed (m s-1)
Y-Distance (m)
X-Distance (m)
a b c d
Individual Turbines
Northern Row Mean
Middle Row Mean
Southern Row Mean
Output Power
Time (UTC)
Height (m)
Wind Speed
Wind Direction


TEXAS TECH UNIVERSITY
National Wind Institute
C
Hub-Height Wind Speed (m s-1)
Y-Distance (m)
X-Distance (m)
a b c d
Individual Turbines
Northern Row Mean
Middle Row Mean
Southern Row Mean
Output Power
Time (UTC)
Height (m)
Wind Speed
Wind Direction



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National Wind Institute

Summary

- The TTUKa Doppler radars are well equipped to explore complex flows in wind plants.
    - Range, range resolution, and scanning speed enable relevant dual Doppler wind fields over wind plant scales
- Measurements have been used to examine:
    - Turbine inflow structure
    - Transient gusts and lulls and their passage through turbine arrays
    - Abruptly changing wind direction and wind speed
    - Turbine-to-turbine interaction
    - Wake structure, meandering, propagation, orientation, etc.
    - Accelerated flow between wakes, array/plant edge effects
    - Impact of turbine controls on flow structure
    - Impact of atmospheric conditions and boundary layer structure (e.g. wind streaks) on flow structure, wake orientation and recovery, and general turbine performance

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National Wind Institute

Acknowledgements

Supporting Materials:
James Duncan

Collaborating wind farm owners, operators, and OEMs

Financial Support:
Contract with Sandia National Laboratories with funding from the US Department of Energy Wind and Water Power Technologies Office

National Science Foundation award (CBET #1336935)

Various contracts with private industry

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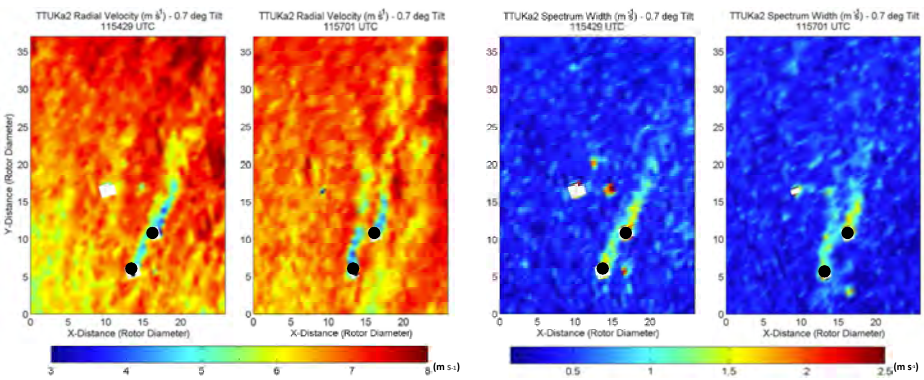
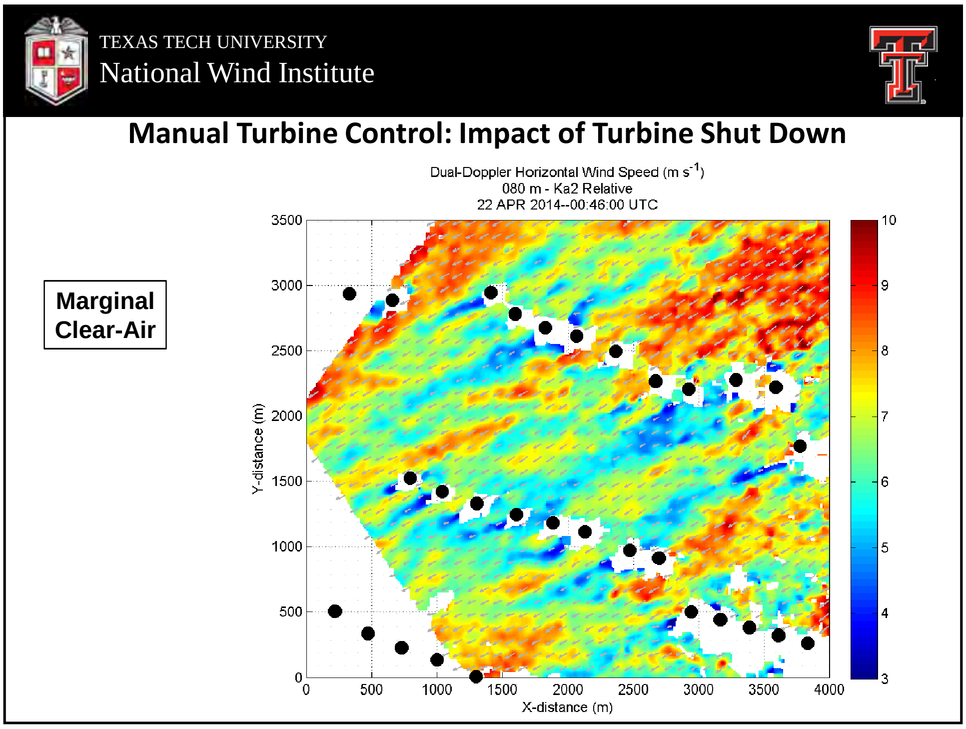
National Wind Institute

A *Proactively* Yawed Turbine Impacting Wake Orientation



Sandia National Laboratories Vestas **Scaled Wind Farm Technology (SWiFT) Facility**


TEXAS TECH UNIVERSITY
National Wind Institute
Manual Turbine Control: Impact of Turbine Shut Down
Marginal Clear-Air
Dual-Doppler Horizontal Wind Speed (m s-1)
080 m - Ka2 Relative
22 APR 2014--00:46:00 UTC
Y-distance (m)
X-distance (m)

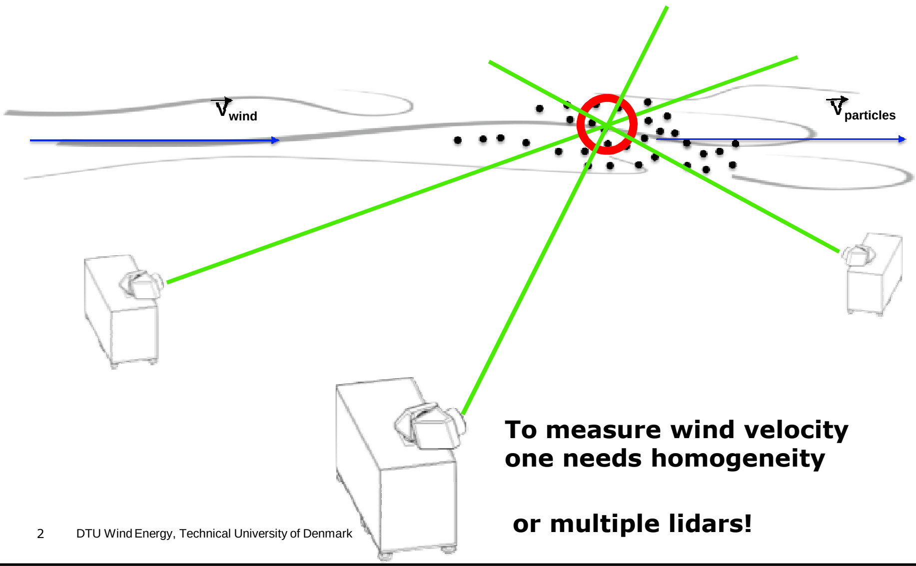
Achievements, Status and Prospects of the DTU Long Range WindScanner System

Mike Courtney
Nikola Vasiljević
Guillaume Lea

Topical Expert Meeting #78
Texas Tech University
07/10/2014

DTU Wind Energy
Department of Wind Energy

Lidar measurements background



To measure wind velocity one needs homogeneity

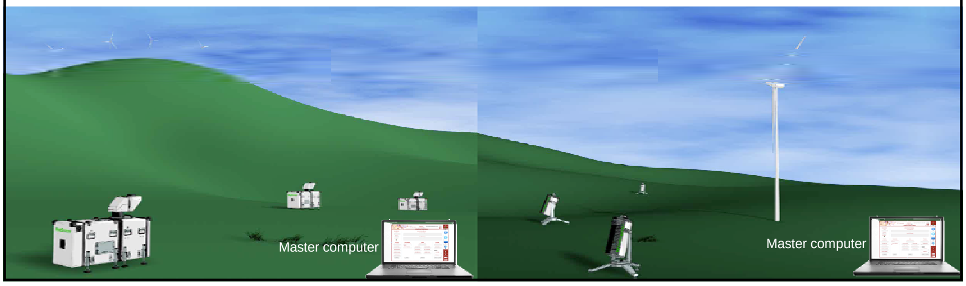
or multiple lidars!

WindScanner.DK and WindScanner.EU

- In 2007, DTU Wind Energy, at that time Risø DTU, presented an ambitious idea about the development of the unified measurement systems, known as windscanner systems, which consist of three time-space synchronized scanning coherent Doppler lidars (i.e. WindScanners), specialized for detailed remote measurements of real-time wind velocity fields
- In 2012, Windscanner.EU pilot project started, to investigate the technical, legal and economic issues related to establishing a European wide windscanner infrastructure.

Long-range WindScanner system

Short-range WindScanner system



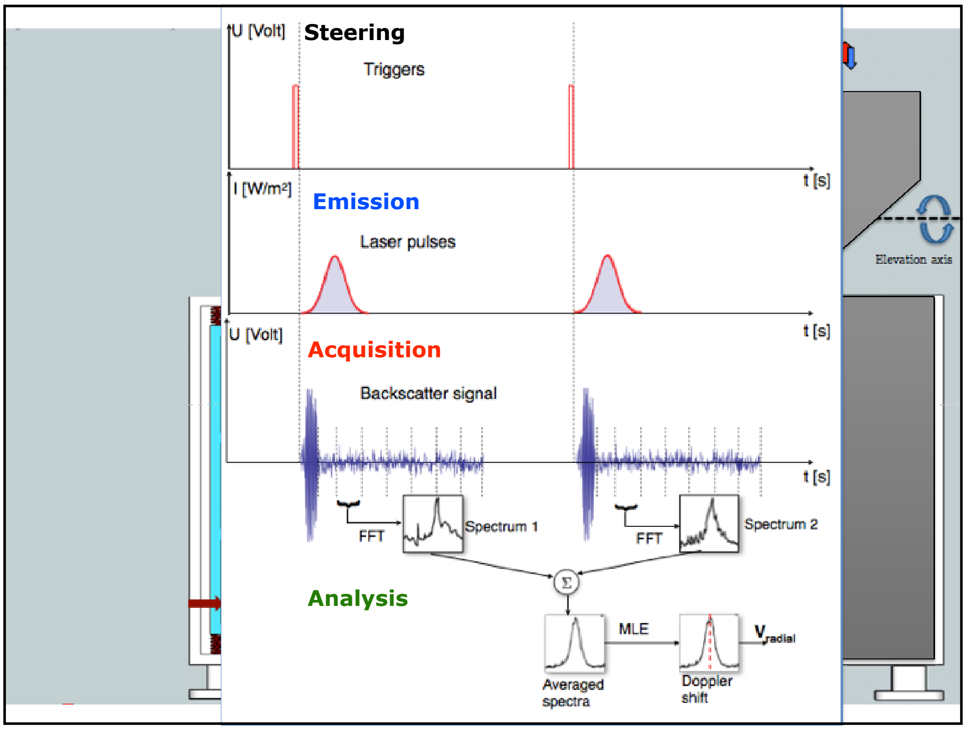
WindScanners

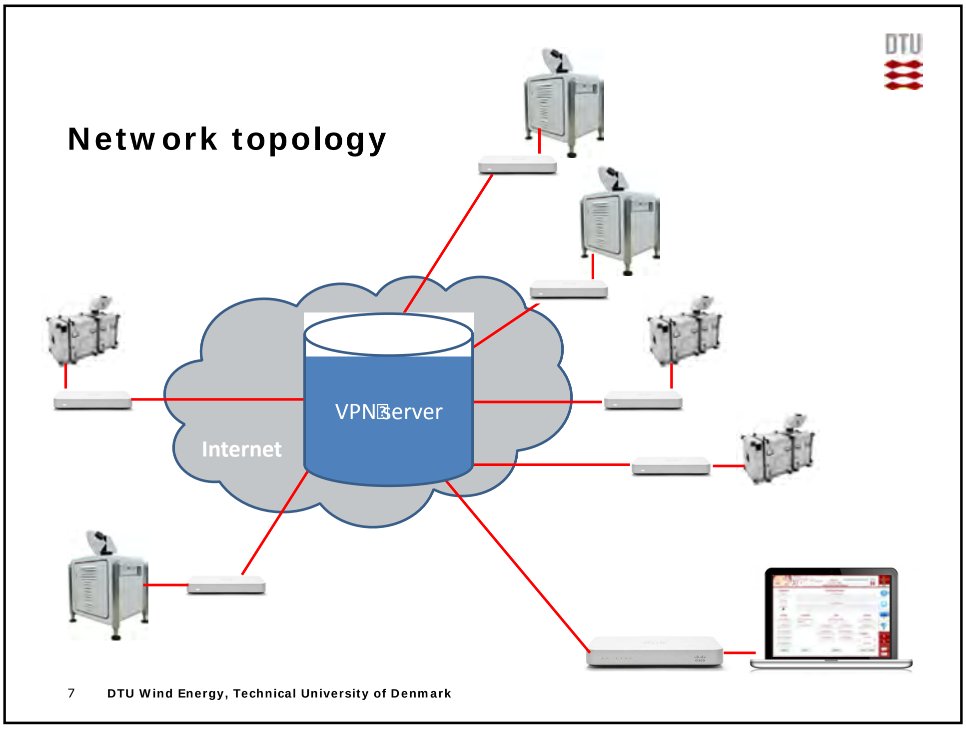
4 DTU Wind Energy, Technical University of Denmark

WindScanners specs

WindScanner	Short-Range	Long-Range
Laser type	Continuous wave	Pulsed
Range	10 - 200 m	25 - 8000 m
Maximum measurement rate	400 Hz	10 Hz
Simultaneous measurements	1	500
Dual axis scanner head	Double prism based	Triple or Dual mirror based
Mechanical rotation	Belt driven	Gear-box driven
Rotation	Endless	Endless
Atmospheric coverage	Cone with a full opening angle of 120°	Hemisphere
Maximum rotational speed	$2880°/s$	$50°/s$
Weight	120 kg	150 kg

5 DTU Wind Energy, Technical University of Denmark





DTU

DTU Wind Energy and ForWind cooperation:

Remote Sensing Communication Protocol (RSComPro)

- Commands sent from master computer to WindScanners
- Appropriate WindScanners’ actions to these commands
- Responses to commands sent from WindScanners to master computer
- Possible alerts sent from WindScanners to master computer
- Packet structure of each command, response and alert

```
<packet Client="Košava" PckNo="1.3" Cmd="2200" Alert="0">
        <element 1> 124520.50 < /element 1>
        <element 2> 141212 < /element 2>
        ...
        <element N> 40.091042 < /element N>
        <msg>< /msg>
< /packet>
```

The XML structure of a RSComPro packet

8 DTU Wind Energy, Technical University of Denmark

Commands

Command	Code
WhoIsThere?	1100
Abort	1200
Unlock	1300
Stop	1400
GetStates	1500
IsBusy?	1600
Shutdown	1700
Reset	1800

UDP commands

Command	Code
GoHome	2100
GetGPS	2200
GetCompass	2300
GetConfiguration	2400
GetPosition	2600
SetPosition	2700
GetScenario	2900
SetScenario	3000
Measure	3100
GetData	3200
Wipe	3300
GetCapabilities	3400
Synchronize	3500

TCP commands

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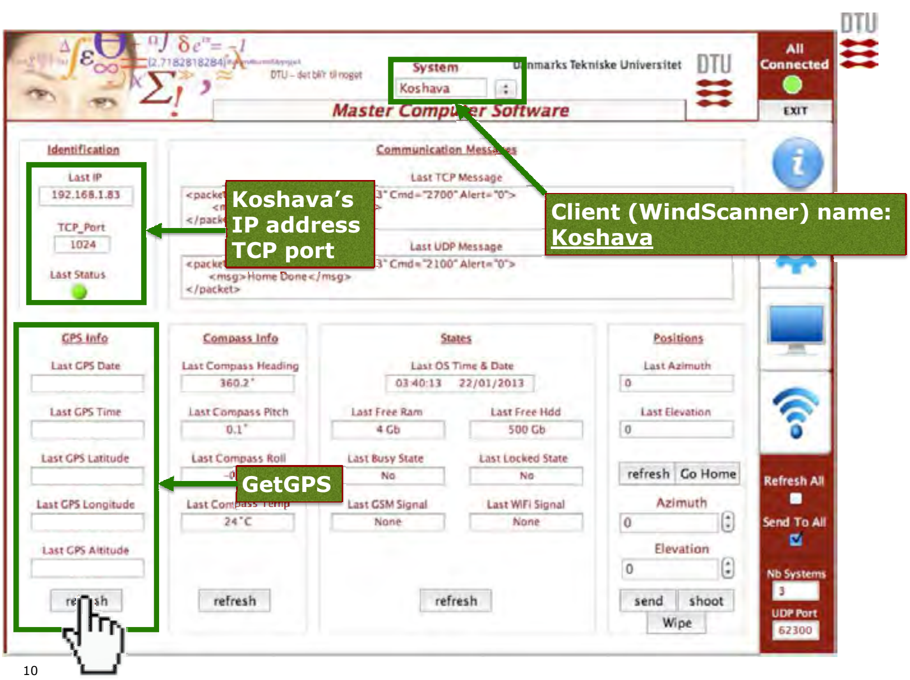
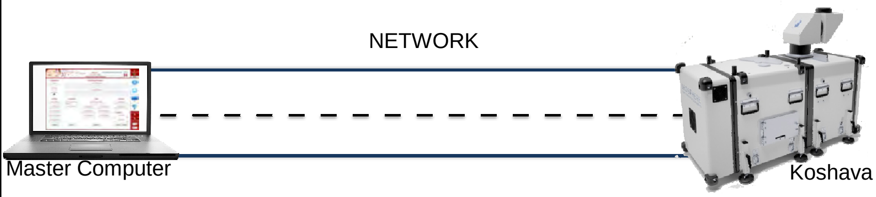
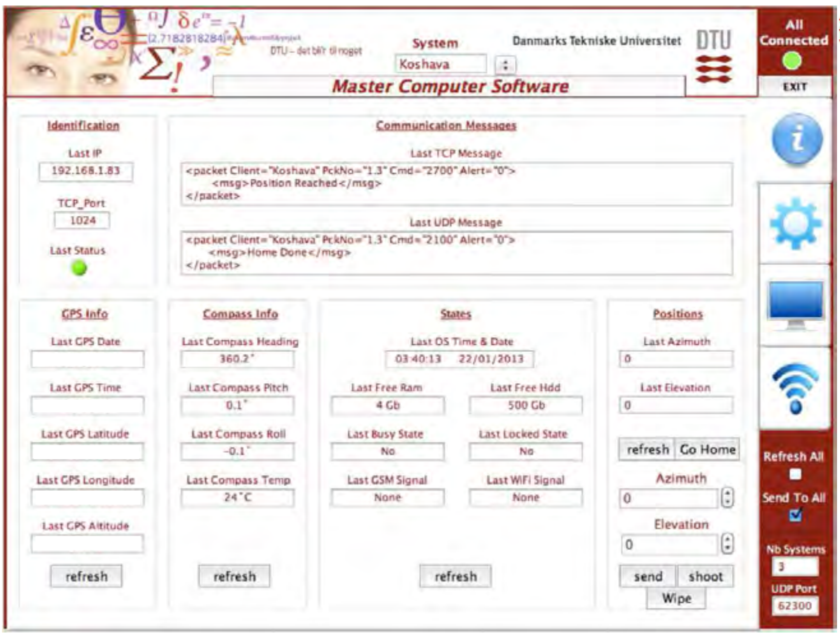


10

Exchange of packets





Master computer in action

https://www.youtube.com/watch?v=oUi1U12vEZw

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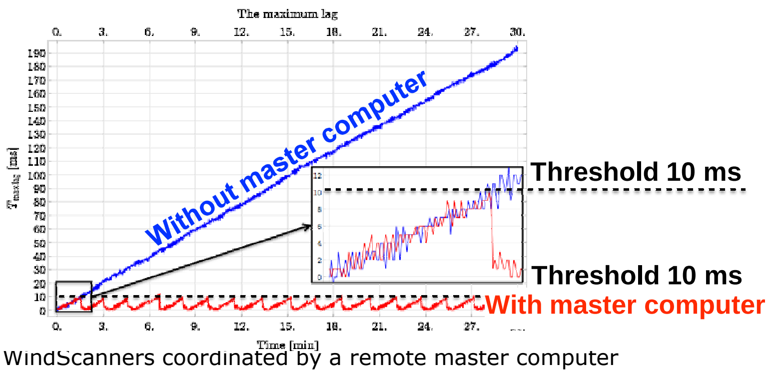
Long-range WindScanner system



- WindScanners coordinated by a remote master computer
- Coordination can be achieved using any type of network
- WindScanners are synchronized
- Arbitrary scanning trajectories
- Measurement rate can be dynamic from one LOS measurement to another
- Distances which the LOS measurements are acquired can be dynamic as well
- **Flexible remote sensing measurement system that can accommodate wide range of atmospheric experiments**

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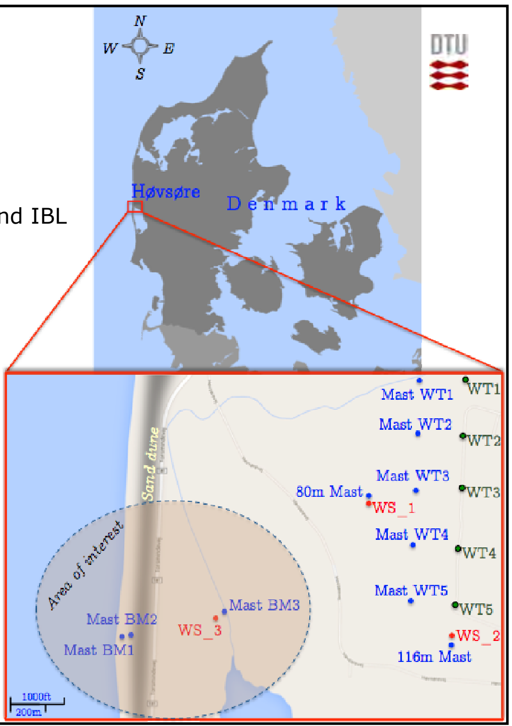
Campaigns completed

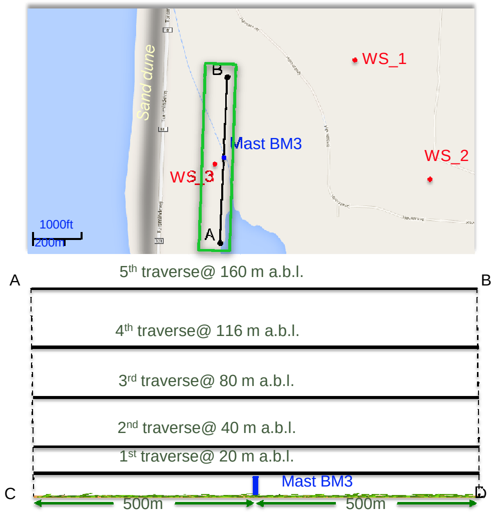
- Swinging musketeer
- IBL WiSH
- 6 beam
- Site calibration
- Dual-Doppler vs. Sector Scan
- Kassel campaign

IBL WiSH

- June 2013
- Investigation of changes of sea-land IBL



IBL WiSH experiment layout



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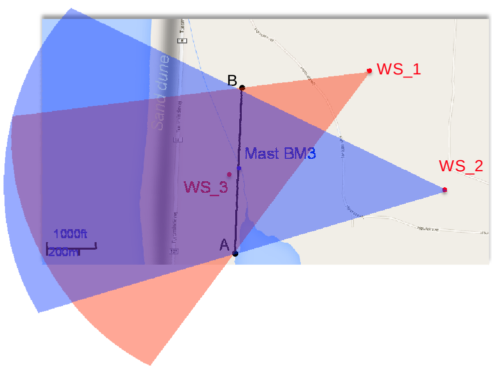
WindScanner 1 / WindScanner 2



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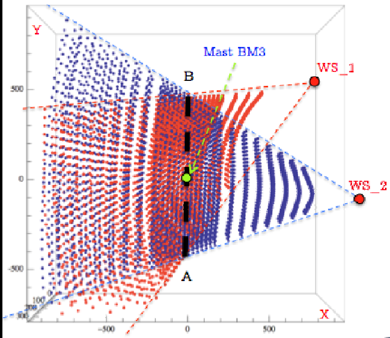
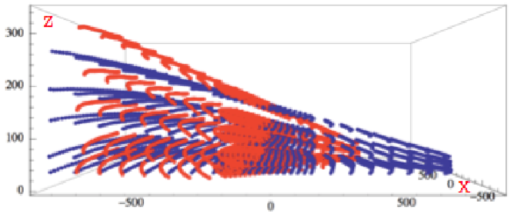
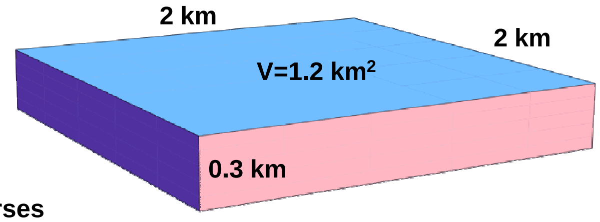
WindScanner 1 / WindScanner 2

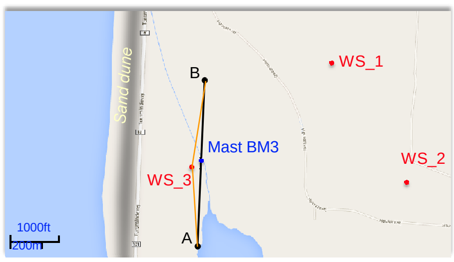


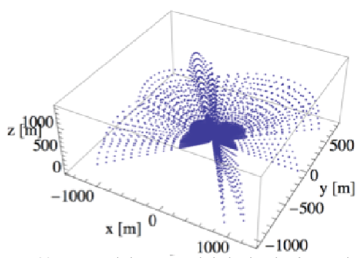


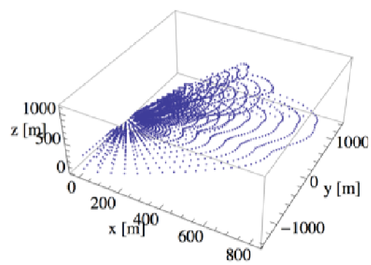


2*3000 radial velocities
60 seconds per volume
Synchronized along 5 traverses

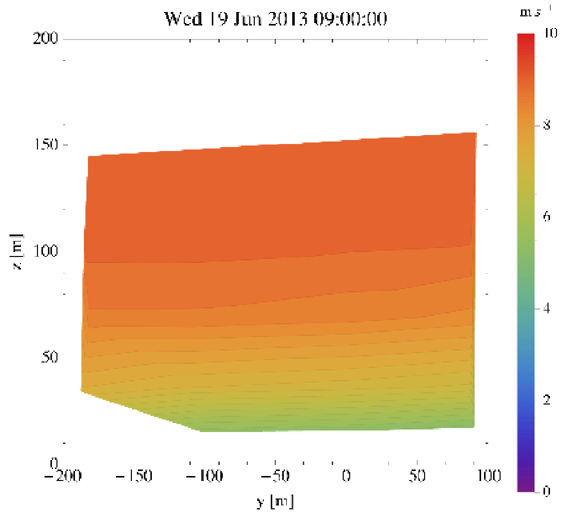
WindScanner 3







Results



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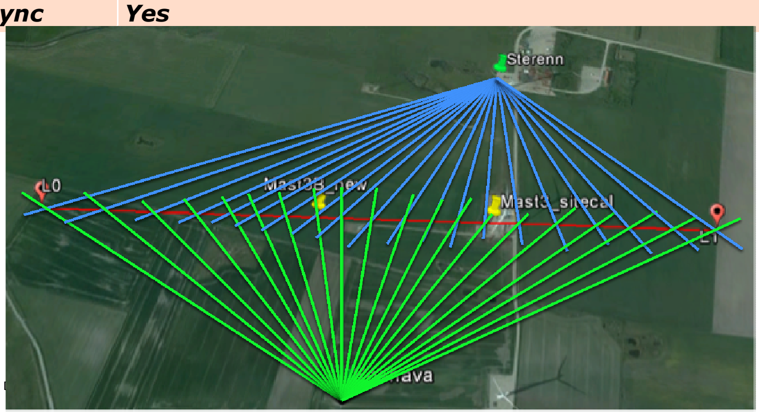
Site calibration

Date	***Sept 2013 - Jan 2014***
Location	***Høvsøre, Denmark***
Aim	***Spatial characterization of the wind field in the prevailing wind direction***
No. of WS	***2***
Sync	***Yes***



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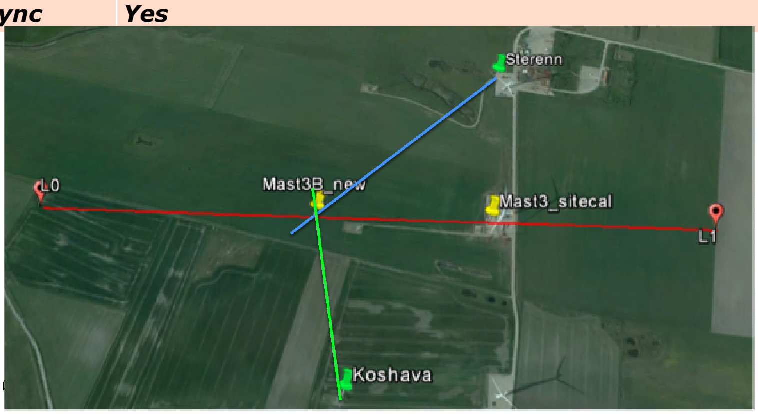
Site calibration

Date	***Sept 2013 - Jan 2014***
Location	***Høvsøre, Denmark***
Aim	***Spatial characterization of the wind field in the prevailing wind direction***
No. of WS	***2***
Sync	***Yes***



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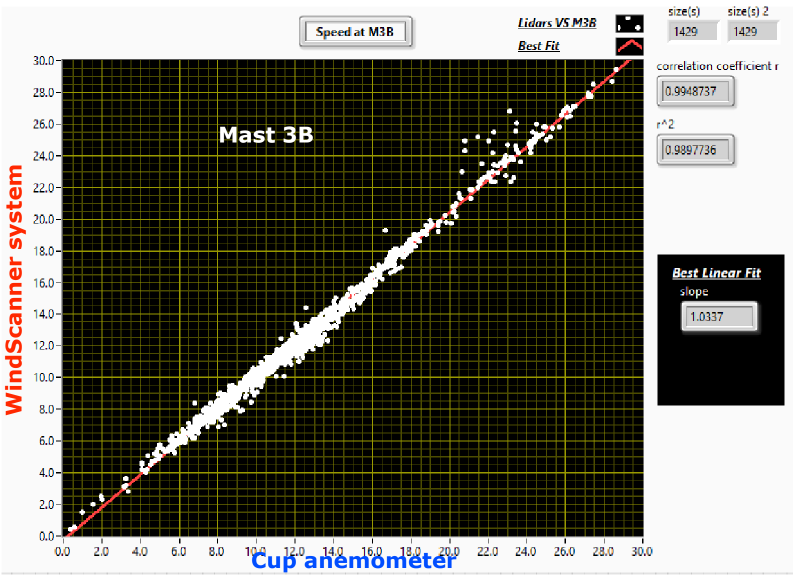
Regression plot for horizontal wind velocity



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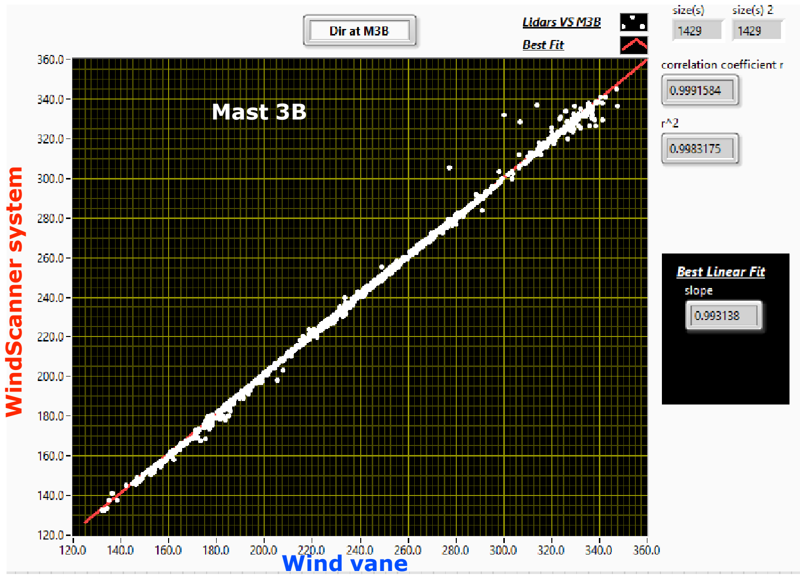
Regression plot for wind direction



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Kassel experiment

WindScanner.eu

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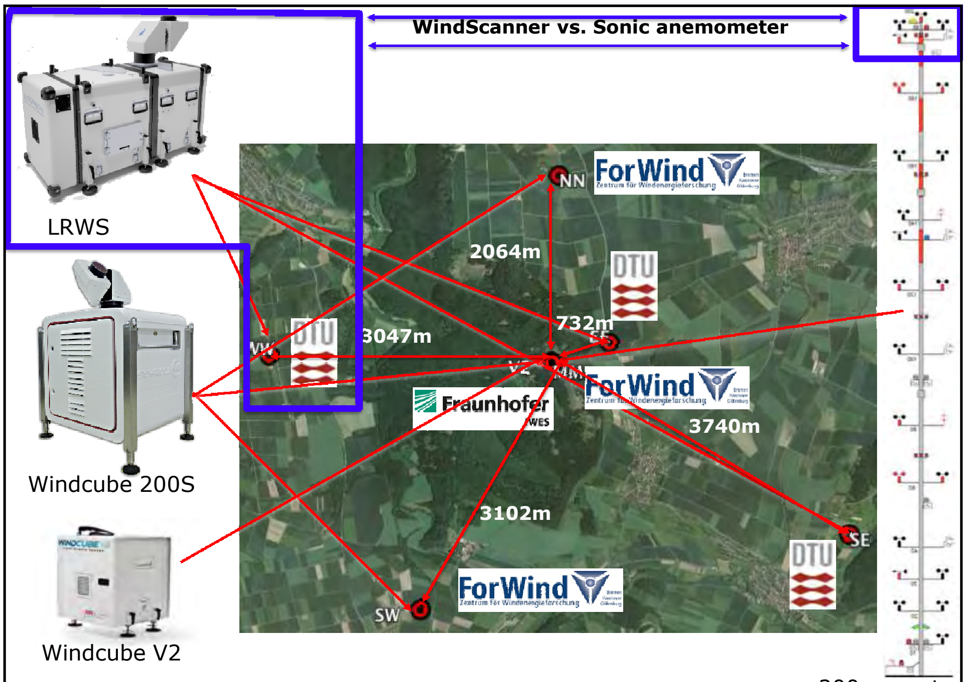

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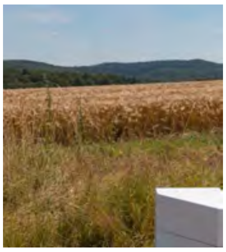
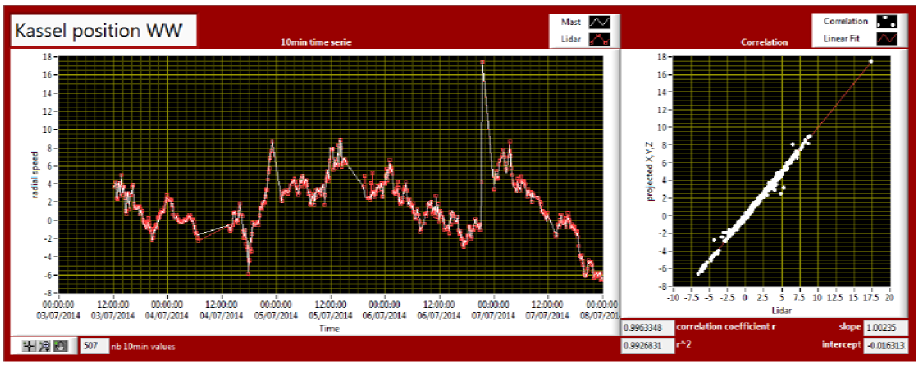
Lidar at West position (WW):

Azimuth: 90,99°
Elevation: 5,69°
Distance: 3102m





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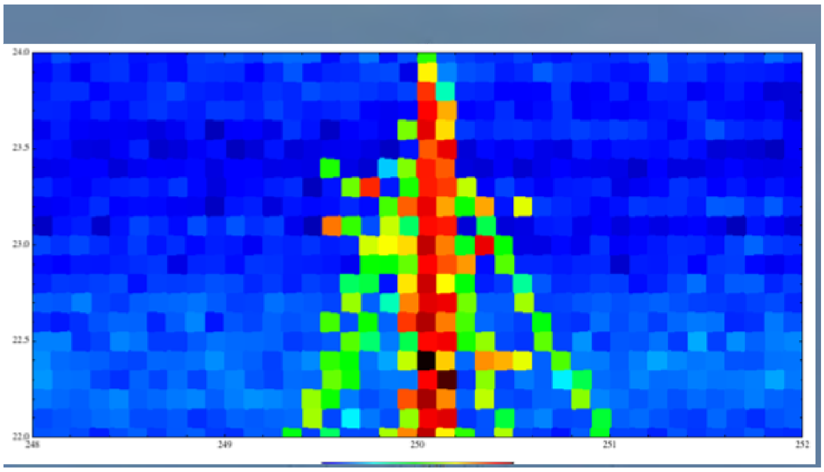
Laser beam pointing accuracy



Accuracy of 0.05° azimuth/elevation (1m over 1km)

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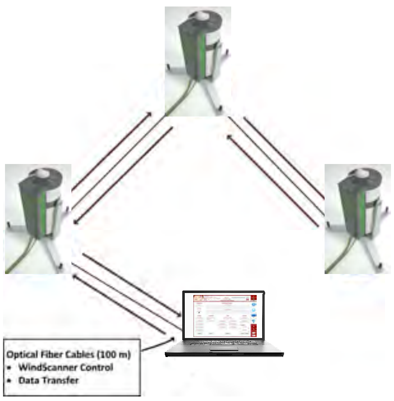
Short-range WindScanner system



- WindScanners controlled via a near-by master computer
- Control achieved using network based on optical fibre cables
- WindScanners are synchronized
- Arbitrary scanning trajectories
- Appropriate for detail measurements in a small volume of interest

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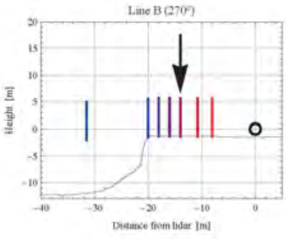
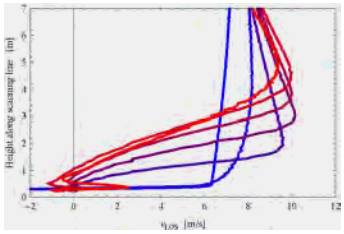
Applications

1. Laser scanning of a recirculation zone on the Bolund escarpment (Mann et. al, 2012)





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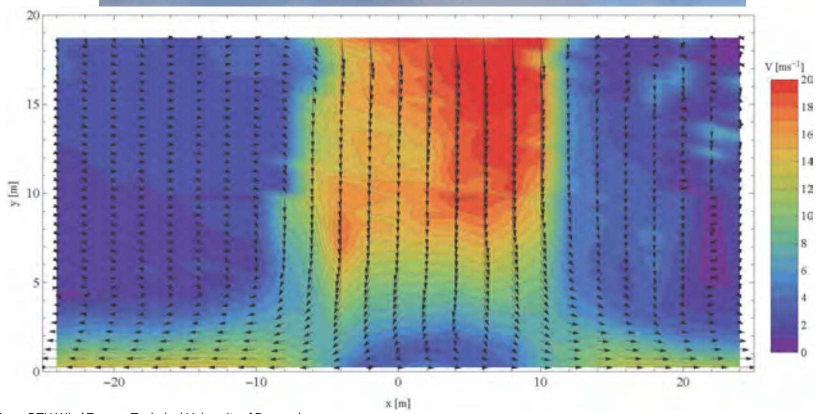
Helicopter downwash: 2D vertical scan



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Prospects – Windscanner plans

- UniTTe – HAWT inflow (Short-range, Spinner, Long-range) – now
- Marinet – Vertiflow (Short-range scanning of VAWT) – Nov-Dec 2014
- RUNE (Long-range coastal resource) – December 2014?
- Windscanner.EU: Pilot Perdigao (Short-range, Long-range), spring 2015?
- New European Wind Atlas (NEWA):
  (Short-range, Long-range +3 + partners) 2015-2018
  - Kassel
  - Coastal
  - Perdigao
  - Turkey
  - Spain
- Windscanner.EU established 2017?

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Things we want to work on

- Extending the range (SR and LR)
- Improving pointing accuracy (especially LR at LR!)
- Better understanding of overall uncertainties
- Integrating short and long-range systems
- Better tools for planning campaigns (trajectory design and generation)
- Better tools for analysing data
- Use them for lots of exciting experiments!
- Get their data used to make science!

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Challenges:

- Getting the funding
  - Scanning lidars are expensive
  - Deploying them is not cheap either
- Spoilt for choice
  - How to find the best ways of measuring to achieve a given aim
- The medium is NOT the message
  - Don't make scanning lidar measurements when there are more appropriate methods available
- Making controls
  - Make sure we know when and where we are measuring
- Making the measurements available
  - How to disseminate large volumes of data meaningfully

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Summary

- Two WindScanner system have been developed
- Two different lidar technologies
- Two different approaches to how we are forming the system

- Systems are complementary

- They have great freedom in deployment
- They are flexible in terms of measurement scenarios
- They can provide synchronous 3D measurements of wind velocity fields

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Thank you!

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Guillaume Lea
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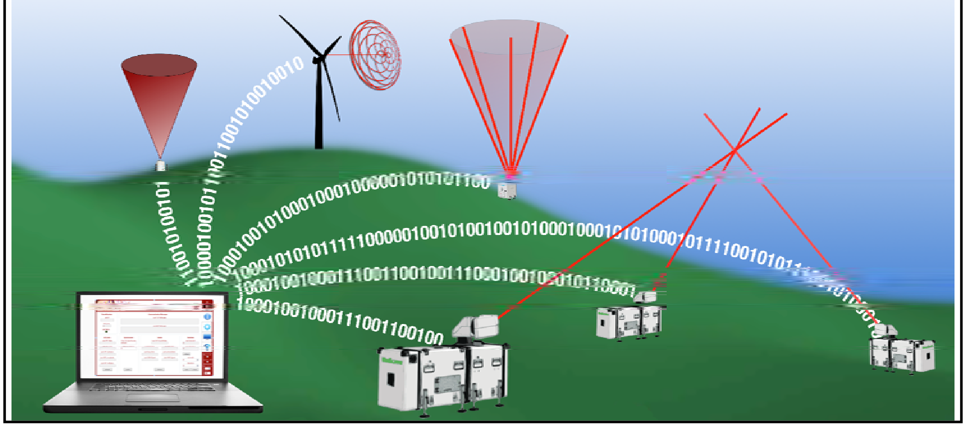


Nacelle Mounted Lidar
are we looking in the wrong direction?

Andrew Swift, Carsten Westergaard, Jon White*
NWI, Texas Tech University, *Sandia National Laboratory
Acknowledgement: Neha Marathe, TTU-WiSE PhD Candidate

IEA: TEM #78, Texas Tech University, October 7, 2014

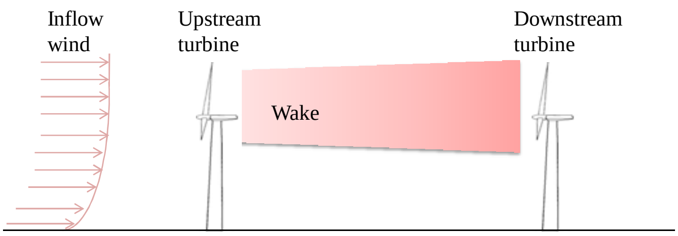
Abstract

Forward looking LIDAR have been researched for almost a decade, predominantly showing promise in load reduction, less so on energy production. Based on recent research at Texas Tech with the TTU ka-band radar and simulations, we will discuss needs for wake steering instrumentation and research needed.

Overview

- The turbine wake challenge
- Turbine yaw
- Power loss, theory and experiment
- Wake deflection, theory
- Wake measurements – remote sensing
- Wake field data
- WE graduate education programs at TTU

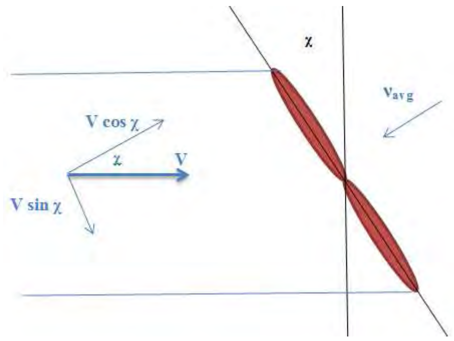
Wake management strategies



Some methods of modifying the wake of the upstream turbine, either independently or in combination are:

- **Yawing the turbine**: A yawed turbine has a tendency to deflect the wake downstream.
- **Pitching the blades**: When blades are pitched, strength of the wake is reduced.
- **Changing the rotor speed:** When rotor speed changes, the induced vorticity is changed.

Turbine Yaw



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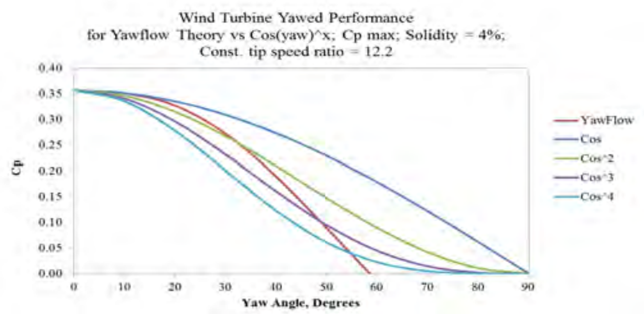
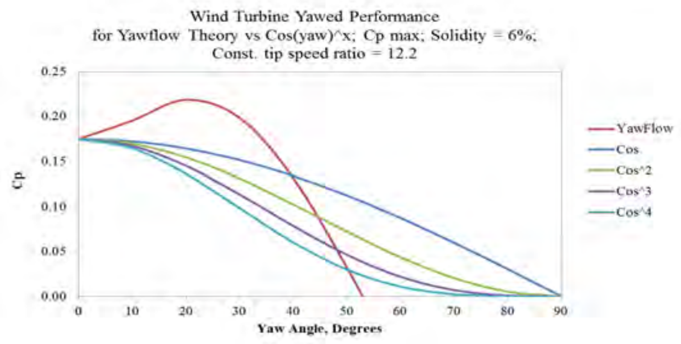
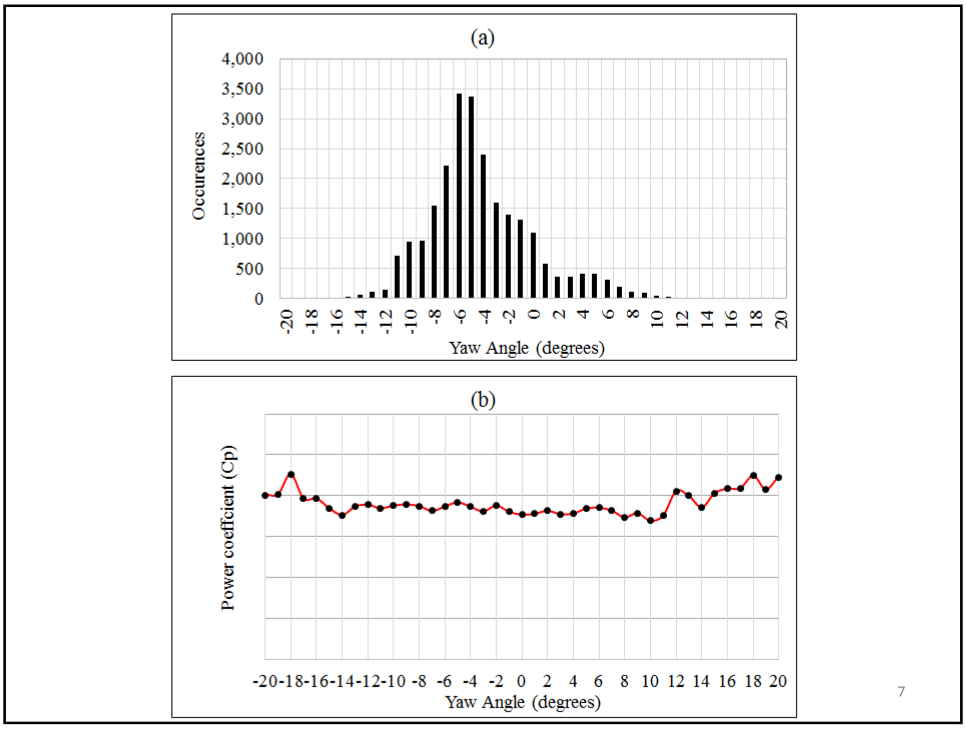
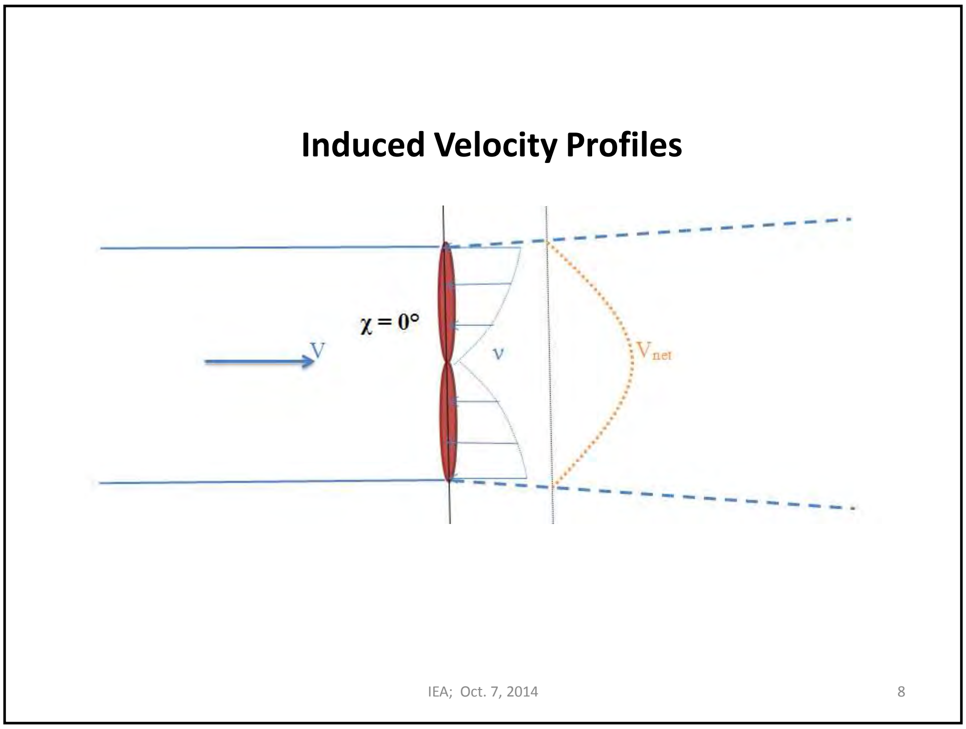




6


(a)
Occurences
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20
Yaw Angle (degrees)
(b)
Power coefficient (Cp)
-20-18-16-14-12-10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20
Yaw Angle (degrees)
7


Induced Velocity Profiles
χ = 0°
V
ν
V net
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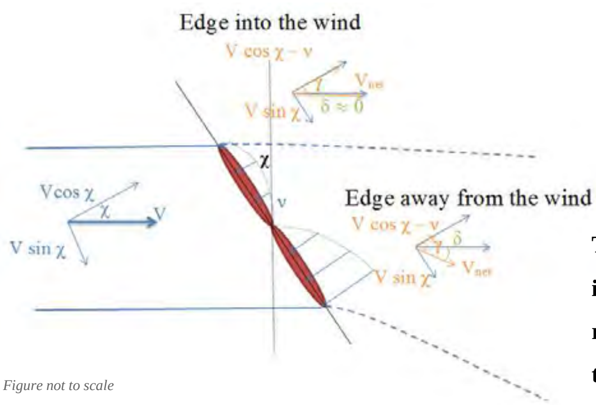
8

Uniform inflow over a yawed rotor disc



The wake deflects to one side immediately downstream of the rotor (near-wake region) due to the induced velocity pattern.

V → Ambient average inflow wind velocity

v → Induced velocity

V_{net} → Net wind velocity behind the rotor

χ → Yaw angle

γ → Wake skew angle

δ → Wake deflection angle

$\gamma = \chi + \delta$

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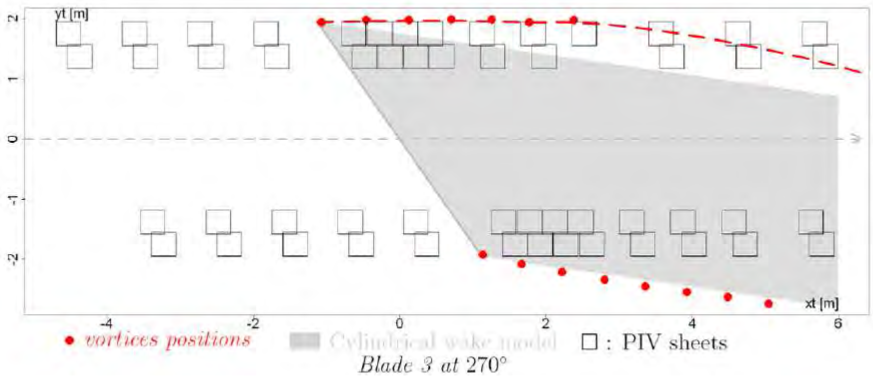

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Test Facility

Utility-scale wind turbine

- 86 m rotor diameter
- 80 m hub height
- 1.67 MW rated power
- 100 Hz SCADA data available

TTU Ka-band radars

- Ka-band (35GHz) Doppler radar systems
- 15m (9m) range gate spacing
- 10- 30 km maximum range
- Utilizes pulse compression technique

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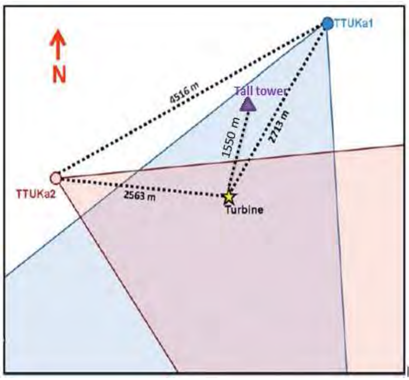
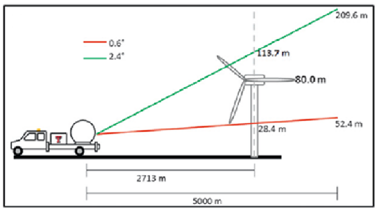
Test Setup

Layout of the turbine, radars and tower



Radar scanning



- Predominant wind direction was from the North-East
- Each radar scanned 10 elevation angles over the rotor span
- Each scan was over a 30° sector
- Each scan took nearly one minute to complete

Dual Doppler wind analysis:

- Spatial Extent:

  3 km (east-west) × 3 km (north-south) × 150 m (vertical)
- Spatial Resolution: 10 m × 10 m × 10 m

IEA; Oct. 7, 2014

Hirth, Brian D., John L. Schroeder, 2013: "Documenting Wind Speed and Power Deficits behind a Utility-Scale Wind Turbine." J. Appl. Meteor. Climatol., 52, 39–46

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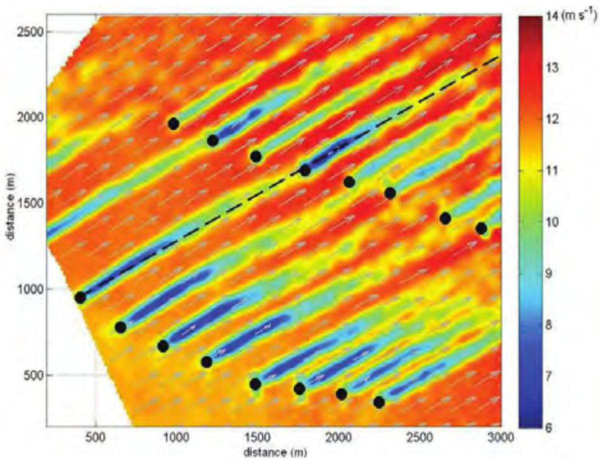
Wake Effects

Horizontal wind speed measured with TTUKa band radars *



- Turbine-to-turbine interactions.
- Power losses due to wake effects can be as high as 20%

* "The Wake Effect: Impacting turbine siting agreements", North American Clean Energy , Jan/Feb 2013. (Credit: NWI, TTU)

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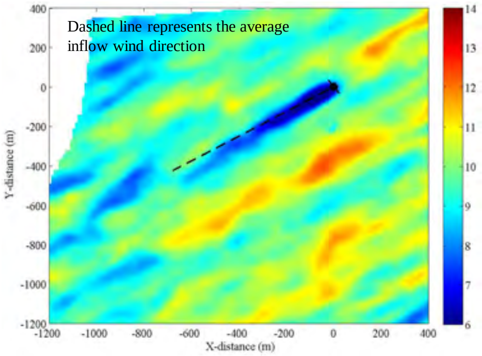
Wake Analysis Case 2

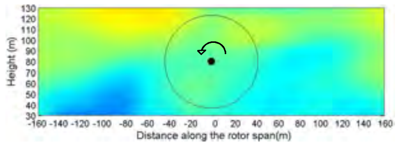
Yaw angle: 2.5 °
Inflow wind speed: 9.7 ms^{-1}

Hub height wind speed (m/s)

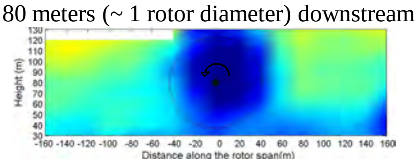


Vertical cross section (perpendicular to the inflow wind direction) wind speed (m/s)

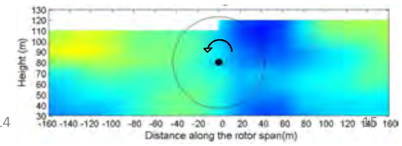
80 meters (~ 1 rotor diameter) upstream



80 meters (~ 1 rotor diameter) downstream



400 meters (~ 4.6 rotor diameters) downstream



Note:
- The rotor rotation was counter-clockwise looking upstream.
- Wind direction did not vary drastically during the measurements.

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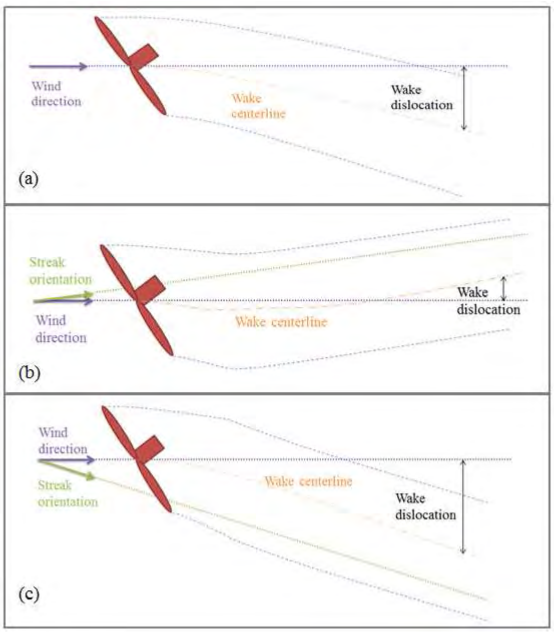
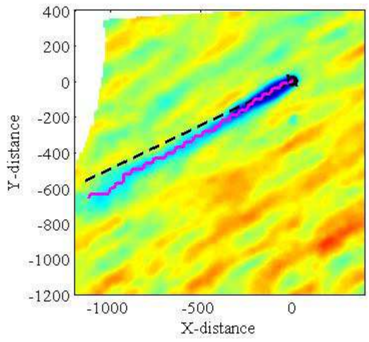
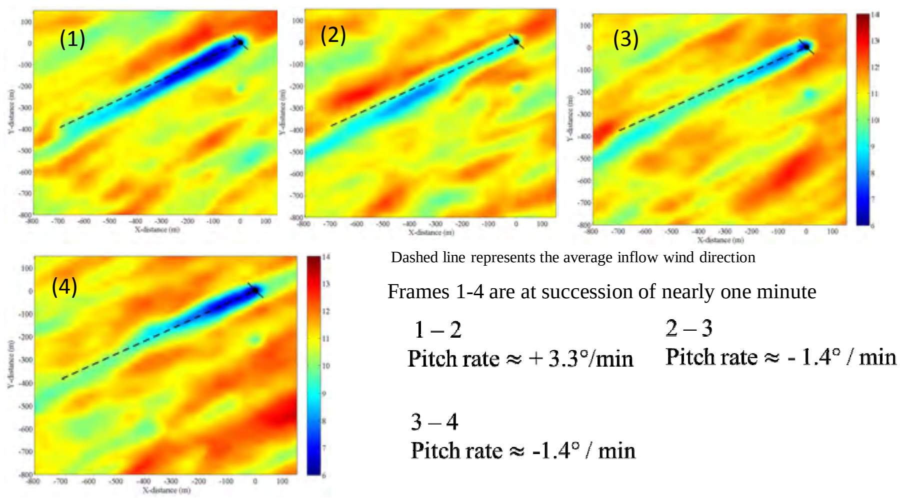


IEA; Oct. 7, 2014 16



Effect of Changing Blade Pitch Angle

Hub height wind speed (m/s)



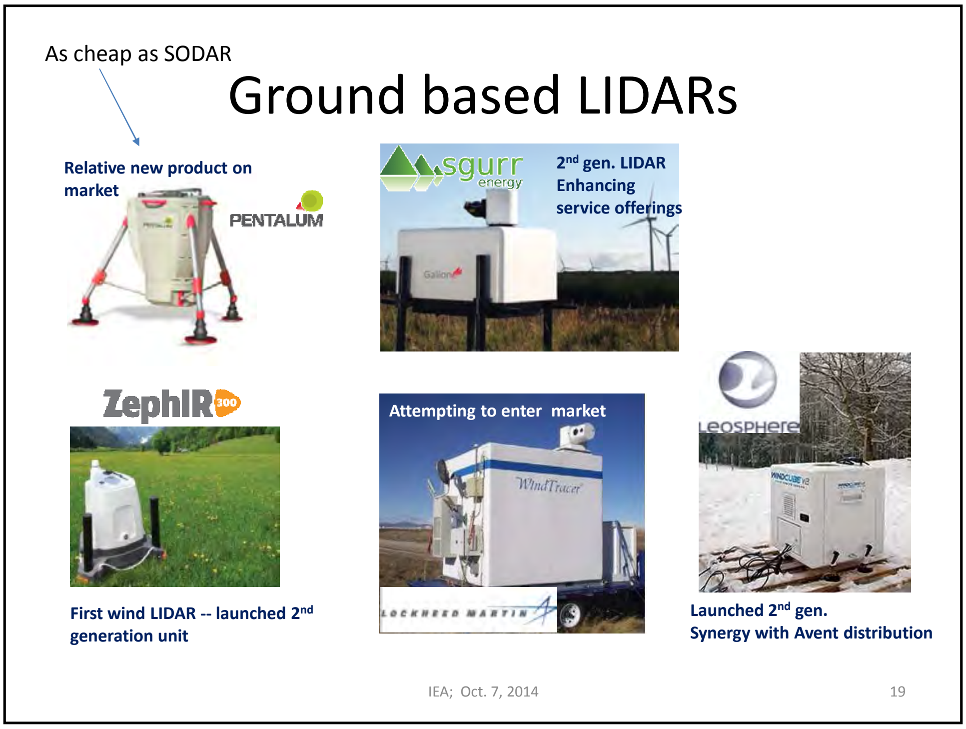
Dashed line represents the average inflow wind direction

Frames 1-4 are at succession of nearly one minute

1 – 2
Pitch rate ≈ + 3.3°/min

2 – 3
Pitch rate ≈ - 1.4° / min

3 – 4
Pitch rate ≈ -1.4° / min


As cheap as SODAR
Ground based LIDARs
Relative new product on market
PENTALUM
sgurr energy
2nd gen. LIDAR Enhancing service offerings
ZephIR 300
Attempting to enter market
WindTracer
LOCKHEED MARTIN
LEOSPHERE
Launched 2nd gen. Synergy with Avent distribution
First wind LIDAR -- launched 2nd generation unit
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Nacelle mounted
avent
windris
WINDAR PHOTONICS
In development
Opto Atmospherics
BlueScout
Bankrupt
Research demonstration
ZephIR 300
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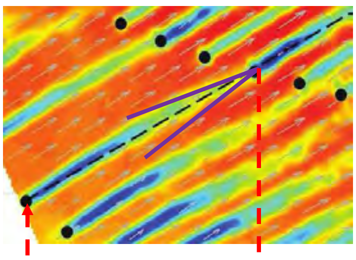
Nacelle mounted controls

IEA; Oct. 7, 2014 – Recharge magazine 05/2013 21

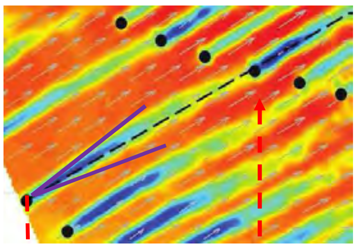
Looking the wrong way ? Backward facing seem to be a more rational approach

Feed forward LIDAR control



Measure wake from downstream
Control pass to upstream

Feed “backward” LIDAR control



Measure wake from upstream
Control pass to downstream

* “The Wake Effect: Impacting turbine siting agreements”, North American Clean Energy , Jan/Feb 2013. (Credit: NWI, TTU)

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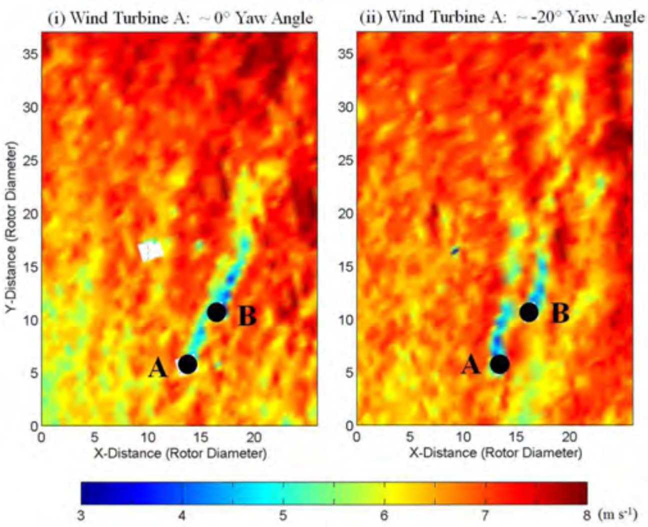
Ka-band radar at SWIFT



IEA; Oct. 7, 2014 Texas Tech University, Neha Marathe, December 2014,
Figure courtesy: Brian Hirth, National Wind Institute

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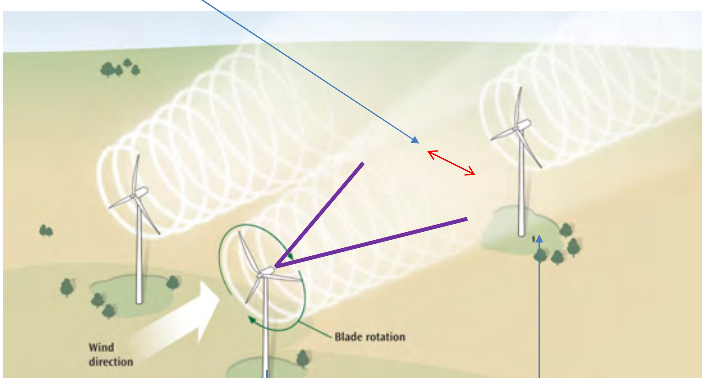
Plans: SWIFT is ideally poised to research a backward facing LIDAR control

Direct wake steering
RPM, Pitch, yaw



Feedback for optimal control

IEA; Oct. 7, 2014

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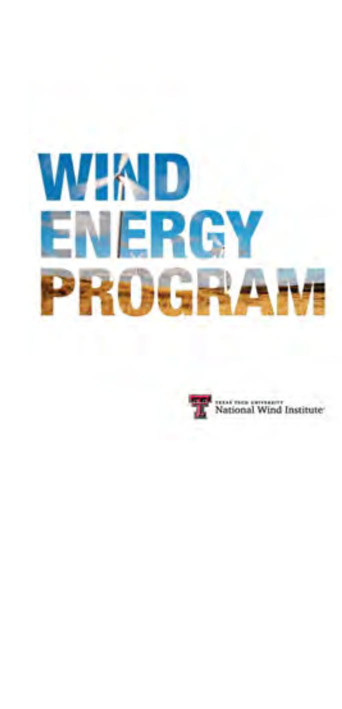


GRADUATE CERTIFICATES IN WIND ENERGY

There are two foci areas available in the Graduate Level Certificate Program in Wind Energy:

1) Technical Track - designed for professionals working in the technical aspects of the wind industry (e.g. engineering, manufacturing or design)
2) Managerial Track - designed for professionals focused on managerial or administrative positions

Both tracks are offered on-line (distance education) and on the Lubbock campus of Texas Tech University.

TECHNICAL TRACK

The Technical Track is a multidisciplinary track intended for students with a physical science or engineering background who wish to pursue a technical approach to the wind energy field. Course topics address the aerodynamic, mechanical and electrical aspects of the industry. Five courses are needed for each track. The three courses from the "Required Courses" section and two courses from the "Optional Courses" section.

Required Courses:

WE 5300 Advanced Technical Wind Energy I
WE 5301 Advanced Technical Wind Energy II
ECE 5343 Power Systems Engineering

Optional Courses
(two selections are required from this list):

ATMO 5301 Wind Power Meteorology
IE 5306 Safety Engineering
IE 5319 Risk Modeling & Assessment
IE 5329 Project Management
LAW 6205 Wind Energy Law & Policy
WE 5320 Renewable Energy Policy
WE 7000 Research

MANAGERIAL TRACK

This is a multidisciplinary track intended for students with a business, managerial or natural sciences background that wish to pursue a non-technical approach to wind energy.

Required Courses:

WE 5310 Advanced Managerial Wind Energy I
WE 5311 Advanced Managerial Wind Energy II
IE 5329 Project Management

Optional Courses
(two selections are required from this list):

ECE 5343 Power Systems Engineering
IE 5306 Safety Engineering
IE 5319 Risk Modeling & Assessment
LAW 6205 Wind Energy Law & Policy
WE 5320 Renewable Energy Policy
WE 7000 Research

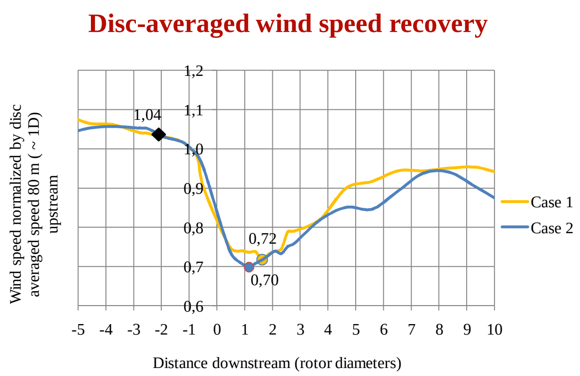
PLEASE NOTE:
While every effort has been made to ensure the accuracy in reporting courses, policies, and other statements within this publication, Texas Tech University reserves the right to make changes at any time without notice. Students are subject to all degree regulations as outlined in the TTU Undergraduate/Graduate Catalogue.

Questions

Contact
andy.swift@ttu.edu

IEA; Oct. 7, 2014 26

Induction factor



Induction factor calculation

For Case 1:

$$V-(V-bV)=1.04-0.72$$

$$b=0.308$$

Using b = 2a

$$a=0.154$$

For Case 2:

$$V-(V-bV)=1.04-0.7$$

$$b=0.327$$

Using b = 2a

$$a=0.164$$

IEA; Oct. 7, 2014 27

ForWind
Center for Wind Energy Research

Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Hauke Beck, Andreas Rott, Jörge Schneemann, Davide Trabucchi,
Juan José Trujillo, Robert Unguran, Stephan Voß, Martin Kühn

Research Group Wind Energy Systems
ForWind – Center for Wind Energy Research
University of Oldenburg

Lubbock, Texas, US, October 7th, 2014

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Center for Wind Energy Research

IEA Wind TEM#78 | "Field Test Instrumentation and Measurement - Best Practices"
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Content

"Dynamic multi-lidar campaigns for offshore wind farm flow"

- Introduction & Motivation
- Offshore campaign at alpha ventus
- Exemplary results
- Outlook & Conclusion

Content

"New type of anemometry"

- Sphere Anemometer
- 2D Laser Cantilever Anemometer

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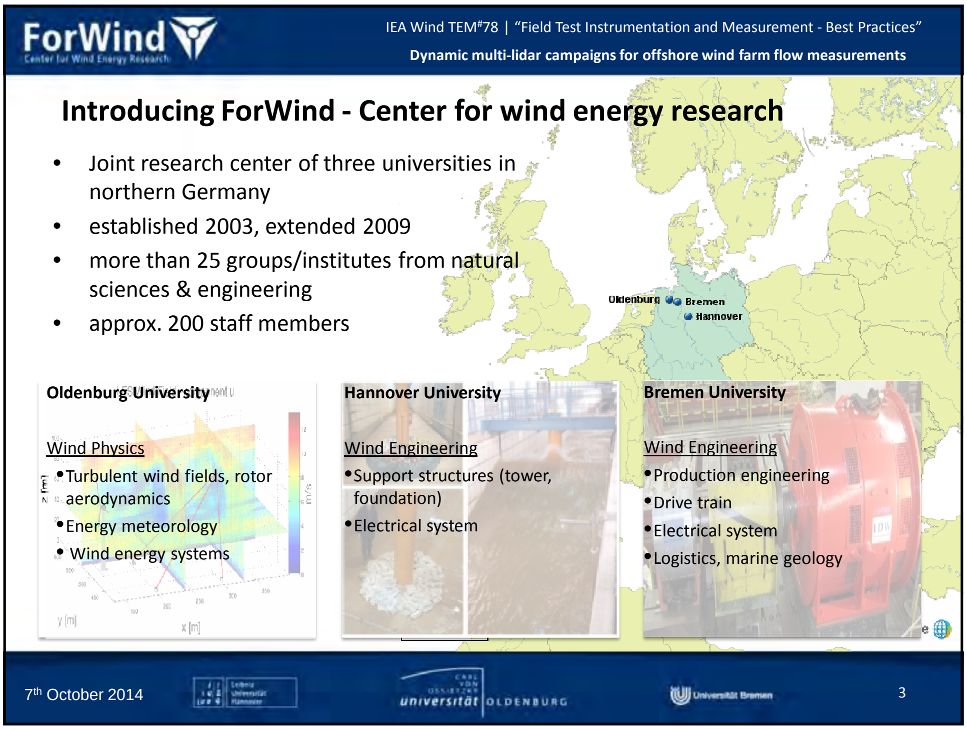
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Introducing ForWind - Center for wind energy research
• Joint research center of three universities in northern Germany
• established 2003, extended 2009
• more than 25 groups/institutes from natural sciences & engineering
• approx. 200 staff members
Oldenburg
Bremen
Hannover
Oldenburg University
Wind Physics
•Turbulent wind fields, rotor aerodynamics
•Energy meteorology
• Wind energy systems
Hannover University
Wind Engineering
•Support structures (tower, foundation)
•Electrical system
Bremen University
Wind Engineering
•Production engineering
•Drive train
•Electrical system
•Logistics, marine geology
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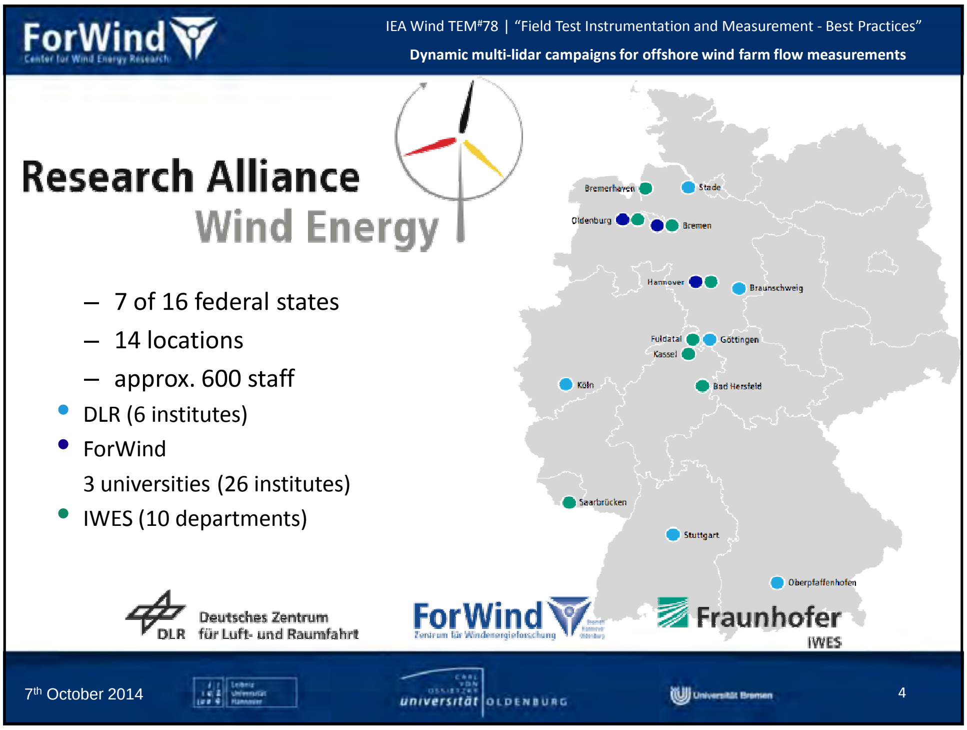
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Research Alliance
Wind Energy
– 7 of 16 federal states
– 14 locations
– approx. 600 staff
• DLR (6 institutes)
• ForWind
3 universities (26 institutes)
• IWES (10 departments)
Bremerhaven
Stade
Oldenburg
Bremen
Hannover
Braunschweig
Fuldatal
Göttingen
Kassel
Köln
Bad Hersfeld
Saarbrücken
Stuttgart
Oberpfaffenhofen
DLR
Deutsches Zentrum für Luft- und Raumfahrt
ForWind
Zentrum für Windenergieforschung
Fraunhofer
IWES
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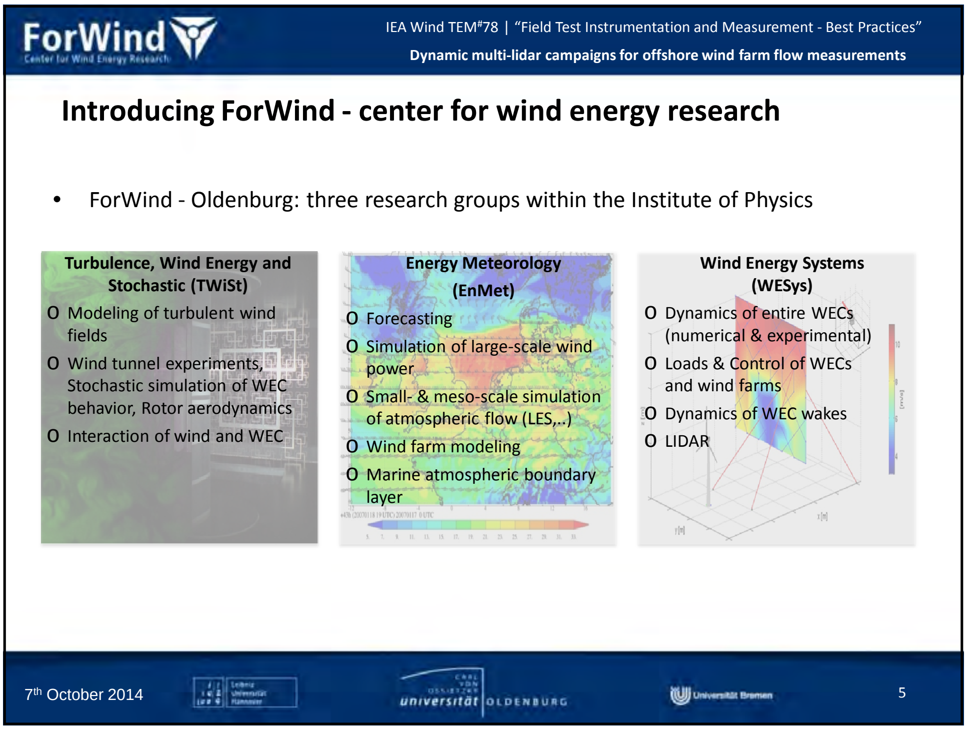
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Introducing ForWind - center for wind energy research
• ForWind - Oldenburg: three research groups within the Institute of Physics
Turbulence, Wind Energy and Stochastic (TWiSt)
o Modeling of turbulent wind fields
o Wind tunnel experiments, Stochastic simulation of WEC behavior, Rotor aerodynamics
o Interaction of wind and WEC
Energy Meteorology (EnMet)
o Forecasting
o Simulation of large-scale wind power
o Small- & meso-scale simulation of atmospheric flow (LES,..)
o Wind farm modeling
o Marine atmospheric boundary layer
Wind Energy Systems (WESys)
o Dynamics of entire WECs (numerical & experimental)
o Loads & Control of WECs and wind farms
o Dynamics of WEC wakes
o LIDAR
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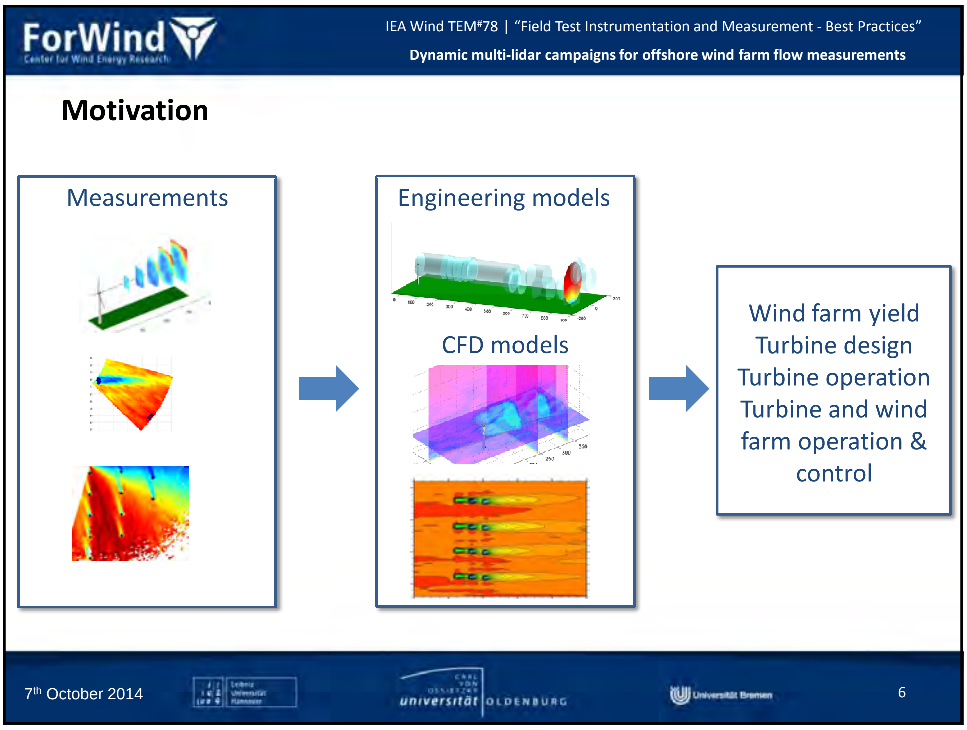
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Motivation
Measurements
Engineering models
CFD models
Wind farm yield
Turbine design
Turbine operation
Turbine and wind farm operation & control
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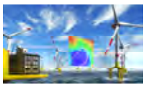
Research infrastructure

full scale field experiments



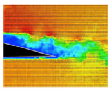
lidar windscanners,
research turbine (planned)

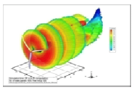
laboratory experiments

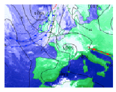
turbulent wind tunnel
- small (existing)
- large (under construction, 2016)

simulation

high performance computing cluster (2232 cores)







Analysis on multiple scales

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Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Examples of Projects at ForWind – Wind Energy Systems

National
- GigaWatt Wakes (GW Wakes)
- Compact Wind

European
- EERA-Design tools for Offshore wind farm cluster (EERA-DTOC)
- Windscanner.eu
- Clusterdesign
- IEA Task 32

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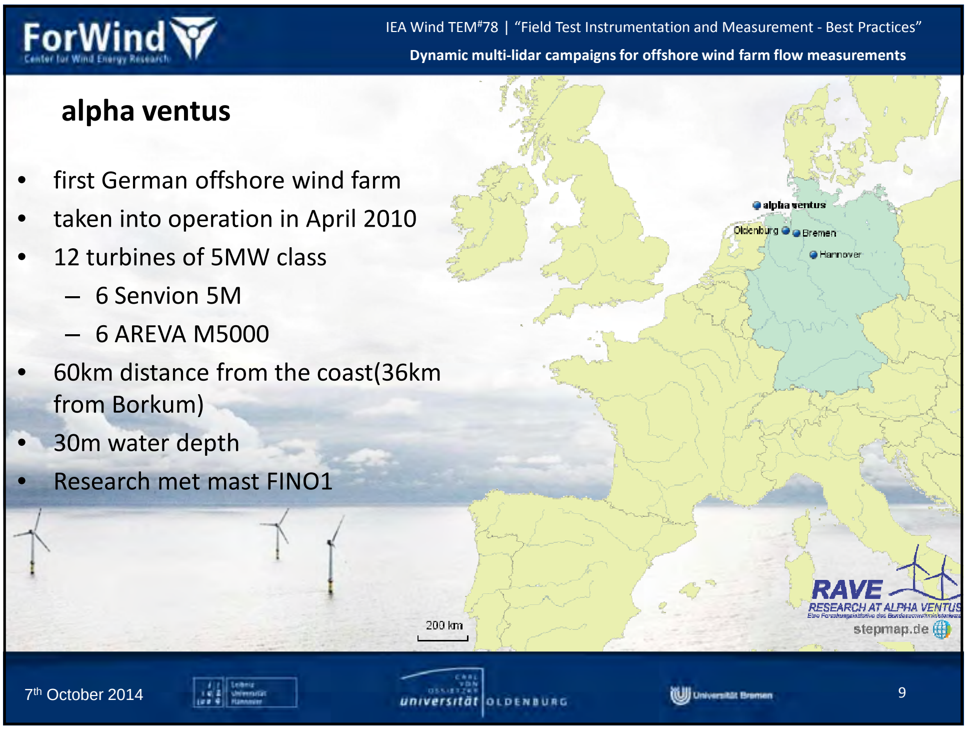
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
alpha ventus
• first German offshore wind farm
• taken into operation in April 2010
• 12 turbines of 5MW class
– 6 Senvion 5M
– 6 AREVA M5000
• 60km distance from the coast(36km from Borkum)
• 30m water depth
• Research met mast FINO1
alpha ventus
Oldenburg
Bremen
Hannover
200 km
RAVE
RESEARCH AT ALPHA VENTUS
stepmap.de
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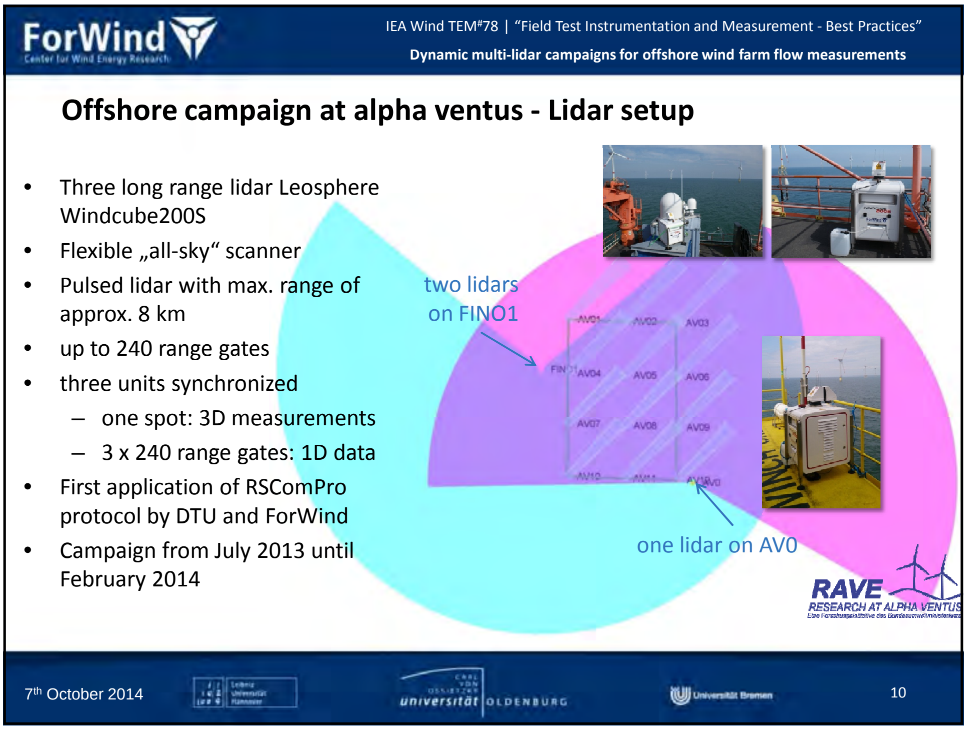
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Offshore campaign at alpha ventus - Lidar setup
• Three long range lidar Leosphere Windcube200S
• Flexible „all-sky" scanner
• Pulsed lidar with max. range of approx. 8 km
• up to 240 range gates
• three units synchronized
– one spot: 3D measurements
– 3 x 240 range gates: 1D data
• First application of RSComPro protocol by DTU and ForWind
• Campaign from July 2013 until February 2014
two lidars on FINO1
one lidar on AV0
RAVE
RESEARCH AT ALPHA VENTUS
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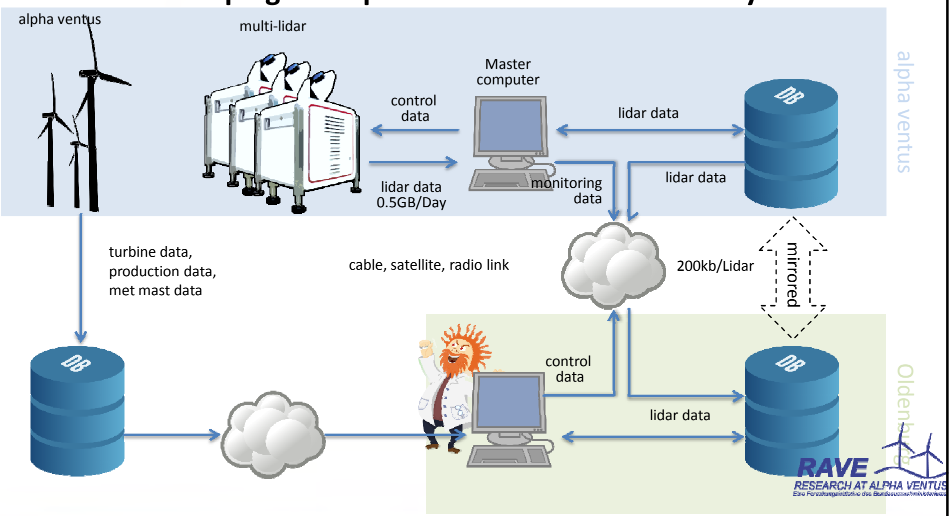
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Offshore campaign at alpha ventus – measurement system



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Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Offshore campaign at alpha ventus – measurement system

- exemplary measurement catalog

Messung	Priorität	Windrichtung	Name	Modus	Kommentar	Verwendung im Projekt	Nutzer	Fragen / Anmerkungen
1	1	**000 +10 / - 30**	LLJ	2D Vertikalprofil (2xRHI) 0 - 500m in freier Strömung	auch bei ausgeschalteten WEA	OWEA Loads	MD	Nur ca. 500 m nördlich AV2
2a	1-2	**040 +/- 30**	Farm Wake	UW: PPI, Fino 1: PPI + Vertikalprofil	10 min Mittel, hohe Reichweite	GW Wakes	ES, GS, JJT, LvB	Nachlauf des Parks mit hoher Reichweite
3	1-2	**090 +/- 15**	Vorstau und Intermittenz	Fino 1: 2xlos auf verschiedene Rotorpositionen, AV0: Los für 2D Information vor und hinter AV06 (Isotropie)	Viele überlappte range gates AV06	GW Wakes	GS, JJT,...	min 3D Vorstau, 4D Nachlauf
4a	Niedrig wegen Offset	**090 +/- 15**	Multiple Wakes	2D Scan eines Schnittes durch die Parkströmung	naher Parknachlauf hinter AV04 + AV05 + AV06	GW Wakes	MW, JJT,...	
5	1-2	**180 +/- 30**	LLJ	Fino: RHI -10° bis 45° in Windrichtung, Fino +AV0: 2D Vertiklaprofil (mit RHIs) von 0 - 500 m abwechselnd 3D in Windrichtung vor und 4D in Windrichtung hinter der WEA	vor und hinter AV 10, 11 oder 12 (abhängig vom Sichtbereich auf der AV0) auch bei ausgeschalteten WEA	OWEA Loads	MD	
4b	Niedrig wegen Offset	**180 +/- 15**	Multiple Wakes	2D Scan eines Schnittes durch die Parkströmung	naher Parknachlauf hinter AV11+ AV08 + AV05 + AV02	GW Wakes	MW, JJT,...	
2b	1-2	**180 - 270**	Farm Wake	UW: PPI, Fino 1: PPI + Vertikalprofil	10 min Mittel, hohe Reichweite	GW Wakes	ES, GS, JJT, LvB	Nachlauf des Parks mit hoher Reichweite
6	Nur wenn die Boje auch draußen ist...	**220 +/- , abh. von Bojenpos.**	Stabilitätscheck	2D hor. Wind 30 m über der Boje	Insbesondere bei ausgeschalteten WEA	GW Wakes	GS, MD, JT	Abweichung abh. von der Bojenpos. / Vorschlag: nicht BSH Boje sondern Boje der Meeresphysik?
7a	1	**230 +/- 15**	2D Area Wake	UW: PPI durch Wake, Fino: RHI + PPI(Elevation angepasst an jeweilige WEA)	AV04 & AV2, Schnitt der Nabenhöhe in ca. 2,5D	GW Wakes	GS,...	Wäre möglich, jedoch mit eingeschränkter Auflösung hinter A4, da Komponente von UW fast senkrecht zum Wind
7b	1a	**270 +/- 15**	2D Area Wake	UW: PPI durch Wake (Fino bis hinter AV06), Fino: RHI + PPI(Elevation abwechselnd angepasst an AV04,05 unf 06)	AV04 & AV5, Schnitt der Nabenhöhe in ca. 2,5D mit PPI Fino	GW Wakes	GS,...	PPI von Fino einzeln für jeweilige Anlage. Z.B: +Scanrichtung von UW mit AV04 und -Scanrichtung von UW mit AV05, damit 2D-Daten möglichst synchron und in Nabenhöhe
8	1b	**270 +/- 30**	Vertikalprofil im Park	2D Vertikalprofil [20:20:200,250,300] m des hor. Windes an 6 Pos. (mit Gerald absprechen)	9 - 13 m/s	GW Wakes	GS	Ca. 3h Daten pro meteorologischer Situation (Windstärke und -richtung) **läuft Parallel mit 8b**
9	3	**325 +/- 45**	Kurzzeitfluktuation	Fino1: PPI 0 - 360 ° (Blinde Sektoren ausgenommen), 0° Elevation, höchste Reichweite, 2°/s, 1Hz	ca. 1 Woche nicht-zusammenhängende Daten, labile Schichtung	SEE	LvB	ca. 1 Woche nicht-zusammenhängende Daten (falls möglich in groben Zeitintervallen Nachführung zur Windrichtung); parallel mit 1 und 8 sehr gut möglich (Ausnutzung des zweiten FINO Lidars) **läuft Parallel mit 8a und 1**
10	2	**270 +/- 30**	Wake AV04+AV05	Fino 1: Los durch AV04 + Los durch AV05 UW: Los für 2D Info an drei verschiedenen Punkten (hinter AV05, hinter AV04, vor AV04)	1 Hz	GW Wakes, OWEA Loads	JJT, MW, LVT, GS	
11	Niedrig wegen Offset	**270 +/- 30**	HD Wakes	2D Scan eines Wake-Schnittes	Einzelnachlauf 5D hinter AV04	GW Wakes	MW, JJT,...	
12	Niedrig wegen Offset	**270 +/- 15**	Multiple Wakes	2D Scan eines Schnittes durch die Parkströmung	naher Parknachlauf hinter AV04 + AV05 + AV06	GW Wakes	MW, JJT,...	

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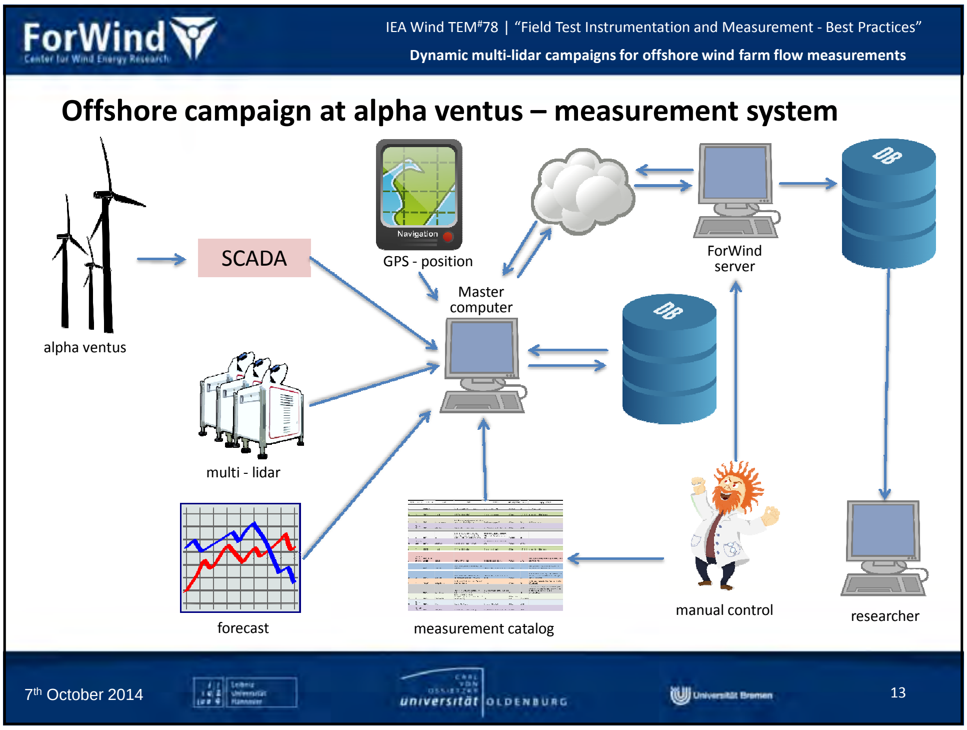
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Offshore campaign at alpha ventus – measurement system
alpha ventus
SCADA
Navigation
GPS - position
Master computer
ForWind server
DB
multi - lidar
forecast
measurement catalog
manual control
researcher
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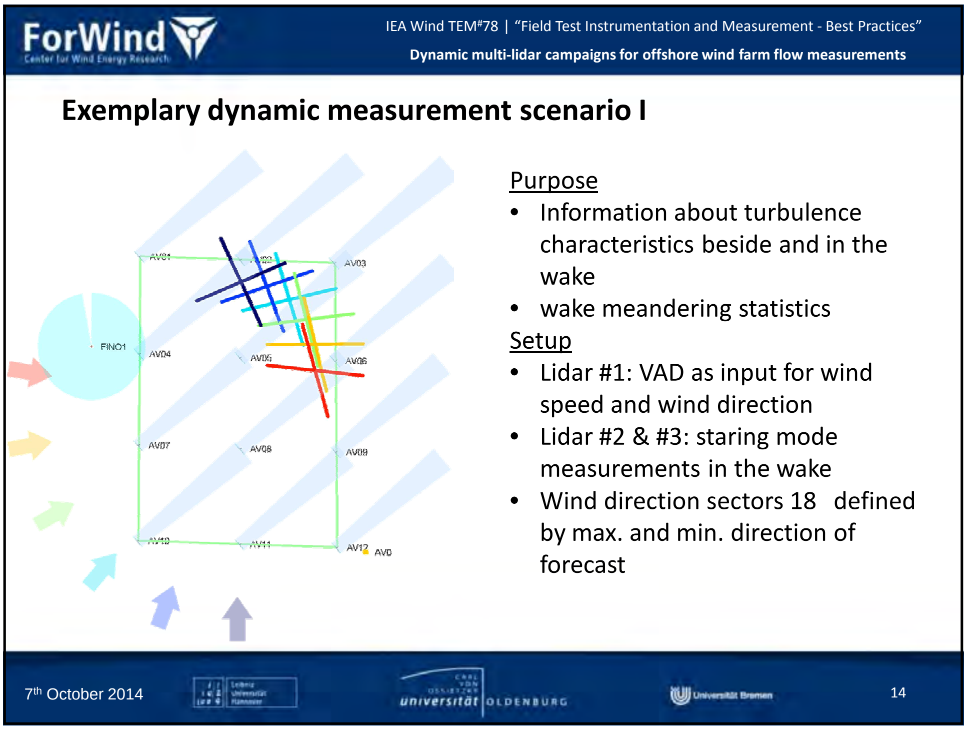
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Dynamic multi-lidar campaigns for offshore wind farm flow measurements
Exemplary dynamic measurement scenario I
FINO1
AV01
AV02
AV03
AV04
AV05
AV06
AV07
AV08
AV09
AV10
AV11
AV12
AV0
Purpose
• Information about turbulence characteristics beside and in the wake
• wake meandering statistics
Setup
• Lidar #1: VAD as input for wind speed and wind direction
• Lidar #2 & #3: staring mode measurements in the wake
• Wind direction sectors 18 defined by max. and min. direction of forecast
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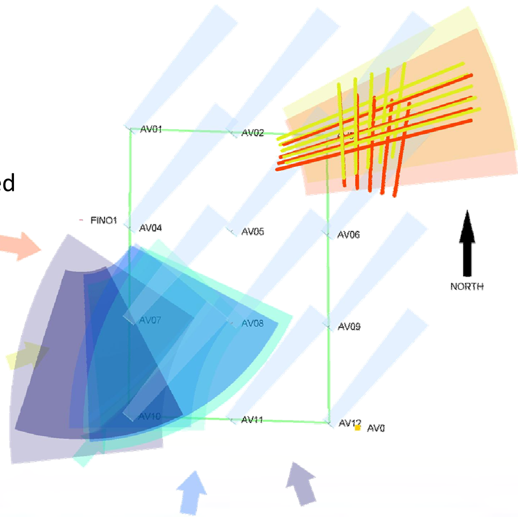
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Exemplary dynamic measurement scenario II

Purpose
- High resolved 2D single wake measurements

Setup
- Wind direction sectors 30° defined by max. and min. direction of forecast
- Input for wind direction based on SCADA data
- Dependent on inflow
  - overlapped PPI scans
  - RHI scans



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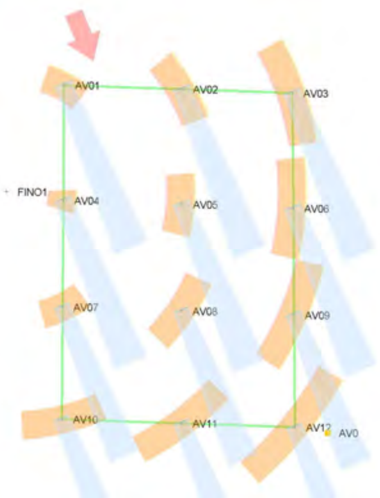
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Positioning and orientation

- Verification and correction of position by Hard targeting
  - Offshore: difficult caused by missing height reference
- Roll und pitch orientation hard to estimate and measure
  - Development of capable method

➡ Sea Surface Leveling



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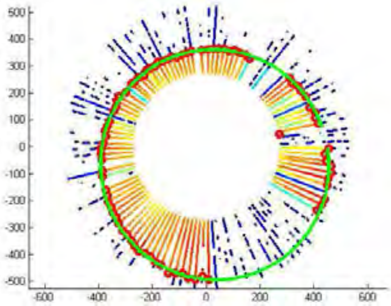
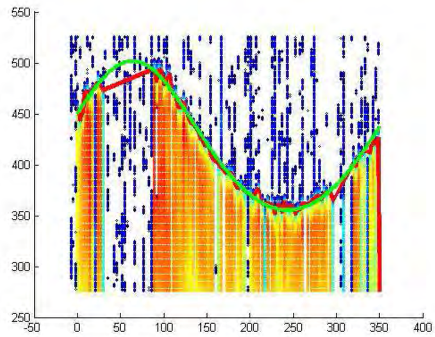
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Positioning and orientation - Sea Surface Leveling



- PPI scans with with different negativ elevation on sea surface



- Fitting the model with the measurements
- Determining height, roll and pitch

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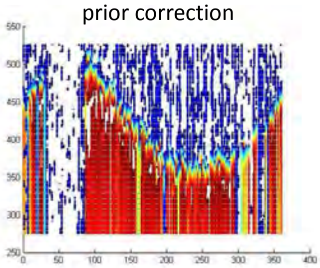
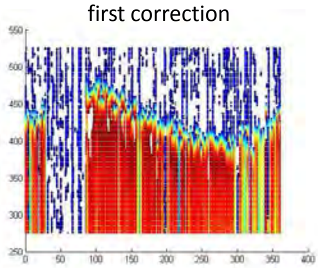
Positioning and orientation - Sea Surface Leveling

prior correction

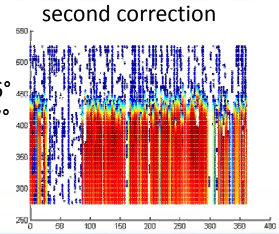


first correction

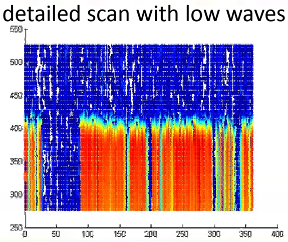


second correction

roll = 0.016°
pitch = -0.007°



detailed scan with low waves



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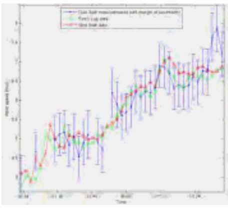
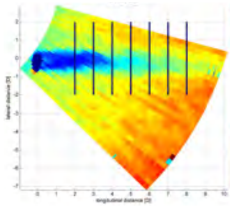
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

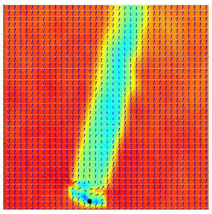
Exemplary results



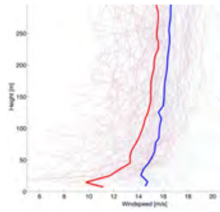
Plausibility check of lidar data



Model adjustments by 1D mean measurements



Analysis of 2D mean measurements



Analysis of wind farm wake

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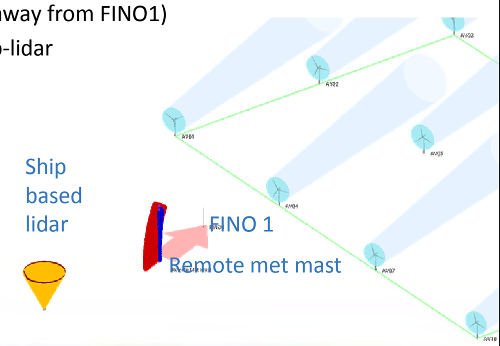
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Exemplary results – Comparison against met mast FINO1

Virtual Met Mast

- two RHI-scans crossing in one vertical line starting at surface level moving upwards
- scan speed adapted for each LiDAR to the measurement points distance to achieve a synchronized measurement in each height
- Remote met. mast. ~ 0 - 300m (500m away from FINO1)
- Comparison with Fraunhofer IWES ship-lidar
- Temporal resolution: 38s per scan



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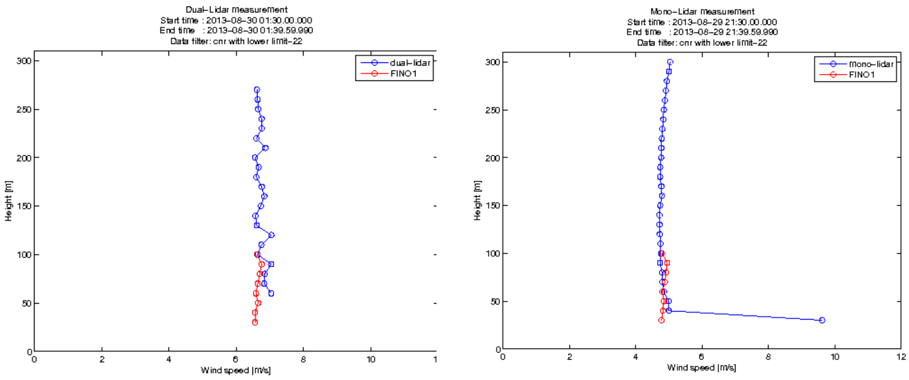
Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Exemplary results – Comparison against met mast FINO1

- Dual RMM vs. Mono RMM against FINO1



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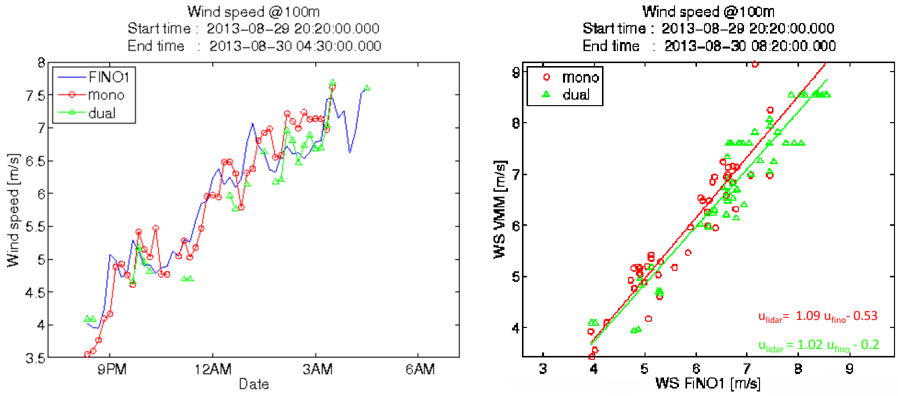
Exemplary results – Comparison against met mast FINO1

- Comparison against FINO1



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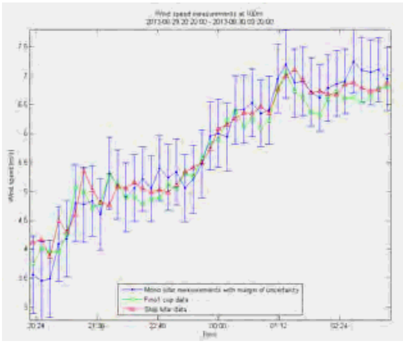
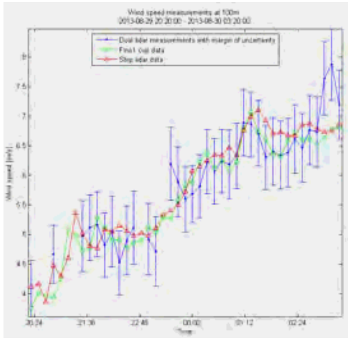
Exemplary results – Comparison against met mast FINO1

- Comparison against Fraunhofer IWES ship lidar





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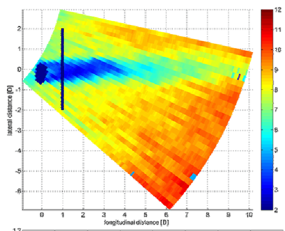
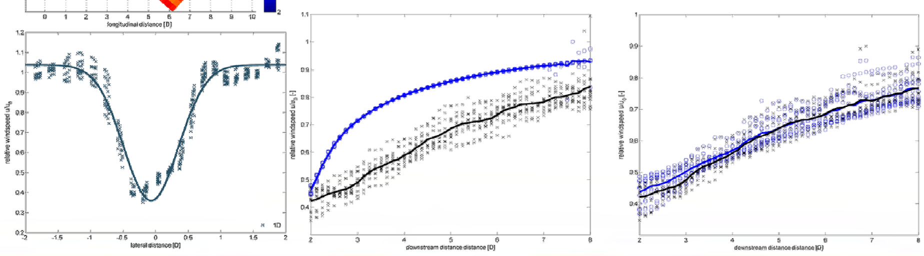
Exemplary results – Adjustment of Engineering model by 1D-PPI scans



- Adjust the Ainslie wake model parameter by means of 1D PPI lidar measurements [1]
- changing turbulence intensity from static input to 1D variable parameter depending on downstream distance
- New parameters for initial wake profile have been determined



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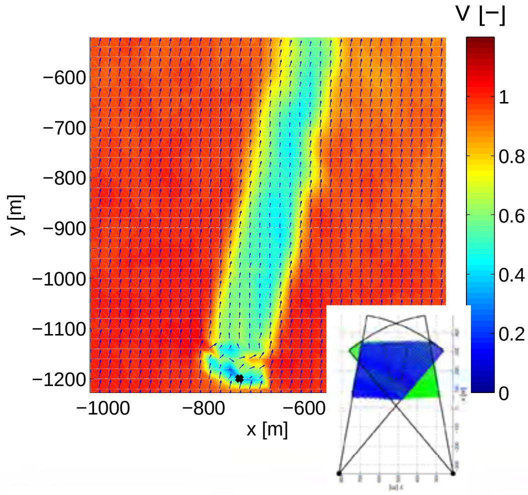
Exemplary results – 2D analysis of overlapping PPI scans

- Two overlapping PPI Scans
- Based on existing algorithms
- Extended Overdetermined Dual-Doppler Formalism (EODD) [2]
- Multiple-Doppler Synthesis and Continuity Adjustment Technique (MUSCAT) [3]



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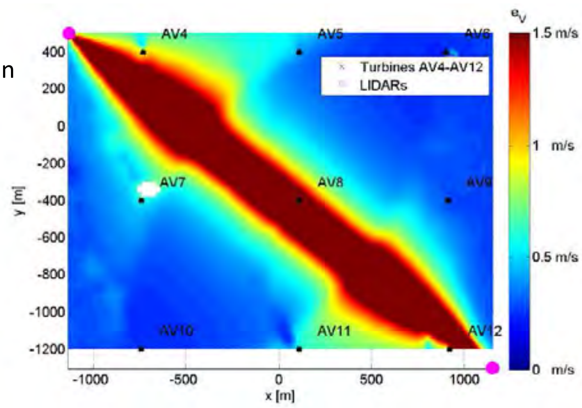
Positioning and Orientation - Error for 2D analysis

- Error has singularity for difference angle between lidars at 0°/180°
- Lowest errors for difference angle 90°



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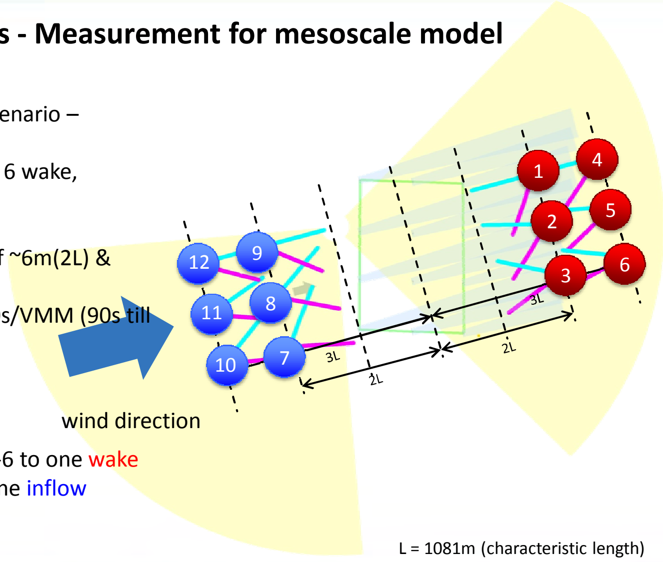
Exemplary results - Measurement for mesoscale model validation

- direction dependent scenario – 15°sector size
- 12 VMMRHI (6 inflow, 6 wake, alternating)
  - 0–400m height
  - spatial resolution of ~6m(2L) & ~8m(3L)
  - time resolution ~60s/VMM (90s till new mast)



- Averaging met masts 1-6 to one wake metmast and 7-12 to one inflow metmast

L = 1081m (characteristic length)

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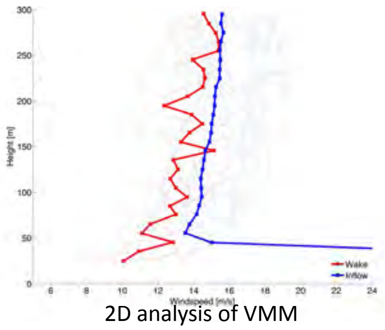
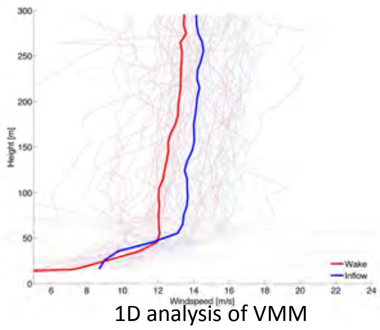
Exemplary results - Measurement for mesoscale model validation



2D analysis of VMM



1D analysis of VMM

- Trade-off: spatial and time resolution
- Insufficient data base for each profile

➡ how to measure representative wind farm inlow and wake profiles?

Outlook

- Projects:
  - Further measurements in offshore wind farm
  - Nacelle based multi-lidar measurements onshore and offshore
- Science:
  - Further development of 2D and 3D measurements
  - Single wake, multiple wakes, wake control (wake deviation and wake margin models)
  - Wake wind field reconstruction
  - Load analysis, enhance models for aeroelastic wake simulations

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Dynamic multi-lidar campaigns for offshore wind farm flow measurements

Conclusion

- Multi-lidar developed together with DTU is flexible enough to perform dynamic and complex measurements
- Limitations by lidar performance and atmospherical conditions
- We started to develop complex measurement and analysis methods

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Acknowledgements

Results and research shown were partly made in the project **GW Wakes** which is funded by
The German Federal Ministry for the Environment

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Dynamic multi-lidar campaigns for offshore wind farm flow measurements

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- [2] M. Chong & C. Campos: Extended Overdetermined Dual-Doppler-Formalism in Synthesizing Airborne Doppler Radar Data. Journal of Atmospheric and Oceanic Technology, 13:58-597,1996
- [3] O. Bousquet & M. Chong: A Multiple-Doppler Synthesis and Continuity adjustments technique (MUSCAT) to recover wind components from Doppler Radar measurements. Journal of Atmospheric and Oceanic Technology, 15:343-359,1998

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New type of anemometry

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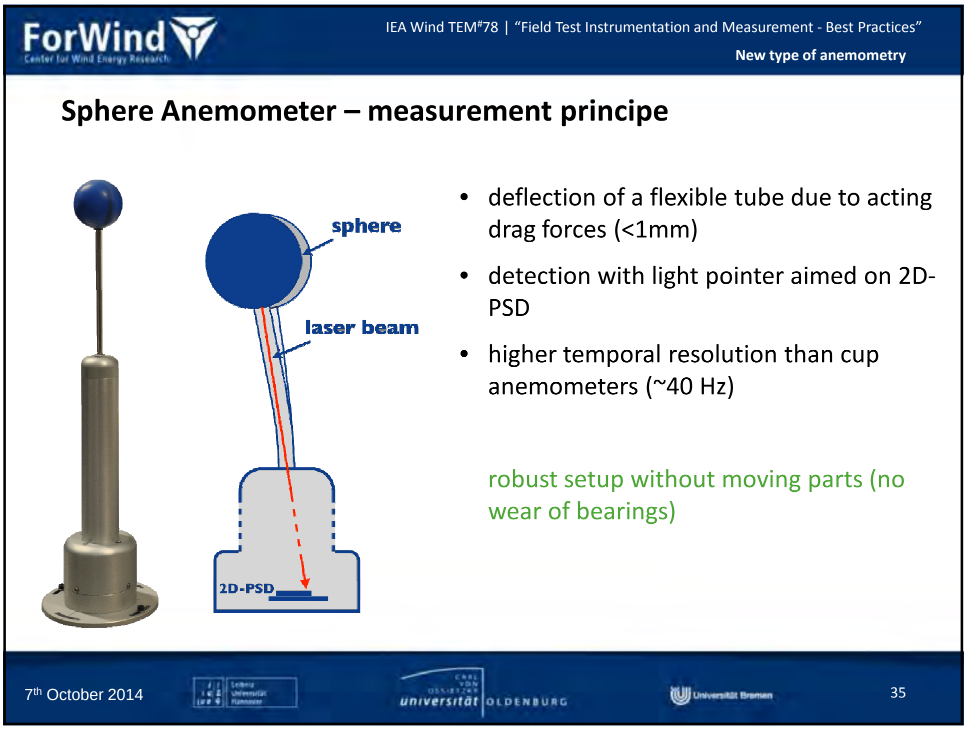
Research Group Turbulence, Wind Energy and Stochastics
ForWind – Center for Wind Energy Research
University of Oldenburg

Lubbock, Texas, US, October 7th, 2014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New type of anemometry
Sphere Anemometer – measurement principe
sphere
laser beam
2D-PSD
• deflection of a flexible tube due to acting drag forces (<1mm)
• detection with light pointer aimed on 2D-PSD
• higher temporal resolution than cup anemometers (~40 Hz)
robust setup without moving parts (no wear of bearings)
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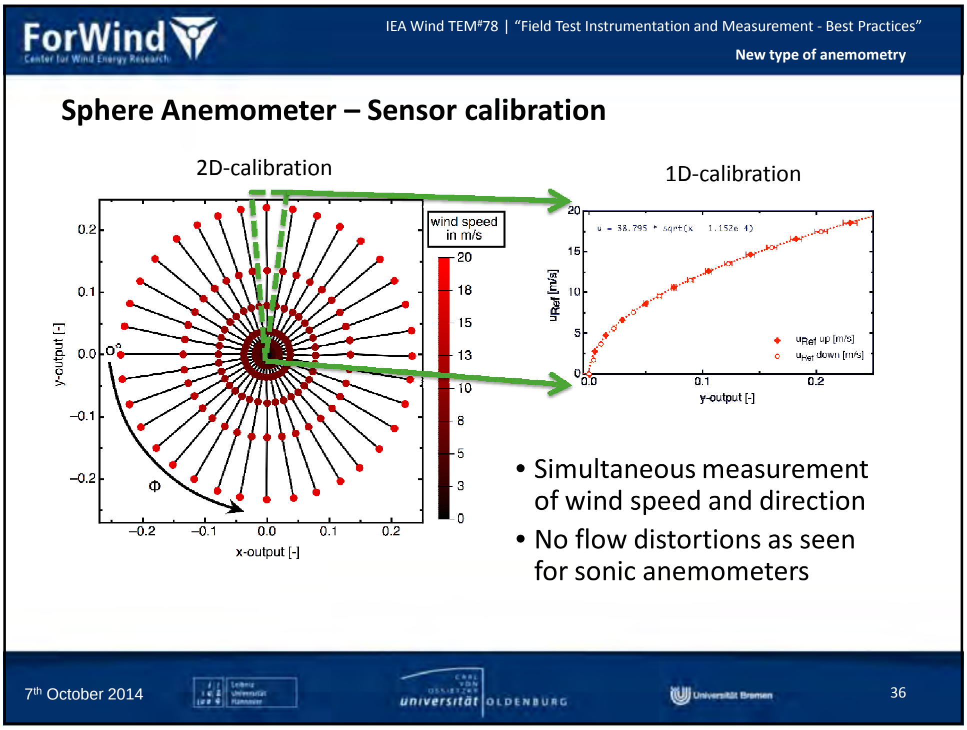
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New type of anemometry
Sphere Anemometer – Sensor calibration
2D-calibration
1D-calibration
wind speed in m/s
y-output [-]
x-output [-]
uRef [m/s]
y-output [-]
Φ
• Simultaneous measurement of wind speed and direction
• No flow distortions as seen for sonic anemometers
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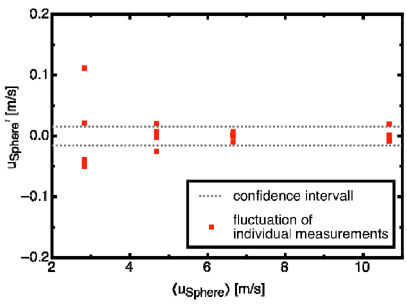
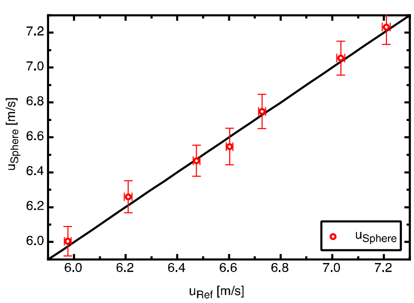
Sphere Anemometer – Precision & accuracy tests



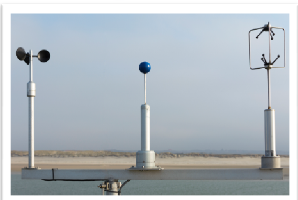


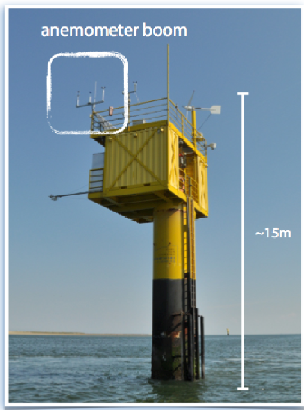
$$u'_{\mathrm{Sphere}} = u_{\mathrm{Sphere}} - \langle u_{\mathrm{Sphere}} \rangle$$

$$\Delta u = u_{Sphere} - u_{Ref}$$

Precision and accuracy better than 0.1 m/s.
(Comparable to standard anemometers)

Sphere Anemometer – Near-Shore Installation

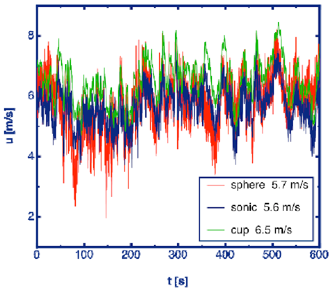


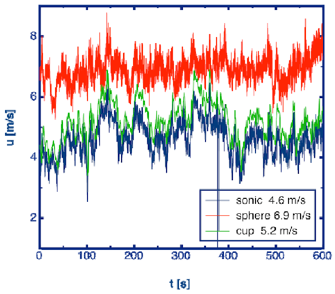


- Near-shore hydrographic station in German Wadden Sea
- Anemometer boom with
  - Sphere anemometer (center)
  - Thies First Class Advanced cup (right)
  - Gill WindmasterPro 32Hz sonic (left)

Sphere Anemometer – Near-Shore - first results

Comparison of 10-min horizontal wind speeds





- general tendencies are captured with sphere anemometer
- mean wind speeds of some intervals match well, while others do not
  - possible reason: offset shifted (still under investigation)

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New type of anemometry

Sphere Anemometer – Near-Shore – rough environment

The sphere anemometer at different stages of operation:


initial state


met platform
~ 3 month


nacelle of WEC
~ 8 month

- met platform: all anemometers covered with soil from nearby islands
  biggest issue: bearings of cup anemometer

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New type of anemometry

2D-Atmospheric Laser Cantilever Anemometer (2D-ALCA)

- developed at the University of Oldenburg
- measurement of two velocity components
- robust alternative to x-films
- highly resolved measurements in atmosphere (spatial res.: about1mm, temporal res.: about 1kHz)
- easy handling and calibration

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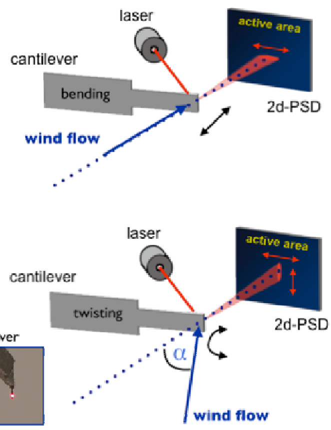
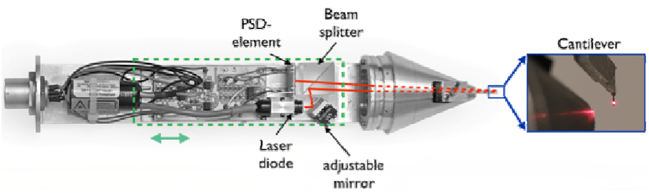
New type of anemometry

2D-ALCA - Working principle

- sensing element is a cantilever of 1,4mm in length made of stainless steel
- when exposed to flow the cantilever is bending and twisting
- position of the reflecting laser spot is tracked using a 2D-PSD element (light leaver principle.)





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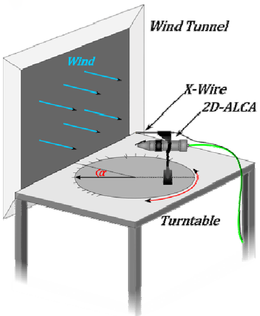
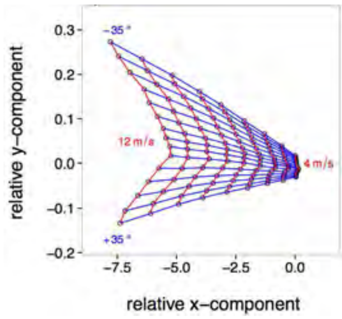
New type of anemometry

2D-ALCA - Calibration





- Calibration takes place in a wind tunnel
- Position of the reflecting spot is recorded
- for several inflow velocities and angles of attack
- resulting in a calibration plane

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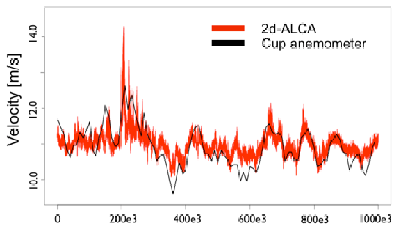
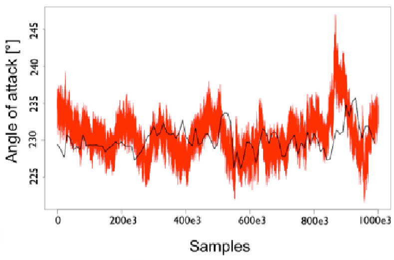
New type of anemometry

2D-ALCA - measurements





- 2D-ALCA installed at about 56m
- Comparison with cup anemometer (with wind vane)
- 2D-ALCA shows more details and more extreme events

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Thank you
for your attention (again)!
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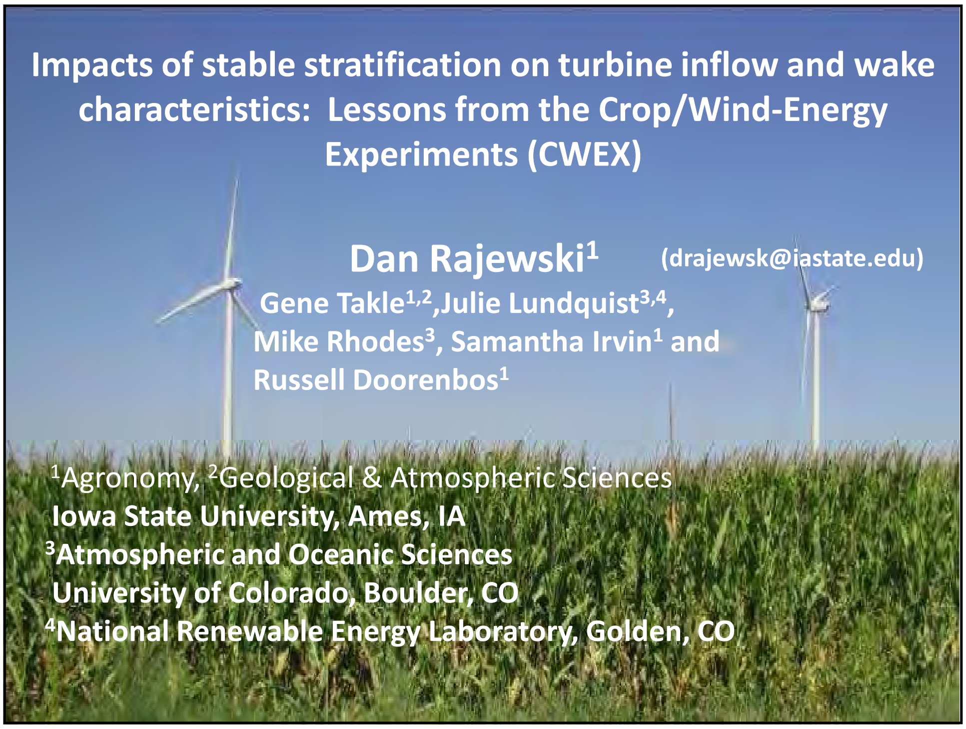
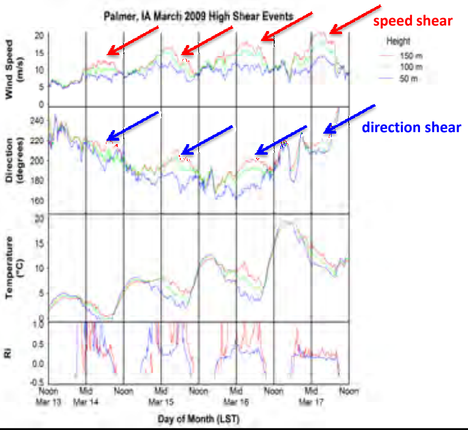


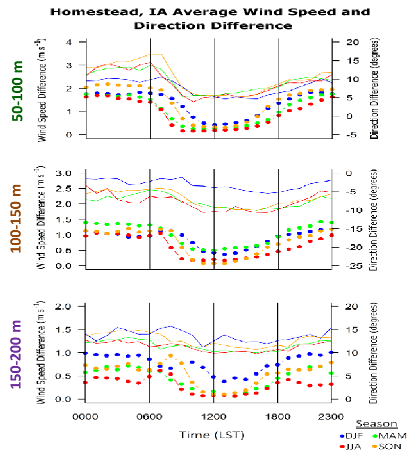
Key messages (summary overview)

- Underperformance of wind farms frequently occurs in stable stratification conditions
- Directional and speed shear within stable boundary layers complicates inflow and wake characterization
- Terrain complicates effect of shear
- Stable stratification conditions more easily reveal turbine-turbine flow interactions when (L~D)
- Profiling systems and in situ surface flux measurements complement detection of inflow and wake characterizations
- Sorting metrics of surface fluxes and hub-height measurements augment identification of wake structure and evolution within highly variable boundary layer stratification

Motivation

- Strongly stratified conditions with large speed and directional shear are important over the widely expanding fleet of wind farms in the Central US (*Wagner et al. 2011*)

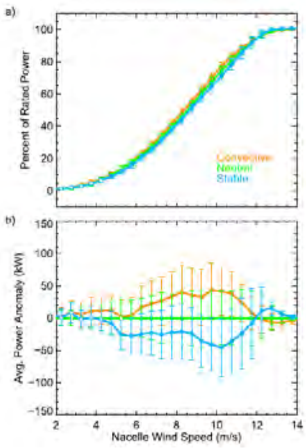




Nocturnal low-level jets are common in both cold and warm seasons (*Walton et al. 2014*)

Motivation (continued)

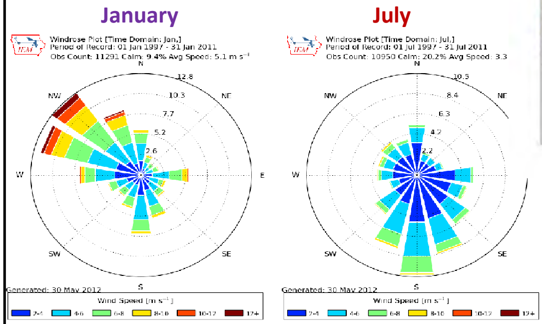
- Stable stratification promotes lower wind farm efficiency
  - Ambient scales of mixing prohibit dissipation of wakes and lead to greater turbine-turbine interactions deeper in the wind farm (Rhodes and Lundquist, 2013; Aitken et al. 2014)
  - loading on turbine components indicates less optimal operating status (Walter et al. 2009; Wharton and Lundquist 2011,2012)
- Need data benchmarks to calibrate wind tunnel and numerical simulations for several scales (individual wind turbines, wind farms, mesoscale effects of wind farms)

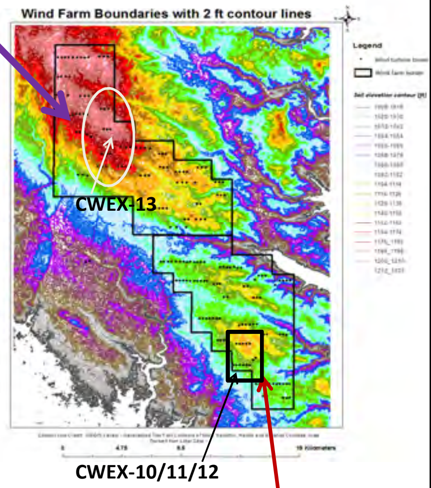


Vanderwende and Lundquist, 2012

CWEX layout

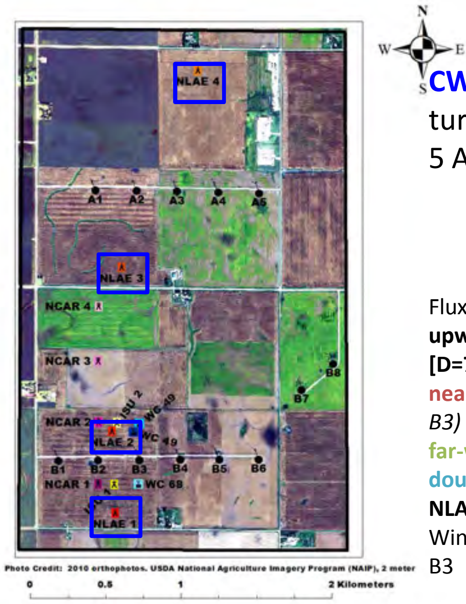
- Central Iowa wind farm (~200 1.5-MW turbines with 80-m hub height and 77 m and 82.5-m rotor diameter **(D)**)
- 2010-2012 Measurements taken on southern edge of a wind farm according to prevailing winds at nearby airports, 2013 measurements at northwest edge of the farm
- surface flux and LiDAR measurements above corn: 2010,2011; above **soybean**: 2012-3013





http://mesonet.agron.iastate.edu/sites/dyn_windrose.phtml?station=DSM&network=IA_ASOS

CWEX-10/11 expanded layout



Corn-soybean cropping pattern (measurements in corn)

CWEX-10: 26 June – 7 September; turbines off 0700 LST 26 July –1740 LST 5 Aug

Four flux towers *(NLAE)*

NREL/CU Lidar (J. Lundquist) from 28 June-9 July in CWEX-10

Fluxes were measured from:

upwind (4.5 D south of B-line of turbines) **NLAE 1 [D=77m]**

near-wake (*2.5 D north and between turbine B2 and B3)* **NLAE 2**

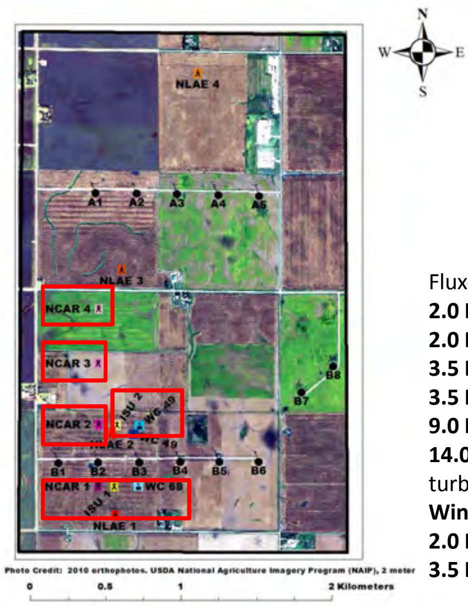
far-wake (*17 D north of B-line of turbines*) **NLAE 3**

double wake (*34 D north of B-line of turbines*)

NLAE 4

Wind cube in near-wake between turbine B2 and B3

CWEX-10/11 expanded layout



Corn-soybean cropping pattern (measurements in corn)

CWEX-11: 29 June - 16 August

6 flux towers in 2011 (*4—NCAR, 2– ISU*)

2 NREL/CU Lidars from 30 June to 16 Aug

Fluxes were measured from:

2.0 D (D=77 m) south of turbine B2 **NCAR 1**

2.0 D south and between turbine B2 and B3 **ISU 1**

3.5 D north of turbine B2 **NCAR 2**

3.5 D north and between turbine B2 and B3 **ISU 2**

9.0 D north of turbine B2 **NCAR 3**

14.0 D north of turbine B2 far-wake from B-line of turbines **NCAR 4**

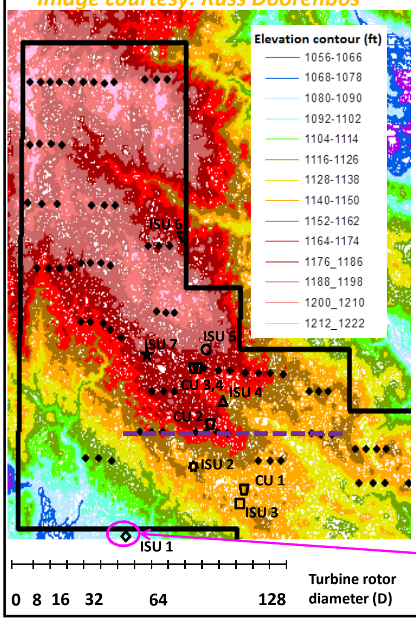
Wind cube measurements at:

2.0 D south of turbine B3 **WC 68**

3.5 D north of turbine B3 **WC 49**

CWEX-13 layout

Image courtesy: Russ Doorenbos



Legend

◆	turbine location
- - -	reference turbine line

Wind profiling LiDARs

- *CU 1 (-13 D)*
- *CU 2 (8.5 D)*
- *CU 3 (20 D)*
- *CU 4 (20 D)*

Surface flux stations

- *ISU 1 (-46 D)*
- *ISU 3 (-23 D)*
- *ISU 2 (-15 D)*
- *ISU 4 (19 D)*
- *ISU 5 (32 D)*
- *ISU 7 (34 D)*
- *ISU 6 (82 D)*

CWEX-13: 27 June – 19 September

Seven flux towers *(ISU)*

3 profiling LiDARs 27 June-5 Sept (CU/NREL)

1 scanning LiDAR 30 July-5 Sept (CU/NREL)

CWEX-13 investigated wakes for multiple turbines within several lines of turbines

Stratification-linked terrain effects observed between ISU 1 and other flux stations

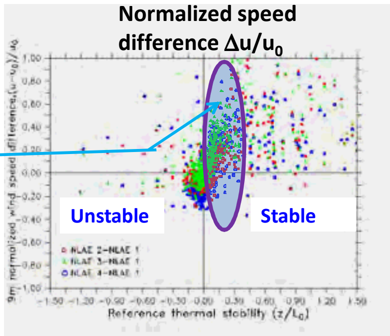
Stable boundary layer concepts learned from CWEX

1. Surface layer and above rotor-layer climatology of stability stratification
   i. directional shear within rotor as large as 30°
   ii. indication of surface convergence (directional deflection)
2. Identification of wake flow fields for single turbine, multiple turbines, and aggregate wind farm effect
   i. Wakes above but not reaching surface
   ii. Wakes directly intersecting surface
   iii. Flow perturbations remediated from pressure field around line of turbines
3. Wake influence most important at surface when surface layer scaling and rotor-sized mixing are similar (L~D)
4. Power reductions in stable stratification are larger and have slower recovery than neutral conditions (consistent with offshore findings)

Classification of stably stratified condition

- 1st method: determine upwind flux station z/L categories similar to Ri:
  - STABLE z/L>0.05 (*Rajewski et al. 2013*)
    - Largest forcing of wake between 0.15<z/L<0.30 (L~ D)

    Applied in CWEX-10/11 (less data period)
- 2nd method: Stability classification applied by *Hansen et al. 2012*
  - retain additional surface fluxes when reference station -50<L<0, (cL=-4), and 0<L<10 (cL=4)



CWEX-13 Stability Categories		cL class
MS	Moderately Stable	cL=2,3,4
WS	Weakly Stable	cL=1
N	Near Neutral	cL=0
WC	Weakly Convective	cL=-1
MC	Moderately Convective	cL=-2,-3,-4

Stability Class	Obukhov length (m)	Atmospheric Stability
cL=-3	-100 ≤ L ≤ -50	Very unstable
cL=-2	-200 ≤ L ≤ -100	Unstable
cL=-1	-500 ≤ L ≤ -200	Near unstable
cL=0	|L|>500	Neutral
cL=1	200 ≤ L ≤ 500	Near stable
cL=2	50 ≤ L ≤ 200	Stable
cL=3	10 ≤ L ≤ 50	Very stable

TAKEAWAY: Strength of stability less important than stratification type (Unstable, Neutral, Stable)

CWEX-13 wind farm modification of stratification

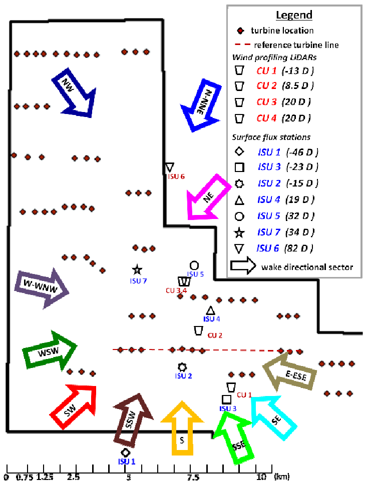
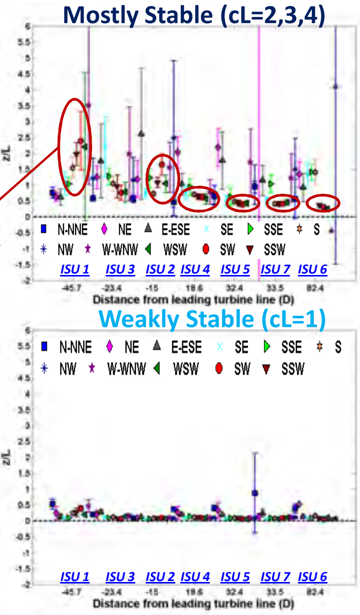


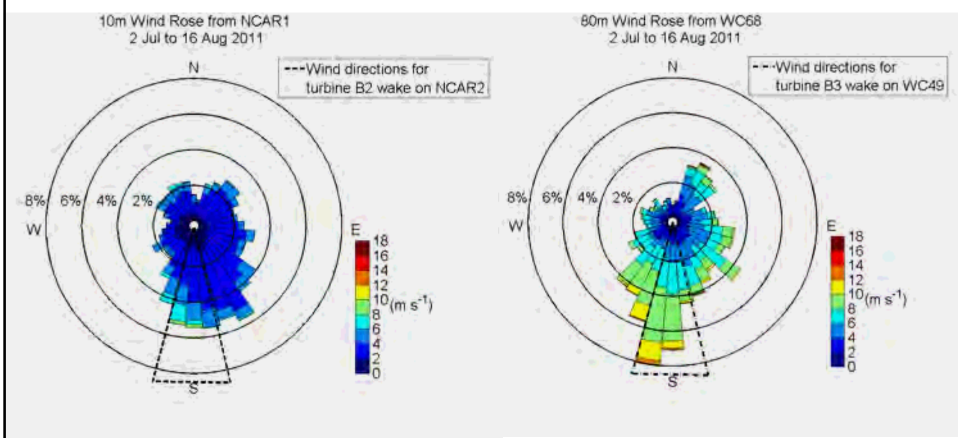
Image courtesy: Russ Doorenbos

Surface stability weakens downwind of additional lines of turbines for southerly wind



TAKEAWAY: Strength of stability less important than stratification type (Unstable, Neutral, Stable)

Directional and speed shear is important over flat terrain



Directional shear can be a complicating factor in wake impacts within the rotor depth vs. near the crop surface

(Rajewski et al. BAMS, 2013)

Low-Level Jet variations during CWEX-11

OBSERVED

surface-data

July 9

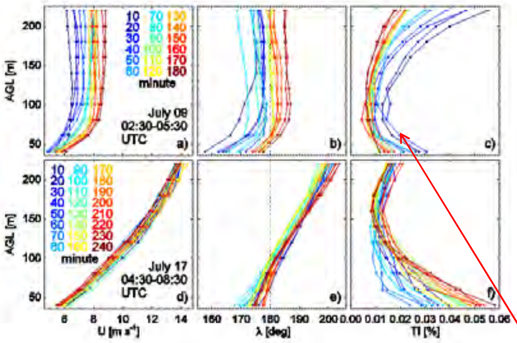
jet max within rotor depth

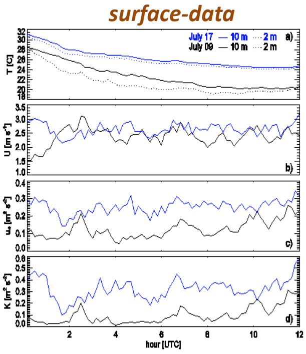
'non-classical'

July 17

jet max above rotor depth

'classical'

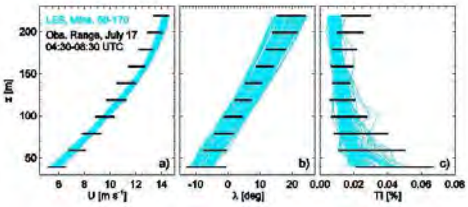




Stronger shear profile quenches rotor layer turbulence

SIMULATED---Jeff Mirocha (LLNL)

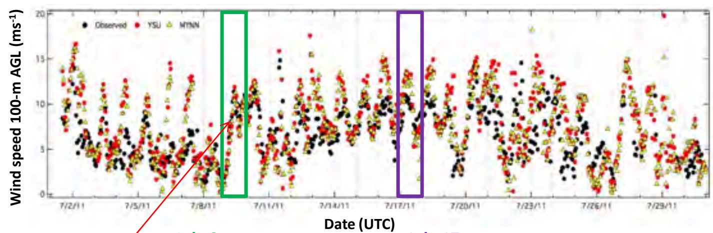
WRF-LES:
10 minute contours for constant surface cooling rate and geostrophic speed drive initial profiles of wind speed and temperature



WRF-LES favorable agreement to LiDAR measurements

PBL model comparisons to observations

Larry Berg (PNNL)

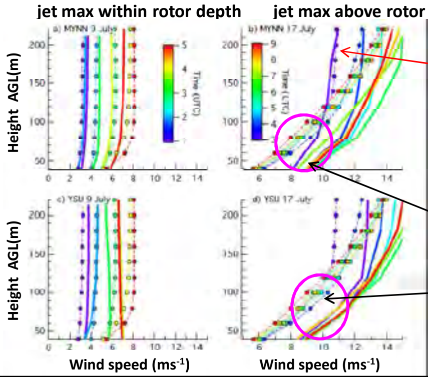


36-hr simulations with 12 hour *'spin-up'* time

Near-hub height wind speeds in PBL scheme have higher agreement in low-altitude jet (slower speed, lower jet maximum)

July 9 — jet max within rotor depth

July 17 — jet max above rotor depth



MYNN local-closure scheme has slightly improved agreement to observations above the rotor

Would QNSE scheme improve the rotor-layer profile fit?

refinements in surface simil schemes seem plausible

Low-Level Jets and wakes during CWEX-11

OBSERVED

July 9

jet max above rotor depth

'non-classical'

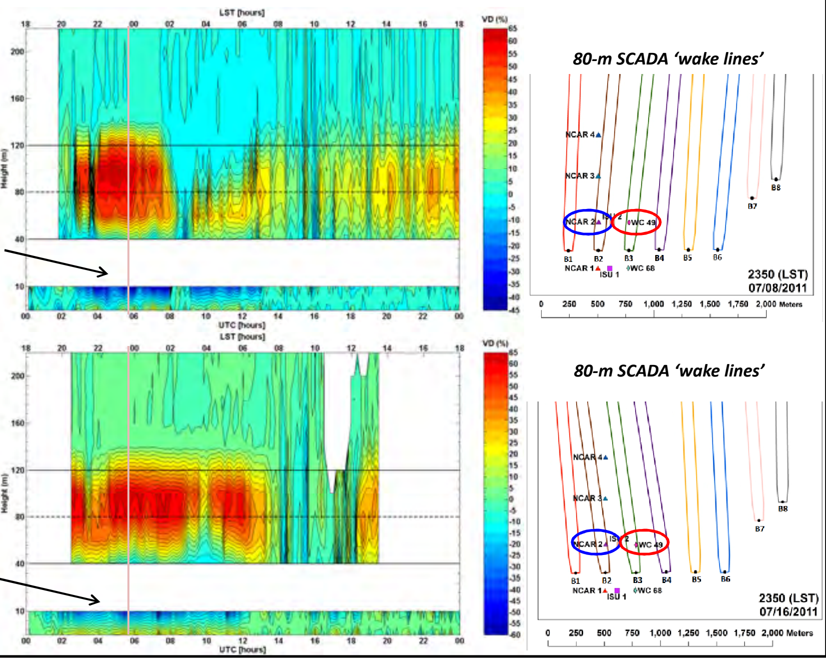
over-speeding 30-40% at NCAR 2 underneath the downward branch of the wake swirl

July 17

jet max within rotor depth

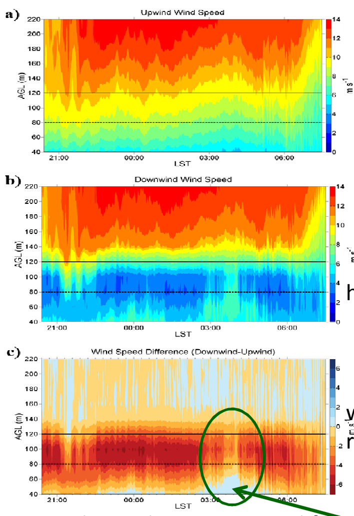
'classical'

over-speeding 20-30% at NCAR 2 underneath the ascending branch of the wake swirl



Wind cube and surface flux detection of wakes

Case study: 20:00-8:00 (LST) 16-17 July, 2011



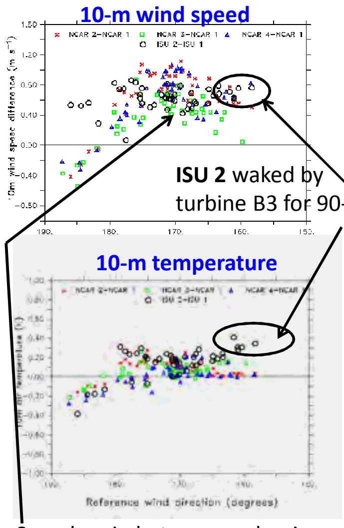
winds remain strong throughout the night

top of turbine rotor

hub height

wake region of reduced wind speed

Wake not being measured for 1.5 hr period?
Wind direction changes from SSE to SE



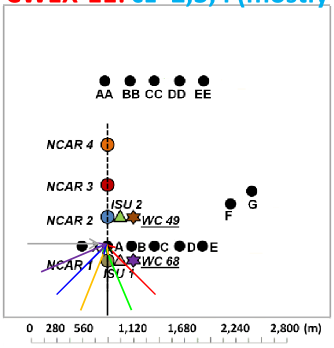
ISU 2 waked by turbine B3 for 90-min

Speed up in between wakes is less than for speed up within the wake

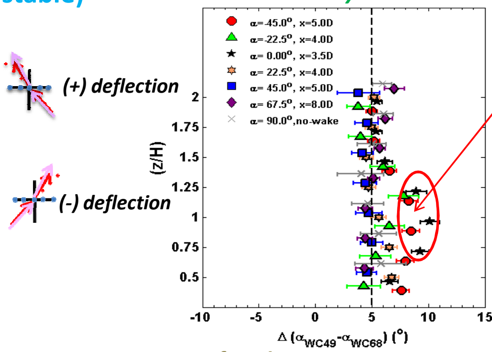
(Rajewski et al. BAMS, 2013)

Directional deflection around the leading line of turbines (Δα)

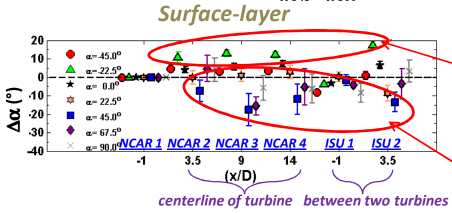
CWEX-11: cL=2,3,4 (mostly stable)



WC68 80-m wind direction category	Direction bin (°)	α bin (°)
SE	122.75-146.25	-45.0
SSE	146.25-168.75	-22.5
S	168.75-191.25	0.0
SSW	191.25-213.75	22.5
SW	213.75-236.25	45.0
WSW	236.25-258.75	67.5
W	258.75-282.25	90.0



maximum 5° directional difference within the turbine wake

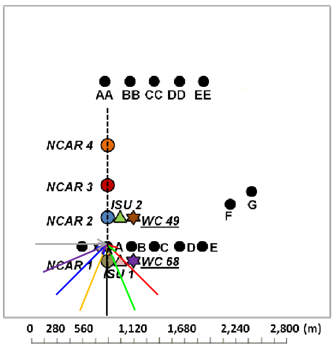


(+) deflection to the normal of the turbine line for α<0°

(-) deflection for α>0°

Directional variability of velocity deficit (VD)

CWEX-11: cL=2,3,4 (mostly stable)



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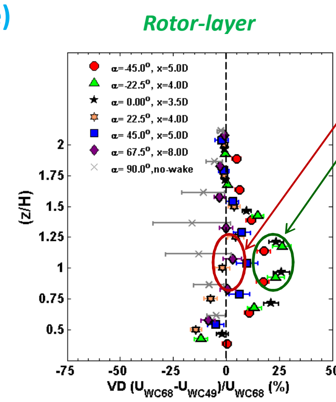
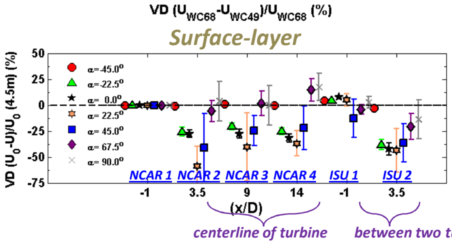


VD negligible at hub-height for SW winds?

VD similar at hub-height for SE,SSE, S winds

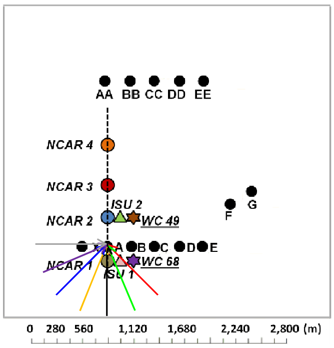
Wake spatial asymmetry because of likely influence from multiple turbines 2km southeast of the leading line



Consistent over-speeding for multiple locations underneath turbine wakes

Directional variability of turbulence intensity $\Delta\sigma_U/U_H$

CWEX-11: cL=2,3,4 (mostly stable)



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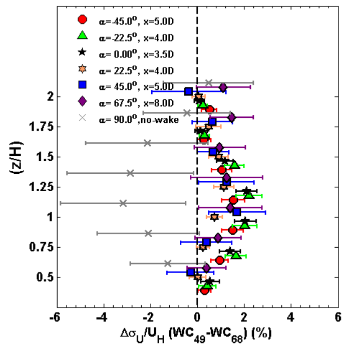
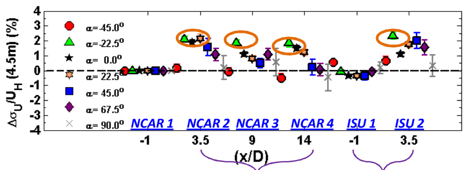
Rotor-layer



(Δ TI<3% increase of ambient value for all directions and positions within the wake

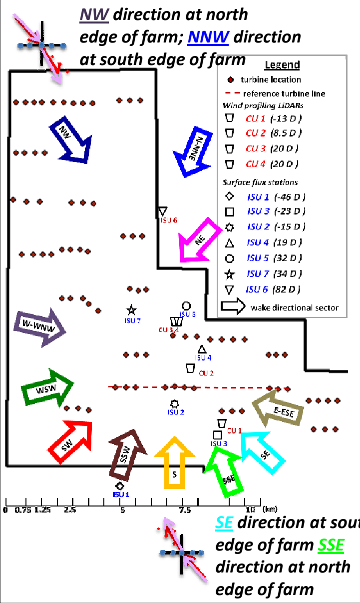
Less spatial variability of turbulence within the wake

Surface-layer

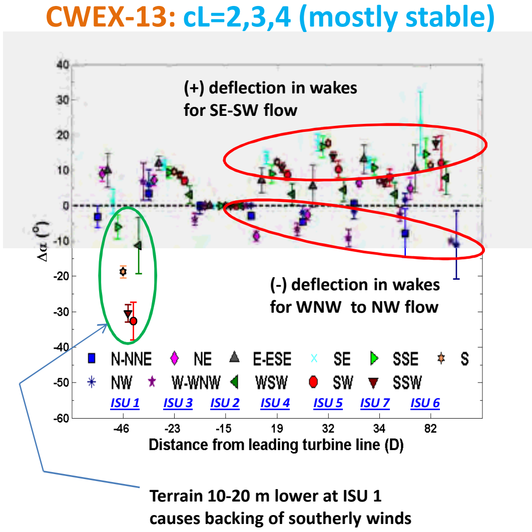


Largest increase in TI (<2%) when edge of wake swirl is above the station

Evidence of wind farm-scale surface convergence

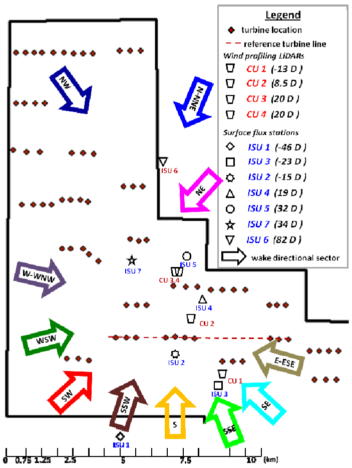


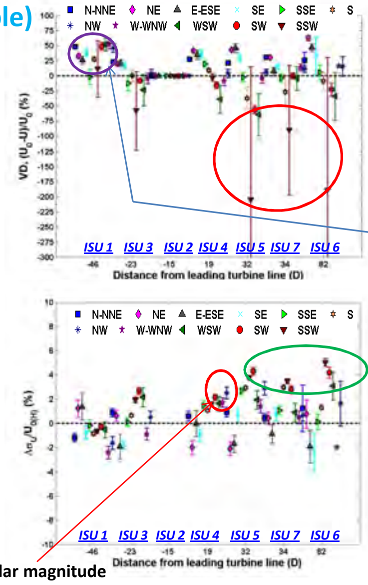
CWEX-13: cL=2,3,4 (mostly stable)



Wind farm influence on velocity deficit and turbulence intensity

CWEX-13: cL=2,3,4 (mostly stable)





high wake entrainment for S, SW, SSW wind 'aggregate farm' velocity deficit for SE or WNW, NW, N winds

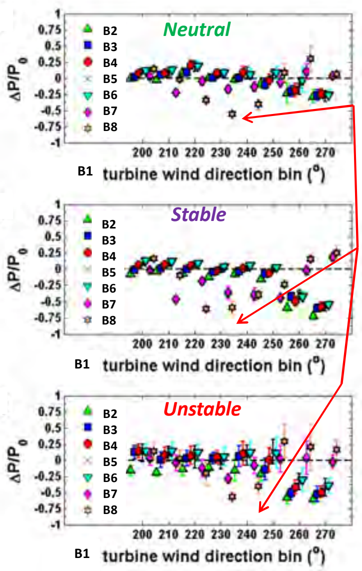
Slower wind speed at ISU 1 from lower terrain

TI increases of 4-6% from multiple turbine wakes for S, SSW, SW wind

ΔTI negligible as flow passes through multiple lines of turbines (SE, SSE winds)

similar magnitude as in single wake from CWEX-11

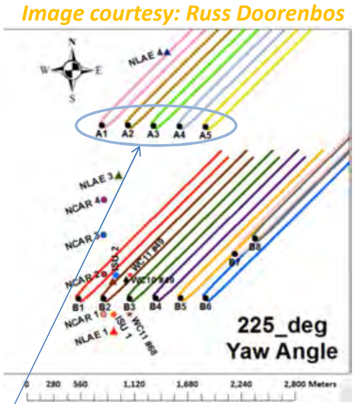
CWEX-10/11 power visualization using surface fluxes, SCADA, and wake animations



Maximum power reduction in all stability conditions for southwesterly wind (turbine B8 in the wake of B5-B7)

Substantial power reduction (50-75%) in westerly flow for non-neutral stability as compared to weaker reduction in neutral conditions

Image courtesy: Russ Doorenbos

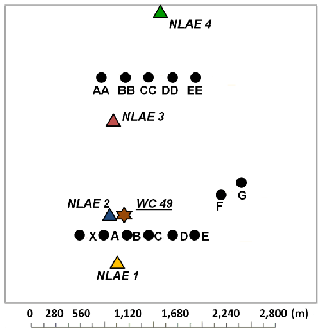


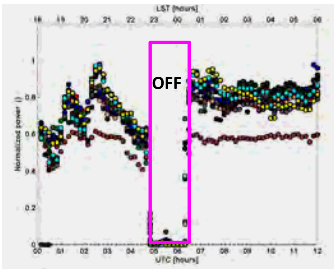
Higher terrain from SW-NE of the A-line increases nighttime power production by 25%

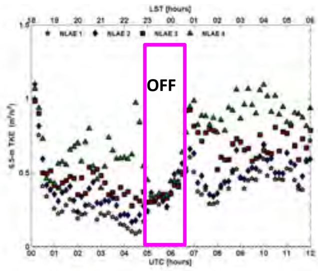
(Takle et al. 2014, DTU Science of Making Wind)

Best practices for measurement analysis

- Operational status of turbines:
  - Turbines ON vs. OFF—filter fluxes for when turbines are not producing power (SCADA, upwind 80-m LiDAR speed)
- (A) Few lines of turbines:
  - Determine ON periods when the majority of the stations in the line:
    - $P_{WTG} < 0$ kW "OFF"
    - $P_{WTG} < 50$ kW "LOW"
    - $P_{WTG} > 50$ kW "ON"
  - If combination of ON and OFF or ON and LOW categories, flag as unusable to isolate all turbine "ON" conditions



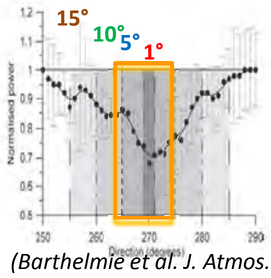




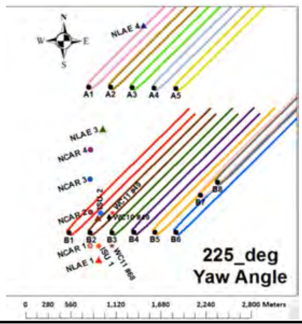
Turbine wake effect on surface is nearly instantaneous in the overnight hours of Aug 27-28, 2010

Best practices for measurement analysis

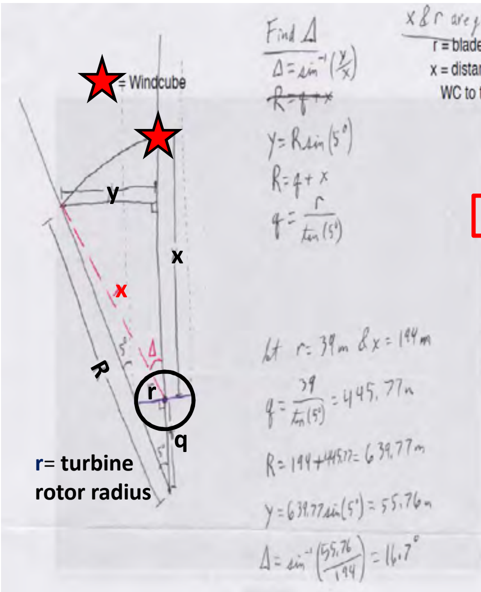
- Wind direction—assemble flux and LiDAR differences for different categories of wake impacts (A or B)
- (A) Few lines of turbines:
  - Retain directions for prevailing directions; no-wake influence for non-prevailing directions clear of wake contamination
  - Assume wake expansion factor of +/- 5° for wakes from leading turbine line
  - Visualize wakes overhead of surface/LiDAR stations
    - position of wake center-point vs. edge of wake
  - Surface-layer wake impacts less clear with using the upwind rotor-layer directional sorting from LiDAR at 40m or 80m
    - reference surface station wind direction



(Barthelmie et al. J. Atmos. Oceanic Technol., 2010)



Wake wind direction procedure

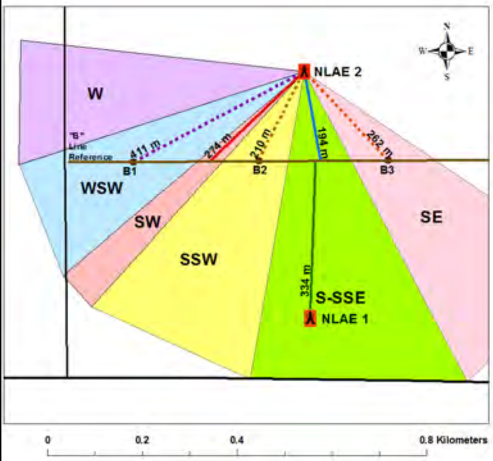


Rajewski et al. 2013, adapted from Lundquist and Rhodes 2010, personal communication

Turbine label	Distance from NLAE 2 (m)	Centerline angle from NLAE 2 (°)	Half-angle with 5° wake expansion (°)	Wind direction for wake (5°) (°)
B1	407	240	11	229-251
B2	215	205	16	189-221
B3	265	137	14	123-151
B4	488	113	10	103-123
B5	735	105	8	97-113
B6	990	101	7	94-108
B7	1289	77	7	70-84
B8	1536	73	6	67-79
Turbine label	**Distance from NCAR 2 (m)**	**Centerline angle from NCAR 2 (°)**	**Half-angle with 5° wake expansion (°)**	**Wind direction for wake (5°) (°)**
B1	351	230	9	212-247
B2	226	180	7	166-195
B3	354	130	9	112 147
B4	597	112	12	89-135
B5	845	106	15	76-135
B6	1097	102	18	66-138
B7	1169	78	18	43-114
B8	1419	74	12	50-98

25

Determination of near-wake impacts with directional bins



Case direction category	Turbine wake Indicator	Sample size (N) DAY	Sample size (N) NIGHT
ΣOFF	(combination turbines offline)	94	98
ΣON	(combination turbines operating)	333	529
W	(Westerly no-wake, turbines on and off)	35	60
WSW [B1]	B1 (5.3 D to turbine)	25	43
SW [B12G]	gap between B1 and B2 (3.8 D to line)	31	19
SSW [B2]	B2 (2.7 D to turbine)	79	51
S-SSE [B23G]	gap between B2 and B3 (2.6 D to line)	198	416

Rajewski et al., 2014 Agric & Forest Meteorol.

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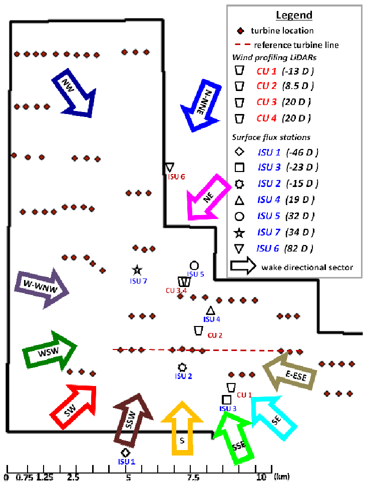
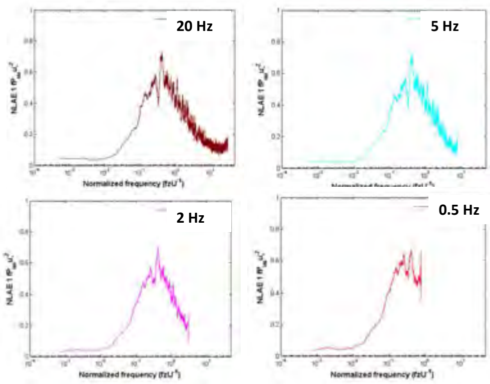
Best practices for measurement analysis

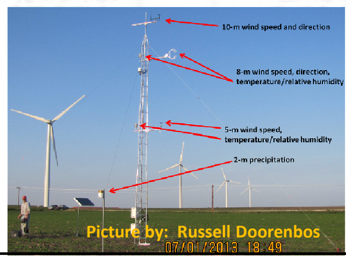
- **Wind direction**
  - (B) Multiple lines of turbines within a wind farm
    - Retain all wind direction categories, appropriate bins according to directional influence of single turbine, line of turbines, or pocket of turbines
    - Surface layer and rotor-layer wake impacts are both cognizant with upwind LiDAR profile measurements of wind direction at 80m



Best practices for measurement analysis

- **Measurement resolution**
  - 10 minute averages to compare with SCADA,
  - at least 5Hz for spectral characteristics from sonic anemometers
- **Measurement duration**
  - 2-3 months during warm season, cold season ?
- **Surface and LiDAR station placement**
  - Reference: at least 2D upwind of turbine line
  - 'Near wake': 2.0-4.0 D downwind of turbine line
  - 'Far wake': >10 D downwind of turbine
- **Surface station sensor placement**
  - 10-m above ground: standard ASOS, Windspeed, Wind direction Temp/RH
  - 6-9 m above ground: sonic anemometer measure turbulence and heat flux
  - Precipitation bucket above the top of canopy (filter erroneous data)
  - Net radiometer above the top of the canopy (determine radiation for cloudiness and clear sky conditions)
  - Sensors placed at 2-5m above ground have high influence from surface roughness, canopy microclimate





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- Experimental support for CWEX
  - Ames Laboratory
  - National Laboratory for Agriculture and the Environment
  - National Center for Atmospheric Research
  - National Renewable Energy Laboratory
- Instrumentation and analysis support provided by
  - National Science foundation under IA-EPSCoR grant EPSC-1101284
- Multiple DOE lab collaboration for numerical modeling
  - Matt Churchfield, Caroline Draxl, Lee Seng, Pat Moriarty (NREL)
  - Bronko Kosovic (NCAR)
  - Jeff Mirocha, Nikola Maranovic (LLNL)
  - Larry Berg, Jerome Fast (PNNL)

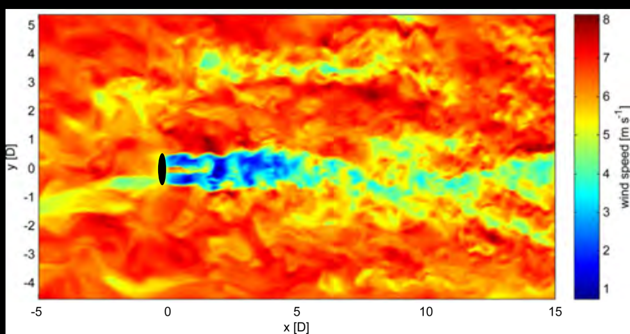
Lidar observations of wind turbine wakes in an onshore wind farm

Julie K. Lundquist [1,2], Eugene S. Takle [3], **Matthieu Boquet** [4], Branko Kosović [5], Michael E. Rhodes[1], Matthew L. Aitken[1], Katja Friedrich[1], Joseph Lee[1], Paul T. Quelet[1], Jiwan Rana[1], Clara St. Martin[1], Brian Vanderwende, [1]Rochelle Worsnop[1], Daniel Rajewski[3], Russell Doorenbos [3], Samantha Irvin [3]

[1] University of Colorado at Boulder, [2] National Renewable Energy Laboratory, [3] Iowa State University, [4] Leosphere, [5] National Center for Atmospheric Research

Wind farms experience complex flow as turbine wakes evolve and interact – this evolution depends on ambient conditions

- Wakes characterized by reduced speed, increased turbulence
  - impact power production (AEP)
  - dominate operations & maintenance costs
- Speed deficit, turbulence enhancement, wake erosion all depend on background turbulence
- Wakes persist longer in stable conditions

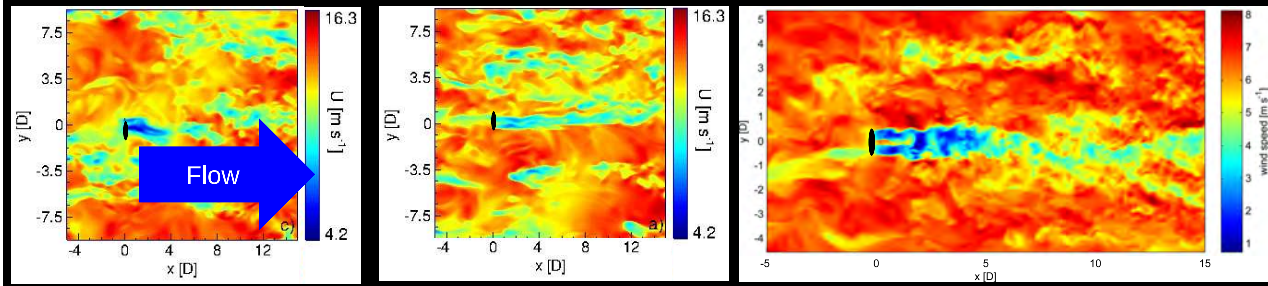


Large-eddy simulations of turbine wake in stable conditions using WRF-LES actuator disk turbine model
Aitken et al., *JRSE* 2014 in review

University of Colorado Boulder

2

Simulations of wake dispersion show variations with atmospheric stability



Convective (Mirocha et al., 2014)

Slightly convective (Mirocha et al., 2014)

Stable (Aitken et al., 2014)

…but what do we see in the atmosphere?

Large-eddy simulations of turbine wakes using WRF-LES actuator disk turbine model
Mirocha et al., *JRSE* 2014 (left, center); Aitken et al., *JRSE* 2014 (right) in review

University of Colorado Boulder

3

CWEX-13 addresses scientific questions regarding complex atmospheric flow within wind farms

- Atmospheric stability effects on wind turbine wakes (wind speed deficit, wake expansion, meander)
- Variability of nocturnal low-level jet
- Impact of stability, wind shear, and wind veer on **power production**
- Validation and improvement of **wind farm parameterizations** in weather and CFD models

CWEX: Crop and Wind Energy Experiment, a multi-year field campaign. Previous campaigns described in:

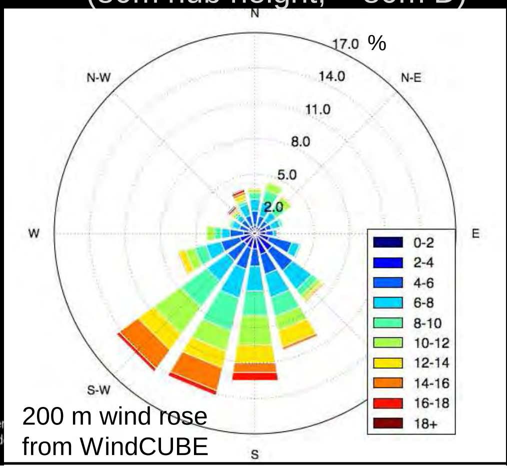
- Rajewski et al., 2013, *Bulletin of the American Meteorological Society*
- Rhodes and Lundquist, 2013, *Boundary-Layer Meteorology*

University of Colorado Boulder

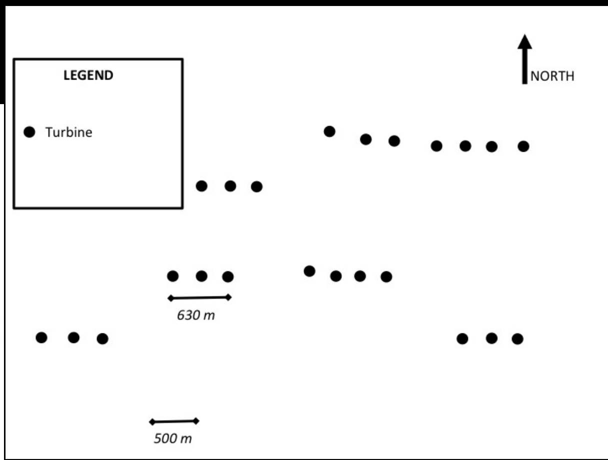
4

CWEX-13 measurements document surface and upper-air variability within the wind farm

- 300 MW of GE 1.5 XLE (80m hub height, ~ 80m D)



200 m wind rose from WindCUBE



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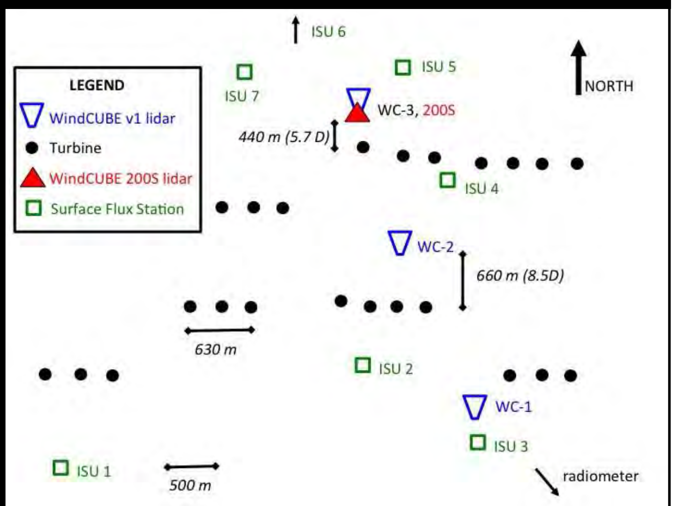
5

CWEX-13 measurements document surface and upper-air variability within the wind farm

- 300 MW of GE 1.5 XLE (80m hub height, ~ 80m D)
- Three profiling lidars (WindCUBE v1) (upwind, after one row, after two rows)
- One scanning lidar (WindCUBE 200S)
- One microwave radiometer (Radiometrics MP3000-A)
- Seven surface flux stations (upwind, after one row, after several rows)



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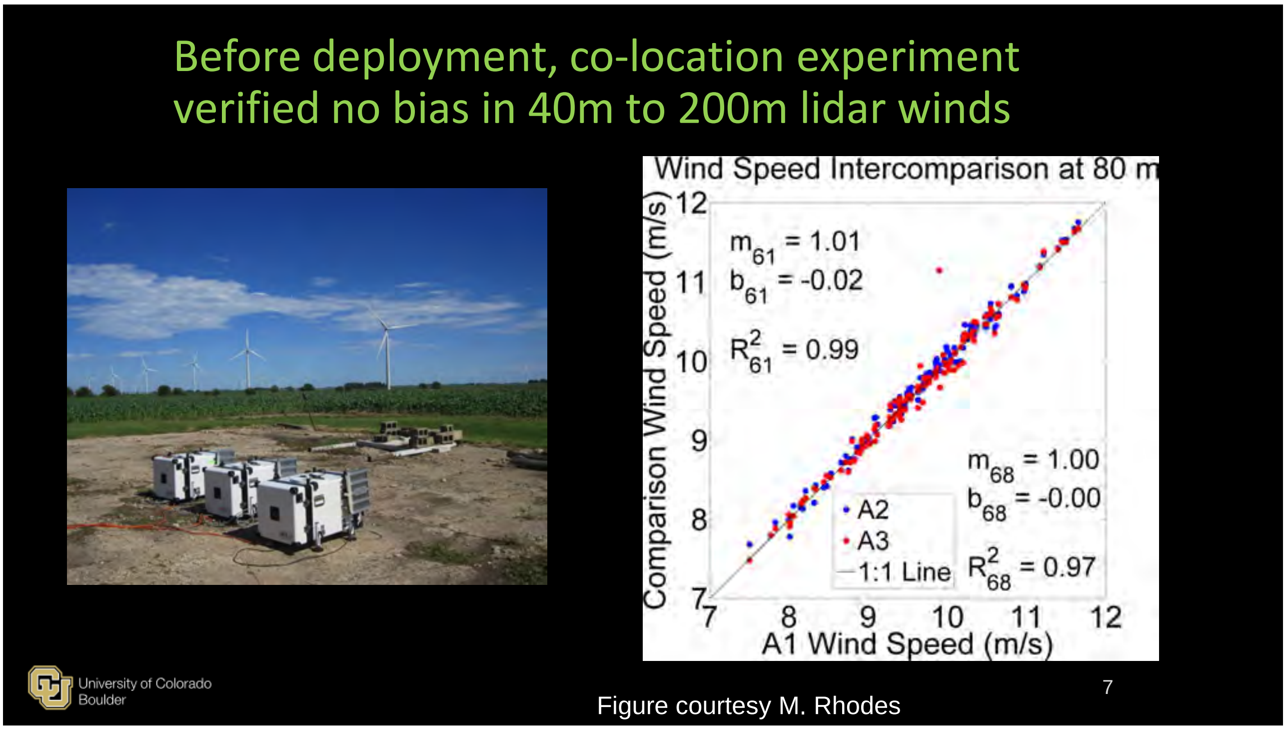
Before deployment, co-location experiment verified no bias in 40m to 200m lidar winds
Wind Speed Intercomparison at 80 m
Comparison Wind Speed (m/s)
A1 Wind Speed (m/s)
m61 = 1.01
b61 = -0.02
R2 61 = 0.99
m68 = 1.00
b68 = -0.00
R2 68 = 0.97
A2
A3
1:1 Line
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Figure courtesy M. Rhodes
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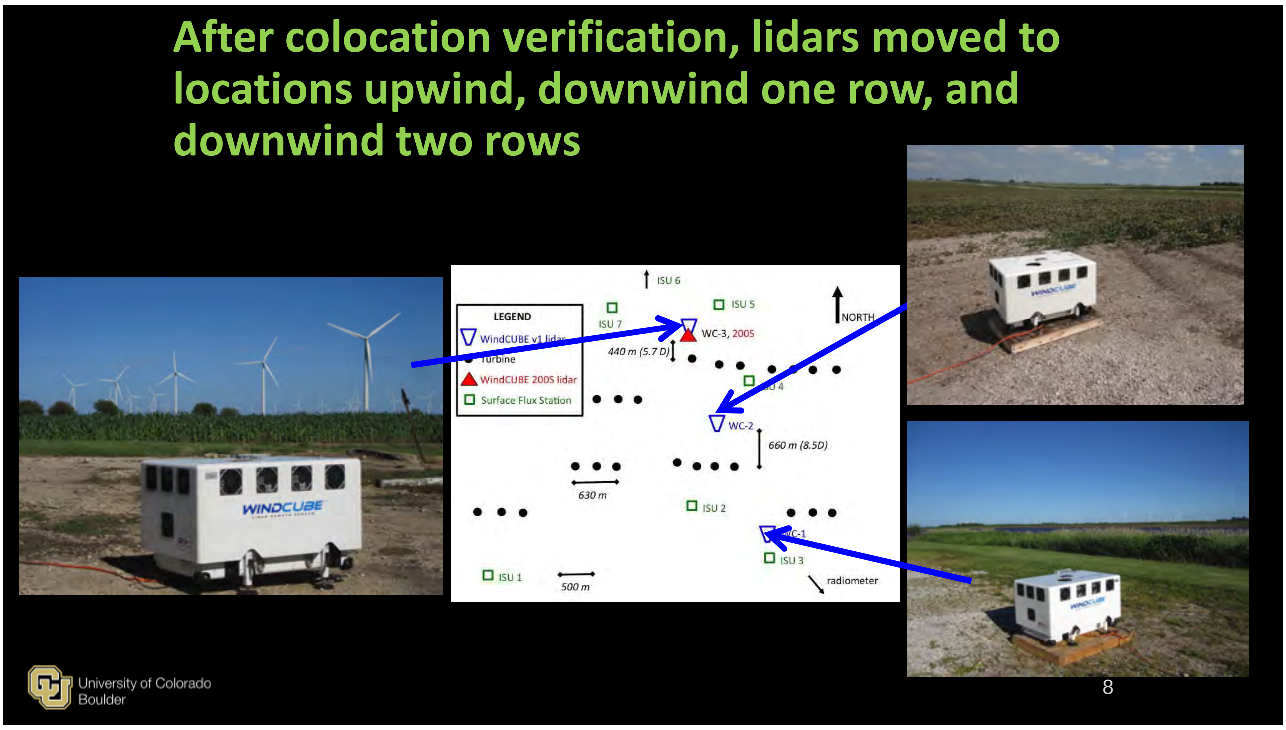
After colocation verification, lidars moved to locations upwind, downwind one row, and downwind two rows
LEGEND
WindCUBE v1 lidar
Turbine
WindCUBE 200S lidar
Surface Flux Station
ISU 6
ISU 5
ISU 7
NORTH
WC-3, 200S
440 m (5.7 D)
WC-2
660 m (8.5D)
630 m
ISU 2
ISU 3
ISU 1
500 m
radiometer
WINDCUBE
University of Colorado Boulder
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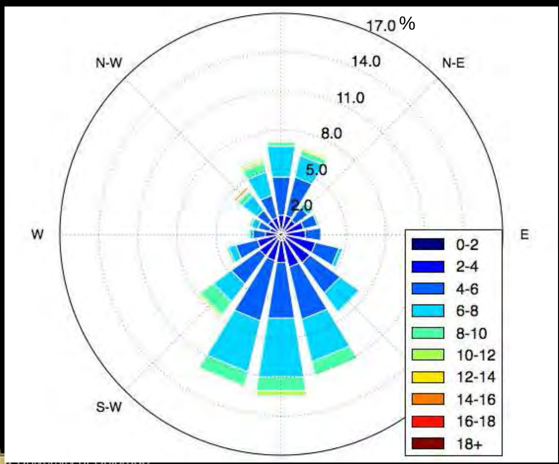
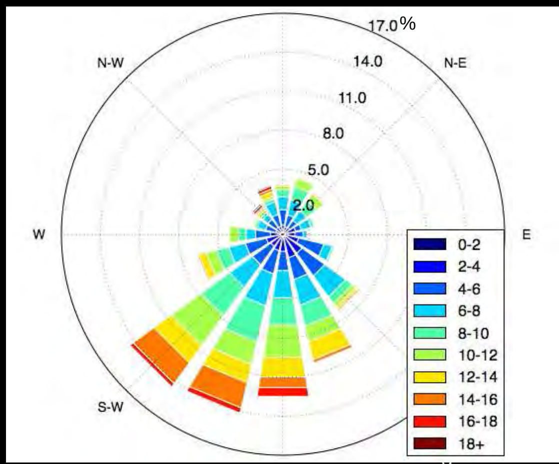
Southerly flow dominated the experiment, with significant veering with height

"Upwind" measurements at 40m



"Upwind" measurements at 200m



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Figures courtesy J. Rana

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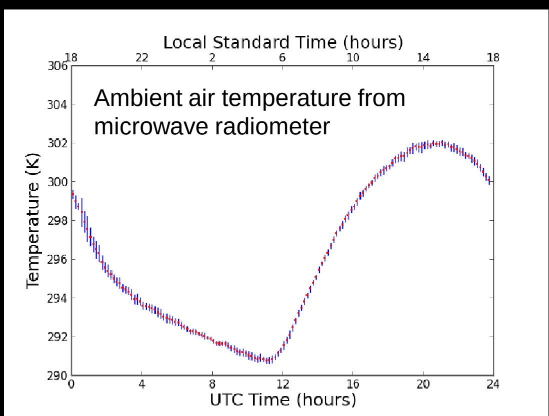
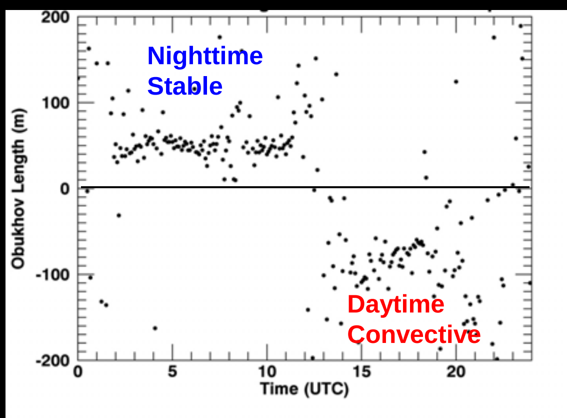
Strong surface heating drives strong diurnal variations in atmospheric stability





Averages over the entire experiment

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Figures courtesy J. Rana, J. Lee

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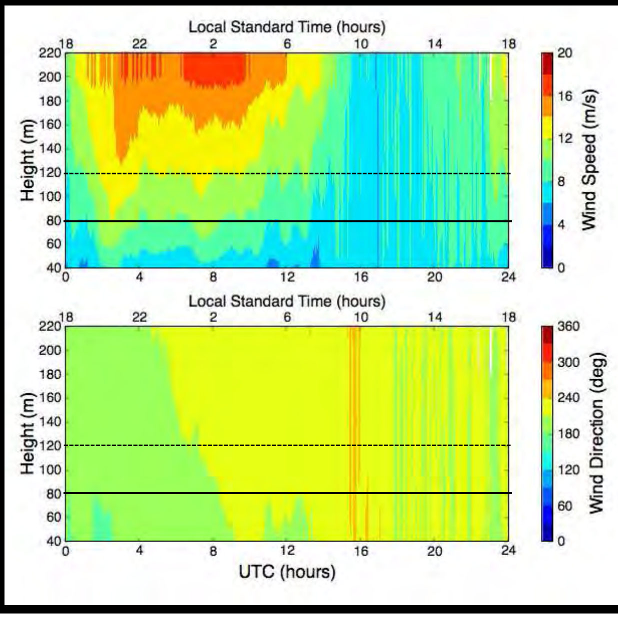
Nocturnal low-level jets (LLJ) occur frequently



Accelerations aloft commence slightly before sunset; significant veer occurs under LLJ wind speed max

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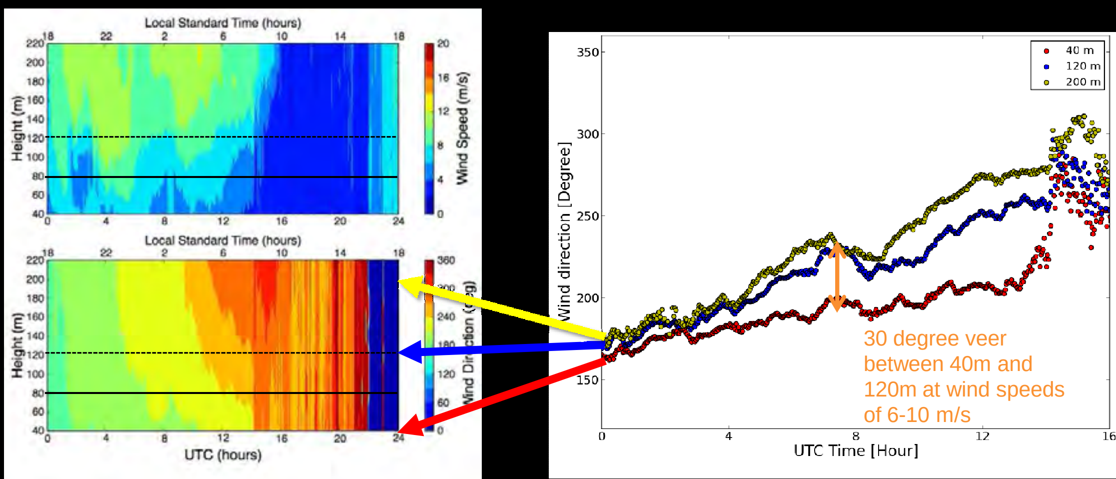
Figures courtesy J. Rana

LLJs often accompanied by strong wind veer (change of wind direction with height)



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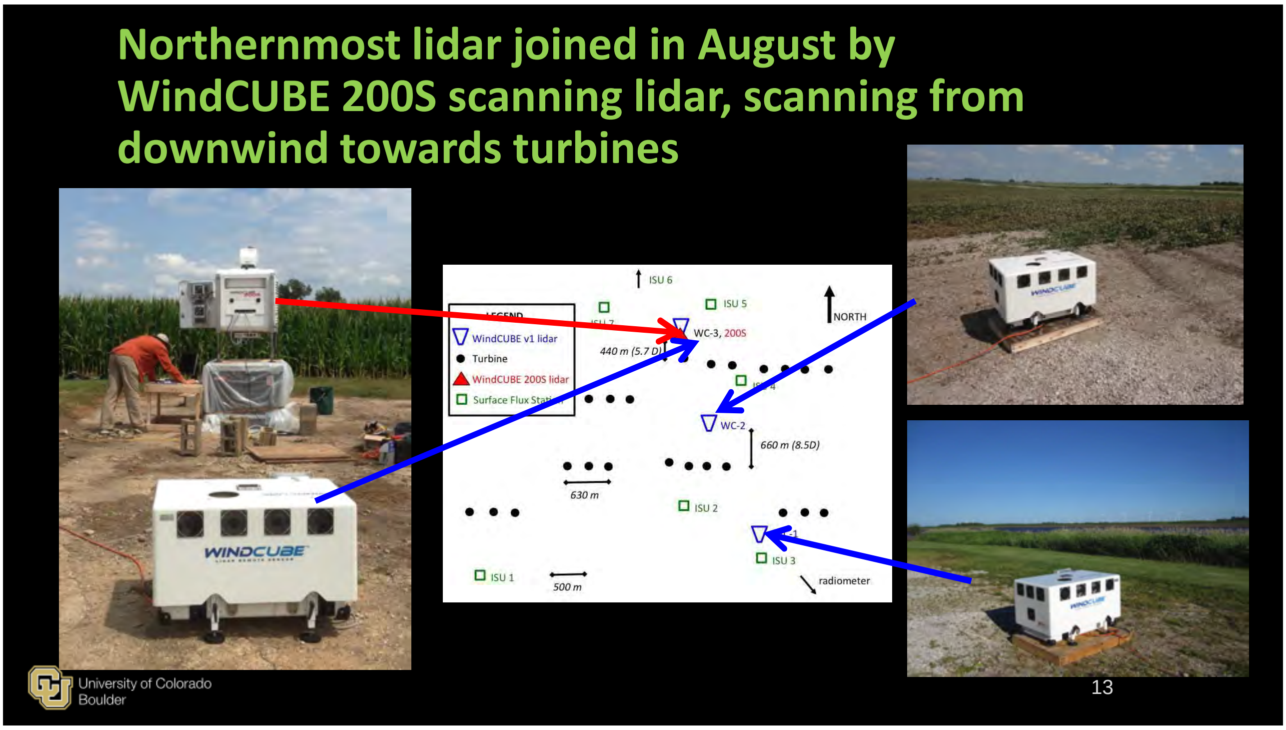
Figures courtesy J. Rana


Northernmost lidar joined in August by WindCUBE 200S scanning lidar, scanning from downwind towards turbines
WINDCUBE
ISU 6
ISU 5
NORTH
WindCUBE v1 lidar
Turbine
WindCUBE 200S lidar
WC-3, 200S
440 m (5.7 D)
WC-2
660 m (8.5D)
630 m
ISU 2
ISU 3
ISU 1
500 m
radiometer
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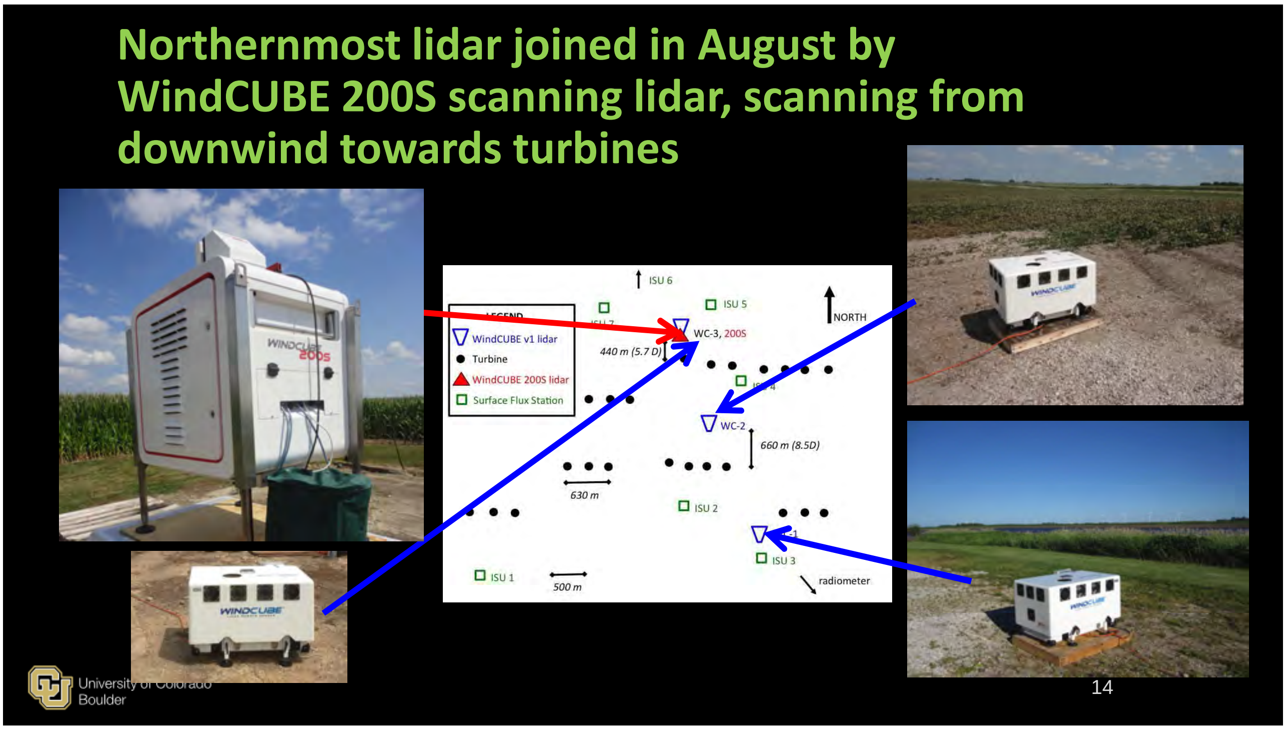
Northernmost lidar joined in August by WindCUBE 200S scanning lidar, scanning from downwind towards turbines
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WC-3, 200S
440 m (5.7 D)
WC-2
660 m (8.5D)
630 m
ISU 2
ISU 3
ISU 1
500 m
radiometer
Boulder
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WindCUBE 200S scanning configuration optimized to achieve multiple goals in each 30-min cycle

- 3 minutes of 60 deg elevation angle VAD at 3 deg/sec
- 3 minutes of 75 deg elevation angle VAD at 3 deg/sec
- 6 stacked horizontal slice PPI scans for 90 deg azimuth at elevations of 1.5, 1.8, 2.1, 2.2, 2.5, 2.8, at 0.5 deg/sec
- 3 RHI slices at azimuths at a turbine and on either side for elevations from 0.5 to 25 deg at 0.5 deg/sec
- Repeat PPI
- Repeat RHI

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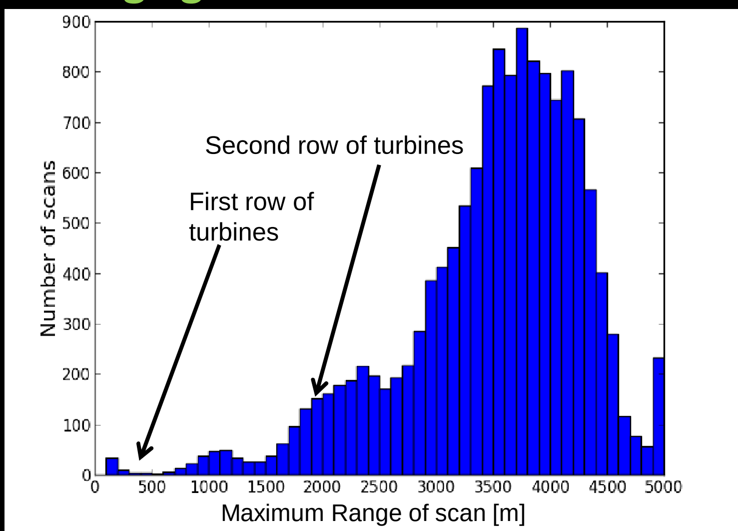
WindCUBE 200S lidar typically provided 3 – 5 km of range, well beyond the range required, at 50m range gate resolution



Figures courtesy J. Rana

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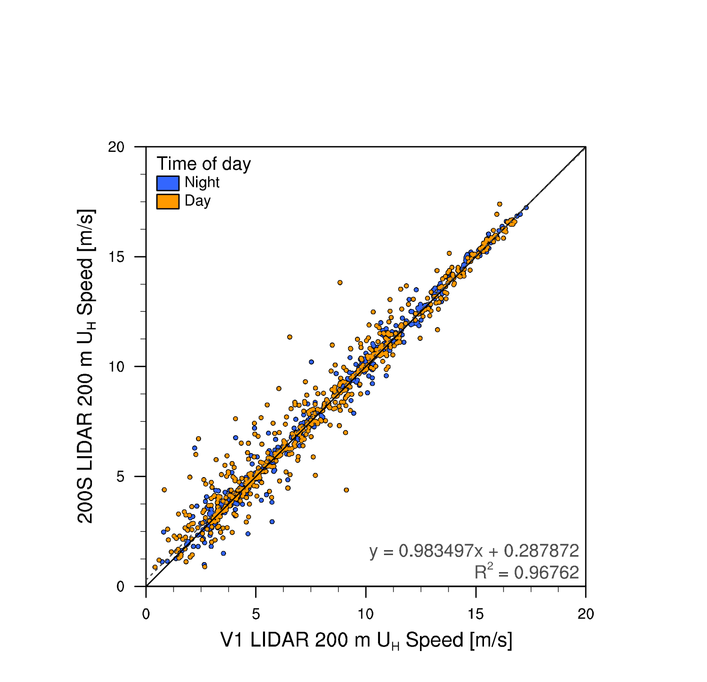
WindCUBE 200S and Wir agree despite differences

- WindCUBE v1 scans vertically, covering 360 degrees in azimutl over **four seconds**
- WindCUBE 200S scans vertical covering 360 degrees in **three minutes**
- Despite difference in scanning approach, the two lidars observ similar measurements of horizontal wind speed, especiall at night.
- Largest differences during dayti convection, when duration of sc will have most impact



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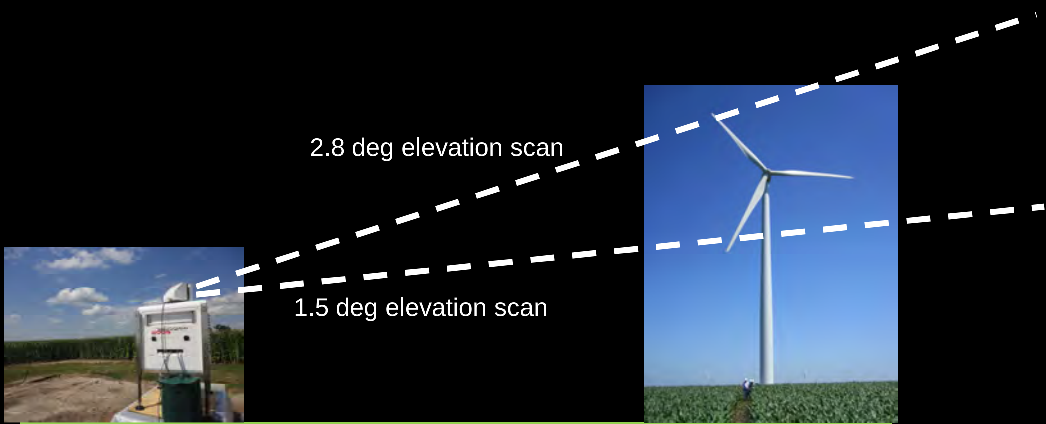
Figures

Windcube 200S scans turbine wakes in stacks of low-elevation scans



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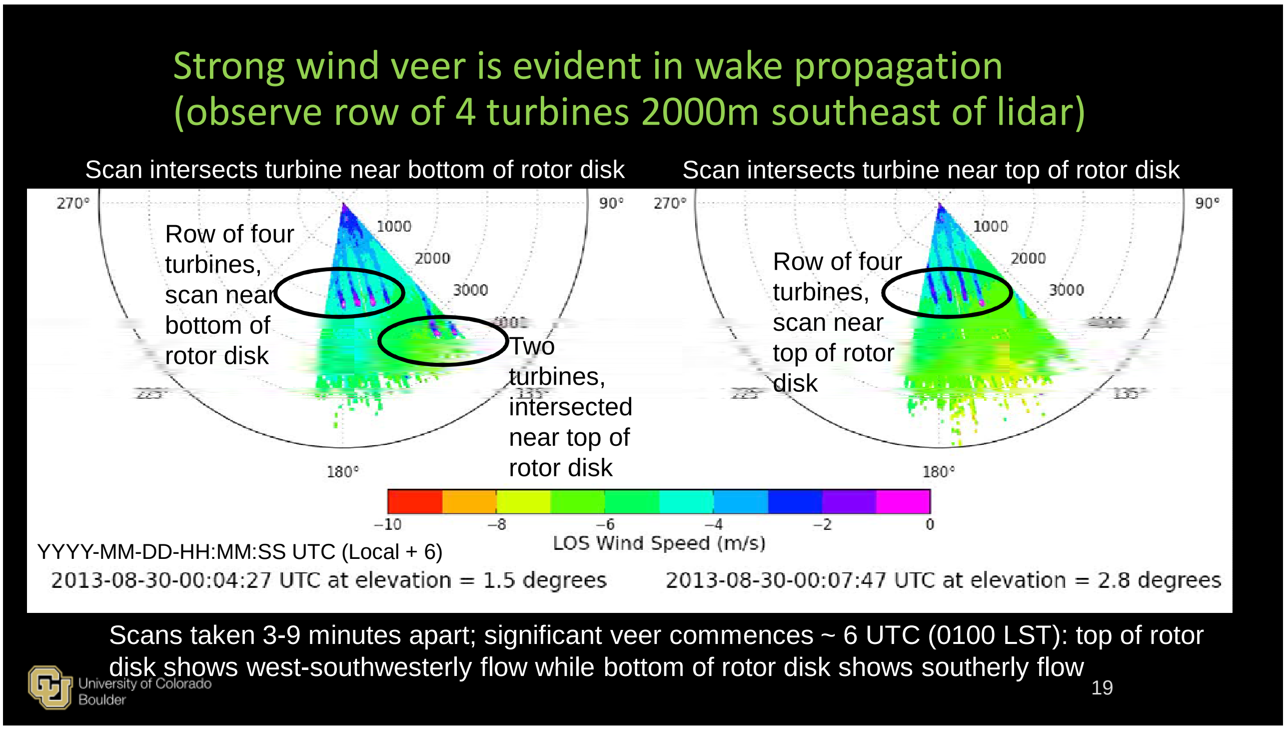
Strong wind veer is evident in wake propagation
(observe row of 4 turbines 2000m southeast of lidar)
Scan intersects turbine near bottom of rotor disk
Scan intersects turbine near top of rotor disk
Row of four turbines, scan near bottom of rotor disk
Two turbines, intersected near top of rotor disk
Row of four turbines, scan near top of rotor disk
270°
90°
180°
225°
135°
1000
2000
3000
LOS Wind Speed (m/s)
−10
−8
−6
−4
−2
0
YYYY-MM-DD-HH:MM:SS UTC (Local + 6)
2013-08-30-00:04:27 UTC at elevation = 1.5 degrees
2013-08-30-00:07:47 UTC at elevation = 2.8 degrees
Scans taken 3-9 minutes apart; significant veer commences ~ 6 UTC (0100 LST): top of rotor disk shows west-southwesterly flow while bottom of rotor disk shows southerly flow
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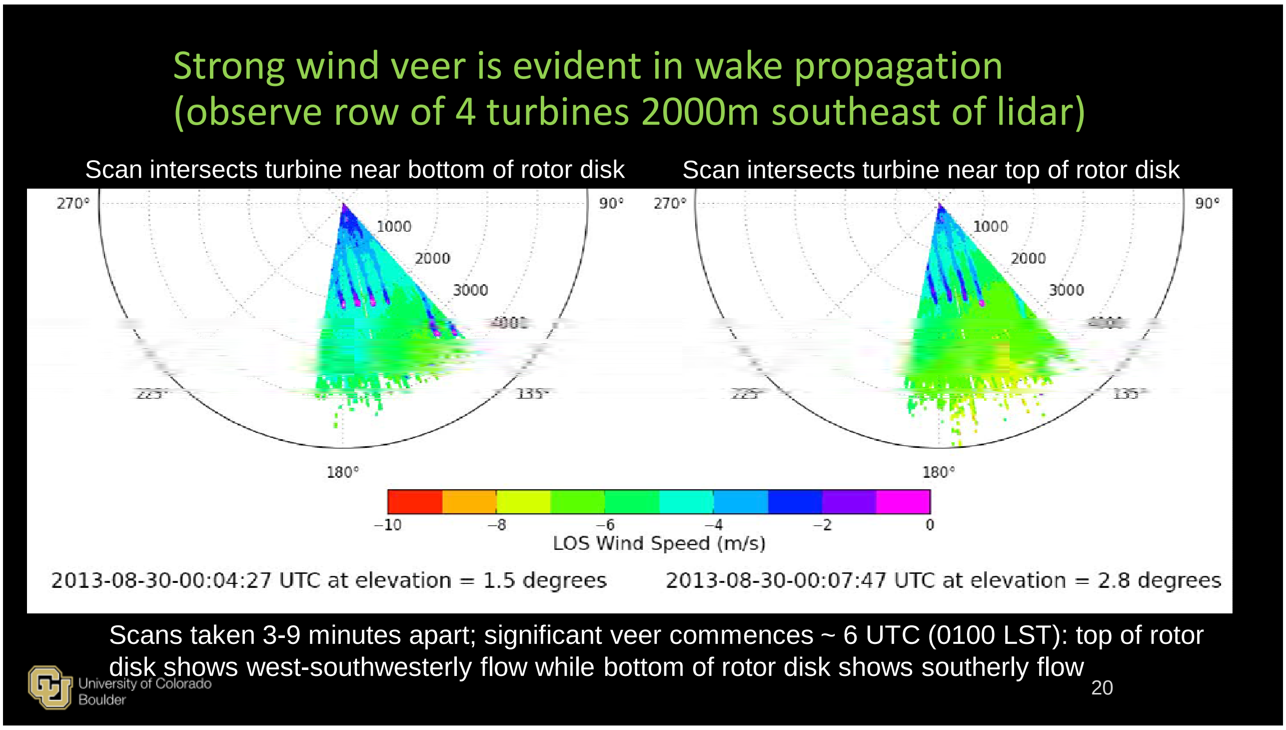
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Scan intersects turbine near bottom of rotor disk
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Scans taken 3-9 minutes apart; significant veer commences ~ 6 UTC (0100 LST): top of rotor disk shows west-southwesterly flow while bottom of rotor disk shows southerly flow
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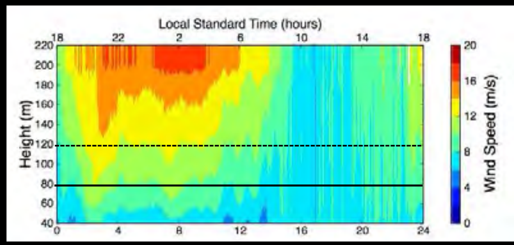
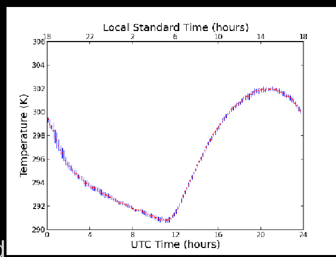
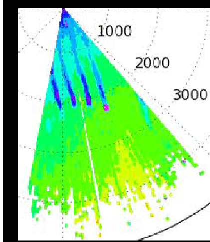
Lidar provides insight into complex flow in wind farms, capturing atmosphere-turbine interactions

- Even in flat terrain, wake flow impacts
  - power production
  - loads, operations & maintenance costs
- Diurnal variation of atmospheric stability → complex wind profiles
  - shear (6 m/s across rotor)
  - veer (up to 30 degrees across rotor)
- Next steps:
  - Quantify wake characteristics (speed deficit, expansion rate, meander) and variation with inflow stability
  - Simulate wakes & improve models
  - Reduce cost of renewably-generated electricity
- Future campaigns at other sites (onshore and offshore) can help optimize production or diagnose production issues related to wakes







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Thanks for your attention

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Continuous Reliability Enhancement for Wind

Visualizing Wind Farm Wake Losses using SCADA Data

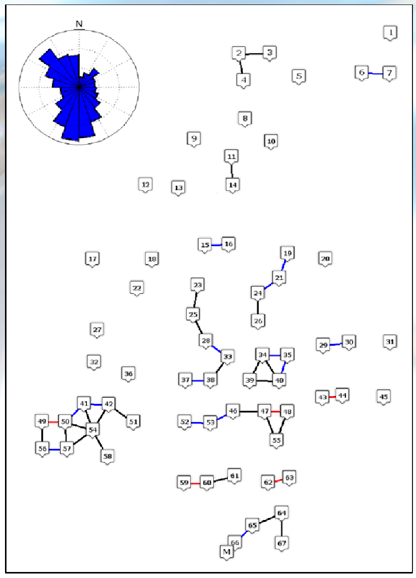
Sandia National Laboratories
Carsten H. Westergaard*, Jonathan White and Shawn Martin
IEA Wind TEM#78 on Field Test Instrumentation and Measurement Best Practices, October 7 and 8, 2014

Acknowledgement: This work has been funded under the Department of Energy's Continuous Reliability Enhancement for Wind (CREW) project. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
Wind farm SCADA data was provided by an energy company that has chosen to remain anonymous. We thank our strategic industrial partner for their contribution and partnership.

* Texas Tech University / Sandia National Laboratory

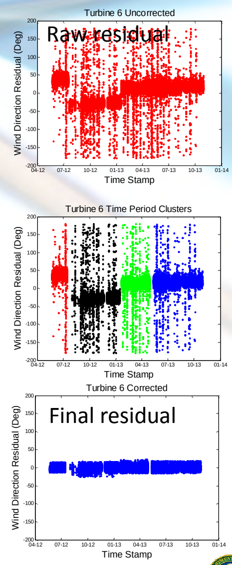
Data

- 1.5 year of SCADA data collected from 67 mid-west MW-class turbines
- Met-mast south of farm {M}
- Flat terrain surrounded by clusters of threes, farm houses and other wind farms
- Data is reduced from 2 sec. resolution to 10 min. value
- Wind rose: NW and S
- Red, blue & black lines show <5D, 5-6D and 6-7D spacing



Correcting nacelle position and initial data cleaning

- Only operational data are used for the analysis
- Initial data is 61,000 10 min values per turbines, keeping only data from 4 m/s to 20 m/s, 46,000 10 min values per turbine remain, which agrees with the annual wind speed distribution for the site
- The nacelle position generally serves only little purpose for the turbine control, so often the sensor is un-calibrated and associated with drift and/or offset
- Steps for correction of nacelle position:
  1. Define residual as deviation from average of met-mast and two neighbor turbines
  2. Identify and remove periods with discrete off-set
  3. Remove outliers larger than one std. dev.
- The remaining data is ~34,000 10 min values per turbine



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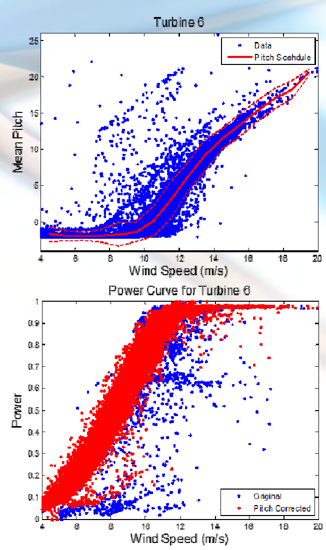
Cleaning power curves

- With the wind range and nacelle position corrected, turbine pitch as a function of nacelle wind is used to filter abnormal power mode operations
- Steps for correction of power curve:
  1. Compute 1 m/s binned pitch curve
  2. Remove outliers larger than one std. dev.
- The method removes:
  - Most severe outliers
  - De-rated power modes
  - Most low wind outliers
- Final number of data available is 32,000 10 min values per turbine or ~ 222 days of operation



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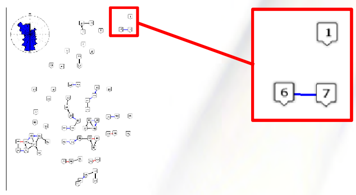
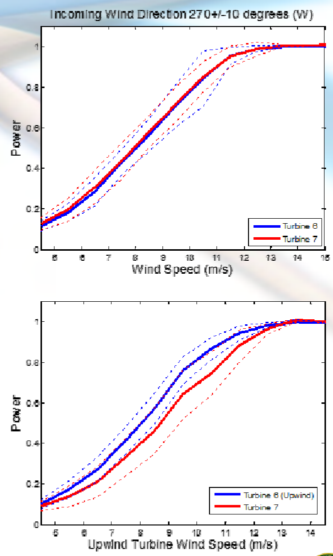
Paired power curve comparison

- Turbine #6 and #7 is 6D apart in NE corner of the wind farm
- Using western wind, mapping turbine #6 and #7 against their own nacelle anemometer, the wake turbine #6 impose on #7 can not be detected
- Mapping both turbines to turbine the upstream nacelle anemometer of #6, turbine #7 (obviously) show a wake deficit in region II of the power curve as expected
- This method can only be used when the upstream turbine is free, which for most complex layouts, never is the case





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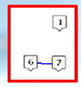
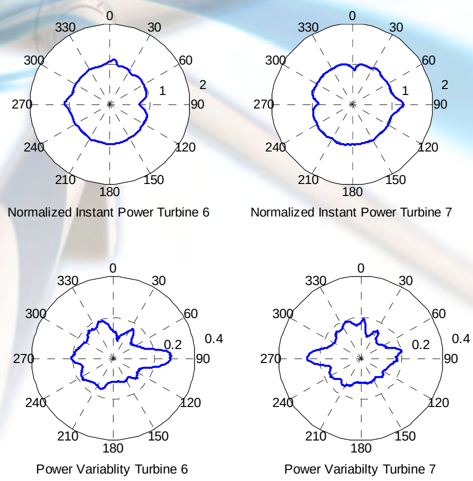
Paired directional comparison



- For each wind direction the average normalized instant power and variability reveals wakes clearly by direction, magnitude and shape
- Neighboring features, for example turbine#1 in NE direction, is also revealed
- For a two turbine situation, the nominator is strongly influenced by the wake. If all the farm is used, this effect becomes negligible

$$P_N(t) = 2P_6(t)/(P_6(t) + P_7(t)).$$



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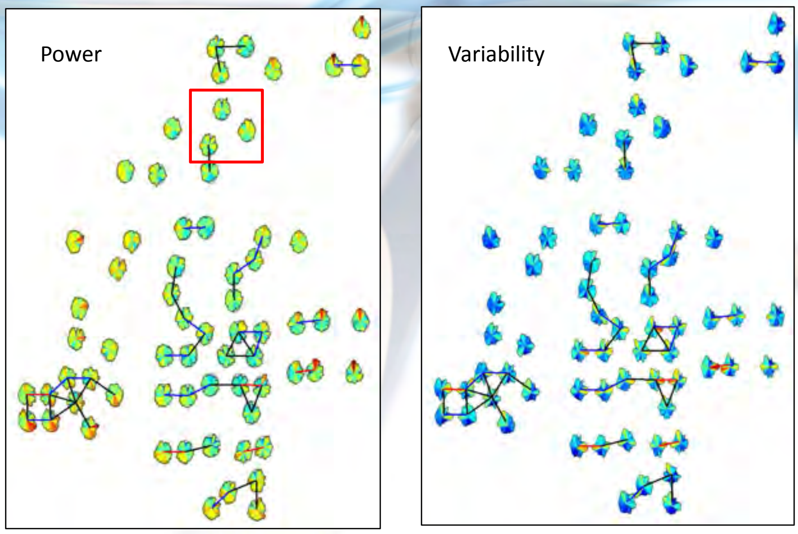
Directional analysis – full wind farm



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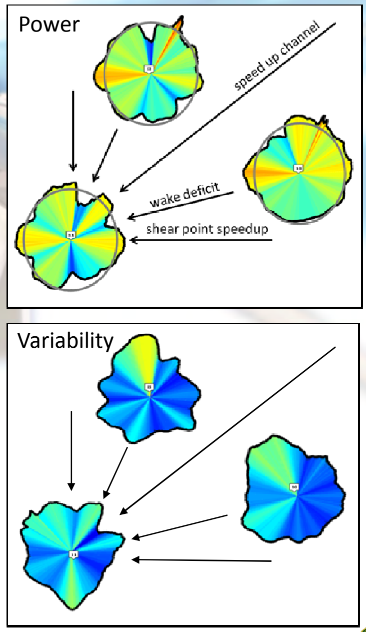
New observations

- Four effects have been identified:
  - Wake deficit
  - Speedup channels from two upstream turbines
  - Shear point speedup from one upstream turbine
  - Shear point speedup from multiple upstream turbines or an upstream wind farm
- The three speedup effects are new, generally not considered in wind farm modeling



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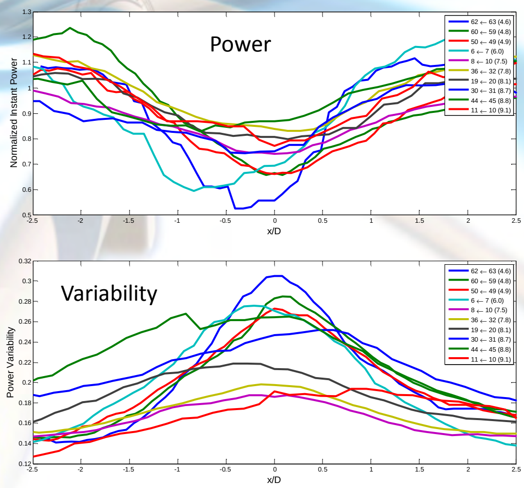
Wake deficits

- Wakes can be identified in profiles of power deficit at expected bearings within a few degrees of accuracy
- Wake width, plotted in x/D using bearing and turbine distance
- Power variability is a strong and consistent indicator of wake
- The site contains almost no clean inflow situations due to landscape, upstream farms and upstream turbines, which skews profiles



Profiles for 4 to 8D turbine distances

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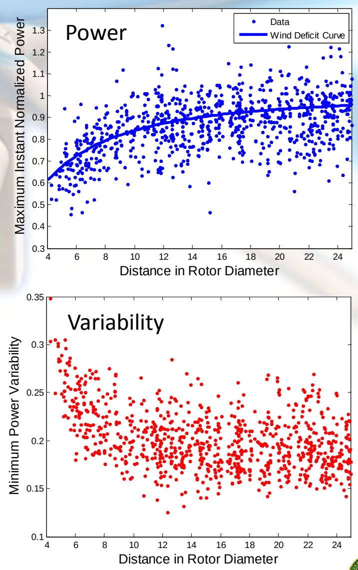
Wake deficit as function of distance

- Data comparing 854 turbine pairs in direct wake of each other
- Power wake deficit follows expected behavior, comparing to classic wake deficit theory:

$$\frac{U_x}{U_0} = 1 - \frac{1-\sqrt{1-C_T}}{1+2k\frac{x}{D}},$$

- Variability drops rapidly as some wake models predicts



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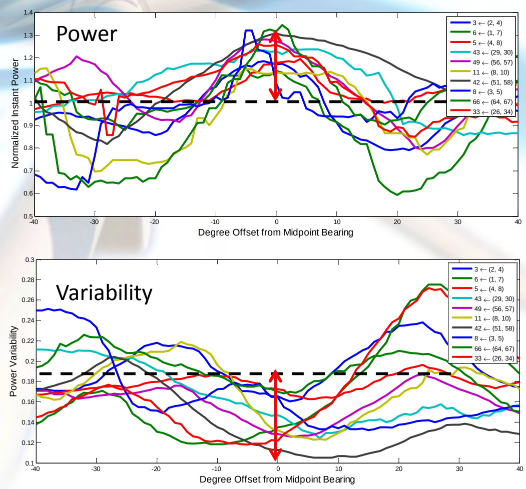
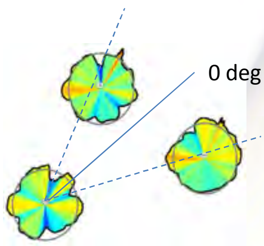
Speedup channels

- Profiles are plotted relative to a bearing of the mid-point between two upwind turbines
- An performance from 1.1 to 1.3 over norm (=1) is found
- Centerline power variability is found to be lower than ambient level
- Both effects are generally not included in wake models





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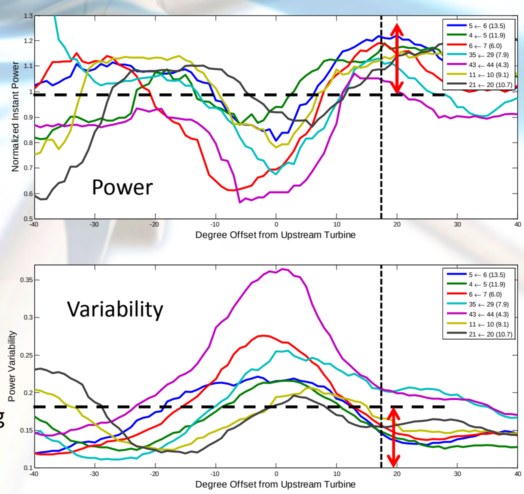
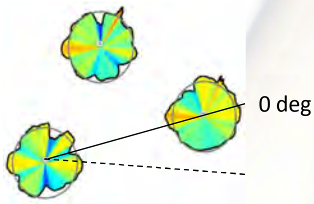
Shear-point speedup

- Profiles are plotted aimed directly at the upwind turbine, where the clockwise upstream airflow is free of obstruction
- Between 15 an 20 degrees speedup with a power boost of 1.1 and 1.22 over average is found
- Power variability in this range is found to be lower than ambient level
- Both effects are generally not included in wake models





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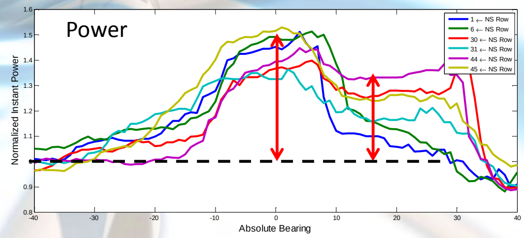
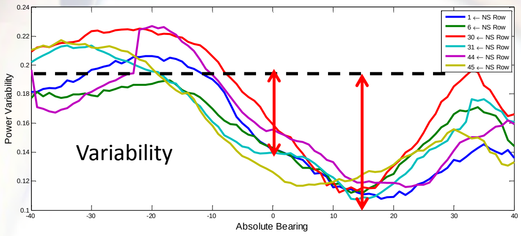
Speedup from multiple turbines

- Six turbines face rows of turbines at due north
- Profiles are plotted at absolute bearing (0= North)
- Speedup power boost of 1.3 and 1.5 over average is found
- Clockwise a 15 to 20 degrees, speedup is still found, and the power variability in this region is found to be significant lower than ambient level
- Complexity is larger at this angle because the effects are a combination of speedup and waking and landscape roughness
- The effects are generally not included in wake models





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Conclusion

- The novel directional analysis applied has proven effective in mapping wake deficit in a complex wind farm layout
- Three new wake effects have been discovered
  - Speedup channels from two upstream turbines
  - Shear point speedup from one upstream turbine
  - Shear point speedup from multiple upstream turbines or an upstream farm
- The new speedup effects identified are generally not included in wake modeling
- High power associated with the speedup effects is counter-intuitively associated with low power variability
- The discovered effects cold affect turbine reliability in a positive way

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WINDFORS
Wind Energy
Research Cluster

Planning a wind energy test site in complex terrain based on experiences in instrumentation and measurements

Topical Expert Meeting #78 – Lubbock, TX, USA
October 8, 2014
Andreas Rettenmeier

WINDFORS
Wind Energy
Research Cluster

Table of contents

- WindForS Research Cluster
- Experiences in instrumentation and measurements
- Lessons learned
- Planned wind energy research test site in complex terrain
- Outlook

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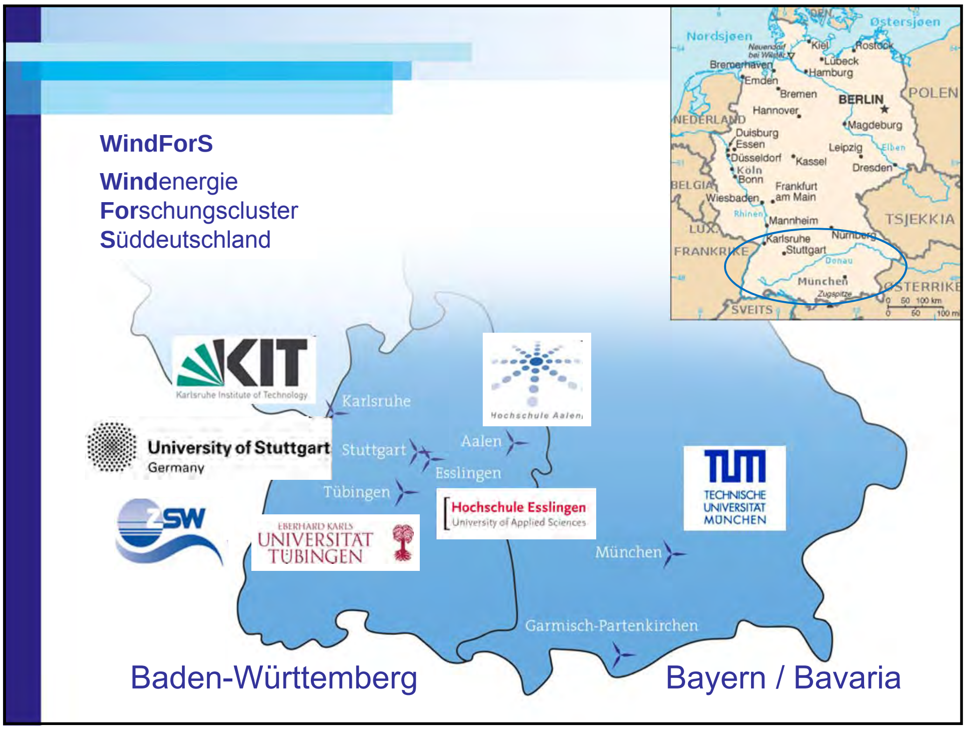
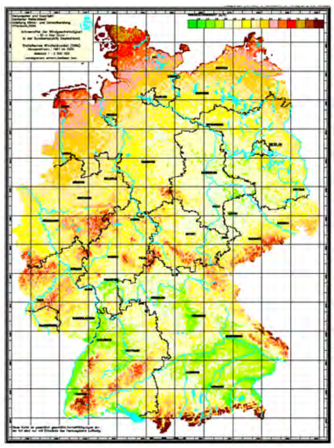


WINDFORS
Wind Energy
Research Cluster

Motivation

- Pooling of competences of southern German universities and research centers in the field of wind energy research
- Visibility at national and international level
- Intensification of location-specific research (taking into account the topological features in southern Germany)
- Tie in with the tradition of southern German Wind energy research



[Source: DWD]

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WindForS Wind Energy Research Cluster

Competences

The competences of WindForS cover the entire wind energy value-added chain:

- Wind, Wave and Climate
- Landscape Architecture and Ecology
- Foundation
- Design, Engineering and Manufacturing
- Test and Measurement
- Operation and Monitoring
- Grid Connection and Energy Storage

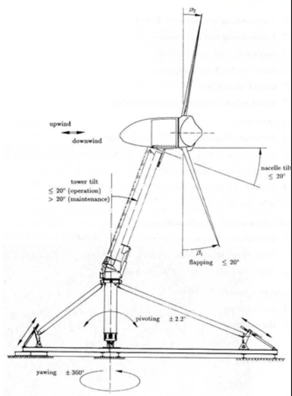
➔ www.windfors.de/en/kompetenzen/

5

WindForS Wind Energy Research Cluster

Tradition in utility-scale testing (examples)

- 1949 Foundation of the „Studiengesellschaft Windkraft (StGW)" in Stuttgart
- Prof. Ulrich Hütter, University of Stuttgart: Pioneering work in the areas of wind turbine design (3 bladed, pitch regulated) and fibre-reinforced composites, “Father of modern wind turbines" (StGW -34, 1957)
- Test site "Ulrich Hütter" in Schnittlingen, Swabian Alb



UNIWEX research turbine
HH: max.15m; Rotor-Ø 16m; Two bladed; up- and down-wind; variable speed, pitch, tilt and stiffness

[Sources: K. Handschuh, ICA University of Stuttgart]

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WindForS Wind Energy Research Cluster

Objectives of the WindForS Cluster

- Initiation and implementation of joint research projects (spectrum from basic to applied research)
- Cooperation with national and international research institutions
- Cooperation with companies in the wind industry for research and preparation of new technologies
- Training and promotion of young scientists
- Advising public bodies
- Southern German test site in complex terrain for testing and validation of new technologies in collaboration with other research institutions and industry

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WindForS Wind Energy Research Cluster

Utility-scale wind energy research in Germany

Current status

- Several national funded research projects
- Several measurement campaigns at commercial turbines, prototypes and wind farms (onshore and offshore)
- German offshore test site “alpha ventus”
- One existing onshore test sites without access for research

Planned

Wind energy research test sites onshore are planned by

- DLR/ForWind (flat terrain, 2x 2,5 MW-class research turbines + 1x experimental turbine)
- WindForS (complex terrain, 2x sub-MW-class research turbines, federally funded, with open access)

8

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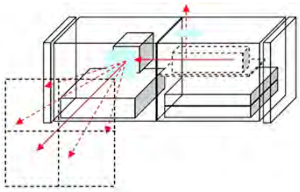
Research Cluster

Experiences in instrumentation and measurements
shown at the example of SWE-Lidar Scanner for nacelle installation

- Developed by SWE, University of Stuttgart
- Based on Leosphere Windcube V1
- Single mirror, 2 DOF



[Fig. SWE]

9

WindForS
Wind Energy
Research Cluster

SWE Nacelle Lidar Scanner in operation

10

WindForS Wind Energy Research Cluster

Test sites

Onshore campaigns

- Bremerhaven 05/2005 – 03/2010
- Risø–DTU 04/2011 – 01/2012
- NREL – NWTC 03/2012 – 07/2013
- Grevesmühlen 01/2013 – 07/2014

Offshore campaigns

- alpha ventus test site 10/2010 – ...

[Fig. SWE,DOTI]

11

WindForS Wind Energy Research Cluster

Bremerhaven experiment setup: wind turbine & met mast

1st Class anemometer

Temperature sensor and 3D-sonic anemometry

AREVA Wind GmbH M5000 prototype

- Rated power: 5 MW
- 116m rotor diameter
- 102m hub height

Measurement project

- Power curve and load measurement acc. to IEC standards (started 2005)
- Met(eorological) mast and sensors (102 m height)
- Data acquisition system
- Lidar device (ground-based and nacelle-based, started 2009)

[Fig. SWE]

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WINDFORS Wind Energy Research Cluster

Installation of nacelle-based Lidar on AREVA Wind M5000 (5MW)

Lidar system + scanner

[Fig. SWE]

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WINDFORS Wind Energy Research Cluster

REpower 5M & AREVA Wind M5000 – inflow and wake

[Fig. DOTI, GH-GL]

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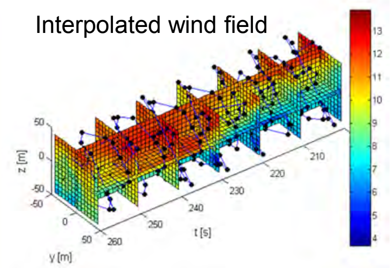
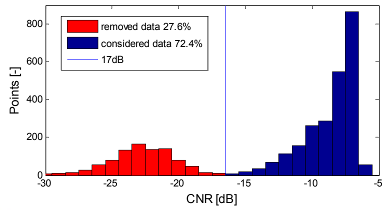
WindForS Wind Energy Research Cluster

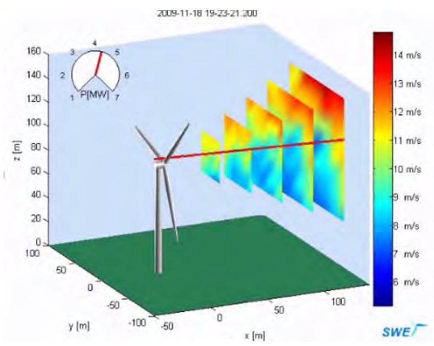
Inflow measurements (2009-10-24)

Interpolated wind field





Impact with blades



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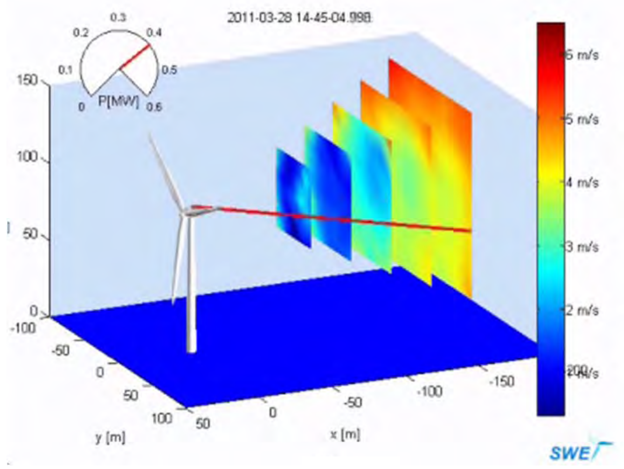
WindForS Wind Energy Research Cluster

Near-wake measurements of M5000 at “alpha ventus”



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WindForS Wind Energy Research Cluster

Joint measurement campaign at Kenersys K-110

K110 - Prototype

- Rated power: 2,4MW
- Rotor diameter :109m
- Hub height: 95m
- Campaign: Spring 2013 – Summer 2014
- Measurement setup designed for
  - Research project “Lidar complex”
  - IEA Annex 32 – Lidar: subtask III
  - Feed-forward wind turbine control

Federal Ministry for Economic Affairs and Energy | Universität Stuttgart | Eberhard Karls Universität Tübingen | KENERSYS | KALYANI

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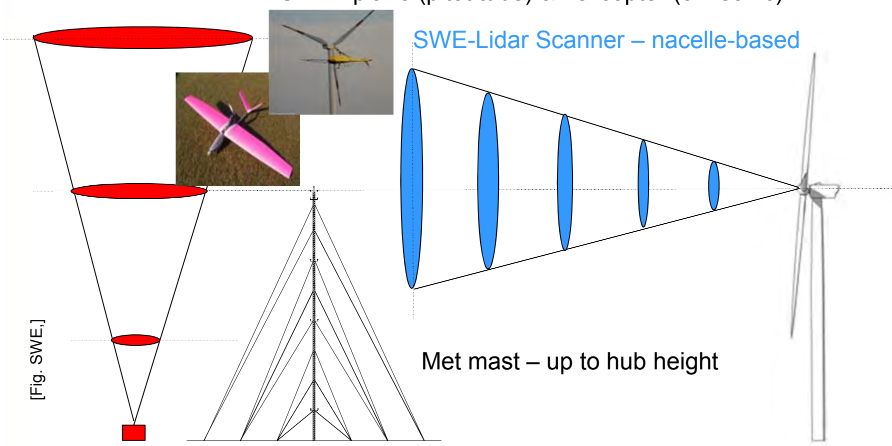
WindForS Wind Energy Research Cluster

Joint measurement campaign at K-110



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Research Cluster

Lidar measurements at Risø Campus (DTU Wind Energy)

- Pointing towards met mast from Nordtank turbine (yaw motion fixed)
  - Vertical shear & turbulence measurements
  - Equivalent wind speed

[Fig. SWE]

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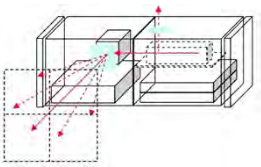
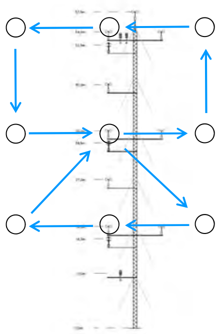
Lidar measurements at Risø Campus (DTU Wind Energy)

- Square grid: 3 x 3, 9 measurement points
- Two times crossing the center point within one run, ~1,9sec per run
- Center points correspond to “the region” of sonic anemometer
- Boom heights correspond to hub height, blade 6 and 12 o’clock



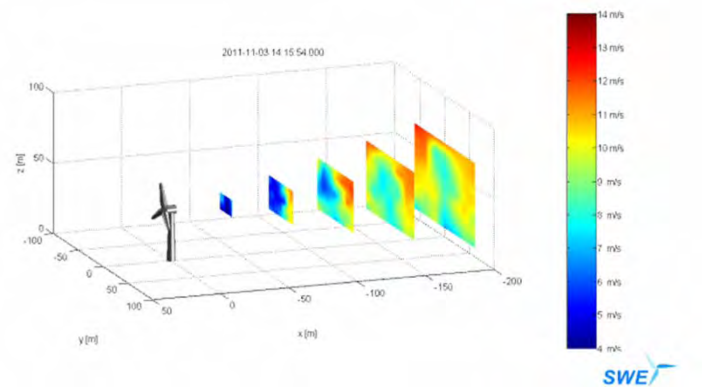


[Fig. SWE, Risø-DTU]

20

Wake measurements at Nordtank turbine, DTU, Risø Campus

- Pointing towards wake wind field of Nordtank turbine (with yaw motion)



Machefaux E. (DTU), Empirical Modelling of Single Wake Advection and Expansion using Full Scale Pulsed Lidar based Measurements,Wind Energy

21

Lidar measurements at NREL's NWTC test site

CART-2 turbine

- Rotor diameter D: 42m
- Rated output: 660 kW

Met Mast

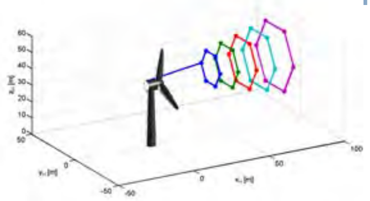
- Installed in 2D distance
- Equipped with various sensors at 3,15, 36.6 and 58.2m

Lidar

- Hexagonal grid: 6 measurement points per focus range
- Five focus ranges simultaneously

Objective

- First proof-of-concept of lidar assisted wind turbine control (by David Schlipf, SWE)



[Fig. SWE, NREL]

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Lessons learned – utility-scale testing

Crane
- Expensive! → Nacelle crane important!

Lidar
- Range must fit to the turbine size, e.g. power performance measurements
- Scanning as flexible as possible
- Scanning as fast as possible

Multi-MW turbines
- Overall costs of sensor installation and later research are very high

Offshore
- Weather access windows, difficult planning, remote devices are important

Design of research turbines
- Individual pitch, variable speed
- Additional: nacelle crane, dampers or masses (see UNIWEX turbine)

Met masts
- Useful up to upper tip height (wind and temperature)

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WindForS Wind Energy Research Cluster

Test site in complex terrain

"Intensification of location-specific research (taking into account the topological features in southern Germany)" (see Motivation of WindForS)

- Mountainous complex terrain
- Low wind speed sites with certain terrain effects

→ A lot of wind sites all over the world do have the same properties.

→ Further research in this field is possible and even needed.

→ Less test sites in complex terrain

  → Alaiz wind farm (in operation), by Cener, Spain

  → Gütsch, just planned by Meteotest, Switzerland

→ BUT, no test site with open-access research turbine

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Research Objectives

- **Testing and validation of new technologies**
  Design, aerodynamics, aero-acoustics, aero-elasticity, manufacturing engineering, operation, measurement sensors, monitoring, noise reduction, …
- **In-depth basic research in meteorology** for wind energy use in mountainous complex terrain, including icing
- **Development and verification of simulation software** for the design of wind turbines as a complete system and **wind field modeling in mountainous, complex terrain** (incl. meso-microscale coupling)
- **Energy storage** (e.g. Power-To-Gas, Batteries) **and grid connection**
- **Landscape architectural planning** to improve social acceptance
- (Limited) **Ecological research**

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WindForS Wind Energy Research Cluster

Test site setup **(current status Oct. 2014)**

- **Two open-access, modifiable research wind turbines downstream of an escarpment**
- **Medium size research turbine** because of boundary layer effects in complex terrain e.g. recirculation zone and due to forests.
- **Access to all design data as well as to the controller** of the research wind turbines, e.g. to develop new control algorithms for performance, load and yield enhancement
- **Turbine model available** for use in common aero-elastic codes as FAST, Flex5, Bladed and in multi-body code as e.g. Simpack
- **Extensive measurement instrumentation** for the detection of **electrical, acoustical**, and **mechanical** parameters
- **Meteorological parameters** are gathered by four meteorological masts and remote sensing devices (e.g. scanning ground- and nacelle-based lidars), ceilometers, UAV, radars?, imaging systems?, radiometers?

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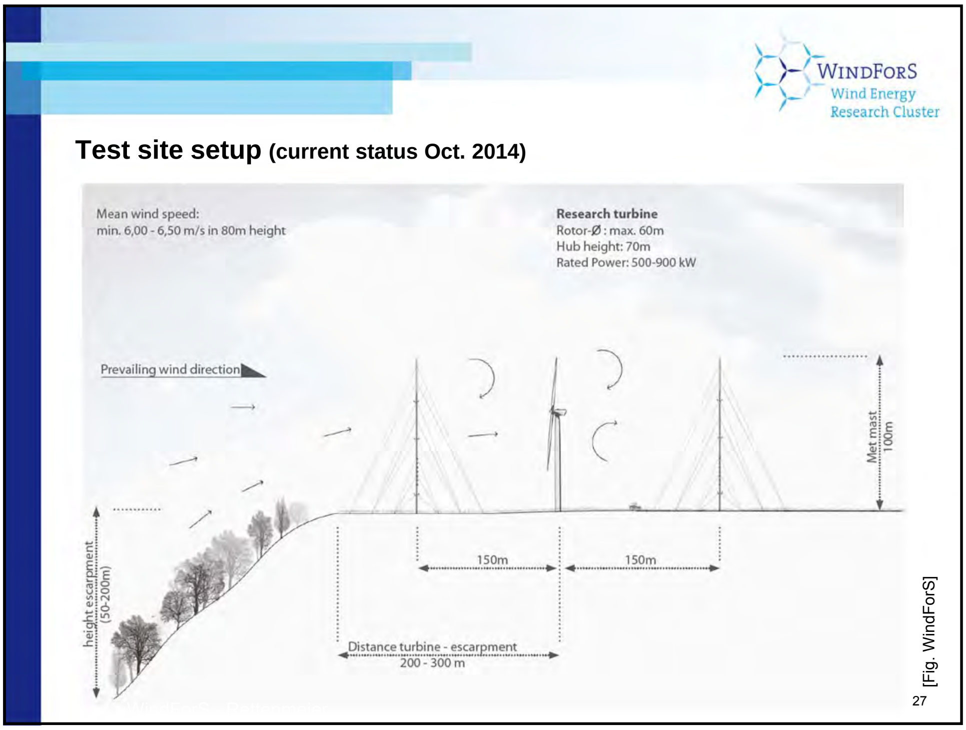
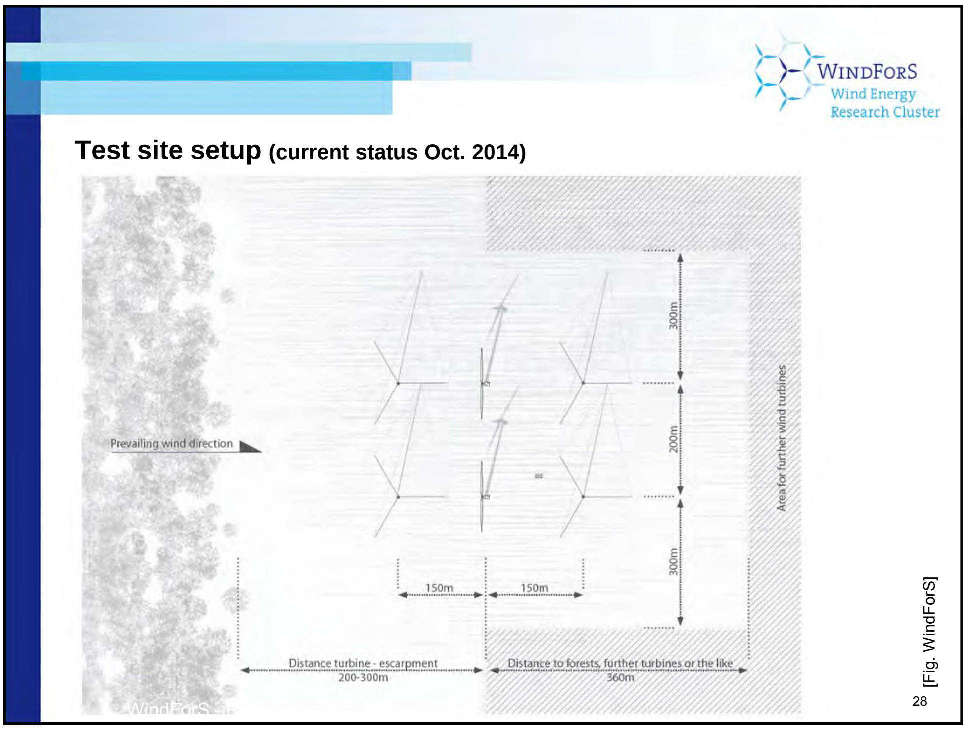

WindForS
Wind Energy
Research Cluster
Test site setup (current status Oct. 2014)
Mean wind speed:
min. 6,00 - 6,50 m/s in 80m height
Research turbine
Rotor-Ø : max. 60m
Hub height: 70m
Rated Power: 500-900 kW
Prevailing wind direction
Met mast
100m
height escarpment
(50-200m)
150m
150m
Distance turbine - escarpment
200 - 300 m
[Fig. WindForS]
27


WindForS
Wind Energy
Research Cluster
Test site setup (current status Oct. 2014)
Prevailing wind direction
300m
200m
300m
Area for further wind turbines
150m
150m
Distance turbine - escarpment
200-300m
Distance to forests, further turbines or the like
360m
[Fig. WindForS]
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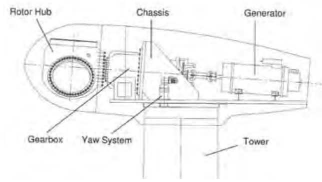
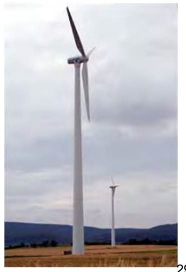
Current status: research turbine

- We are in intensive contact with Fuhrländer (insolvent turbine manufacturer)
- FL-600 no longer built and installed in Germany
- Willing to share controller data, turbine model for simulations, drawings etc. for research purposes (no IP regulations) → full access
- Technical service still available
- Either installation of used wind turbines (approx. 10 years old) or manufacturing of new turbines when more than 4-5 turbines are needed.

Technical specifications

- Rated Power: 600kW
- Hub height: 75m
- Rotor diameter: 50m
- Variable speed
- Three individual el. pitch motors





[Fig. Fuhrländer, WindForS]

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Vision: Research turbines on different sites and in different terrain

- Different sites (flat terrain, forested terrain, complex terrain, etc.)
- Same turbine type at each site
- Comparison of turbine behaviour, turbine control, meteorology, etc.

TEXAS TECH UNIVERSITY
IOWA STATE UNIVERSITY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories
University of Colorado Boulder

DTU Wind Energy
Department of Wind Energy
ECN
CENER
ADItech
WindForS
DLR
ForWind

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Outlook

Turbine

- Further research institutes interested?
- More detailed planning with manufacturer

Site

- Deadline of tender to find suitable sites: October 15th, 2014
- Selection of one site after measurement campaigns and wind flow simulations

Others

- Establishing a scientific and technical advisory board of European and transatlantic members.
- Useful: support letter of our planning of other national and international research institutes

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WINDFORS Wind Energy Research Cluster

Thank you for your attention!

Questions?

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T: +49 160 9634 1447
W: www.windfors.de

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Additional Sides:
Wind Tunnel Testing

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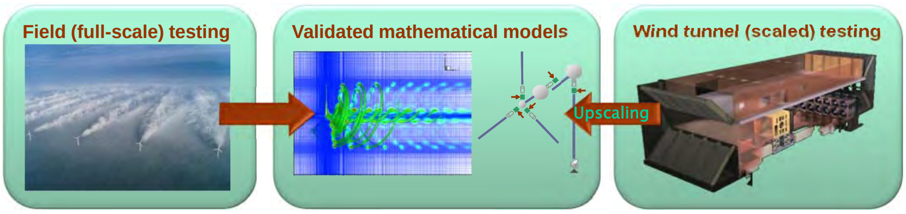
The Role of Wind Tunnel Testing for Model Validation/Calibration (by C.L. Bottasso, TU Munich)



Wind tunnel testing:

– Cons:

Usually impossible to exactly match all relevant physics due to scaling

+ Pros:

Better control/knowledge of conditions/errors/disturbances

Much lower costs

Does not replace simulation nor field testing, but works in synergy with them

Important remark: wind tunnel role is not limited to aerodynamics

WT², the Wind Turbine in a Wind Tunnel

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The first wind tunnel model of a wind turbine with
- Aeroelastic-scaling
- Real-time individual blade pitch and torque control

(by C.L. Bottasso, TU Munich)

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Additional Slides:
WindForS - Partners

WindForS
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Research Cluster

University of Stuttgart
Germany

Stuttgart Chair of Wind Energy (SWE)
www.uni-stuttgart.de/windenergie

Institute of Aerodynamics and Gas Dynamics (IAG)
www.iag.uni-stuttgart.de

Institute of Systems Theory and Automatic Control (IST)
www.ist.uni-stuttgart.de

Institute for Lightweight Structures and Conceptual Design (ILEK)
www.uni-stuttgart.de/ilek

Institute of Power Transmission and High Voltage Technology (IEH)
www.ieh.uni-stuttgart.de

Institute of Engineering and Computational Mechanics (ITM)
www.itm.uni-stuttgart.de

Material Testing Institute (MPA)
www.mpa.uni-stuttgart.de

Institute of Applied and Experimental Mechanics (IAM)
www.iam.uni-stuttgart.de

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KIT
Karlsruhe Institute of Technology

Institute of Soil Mechanics and Rock Mechanics (IBF)
www.ibf.uni-karlsruhe.de

KIT Research Centre for Steel, Timbre and Masonry (VAKA)
http://stahl.vaka.kit.edu

Institute for Meteorology and Climate Research (IMK)
www.imk.kit.edu

ZSW

Centre for Solar Energy and Hydrogen Research
Baden-Württemberg (ZSW)
www.zsw-bw.de

WINDFORS Wind Energy Research Cluster

Technische Universität München

Wind Energy Institute
www.wind.mw.tum.de

Institute for Carbon Composites (LCC)
www.lcc.mw.tum.de

Chair of Non-destructive Testing (ZfP)
www.zfp.tum.de

Department of Landscape architecture and regional open space (LAREG)
www.lareg.wzw.tum.de

Chair of Structural Analysis
www.st.bv.tum.de

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Eberhard Karls Universität Tübingen

Center for Applied Geoscience - Environmental Physics (ZAG)
www.geo.uni-tuebingen.de/umphy

Physical Geography - Geographic Information Systems
www.geo.uni-tuebingen.de/arbeitsgruppen/geographie/forschungsbereich/

Aalen University

Mechanical Engineering
www.htw-aalen.de/studium/m

Hochschule Esslingen
University of Applied Sciences

Faculty of Mechatronics and Electrical Engineering
Faculty of Building Services, Energy and Environmental Engineering
www.hs-esslingen.de

WindForS Wind Energy Research Cluster

Additional Slides: WindForS - Competencies

WindForS Wind Energy Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- **Wind, waves, climate**
    - Mesoscale and microscale wind field modeling
    - Measurement of wind, turbulence and temperature profiles
    - Use of met masts, lidars and UAV
    - Data analysis of meteorological and oceanographic parameters
    - Wind power prediction

[Fig. USTUTT]

WindForS Wind Energy Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- **Landscape architecture and ecology**
  - Landscape-orientated design
  - Social acceptance
  - Geographic information systems
  - Landscape planning and nature conservation

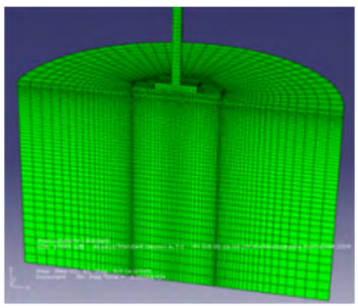
[Fig. LAREG]

WindForS Wind Energy Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- Landscape Architecture and Ecology
- **Foundation**
  - Subsoil investigation
  - Material behaviour
  - Constitutive relations
  - Modeling of the polycyclic behavior of soils and foundation structures for wind turbines
    - numerically
    - physically



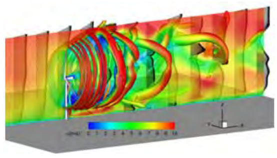
[Fig. KIT-IBF]

WindForS Wind Energy Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- Landscape Architecture and Ecology
- Foundation
- **Design, engineering and manufacturing**
  - Wind turbine - overall dynamics (coupling of structure, wind and waves)
  - Aerodynamics, aero-acoustics, aero-elastics
  - Foundation and support structures
  - Steel, reinforced and pre-stressed concrete structures for wind turbines
  - Gear and bearing design



[Fig. IAG, VAKA]

WindForS Wind Energy Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- Landscape Architecture and Ecology
- Foundation
- Design, Engineering and Manufacturing
- **Test and measurement**
  - In-situ and remote sensing measurements
  - Load and power performance measurements
  - Static and dynamic loading
  - Corrosion protection
  - Wind tunnel measurements (aifoils including noise measurements and scaled wind turbines)
  - Electrical lifetime simulations

[Fig. HTWAA, IAG]

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Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- Landscape Architecture and Ecology
- Foundation
- Design, Engineering and Manufacturing
- Test and Measurement
- **Operation and Monitoring**
  - Wind turbine and wind farm control
  - Load monitoring
  - Quality control
  - Inspection and structural health monitoring of wind turbines including rotor blades, tower, gearbox, foundation

[Fig. SWE, ZFP]

WindForS
Wind Energy
Research Cluster

Competencies

The competencies of WindForS cover the entire wind energy value-added chain – both onshore and offshore:

- Wind, Waves, Climate
- Landscape Architecture and Ecology
- Foundation
- Design, Engineering and Manufacturing
- Test and Measurement
- Operation and Monitoring
- **Grid Connection and Energy Storage**
  - High Voltage Engineering and Smart Power Grids
  - Electromagnetic Compatibility
  - Power Electronics
  - Electrical machines and propulsion concepts
  - Design and simulation of mechatronic systems
  - Power-to-Gas (methanization) and batteries

[Fig. IEH]

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Additional Slides:
Research Project „KonTest"

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Joint research project „KonTest"

Creating the design of a wind energy test site in mountainous complex terrain

- Supported by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
- Launched on 1st November 2013
- Duration: two years
- Funding: ~ 1 Mio. €
- Participation of five WindForS- Institutions:
  - University of Stuttgart (project leader)
  - Karlsruhe Institute of Technology (KIT)
  - University of Tübingen
  - Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)
  - Technische Universität München (TUM)

Federal Ministry for Economic Affairs and Energy

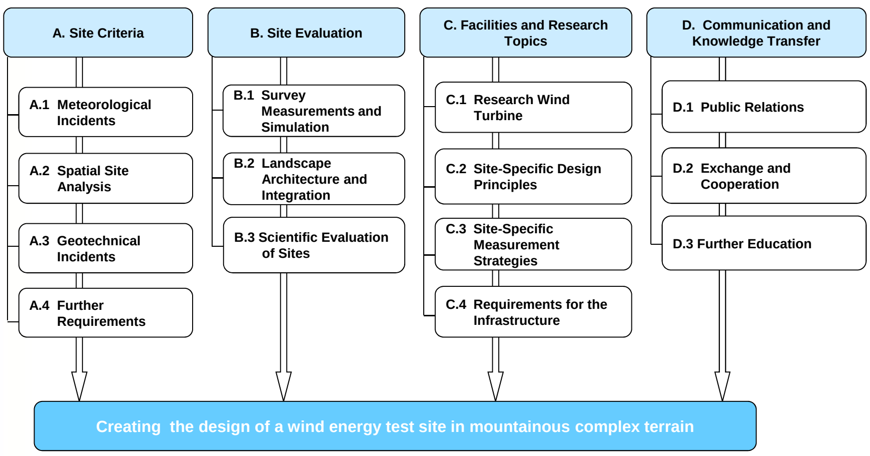
WINDFORS Wind Energy Research Cluster

Objectives

1. **Scientific monitoring** of the test site design in order **to maximize the benefit** and use of the research **test site for research institutions and industry**.
2. **Intensive cooperation and exchange with the planning teams of other test sites**, which will be realized in the coming years (cost saving through joint development of the system, avoid duplicate work).
3. The **accompanying ecological research and landscape planning** should be more visible to **increase general acceptance** among the population living near wind turbines. This topic is particularly important for the development of wind energy inland.

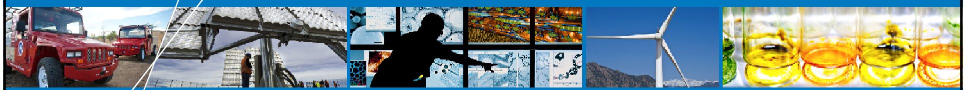
WINDFORS Wind Energy Research Cluster

Organisation of the work packages



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Wind Tunnel Experiments for Model Validation



IEA TEM #78

S. Schreck

8 October 2014

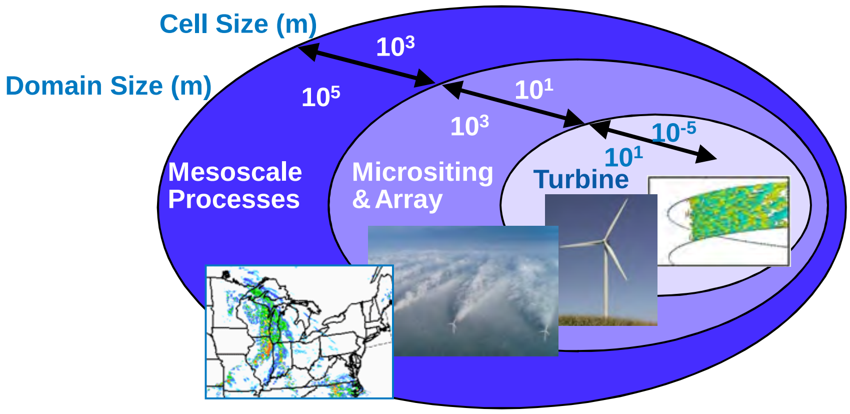
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

TEM #78 Objectives & Focus of Presentation

- **Objectives of this TEM are:**
  - Review utility-scale field campaigns to date, and assess strengths/limitations
  - Establish current SOA in field instrumentation, limitations, and future needs
  - Identify lessons learned from past campaigns, as a baseline for future campaigns
  - Develop guidelines for future campaigns by assessing gaps, challenges, data needs, etc.
  - Establish best practices for complementing subscale and/or controlled inflow experiments with utility-scale tests

NATIONAL RENEWABLE ENERGY LABORATORY 2

A2e for Wind Plant Flow Physics

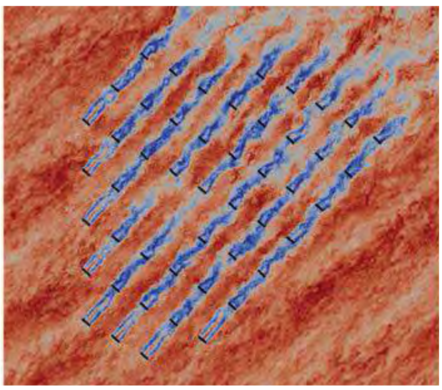


- Large domain with diverse constituents
- Viscous and time varying flow physics
- Broad range of space and time scales

NATIONAL RENEWABLE ENERGY LABORATORY 3

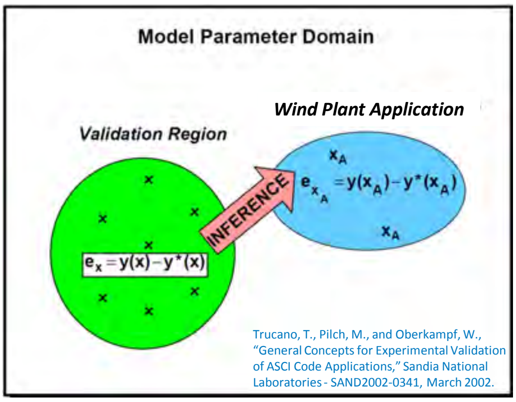
A2e High Fidelity Computational Modeling

- Large, nonuniform computational grids
- Solvers for nonlinear, time varying PDE sets
- Broad range of space and time scales
- Reliably predict novel geometries, conditions



NATIONAL RENEWABLE ENERGY LABORATORY 4

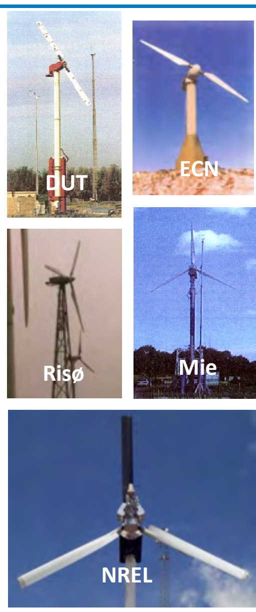
A2e Model Validation Crucial



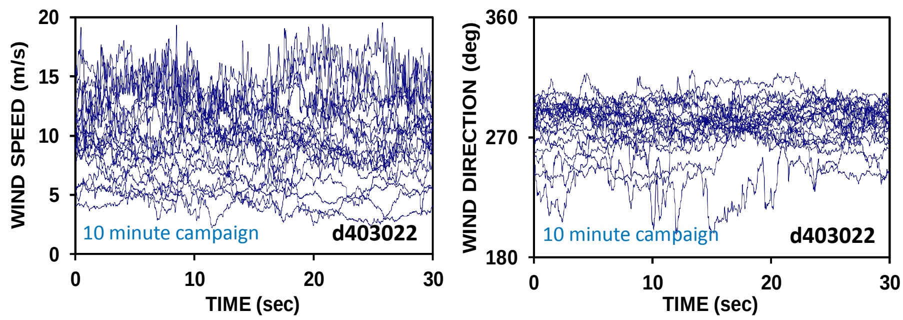
- **Measurement database quality <u>and</u> quantity**
- **Validate across broad, pertinent parameter range**
- **Support extrapolation to wind plant application**

Lesson Learned – Aero Modeling & Validation

- **Research grade field measurements**
  - + High sensitivity, high signal-to-noise
  - + Well resolved in space and time
  - + Rotor D ~ 10 m for feasibility
- **Intense analysis, detailed reporting**
  - + Multi-national, multi-year collaborations
  - + IEA Annex 14: "Field Rotor Aerodynamics"
  - + IEA Annex 18: "Enhanced Field Rotor Aerodynamics Database"
- **Constraints due to inflow variations**
  - + Obscured key flow physics details
  - + Drove large wind tunnel experiments



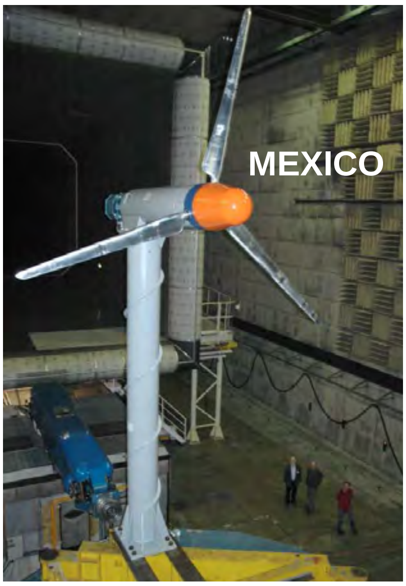
UAE Phase IV Inflow Variations



	All Phase IV		d403022	
	Mean	SD	Mean	SD
Wind Speed (m/s)	11.4	3.9	10.1	4.5
Wind Direction (deg)	286.9	15.8	303.0	23.7
Yaw Error (deg)	-8.9	13.6	-11.5	16.9

NATIONAL RENEWABLE ENERGY LABORATORY 7

Large Wind Tunnel Wind Turbine Experiments



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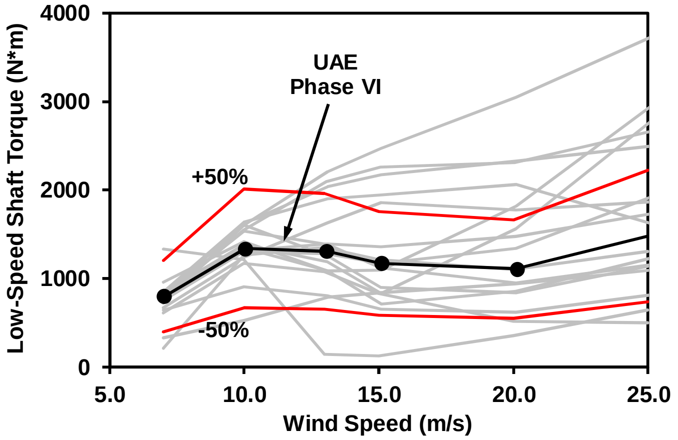
NREL Blind Code Comparison



- Aero models validated with field experiments
- Models applied by their developers
- Inflow anomalies likely impacted accuracy

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SWT-2.3-101 at NREL/NWTC

- **Rotor**
  - D = 101 m
  - h = 80 m
- **Blade**
  - Surface pressure @ 9 rad
  - Five hole probes @ 4 rad

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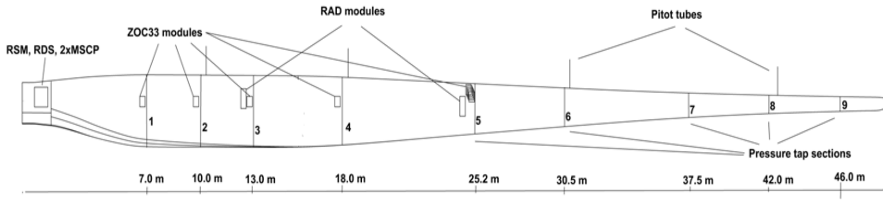
SWT-2.3-101 Pressure Blade Data



- Subdivided into 19,870 1-minute records
- Search Region 2 for [-25° < Yaw Error < 25°]
- Yielded 191 1-minute records (~1% of data)
- Mean STD of yaw error = 3.5°
- Mean STD of wind speed = 0.5 m/s
- Five hole probe data for local inflow angle

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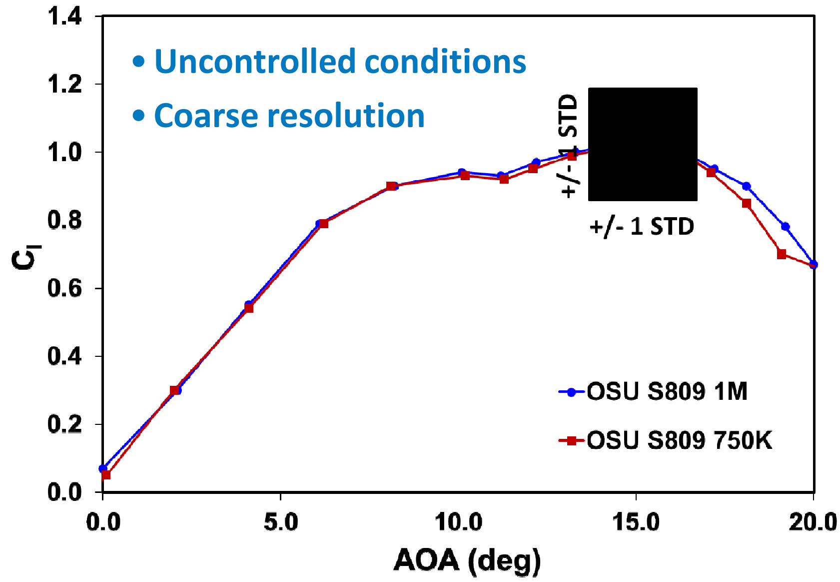
SWT-2.3-101 Data Variability (Rare)



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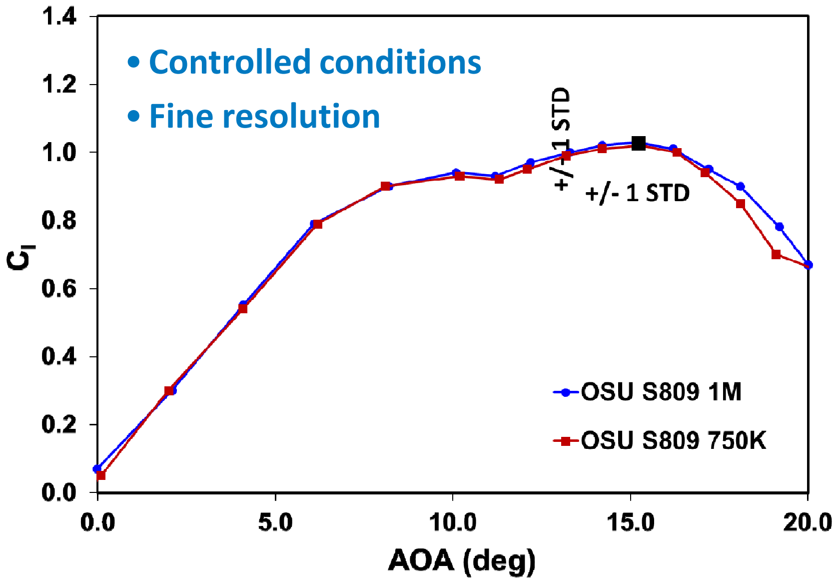
UAE Phase VI Data Variability (Routine)



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Measurements to Acquire in Wind Tunnel

- **Blade/rotor measured data**
  - Surface flow visualization
  - Root flap and edge strains
  - Sectional c_p distributions
  - Boundary layer state
- **Wake measured data**
  - Wake helix visualization
  - Particle image velocimetry
  - 3-D unsteady velocity surveys
  - Reynolds stresses

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Phenomena to Resolve in Wind Tunnel

- **Blade/rotor flow field**
  - Rotational augmentation
  - Dynamic stall
  - Steady/unsteady separation
  - Boundary layer transition
- **Wake flow field**
  - Expansion and skew
  - Meander
  - Momentum deficit and swirl
  - Tip vortex instabilities
  - Tip vortex dissipation

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Conclusions

- **Wind plant flow physics challenging**
- **Computational modeling complex**
- **Thorough model validation crucial**
- **Wind tunnel inflow control necessary**
- **Measured data quality and quantity**
- **Fine resolution absent inflow variation**
- **Broad parameter range with inflow control**
- **Support extrapolation to wind plant**
- **Complement full-scale measurements**

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Thank you for your attention

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