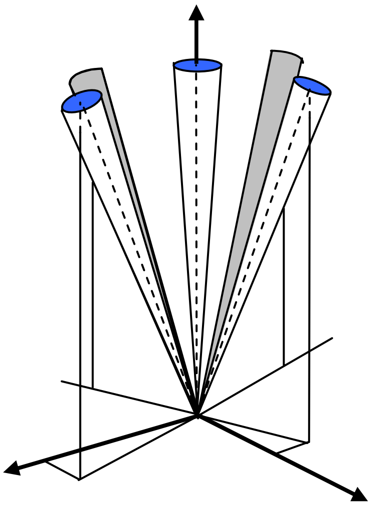
INTERNATIONAL ENERGY AGENCY

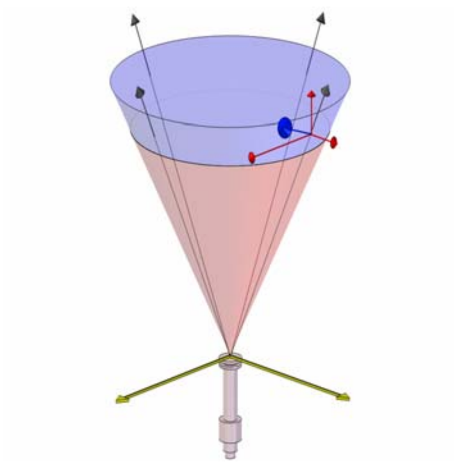
Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

51st IEA Topical Expert Meeting

State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites

Risø, Roskilde, Denmark, January 2007
Organised by: Risø





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CONTENTS

IEA RD&D Wind Task 11

Topical Expert Meeting #51

State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites

INTRODUCTORY NOTE

IEA TOPICAL EXPERT MEETING 51

ON

STATE OF THE ART OF REMOTE WIND SPEED SENSING TECHNIQUES USING SODAR, LIDAR AND SATELLITES

Ioannis Antoniou, Torben Mikkelsen, Hans E. Jørgensen, Charlotte Bay Hasager, Jakob Mann

Risø National Laboratory

Background

Wind power is moving towards the installation of wind farms in complex terrains, off-shore, in forests, and at high levels in the atmosphere. Marketing of large, multi-MW wind turbines is in continued growth. At the same time our basic knowledge on winds in these challenging environments is inadequate.

The method traditionally used for accredited measurements for wind energy purposes is to mount cup anemometers on met masts. As turbines grow in height, mast instrumentation, erection and maintenance, has become expensive; prices increase geometrically with height and built permits can be time consuming. At the same time the discrepancies between the measured wind at the rotor centre and the turbine performance have increased the need for knowing and measuring the wind over the whole turbine rotor.

Successful development of wind power should be based on sound information on winds in each location. To achieve this it is relevant to place emphasis on new observation methods and strategies. Most promising are the new (for wind energy purposes) remote sensing techniques SODAR, LIDAR and satellite. SODAR is based on sound propagation, LIDAR on laser Doppler and satellite on microwave scatterometry and Synthetic Aperture Radar (SAR) methods. Advantages and limitations of the various techniques will be described and discussed.

Techniques

Briefly described the SODAR, LIDAR and satellite techniques for wind observation are summarized below:

SODAR (SOund Detection And Ranging) provides a method for wind speed measurements. The instrument is ground based and emits a short pulse of sound at a certain frequency to the atmosphere. The sound propagates upwards while at the same time a part of the sound is reflected back. The Doppler frequency shift of the received signal is proportional to the wind speed aligned to the transmission sound path. By combining three or five of these pulses, usually one along the vertical and two or four inclined to the vertical, the three dimensional velocity field of both the mean values and the turbulent values is calculated.

SODARs are widely used for meteorology applications however their usage in wind energy, e.g. for measuring the wind field or the energy potential at a site or power curve measurements, is relatively new and involves a number of advantages and drawbacks. Among the advantages, the SODAR gives the possibility to measure the wind profile over the whole rotor, it is ground based instrument and therefore it is faster, easier and cheaper to use relative to cup anemometers mounted on met masts. Among the drawbacks, the most serious are the limited experience in the use of the instrument, its decreasing performance with height, its dependence on the prevailing atmospheric conditions and finally the need for a rigorous well-established “absolute” calibration method. Among the SODAR users, there is also a debate as to what degree the instrument can be used for the measurement of turbulent quantities other than the one in a vertical direction and still there is an open question to what extend can the instrument be used for measurements in complex terrain as the separate wind components are not being estimated within the same volume.

LIDAR is a remote sensing technique that offers the ability to determine wind speed and direction at substantial heights using a ground-based instrument. In this respect it is similar to SODAR but operates via the transmission and detection of light rather than sound. The basic LIDAR principle relies on measuring the Doppler shift of radiation scattered by natural aerosols carried by the wind. Typically, these are dust, water droplets, pollution, pollen or salt crystals. A new generation of fibre-based LIDARs has emerged the recent years that operates close to the theoretical limit of sensitivity and typically only needs to detect one photon for every 10E+12 transmitted in order to measure wind speed. As the Doppler-shifted frequency is directly proportional to line-of-sight velocity, the wind speeds obtained by LIDAR instrument seem not to need calibration. This however remains still to become documented by more measurements and by a full description of the whole measurement chain. As in the case of SODARs, the LIDAR is also a new instrument and its merits and limitations are neither fully documented nor are they known. In the case of the LIDAR, the measurement of the wind speed takes place on the surface of a cone where the depth changes as a function of the focus distance. The measurement of the turbulence quantities using LIDARs remains also to be documented.

Satellite remote sensing provides wind maps (snap-shot images) of the surface wind at 10 m above sea level. From scatterometer twice-daily wind maps at grid resolution of 25 km are available. The data series from July 1999 to present holds more than 5000 observations at most locations of the globe. Due to the resolution of 25 km observations are not available close to the coastline (usually a void around 40 to 50 km distance offshore). In contrast, SAR wind maps cover the near coastal zone in which most wind farms are located. Far fewer SAR wind maps are available (e.g. a few hundred or less), but using statistical treatment of few samples, rough estimates of the wind resource can be obtained. The accuracy, around 1.1 m/s standard error on a series of wind maps compared to offshore mast observations is useful in pre-feasibility and for decision on siting of offshore masts (or LIDAR/SODAR). In addition, if high-quality met-observations are available within a mapped area, the relative differences in winds between different locations can be estimated with higher accuracy, possibly around 0.6 m/s.

TENTATIVE AGENDA

The tentative agenda covers the following items:

1. Introduction by host
2. Introduction by Operating Agent, Recognition of Participants
3. Collecting proposals for presentations. The participants are encouraged to inform the Operating Agent on the contents of their presentation in advance and if possible provide a copy. The participants are also encouraged to in advance suggest relevant discussion matters that would have their interest.
4. Presentation of Introductory Note.
5. Individual presentations
6. Discussion
7. Summary of meeting

Objectives

To hold a symposia meeting to discuss and gather information on:

- Overview of existing knowledge and experience on LIDAR and SODAR technical issues, regarding the measurement of mean wind speeds, turbulence quantities, and vertical wind profiles for wind energy applications.
- Calibration of SODARs and LIDARs.
- Accuracy and reliability of the different systems and comparisons with other point measurement techniques, e.g. cup anemometers
- Suggestion for a “good measurement practice” using remote sensing equipment.
- Overview of existing knowledge on offshore wind mapping from satellite.
- Challenges off-shore compared to on-shore work.
- Getting closer to certification and how?
- Future options for wind energy using LIDAR, SODAR and satellite wind observations.

The participants are encouraged to prepare presentations relevant to these objectives.

Expected Outcomes

One of the goals of the meeting will be to gather the existing knowledge on the subject and come up with suggestions / recommendations on how to proceed with thefollowing:

1. Define a procedure of how should the instruments be used in order to make their results acceptable by developers and others active in wind energy?
2. How should the instruments be used in different terrain types?
3. In what assignments should the instruments be used for (e.g. siting, power curves,...)?
4. Limiting the measurement, until further, to only certain parameters (e.g. mean values, turbulence,...)?
5. Calibration or verification procedures for the results?

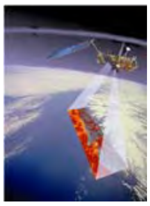
Based on the above a document will be compiled containing:

- Presentations by participants
- Compilation of the most recent information on the topic
- Input to define IEA Wind RD&D’s future role in this topic

Intended Audience

The national members will invite potential participants from research institutions, utilities, manufacturers and any other organizations willing to participate in the meeting by means of presenting proposals, studies, achievements, lessons learned, and others. This means then that the symposia will be wide open, taking into account that it is the first time that this subject will be discussed within the framework of the IEA Wind RD&D.

Introductory Note

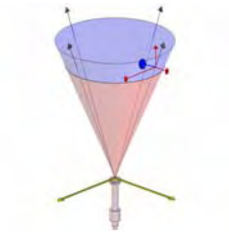


Welcome to the

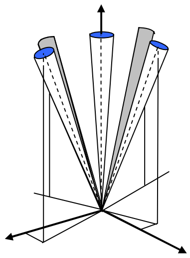
IEA Topical Expert Meeting 51

on

State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites



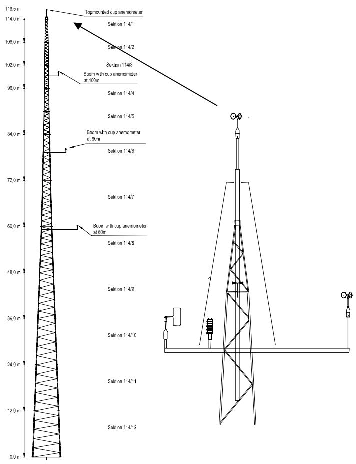
The Remote Sensing Group
of the Risø Wind Energy Department

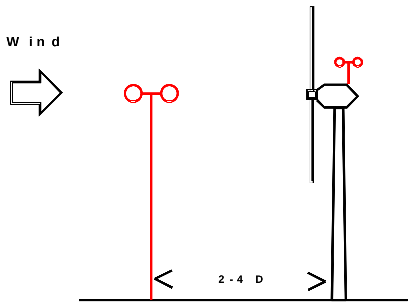


www.risoe.dk

The IEC61400-121standard for power curve measurements

- One or two cup anemometers at hub height



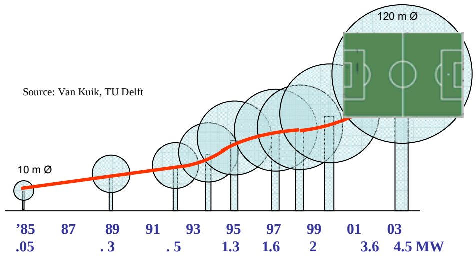


Anemometers are robust and well known instruments

Need for remote sensing (lidars-sodars)

- Turbine rotor size increase.
- Hub height increase.

- Need to know the wind energy potential at higher heights.
- Need to measure / verify the power curves.



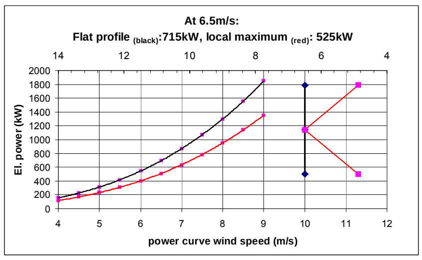
- Need for higher met masts.
  - ✓ Costs and difficulties (installation, maintenance) increase exponentially.
  - ✓ Limited mobility and access.

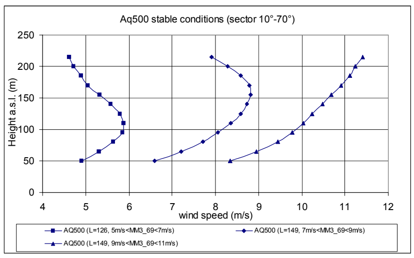
UPWIND EU project:
Upscale a 5MW w/t to 20MW

Need for remote sensing (lidars-sodars)

- The power production of a w/t depends on the energy (wind speed, turbulence) of the wind over the whole rotor.
- The wind profile, for a given terrain, depends on the atmospheric stability.
- A measurement at the center of the rotor gives limited information

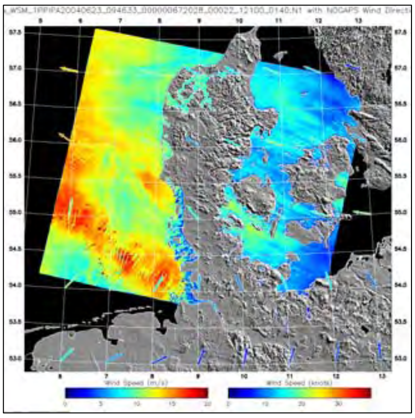
- By using remote sensing, wind profiles over the whole turbine rotor can be measured.
- Improved power curve and siting measurements when not limited to hub height measurements.





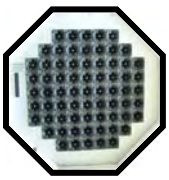
Wind resource mapping (satellites)

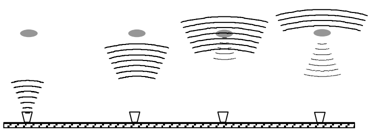
- Mapping of offshore wind resources.
- Offshore wind farm wake interaction.
- Aid in calculating on-land wind resources by providing information on topography, roughness and obstacles.

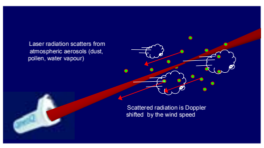


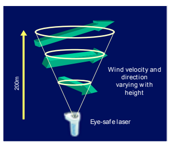
Wind field from Envisat ASAR WSM (Courtesy: JHU/APL)

The sodar and lidar instruments









Introducing lidars and sodars for wind energy purposes

- Both sodars and lidars can measure the wind speed and the turbulent characteristics of the wind (many scientific papers witness this). This is not the issue...
- The issues are:
  - What do sodars and lidars measure and how and what are their limitations (existing knowledge and experiences)?
  - What is their accuracy when performing wind measurements?
  - Calibration issues and methods for lidars and sodars?
  - Recommendations on how to use the instruments.
  - Suggestions for a "good measurement practice" until their introduction to the measurement standards.
  - Introduction of the instruments to the standards .

Have

a successful meeting

IEA Remote Sensing Seminar

Remote Sensing in IEC Power Performance Measurements

Troels Friis Pedersen
Wind Energy Department
Risø National Laboratory
Denmark Technical University

IEA Remote Sensing Seminar

Remote Sensing in IEC Power Performance Measurements

Status of IEC power performance measurement standard:

IEC 61400-12-1, First edition 2005-12

Wind turbines – Part 12-1 Power performance measurements of electricity producing wind turbines

Purpose: The purpose is to provide a uniform methodology that will ensure consistency, accuracy and reproducability in the measurement and analysis of power performance by wind turbines.

Users: manufacturers, turbine purchasers, turbine operator, turbine planner or regulator

From 1 January 2007, Risø National Laboratory, the Danish Institute for Food and Veterinary Research, the Danish Institute for Fisheries Research, the Danish National Space Center and the Danish Transport Research Institute have been merged with the Technical University of Denmark (DTU) with DTU as the continuing unit

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Remote Sensing in IEC Power Performance Measurements

Status of IEC power performance measurement standard:

Additional power performance standards:

IEC 61400-12-2

Wind turbines – Part 12-2 Power performance verification of electricity producing wind turbines

Purpose: The purpose is to provide a methodology to verify power performance of wind turbines at production sites by the use of nacelle anemometry.

Status: First CD expected spring 2007

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Remote Sensing in IEC Power Performance Measurements

Status of IEC power performance measurement standard:

Additional power performance standards:

IEC 61400-12-3

Wind turbines – Part 12-3 Power performance measurements of wind farms

Purpose: The purpose is to provide a methodology to measure power performance of whole wind farms

Status: First CD expected spring 2008

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Remote Sensing in IEC Power Performance Measurements

Wind speed measurement requirements in IEC 61400-12-1:

1. Hub height point wind speed measurement
2. Distance to wind turbine 2-4 rotor diameters (preference for 2.5)
3. Wind speed is defined as horizontal wind speed
4. Instantaneous measurements are averaged over 10min.
5. Only cup anemometers of a certain class are accepted for the measurements. Annexes on calibration, classification and mounting on mast.

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Remote Sensing in IEC Power Performance Measurements

Drawbacks of present standard IEC 61400-12-1:

1. Wind shear and turbulence effects are not taken into account in measurement procedure. These can be significant for the MW size wind turbines.

2. Costs of the use of masts are increasingly high

3. Use of remote sensing equipment is not allowed

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Remote Sensing in IEC Power Performance Measurements

Scenarios of inclusion of remote sensing in power performance measurement standards:

1. New performance standards are made for each type of remote sensing equipment
2. Revision of IEC 61400-12-1, including how to handle turbulence and wind shear, and including use of remote sensing equipment
3. Revision of IEC 61400-12-1, including how to handle turbulence and wind shear, but excluding measurements. Measurements are handled in separate measurement standards for each type of sensing equipment (mast mounted equipment, ground based LIDAR, nacelle based LIDAR, ground based SODAR) also to be used for other purposes.

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Remote Sensing in IEC Power Performance Measurements

Requirements for inclusion of remote sensing in power performance measurement standards:

1. A consistant definition of measured wind speed, including averaging over the rotor plane due to wind shear, time averaging and influence of turbulence
2. Detailed description of physical principle of wind measurement
3. Analysis of influence parameters on wind measurement
4. A consistant uncertainty analysis of measured wind speed
5. Traceability of calibration
6. RR testing of instruments individually and in comparison to existing methods
7. Setting up of environmental requirements for classification
8. Classification methods for instruments
9. Certification of instruments

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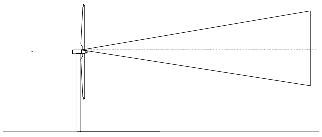
Remote Sensing in IEC Power Performance Measurements

Potential LIDAR set-up for power performance measurements

Point from nacelle

Re: Rene Skov

Conical scan from nacelle



Conical scan from ground

Re: Qinetiq

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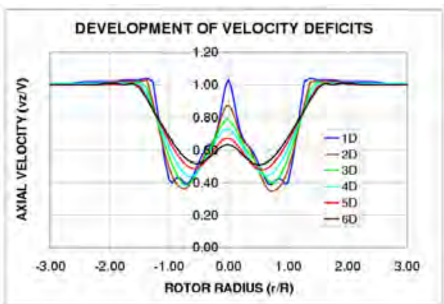
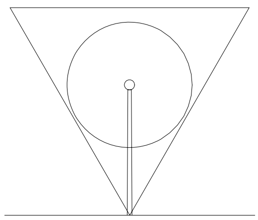
Remote Sensing in IEC Power Performance Measurements

Potential LIDAR set-up for power performance measurements

Wake velocity deficits



Projected scanning profiles



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Remote Sensing in IEC Power Performance Measurements

Conclusions:

1. Present IEC61400-12-1 standard does not allow remote sensing
2. IEC61400-12-1 lacks inclusion of shear and turbulence
3. Several scenarios for inclusion of remote sensing in standardisation
4. Requirements for remote sensing to be met before standardisation
5. Remote sensing may be applied from ground or nacelle

Experiences with Power Curve Measurements at Large Turbines, Which Indicate the Need to Change the Power Curve Testing Procedure

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testing- and calibration laboratory with
quality management system according EN ISO/IEC 17025:2000

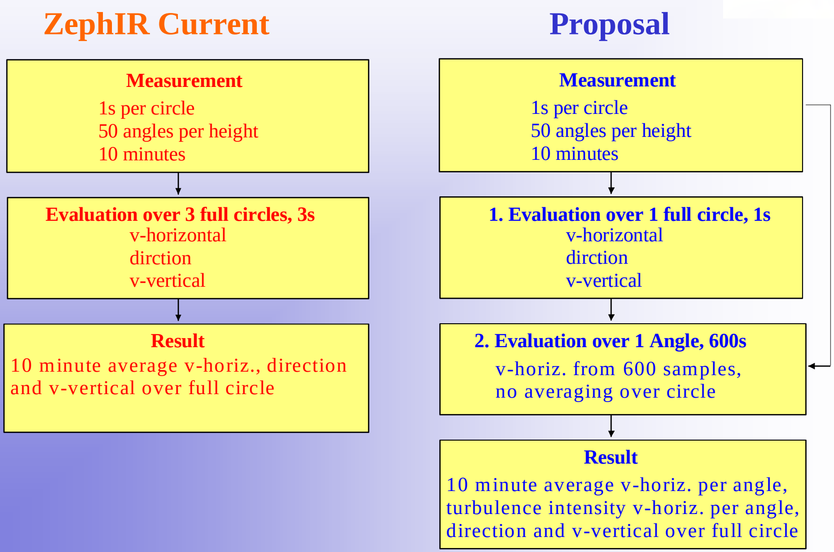
Background

- Since 2002 scientific evaluation of power curve measurements for Enercon
- Aim: improve power curve testing procedures and methods to describe power performance
- Investigated turbines so far:
  - E-112, 4.5MW. D=112m, H=124m, flat terrain inlands
  - E-112, 6MW, D=114m, H=124m, flat terrain, wind coming over sea
  - E-70, 2.05-2.3MW, D=71m, H=65m, flat terrain
  - E-30, 300kW, D=30m, H=50m, flat terrain
  - E-82, 2.05MW, D=82m, H=98m, flat terrain
  - E-48, 800kW, D=48m, H=50m, flat terrain
  - E-44, 800kW, D=44m, H=50m, flat terrain
  - E-53, 800kW, D=53m, H=72m, flat terrain
- First results will be shown at EWEC2007

Turbulence Effects

- Large effect of turbulence intensity on power curves
- Same effect at large and small machines
- About 1% increase of power output with 1 % increase of turbulence intensity at wind speeds around maximum cp.
- Effect partly due to 10-minute averaging and partly due to other effects
- New approach for normalisation of 10-minute averaging effect to be published at EWEC 2007, substitute to Taylor-series procedure of 1995/1996
- **Consequence: Remote sensing must allow to evaluate turbulence intensity**

Proposed Turbulence Evaluation with Lidar



Vertical Wind Shear

- Large effect of vertical wind speed gradient on power curves at large machines with small towers
- At large machines up to 20° wind veer in lower half of rotor at stable stratification
- **Consequence: The wind speed should be measured over the full height range of the rotor**

Distance Between Wind Turbine and Wind Measurement

- 2.5D distance means at large machines much larger distance than at small machines: loss of correlation, longer wind travelling time
- Even in very flat terrain significant site effects observed at large machines
- **Consequence: Wind measurement at different positions could be useful**
- ZephIR measures at 30° cone, i.e. circle with 1.15*H: offers different positions if data evaluated for each azimuth angle

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NREL National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

Remote Wind Speed Sensing Techniques At NREL

George Scott
National Renewable Energy Laboratory
Golden, CO, USA

IEA Topical Expert Meeting
Remote Wind Speed Sensing Techniques
RISØ National Laboratories

January 23-24, 2007

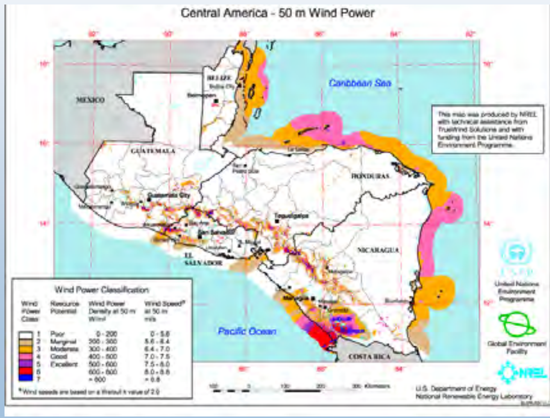
NREL is operated by Midwest Research Institute • Battelle

NREL/NWTC

- National Renewable Energy Laboratory
  - Funded by US Department of Energy
- National Wind Technology Center
  - Located between Golden and Boulder in Colorado

NREL Research Areas

- Turbine inflow studies
- Characterization of offshore wind loads
- Regional wind resource assessment studies



Overview

- Technologies Used at NREL
  - Satellite wind data (SSMI, QuikScat, etc.)
  - Sodar
  - Lidar
  - SAR
- Priorities
- Questions
- Future work

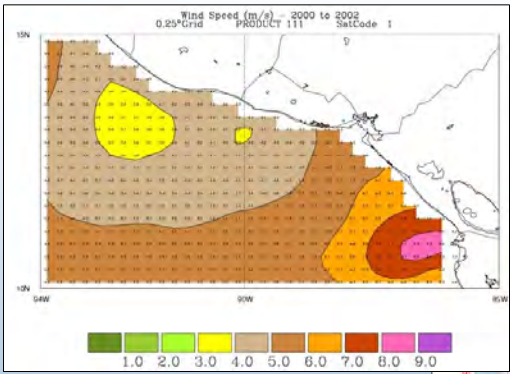
Satellite Ocean Wind Data

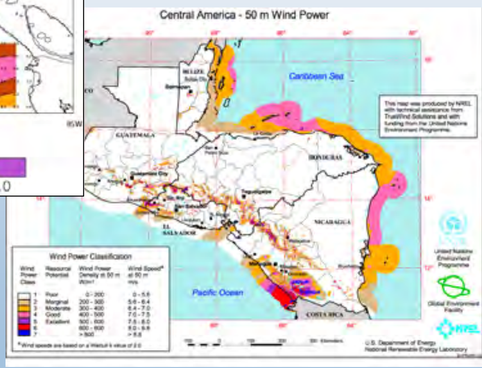
- Special Sensor Microwave/Imager (SSM/I)
  - 1988 to present
- TRMM Microwave Imager (TMI)
  - Tropical Rainfall Measuring Mission (TRMM)
  - 1998 to present
  - 40°S to 40°N
- QuickScat
  - July 1999 to present
- Data obtained from Remote Sensing Systems
  - (Santa Rosa, CA) http://www.remss.com
  - Data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project or the NASA Ocean Vector Winds Science Team. Data are available at www.remss.com.

Satellite Ocean Wind Data

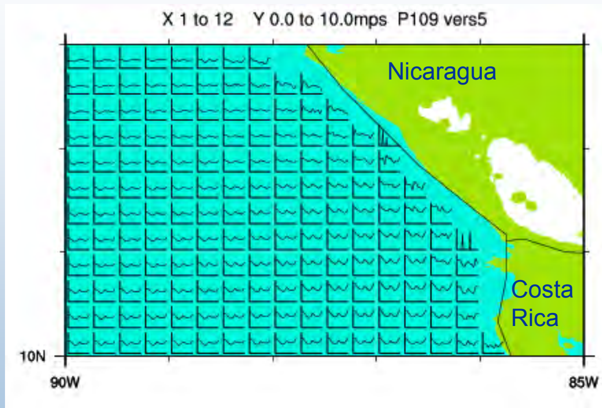
- Sensors
  - Passive (radiometers) – SSM/I, TMI
    - Solve Radiative Transfer Equation
  - Active (scatterometers) – QuikScat
    - Analyze backscattered signa
- Returns wind speed and direction, water vapor and liquid
- Accuracy: ±2.0 mps WS, ±20° WD
- Less accurate in coastal/shallow regions
- RSS daily files combined into monthly 0.25° grids
- Monthly grids combined into annual or long-term grids

Satellite Data as Input to Wind Resource Model

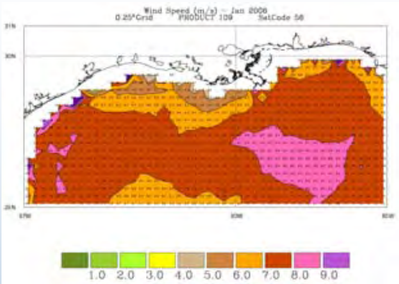


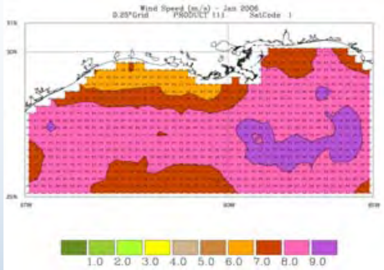


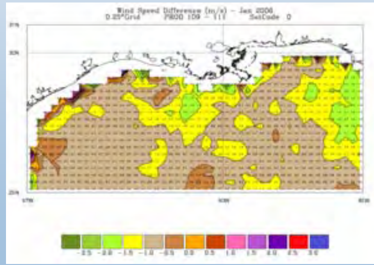
Monthly Patterns of Wind Speed



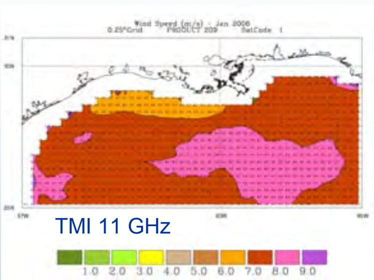
Comparison of SSMI and Quikscat

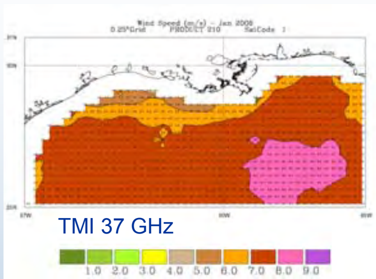


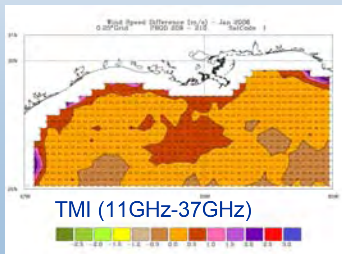




Comparison of TMI Channels







Unresolved Questions

- Reconcile differences in wind speeds from different satellites and from different channels on TMI
- Is there a 'best' satellite and/or frequency band?
  - Seasonal and regional dependence
- Near-shore reliability – which satellites and algorithms work best?

Sodar and Lidar

Low-Level Jet Turbulence Measurement Campaign

120 meter meteorological mast south of Lamar, Colorado

- **Objective**
  - To obtain detailed wind fields, turbulence, and associated atmospheric thermodynamic measurements in the nocturnal boundary layer currently or expected to be occupied by wind turbine rotors in order to establish the severity of coherent turbulent motions at a identified Great Plains wind resource area where low-level jet streams are expected to occur relatively often.
- LLLJP data and images courtesy of Neil Kelley, NREL

Observation Systems Used

REMOTE SENSING

High-resolution turbulence

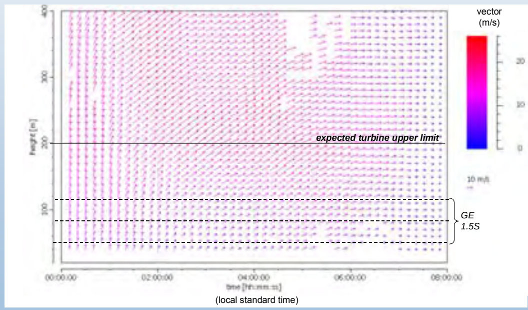
Mean wind profiles
From Scintec MFAS Sodar

Turbulence spatial structure

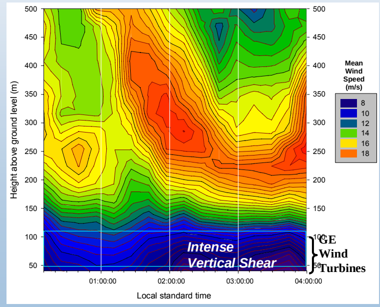
Evolution of Low-Level Jet at Lamar

Derived from SODAR Measurements
June 17, 2002

Wind Flow Vector



Wind Speed Contours



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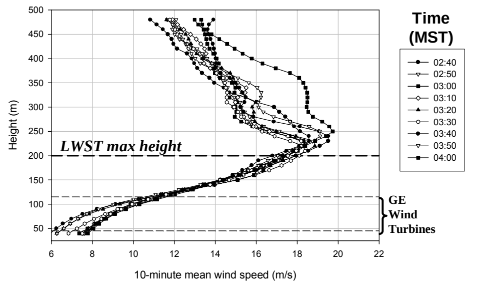
NREL National Renewable Energy Laboratory

Initial Conclusions from Lamar Measurements

SODAR Wind Profiles



- Low-level jets can significantly influence LWST turbine inflows
- Intense vertical shears can extend up to at least 200 m
- Intense shears can become unstable and create high levels of organized turbulence

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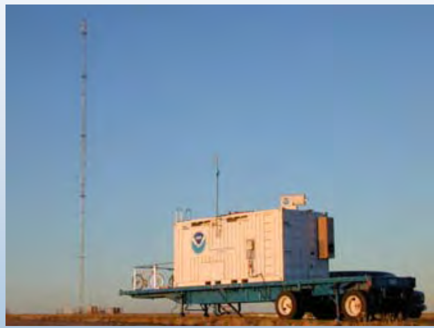
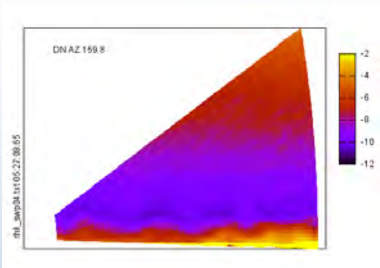
NREL National Renewable Energy Laboratory

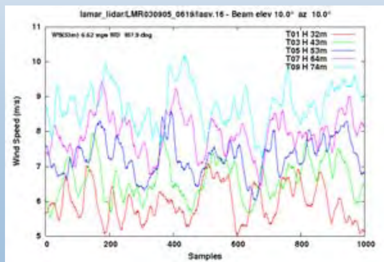
NREL Lamar Low Level Jet Project

- In cooperation with NOAA's Earth System Research Lab
- High Resolution Solid State Doppler Lidar (HRDL)

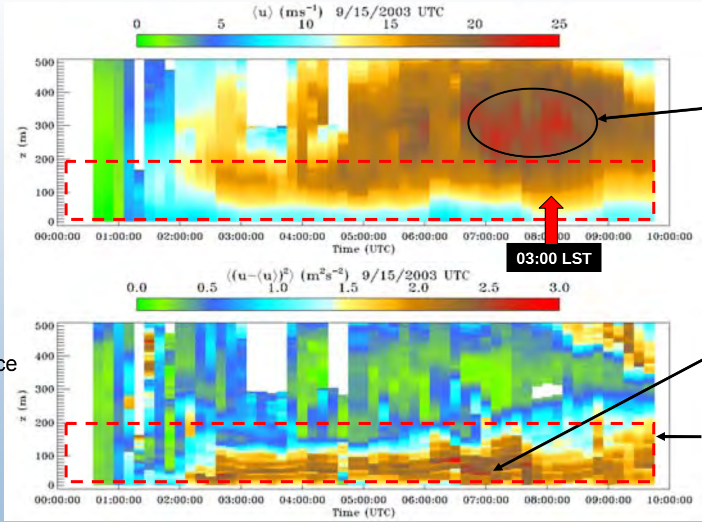


LLLJP Lidar Scans



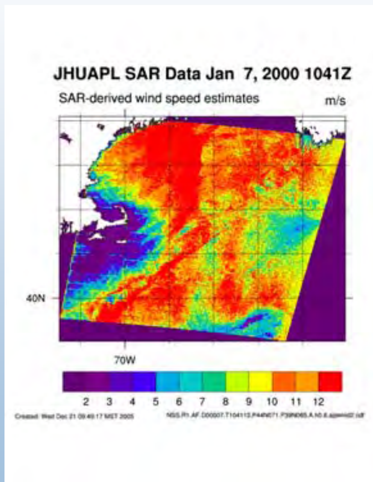


LIDAR Low-Level Jet Observations
15 Sept 2003



SAR – Synthetic Aperture Radar

- Example from E Coast US



nss_00007_104112.gif
DATE: 2000-01-07:1041
LAT: 39.028 to 44.098
LON: -71.477 to -65.038
LAT RANGE: 5.0699 deg
LON RANGE: 6.4385 deg
IMAGE ASPECT RATIO: 1.270:1
NX: 1000
NY: 1000
LAT CELL SIZE: 0.00507 deg
LON CELL SIZE: 0.00644 deg
CELL ASPECT RATIO: 1.270:1

•SAR Data courtesy of Nathaniel Winstead, Johns Hopkins University, Applied Physics Lab

Future Work

- Satellite wind data
  - Validation against buoy and other offshore data
  - Correlation with sea-surface temperature
- Lidar
  - Processing of Lamar Lidar data and correlation with tower measurements
  - Field Verification for Lidar-Based Turbulence Measurements at NWTC in cooperation with University of Colorado – CIRES

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Practical Experience with Remote Sensing

- A Consultancy Perspective

Risø, January 2006

Neil Douglas
The Natural Power Consultants Ltd.

natural power

Overview

- Background
- SODAR
- LIDAR
  - Logistics
  - Acceptance testing
  - Deployment procedures
  - Lessons learnt
- Future Work

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Background

- NPC are an established and experienced wind energy consultancy company
  - Wind Farm development, design/analysis, construction, operations and maintenance
- Experience with AQS 500 SODAR
- Manage 2 x Qinetiq ZephIR LIDAR and remote power packs

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Background

- Our drivers to use remote sensing:
  - Reduction of uncertainties in annual energy yield analyses
    - flow modelling on complex sites
    - To be used in addition to conventional cup anemometry
    - Shear across rotor
  - Rapid deployment for initial "look-see" and for short noise monitoring campaigns

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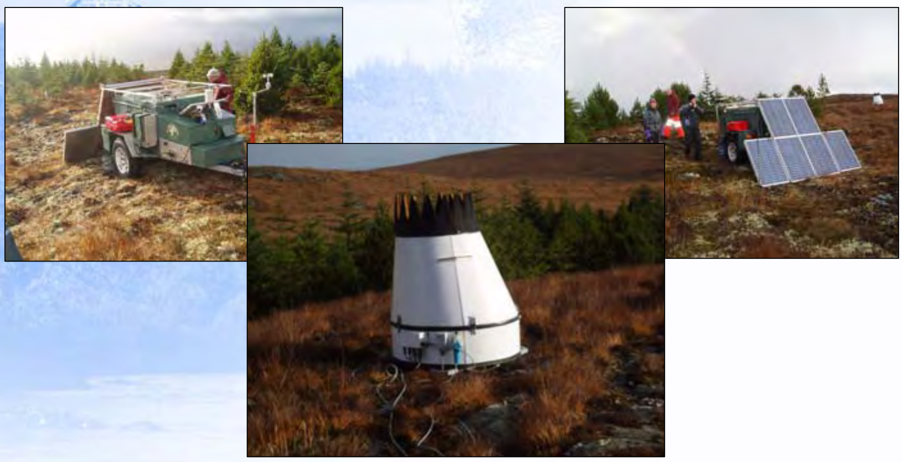
SODAR



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SODAR

- Initial “look-see” on a clients’ development site in Northern Scotland
- 4 month campaign
- 5 heights (30, 50, 70, 110, 140m)
- Data coverage was good (93% availability)
- Data quality was fit for purpose
- No on-site or off-site deployment testing or calibration

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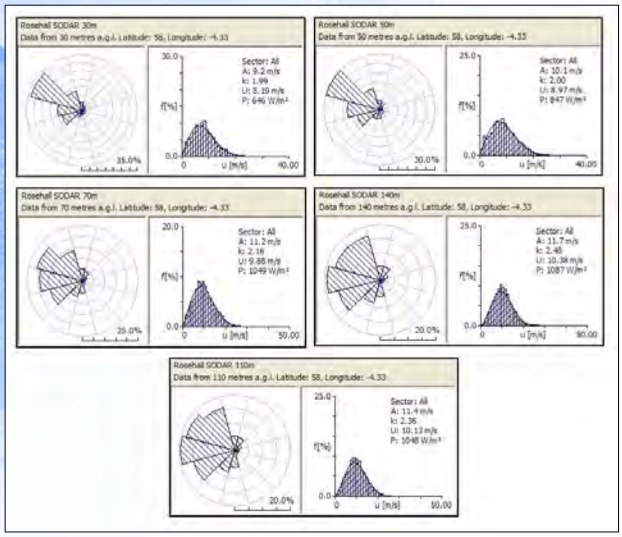
SODAR



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LIDAR

- 2 x Qinetiq ZephIR LIDAR since November 2005:
  - Deployment
  - Data collection and management
  - Acceptance testing
  - Deployment procedures

- Working closely with Oldbaum Services Ltd.

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Transportation logistics

- Trailer unit contains both LIDAR and power units
- Weights
  - – LIDAR pod 150kg
  - – Pod + box 880kg
  - – Power pack box 880kg
  - – Total with trailer 2300kg
- Can be towed by a 4x4 on firm level ground

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Complex site in Southern Norway….

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- Truck to close to site
- 2 lifts
  - LIDAR unit
  - Power unit
- Sensitive optics unit can be removed and carried up
- Small helicopter

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Contractual Acceptance Testing

- Contracted set of criteria for unit acceptance :
  - 2 week data period
  - R^2 value on wind speed correlations >0.96
  - Slope of wind speed correlation: $0.97<x<1.03$
  - RMS on wind direction difference $<5^o$
- Units were located adjacent to a 60m mast:
  - Calibrated instruments
  - Mounting in accordance with IEC Pt .11
  - Sited to minimise differences in wind between locations…

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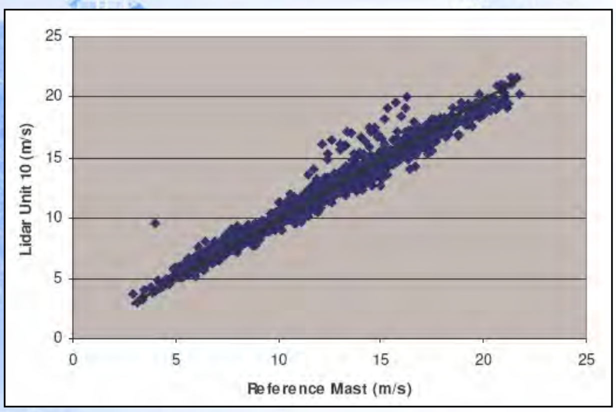
Sample Results

Acceptance test



- 2141 pts.
- 60m from mast

- $R^2 = 0.97$
- Slope = 0.99x
- Cloud correction ON

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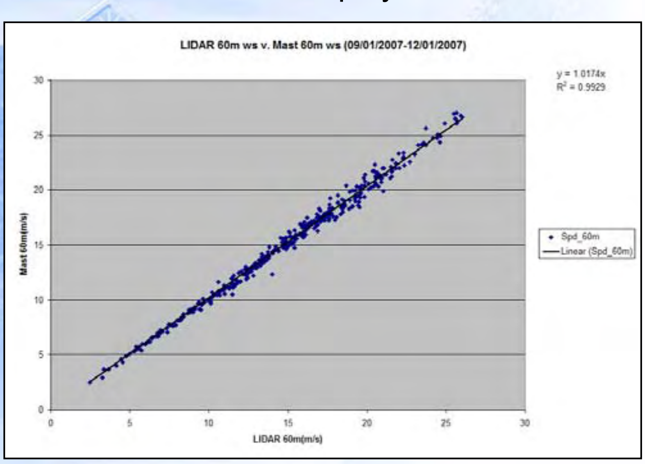
Sample Results

Deployment Verification



- Initial data
- 10m from mast
- $R^2 = 0.99$
- Slope = 0.1.02x
- Cloud correction ON

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Deployments to date

- Contractual acceptance tests
- Site in Southern Norway
  - For full yield analysis, in conjunction with conventional anemometry
- Site in Wales
  - For noise monitoring campaign
- Site in Scotland
  - For full yield analysis, in conjunction with conventional anemometry

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Deployment Verification Procedure

- Pre-deployment test against tall mast on-site
- Same criteria as acceptance test
- Test repeated at tall mast after other locations on-site have been monitored
- Report prepared to a standard format
- Raw data available for independent analysis

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Lessons Learnt

- High-tech side:
  - Steep learning curve in terms of operation and post-processing data
  - A few technical problems, early adopter teething
  - LIDAR units work reliably
- Low-tech-side problematic:
  - Remote power supply from 3rd party supplier
  - Cold weather power-pack operation

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Future Work

- Use in development sites:
  - To reduce uncertainty in flow and forest canopy models
- Inter-comparison study
- Turbulence measurements
- Improvements to remote power supply and logger programs
- Standards for deployment and data treatment
  - Focus on “Bankability” of RS data

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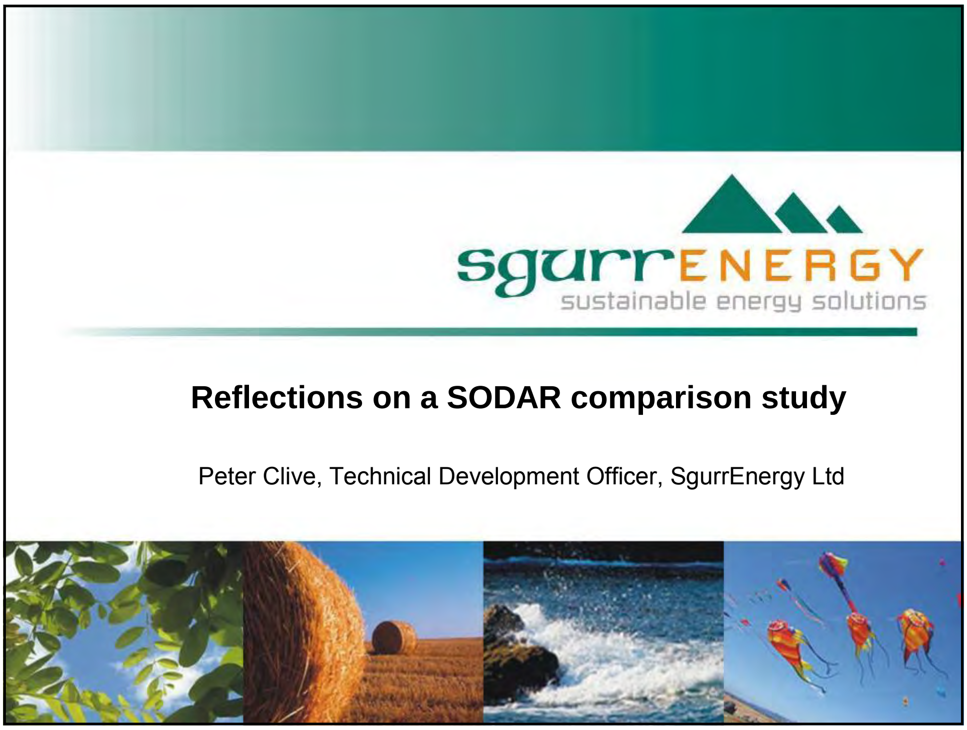
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Reflections on a SODAR comparison study
Peter Clive, Technical Development Officer, SgurrEnergy Ltd


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sustainable energy solutions
Geothermal
Offshore
SgurrEnergy Ltd is a leading independent consultancy based in Glasgow and Beijing specialising in renewables.
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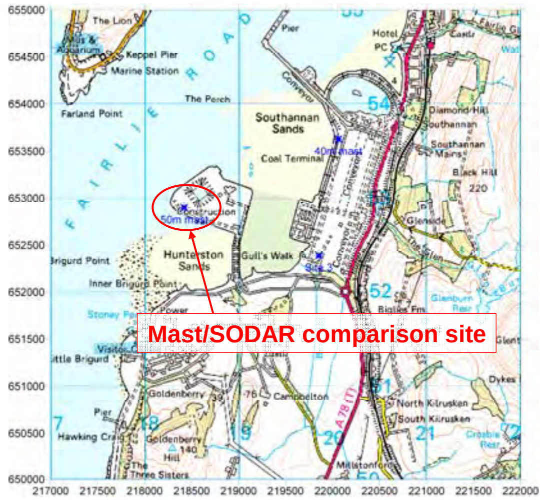

An AQ500 Mini-SODAR was compared with cup anemometry in 2004 at three locations in each of two different sites in Scotland.

The results were disappointing, and only the results from one location are presented here.

It should be stressed that the AQ500 has undergone significant further development since these results were obtained and has more recently been demonstrated to perform more satisfactorily. These results are presented here only to illustrated some more general points.

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Acceptance criteria

Figure 1 shows the following comparison statistics

- Bias, comparability and precision
- Slope, offset and correlation associated with linear regression
- Availability

These are plotted against the signal to noise ratio (SNR) threshold below which data were rejected when compiling these statistics. The statistics can be used to select a SNR threshold to act as a data acceptance criterion, or the statistics themselves can be explicitly used in formulating acceptance criteria.

Key issues:
- the availability that results must be such that the data is representative of the wind regime being assessed
- a set of guidelines or recommendations regarding acceptance criteria is desirable

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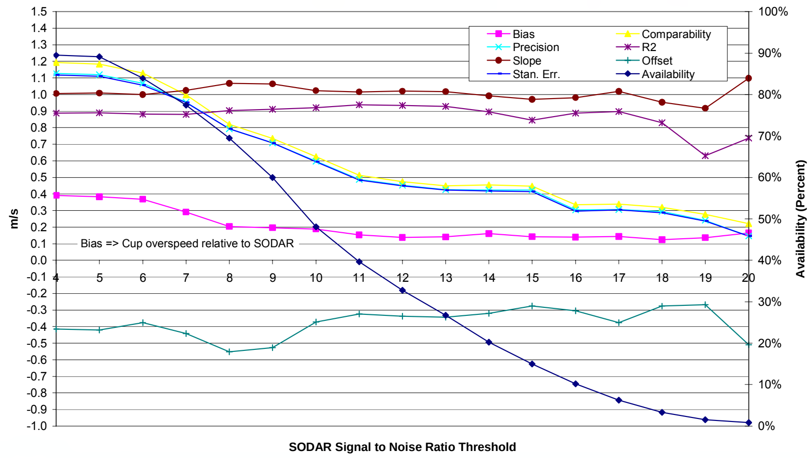
Figure 1: SODAR Comparison Study: NAC 50m Mast, 50m NW Cup Anemometer



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Wind speed and SNR

Figure 2 shows the wind speed measured by the SODAR plotted against the wind speed measured by the cup anemometer. The SNR associated with each data point is colour coded as described in the legend.

It is clear that lower SNRs occur at higher wind speeds, as has been noted elsewhere. It was speculated that this might provide a mechanism for SODAR overspeed relative to cup anemometry. If noise is not handled appropriately during the accumulation of the Doppler spectrum from which the radial velocity is calculated by adding instantaneous Doppler spectra, a pedestal of noise might cause the over representation of SODAR returns associated with higher wind speeds.

If this is the case it will be apparent from the skewness of the Doppler spectra.

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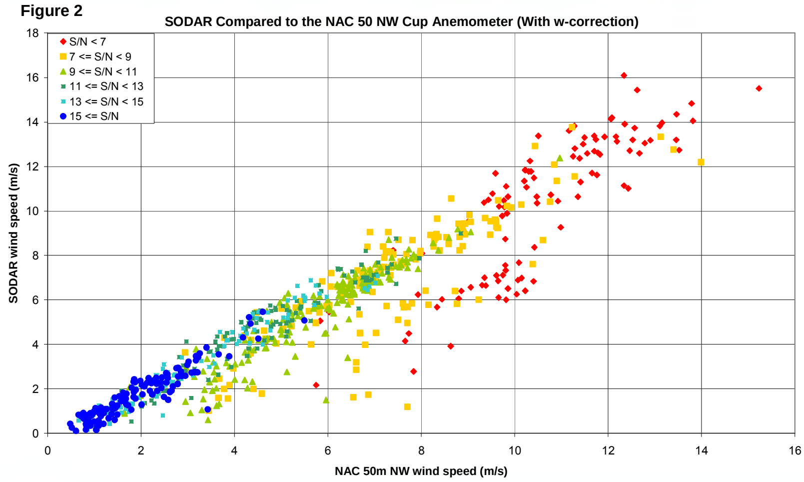
Figure 2



Vector vs. Scalar averages

It was observed that although cup anemometers and indeed wind turbines respond in a way that can be characterised by scalar averaged wind speeds $\mathbf{v}_s$, remote sensing devices such as SODAR and LIDAR give results derived from vector averages $\mathbf{v}_v$.

An analytical result describing the ratio of the vector to scalar averaged wind speed ($\mathbf{v}_v / \mathbf{v}_s$) that would be obtained for a distribution of wind directions was obtained. This result holds for a constant wind speed and uniform wind direction distribution of standard deviation σ and is shown in figure 3. These approximations were considered reasonable for deriving a simple analytical result (Bessel function) for 10 minute averages. This result should be compared to empirical results obtained elsewhere for this ratio.

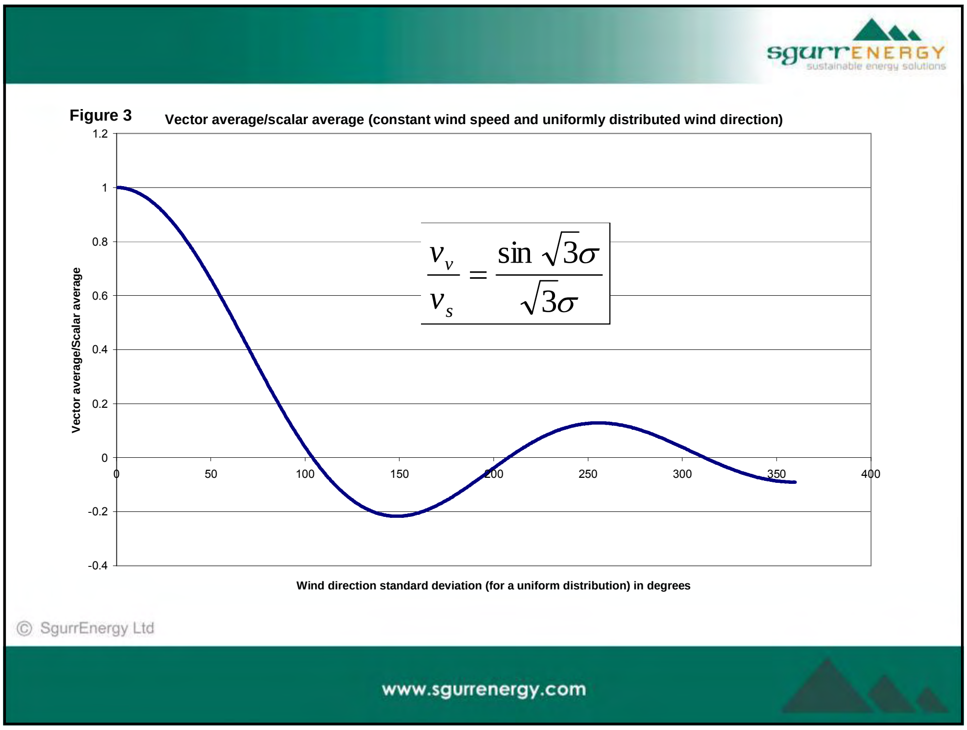


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Figure 3
Vector average/scalar average (constant wind speed and uniformly distributed wind direction)
Vector average/Scalar average
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
50
100
150
200
250
300
350
400
$\frac{v_v}{v_s} = \frac{\sin\sqrt{3}\sigma}{\sqrt{3}\sigma}$
Wind direction standard deviation (for a uniform distribution) in degrees
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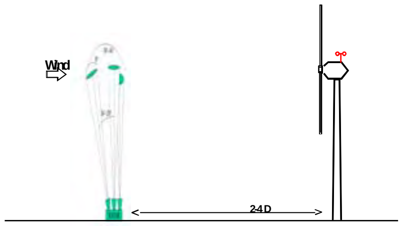
Wind measurements in flat terrain and offshore using sodars

Ioannis Antoniou, Hans E. Jørgensen
Dept. of Wind Energy Risø



www.risoe.dk

Contents of the presentation

- Experience from previous measurement campaigns:
- The PIE experiment (Profiler Inter-comparison Experiment) within the WISE project (WInd energy Sodar Evaluation)
- Qualitative offshore measurements using sodars and lidars from the Nysted wind farm.
- Lidar/Sodar work planned within the UPWIND EU project.
- Conclusions / Recommendations.

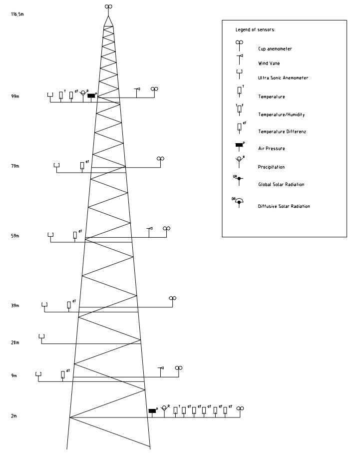
PIE: The sodars examined (1)

- Three phased array sodars have been tested:
  - AeroVironment 4000 (Risoe)
    - 3000 enclosure, 50 element array, operating frequency at 4500Hz, height resolution of 10m
  - Metek PCS2000-64 Sodar with RASS Extension (1290 MHz), University of Salford
    - 64 element array, acoustic operating frequencies: 1674 Hz for Sodar, (2950 +-50) Hz for RASS, height resolution of 15m
  - Scintec SFAS (Windtest)
    - a 64 element array, and a choice of 10 out of a total of 64 selectable frequencies in the range between 2540 to 4850 Hz, height resolution of 5m

PIE: The site (1)

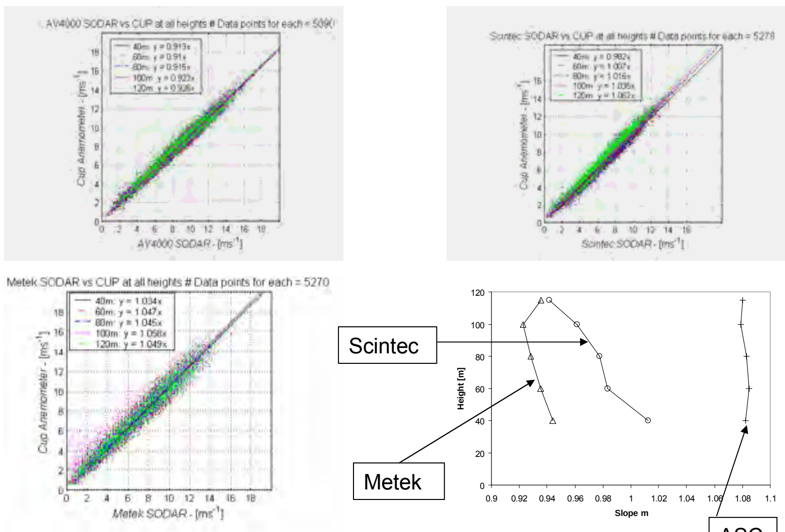
- The three sodars were deployed at the National Danish Test Station for Large Wind Turbines
- Measurements commenced primo April and ended the 20th of June 2004

PIE: The instrumentation of the met mast



Sensor	Position
Cup anemometer	116.5m
Cup anemometer, wind vane, sonic anemometer, temperature, differential temperature, relative humidity, air pressure	100m
Cup anemometer, sonic anemometer, differential temperature	80m
Cup anemometer, sonic anemometer, differential temperature, wind vane	60m
Cup anemometer, sonic anemometer, differential temperature	40m
Sonic anemometer	20m
Cup anemometer, sonic anemometer, differential temperature, wind vane	10m
Cup anemometer, temperature, differential temperature, relative humidity, air pressure, rain	2m

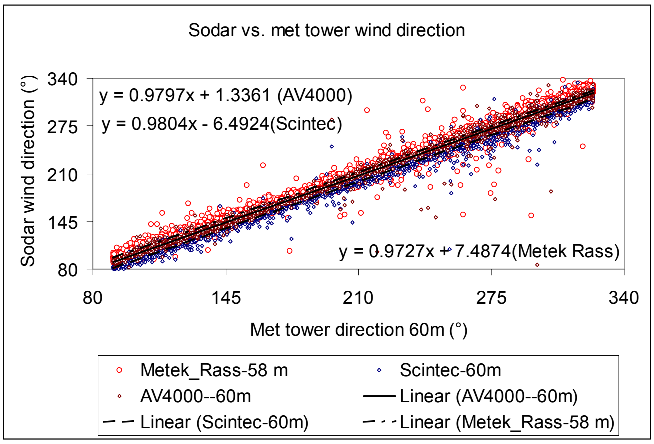
PIE: Sodar vs. cup wind speed at different heights



DTU

RISØ

PIE: The wind direction



DTU

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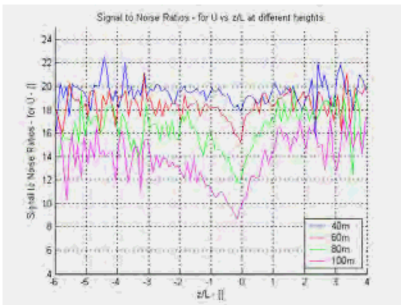
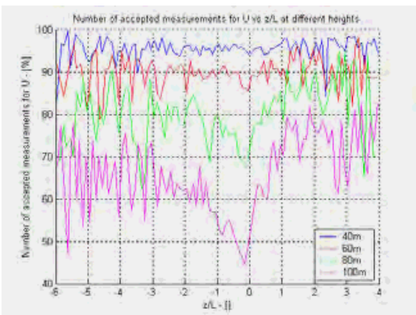
Factors influencing the sodar response

- Fixed echoes
- Atmospheric stability
- Losses due to absorption
- Scattering from turbulence
- Doppler shift from wind and turbulence
- Scattering from rain and other precipitation
- Background and system noise

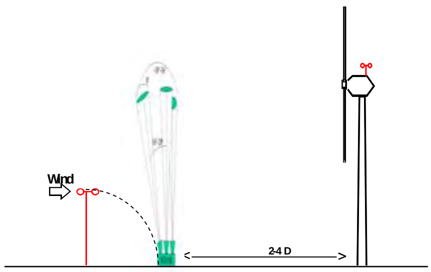


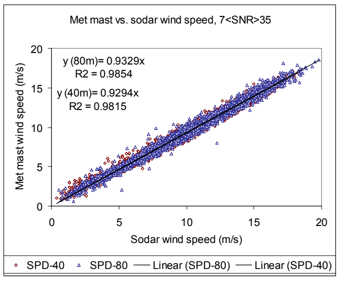


Relative calibration of the sodar

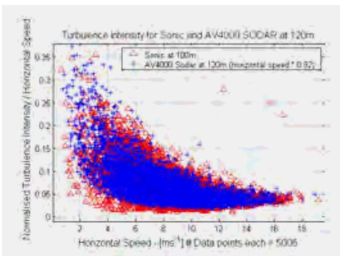
- Calibrate the sodar against the met mast:
- Use the relation sodar=f(cup) at hub height.

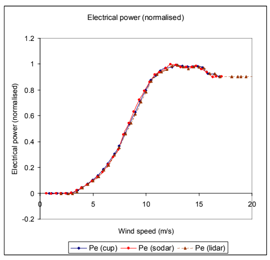
- Filtering of the data (SNR, remove of outliers using the met mast data,...)
- Uncertainty analysis of the sodar wind speed measurements made with the help of the cup anemometer data.

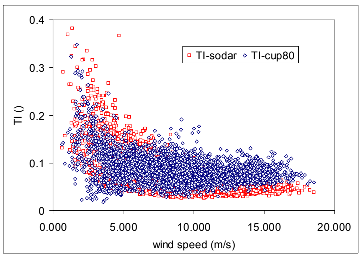




Measurement of turbulent quantities and power curve

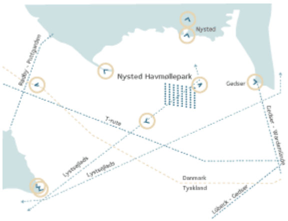


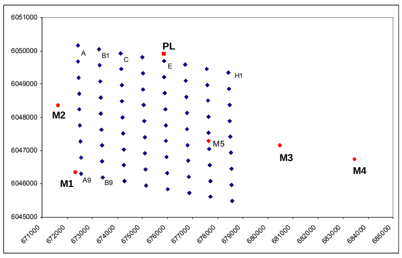




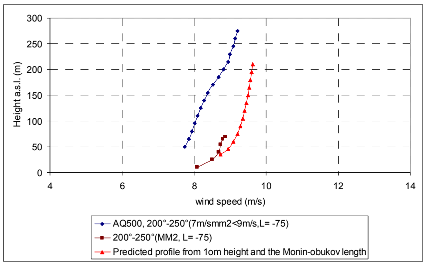
	cup anemometer		sodar	
[m/s]	AEP measured	Uncertainty AEP measured	AEP measured	Uncertainty AEP measured
4	1747	192	1799	249
5	3263	264	3310	345
6	4940	312	4977	407
7	6509	334	6536	436
8	7780	339	7798	440
9	8667	332	8679	429
10	9174	319	9181	409
11	9362	301	9365	385

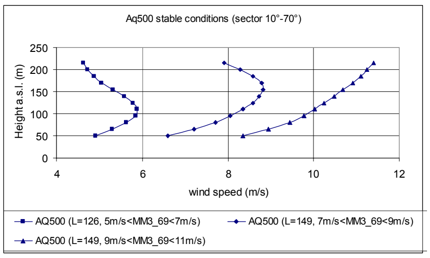
Offshore measurements, Nysted wind farm

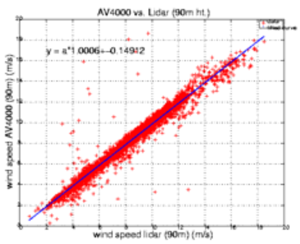


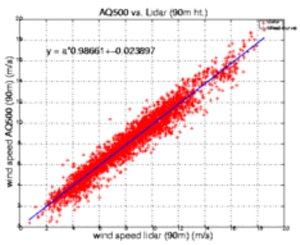


Offshore measurements, Nysted wind farm









The present work

- UPWIND WP6 (Remote sensing) EU-project:
  - What do lidars and sodars measure?
  - Calibration work for both lidars and sodars.
  - Measure with lidars and sodars in flat and complex terrain.
  - Placement of a lidar on the nacelle and measurement of the oncoming wind speed. Can the lidar be used for the turbine control?
  - Power curve measurements using a lidar and a sodar.
  - Work to introduce remote sensing in the standards.
- Improved performance methods (Danish funding):
- Measuring the performance of the wind turbine as a function of the wind speed over the whole turbine rotor.

Using the sodar for wind energy applications.

- Distinguish sodars (monostatic, bistatic, phased array or parabola dish sodars)
- Describe the measurand.
- Develop calibration procedure (until then rules for a relative calibration against a cup should be used).
- An uncertainty analysis for the measurement needs to be introduced.
- Rules for deploying the instruments.
- Rules for storing and handling.

Suggested actions

- A remote sensing forum for sodars and lidars is needed (either a common one for both or one for each family).
- We can individually continue to write papers but there is really...
- Need for cooperation among the people involved to collect the existing knowledge from wind energy applications of sodars and lidars and compile recommendations on:
  - **"Wind speed measurements and use of lidars".**
  - **"Wind speed measurements and use of sodars".**

ECN

Energy research Centre of the Netherlands

KNMI

LOFAR

Wide area wind speed measuring network

A LOFAR meteorology application

Arno J. Brand (ECN)
Iwan Holleman (KNMI)
Joris van Enst (LOFAR)

www.ecn.nl

ECN KNMI LOFAR

Outline

- Weather forecasting brush-up
- Wide area wind speed measuring network
- LOFAR

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Weather forecasting brush-up

- Weather forecasting ingredients
- Enhancing weather forecasts
- High-resolution wind energy forecasts

Weather forecasting ingredients

Actual meteo signals — Sensors

Assimilation

Weather prediction model — Network Processor Distribution

Expected meteo signals

Enhancing weather forecasts

Actual meteo signals ← **Sensors**

Assimilation

Weather prediction model ← Network Processor Distribution

↓

Expected meteo signals

High resolution wind energy forecasting

- Research project (proposed)
- We@Sea programme
- 2007 - 2009
- Work packages:
  - **Meteorological observations**
  - Numerical weather prediction
  - Wind energy forecasts

Meteorological observations

Wide area wind speed measuring network

- European weather radar network
- Optimal use of in-situ observations
- Network of wind measuring wind turbines

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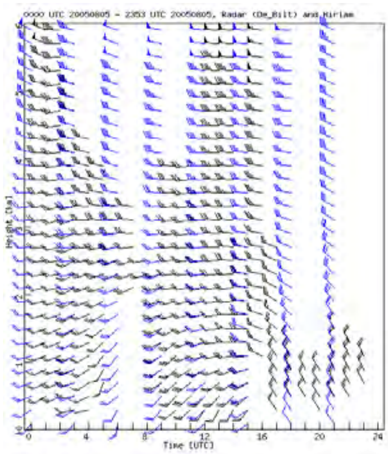
Wide area wind speed measuring network

European weather radar network



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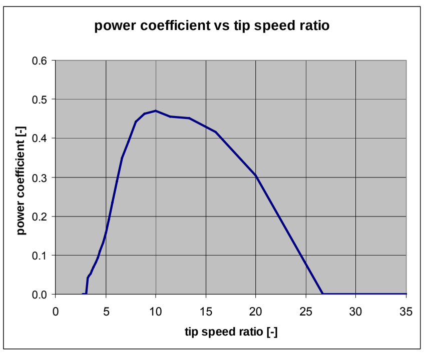
Optimal use of in-situ observations

ECN KNMI LOFAR Wide area wind speed measuring network

Network of wind measuring wind turbines



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ECN KNMI LOFAR Wide area wind speed measuring network

Technical challenges

- Homogeneity of wind data
- Check/conversion of weather radar data
- Interpretation of wind turbine data

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LOFAR

- Research facility
- Applications
- Meteorological applications

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Research facility

- Interferometric array radio telescope
  - Across NL and northern GE
  - Antennas: 15000 → 25000
  - Baseline: 100 km → 350 km
- Central processor
- Data transport network

ECN KNMI LOFAR LOFAR

Applications

- Astronomy
- Geophysics
- Agriculture
- **Meteorology**

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Meteorological applications

- Severe weather warnings
- Air quality and (chemical) incidents
- **High-resolution wind energy forecasting**

Validation of SODAR properties

Kurt S. Hansen
ksh@mek.dtu.dk

Fluid Mechanics Section, MEK
Technical University of Denmark

Outline

- Introduction
- Objectives
- Participants and funding
- System setup (SODAR,power supp., mast, eqipment)
- Data transmission
- Sensitivity/limitations
- Results and findings
- Conclusion
- Recommendations
- References

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Technical University of Denmark

Introduction

Modern wind turbines have reached a size that makes hub height wind speed measurements rather expensive. The cost of masts increases rapidly with height (distinctly more than linearly) and their installation is subject to a (often) lengthy authorization procedure.
A ground-based SODAR (Sonic detection and ranging) is able to measure at many levels simultaneously and is economically competitive with other forms of measurements.

Objectives

- The main objectives has been to optimize the SODAR availability and the quality of the SODAR readings.
- Based on the SODAR readings the reliability, accuracy, limits and limitations of the SODAR have been determined.
- A validation program with a SODAR has been performed for 1½ years at a remote location without any access to an electricity grid.
- The program will study whether the SODAR wind measurements are accurate enough for wind power assessment and whether the SODAR is applicable as a stand-alone instrument or as a “profiler” in combination with reference instruments on a 30-50m tower.

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Technical University of Denmark

Participants and funding

- ELSAM Engineering, DK
- MEK, DTU, DK
- METSUPPORT ApS, DK (closed)
- METEK GbmH, DE
- HRAFNKEL SARL, F (wind ressource meas.)

Elsam

metsupport aps

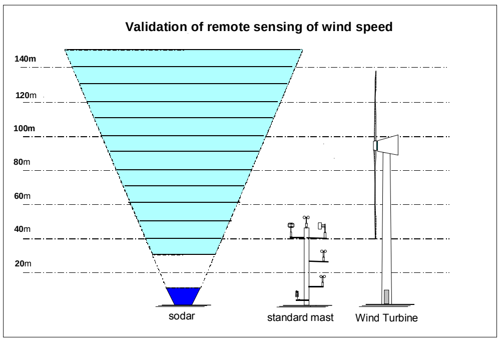
HRAFNKEL SARL (F)

Acknowledgement:
This project was been initiated and funded by ELSAM Kraft A/S, Fredericia, Denmark

Remote setup without grid: challenges

- Establish remote power supply for 120W
- GSM, data transfer from a remote location
- Mounting and system protection
- Automatic, remote controlled operation
- Data quality control and qualification
- Data visualisation
- Data analysis
- Technology transfer and education
- New partners!

System setup (in France)



SODAR setup: Δh= 10 & 20 m, max(h)=150 m

<u>Equipment:</u>
- METEK SODAR (low power)
- 50 m mast
- 3 cups (h=16,31,50m)
- 1 vane (h=47m)
- 3-D METEK sonic (h=47m)
- Temp+pressure

<u>The test site:</u> is located in the eastern part of France, in a farmland with an open appearance and with a moderate complexity in terms of hill effects in the northern direction.

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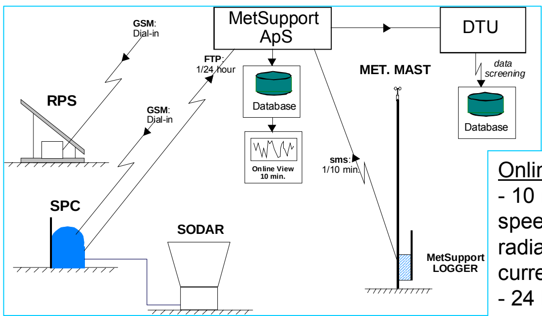
Technical University of Denmark

System setup (in France)

Remote system access
and automatic data transfer



<u>Online graphics</u>:
- 10 min. mean values (SMS): speeds, directions, temps, radiation, battery voltage & current
- 24 hours reduced SODAR measurements (ftp)

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Technical University of Denmark

Installation


Instruments: SODAR,cup anemometer, wind vane and 3-D sonics

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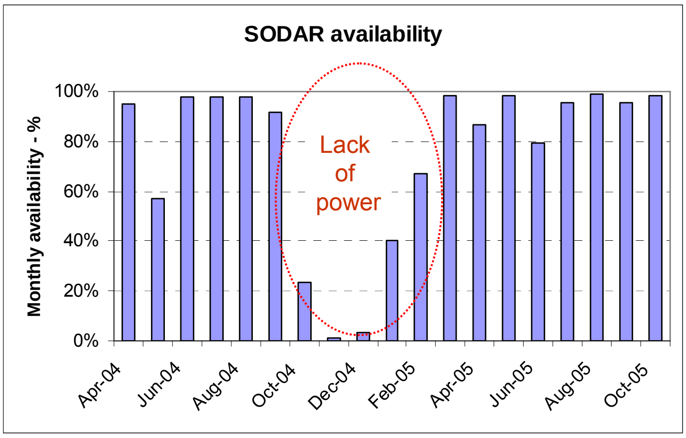
Operational results



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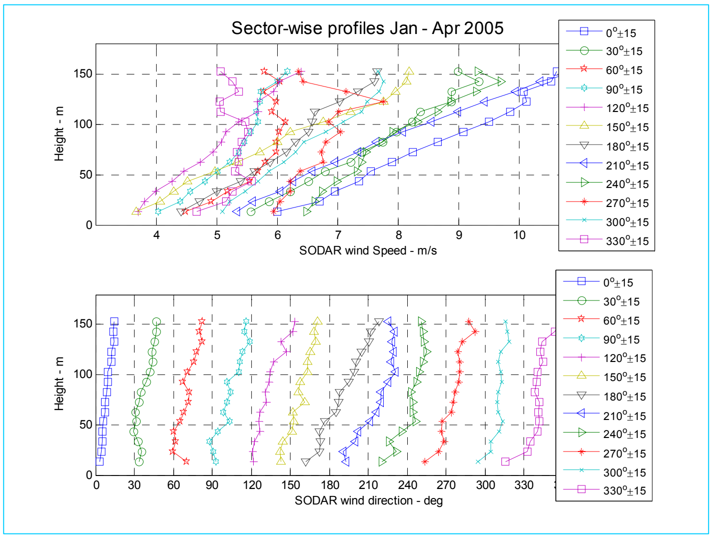

Mean wind direction change (h=50-150) > 40 deg!

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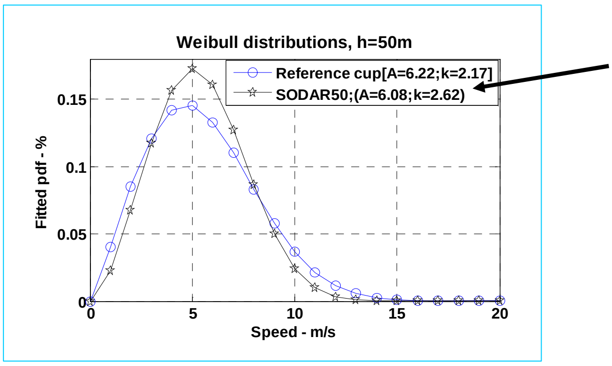
Wind speed distributions



Lack of high wind speeds, results in a very high Weibull shape factors (k)!

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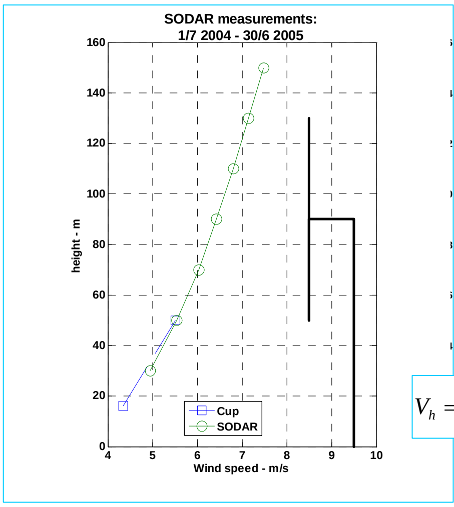
Annual mean wind speed profile



$$V_h = 5.53 \times \left(\frac{h}{50}\right)^{0.25}$$

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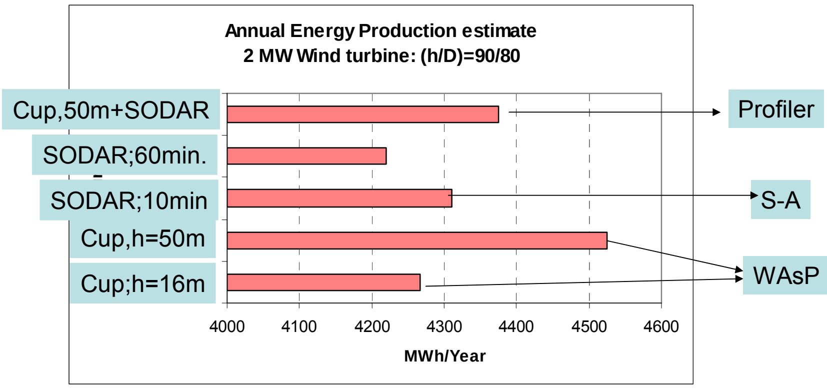
Annual Energy Production



The profiler operation results in realistic AEP values - compared to the cup estimates.
The stand-alone AEP is lower (2%) due to an un-realistic Weibull shape factor (k>2.60).

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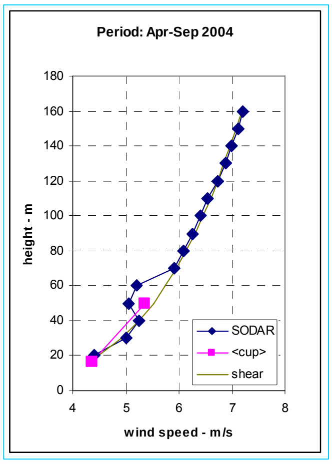
Problem: Fixed echo at level 50-60 m



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Findings

1. Recommended distance between SODAR and obstacle should be larger than the height of the obstacle to eliminate fixed echo problems.
2. Increased height resolution (>10 m) will increase the signal availability at all heights.
3. Selecting a proper signal screening and an averaging procedure are very important.
4. The lack of measurements, at low wind speeds and low turbulence, is not critical for the wind speed power density distribution.
5. The lack of high wind measurements is important for the wind speed distribution, this causes an increased Weibull shape factor (k) and a decreased power density value.
6. The lack of wind speed measurements during heavy rain is assumed to be randomly distributed and it therefore does not influence the estimated wind speed power density distribution significantly.

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Conclusion on wind resources - I

A SODAR has been tested in pastoral terrain with low to moderate turbulence and a limited amount of precipitation, suitable for a potential wind turbine installation site in the Eastern part of France.

Performing complete long-term resource measurements is costly especially with a SODAR since such a complicated system (power supply unit, reference instrumentation and SODAR) requires a high level of operational supervision.

The operation during the latest period (Aug-Oct 2005) has given acceptable system reliability and resulted in a high SODAR signal quality.

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Conclusion on wind resources - II

Based on the experience obtained during 1½ years of operation, it is obvious to limit the SODAR operation to a short-term profiler, since the SODAR is unable to measure high wind speeds (>15m/s) and this influences the wind speed distribution.

The benefit of short-term profiler measurements combined with long-term mast measurements is much higher and the output is sufficiently robust to be used in wind resource assessment.

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Conclusion on wind conditions

The SODAR can measure 10-minute maximum wind shear Values, wind shear distributions and maximum wind direction changes.

The SODAR combined with a 3-sonic anemopmeter can be used to estimate both vertical and horizontal turbulence at all heights levels – but be carefull!

Recommendation for PROFILER OPERATION

Operating the SODAR as a short-term profiler in combination with an anemometer at low height requires a [short] periods with wind measurements in representative sectors and stratifications.
The sector-wise shear values are used to adjust the log-term cup readings hub height.

Recommendation for STAND-ALONE OPERATION

Stand-alone operation for wind resource measurements with the SODAR is possible and costly, but the quality of the SODAR measurements is reduced during three specific situations:

i) low turbulence,
ii) at high wind speeds and
iii) precipitation.

Fluid Mechanics Section, MEK
Technical University of Denmark

References

- VALIDATION OF THE SODAR PROPERTIES
  ELSAM: VU106, June 2006, MEK-FM-2006-01
- VALIDATION OF SODAR MEASUREMENTS FOR WIND POWER ASSESSMENT; Presented at EWEC 2006, Athens 27 February – 2 March 2006

Fluid Mechanics Section, MEK
Technical University of Denmark

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I) Chances and limitations of measuring wind and turbulence profiles by acoustic remote sensing

II) Offshore wind and turbulence data

Stefan Emeis, Inst. for Meteorology and Climate Research,
Dept. Atmospheric Environmental Research (IMK-IFU)
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Garmisch-Partenkirchen, Germany

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I) Chances and limitations of measuring wind and turbulence profiles by acoustic remote sensing

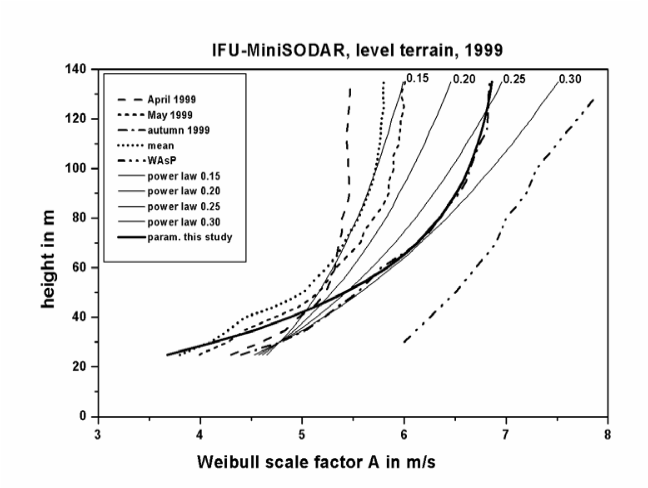
Chances
(of profile measurements in general)

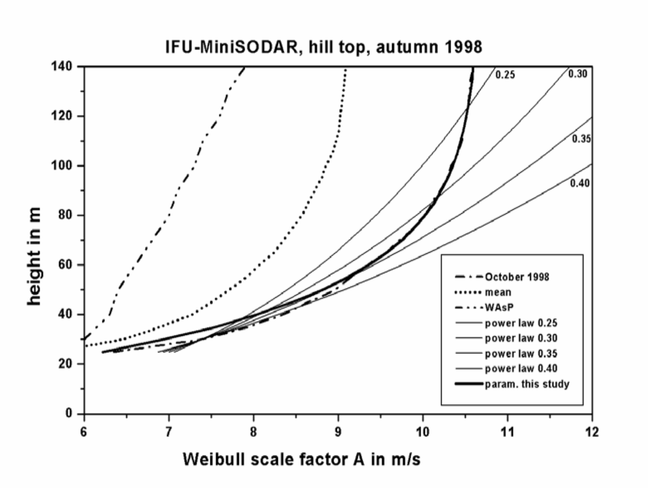
Results from the EU-project WISE

Funded by the European Union under Grant NNE5-2001-297
(partners: ECN, Risø, Univ. of Salford, IMK-IFU, DEWI, Windtest-KWK, CRES)

SODAR measurements against standard vertical extrapolations

wind speed (scale factor of Weibull distribution)





(Emeis 2001)

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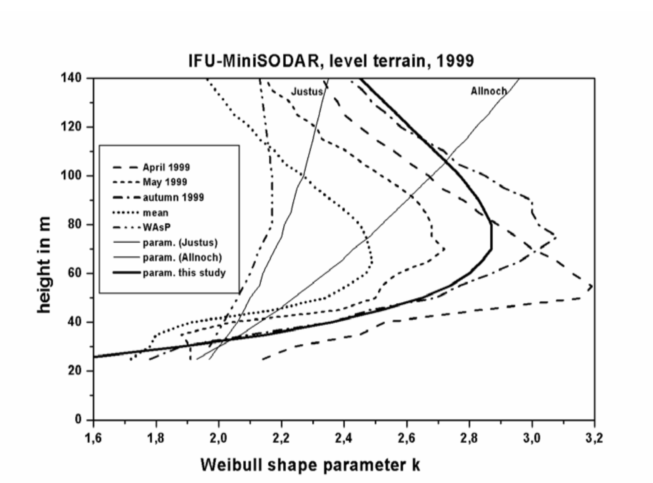
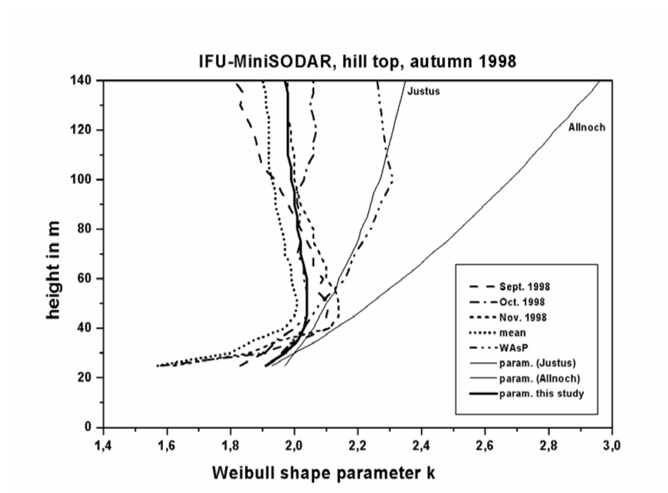
SODAR measurements against standard vertical extrapolations

wind variance (shape factor of Weibull distribution)

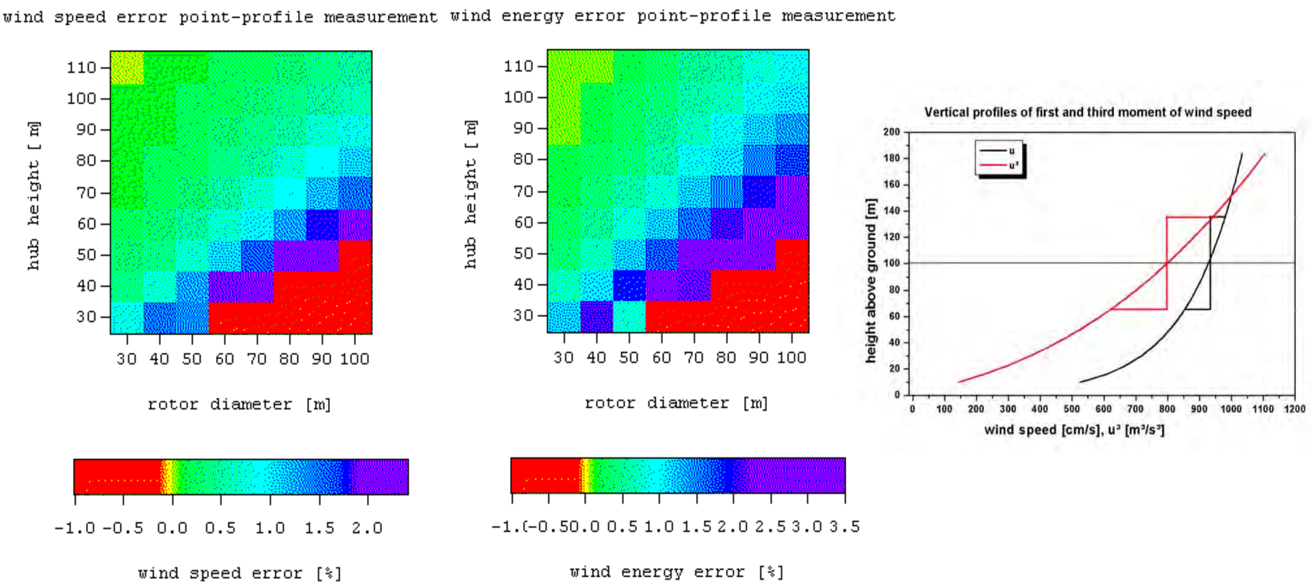




(Emeis 2001)

Differences between point and SODAR (profile) measurements

rotor plane mean wind speed and energy output



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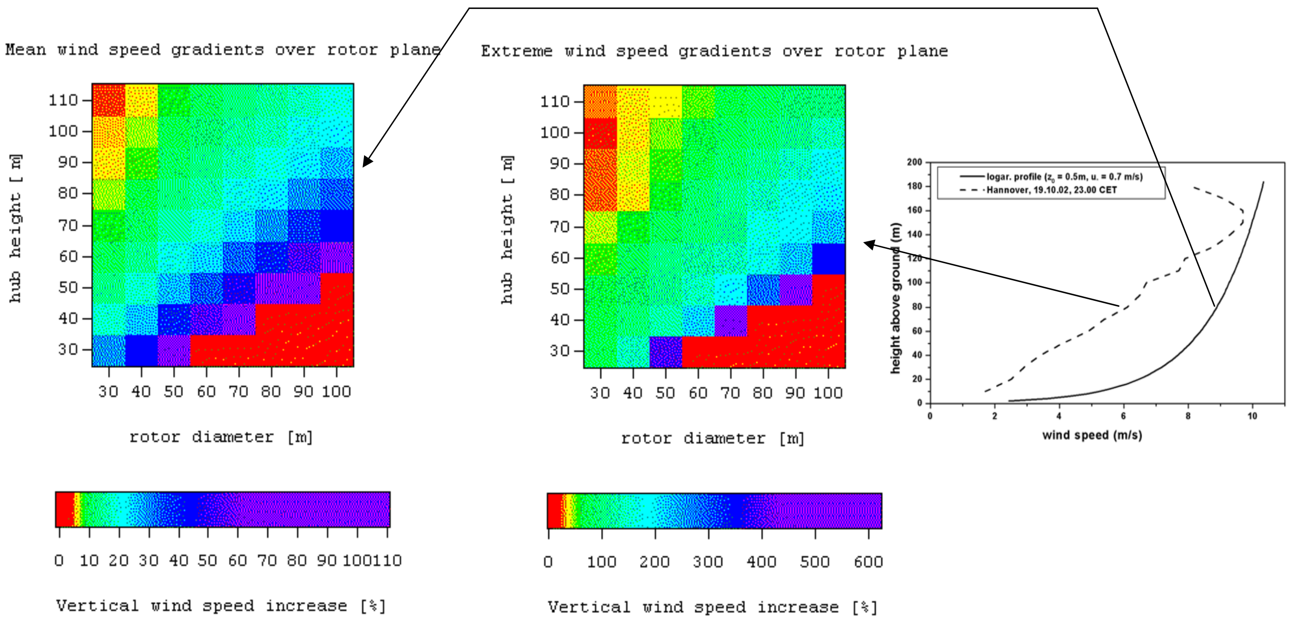
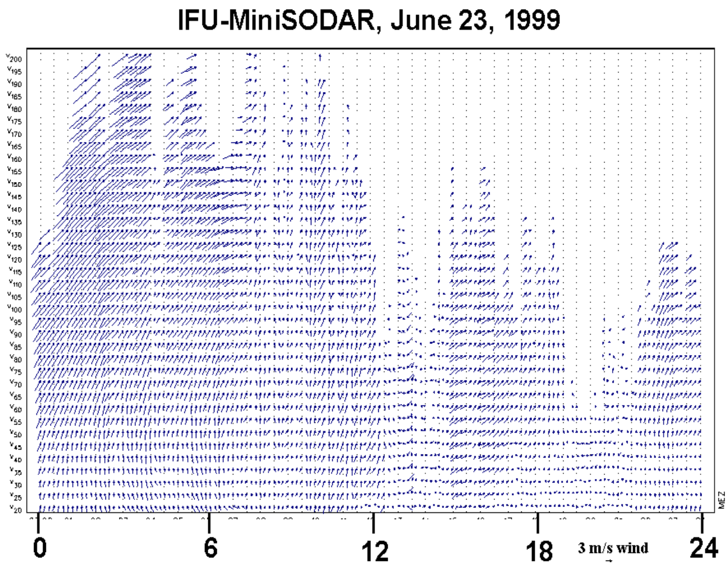
Differences between point and SODAR (profile) measurements

vertical wind speed increase over rotor plane



Turning of wind direction from SODAR measurements



Observed turning of winds (extreme case)

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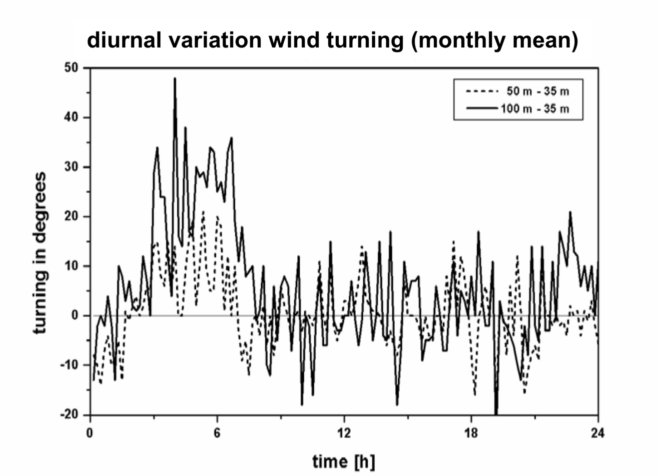
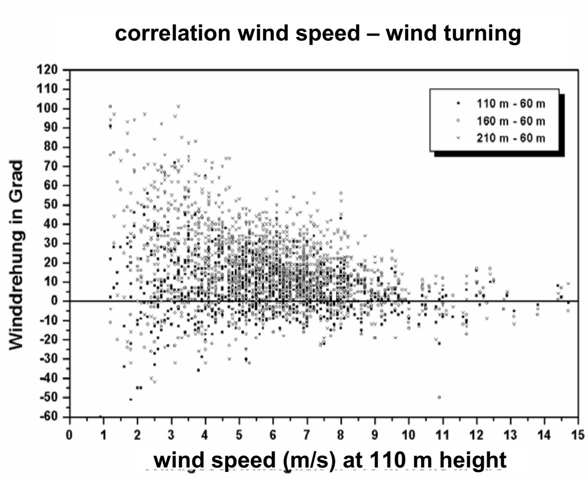
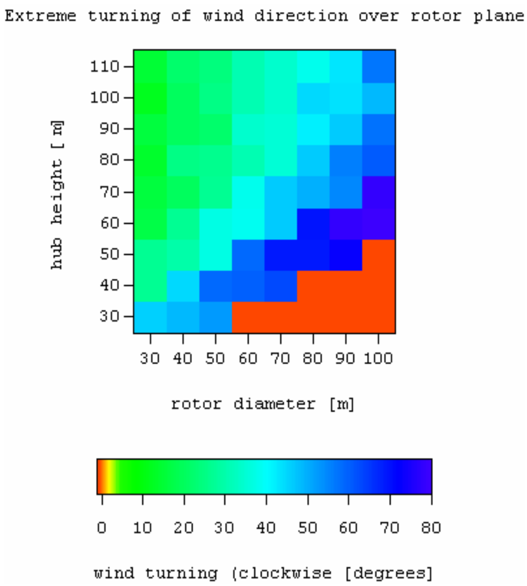
Turning of wind direction from SODAR measurements





Observed turning of winds

Turning of wind direction from SODAR measurements



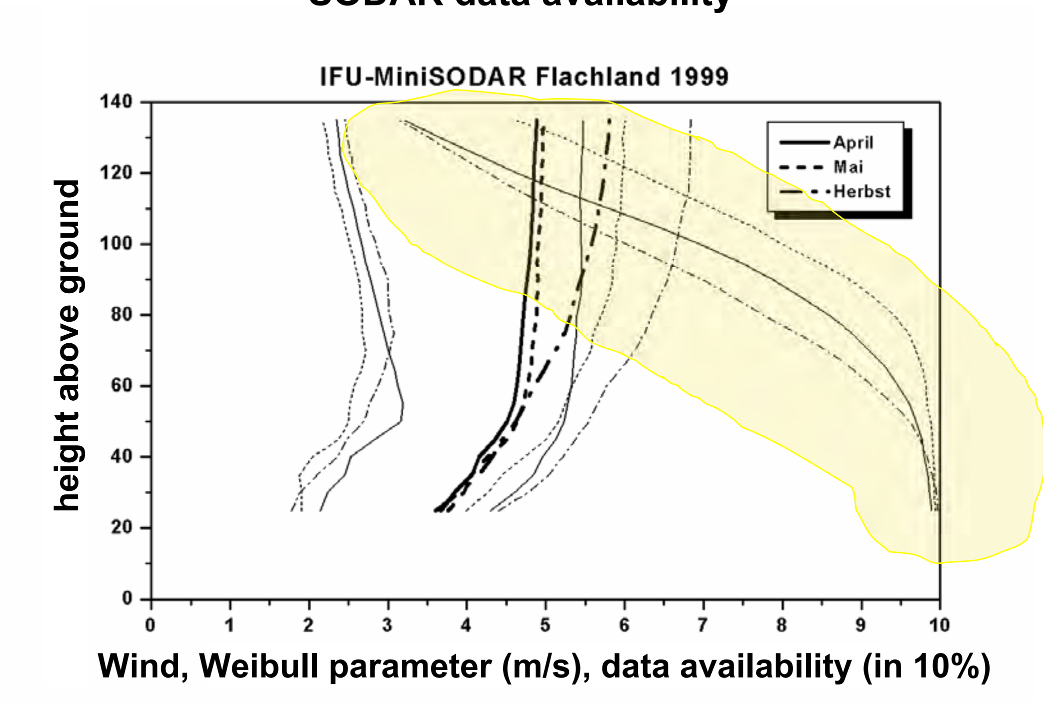
I) Chances and limitations of measuring wind and turbulence profiles by acoustic remote sensing

Limitations
(especially for acoustic remote sensing)

Results from the EU-project WISE

Funded by the European Union under Grant NNE5-2001-297
(partners: ECN, Risø, Univ. of Salford, IMK-IFU, DEWI, Windtest-KWK, CRES)

SODAR data availability



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Circumstances that cause unreliable SODAR data

- a) well-mixed boundary layer in the late afternoon
- b) rain, snow
- c) very strong winds
- d) external noise
- e) fixed echos

Filtering techniques to detect and handle unreliable data

- a) SNR too low (high sigma w)
- b) high backscatter, negative vertical velocity
- c) SNR too low, high background noise level
- d) SNR too low, high background noise level
- e) high backscatter, wind speed too low

Operational parameter under which SODARs deliver reliable data

calm place, no obstacles, no precipitation, not too strong winds

II) Offshore wind and turbulence data

This data is presented here as possible evaluation data for satellite offshore wind mappings

Results from FINO1-measurements (running since Sept. 2003) in the German Bight 45 km off the coast

Funded by the German Ministry for the Environment (BMU) under Grant 0329961 (project: OWID, partners: IMK-IFU, DEWI, DEWI-OCC, GE Wind, Multibrid, Repower, Enercon)

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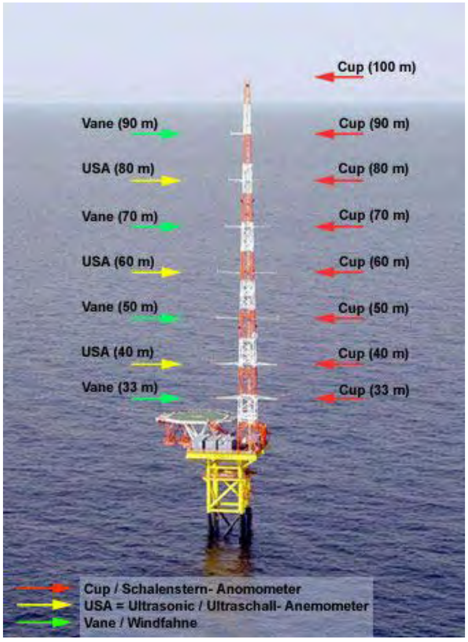
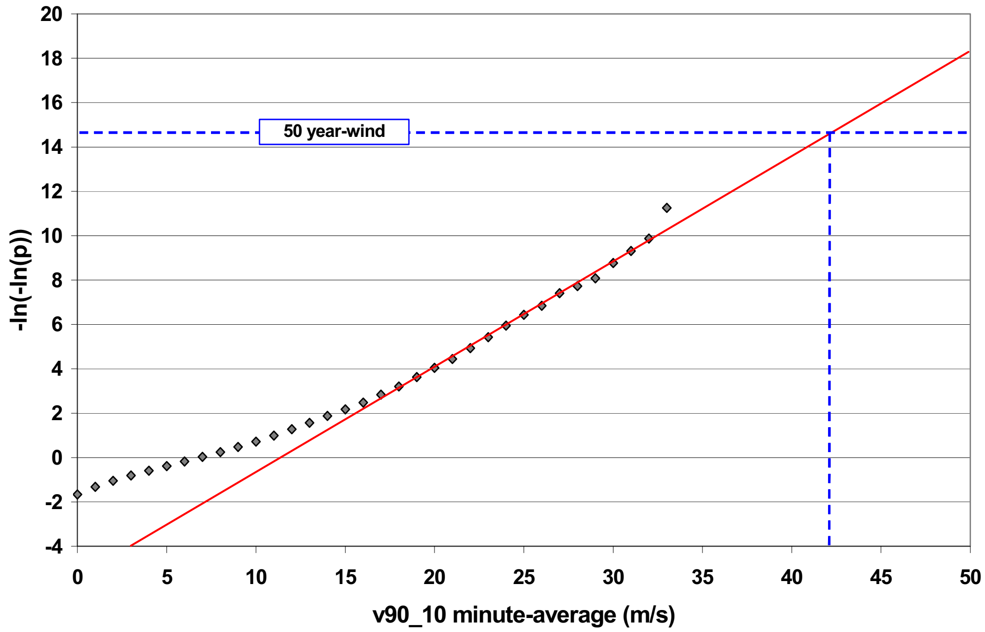
FINO1 research plattform

- **Measuring of wind components from 33 to 100m**
- **Monitoring of all standard meteorological parameters**
- **Measuring of structural loads**
- **Oceanographic measurements**
- **Biological measurements**
- **Located 45km north of the island of Borkum**

⇒ Long running measurements since September 2003



Extrapolation of the 50-year mean wind speed at FINO1 [p: cumulative frequency of 10-minute averages]



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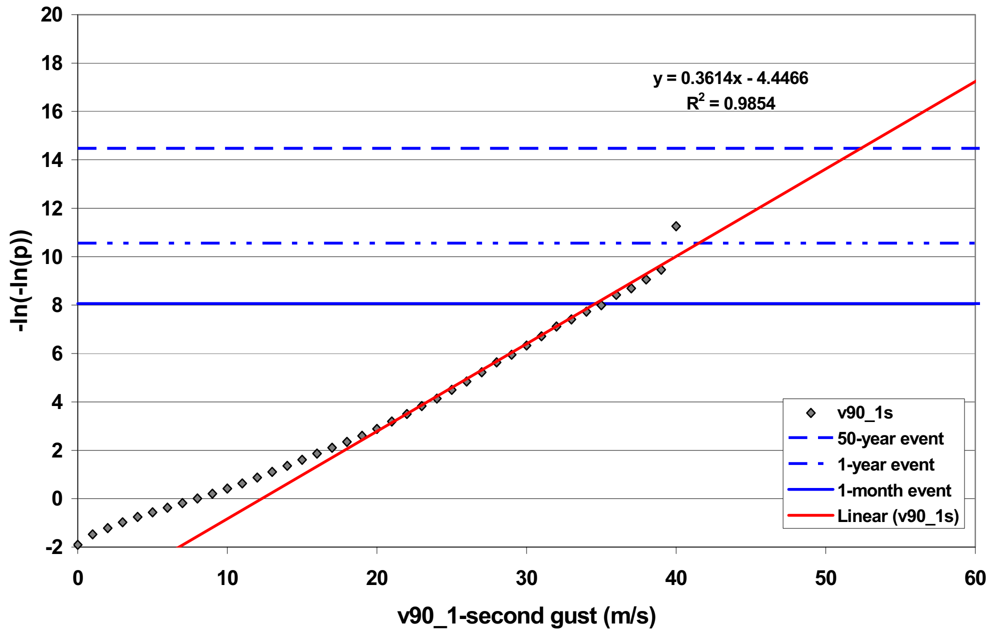
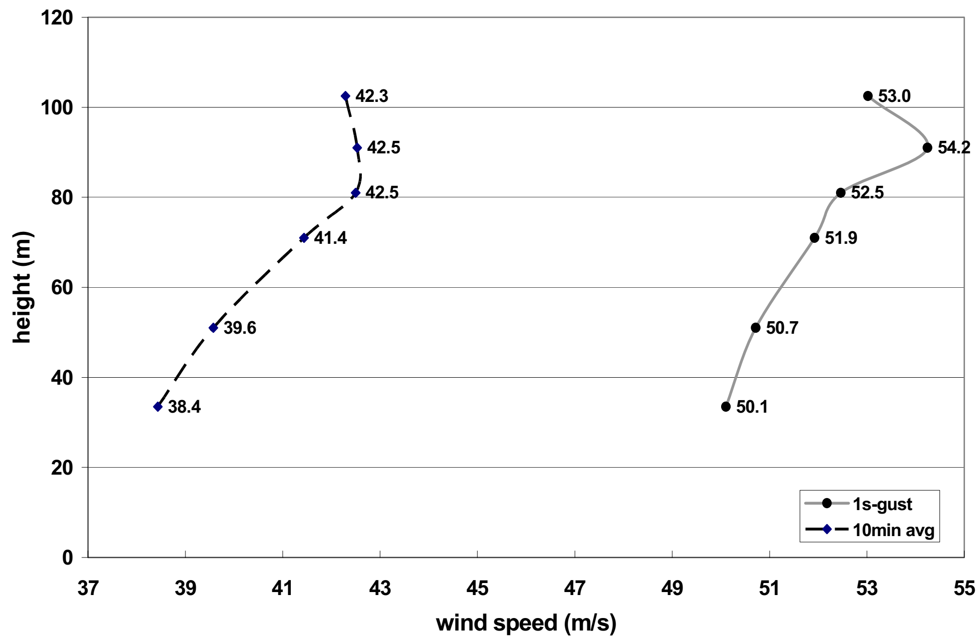
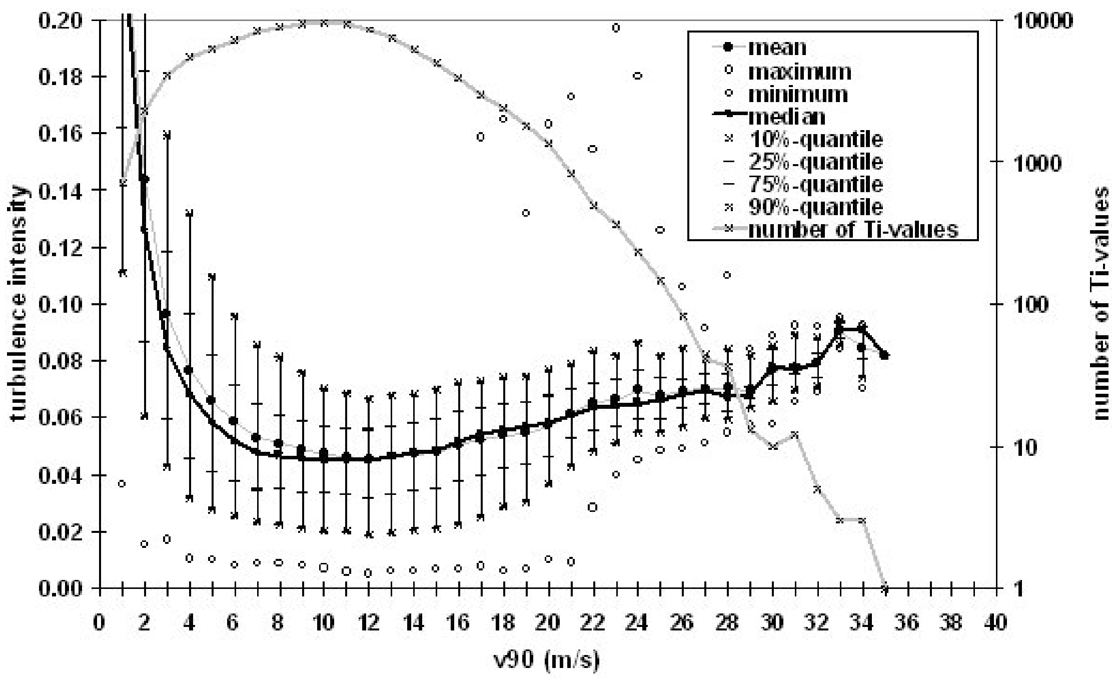
Extrapolation of the 50-year gust wind speed at FINO1 [p: cumulative frequency of 10-minute averages]



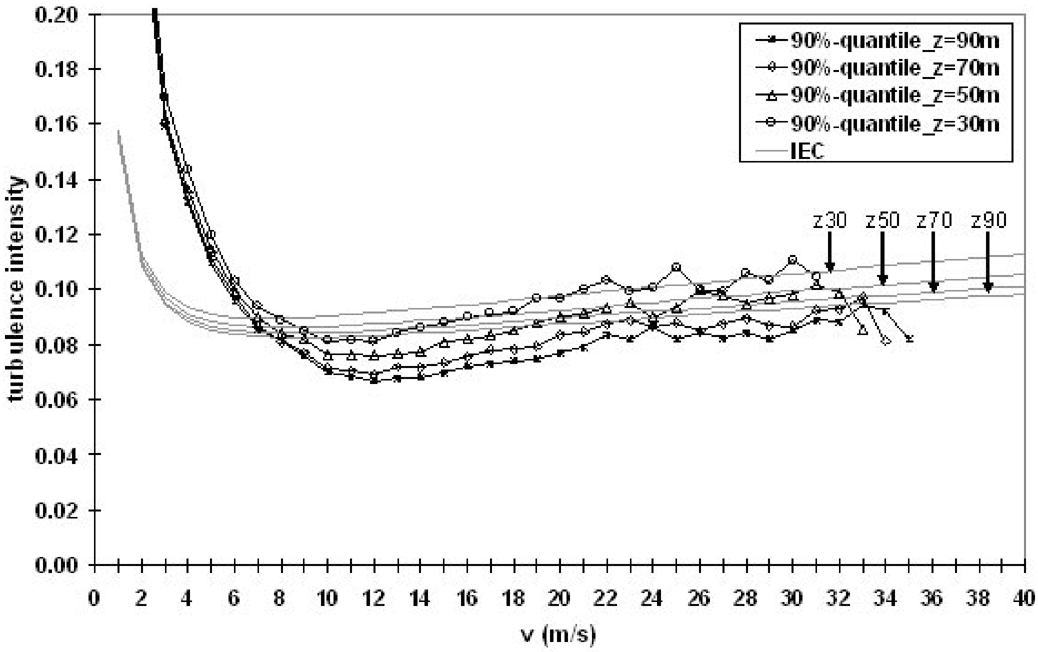
Vertical profiles of extrapolated 50-year mean and gust wind speeds at FINO1 (2004-2005, excluded: 280-350°)



Turbulence intensity as function of mean wind speed at FINO1



90%quantile of turbulence intensity as function of mean wind speed at FINO1, comparison against norm (IEC 61400-3)



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The influence of the static atmospheric stability and terrain speed up on wind speed profiles

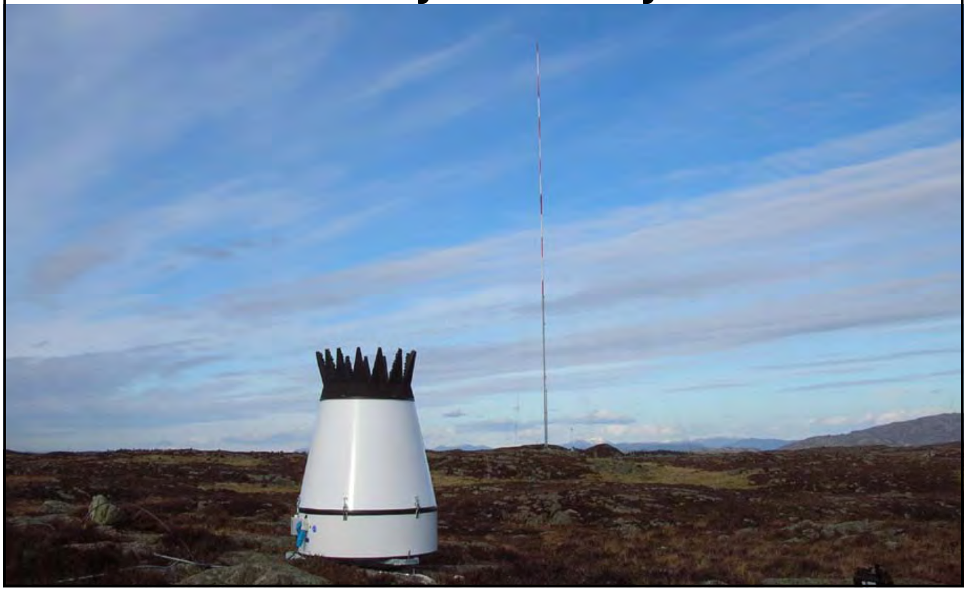
Case studies with SODAR at Norwegian Coastal Sites

Finn K. Nyhammer
Kjeller Vindteknikk AS
Norway

Introduction

- Kjeller Vindteknikk AS was founded in 1998
- Experience from more than 140 met. masts
- Started with SODAR measurements in 2005
- Owner of 2 AQ-systems SODARs
- Measured with SODAR at 5 sites
- All SODAR projects financed by customers
- The data use in this presentation are from project financed by Norsk Hydro and Statkraft

Case 1: Karmøy - Norsk Hydro



100m mast and SODAR

Instrumentation

100m mast:

- Wind Speed sensors: Risø P2546A
- Heights: 10, 30, 50, 65, 86, 99, and 100m.
- Temperature measurement at 2 and 99m.

Sodar:

- AQ-500
- Altitude range: 20-200m
- Height interval: 5m
- Powered by diesel engine/generator and battery

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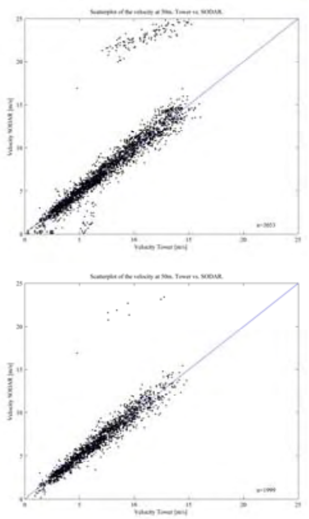
Data quality and filtering



- SNR: <3 and >15
- Removing samples were data are missing in one or more heights
- Manuel filtering of out-layers. (Large difference between mast and SODAR)
- We aim to find more effective methods for filtering

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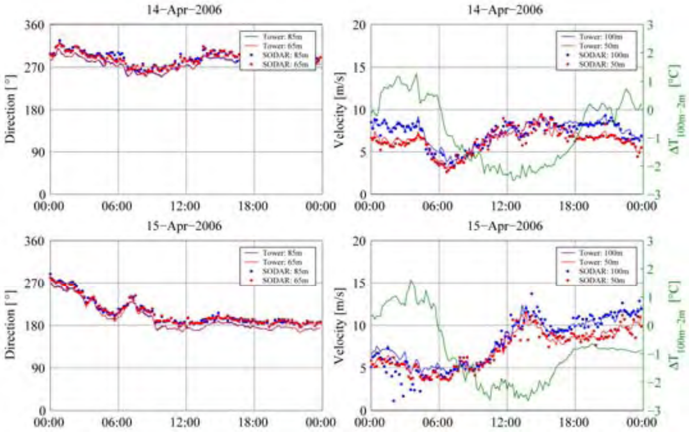
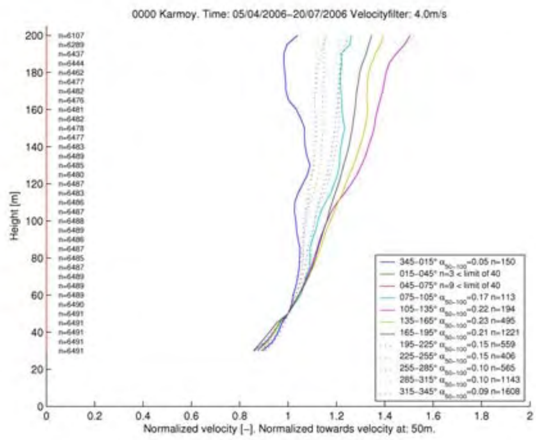
Time Series from 100m Mast and SODAR

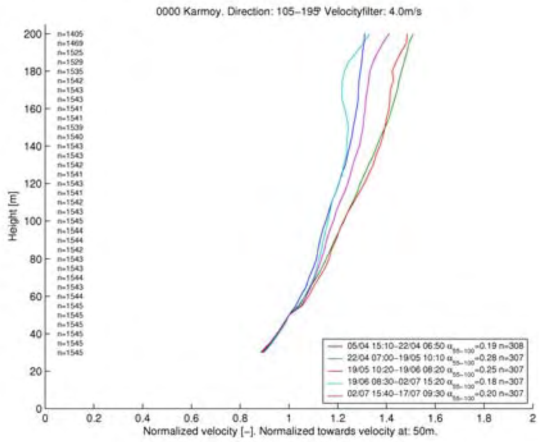


SODAR Profiles 12 Sectors

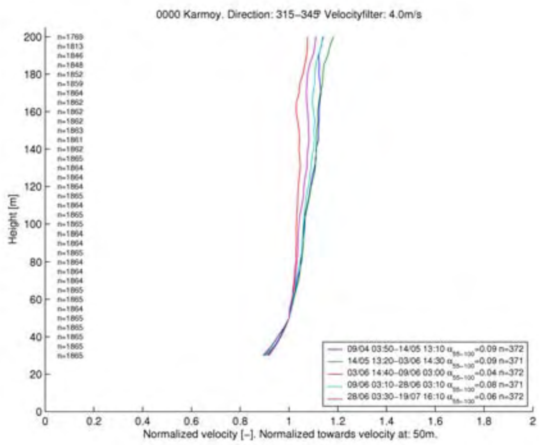


$$\frac{U(z_2)}{U(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha}$$

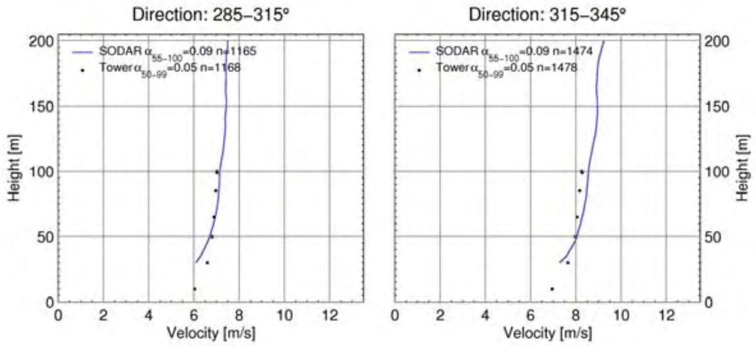
SODAR Profiles 105°- 195°



SODAR Profiles 315°- 345°



SODAR and Mast, Sector 11 and 12



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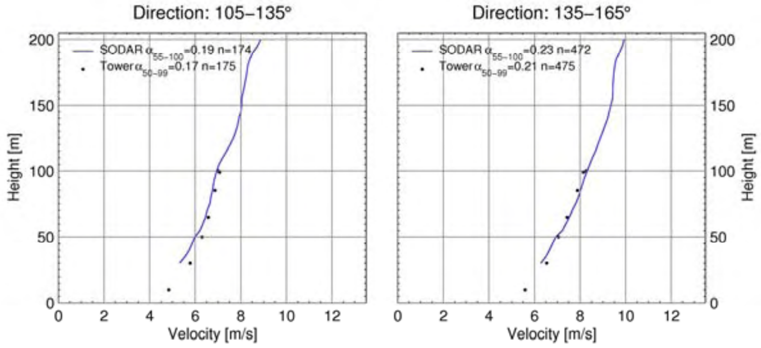
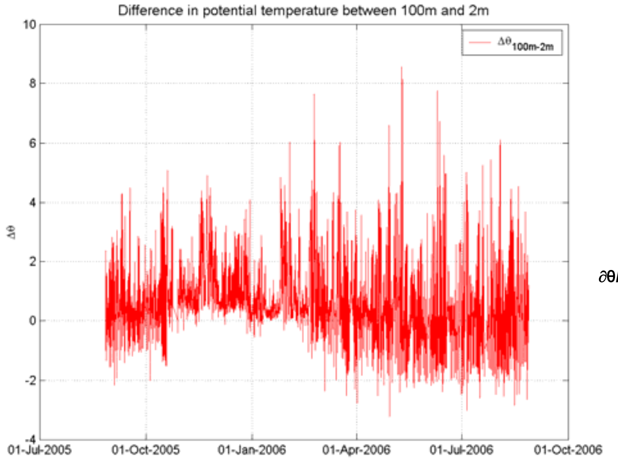
SODAR and Mast, Sector 5 and 6



KJELLER VINDTEKNIKK

Static Stability



$$\theta = T\left(\frac{p_o}{p}\right)^{\frac{R}{c_p}}$$

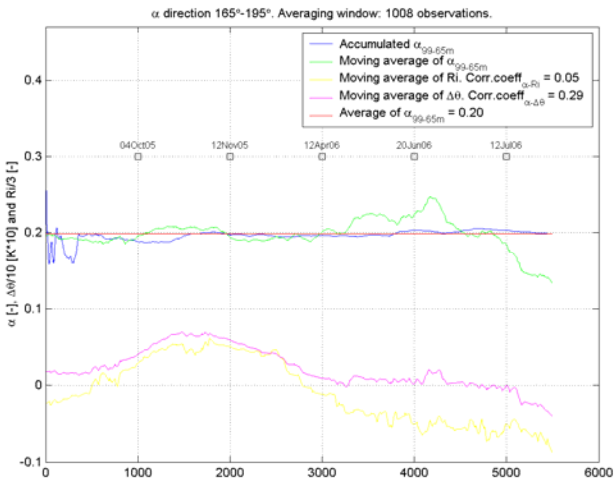
Stable:
∂θ/∂z > 0.2 K/100m
65.3%

Neutral:
∂θ/∂z ∈ [-0.2 0.2] K/100m
13.9%

Instable:
∂θ/∂z < -0.2 K/100m
20.8%

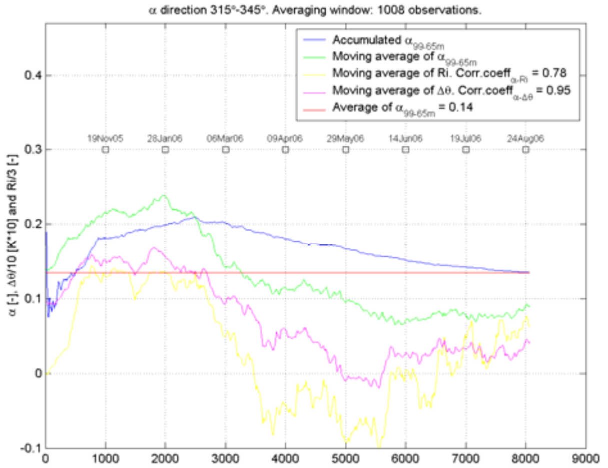
KJELLER VINDTEKNIKK

Directional Development of the Wind Shear Parameter α and the Stability Parameters Δθ and Ri (165°- 195°)

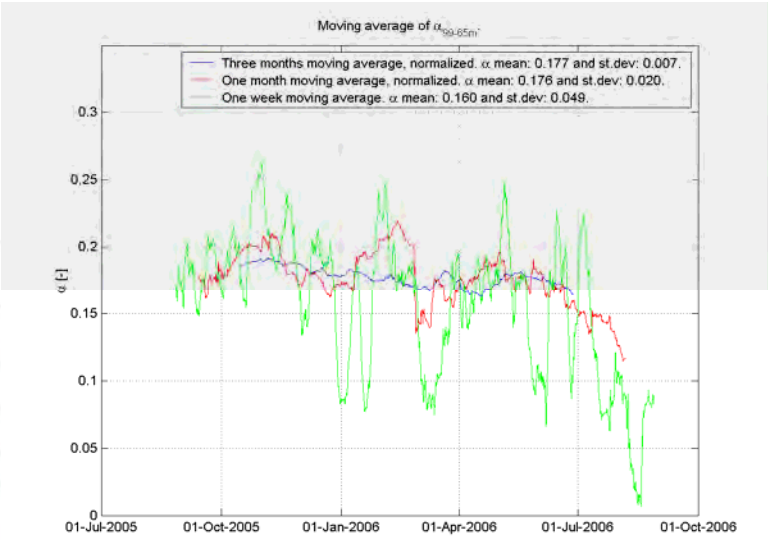


KJELLER VINDTEKNIKK

Directional Development of the Wind Shear Parameter α and the Stability Parameters Δθ and Ri (315°- 345°)

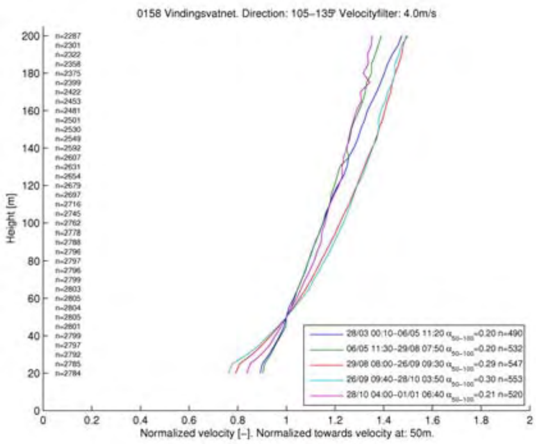


Moving Averages of the Calculated α



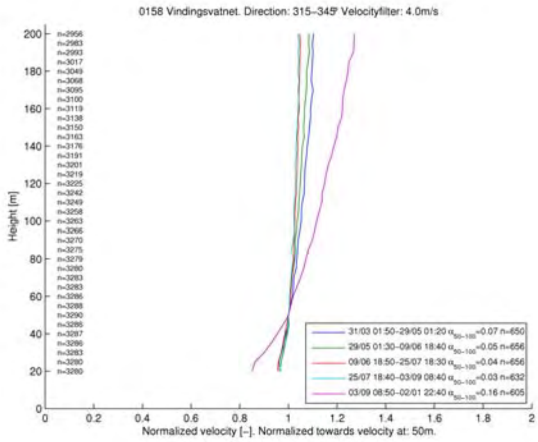
Case 2: Bømlo - Statkraft

SODAR Profiles 105°- 135°



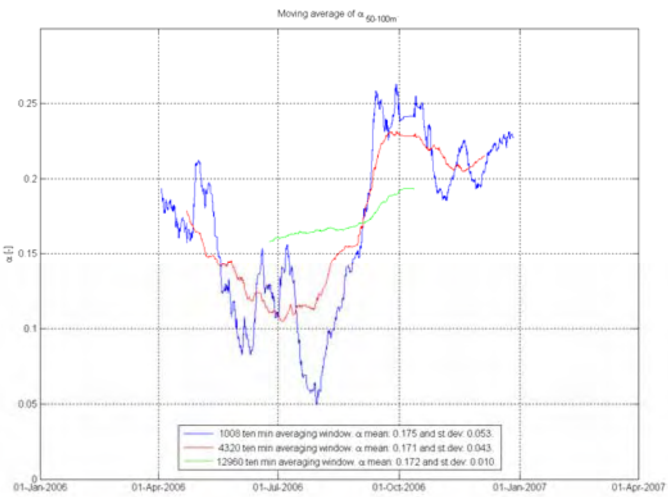
KJELLER

SODAR Profiles 315°- 345°



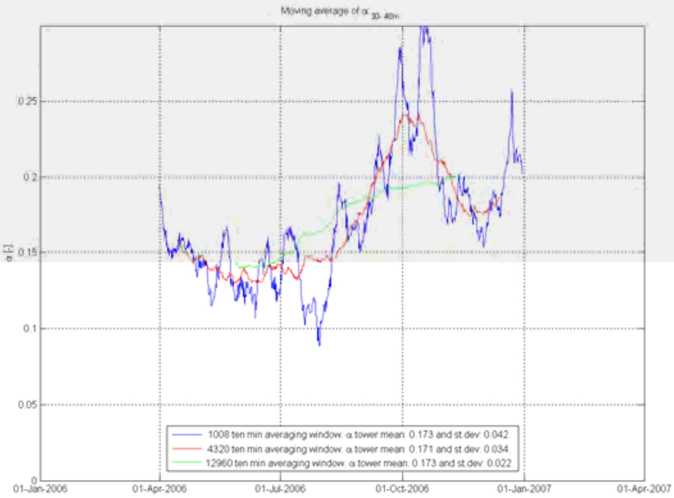
KJELLER VINDTEKNIKK

Moving Averages of the Calculated α from the SODAR Measurements



KJELLER VINDTEKNIKK

Moving Averages of the Calculated α from the Tower Measurements



Summary and Conclusions

- There are good agreements between the tower and the SODAR measurements
- There are large seasonal variations in the vertical wind profile
- The wind profile is strongly dependent on the atmospheric stability
- For a significant wind profile, it is recommended to measure for about a year
- If a shorter time is wanted it may be advisable to collect measurements in the spring or the autumn

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SODAR Sound disturbance test

Ola Friberg, E.ON Vind Sverige AB

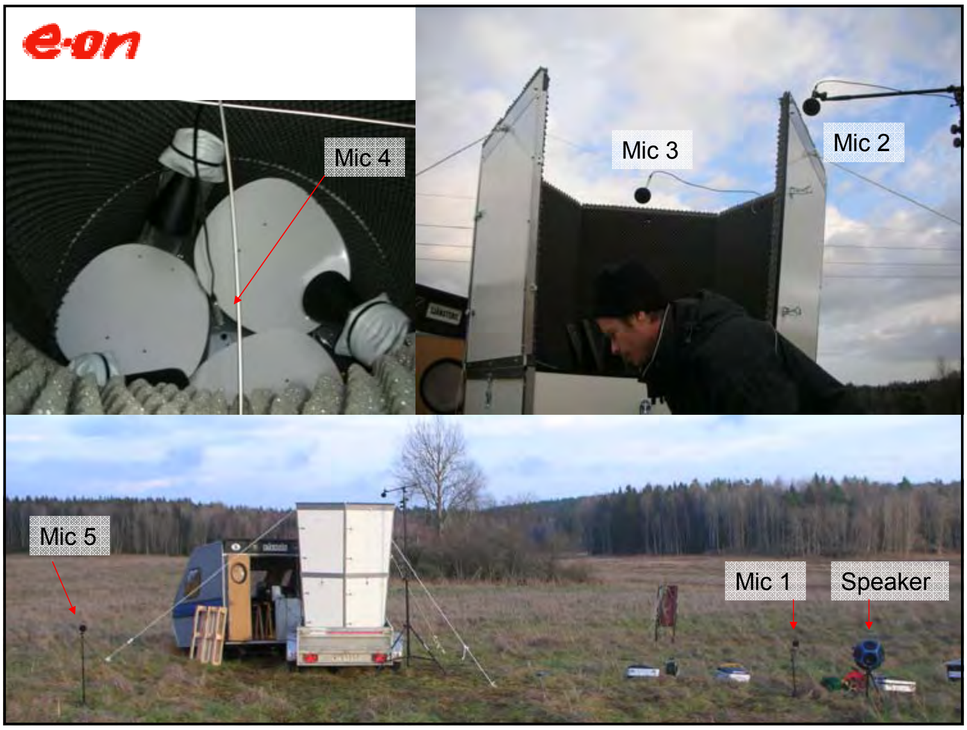
Background

- Interesting to use SODAR/LiDAR in offshore measurements

- Concern: SODAR – may be disturbed by sea noise (waves)

- Hired sound & vibration consultants (Ingemansson AB)

- Measurements carried out on SODAR AQ500 on a military field using recorded wave noise



Worst case scenario

- No sound damping with altitude or from the atmosphere

-The sea sound increases linearly with the wave height at 3 kHz

- Wave noise is equal close to the shore and far out from the shore

→ 5 m high sea waves gives 60 dB (at 3 kHz) at the SODARs position

Results

- Strongest acceptable disturbance: 66 dB (at 3KHz)

- Endures easily waves at 5 m height

- The wave noise does not increase considerably with the wave height at high frequencies

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University of Salford
A Greater Manchester University

A new approach to SODAR wind calibration

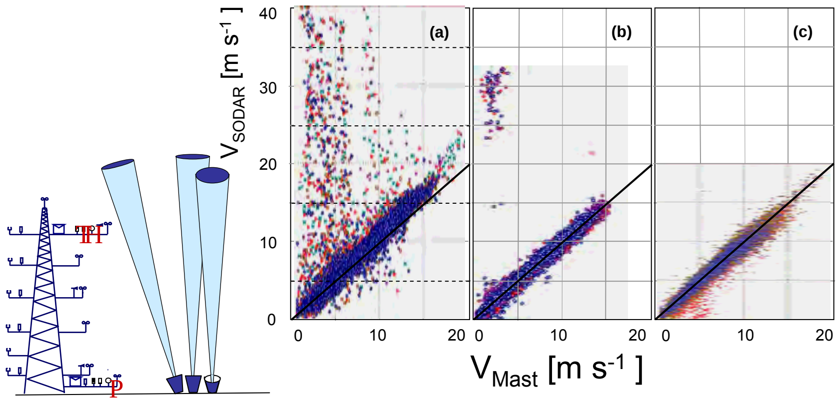
Sabine von Hünerbein
Stuart Bradley

Introduction | Technology | Applications | Conclusions

Introduction

Status quo?

Comparison with other instruments

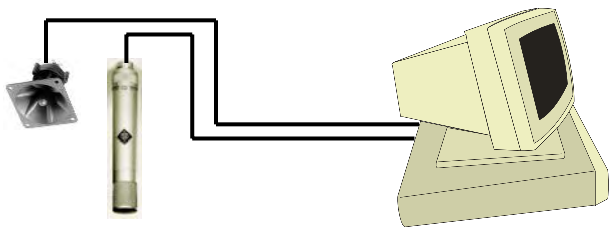


Introduction

Where do we want to go?

- Independent calibration system for wind measurements
- Operational on-site
- Usable with any SODAR (arrays + dishes, any manufacturer …)
- Independent on atmospheric conditions
- Applicable to all commercial SODARs

Performance Auditing



Baxter, ISARS, 1994

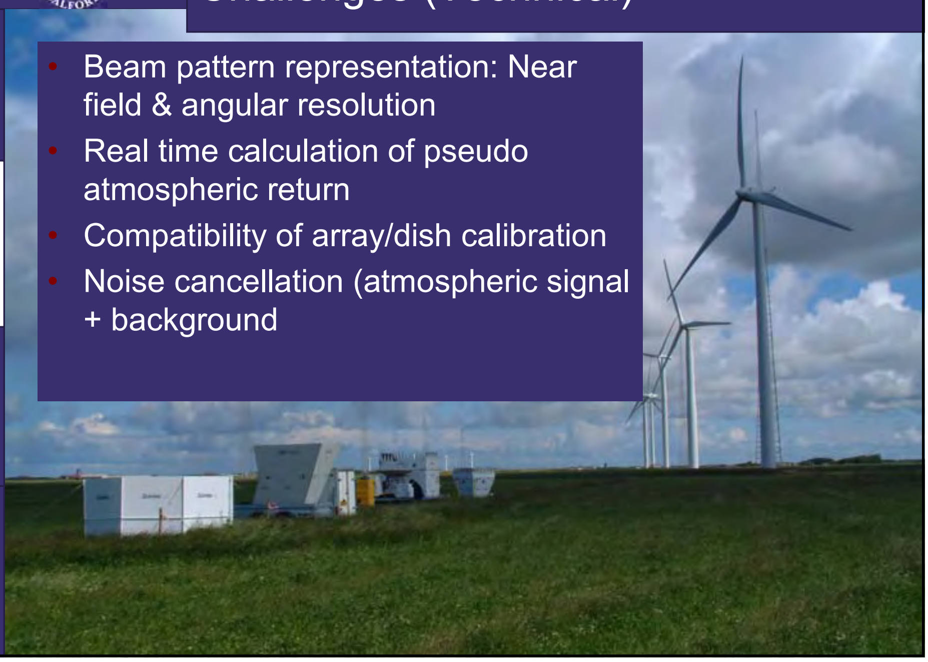
To extend to calibration

- Real time recording of pulse
- Calculation of atmospheric signal based on atmospheric scattering theory and realistic wind profiles
- Feed signal back into SODAR
- Compare results with expectations

Introduction Technology Applications Conclusions

Challenges (Technical)

- Beam pattern representation: Near field & angular resolution
- Real time calculation of pseudo atmospheric return
- Compatibility of array/dish calibration
- Noise cancellation (atmospheric signal + background



Challenges (Acceptance)

Introduction | Technology | Applications | Conclusions

- By manufacturers (fair comparison)
- By users (easy to handle)
- By standards organisation (reproducible, traceable algorithms and hardware)

Aim

Introduction | Technology | Applications | Conclusions

Develop proper wind calibration transponder for SODARs

Bi-static SODARs reduce errors

Stuart Bradley
1. Physics Department, University of Auckland, New Zealand
2. Acoustics Research Center, University of Salford, UK

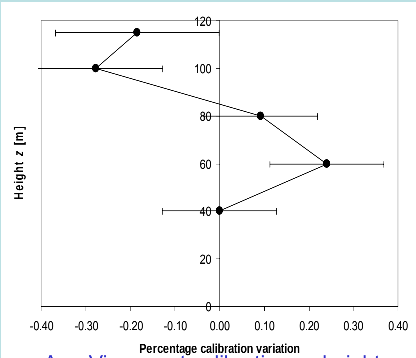
Erich Mursch-Radlgruber
Institute for Meteorology and Physics, University of Boku, Vienna, Austria

LIDAR & SODAR Errors

- Calibration: ✓
  - Knowledge of beam direction and width
- Set-up: ✓
  - Orientation and leveling
- Clutter: ?
  - Rain and/or fog
  - In-band sources
  - Unwanted reflections
- Operation: ?
  - Averaging
  - Use of multiple beams
  - 3D effects

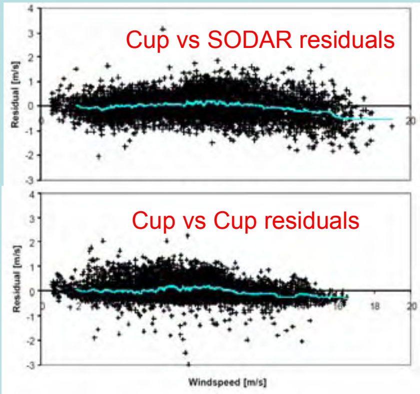
EU 'WISE' Project Results

Calibration uncertainty ±0.1%
Variation with height ±0.3%

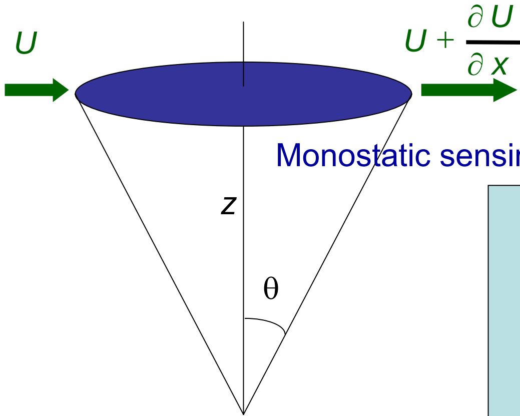


AeroVironment calibration vs height

Cup-cup variation equivalent to SODAR-cup variation



Horizontal Velocity Divergence



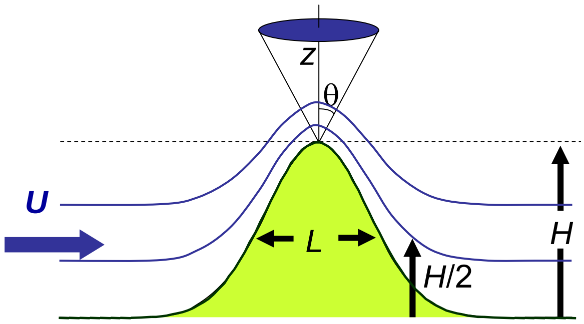
$$U + \frac{\partial U}{\partial x} 2z \tan\theta$$

$$\hat{U} = U + \frac{\Delta U}{2}$$

$$\hat{W} = W + \frac{\Delta U}{2}\tan\theta$$

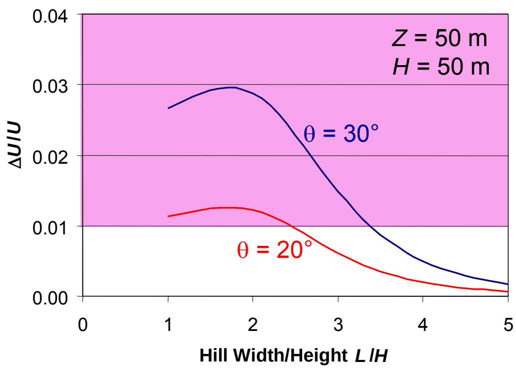
Accuracy of 1% if $\Delta U < 0.02\,U$ *e.g.* U=5 m s^{-1}, ΔU < 0.1 m s^{-1}

Simple Potential-Flow Model



Speed-up over topography causes ΔU

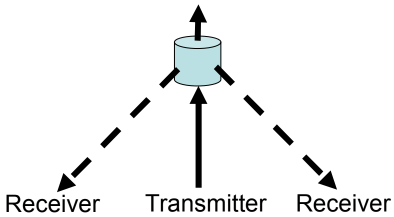
Results for a small hill



1% accuracy often not achieved

Bi-static SODAR:

a single scattering volume

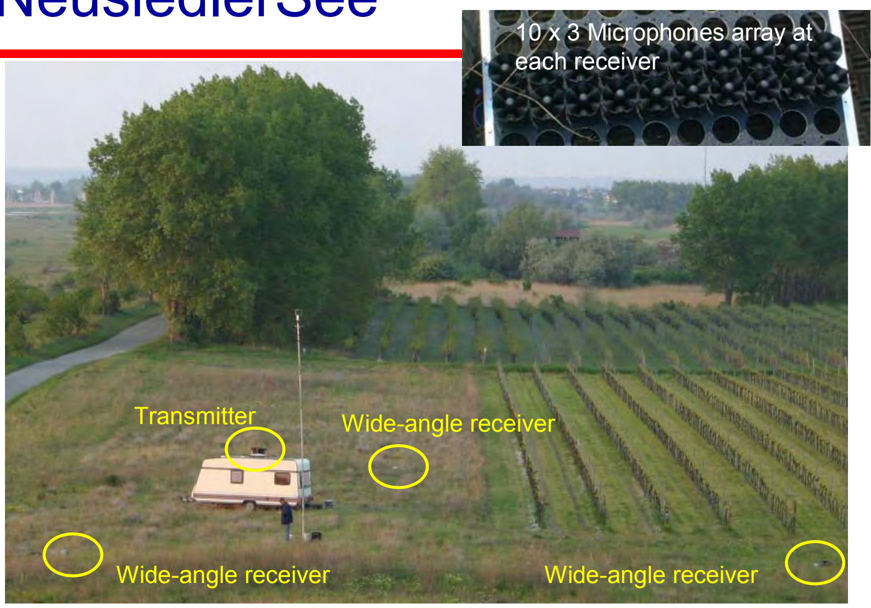


Velocity divergence problems disappear

Other advantages:

- signal levels increased by factor of 20-40 dB
  - Clutter (from fixed objects and rain) greatly reduced
  - Enhanced data availability
- Doppler shift larger
  - Easier to distinguish non-moving clutter
  - Better wind-speed resolution

NeusiedlerSee



Field work

Summary

- LIDAR and SODAR have generic errors
- Some errors *can not* be removed via calibration and/or system configuration
- Bi-static SODAR design offers improved performance through:
  - A single well-defined scattering volume
  - Strong signal dominating all clutter
  - Vertical transmission with reduced side-lobes
- Current work: auto-alignment & optimized footprint

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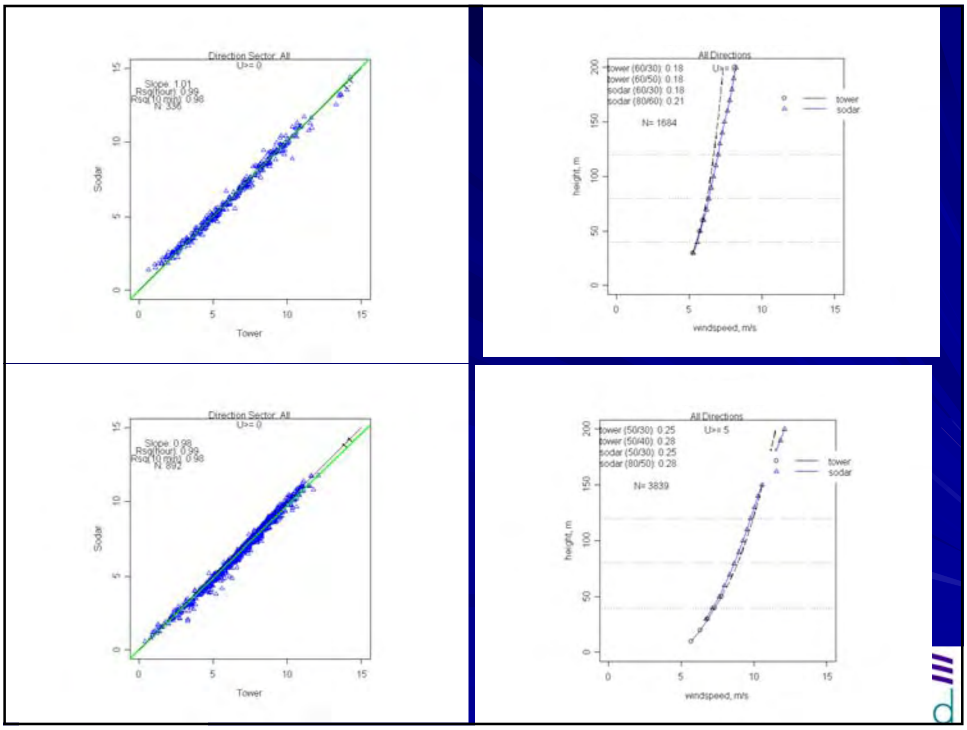
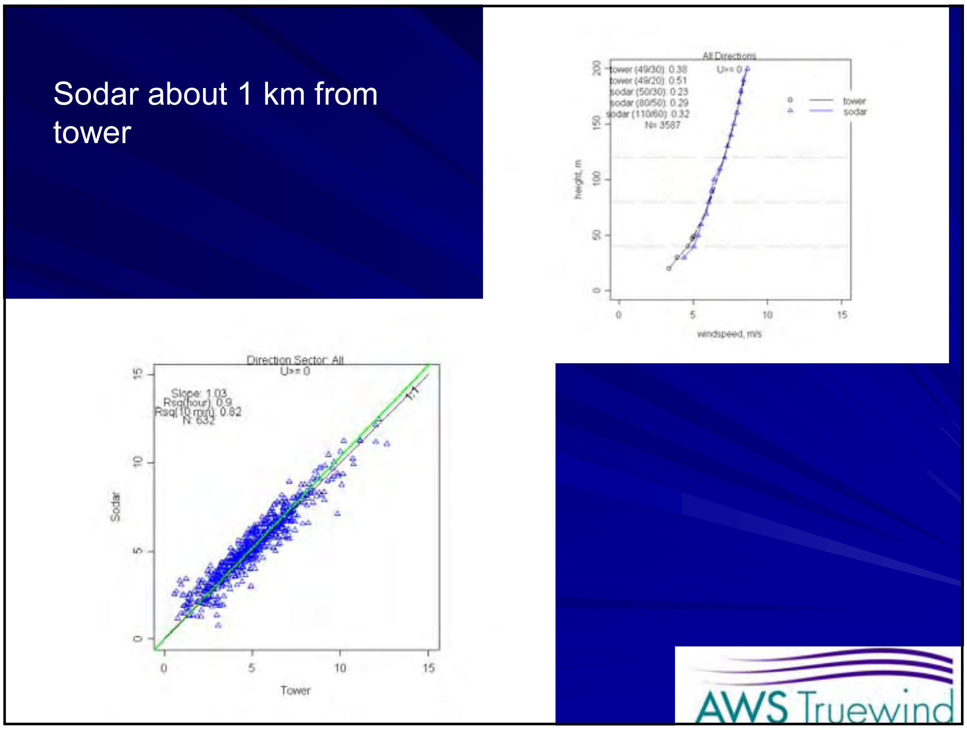
Operational use of Sodar for Wind Resource Assessment

Kathleen E. Moore
Integrated Environmental Data, LLC
Bruce H. Bailey
AWS Truewind, LLC

- Perspective of active user
- Used operationally for more than 110 sites
- Shear vs. mobile met. tower—always comparing to a tower



Direction Sector: All
Sodar
Tower
All Directions
height, m
windspeed, m/s
tower
sodar



Sodar about 1 km from tower
All Directions
height, m
windspeed, m/s
tower
sodar
Direction Sector: All
U>= 0
Slope: 1.03
Sodar
Tower
AWS Truewind

How Sodar Differs from Anemometters ….and what to do about it!

- Sodar beam tilt (temperature)
- Vector versus scalar wind speed (σ_w)
- Turbulence intensity and anemometer overspeeding (σ_w)
- Flow Inclination (w/U)
- Volume Averaging

See Moore, K. E. and B. H. Bailey, 2005. Maximizing the Accuracy of Sodar Measurements for Wind Resource Assessment. AWEA, WindPower 2005.

Best Practices Guide

http://www.iedat.com/sodar.html

Input from more than a dozen sodar users in the wind industry

Conclusions

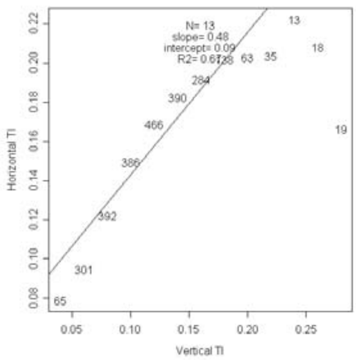
- Sodar an effective tool, combined with anemometry
- Must account for differing physics between sodar and anemometry
- Sodar σ_w a useful measure of turbulence
- Forested sites remain challenging
- "underspeeding?"
- Echo rejection and bias?

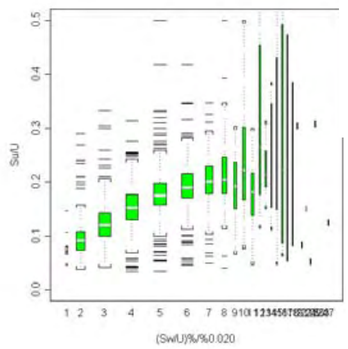
Using Sodar Sigma-W as a measure of turbulence

- σ_w vs solar radiation
- $\sigma_w \rightarrow \sigma_\theta \rightarrow$ vector-scalar conversion
- $\sigma_w / u \longrightarrow \sigma_u/u$
- Use σ_w/u (vertical turbulence intensity) to adjust for anemometer overspeeding

Tower horizontal TI vs. Sodar vertical TI

Weighted regression on the Medians by bin →





← Boxplot (width of box proportional to number of observations)

iedat integrated environmental data

AWS Truewind

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Field experience with a commercial SODAR system

Günter Warmbier, GWU-Umwelttechnik GmbH

IEA TOPICAL EXPERT MEETING ON
STATE OF THE ART OF REMOTE WIND SPEED SENSING TECHNIQUES
USING SODAR, LIDAR AND SATELLITES
Risø, January 2007

GWU-Umwelttechnik

Instrumentation

The SODARs used for the presented measurements are ASC miniSoDARs Model 4000 (formerly produced by AeroVironment)

3 beam, 4500 Hz, capability to report raw data of every pulse, every height, vertical phased-array 32 element antenna with reflector board

Reference anemometers on WINDTEST Grevenbroich's test field:

Young Model 81000
3-D ultra sonic anemometers

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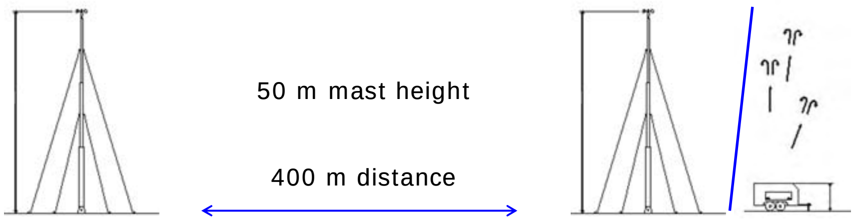
Verification of wind measurements

SODAR measurements with reference to meteorological masts

field experiment:

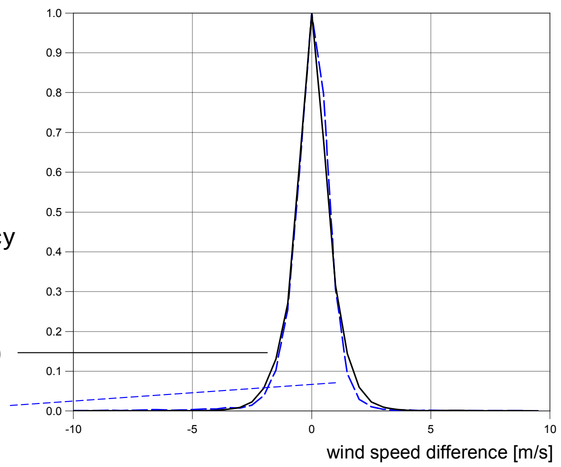
2 masts with ultra sonic anemometers – correlate sonic vs. sonic

replace one of these masts with a sodar – correlate sonic vs. sodar

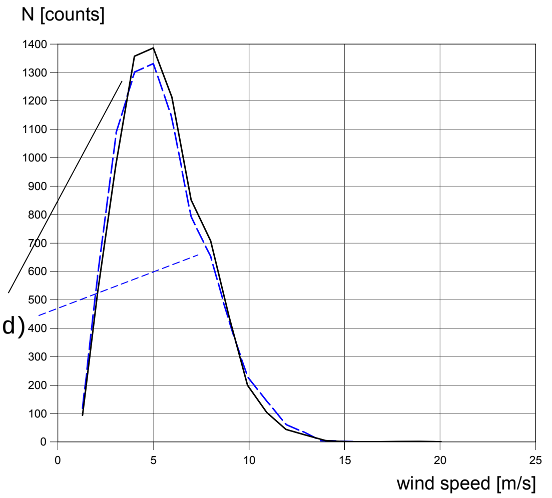


Verification of wind measurements

normalized frequency distribution of wind speed differences between
sonic – sonic (black)
and
sonic – sodar (blue)



Verification of wind speed frequency distribution



frequency distribution for sonic (black, solid) and sodar (blue,dashed) measurements

avg. speed
sonic 5.46 m/s
sodar 5.43 m/s

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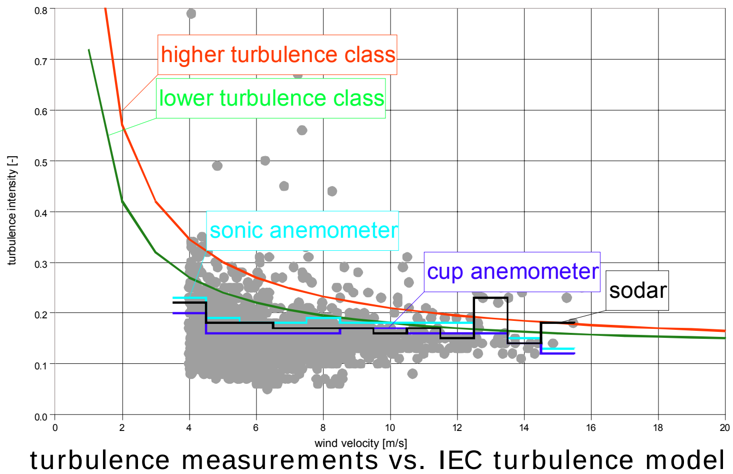
Verification of turbulence measurements



turbulence measurements vs. IEC turbulence model

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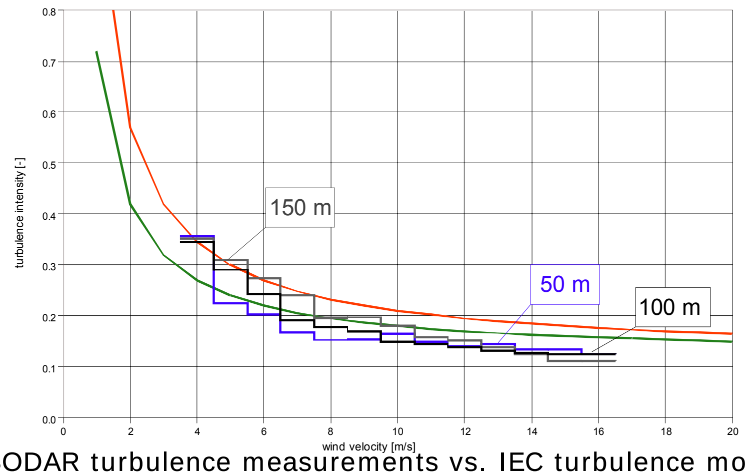
Verification of turbulence measurements



SODAR turbulence measurements vs. IEC turbulence model

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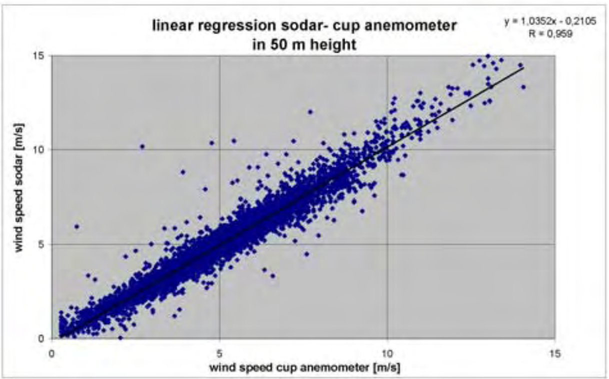
Verification of wind measurements

SODAR compared to calibrated cup anemometer on 50 m mast



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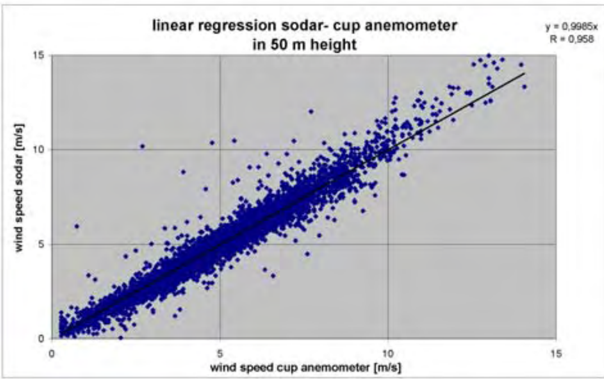
Verification of wind measurements

SODAR compared to calibrated cup anemometer on 50 m mast



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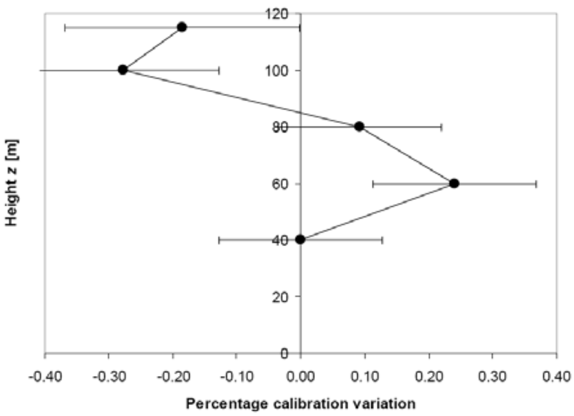
Verification of wind profile measurements



Height dependence of the variation in calibration for AeroVironment (ASC)
source: EU project WISE

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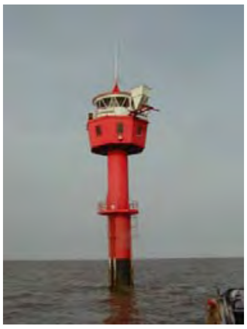
Wind energy applications of sodars



Sodar application

off-shore (picture Ecofys)

and within wind farm

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Verification of sodar operation conditions

SODAR application in wind energy

requires some rules

> make sure the sodar is technically in optimum condition

> make sure site conditions do not affect data quality (fixed echoes, noise sources,...)

> knowledge of characteristics and limitations

> if in doubt consult experienced sodar user

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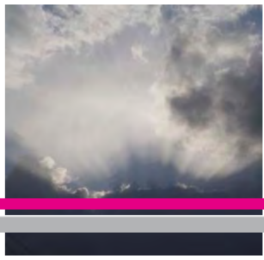
Field experience with a commercial SODAR system



www.gwu-group.de

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Comparison

SODAR

volume measurement

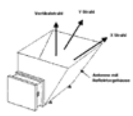
vector measurement & averaging

no inertia

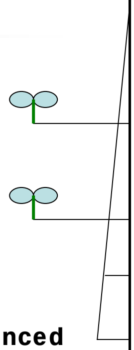
continuous wind profile

horizontal wind not influenced by vertical component

no mast required



Cup-Anemometer



spot measurement

scalar measurement & averaging

„overspeeding“

discrete heights

„horizontal wind“ influenced by vertical component

mast required

blue = properties of ultrasonic anemometers

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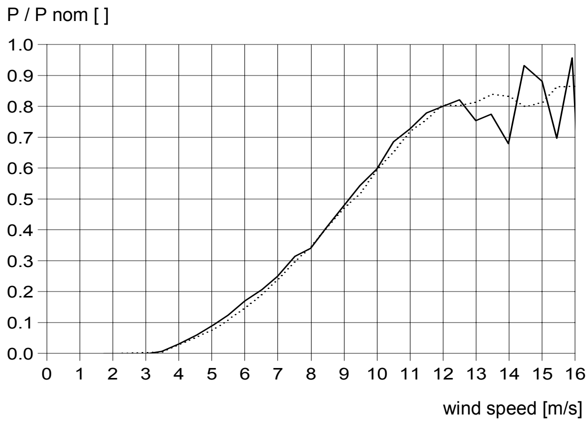
Verification of power curve measurements



Power performance curve measured with sodar (solid) and cup anemometer (dashed curve) data collective too small above 12 m/s

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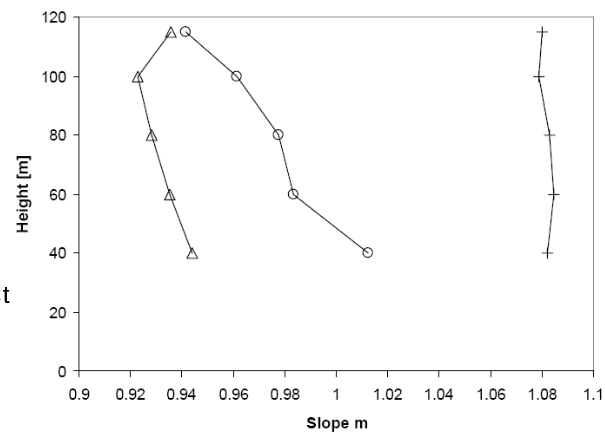
Verification of wind profile measurements



Height dependence of regression slope vs. mast for 3 different sodars
O Scintec
Δ Metek
+ AeroVironment (ASC)
source: EU project WISE

GWU-Umwelttechnik

SODAR TECHNOLOGY UPDATE

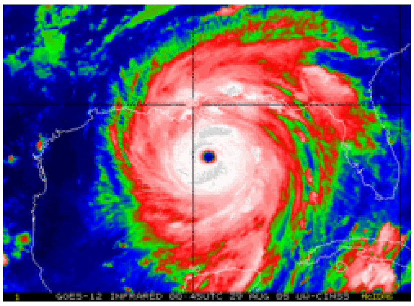
Presented by
Kenneth H. Underwood, Ph.D., C.C.M
Atmospheric Systems Corporation
Valencia, CA
661-294-9621 (w)
ken@minisodar.com
www.minisodar.com

Atmospheric Systems Corp

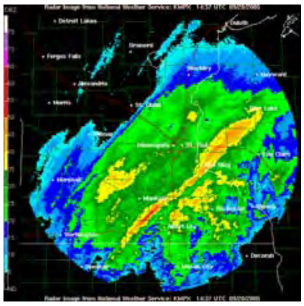
- Established in May 2005.
- Purchased the AeroVironment sodar product line as basis for business
- Moved to current location in Valencia, CA (North LA County)
- Vision:
  - (1) To provide quality SoDAR (monostatic and bistatic) products and services.
  - (2) To promote SoDAR usage worldwide.

“HORIZONTAL” REMOTE SENSING

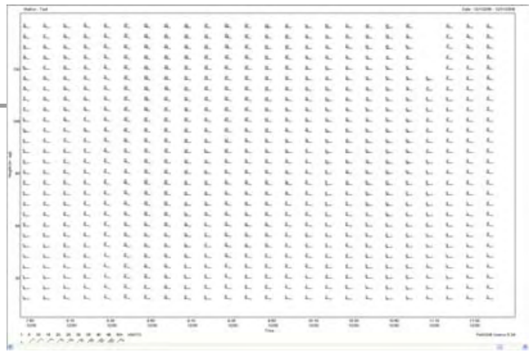
SATELLITE



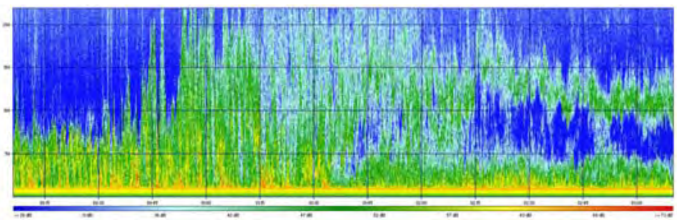
RADAR



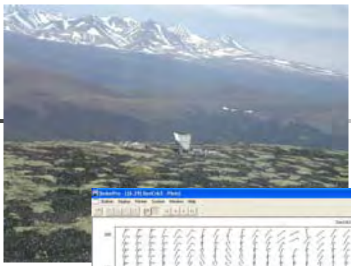
“VERTICAL” REMOTE SENSING

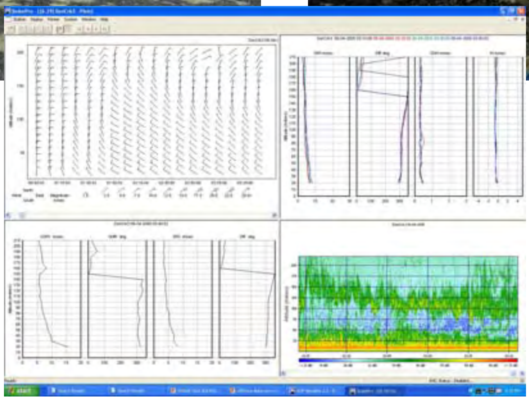


- Wind Profilers
    - o Radar
    - o Sodar
    - o Lidar

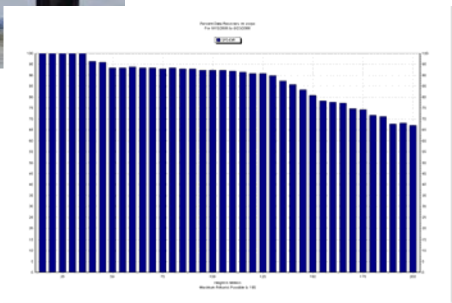


AUTONOMOUS REMOTE DEPLOYMENTS

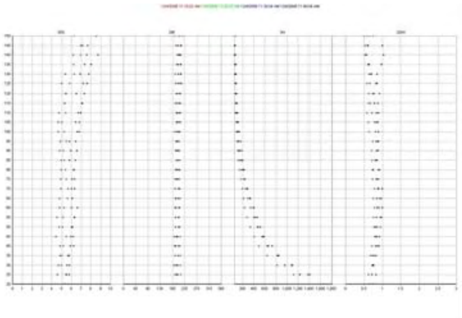


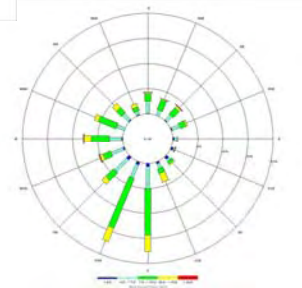


OCEAN DEPLOYMENTS

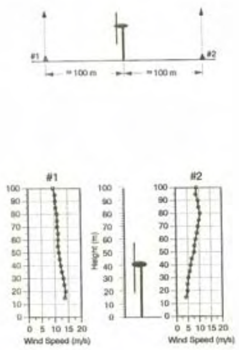


AUTONOMOUS DESERT DEPLOYMENTS





SPECIALIZED STUDIES



WIND EXPLORER

SUMMARY

- Sodars provide a cost effective and unique 3-dimensional, high resolution view of the ABL
- Proper siting, operation and maintenance procedures need to be defined and followed.
- Objective data qc standards applied to the data tables are used to mitigate:
  - Noise
  - Ground clutter
- Results are high quality, accurate data for characterization of the local wind profile.

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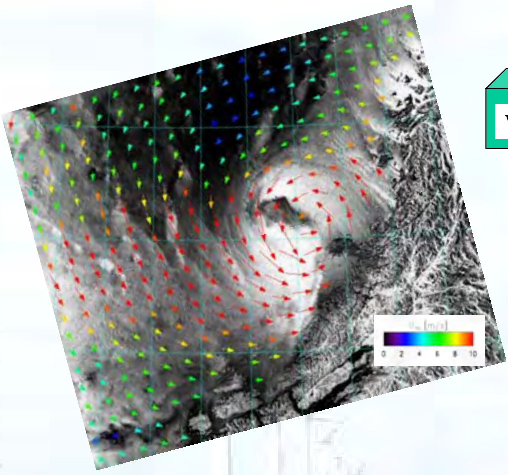
SAR-Oceanography Activities at DLR

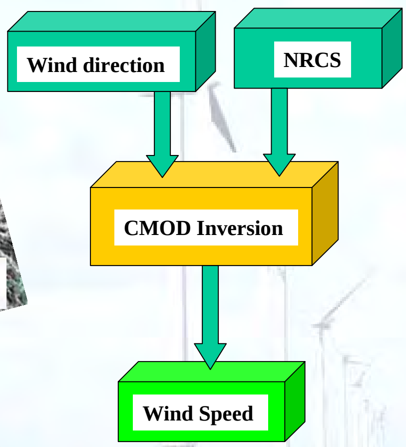
S. Lehner, J. Schulz-Stellenfleth
German Aerospace Center (DLR)

- Develop algorithms for the retrieval of
  - Near ocean surface wind fields
  - Ocean Waves (2-D spectra, …)
  - Ocean Surface Currents
  - Synergy with other sensors
- Use of retrieval algorithms for specific applications, e.g.
  - Offshore Wind farming
  - Ocean Wave farming
  - Climatological Studies
- Concept Studies for Future satellite systems, e.g.,
  - Tandem-X Mission
  - Tsunami detection

Remote Sensing Technology Institute

SAR Wind Measurements

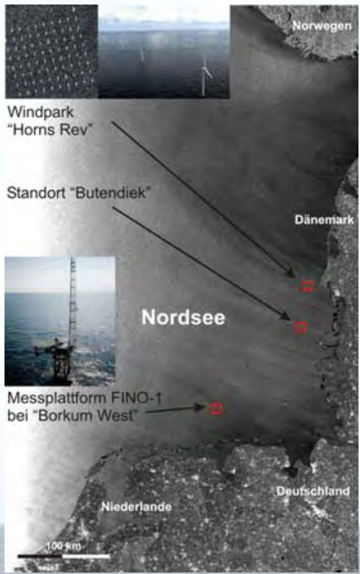




ENVSAT ASAR image of a polar low at the Norwegian Coast acquired on March 20, 2003. The Wind field in 10 m height was computed with the DLR SeaASAR algorithm

Remote Sensing Technology Institute

Application of SAR to support Offshore Windfarming



Use of SAR data to support:

- Optimal Siting
- Optimal Design
- Optimal operation

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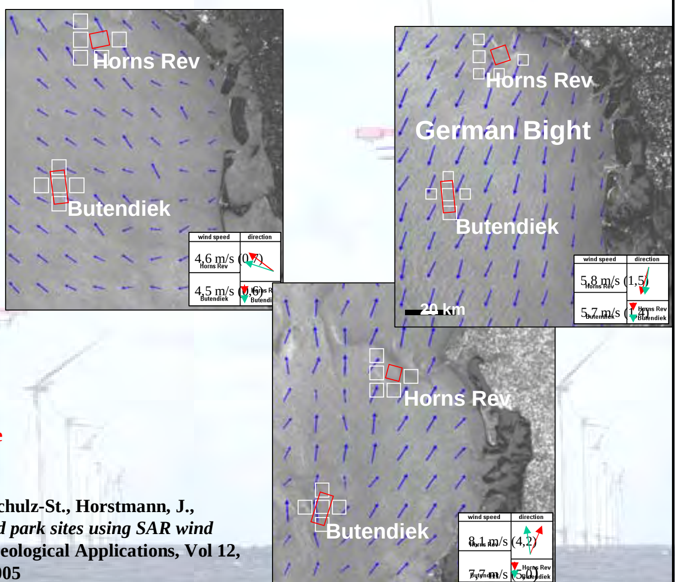
Intercomparison of two windpark sites



PhD Thesis of
Tobias Schneiderhan
Tobias.schneiderhan@dlr.de

Schneiderhan, T., Lehner, S., Schulz-St., Horstmann, J., *Comparison of two offshore wind park sites using SAR wind Measurement techniques*, Metereological Applications, Vol 12, Cambridge University Press, 2005

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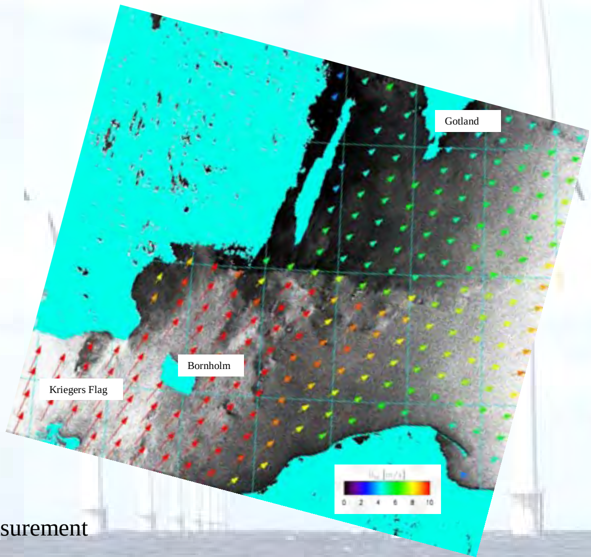
Windfarm Activities in the Baltic

FINO-2 Measurement Platform



ENVISAT ASAR image acquired over the Baltic

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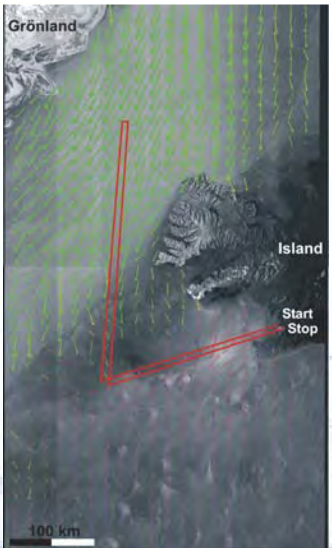
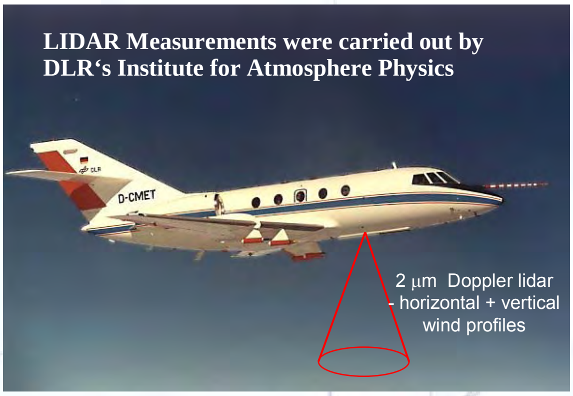
Synergy with LIDAR Measurements



ASAR image acquired during the NATReC Campaign on Sep 18, 2003.



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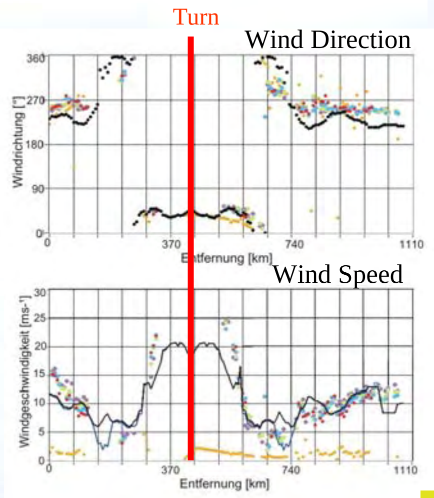
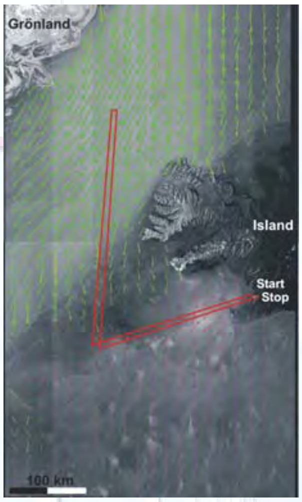
Comparison of SAR and LIDAR





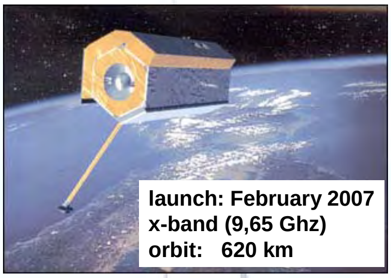
Orange: ground
Red: 200 m
Blue: 300 m
Yellow: 400 m
Purple: 500 m

Remote Sensing Technology Institute

TerraSAR-X

German Mission
Public Private Partnership

Modes:
scanSAR: 100-200 km swath
15-30 m spatial resolution
stripmap: 40-60 km swath
3-15 m spatial resolution
spotlight: 10 km swath
up to 1 m resolution



launch: February 2007
x-band (9,65 Ghz)
orbit: 620 km

Advanced Features

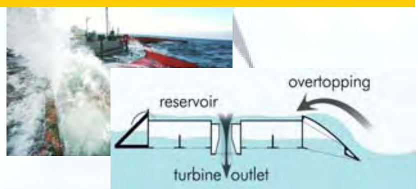
- **Spatial Resolution up to 1m**
- **Surface Current information**
- **Full Polarimetric**

Remote Sensing Technology Institute

OCEAN-POWER AO project

Assess Potential of TerraSAR-X to support the renewable ocean energy sector

- **Ocean Wave Energy**



- **Wind Energy**

- Current Energy

Subject of a separate after launch AO

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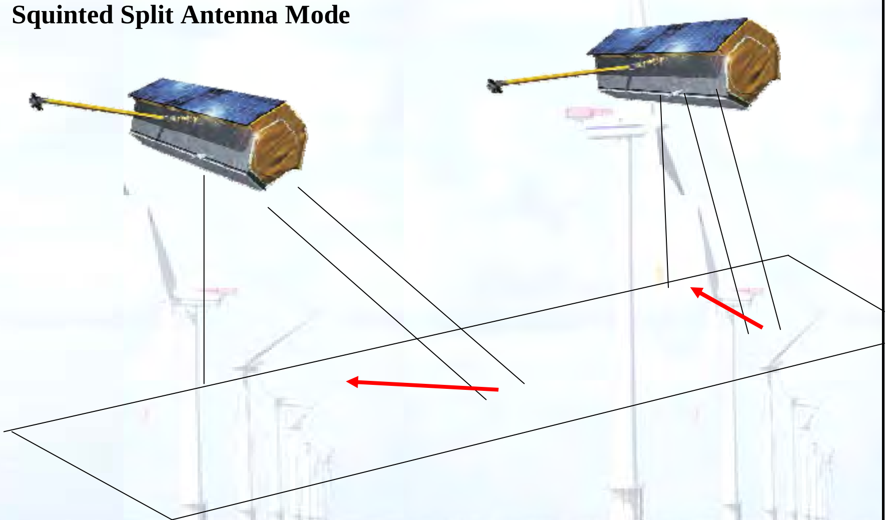
Tandem-X proposal „COTAR“

Squinted Split Antenna Mode



Measurement of <u>two</u> current/wind components

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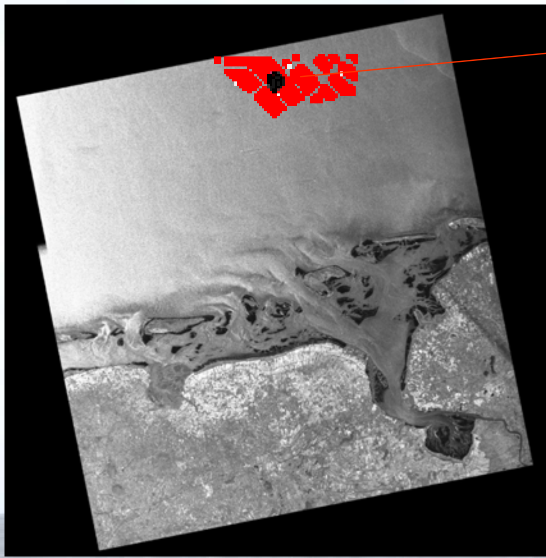
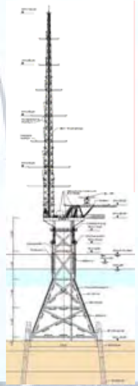
Windpark Borkum West



Approved Windpark Borkum West

● Measurementplatform FINO

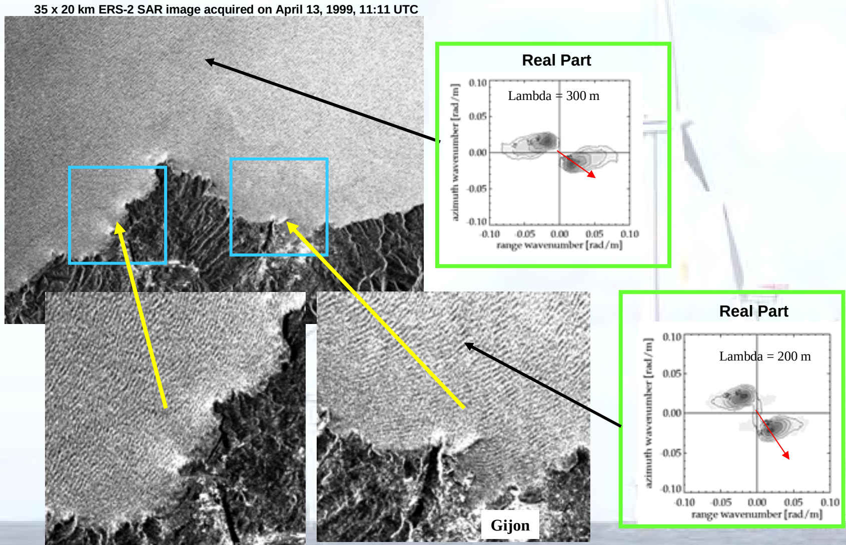


SAR Szene:
7-2-1999,
21:35 UTC

Remote Sensing Technology Institute

SAR-Ocean Wave Measurements

35 x 20 km ERS-2 SAR image acquired on April 13, 1999, 11:11 UTC



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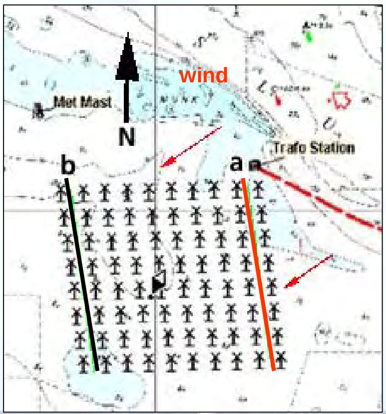
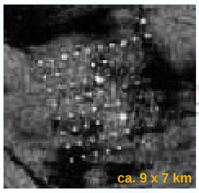
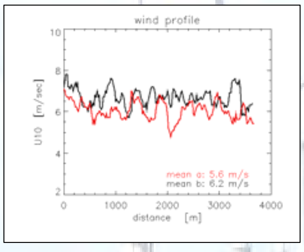
High Resolution SAR Data

Offshore Windpark
Horns Rev



zoom





© ELSAM

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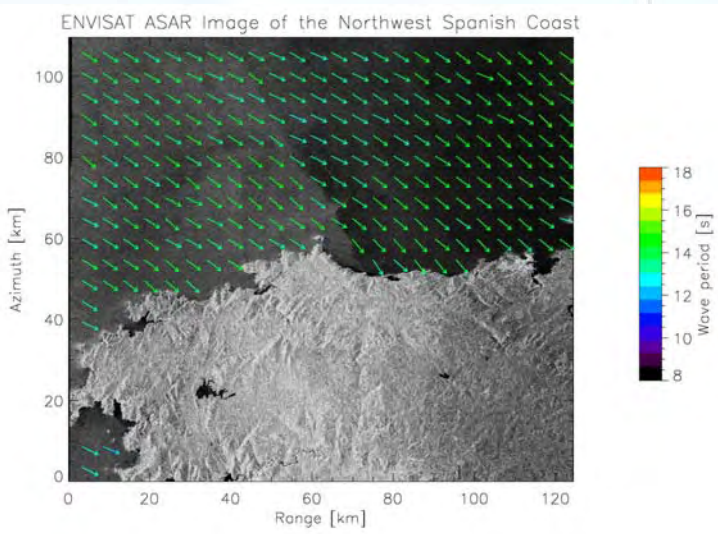
Ocean Wave Fields at the Coast

Wave Peak Periods



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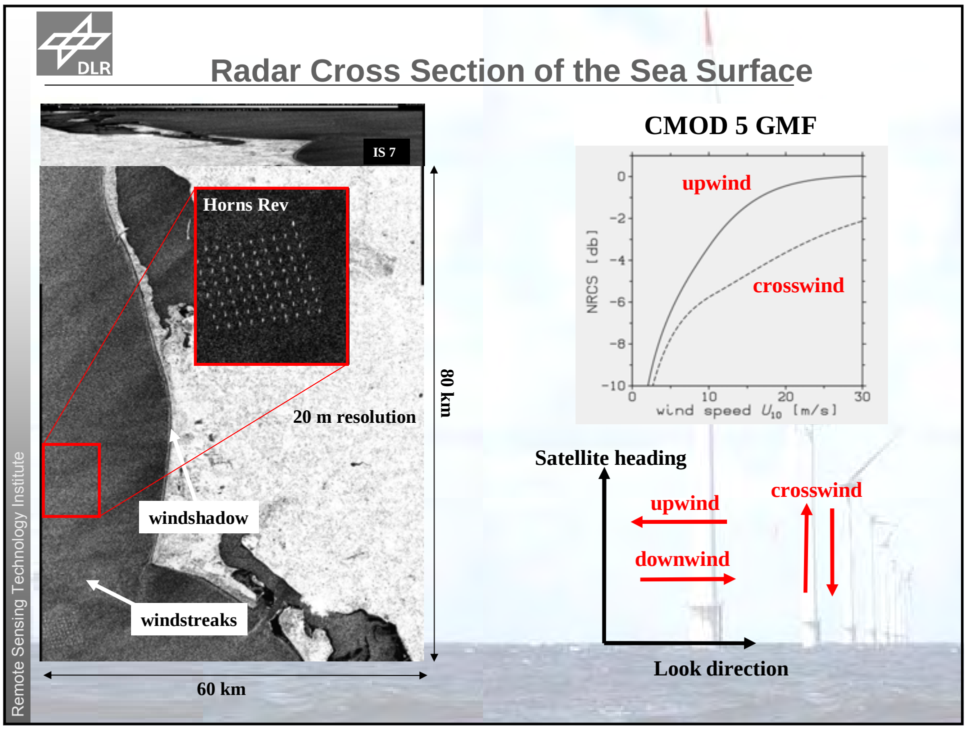
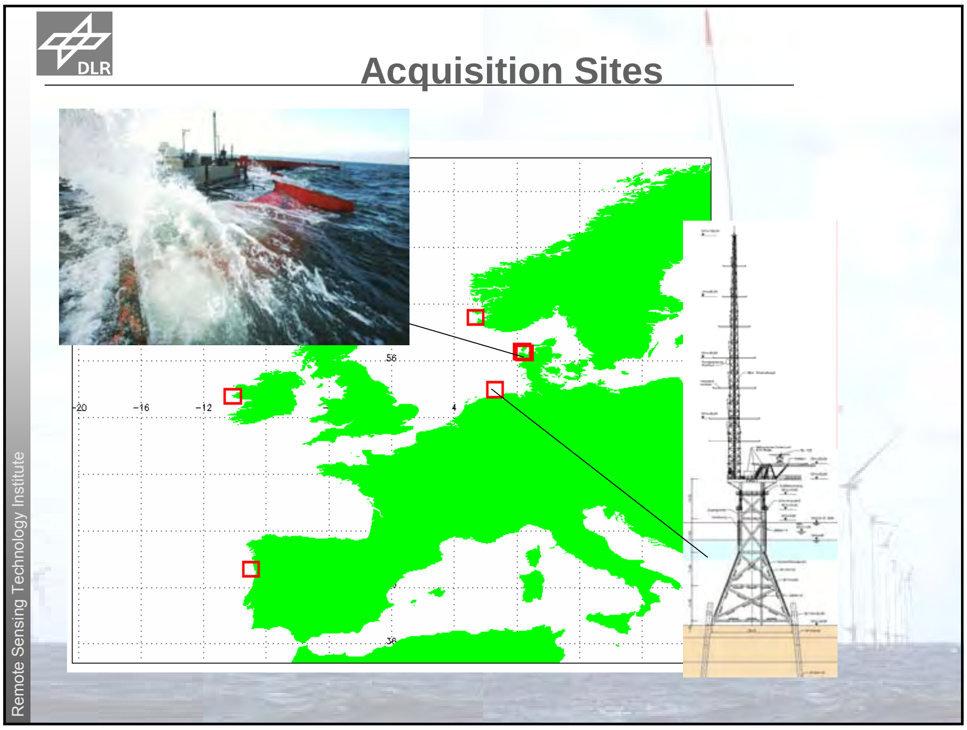
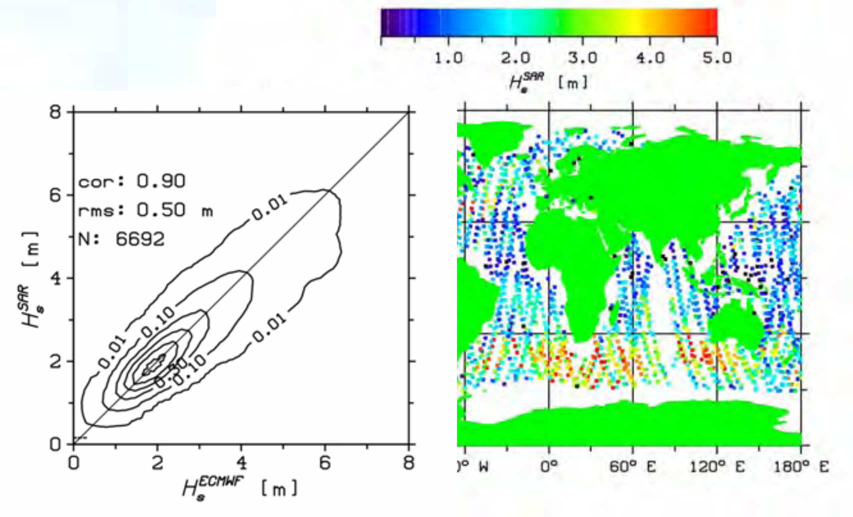

DLR
Radar Cross Section of the Sea Surface
IS 7
Horns Rev
20 m resolution
windshadow
windstreaks
80 km
60 km
CMOD 5 GMF
upwind
crosswind
NRCS [db]
wind speed U10 [m/s]
Satellite heading
upwind
downwind
crosswind
Look direction
Remote Sensing Technology Institute


DLR
Acquisition Sites
Remote Sensing Technology Institute

8 Parameter Model for H_s



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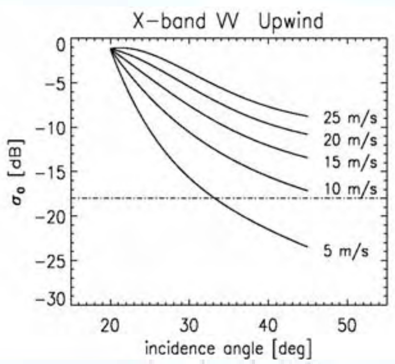
Adaption of existing C-Band Algorithms



-Use of X-Band Scattering Models

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RISØ

Satellite remote sensing for wind energy

Charlotte Bay Hasager, Merete Bruun Christiansen,
Poul Astrup, Morten Nielsen

IEA R&D Wind Task11, Topical Expert Meeting 51
Risø, 23-24 Januar 2007

Risø's mission is to create new knowledge based on world-class research, and to ensure that our knowledge is used to promote the development of an innovative and sustainable society

www.risoe.dk

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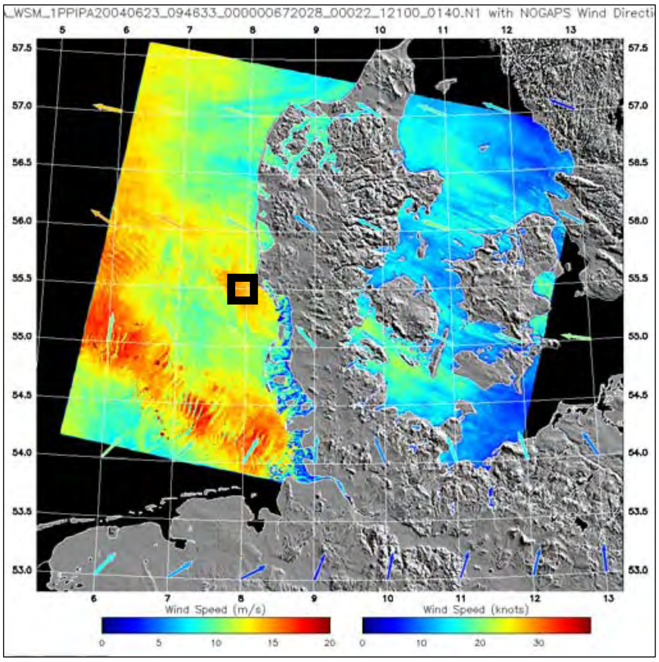
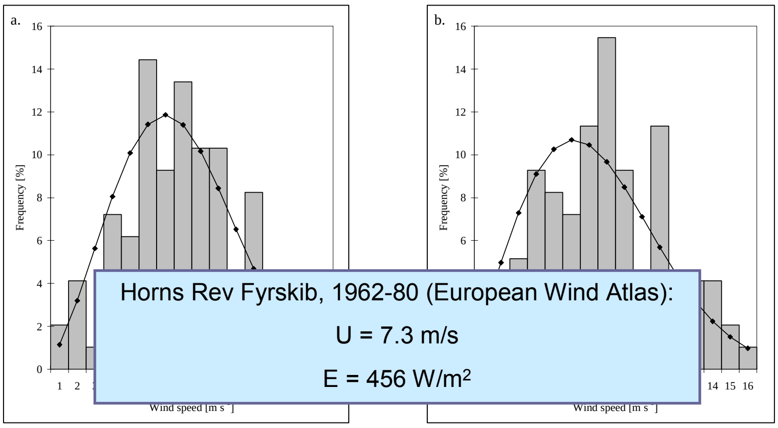
Based on radar satellite images of high resolution



We calculate from radar raw data to satellite wind maps

Envisat ASAR

Weibull fit for 91 wind maps



Horns Rev Fyrskib, 1962-80 (European Wind Atlas):

U = 7.3 m/s

E = 456 W/m^2

Meteorology mast wind speed

U = 7.6 m/s

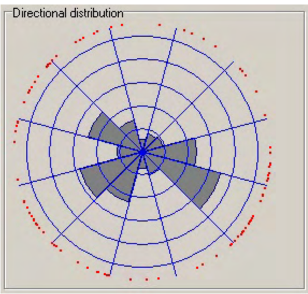
E = 422 W/m^2

Satellite wind map wind speed

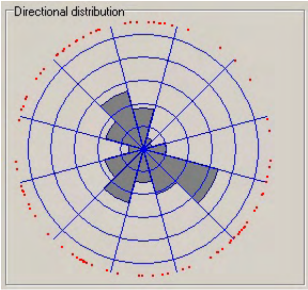
U = 7.3 m/s

E = 421 W/m^2

Wind distribution from 91 SAR scenes



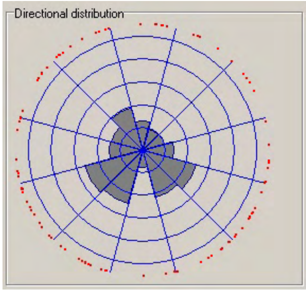
Directions from met. mast



Directions from image, LG supervised

Deviation from mast = 21°

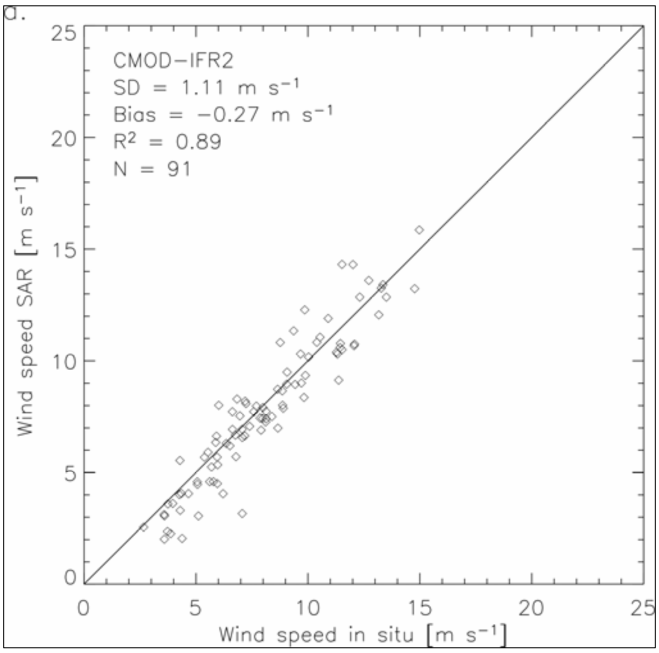
(U > 5 m/s, N = 78)



Directions from image, LG automatic

Deviation from mast = 33°

(U > 5 m/s, N = 78)



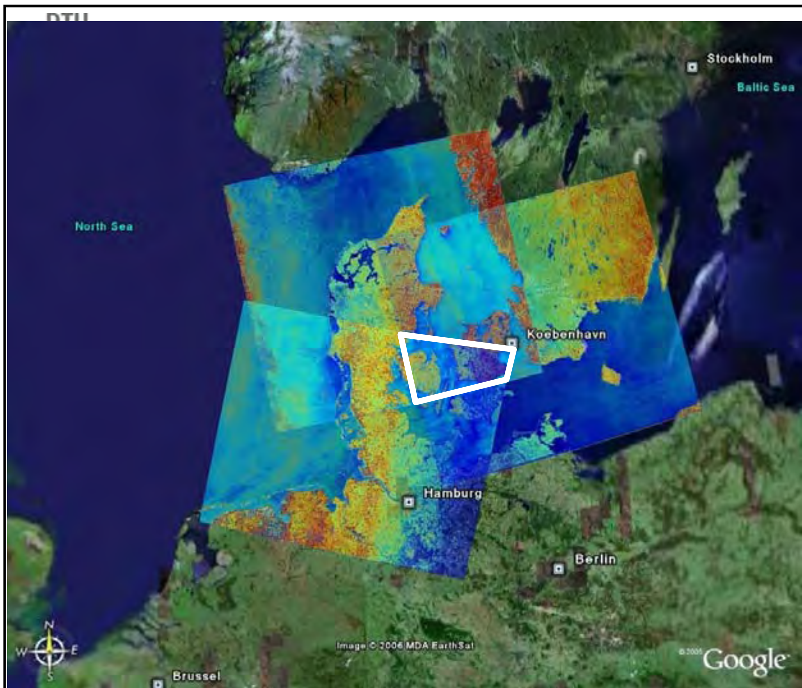
Atmospheric influences

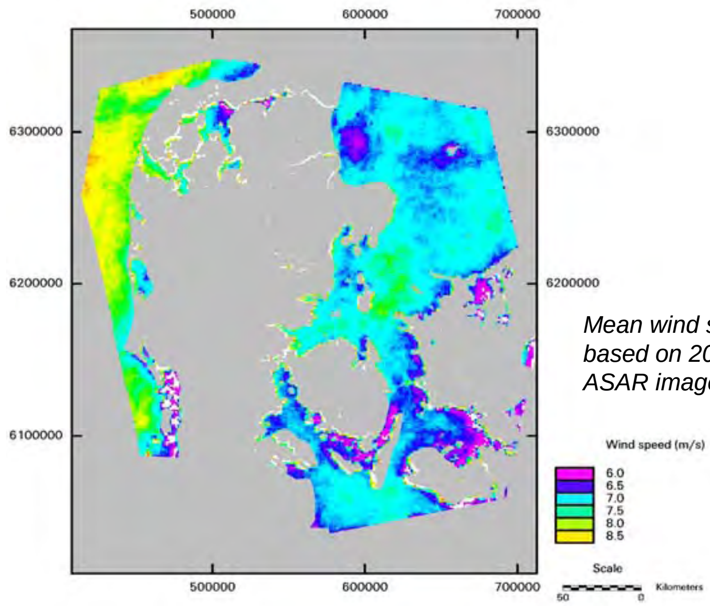
- altering the vertical wind profile

	SD [m s^{-1}]	Bias [m s^{-1}]	R^2	N
Onshore winds	1.10	-0.06	0.89	49
Offshore winds	1.08	-0.52	0.88	42

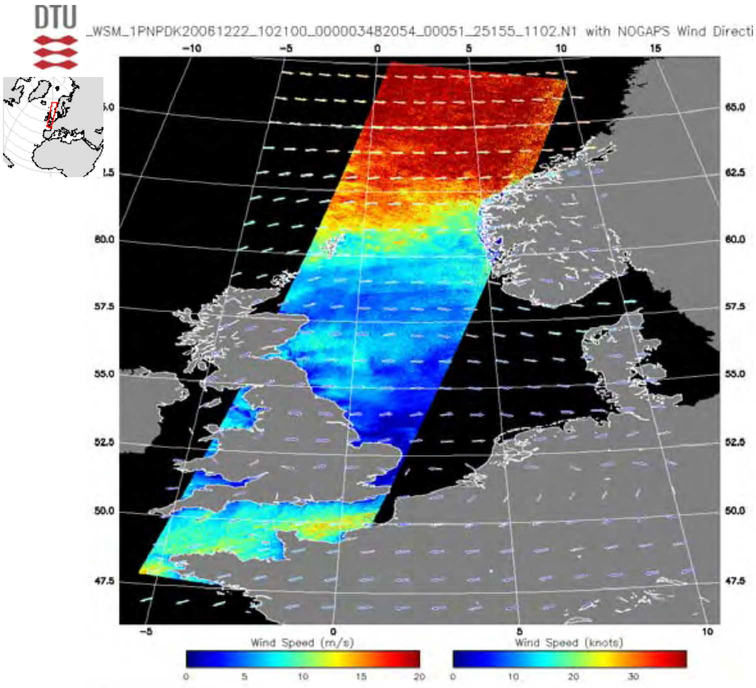
	SD [m s^{-1}]	Bias [m s^{-1}]	R^2	N
Stable	1.47	-0.86	0.88	11
Near-neutral	0.95	-0.13	0.93	22
Unstable	1.06	-0.26	0.85	52

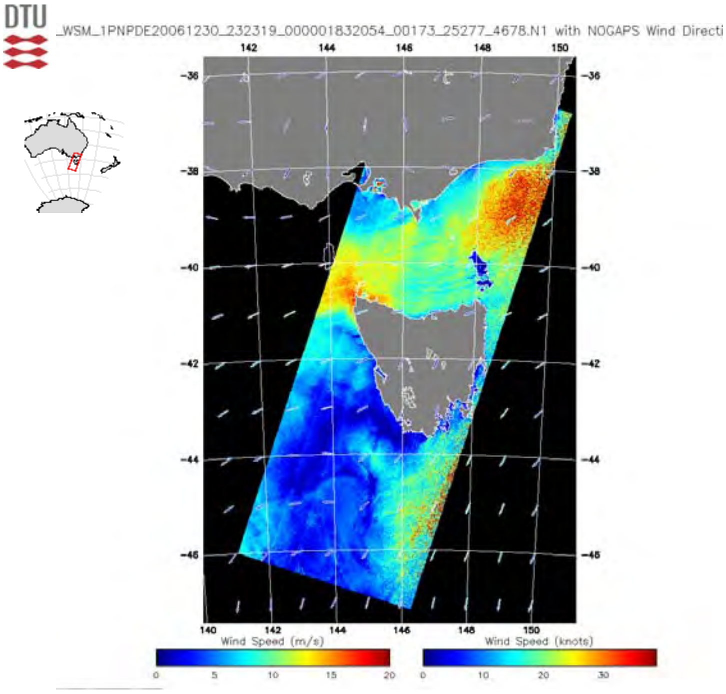
	SD [m s^{-1}]	Bias [m s^{-1}]	R^2	N
No wind farm	0.93	-0.57	0.90	46
Wind farm	1.20	0.04	0.87	45



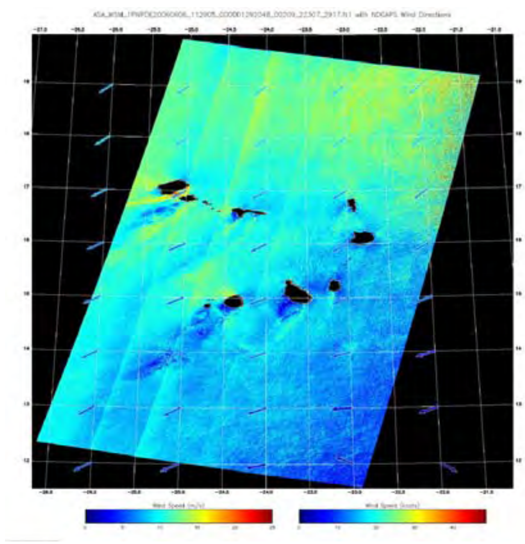


Mean wind speed based on 20 Envisat ASAR images




_WSM_1PNPDE20061230_232319_000001832054_00173_25277_4678.N1 with NOGAPS Wind Directi
Wind Speed (m/s)
Wind Speed (knots)

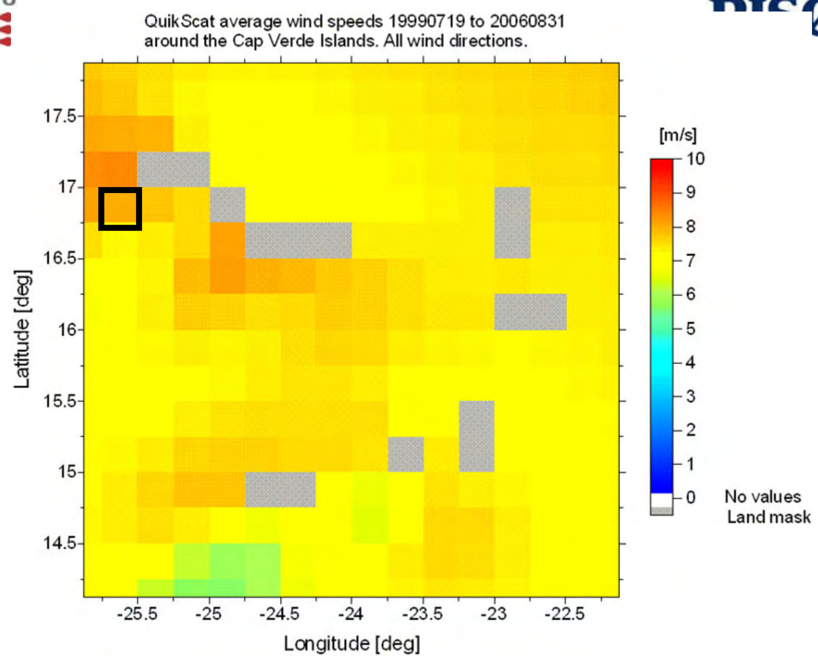
Cape Verde



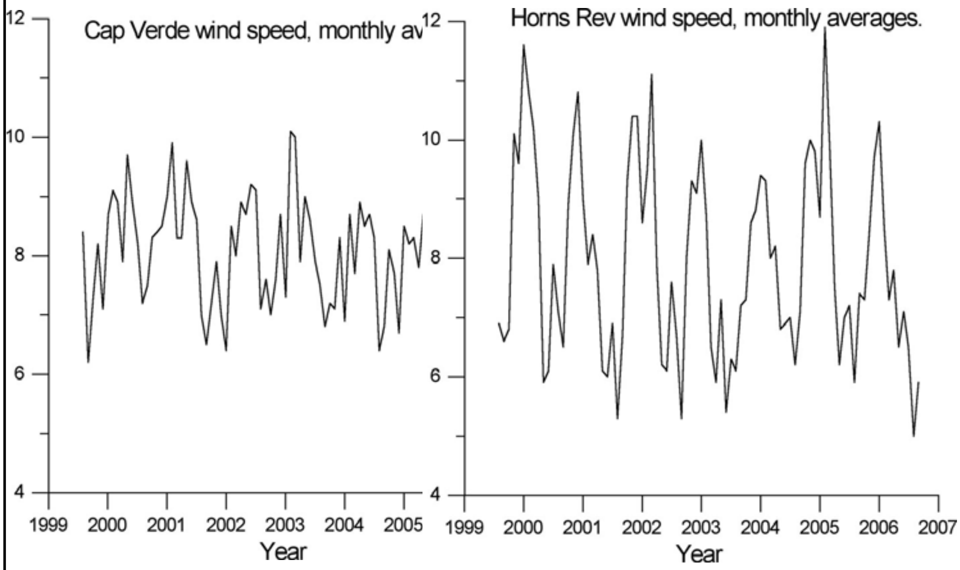
Visit our online wind maps based on Envisat ASAR at

http://www.risoe.dk/galathea/opslag/satellit_arkiv.htm

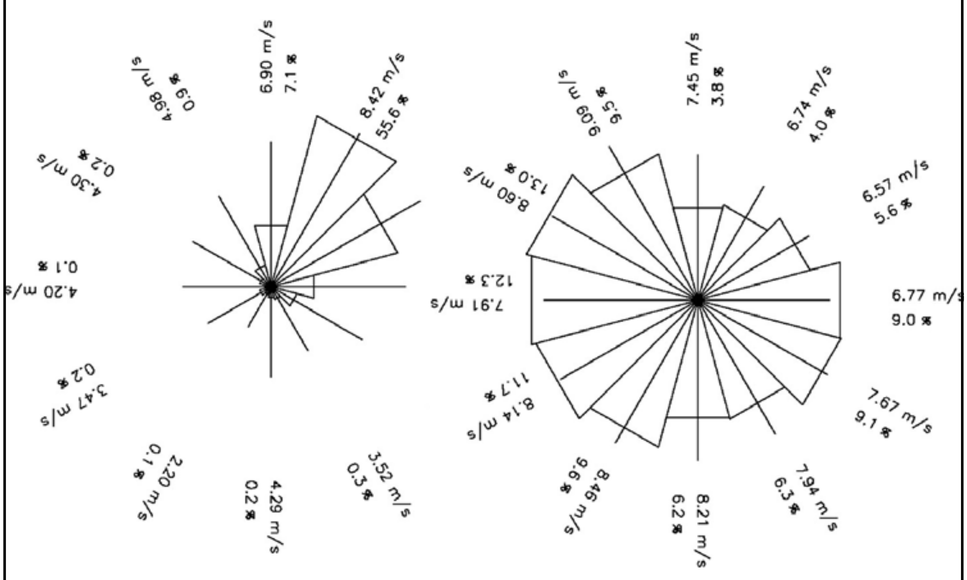
Merete Bruun Christiansen
in cooperation with JHU APL (USA)



QuikSCAT wind maps for 7 years

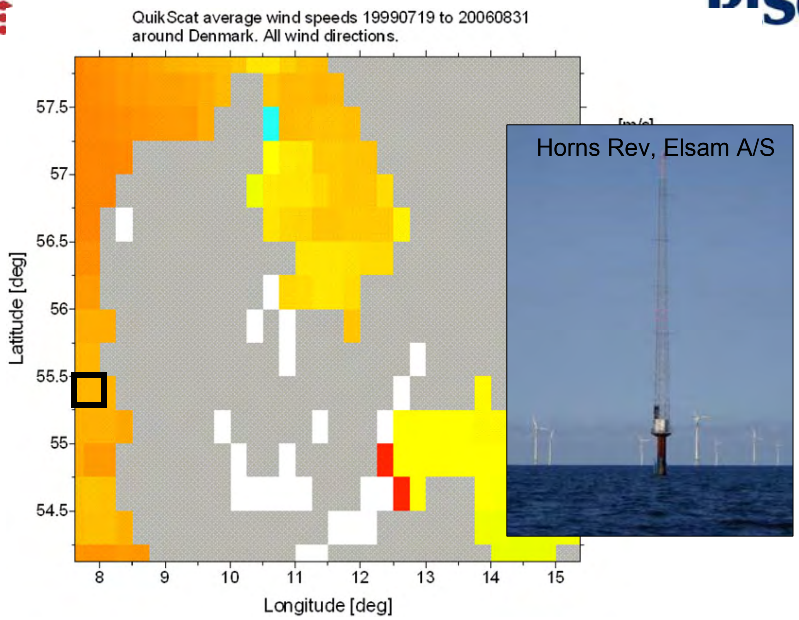


QuikSCAT wind maps for 7 years

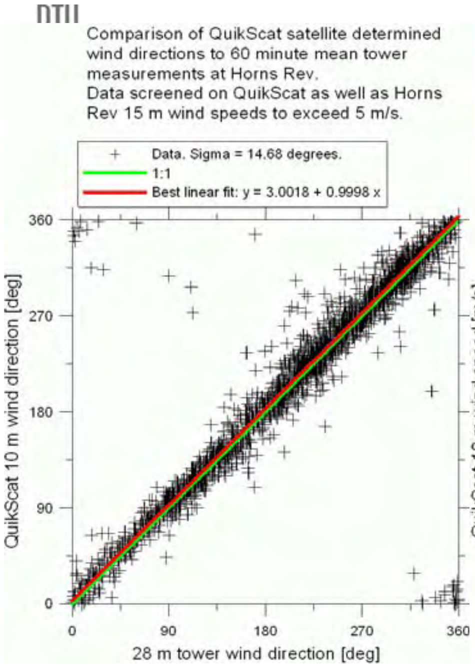


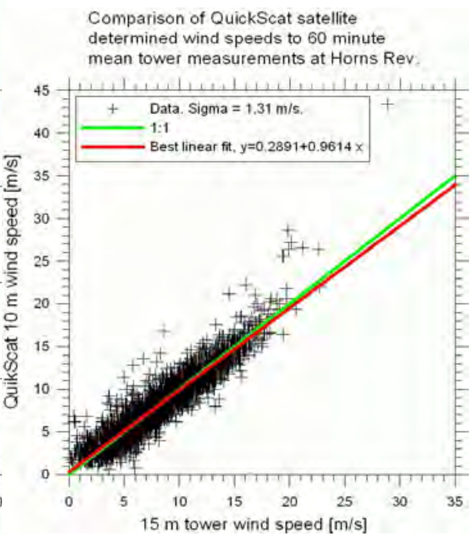
QuikSCAT wind maps for 7 years

	Longitude and latitude (°)	Mean wind speed (m/s)	Weibull A (m/s)	Weibull k
Cape Verde	334.25 E, 16.75 N	8.04	8.86	4.57
Denmark	7.75 E, 55.50 N	7.95	9.06	2.26
Cape Horn	67.5 W, 56.50 S	11.2	12.88	2.44



Courtesy: Poul Astrup



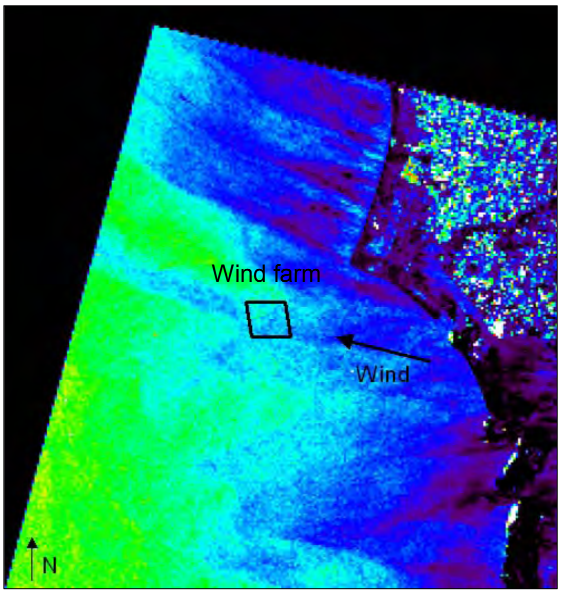


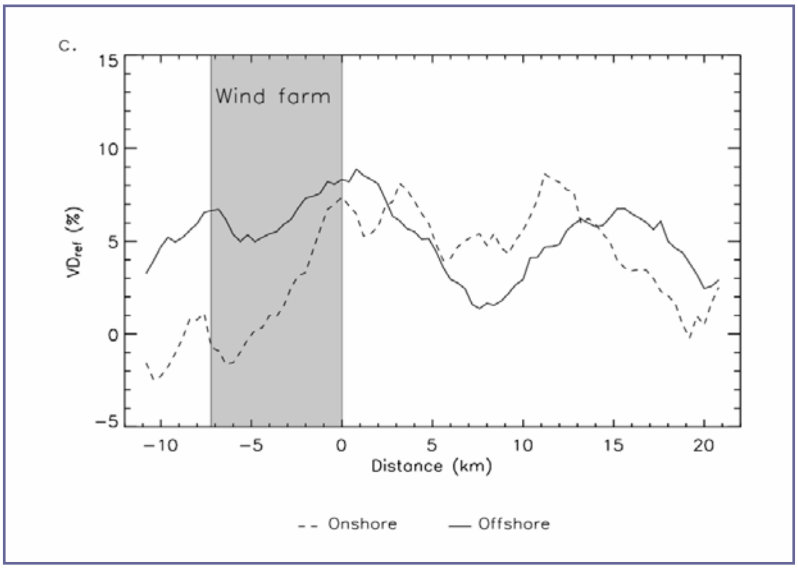
Wind farm wake effects

ERS

Horns Rev

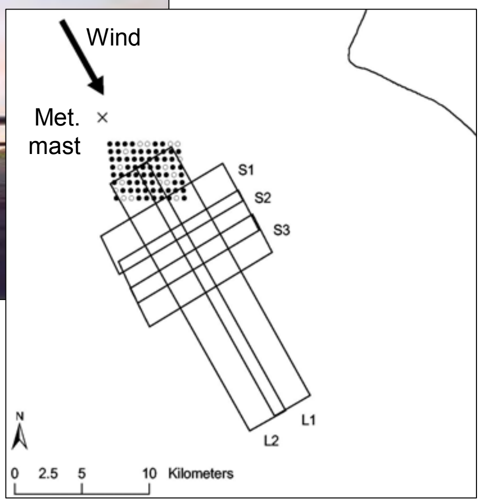
Merete Bruun Christiansen





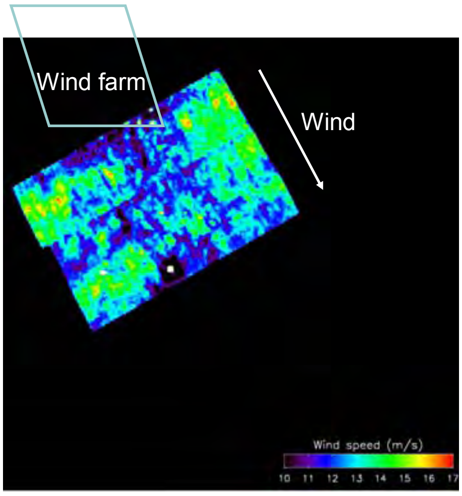
Airborne SAR (E-SAR)

12 October 2003

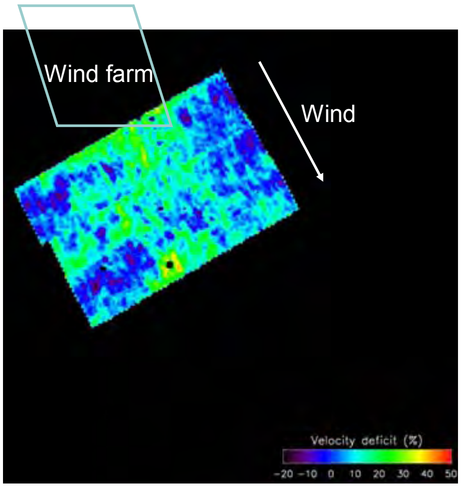


5 flight tracks in C-band VV

Winds from E-SAR in CVV

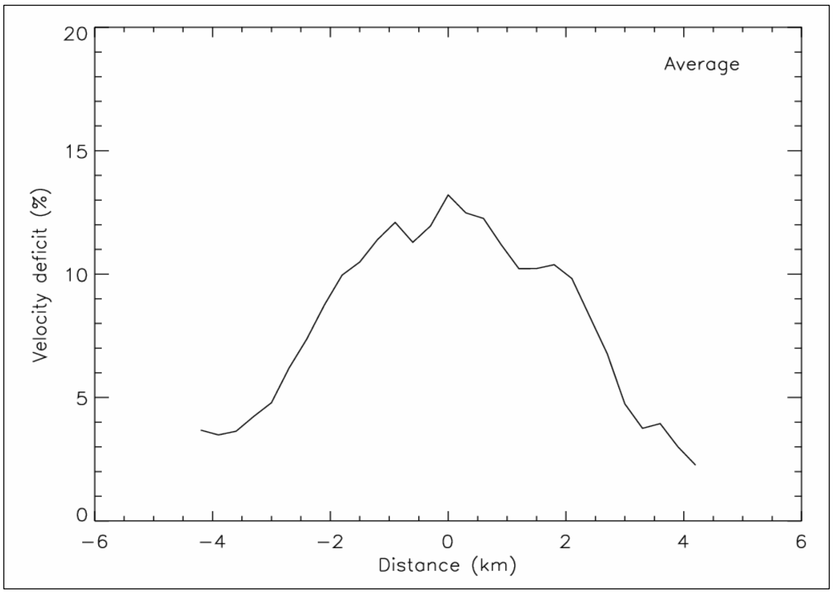


Wind speed



Velocity deficit

Merete Bruun Christiansen



Conclusions

Wind resources can be estimated from satellite wind maps as a supplement to in-situ data:

- ERS SAR and Envisat ASAR with high spatial but low temporal resolution
- QuikSCAT with medium spatial but high temporal resolution

Wake velocity deficit can be quantified from SAR satellite and airborne wind maps.

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Offshore winds using remote sensing techniques

Description of a 6-months wind assessment campaign at the world's largest wind farm using LIDAR and SODAR measurements

IEA R&D Wind Task11, Topical Expert Meeting 51

Alfredo Peña[1] Charlotte Hasager[1], Sven-Erik Gryning[1], Torben Mikkelsen[1], Ioannis Antoniou[1], Michael Courtney[1], and Paul Sørensen[2]

[1] Risø National Laboratory
[2] Dong Energy

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Goal

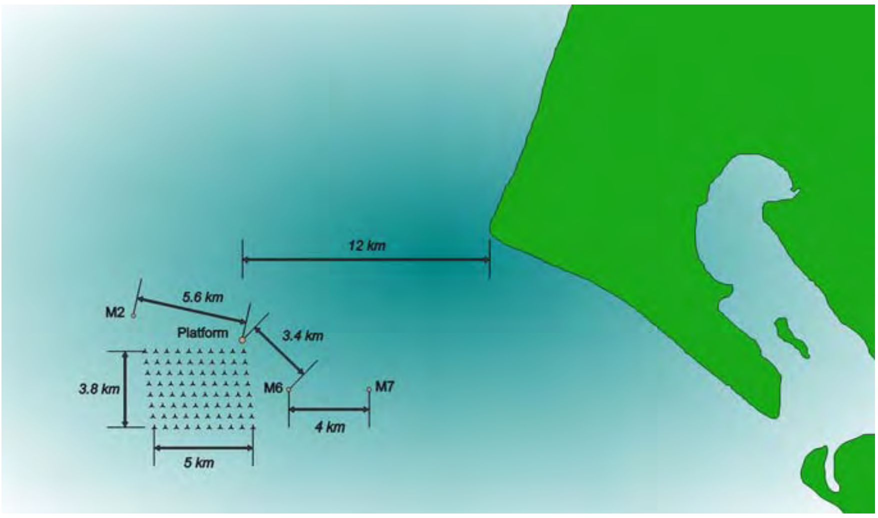
- Experimental investigation of offshore wind and turbulence characteristics for heights between 70 and 200m using state of the art remote sensing techniques.

Why?

- Wind turbines are starting to operate in higher range of heights because wind speeds are higher and less turbulent at these levels.
- Offshore conditions have great potential for wind industry (higher winds, less turbulence, low roughness lengths).
- LIDAR and SODAR have been tested by Risø mainly on land showing high correlations with cup and sonic anemometers
- Difficulties to erect high masts at offshore locations due to costs and structural problems.

DTU RISØ

Horns Rev wind farm



DTU RISØ

Meteorological masts and transformer platform


Courtesy: Dong Energy

- Cup anemometers and vanes at different levels on all masts (15~70m)
- Pressure, humidity, rain and irradiation are also available

- LIDAR/SODAR installed at 20m on the platform
- Campaign period: May 2 – Oct 29, 2006

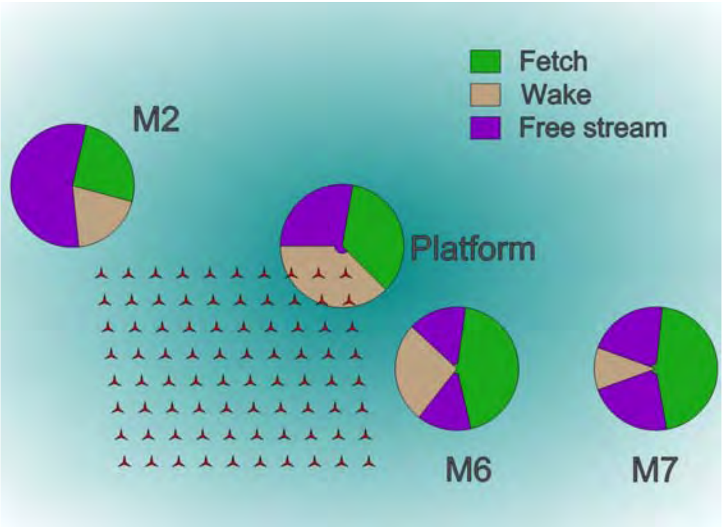

Courtesy: Dong Energy

LIDAR/SODAR

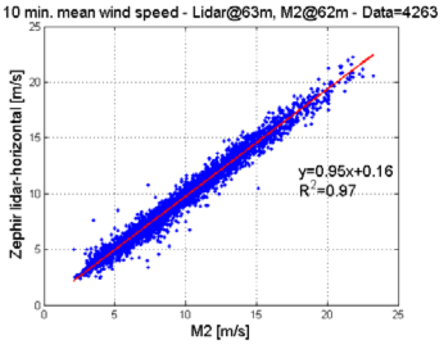
- LIDAR: QinetiQ's ZephIR Wind Lidar
- Measuring heights: 63, 91, 121, 161m (300m for cloud correction)
- u, w, wind direction, TQE ~18s from the spectra

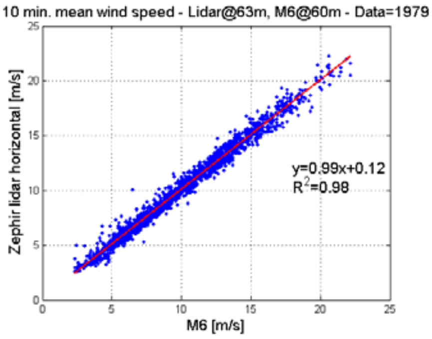
- SODAR: AQ500 system
- Measuring heights: 30m to 210m steps at 15m
- 10 min average values showing u, v, w, wind dir, σ_u, σ_v, σ_w and σ_{dir}

Sectors for the four main locations

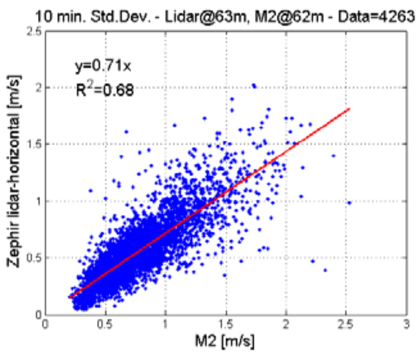


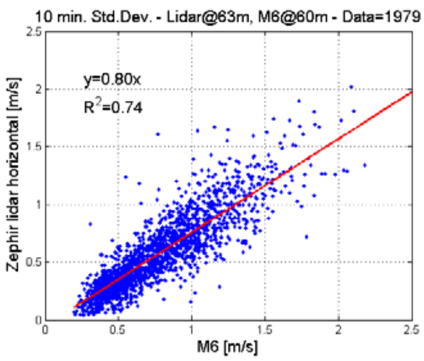
Correlations between LIDAR and M2/M6 for free sectors



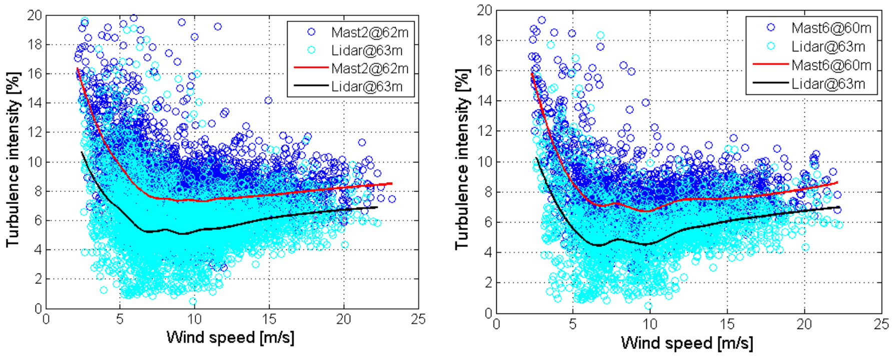


Correlation of turbulent parameters in free sectors for M2/M6

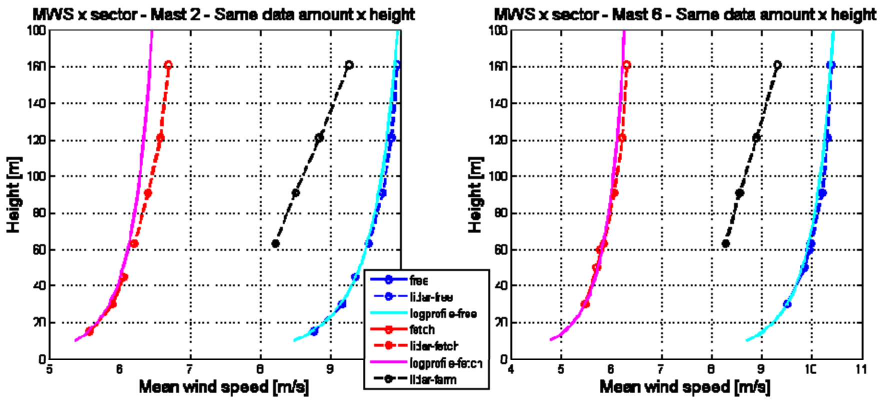




Turbulence intensity behavior with wind speed for M2/M6



Wind profile extension with LIDAR data at M2/M6



Summary

- LIDAR shows a very high correlation compared to Mast data in free sectors (Masts at ~4 km from the platform)
- LIDAR turbulence follows cup's turbulence. Further investigation at Risø on the effect of the averaging volume in LIDAR's measurements
- T.I. increases at high wind speeds (>10 m/s) for both LIDAR and cup measurements
- Wind farm's wake is measured for first time with a LIDAR in offshore conditions
- Offshore wind speed profiles are extended beyond surface layer for first time using LIDAR measurements. Stability analysis of the profiles is in process
- Further analysis of SODAR data. Availability of data depends on height

Horns Rev wind farm

Other uses of the QinetiQ lidar at Risø

J. Mann, F. Bingöl, G. C. Larsen, E. Dellwik and S. Ott
Risø National Laboratory/DTU, Denmark

January 21, 2007

Other uses of the QinetiQ lidar at Risø

J. Mann, F. Bingöl, G. C. Larsen, E. Dellwik and S. Ott
Risø National Laboratory/DTU, Denmark

January 21, 2007

- Flow over a forest: mean wind and turbulence

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- The wake behind a wind turbine

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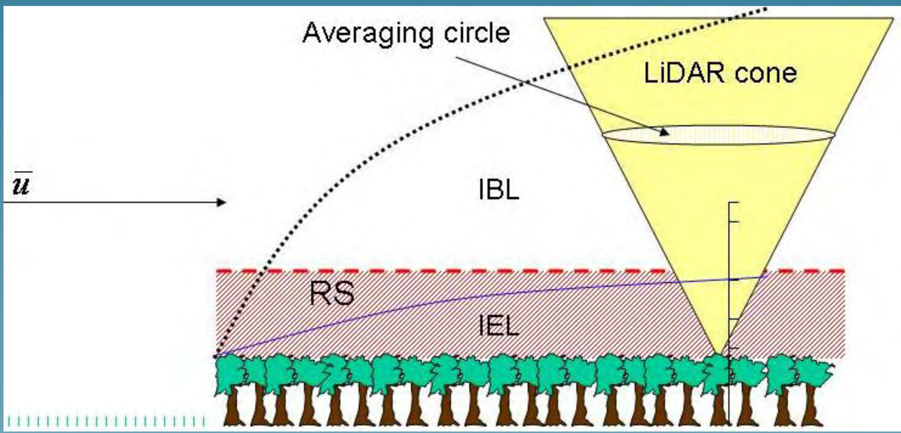
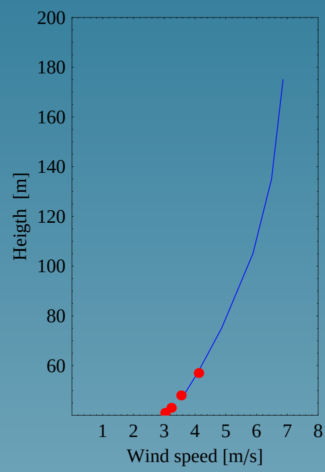
Risø National Laboratory/DTU, Denmark

January 21, 2007

- Flow over a forest: mean wind and turbulence
- The wake behind a wind turbine

The Sorø Forest Experiment





Lidar measures radial velocity

Because the half opening angle of the cone is $\approx 30^\circ$ the radial velocity is

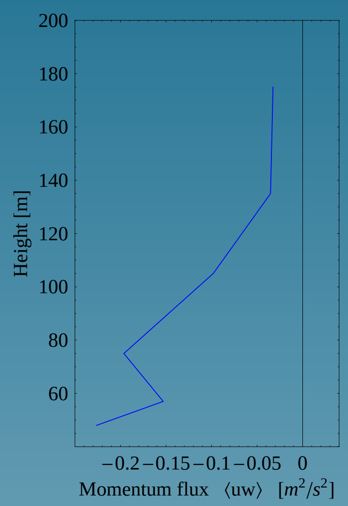
$$v_r = \left| \frac{1}{2} u \cos\theta + \frac{1}{2} v \sin\theta + \frac{\sqrt{3}}{2} w \right|,$$

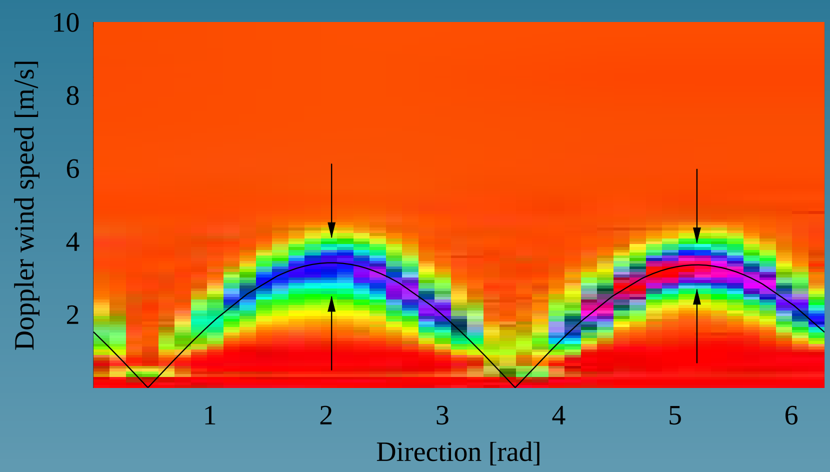
where θ is the horizontal angle from the downwind direction. The fluctuations in the upwind ($\theta = \pi$) and downwind ($\theta = 0$) directions are

$$\begin{aligned}\sigma^2(v_{r,up}) &= \frac{1}{4}\sigma_u^2 + \frac{3}{4}\sigma_w^2 - \frac{\sqrt{3}}{2}\langle u'w' \rangle \\ \sigma^2(v_{r,down}) &= \frac{1}{4}\sigma_u^2 + \frac{3}{4}\sigma_w^2 + \frac{\sqrt{3}}{2}\langle u'w' \rangle\end{aligned}$$

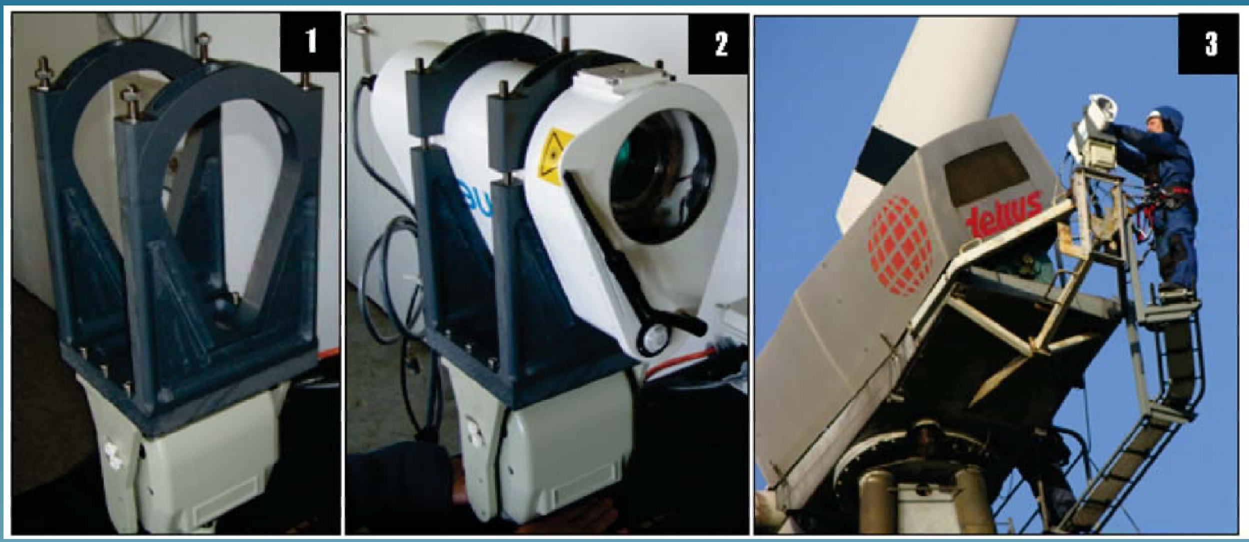
so subtracting these equations the momentum flux $\langle u'w' \rangle$ can be obtained.

Momentum flux profile and average Doppler spectra



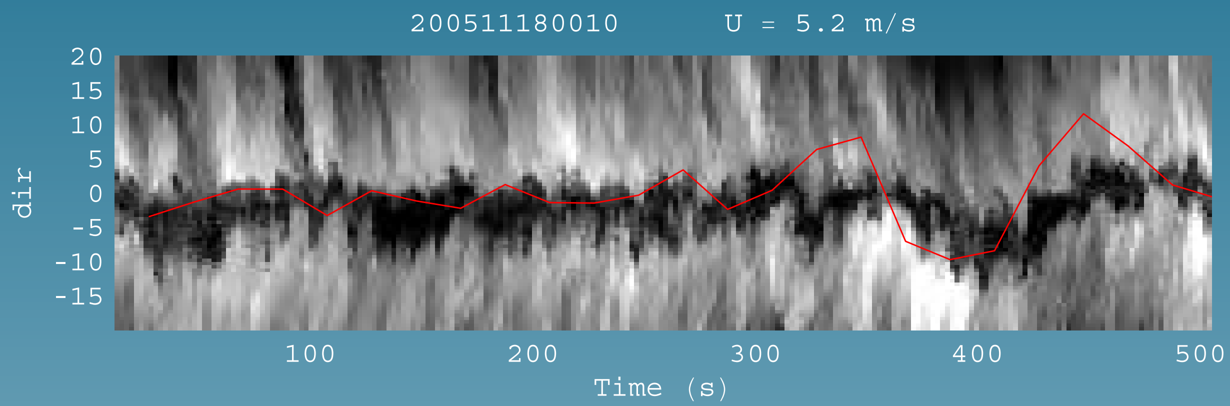


The Tellus wake experiment



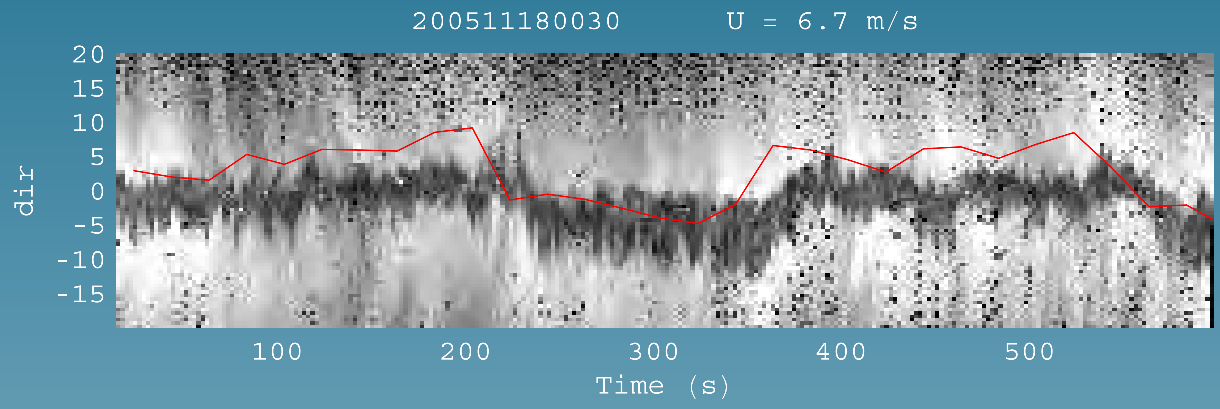
Laser Doppler data (1:5)

Comparison with averaged wind direction:



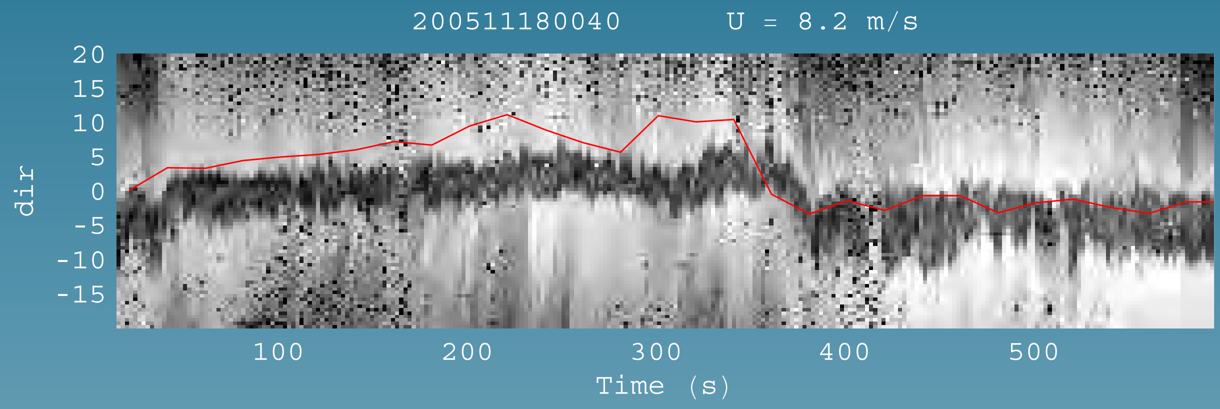
Laser Doppler data (2:5)

Comparison with averaged wind direction:



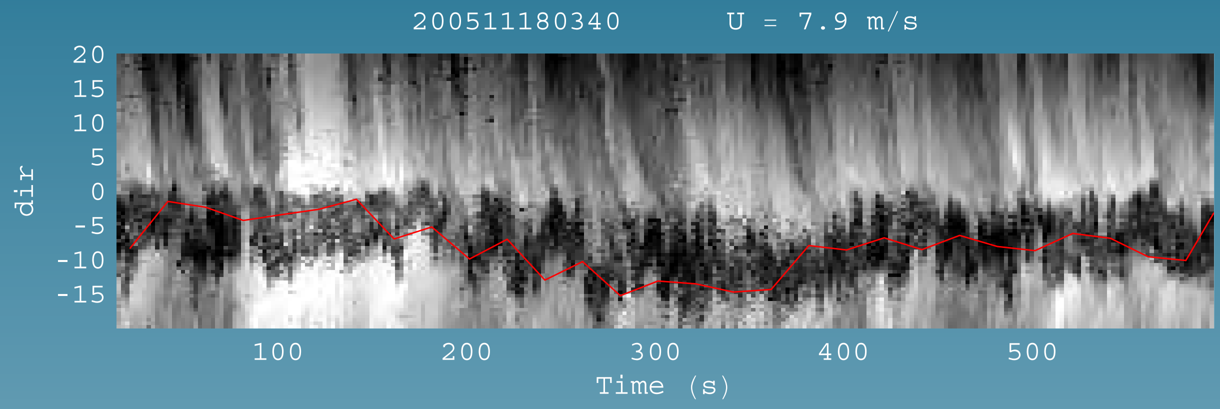
Laser Doppler data (3:5)

Comparison with averaged wind direction:



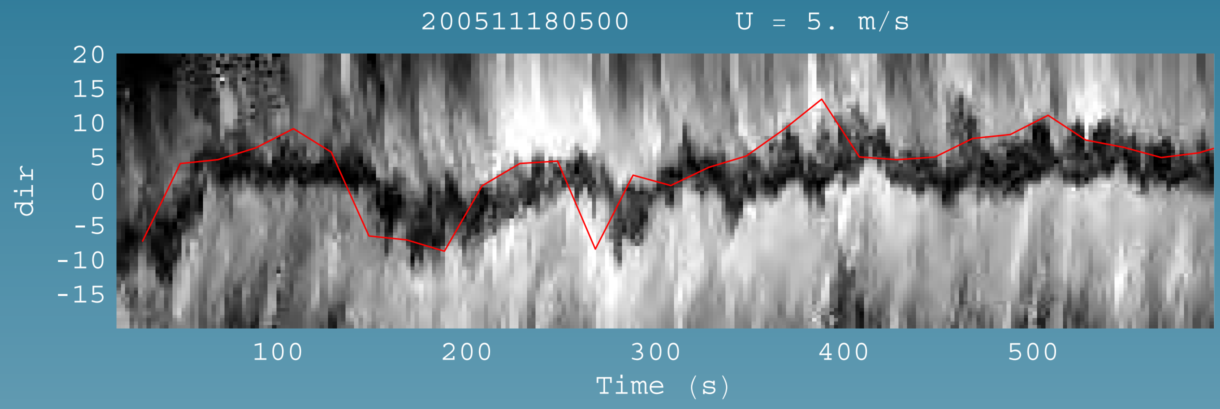
Laser Doppler data (4:5)

Comparison with averaged wind direction:

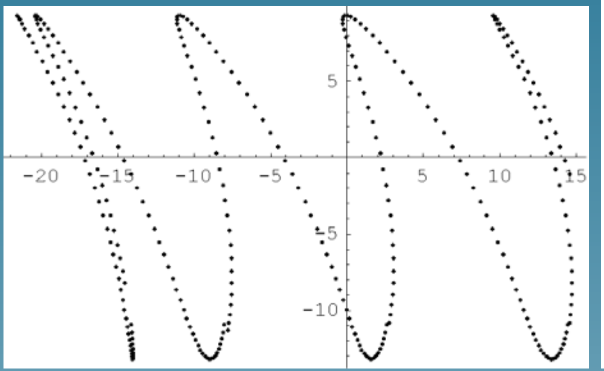


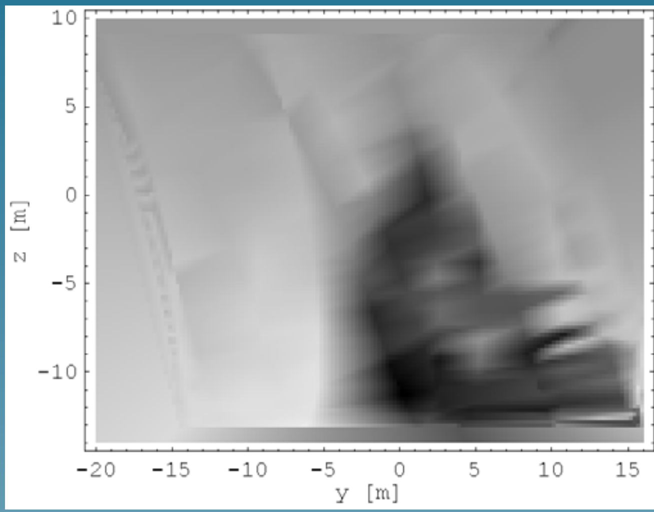
Laser Doppler data (5:5)

Comparison with averaged wind direction:

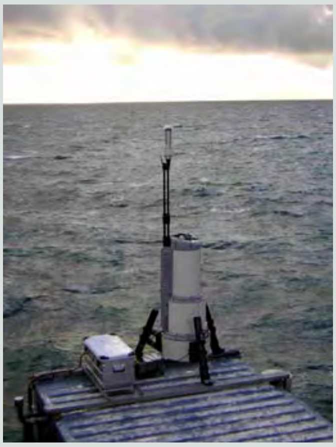


"TV scanning" of a wake





On- and Offshore Assessment of the ZephIR Wind-LiDAR



Detlef Kindler
WINDTEST Kaiser-Wilhelm-Koog GmbH

Andy Oldroyd
Oldbaum Services Ltd.

IEA R&D Task 11, Wind Energy

51st Topical Expert Meeting

on Remote Sensing

RISØJanurary 2007

Scottish and Southern Energy plc

TALISMAN ENERGY

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Title

IEA T.E.M. RISØ Jan 2007 Slide No. 1

Oldbaum Services Ltd.

- Motivation of test programm, acceptance criteria
- Onshore campaign at 5M site, Brunsbüttel
- Offshore campaign on FINO-1:
- Summary of assessment campaign

- o WS turbulence
- o Met. conditions: precipitation and visibility
- o WS profiles
- o Twin experiment

➢ Further objectives
  - technical experiences
  - offshore challanges
  - future applications

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Outline

IEA T.E.M. RISØ Jan 2007 Slide No. 2

Oldbaum Services Ltd.

- Remote Sensing (LiDAR) chosen as the primary wind resource monitoring method for the DOWNViND / *Beatrice Windfarm Demonstrator Project*

- Assessment of the capabilities of the the system in terms of availability and data quality
- Suitability for offshore challanges as of an installation on Beatrice

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Motivation

IEA T.E.M. RISØ Jan 2007 Slide No. 3

Oldbaum Services Ltd.

Acceptance criteria for the ZephIR being used as the primary wind monitioring method on the Beatrice Alpha platform:

→ **Availability** **> 95 % (system & data)**

→ **Data quality** **relative to cups**
linear regressions through origin

Y = mx + b (i.e.with b==0)

0.97 < m < 1

R^2 > 97%

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Acceptance Criteria

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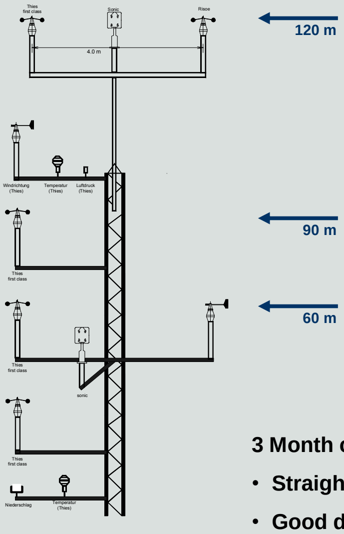

3 Month campaign

- Straight forward setup procedures
- Good data access

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Onshore Test Site

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Data Storage Period No.	Start Date	End Date	Height Settings	Cloud Correction
1 to 6	14.9.2005	30.9.2005	120 / 300	off
7 to 16	30.9.2005	8.11.2005	120 / 300	off
17 to 24	8.11.2005	19.12.2005	60, 90, 120, 150 / 300	off
24 twin	15.12.2005	19.12.2005	60, 90, 120, 150 / 300	off
25 to 27	19.12.2005	5.1.2006	60, 90, 120, 150 / 300	on

Overall System Availability: 99.6 %

Overall Data Availability (10-Min.-Av.): 95.2 %

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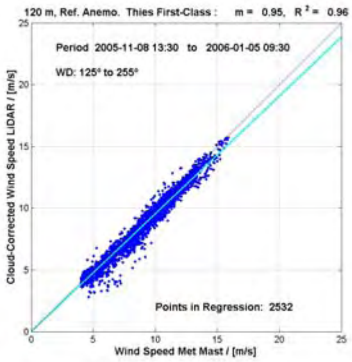
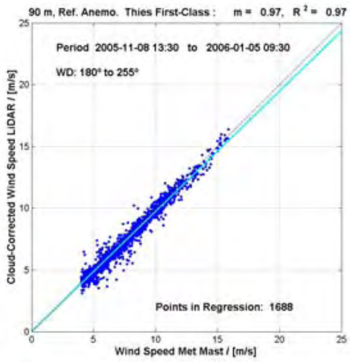
Availability Onshore

IEA T.E.M. RISØ Jan 2007 Slide No. 6

Oldbaum Services Ltd.





120m **Slope:** m = 0.95

Regr. coefficient: $R^2 = 0.96$

90m **Slope:** m = 0.97

Regr. coefficient: $R^2 = 0.97$

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WS Regressions Onshore

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Oldbaum Services Ltd.

Onshore

Sector	125° to 255°	180° to 255°			
	CUP	CUP		CUP	
1st Period	**120 m**	**90 m**		**60 m**	
10-min-avg. values	3034	/		/	
Slope "m"	**0.94**	/		/	
Regr. Coeff "R^2"	**0.95**	/		/	
	CUP	CUP		CUP	SONIC
2nd Period	**120 m**	**90 m**		**60 m**	
10-min-avg. values	2532	1688		1577	1568
Slope "m"	**0.95**	**0.97**		**0.99**	**1,00**
Regr. Coeff "R^2"	**0.96**	**0.97**		**0.95**	0.93

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Onshore results

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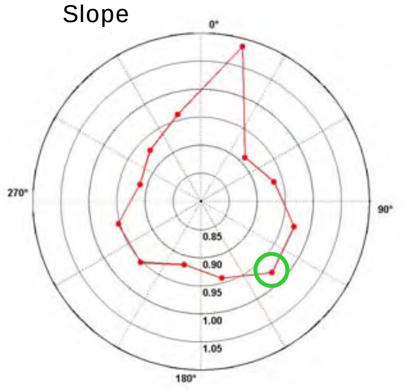
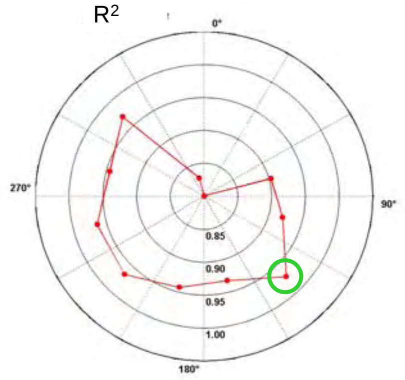
Cup / LiDAR Sector Wise Comparison 120m

Slope



R^2



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WS Regressions Onshore

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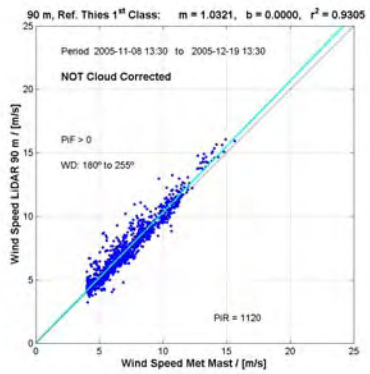
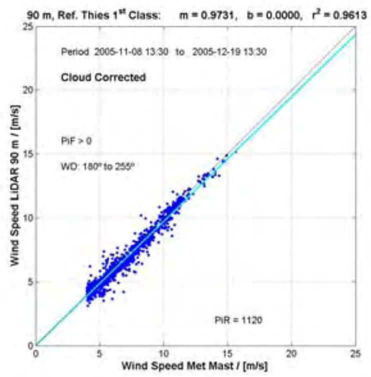
No Correction **90 m AGL** **Cloud Correction Applied**





Slope:
m = 1.03

Regr. coefficient:
R^2 = 0.93

Slope:
m = 0.97

Regr. coefficient:
R^2 = 0.96

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Cloud correction check

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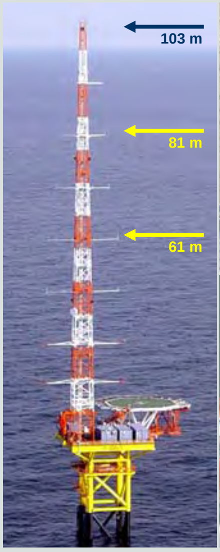
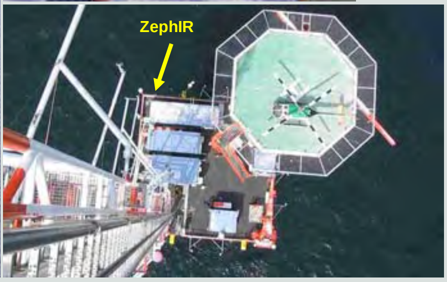
Oldbaum Services Ltd.



- North Sea, 45 km North of Island Borkum (D)
- Platform height: 20 m
- Mast top height: 103 m
- Annual mean wind speed on 100m app. 10 m/s
- Prevailing wind dir. SW



- 5 Month campaign March to July 2006
- 3 Comparison levels cups, vanes, sonics

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FINO-1 Offshore Test Site

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Period No.	Data Storage Period No.	Start Date	End Date	Heigth Settings	Cloud Correction
1	1 & 2	2.3.2006	11.4.2006	78 / 300	on
2	3 - 6	11.4.2006	26.6.2006	36, 56, 78, 100 / 300	on
2a	7 & 8	26.6.2006	1.7.2006	36, 56, 78, 100 / 300	off
2b	9	3.7.2006	5.7.2006	36, 56, 78, 100 / 300	on
2c	10	5.7.2006	13.7.2006	36, 56, 78, 100 / 300	off

Overall System Availability: 100.0 %

Overall Data Availability (10-Min.-Av.): 99.6 %

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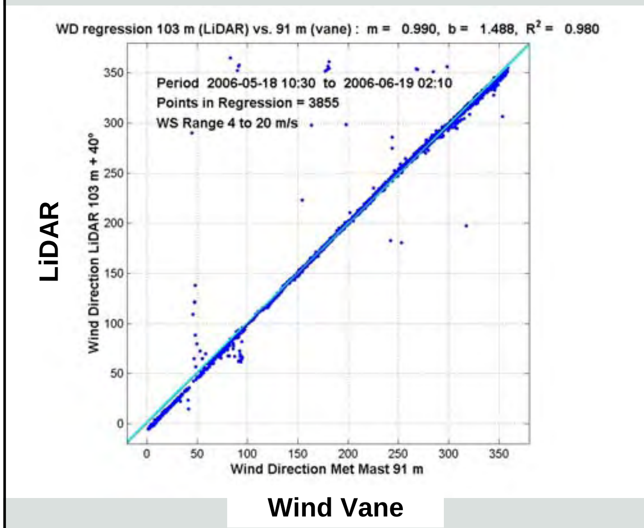
Availability Offshore

IEA T.E.M. RISØ Jan 2007 Slide No. 12

Oldbaum Services Ltd.



Height:
103 (78) m

WS range:

2 to 20 m/s

Slope:
m = 0.99
b = 1.48

Regr. coefficient:

R^2 = 0.98

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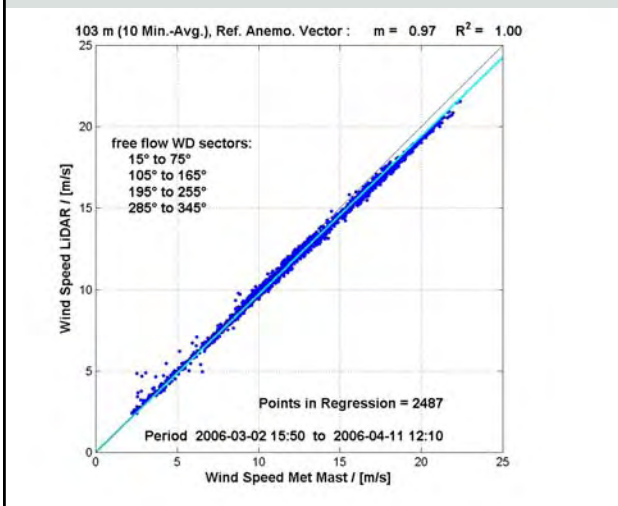
Wind Direction Comparison

Oldbaum Services Ltd.

IEA T.E.M. RISØ Jan 2007 Slide No. 13



Height:
103 (78) m

WS range:

2 to 23 m/s

Slope:
m = 0.97

Regr. coefficient:

R^2 = 0.99

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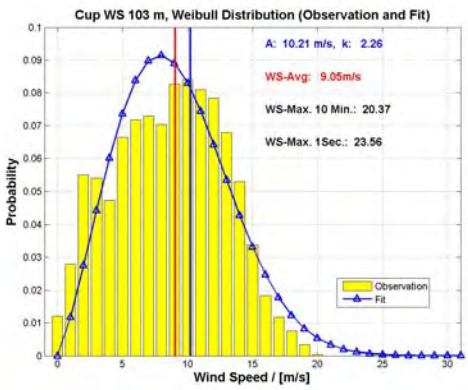
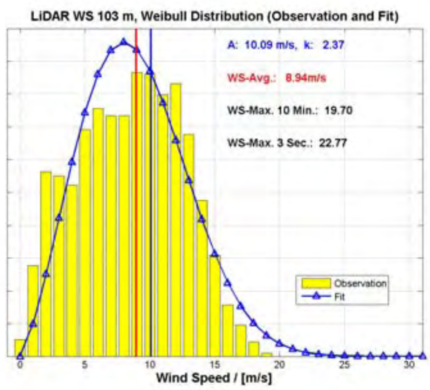
WS Comparison Offshore

Oldbaum Services Ltd.

IEA T.E.M. RISØ Jan 2007 Slide No. 14





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WS Weibull Distribution

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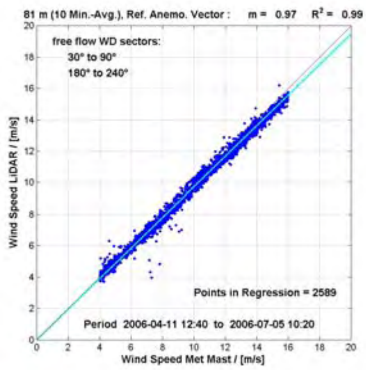
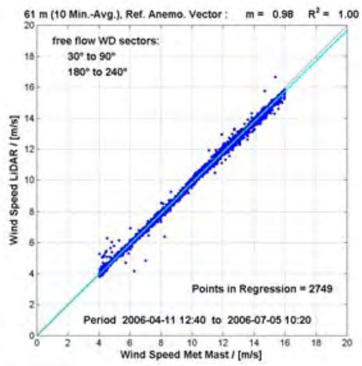
81 (56) m

61 (36) m





Slope:
m = 0.97

Regr. coefficient:
R^2 = 0.99

Slope:
m = 0.98

Regr. coefficient:
R^2 = 1.00

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WS Regressions Offshore

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Offshore

Analysis Sector	15°-75°, 105°-165°, 195°-255°, 295°-345°	30° to 90° and 180° to 240°		0° to 60° and 210° to 270°	
	CUP				
1st Period	103 (78) m	81 (56) m	61 (36) m		
10-min-avg. values	1965	/	/		
Slope "m"	0.97	/	/		
Regr. Coeff "R^2"	0.99	/	/		
	CUP			SONIC	
2nd Period	103 (78) m	81 (56) m	61 (36) m	81 (56) m	61 (36) m
10-min-avg. values	6005	2589	2749	3228	3245
Slope "m"	0.98	0,97	0,98	1,01	1,01
Regr. Coeff "R^2"	0.99	0.99	1,00	0.99	1,000

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Offshore results

IEA T.E.M. RISØ Jan 2007   Slide No. 17

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- **The QinetiQ ZephIR system has been subject to a stringent test campaign to test the quality of data output;**
- **The system has performed well onshore despite the complexity of the terrain surrounding the test site and passed acceptance;**
- **System has been tested offshore in similar conditions to the final deployment location on Beatrice, results offshore show better correlation than that returned onshore;**
- **Most promising results are**
  - **→ WS deviation from Cups < 3%**
  - **→ Availibility close to 100% (NO weather dependence seen)**
  - **→ good handling, easy to install**
- **System has passed acceptance onshore and offshore;**
- **ZephIR has returned quality results in both on- and offshore environments indicating its potential for deployment in the wind industry in both on- and offshore environments.**

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Summary of Assessment

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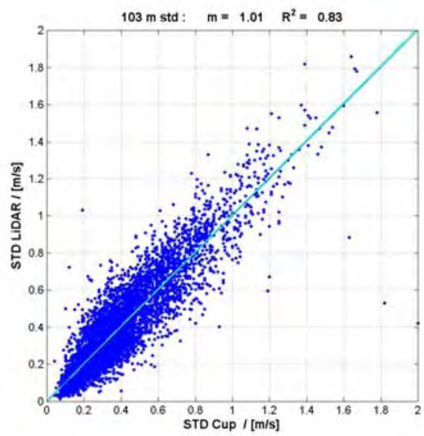
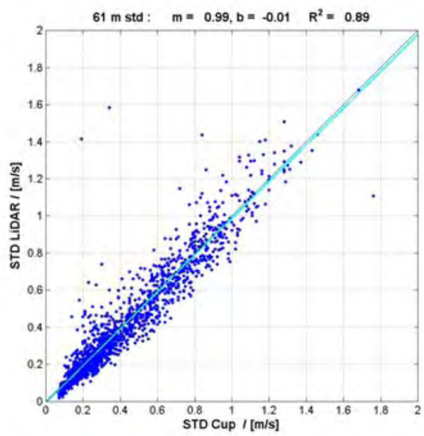
Oldbaum Services Ltd.





103m **Slope:**
m = 1.01
Regr. coefficient:
R^2 = 0.83

61m **Slope:**
m = 0.99
Regr. coefficient:
R^2 = 0.89

Turbulence Offshore (%)

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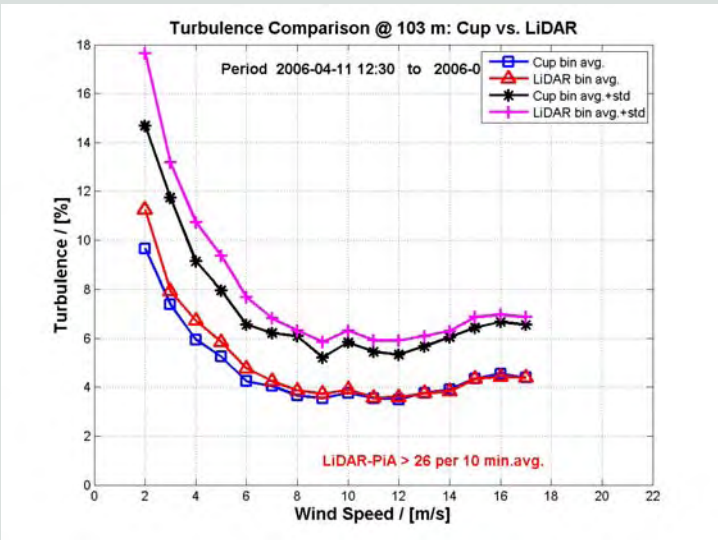
IEA T.E.M. RISØ Jan 2007 **Slide No. 19**

Oldbaum Services Ltd.

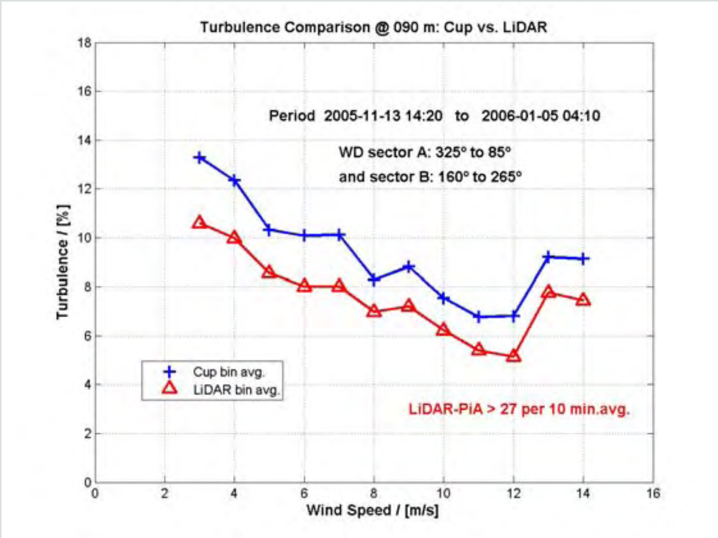


Turbulence Offshore (%)

WINDTEST
Kaiser-Wilhelm-Koog GmbH

IEA T.E.M. RISØ Jan 2007 **Slide No. 20**

Oldbaum Services Ltd.



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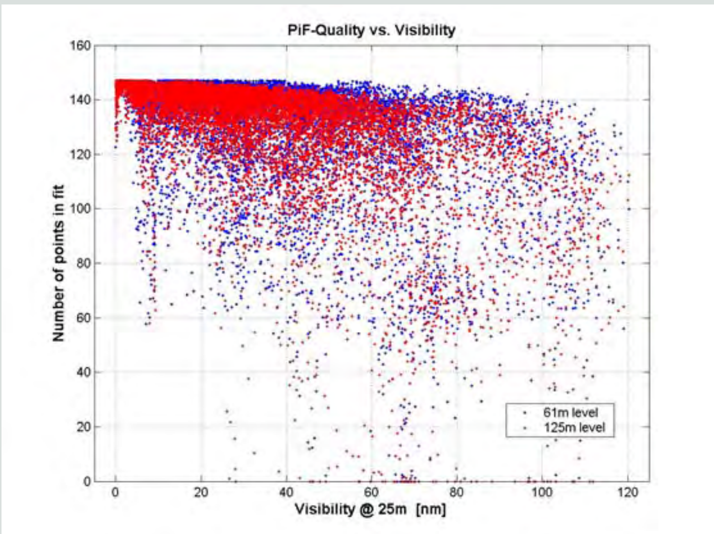
Turbulence Onshore (%)

Oldbaum Services Ltd.

IEA T.E.M. RISØ Jan 2007 Slide No. 21



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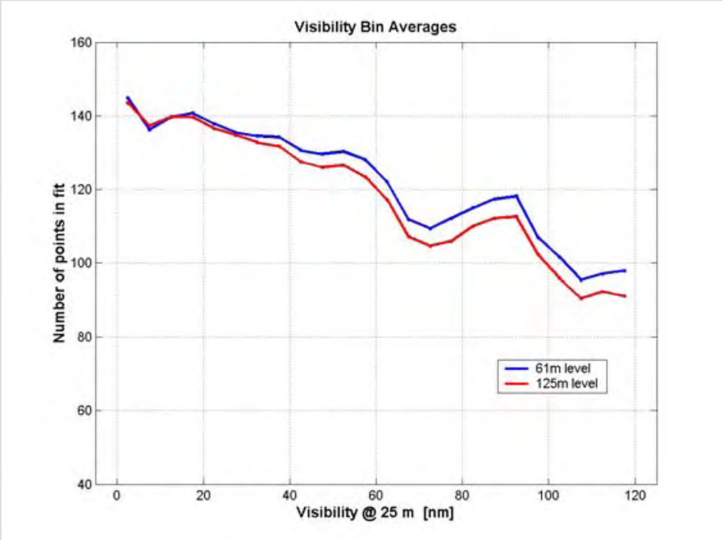
Quality (PiF) vs. Visibility

Oldbaum Services Ltd.

IEA T.E.M. RISØ Jan 2007 Slide No. 22



Quality (PiF) vs. Visibility

Case		2nd Period				
	WD Sector	15°-75°, 105°-165°, 195°-255°, 295°-345°	30° to 90° and 180° to 240°			
	Meas. Height	103 m	81	61	81	61
	Anemometer	CUP	CUP	CUP	SONIC	SONIC
		WS range: 4 to 16 m/s				
I. Without Filtering						
	10-min-avg. values	6005	2589	2749	3228	3245
	Slope "m"	0,98	0,97	0,98	1,01	1,01
	Regr. Coeff "R^2"	0,99	0,99	1,00	0,99	1,00
II. Precipitation NO						
	10-min-avg. values	5460	2234	2370	2876	2881
	Slope "m"	0,98	0,97	0,98	1,01	1,01
	Regr. Coeff "R^2"	0,99	0,99	1,00	1,00	1,00
III. Precipitation YES						
	10-min-avg. values	545	355	379	352	364
	Slope "m"	0,98	0,97	0,98	1,00	1,00
	Regr. Coeff "R^2"	0,99	0,99	0,99	0,99	0,99

→No precipitation influence

Precipitation Offshore

Sector	125° to 255°	180° to 255°		
No Filtering [a]	**CUP**	**CUP**	**CUP**	**SONIC**
2^{nd} Period	**120 m**	**90 m**	**60 m**	
10-min-avg. values	2532	1688	1577	1568
Slope "m"	**0.95**	**0.97**	**0.99**	**1,00**
Regr. Coeff "R^2"	**0.96**	**0.97**	**0.95**	**0.93**
Precipitation NO [b]	**CUP**	**CUP**	**CUP**	**SONIC**
2^{nd} Period	**120 m**	**90 m**	**60 m**	
10-min-avg. values	1787	1209	1146	1133
Slope "m"	**0.95**	**0.97**	**0.98**	**0.99**
Regr. Coeff "R^2"	**0.96**	**0.97**	**0.95**	**0.95**
Precipitation YES [c]	**CUP**	**CUP**	**CUP**	**SONIC**
2^{nd} Period	**120 m**	**90 m**	**60 m**	
10-min-avg. values	745	479	431	435
Slope "m"	**0.96**	**0.98**	**1.00**	**1.01**
Regr. Coeff "R^2"	**0.96**	**0.97**	**0.93**	**0.89**

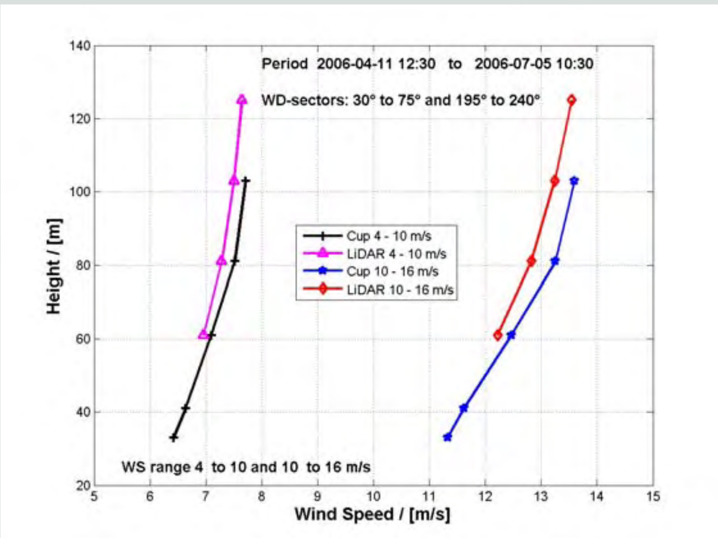
→No significant precipitation influence

WINDTEST
Kaiser-Wilhelm-Koog GmbH

Precipitation Onshore

IEA T.E.M. RISØ Jan 2007 **Slide No. 25**

Oldbaum Services Ltd.



WINDTEST
Kaiser-Wilhelm-Koog GmbH

Profiles Offshore

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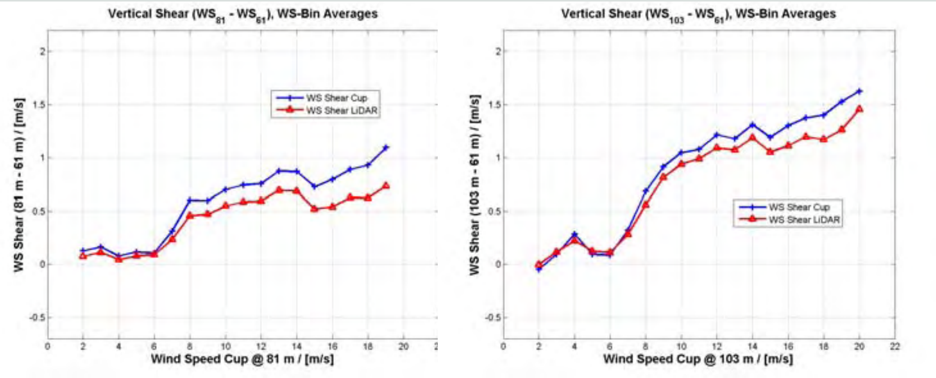
Oldbaum Services Ltd.



WS Shear Offshore (%)

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Twin Experiment

Device to Device

WINDTEST
Kaiser-Wilhelm-Koog GmbH

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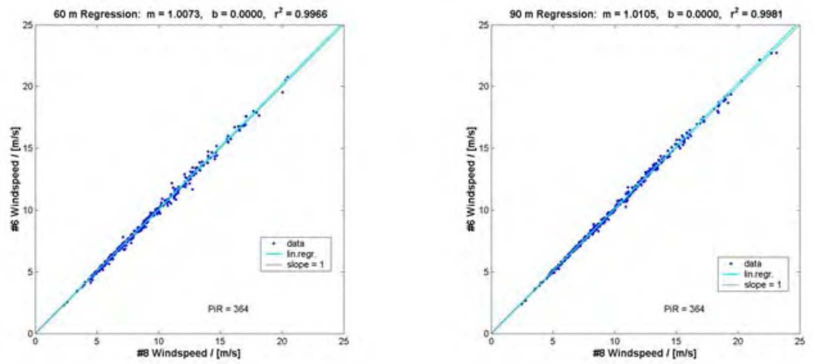

Technical Experiences

- handling, general
- setup on site
- theft pre-cautions
- data retrieval
- wind data acquisition
- turbulence measures

Challenges Offshore

- accessibility
- structural stability
- weather during erection
- proximity to mast / available space
- power supply
- screen clearance, salt & spray
- debris from birds
- corrosion: joints and aluminium parts
- remote control & data retrieval

Acceptance and Standardized Application

- perform a number of real applications to increase experiences and knowledge of the system
- share experiences within the user community
  - scientific
  - best practice application
- create reproducible calibration procedures
  - focal length
  - absolute wind speed accuracy
- assure device to device reproducibility
- test site and position independent behaviour of system
- test each device individually against same standard prior to (and after?) actual deployment

Applications & Options

- wind resource studies
- power performance tests
  - profiles over rotor plane
- site assessments
  - Turbulence
  - WS WD shear
  - Max. WS
- gust forecasting
- wind turbine wake studies

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Our Results Gained with Lidar, and How we Interpret the Status

Axel Albers
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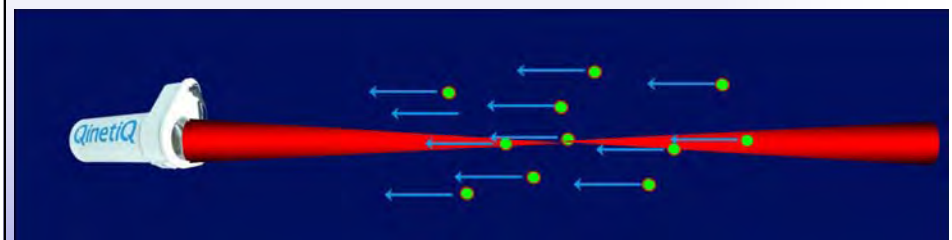
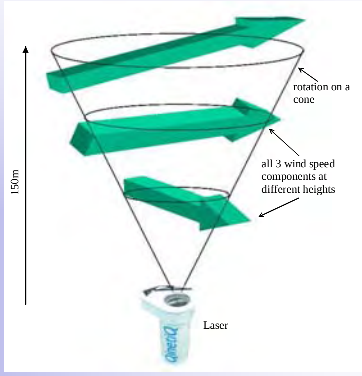
testing- and calibration laboratory with
quality management system according EN ISO/IEC 17025:2000

LIDAR: Light Detection And Ranging



- laser beam reflects at particles (aerosols, dust, droplets)
- QinetiQ's ZephIR: definition of measurement position by focussing of the laser beam
- reflected laser beam has a Doppler-shift in the frequency proportional to the wind speed component in the direction of the laser beam

QinetiQ's ZephIR: Wind Scanning by Rotation of Laser Beam



- determination of all 3 wind speed components by rotation of laser beam on a cone
- determination of wind speeds at different heights by successive focussing of laser at different distances

Technical Specification ZephIR

- 1575nm eye safe laser
  - no permit needed
- high sensitivity laser
  - only 1 of 10^{12} photons has to be reflected
- sample rate: 50 MHz
- rotational speed: 1 Hz
- measurements at 50 azimuth angles
- 3 revolutions per measurement height:
  - output of 3-s-averages
- cone angle: 30°
- automatic elimination of reflections from moving objects
- total weight 134 kg
- power consumption: 100W

Measurement Sites

Westdorf 65m Mast
flat terrain

Emden 124m mast
wind comes over sea

Data Availability of ZephIR

65m measurement height:

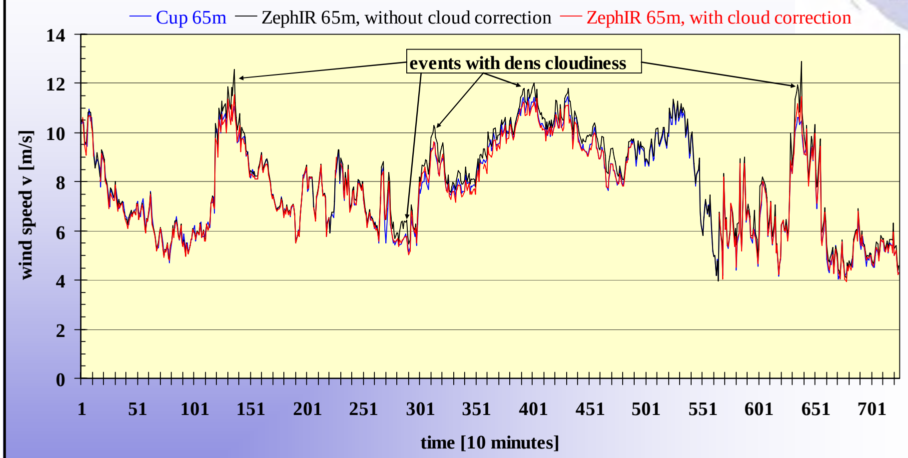
99.7% valid data of horizontal components

124m measurement height:

96.1% valid data of horizontal components

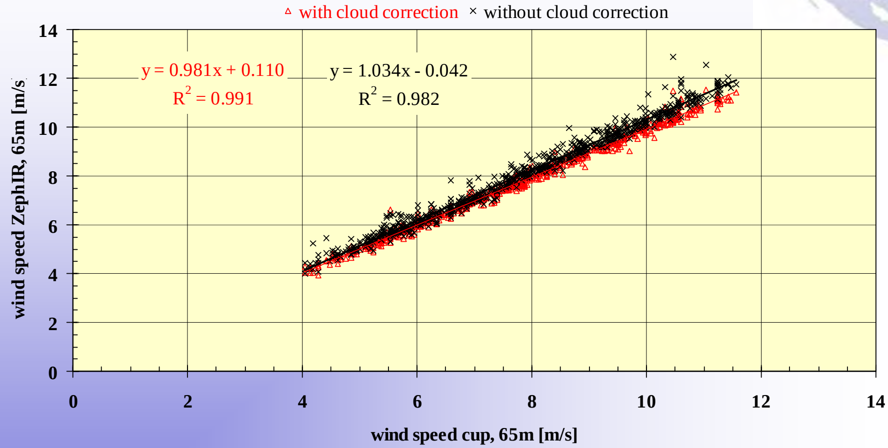
- very high rate of valid data, despite partly bad weather like heavy rain, snow, icing conditions
- availability of vertical component: 71.8% in Emden
- vertical component invalid at rain, snow etc.

Cloud Correction



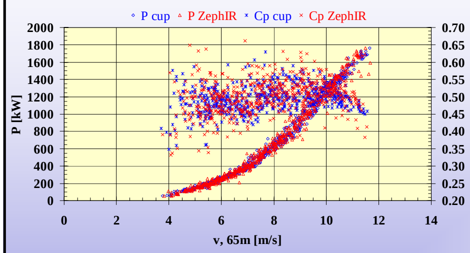
- at bad weather overestimation of wind speed by high cloud backscatter
- solution: cloud correction, additional measurement at 300m. Spectrum at 300m is subtracted from spectrum at target height.

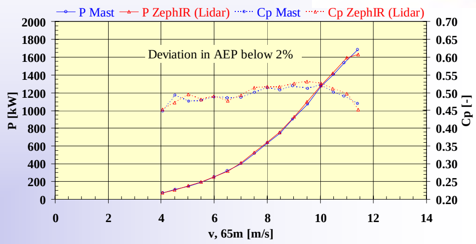
v-horizontal, 65m height



- brilliant performance with cloud correction: bias=-0.04m/s, standard deviation of deviation=0.18m/s
- no filtering applied (except of wind direction), i.e. rain data included

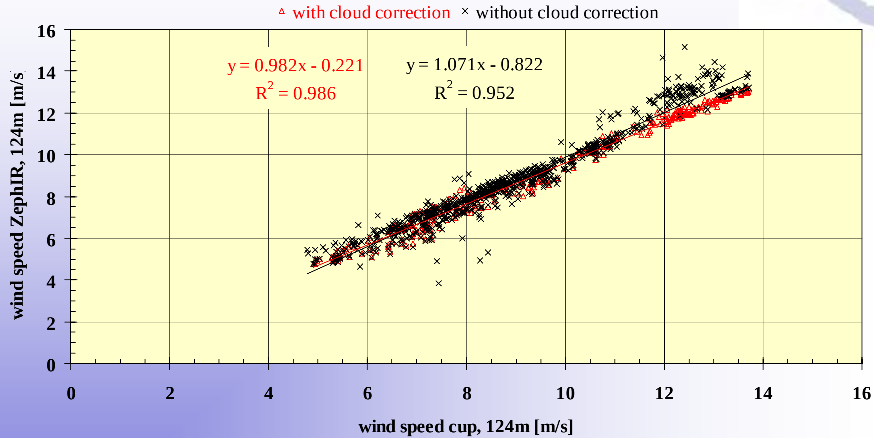
Power Curve Measurement H=65m





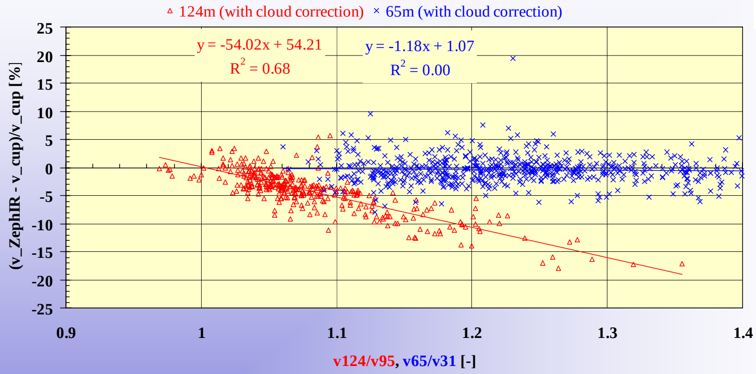
- deviations smaller than uncertainty of cup anemometer

v-horizontal, 124m height



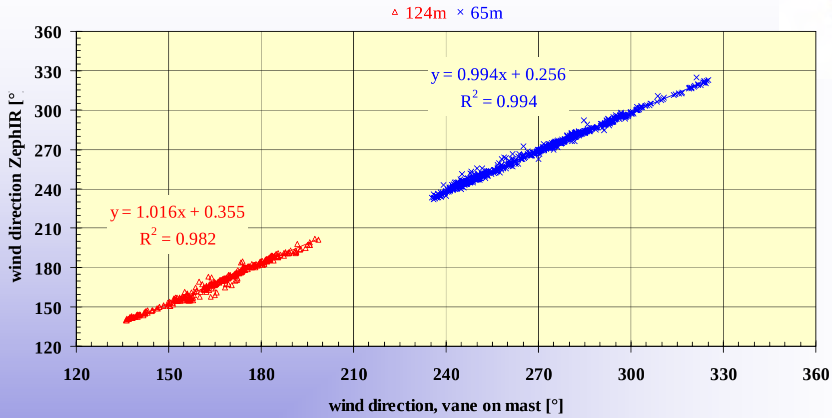
- with cloud correction: bias=-0.39m/s, standard deviation of deviation=0.30m/s
- with cloud correction: same slope of 0.98 at 65m height and 124m height, but different offsets

Underestimation of Wind Speed at Large Measurement Heights



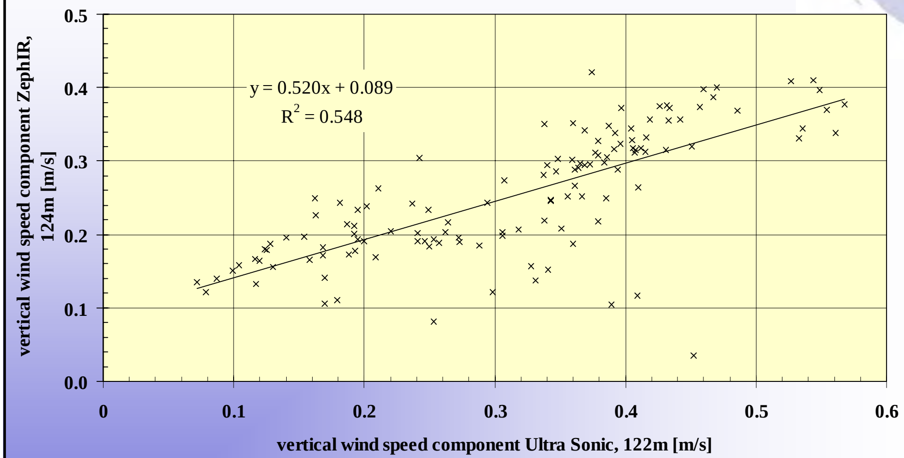
- Investigation: Which variables influence deviation to cup anemometer
- Result: At large measurement height increasing underestimation of wind speed with increasing wind shear
- Assumed origin: The effective probe lengths increases from about 5m at 65m height to about 30m at 124m height.
- Solutions under development: corrections, filter

Wind Direction



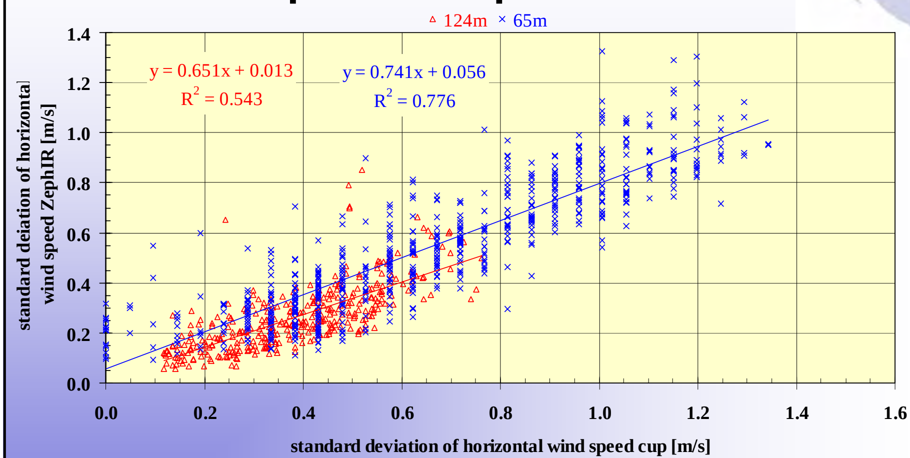
- good statistics of 10-minute averages
- At single 3-second averages the detected direction is switched around.

Vertical Wind Speed Component



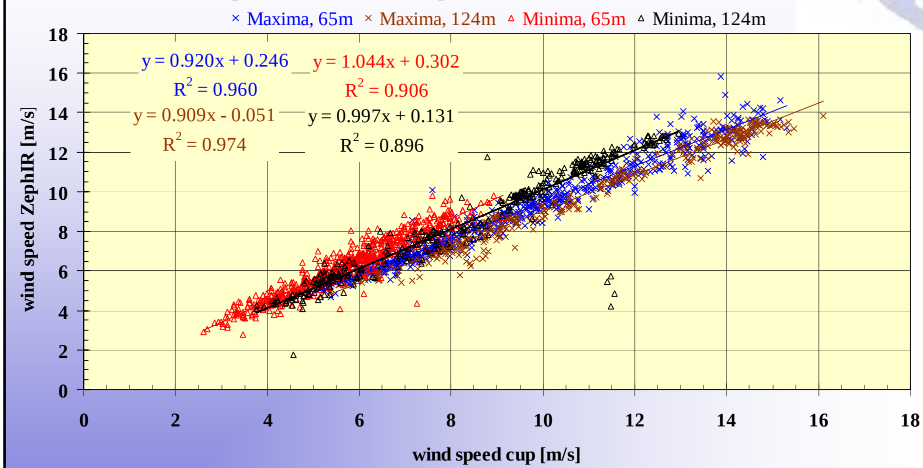
- poor correlation, eventually due to relatively low vertical component at the site Emden
- average deviation: 0.06m/s
  standard deviation of deviation: 0.08m/s

Standard Deviation of Horizontal Wind Speed Component



- underestimation of turbulence due to spatial averaging and 3s-averaging (cup-anemometer: 1s-averaging)

Extreme Values of Horizontal Wind Speed Component



- maxima are underestimated, minima are overestimated
- underestimation of extreme values due to spatial averaging and 3s-averaging (cup-anemometer: 1s-averaging)

Conclusions

- high availability of valid data
- very accurate at lower measurement heights
- at larger measurement heights tendency to underestimation of wind speeds, increasing with vertical wind shear (improvement under development)
- accurate wind direction measurement
- vertical wind speed components need further investigation
- turbulence intensity and extreme values are underestimated
- room for improvement by further data correction and filtering

Preliminary comparative ZephIR Lidar results to cup anemometer measurements

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Test and Measurements
Wind Energy Department
Risø-DTU

www.risoe.dk

Contents of the presentation

- Experiences with ZephiR lidar I 2006
- ZephIR Lidar comparisons to the met mast measurements
- The planned measurement campaigns within the "UPWIND" and the "Improved Performance Methods" projects.

ZephiR experiences in 2006

- 2 ZephiR lidars (unit 8 and unit 2)
- Comparative measurements at Risø and Høvsøre
- Offshore measurements at Horns Rev
- Much “childhood sickness”
- Problems often arising after shipment
- Software ok for typical “developer” applications
- Software poorly suited to research and on-line measurements

The Høvsøre Test Station and the experimental setup (1)

- Measurement sector: 240°-300°
- The measurements started primo December. They will continue for at least one year (ZephIR unit 8).
- The ZephIR unit 2 will be deployed next to unit no. 8 on Tuesday 23-01-07.
- One ceilometer will be permanently deployed within two weeks.

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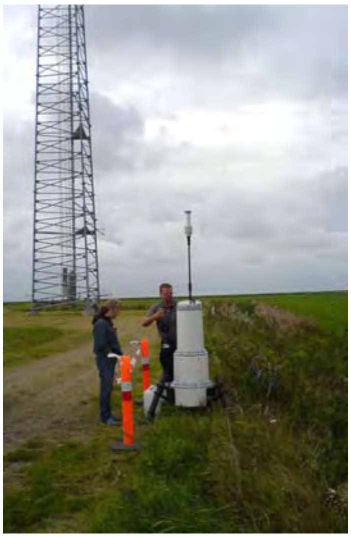
The Høvsøre Test Station and the experimental setup (2)



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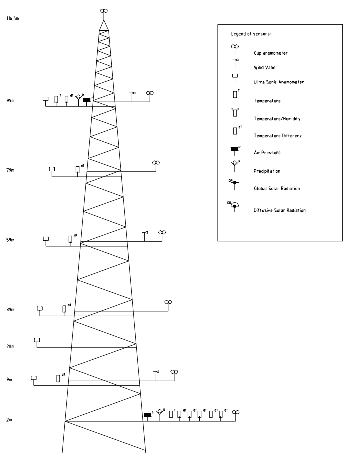
The Høvsøre Test Station and the experimental setup (3)

The instrumentation of the met mast

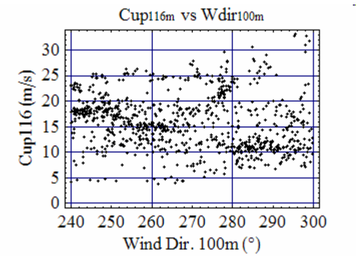


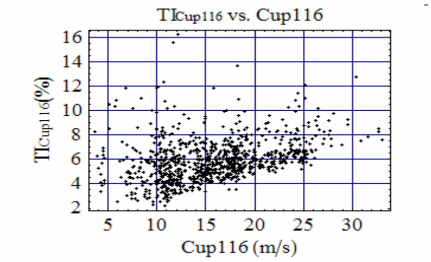
Sensor	Position
Cup anemometer	116.5m
Cup anemometer, wind vane, sonic anemometer, temperature, differential temperature, relative humidity, air pressure	100m
Cup anemometer, sonic anemometer, differential temperature	80m
Cup anemometer, sonic anemometer, differential temperature, wind vane	60m
Cup anemometer, sonic anemometer, differential temperature	40m
Sonic anemometer	20m
Cup anemometer, sonic anemometer, differential temperature, wind vane	10m
Cup anemometer, temperature, differential temperature, relative humidity, air pressure, rain	2m

The lidar ZephIR measured parameters

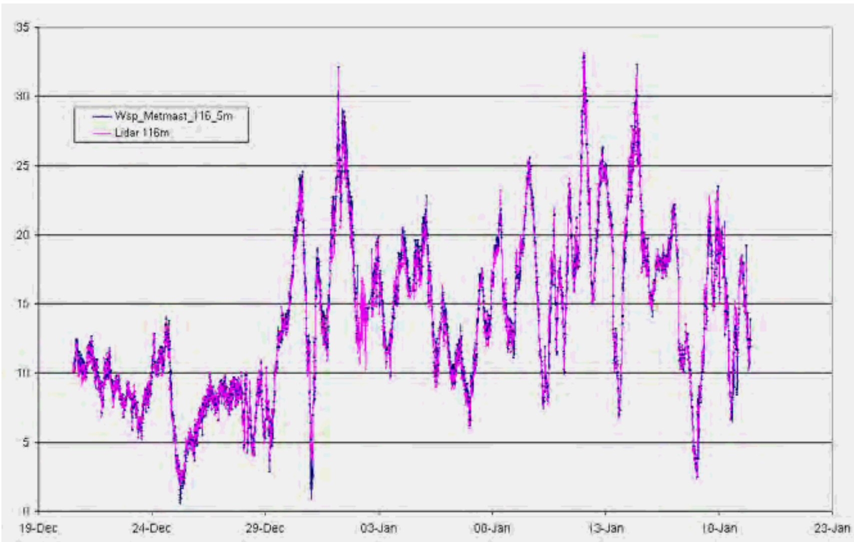
- Measuring heights 300,116,100,80,40m
- Data collected – 3sec ZephiR results and 50Hz raw spectra
- Derived 10 minute means and standard deviations of:
  U, W, dir
- Re-calculation using own algorithms from 50Hz spectra.
- Mast cup (10Hz) and sonic data (20Hz) saved .

Cup anemometer measurements

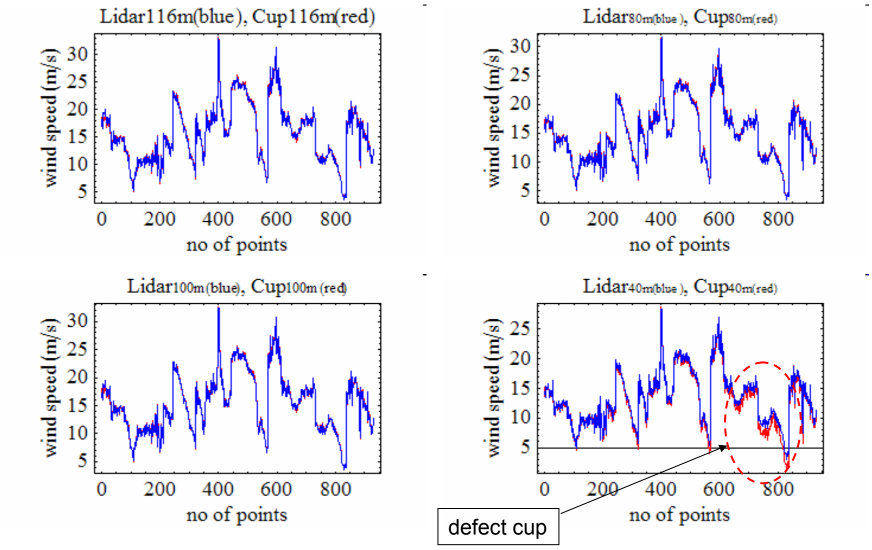




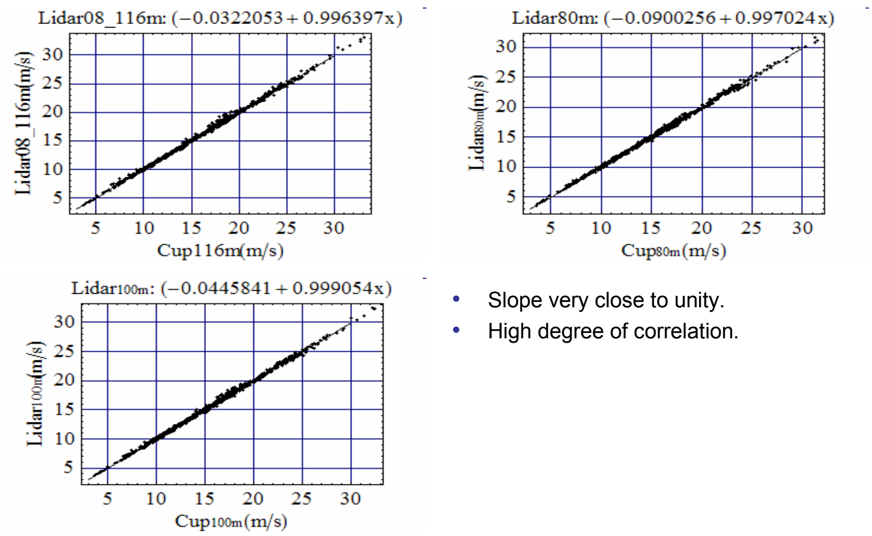
Lidar and cup at 100m vs time, all data (unfiltered)



Lidar-cup hor. wind speed measurements (dry weather data)

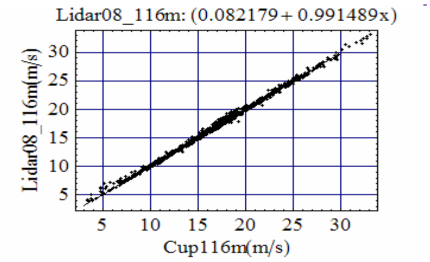


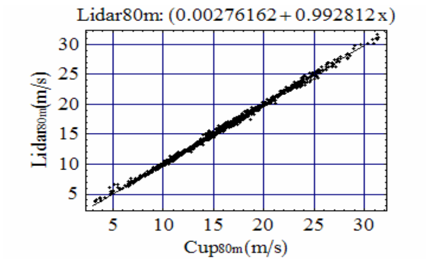
Lidar-cup slope (dry weather data)

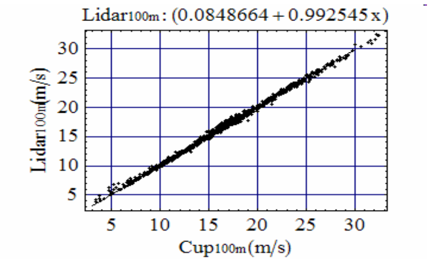


- Slope very close to unity.
- High degree of correlation.

Lidar-cup slope (ALL weather data, wsp>3m/s, 20% rain points)

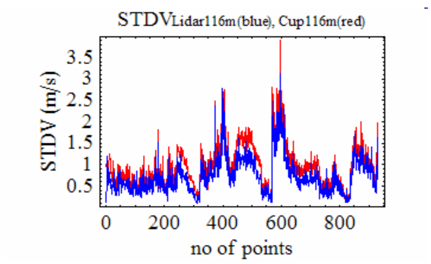


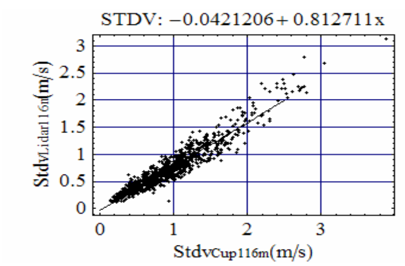


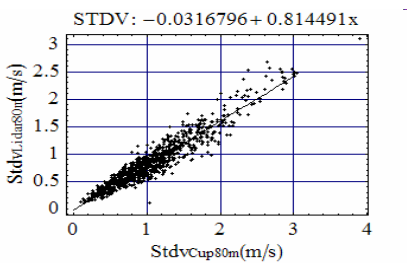


- Rain influences the relation lidar-cup.
- However it is difficult to evaluate the influence of rain on each instrument as both are influenced.
- Increased scatter.
- More work is needed.

Lidar-cup STDV (dry weather data)







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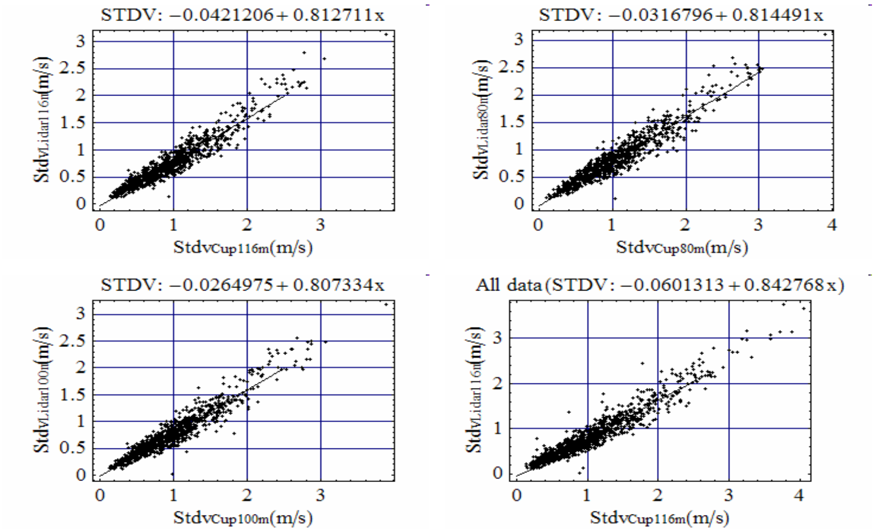
Lidar-cup STDV slope (dry weather data)



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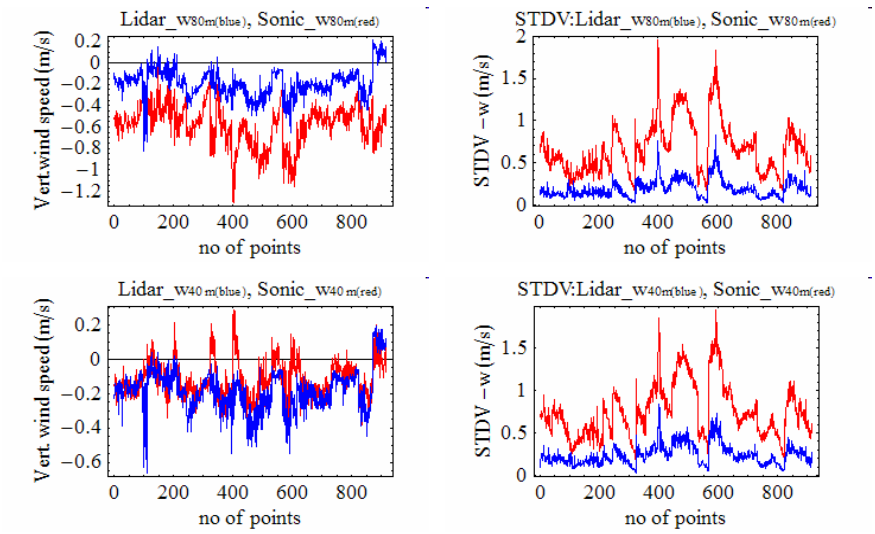
Lidar-sonic vertical wind speed (dry weather data)



Future plans

- Commissioning of remote sensing test sites (now)

- Long term ZephiR evaluation (1 year)
- Side-by-side ZephiR evaluation (3 months)

- Power curve measurements 1 (hub cup replacement)
- Power curve measurements 2 (vertical wind profile over rotor)
- Power curve measurements 3 (wind over whole rotor)

- Test of other lidar concepts

- Introduction of lidar to standards

Conclusions

- Zephir very promising

- Teething problems being solved

- Høvsøre remote sensing test facility now in operation

Turbulence measured by the ZephIR™:

The Effects of Conical scanning and Lorentzian Probe Volume Filtering

by

Torben Mikkelsen and Hans E. Jørgensen

Wind Energy Department
Risø National Laboratory

1. Introduction

The purpose of this note is to investigate the effective turbulence obtained from horizontal “figure of eight” averaged scans obtained with the conically scanning Coaxial ZephIR™ wind Lidar system.

We start with the usual neutral Kaimal spectra:

$$\begin{aligned} n\,S_u(n)/u_*^2 &= \frac{102n}{(1\ +\ 33n)^{5/3}} \\ n\,S_v(n)/u_*^2 &= \frac{17n}{(1\ +\ 9.5n)^{5/3}} \\ n\,S_w(n)/u_*^2 &= \frac{2.1n}{(1\ +\ 5.3n^{5/3})} \end{aligned} \qquad (1.1)$$

where the dimensionless frequency n has been defined as $n = fz/U$, where f is frequency in Hz, z is measurement height above the ground, and U is the (10-min averaged) mean wind speed.

If we let the upper non-dimensional frequency $n_{max} = f_{\max} z/U$ go to infinity the corresponding definite integrals can be evaluated (u, v analytically, and w via Mathematica , cf. the figures in Eqs.(1.2). For comparison is added: the figures in parentheses ( ) are text book “standard” relations. The figures in (( )) come from Panofsky H.A. & J.A Dutton. Atmospheric Turbulence: Models and Methods for Engineering Applications; Wiley: New York (1984).

$$\frac{\sigma_u^2}{u_*^2} = \int_0^\infty \frac{102}{(1 + 33n)^{5/3}} dn \approx 2.15^2; \qquad (2.5^2); \qquad ((2.39^2))$$
$$\frac{\sigma_v^2}{u_*^2} = \int_0^\infty \frac{17}{(1 + 9.5n)^{5/3}} dn \approx 1.64^2; \qquad (2.0^2); \qquad ((1.98^2)) \tag{1.2}$$
$$\frac{\sigma_w^2}{u_*^2} = \int_0^\infty \frac{2.1}{(1 + 5.3n^{5/3})} dn \approx 1.24^2; \qquad (1.3^2); \qquad ((1.25^2))$$

To investigate the effect of filtering, both by the focussed beams probe volume (the Lorentzian optical probe filter), and by the horizontal conical scanning, we first rewrite the Kaimal spectra in dimensional form:

$$\frac{\sigma_u^2}{u_*^2} = \frac{z}{U} \int_0^{n_{max} U/z} \frac{102}{(1 + 33 fz/U)^{5/3}} df$$

$$\frac{\sigma_v^2}{u_*^2} = \frac{z}{U} \int_0^{n_{max} U/z} \frac{17}{(1 + 9.5 fz/U)^{5/3}} df \tag{1.3}$$

$$\frac{\sigma_w^2}{u_*^2} = \frac{z}{U} \int_0^{n_{max} U/z} \frac{2.1}{1 + 5.3\left(fz/U\right)^{5/3}} df$$

Eqs.(1.3) is of the form

$$\sigma_i^2 = \int_0^{n_{max} U/z} S_i(f)\, df;$$

where

$$S_u(f) = u_*^2 \frac{z}{U} \frac{102}{(1 + 33 fz/U)^{5/3}} \quad \left[\frac{m^2}{s^1}\right] \tag{1.4}$$
$$S_v(f) = u_*^2 \frac{z}{U} \frac{17}{(1 + 9.5 fz/U)^{5/3}} \quad \left[\frac{m^2}{s^1}\right]$$
$$S_w(f) = u_*^2 \frac{z}{U} \frac{2.1}{1 + 5.3\left(fz/U\right)^{5/3}} \quad \left[\frac{m^2}{s^1}\right]$$

To evaluate the effect of spatial filtering we transform these frequency spectra into wave number spectra by use of the relations

$$S_i(f)df = F_i(k_1)dk_1$$
$$\frac{d\omega}{dk} = U = 2\pi\frac{df}{dk} \text{ (Taylors frozen turbulence hypothesis)}$$
$$\omega = 2\pi f = Uk_1$$
$$f = \frac{U}{2\pi}k_1; \quad f_{max} = \frac{U}{2\pi}k_{1,\max} \Leftrightarrow k_{1,\max} = \frac{2\pi}{U}f_{max}$$
$$df = \frac{U}{2\pi}dk_1$$

So that

$$\sigma_i^2 = \int_0^{n_{max}U/z} S_i(f)\,df = \int_0^{\frac{2\pi}{z}n_{max}} S_i(\frac{U}{2\pi}k_1)\,\frac{U}{2\pi}dk_1 = \int_0^{k_{1,\max}} F_i(k_1)dk_1$$

by use of the relations: (1.5)

$$f = \frac{U}{2\pi}k_1; \quad f_{max} = \frac{U}{2\pi}k_{1,\max}; \quad k_{1,\max} = \frac{2\pi}{U}f_{max} = \frac{2\pi}{U}n_{max}U/z = \frac{2\pi}{z}n_{max} \quad ; df = \frac{U}{2\pi}dk_1$$

For instance, the Kaimal u- spectrum in wave number space then looks like:

$$F_u(k_1) = u_*^2\frac{z}{U}\frac{U}{2\pi}\frac{102}{(1 + 33\left(\frac{U}{2\pi}k_1\right)z/U)^{5/3}} = u_*^2\frac{z}{2\pi}\frac{102}{(1 + 33\frac{k_1 z}{2\pi})^{5/3}}\left[\frac{m^3}{s^2}\right] \qquad (1.6)$$

2 Models for the ZephIR's spatial filters due to averaging

2.1 Averaging associated with the Lorentzian optical probe volume:

In the note " On the Lorentzian weighting function-LIDARs spatial weighting" it was shown that the variance as measured with an upwind-looking (Spinner-based) Lidar, could be calculated from a low-pass Lorentzian-filtered turbulence of the Horizontal wave number spectrum $F_u(k_1)$

$$\overline{\langle u\rangle^2} = \int_{-\infty}^{\infty} F_u\left(k_1\right) e^{-2z_R k_1} dk_1 \qquad (1.7)$$

That is, the lidar measured variance results from the Longitudinal turbulence spectrum low-pass filtered by an exponential filter with a cut-off wave number given by $k_1 \approx 1/2z_R$.

In standard constant azimuth $(\varphi = 30^0)$ LDA scanning mode, the ZephIR lidar measures a combination of the *(u, v, w)* velocity components. If we assume that the boundary layer turbulence is approximately isotropic on the limited scale of the Lorentzian filters HWHM parameter z_R, we can assume that the Lorentzian filter applies to all three velocity components, so we can define:

The Lorentzian optical probe volume is given by:

$$L_{Lorentzian}(k_1) = e^{-2z_R k_1} \qquad (1.8)$$

2.2 Averaging associated with the three-revolution 3-s horizontal azimuth scans:

A simple model can be made if we assume that the resulting 3-s wind vector is obtained from an average of the stream wise wind component over the area covered by three revolutions:

An effective instantaneous horizontal averaging length scale can be estimated as the combined result of time lag and the circular coverage, which for the ZephIR lidar is equal to the scan diameter (The ZephIR lidar scans a horizontal circle of diameter D equal to $\frac{1}{Cos(30)} = \frac{2}{\sqrt{3}}$ times the measurement height, i.e. $(D \approx 1.15z)$. For example, at a measuring height of 100 meters, the lidar beam rotates at a speed of $\pi D \approx 363\left[ms^{-1}\right]$. With the ZephIR's inherent spectral sampling frequency of 200.000 samples per second, it corresponds to an azimuthal displacement of the laser beam of ~ 1.81 mm between two consecutive raw-spectral estimates. The ZephIR then averages such 4000 spectra during (5µS x 4000 averages), i.e. in ~ 20 milliseconds (50 Hz) over an azimuth distance corresponding to 1.81 mm times 4000scans equal to an azimuthal conical segment of ~ 7.26 meters.

In addition, the scan area covers a horizontal length scale given by the advection of the wind field by the mean wind speed during the ZephIR sampling time (3 s), see Fig.1:

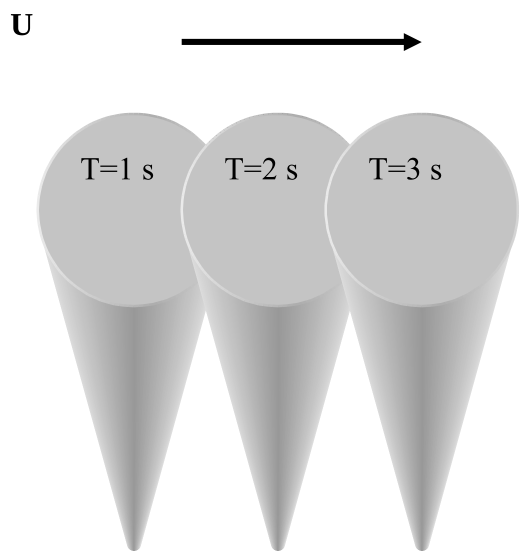


Fig.1 The measurement area covered by the ZephIR lidar after three complete 2π- azimuth scans, one per second, in a flow with mean wind speed U.

Therefore, a simple effective horizontal length scale, l_{az}, representing an effective filter-averaging length scale from sampling over three consecutive perpetual revolutions (6π azimuth), can to a first approximation be modelled by:

$$l_{az} = D + U\Delta T = \frac{1}{Cos(30)} z + 3U = \frac{2}{\sqrt{3}} z + 3U \tag{1.9}$$

If we model the effect of the 3-sec lasting 2 revolution azimuth scanning with a "Box car-like" filter function, we can further assume that the corresponding *Sinc* filter function ($\frac{\sin^2 x}{x^2}$) applies as a low-pass filter on the turbulence in wave-number space, so that the combined 3-s 6π azimuth filter function becomes

$$L_{Azimuth\,Scan}(k_1) = \frac{\sin^2(\pi k_1 l_{az})}{\left(\pi k_1 l_{az}\right)^2} \tag{1.10}$$

3 The Effect on ZephIR Lidar measurements:

With the above defined filters, we next investigate their combined effect on the QinetiQ ZephIR Lidar measured turbulence.

3.1 The combined Lorentz-filter and 3-s sampling effect on stream wise variance

For comparison with mast-mounted sonic anemometer measured variances, we first calculate the stream wise wind speed variance of the 3-sec averaged horizontal wind speeds, measured by the lidar (Lorentz- and Azimuth averaged), as :

$$\left\langle u'^2 \right\rangle_{ZephIR} = \int_0^\infty F_u\left(k_1\right)\, L_A(k_1)\;\; L_L(k_1)\; dk_1$$

with

$$L_L(k_1) = \qquad e^{-2 z_R k_1},\; L_A(k_1) = \qquad \frac{\sin^2(\pi k_1 l_{az})}{\left(\pi k_1 l_{az}\right)^2}$$

where

$$F_u(k_1) = u_*^2 \, \frac{z}{2\pi} \frac{102}{(1\; + \;\; 33\dfrac{k_1 z}{2\pi})^{5/3}} \left[\frac{m^3}{s^2}\right]$$

and

$$l_{as} = \frac{2}{\sqrt{3}} z + 3U \text{ and } z_R(z) \approx \;\; 0.0012 \left(\tfrac{2}{\sqrt{3}} z\right)^2 = 0.0016\; z^2 \;\; [m]$$

For the vertical wind speed profile we will assume typical danish Høvsøre Test Site parameters:

$$\text{Roughness } z_0 = 0.001[m];\; \text{Friction velocity } \mathrm{u}_* = 0.5[ms^{-1}]; U(z) = \frac{\mathrm{u}_*}{0.4} \ln\frac{z}{z_0} \Rightarrow U(100) \sim \; 15\, ms^{-1}. \qquad (1.11)$$

The variance expression Eqs(1.11) is integrated in Mathematica, cf. Appendix I.

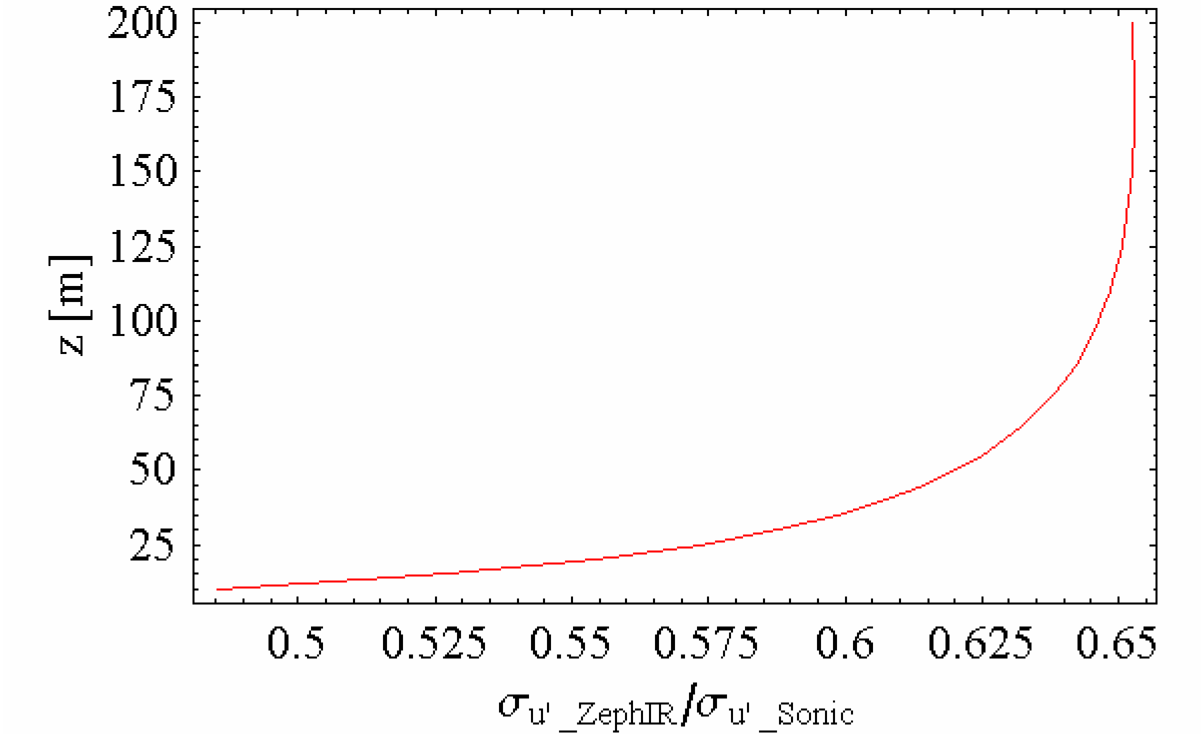


Fig.2 *Kaimal-modeled ZephIR stream wise wind speed standard deviations (inferred from consecutive three x 2π azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.*

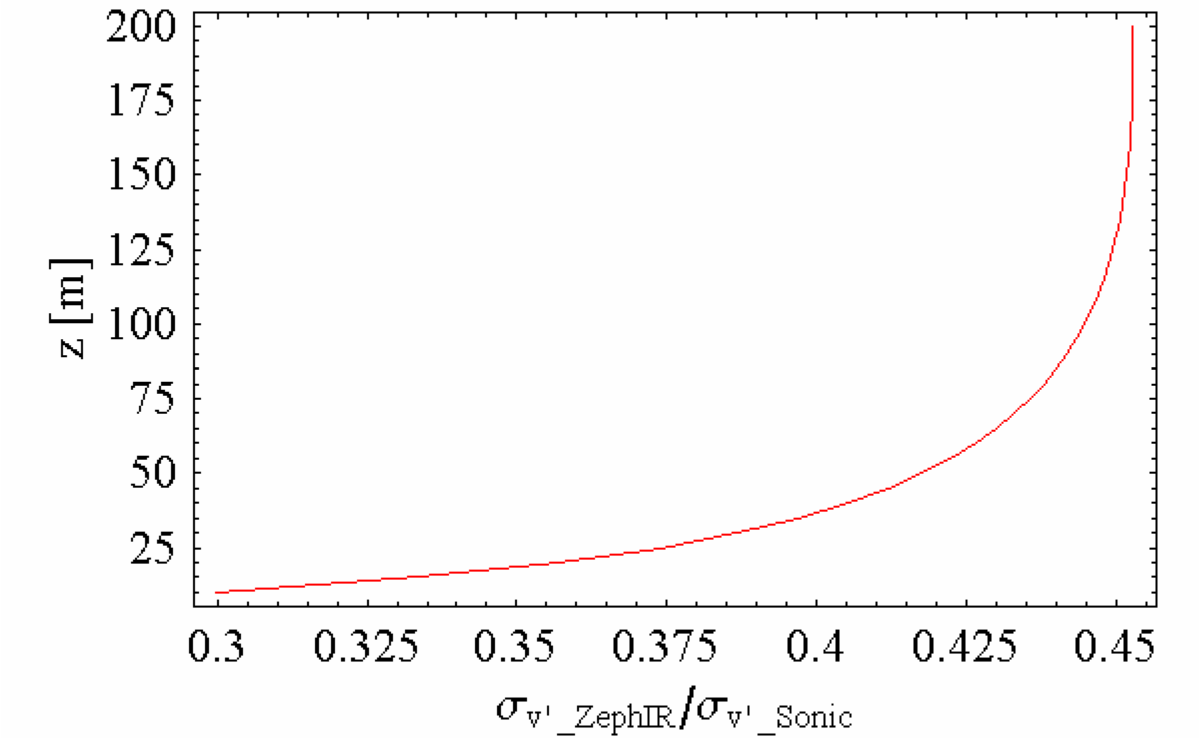


Fig.3 Predicted ZephIR lateral wind speed standard deviations (inferred from consecutive three x 2 π azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.

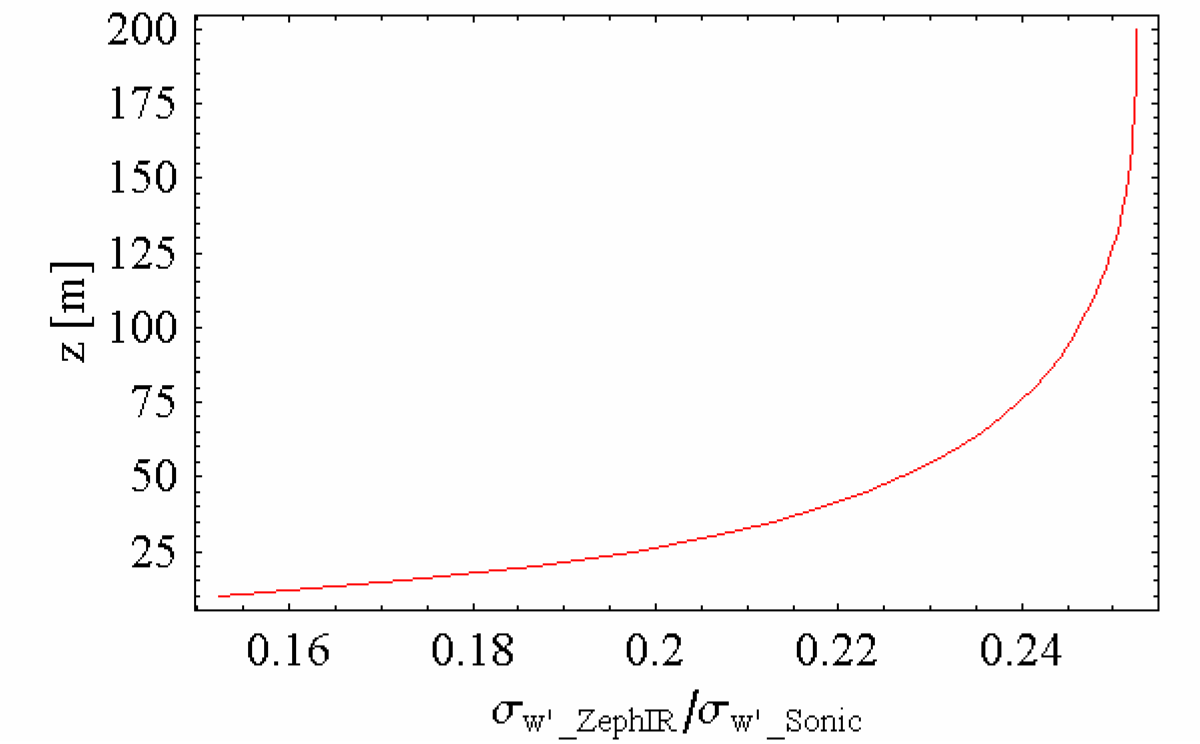


Fig.4 Predicted ZephIR vertical wind speed standard deviations (inferred from consecutive three x 2 π azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.

3.2 The filter effects on the ZephIR measured "TQE"

In the note "TQE & Shear stress_Tensor_from_QQZephIR.doc", it was shown that the ZephIR lidar measured "turbulence parameter" could be compared to the standard expression for Turbulent Kinetic Energy, TKE, defined as

$$TKE = ½\left(< u^2 > + < v^2 > + < w^2 >\right) \qquad (1.12)$$

but with the following modifications:

By use of 25% of the full $< u^2 >$ variance; 25% of the full $< v^2 >$ variance, and 150% of the full $< w^2 >$ variance, the QinetiQ ZephIR lidar's internal calculated "Turbulence parameter" was shown to be identical with a turbulence intensity based on the following definition of "Total "QinetiQ Eenergy":

$$TQE \equiv ½\left(\tfrac{1}{4} < u^2 > + \tfrac{1}{4} < v^2 > + \tfrac{3}{2} < w^2 >\right) \qquad (1.13)$$

Based on the Kaimal spectra variance estimations in Eqs (1.2) we find

$$TKE \approx 4.43 u_*^2;\ TQE \approx 2.06 u_*^2,\ \text{and}\ \frac{TQE}{TKE} \approx 0.46 \qquad (1.14)$$

The definition of TQE in Eqs. (1.13) is defined in terms of "un-filtered" variances, that is, with no effects of the lidar's spatial and temporal averaging considered.

To investigate and evaluate the averaging effects of ZephIR measured turbulence, we next re-calculate the variances in eqs. (1.13) including the filter effects.

Define the filter-averaged Total QinetiQ Energy in terms of ZephIR measured space and time averaged variances as

$$TQE_{av} \equiv ½\left(\tfrac{1}{4} < u^2 >_{av} + \tfrac{1}{4} < v^2 >_{av} + \tfrac{3}{2} < w^2 >_{av}\right) \qquad (1.15)$$

Where we as above calculate the ZephIR averaged variances by filtering, viz.:

$$\langle u\rangle_{av}^{2}=\int_{0}^{\infty}F_{u}\left(k_{1}\right)\,L_{A}(k_{1})\;\;L_{L}(k_{1})\;dk_{1}$$

$$\langle v\rangle_{av}^{2}=\int_{0}^{\infty}F_{v}\left(k_{1}\right)\,L_{A}(k_{1})\;\;L_{L}(k_{1})\;dk_{1}$$

$$\langle w\rangle_{av}^{2}=\int_{0}^{\infty}F_{w}\left(k_{1}\right)\,L_{A}(k_{1})\;\;L_{L}(k_{1})\;dk_{1}$$

where: $L_L(k_1)= \quad e^{-2z_R k_1};\; L_A(k_1)= \quad \dfrac{\sin^2(\pi k_1 l_{az})}{\left(\pi k_1 l_{az}\right)^2}$

and with standard Káimál power spectra (in wavenumber presentation) given by

$$F_u(k_1)=u_*^2\,\frac{z}{2\pi}\,\frac{102}{(1\;+\;33\dfrac{k_1 z}{2\pi})^{5/3}}\left[\frac{m^3}{s^2}\right]$$

$$F_v(k_1)=u_*^2\,\frac{z}{2\pi}\,\frac{17}{(1\;+\;9.5\dfrac{k_1 z}{2\pi})^{5/3}}\left[\frac{m^3}{s^2}\right]$$

$$F_w(k_1)=u_*^2\,\frac{z}{2\pi}\,\frac{2.1}{1\;+\;5.3\left(\dfrac{k_1 z}{2\pi}\right)^{5/3}}\left[\frac{m^3}{s^2}\right] \qquad (1.16)$$

As before: $l_{as}=\dfrac{2}{\sqrt{3}}z+3U(z)$ and $z_R(z)$ 0.0016 z^2 $[m]$.

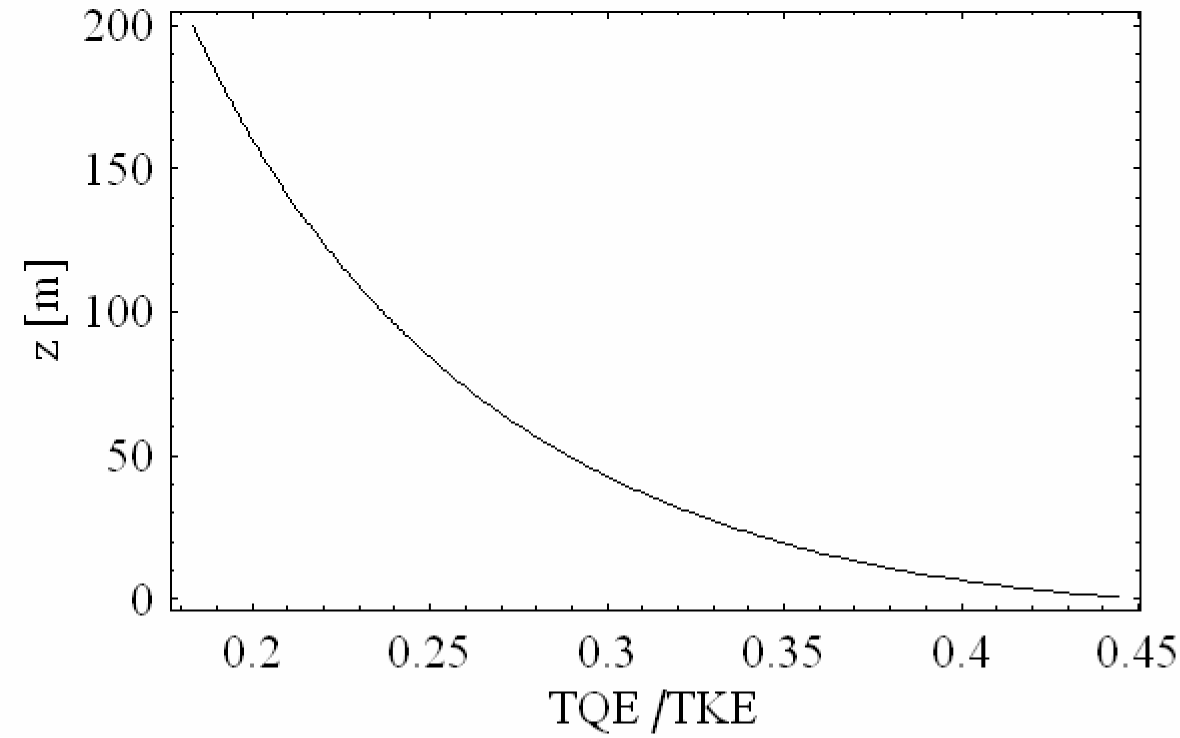


Fig3. Prediction of ZephIR sampled TQE turbulence relative to unfiltered (Sonic) variance TKE, as function of measurement height. (Averaging time corresponding to 10-min).

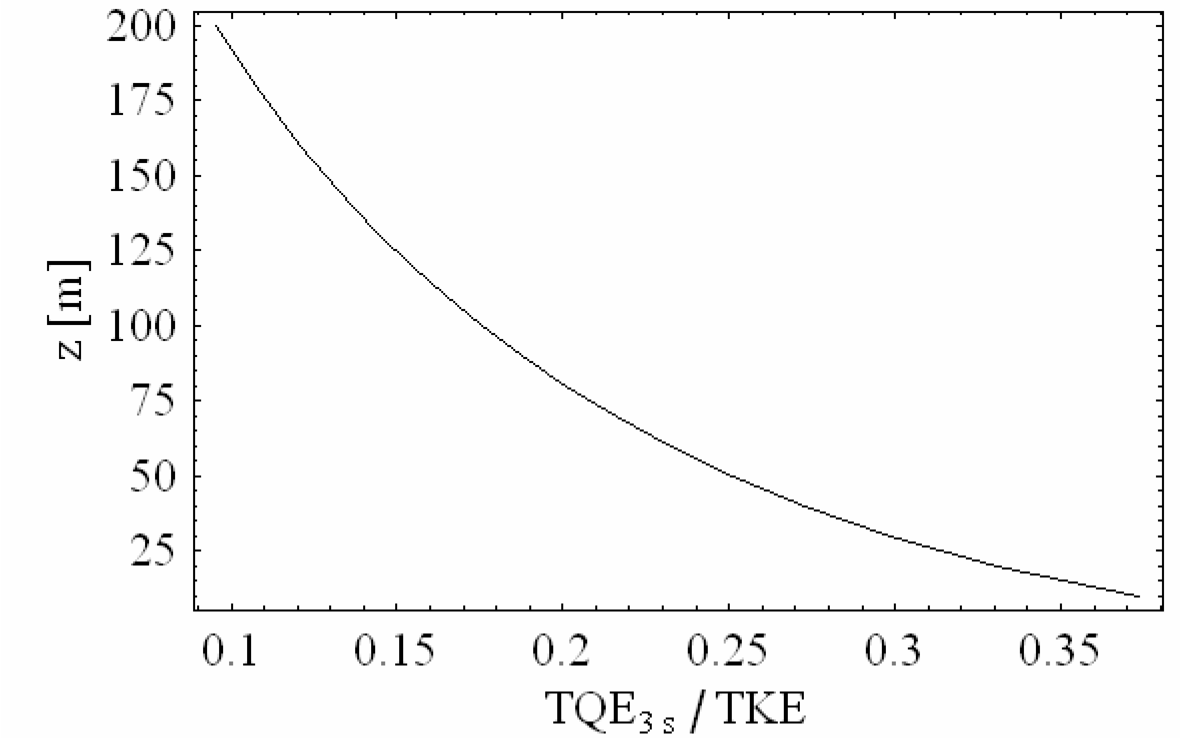


Fig4. Prediction of 3-sec averaged TQE turbulence relative to unfiltered (Sonic) variance TKE, as function of measurement height.

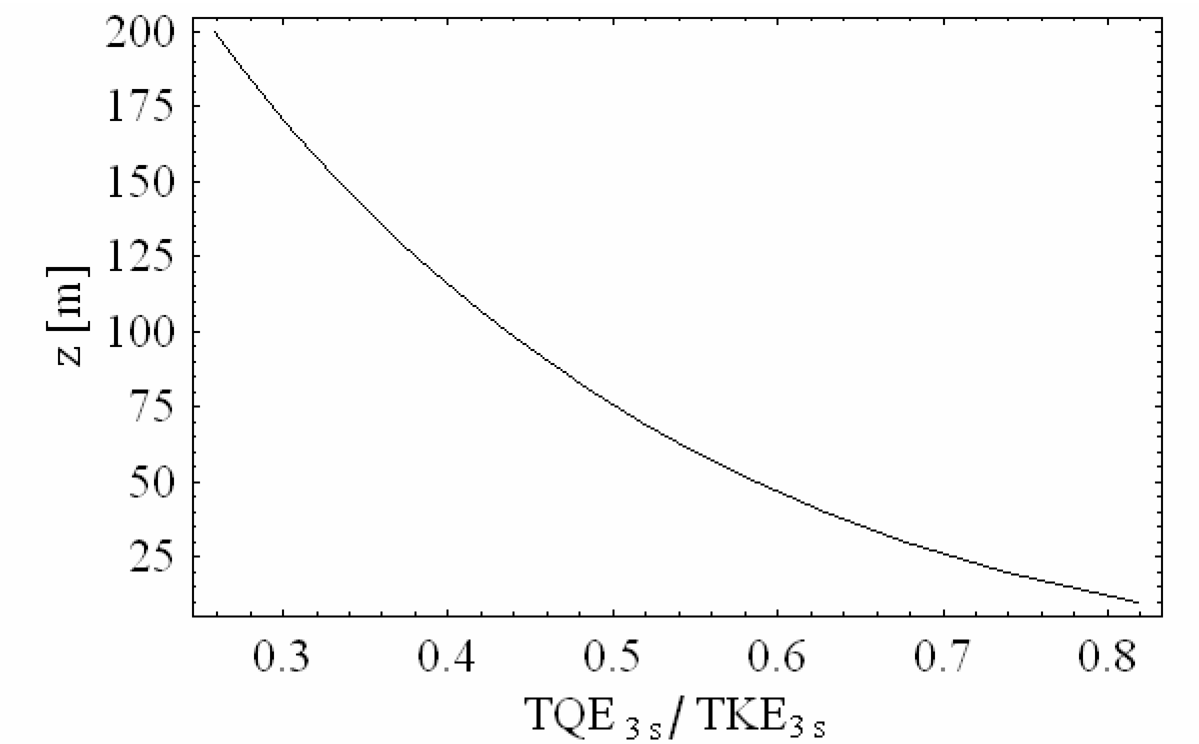


Fig5. Prediction of 3-sec averaged TQE_{3s} *turbulence, relative to 3-s averaged (Sonic) turbulence* $TKE_{3\,s}$ *as function of measurement height.*

Appendix I:

Mathematica filter evaluation program: lidarfilter_HEJ_TM_04.nb

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Measurement of Turbulence with a CW Lidar:

Effects of Conical scanning and Probe Volume

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Meteorology Program
Wind Energy Department
Risø-DTU

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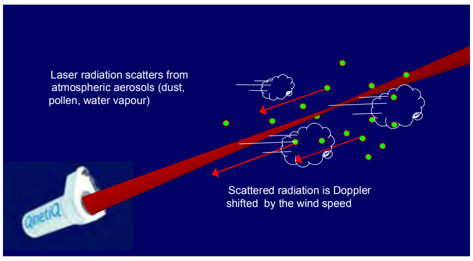
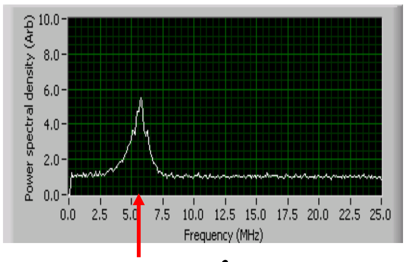
Outline

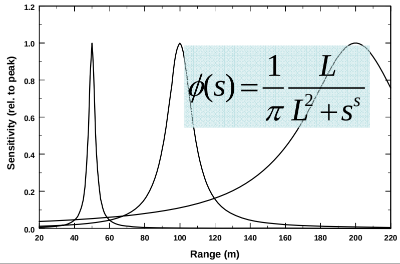
- Principles of CW Doppler Lidar measurements:
- Theory of Lidar measured Turbulence
- Effects on measurements

Principles of the Doppler LIDAR





$$peak = \frac{\int f\,P(f)\,df}{\int P(f)\,df}$$



Altitude	L
40m	2.5 m
60m	6 m
100m	16 m
200m	65 m

Figure 3. Stages of evolution of the ZephIR lidar. Figure 3a shows the lidar head mounted on the nacelle of a Nordex N-90 wind turbine. Figure 3b shows prototype ground-based wind profiler at Risø wind energy test site, Høvsøre, Denmark. Figure 3c shows the ZephIR production model deployed in the field

The scanning version of the ZephIR lidar instrument has been widely employed as a wind profiler, measuring wind speed and direction from a ground-based platform to altitudes up to 150 m. This was achieved by offsetting the beam at an angle of 30 degrees to the vertical and scanning in azimuth at a rate of 1 revolution per second. As the beam rotates, it intercepts the wind at different angles, thereby building up a map of wind speed around a disc of air [22]. In a uniform air flow, a plot of Doppler velocity (V_{LOS}) versus scan angle takes the form of a rectified sine wave, with the peak Doppler values corresponding to upwind and downwind measurements:

$$V_{LOS} = |a \cos(\phi - b) + c| \quad (2.4)$$

where ϕ is the scan azimuth angle. A non-linear least-squares fit is performed of this model to the data, from which the three best-fit parameters—a, b and c—are extracted. The wind data is then computed as follows:

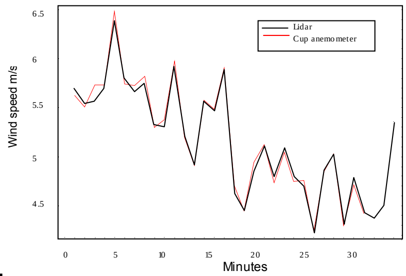
$$Horizontal\ speed\ (u) = a / \sin 30°$$

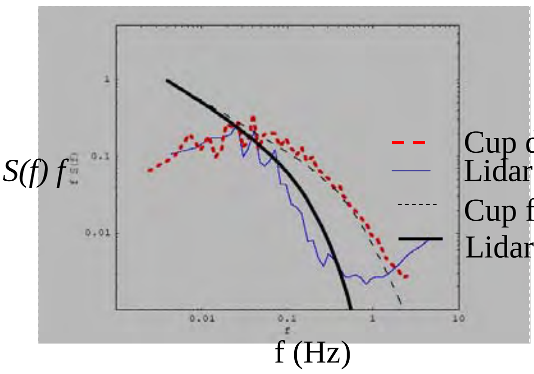
$$Vertical\ speed\ (w) = c / \cos 30°$$

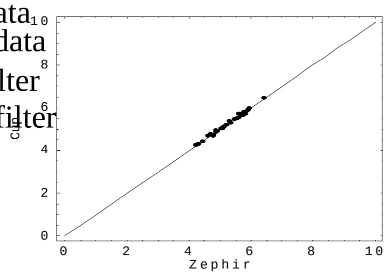
Experimental setup #1: *Staring mode*

Turbulence measurements with QQ

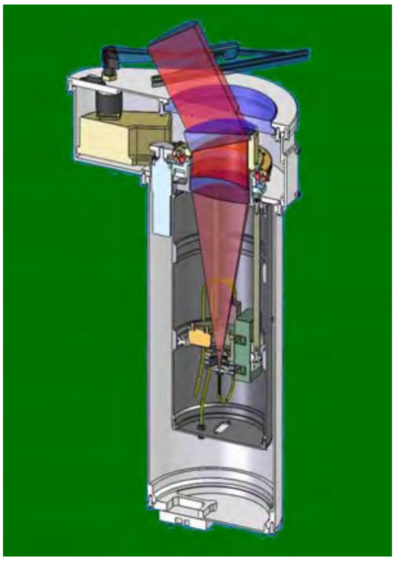
Lidar test: Beam pointed upwind:



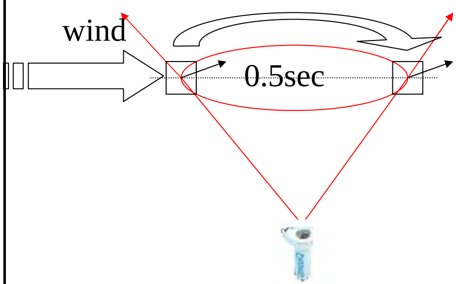


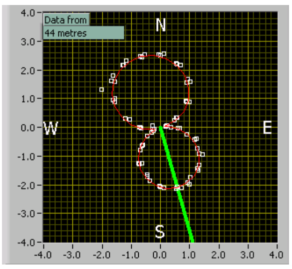


ZephIR (scanning)

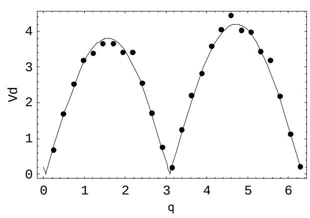


Profile measurements with the Zephir





Altitude [m]	Diameter of the cone [m]
40	43.88
60	66.97
80	90.07
100	113.16



$$V_D = \left| a \quad \cos(\phi - b) + c \right|$$
$$U = a / \sin 30°$$
$$W = c / \cos 30°$$
$$D = b$$

QinetiQ ZephIR Wind LIDAR:

Profiler Intercomparison Experiment at Høvsøre (DK)

Starting date Zephir 2/4 –2004

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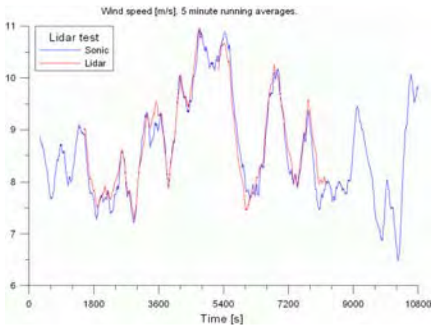


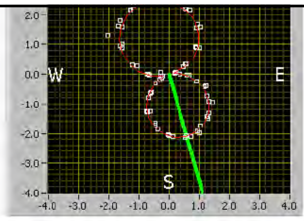


Figure 4. Polar plot of line-of-sight velocity component in m/s versus azimuth scan angle. White squares: 75 measurements obtained over 3 seconds. Continuous curve: best-fit solution. Bold line from origin: upwind bearing. The excellent fit indicates uniform flow across the scanned area. Note also a slight asymmetry in the lobe sizes, indicating a small vertical component to the wind velocity. By adjusting the focus, wind measurements can be made at all heights from 5 m to >150 m above ground level.

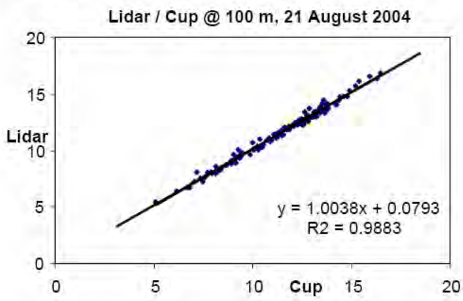
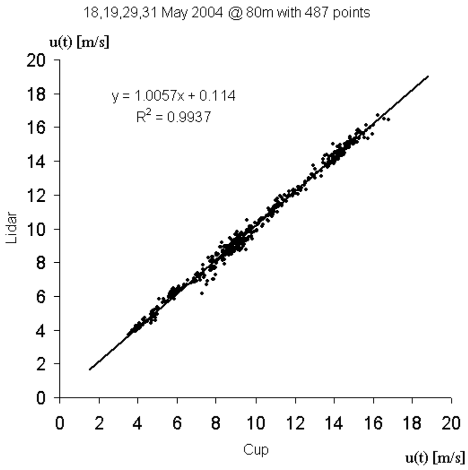
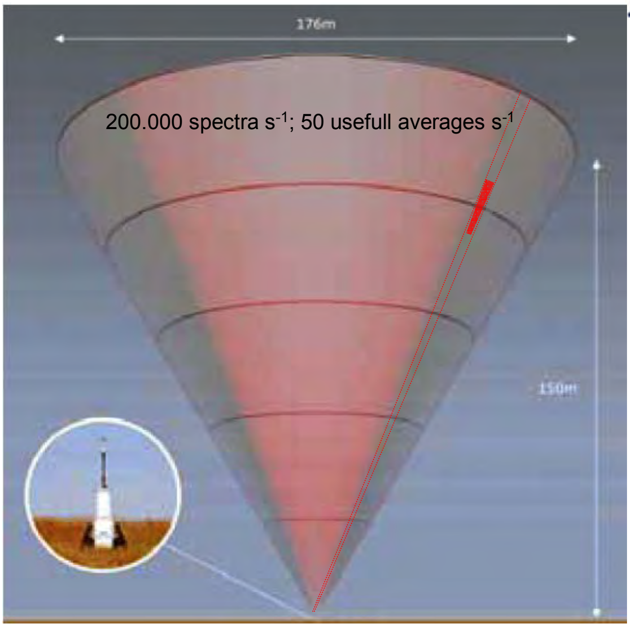


Figure 5. Regression plot of 10-minute averaged wind speed 100 m above ground in m/s, measured by lidar and calibrated cup anemometer. The lidar was situated 120 m from the

Comparison between tower and QQ



Ongoing research regarding reliability and availability



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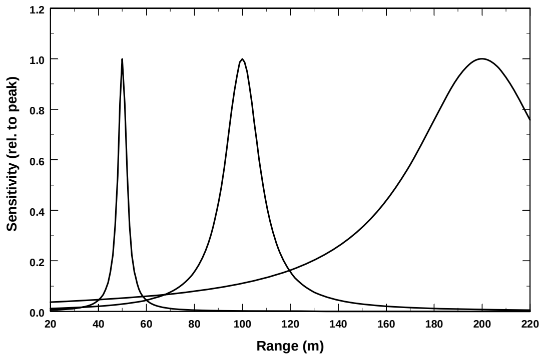
Spatial weight function



Altitude	L
40m	2.5 m
60m	6 m
100m	16 m
200m	65 m

Lorenzt function : $$\phi(s) = \frac{1}{\pi}\frac{L}{L^2 + s^s}$$

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Turbulence measured by the ZephIRTM: The Effects of Conical Scan and Lorentzian Probe-volume Filtering:

1. Kaimal model spectra:

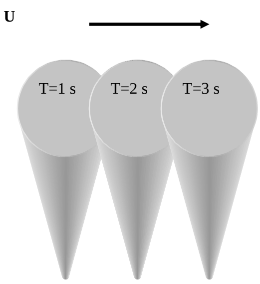
$$n\,S_u(n)/u_*^2 = \frac{102n}{(1 + 33n)^{5/3}}$$

$$n\,S_v(n)/u_*^2 = \frac{17n}{(1 + 9.5n)^{5/3}}$$

$$n\,S_w(n)/u_*^2 = \frac{2.1n}{(1 + 5.3n^{5/3})}$$

2. CW Lidar's Lorentzian probe volume:

$$\phi(s) = \frac{1}{\pi}\frac{L}{L^2 + s^s} \longleftrightarrow L_{Lorentzian}(k_1) = e^{-2 z_R k_1}$$

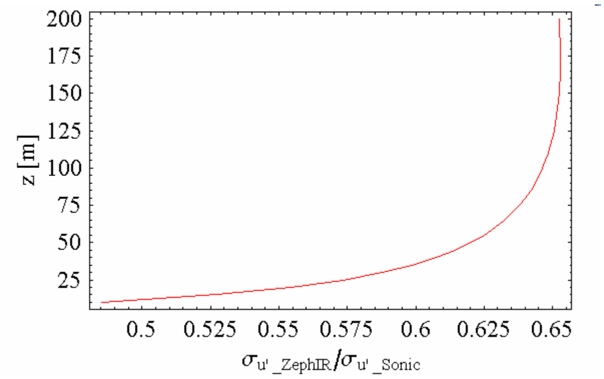


3. Length scale filter associated with three-revolution 3-s averaged azimuth scans:

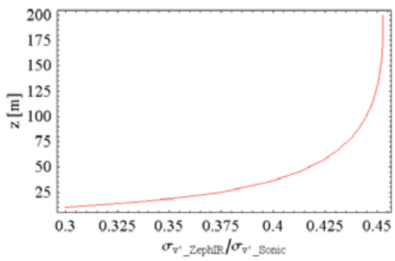
$$l_{az} = D + U\Delta T = \frac{1}{Cos(30)}z + 3U = \frac{2}{\sqrt{3}}z + 3U$$

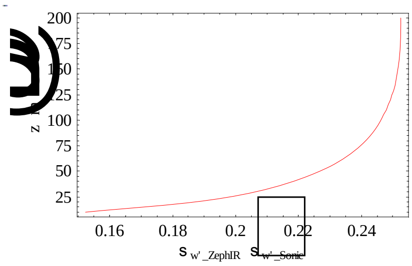
$$\updownarrow$$

$$L_{AzimuthScan}(k_1) = \frac{\sin^2(\pi k_1 l_{az})}{(\pi k_1 l_{az})^2}$$



*Kaimal-modeled ZephIR **stream wise** wind speed standard deviations (inferred from consecutive three x 2□ azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.*

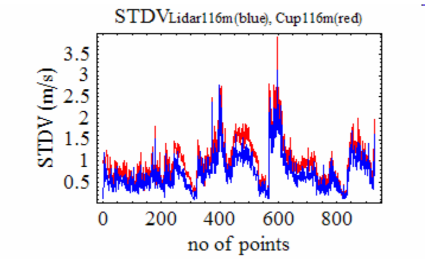


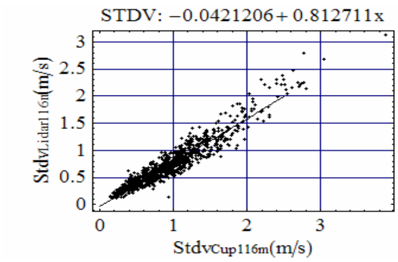


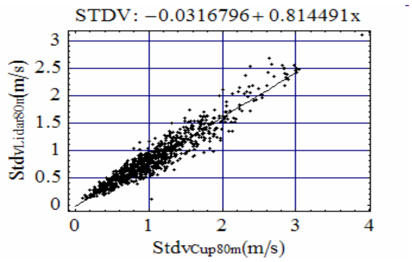
*Predicted ZephIR **lateral** wind speed standard deviations (inferred from consecutive three x 2□ azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.*

*Predicted ZephIR **vertical** wind speed standard deviations (inferred from consecutive three x 2□ azimuth scans), relative to unfiltered (Sonic) values, as function of measurement height.*

Lidar-cup STDV (dry weather data)







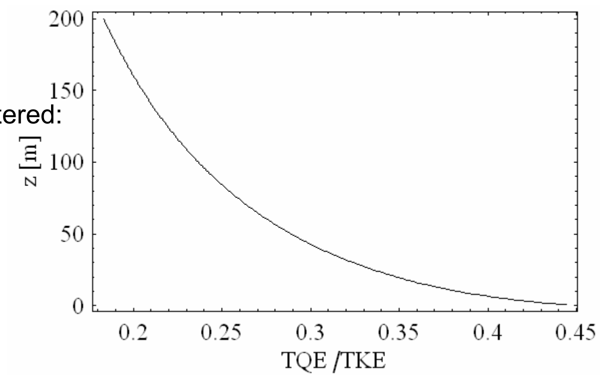
The Lidar's filter effects on measured "TQE"

- Kinetic Energy: $TKE = ½\left(<u^2> + <v^2> + <w^2>\right)$

  $TQE \equiv ½\left(\frac{1}{4}<u^2> + \frac{1}{4}<v^2> + \frac{3}{2}<w^2>\right)$

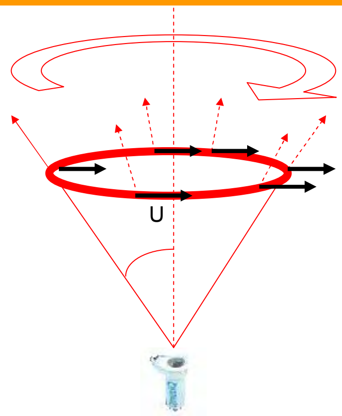
- Kaimal spectra unfiltered: $TKE \approx 4.43u_*^2$; $TQE \approx 2.06u_*^2$, and $\frac{TQE}{TKE} \approx 0.46$

- Kaimal ZephIR-filtered:



LIDAR Measurement of Friction Velocity u*.

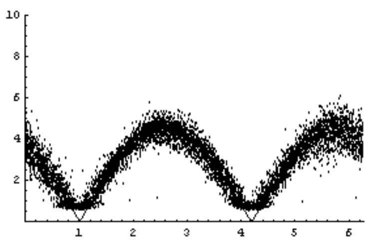
$$\overline{v'^2_D(\pi)} = \overline{(-u'+w')^2}$$

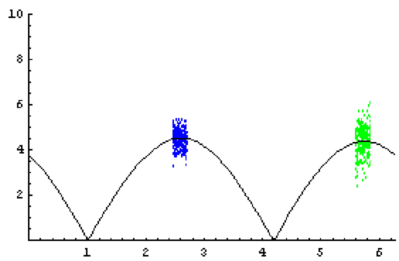


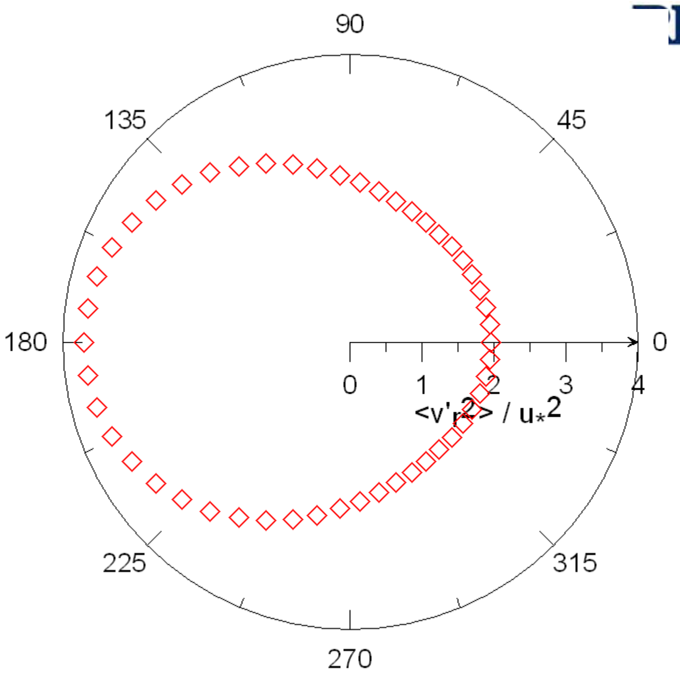
$$\overline{v'^2_D(0)} = \overline{(u'+w')^2}$$

$$u_*^2 = -\overline{u'w'} = \left(\overline{v'^2_D(\pi)} - \overline{v'^2_D(0)}\right)/4$$

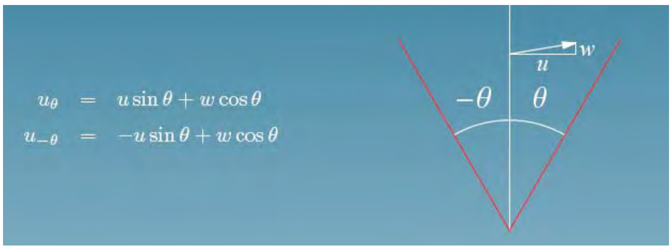
Signal processing







How to obtain the momentum flux



$$\mathrm{Var}(u_\theta) = \tfrac{1}{4}\mathrm{Var}(u) + \tfrac{3}{4}\mathrm{Var}(w) + \tfrac{\sqrt{3}}{4}\mathrm{Cov}(u,w) \quad (1)$$

$$\mathrm{Var}(u_{-\theta}) = \tfrac{1}{4}\mathrm{Var}(u) + \tfrac{3}{4}\mathrm{Var}(w) - \tfrac{\sqrt{3}}{4}\mathrm{Cov}(u,w) \quad (2)$$

$$\mathrm{Var}(u_\theta) - \mathrm{Var}(u_{-\theta}) = -\tfrac{\sqrt{3}}{2}\mathrm{Cov}(u,w) \quad = \tfrac{\sqrt{3}}{2}u_*^2$$

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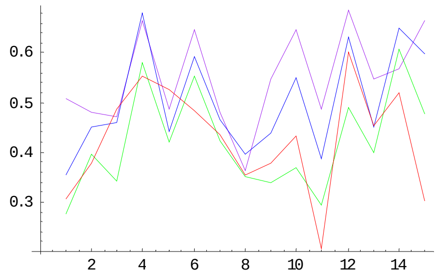
u_* filtered @ 80m



u_* sonic 60m

u_* sonic 80m

u_* sonic 100m

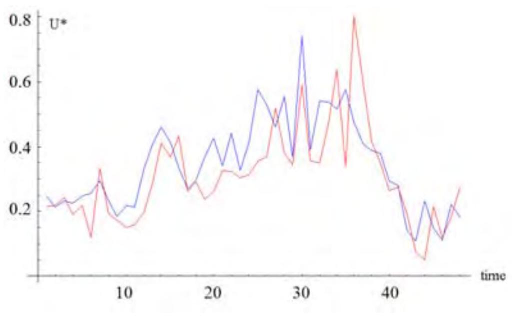
u_* Lidar 80m

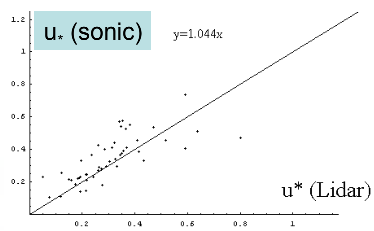
10-min averages

2½ Hr ~16 points

RISØ

Comparison of Lidar and Sonic measured u_* :





30-min averages at 80 m

Red : Lidar

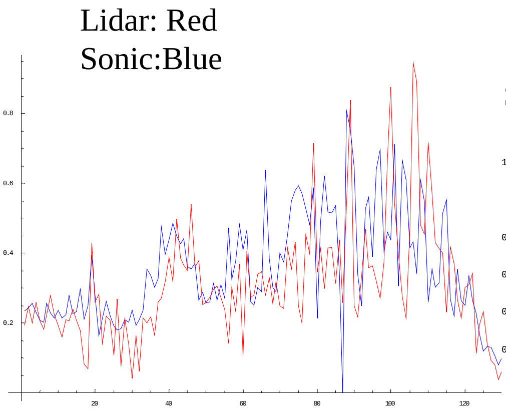
Blue : Sonic data (METEK USA-1)

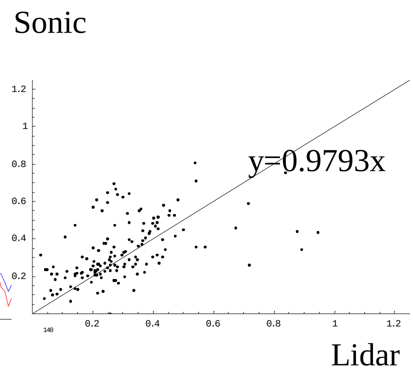
DTU

RISØ

Corresponding 10-min averages:

1:1





DTU

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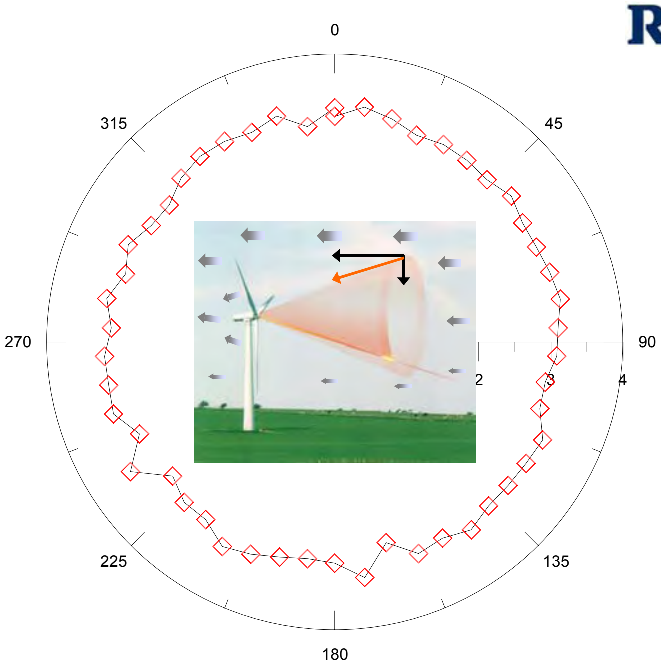

DTU

RISØ

Summary and Conclusionss

The ZephIR Lidar provide vertical profiles of:

- Momentum flux u_*
- Turbulent Kinetic Energy (TQE)
- Wind component wind speed variances: $<u'^2>_{3\text{-}s}$, $<v'^2>_{3\text{-}s}$, $<w'^2>_{3\text{-}s}$

taking into account the filter and volume averaging of the probe volume of the QinetiQ ZephIR LIDAR.

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IEA Topical Expert Meeting “State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites”

Research proposal: „Development of LIDAR wind sensing for the German offshore test field“

Andreas Rettenmeier, Martin Kühn

Endowed Chair of Wind Energy, Universität Stuttgart

Risø, January 23-24 ,2007

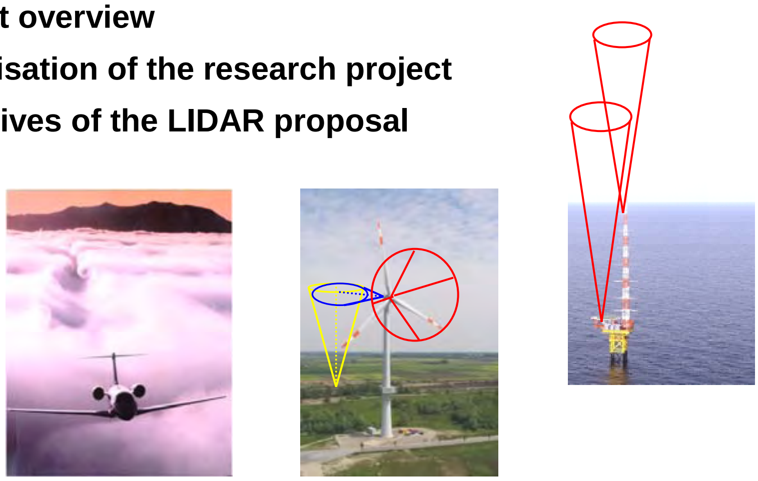
[Fig. QinetiQ, SWE, DLR]

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

Universität Stuttgart

Contents

- Project overview
- Organisation of the research project
- Objectives of the LIDAR proposal



[Fig. SWE, DLR]

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

Universität Stuttgart

Project overview

Proposal of research project: „Development of LIDAR wind sensing for the German offshore test field“ at the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

- **Research project consists of six participants**
- **Positive pre-evaluation last year**
- **Earliest start date: April 2007**
- **Duration: 2.5 years**

Offshore test field

Offshore test field „Borkum-West“
planned 2008:
est. 6 x REpower 5M
est. 6 x Multibrid M5000

Water depth: approx. 30m

Research platform FINO 1

[Fig. BMU]

Organisation and participants of the research project

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

- **Projektträger Jülich ptj/BMU**
  - **Endowed Chair of Wind Energy (Universität Stuttgart)** Prof. Dr. M. Kühn (coordinator of project)
    - **German Wind Energy Institute (DEWI)** Dr. T. Neumann
    - **Institute of Atmospheric Physics (DLR)** Dr. G. Ehret
    - **Federation of German Windpower (FGW)** L. Reeder, Dipl.-Phys.
    - **Multibrid Entwicklungs-gesellschaft mbH (MEG)** N. Erdmann, Dipl.-Ing.
  - **ForWind (Universität Oldenburg)** Prof. Dr. J. Peinke

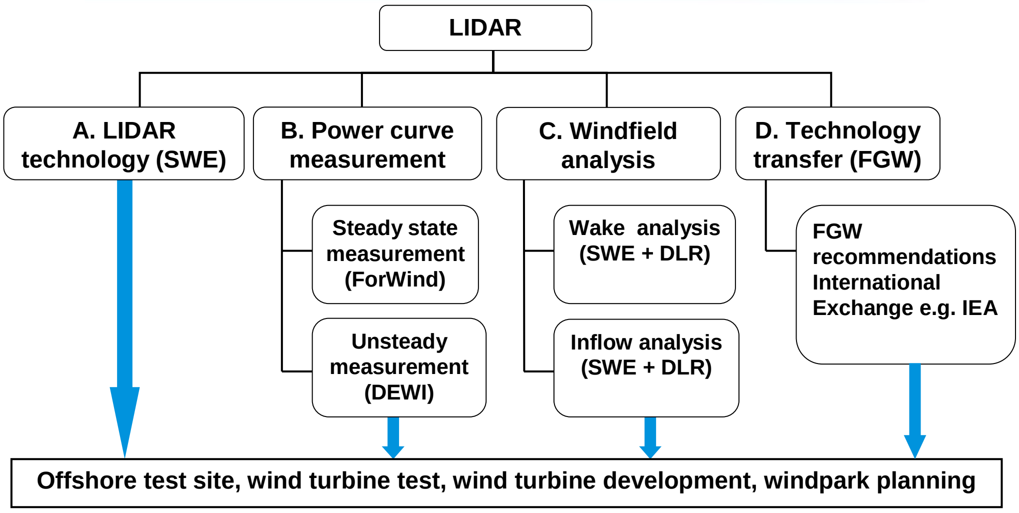
Deutsches Zentrum für Luft- und Raumfahrt e.V.

Objectives of the LIDAR research proposal

- Development and demonstration in four typical areas:
  1. Power curve measurements without met mast
     Offshore capability of the LIDAR system
     (in preparation for measurements in the offshore test field)
  2. Measurements of turbulent wind fields in dynamic wakes and in the inflow of Multi-MW wind turbines
  3. Development of wind field simulation techniques for inflow in wind farm operation including dynamic wake effects
  4. Measurements of turbulence properties of windfields in a high resolution as base for new and faster methods for power curve determination
- Formulation of standardised power curve measurements in the offshore test field taking into consideration the FGW technical guideline „Part 2: Determining the Power Performance and Standardised Energy Yields " [1)]
- Provision of LIDAR hardware and of the know-how needed for the application in the offshore test field and other R&D projects

1): http://www.wind-fgw.de/tr_engl.htm

Main structure of the project



Conclusions

- **Proposal of a joint research project of 4 scientific partners and 2 industrial partners**
  - Potential start: April 2007, 2.5 years duration
- **Main objective: further scientific development of LIDAR application for**
  - German offshore test field
  - Power curve measurements: onshore/offshore, new fast methods
  - Other research questions, e.g. dynamic wake loading
- **National project but exchange of experience proposed**
  - National through Federation of German wind power (FGW)
  - International, e.g. in scope of IEA or EAWE activities desired

Contact

Endowed Chair of Wind Energy (SWE)
Head of department: Prof. Dr. Dipl.-Ing. Martin Kühn

- **Measurement engineering: Andreas Rettenmeier**
- **Wake analysis: Juan José Trujillo**

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Capability of Doppler lidar and evaluation of a new autonomous Doppler lidar system

C G Collier[1], K. E. Bozier[1], G. Pearson[2] and F. Davies[1]

[1]University of Salford, UK

[2] Halo Photonics, UK

Variable	Symbol	Lidar Perspective
Mixed layer height (Boundary layer depth)	h	Strength of back-scatter signal identifies aerosol layer(s). (Mok and Rudowicz, 2004)
Mean velocity Turbulence	$\overline{w}$ [u,v] σ_w	 From w'
Eddy dissipation rate	ε	From spectra ε
Lagrangian integral timescale and Integral length scale	$\tau_L = \int_0^\infty R(\tau) d\tau$ $L_i = \int_0^\infty R(s) ds$	Decay time scales for auto correlation coefficient $R(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\sigma_w^2}$ for lag τ, $R(s) = \frac{\overline{u'(x)u'(x+s)}}{\sigma_w^2}$ for lags.
Sensible heat flux Flux of temperature fluctuation	H or Q $H = Q_H = \rho C_p \overline{w'\theta'}$ $\overline{w'\theta'}$	Indirectly from lidar third moment $\overline{w'^3}$. (Gal-Chen et al 1992) Or from w_* as below.
Convective velocity scaling (for unstable conditions).	$w_* = \left[hg \frac{(\overline{w'\theta'})}{\theta} \right]^{\frac{1}{3}}$	From $\sigma_w^2 \approx \beta w_*^2$ (Angevine et al 1994) where β ? 0.52 within 0.2< z/h<0.5

- List of Boundary Layer Parameters
- obtained from lidar data
- for dispersion modelling
- Helsinki data primarily vertically pointing
- Collier et al 2005 (Bulletin of AMS)

Autonomous Doppler lidar system – requirements

❖ Traditionally lidar systems have been expensive, bulky and require a high level of routine maintenance.
1998 – 2006: CO_2 TEA system, 112 m range gates, 600 m min. range, housed in 4.6 tonne vehicle, dedicated operator

Doppler lidar system designed and developed to meet the following objectives:

❖ Long term velocity and backscatter measurements in urban and rural environments – system is eye safe, near IR

❖ Require measurements from close to street level → top of boundary layer – high spatial resolution to retrieve measurement at many levels in urban canyon

❖ Air quality and pollution dispersion – high temporal resolution of system to retrieve turbulence and velocity variance information

❖ Field deployable – compact system

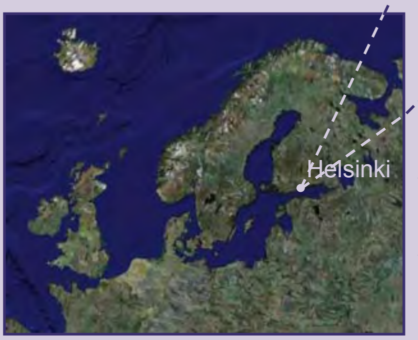
❖ No dedicated user required – remote access to system with software that will allow full control of system, view and download data

Autonomous Doppler lidar system for range resolved remote sensing of the atmosphere

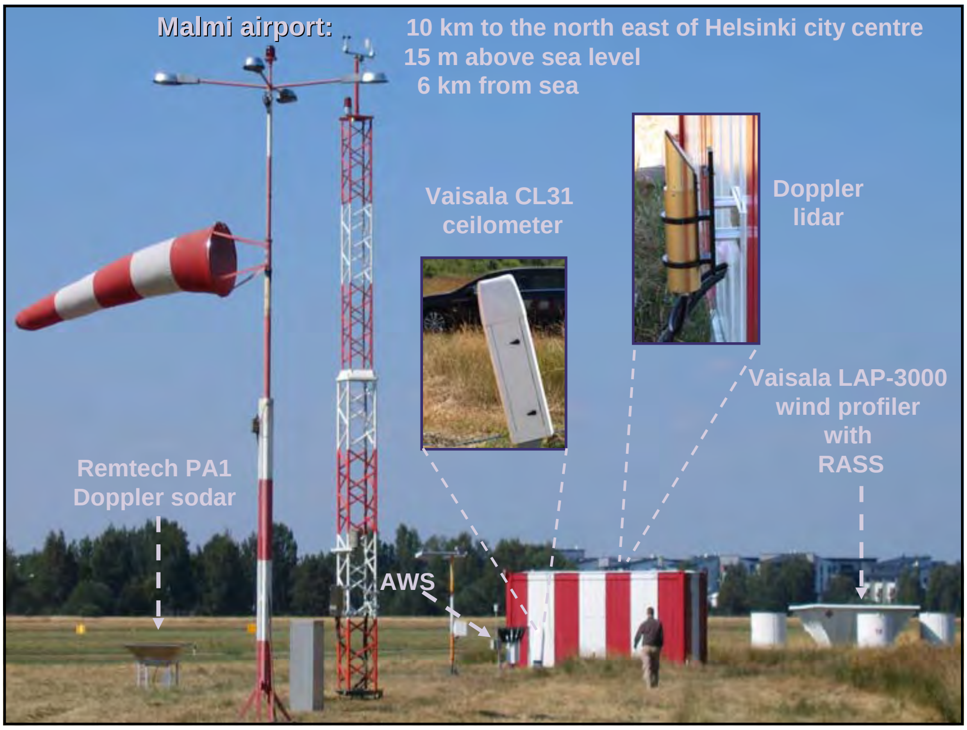
Parameter	Value
Operating wavelength	1.5 microns
Pulse repetition frequency	20 kHz
Beam divergence	50 μrad ~ 5 cm at 1 km
Range gate	20 – 60 m
Minimum range	30 m
Maximum range	Up to 7 km
Temporal resolution	0.1 – 30 s
Optical base unit (1) Antenna (2) Signal processing and data acquisition unit (3)	56 x 54 x 18 cm 8 cm diameter Standard desktop pc
Hemispheric scanner & Video camera for alignment and sighting	50 mm aperture 0 – 360 ° azimuth 0 – 180 ° elevation 0.5 ° resolution

Helsinki Testbed: Helsinki, Finland - August & September 2006

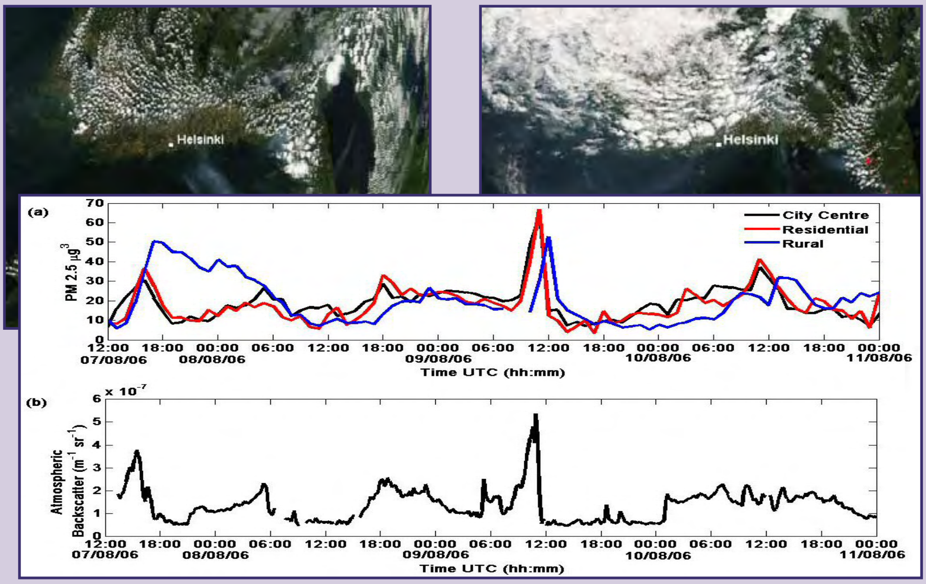
- Mesoscale observation network January 2005 until September 2007
- Opportunity to measure, study and predict atmospheric processes
- Promote testing of new measurement systems



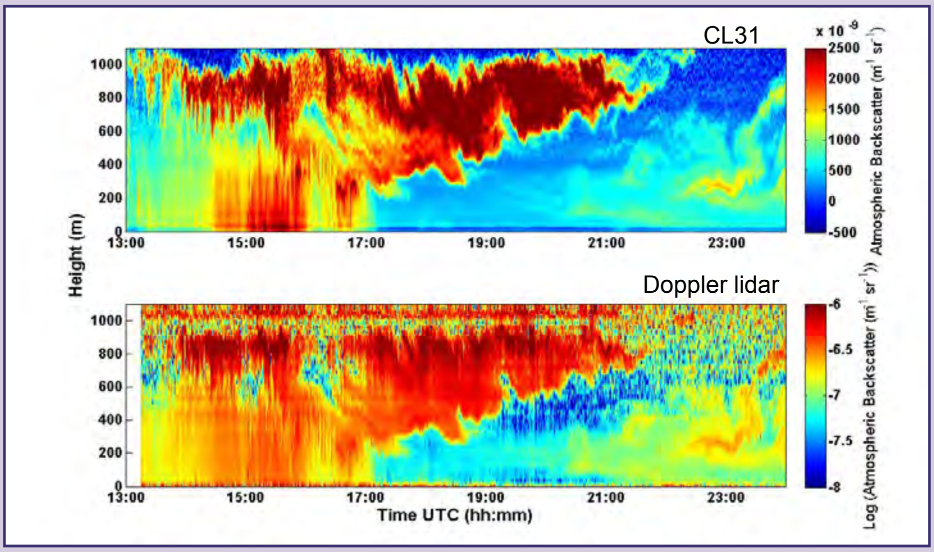
- Continuous operation of lidar system for 49 days - 1052 hours of vertical measurements
- 75 hours off zenith measurements for comparison with Vaisala wind profiler
- System monitored, controlled and data downloaded via simple remote access software via an internet connection



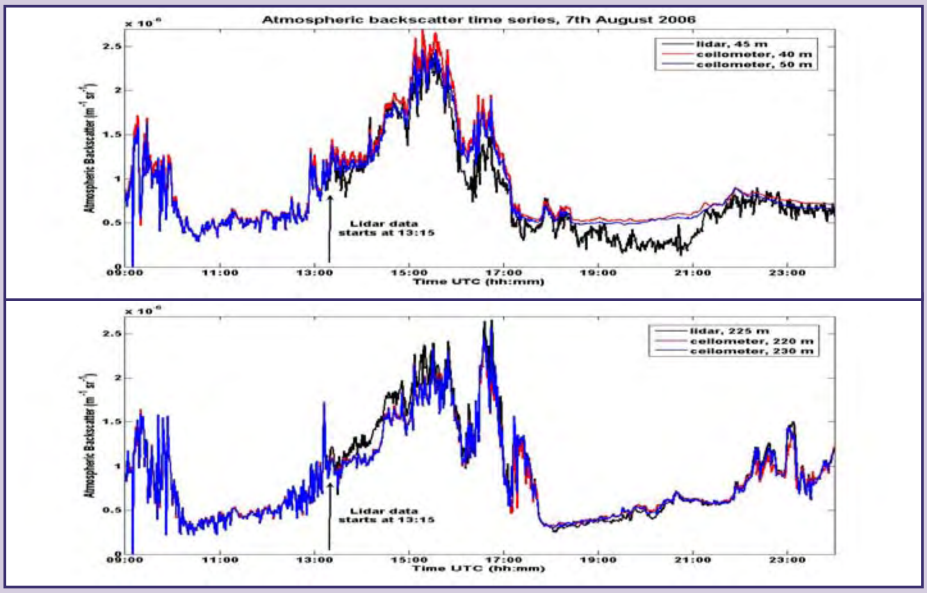
7th – 14th August 2006: Poor air quality in Helsinki region - partially due to forest fires in north western Russia



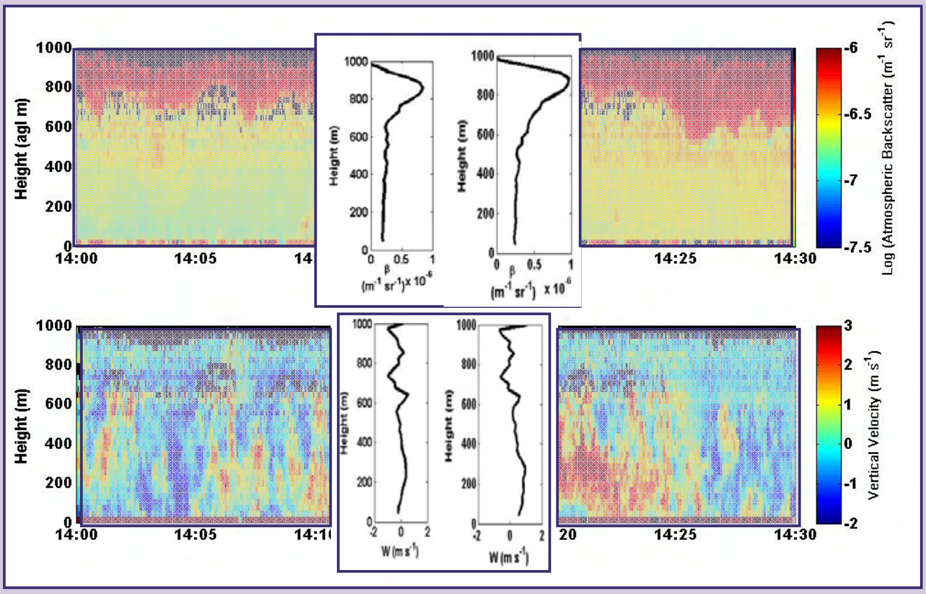
7th August 2006: Atmospheric backscatter measurements – lidar and ceilometer

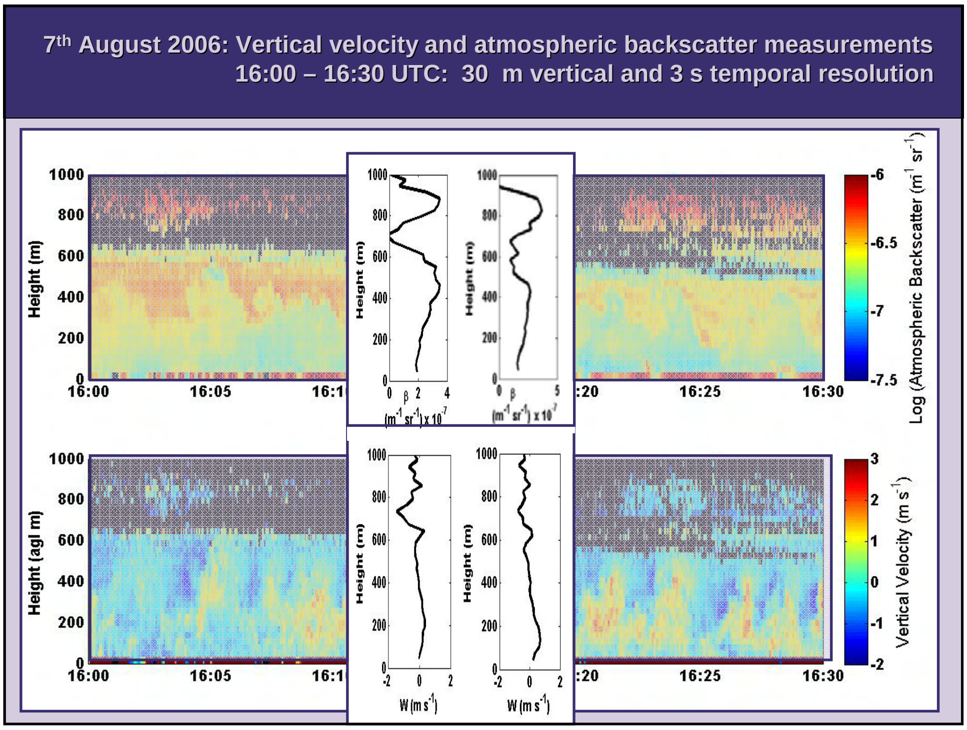


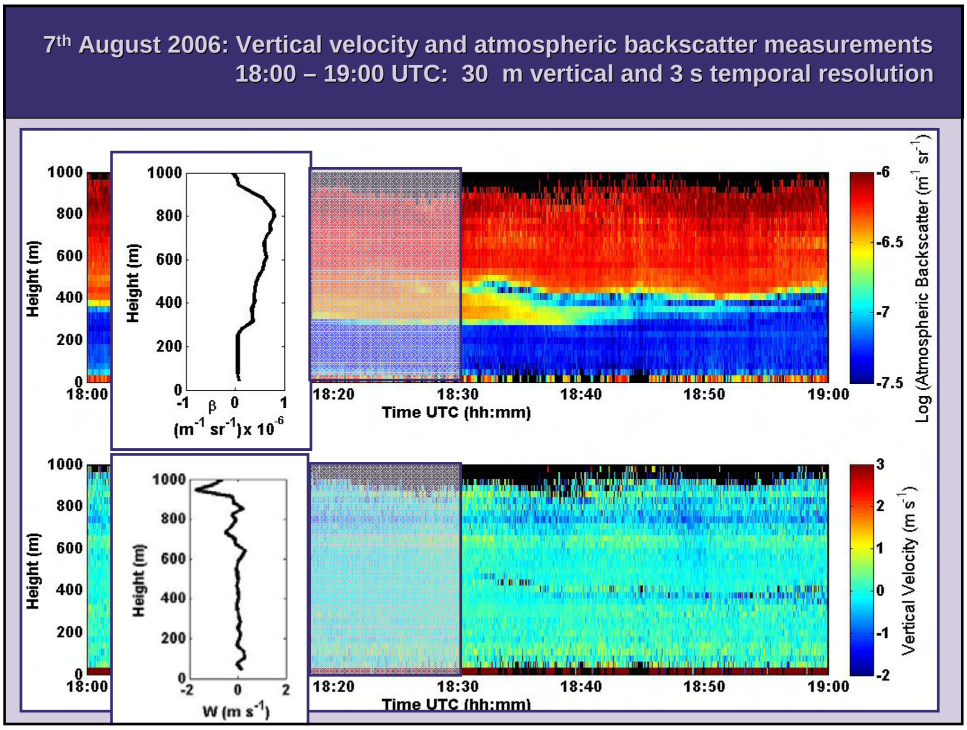
7th August 2006: Comparison of lidar versus ceilometer time series



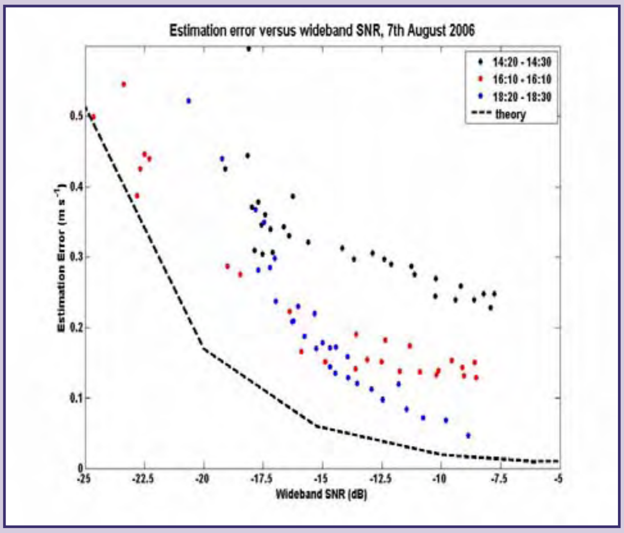
7th August 2006: Vertical velocity and atmospheric backscatter measurements 14:00 – 14:30 UTC: 30 m vertical and 3 s temporal resolution




7th August 2006: Vertical velocity and atmospheric backscatter measurements
16:00 – 16:30 UTC: 30 m vertical and 3 s temporal resolution
Height (m)
Height (agl m)
16:00
16:05
16:25
16:30
Height (m)
W (m s-1)
Log (Atmospheric Backscatter (m-1 sr-1)
Vertical Velocity (m s-1)


7th August 2006: Vertical velocity and atmospheric backscatter measurements
18:00 – 19:00 UTC: 30 m vertical and 3 s temporal resolution
Height (m)
18:00
18:20
18:30
18:40
18:50
19:00
Time UTC (hh:mm)
(m-1 sr-1) x 10-6
W (m s-1)
Log (Atmospheric Backscatter (m-1 sr-1)
Vertical Velocity (m s-1)

7th August 2006: Estimation of errors in velocity measurements



Error calculated from differencing method:

$V_r(r,t) = V_m(r,t) + e(r,t)$

Vr = radial velocity
r = range *t* = time
Vm = effective radial velocity
e = error

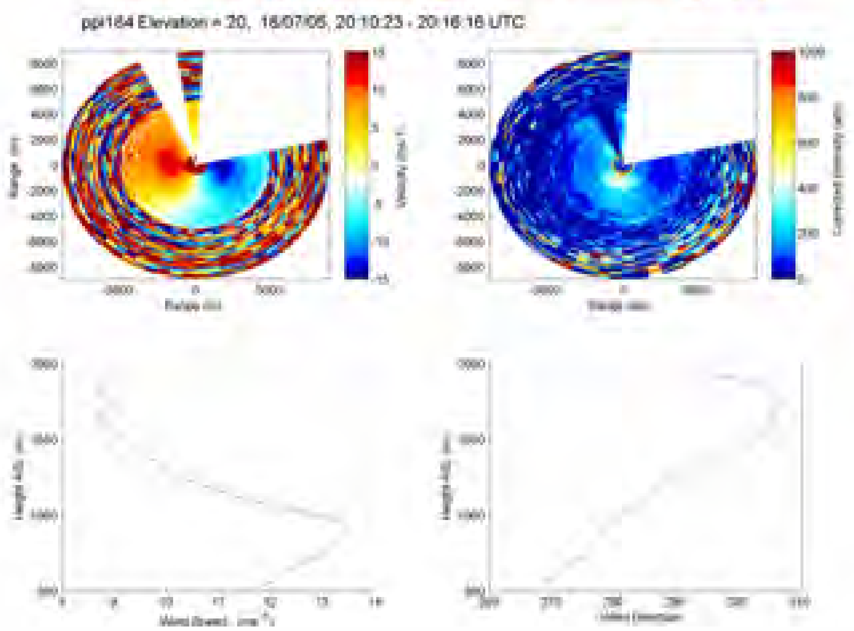
If two velocity estimates, *v1* and *v2* have the same mean value and statistically independent random errors, *e1*and *e2*, the random error is given by:

$$\sigma_e^2(r,N)=\frac{1}{2}\sigma_e^2\left(r,\frac{N}{2}\right)=\frac{\sigma_{\Delta v}^2}{4}$$

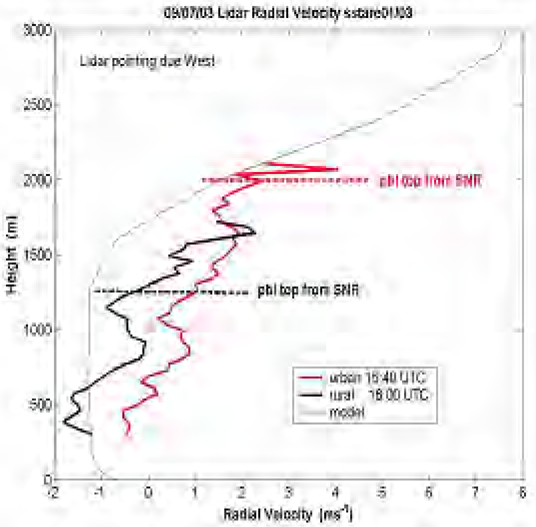
(Frehlich, 2001)

Frehlich. R., 2001: Estimation of velocity error for Doppler lidar measurements. J. *Atmos. Oceanic Technol.*, 18, 1628 – 1639.

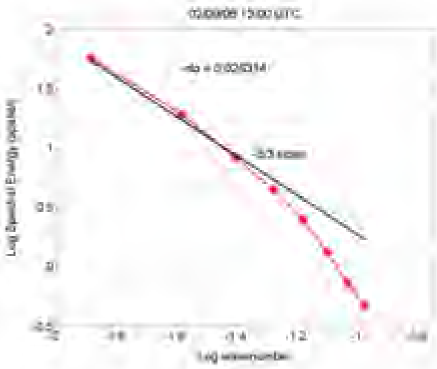
salford-lidar-dop-1_faccombe_YYYYMMDDhhmmss_ppi.jpg



Radial wind speed across the rural - urban boundary



Spatial data

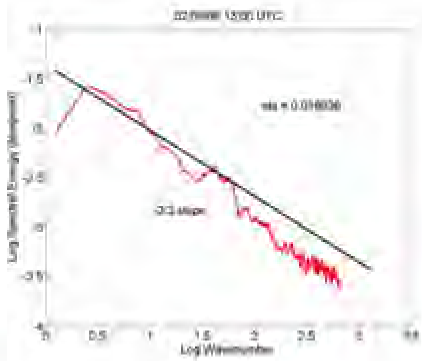


$S(k) = 1.53\ \varepsilon^{2/3}\ k^{-5/3}$

k - wavenumber

(Gal-Chen et al 1992)

temporal data

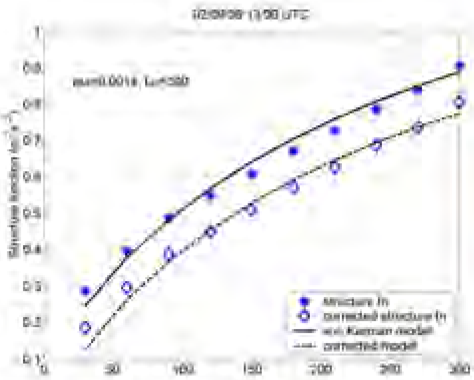


$nS(n) = 0.68\ \varepsilon^{2/3}\ (2\pi n/U)^{-2/3}$

n – frequency

U – mean wind speed

(Champagne et al 1977)



Davies et al (2004)

Data can be corrected for both spatial averaging and velocity estimation

Structure Function :

$D_w(s) = [\, w(r_o) - w(r_o + s)]^2$

w(r)* – vertical velocity at range *r

s - separation

(Frehlich and Cornman 2002)

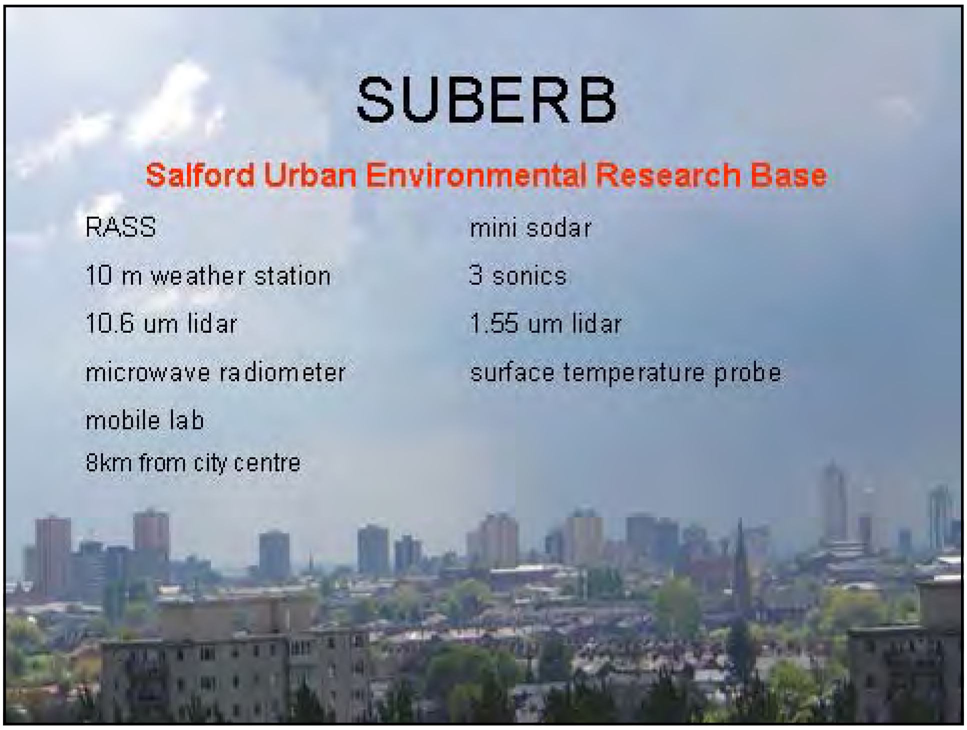
Von Karman Model Structure Function :

$D_w(s) = 2\,\sigma_w^2\,\Lambda\,(s/L_o)$

σ_w^2 ***– velocity variance***

$\varepsilon = 0.93\,\sigma_w^2 / L_o$

(Frehlich 2000)



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Doppler Lidar Measurements Using a Fibre Optic System

Michael Bennett and Simon Christie

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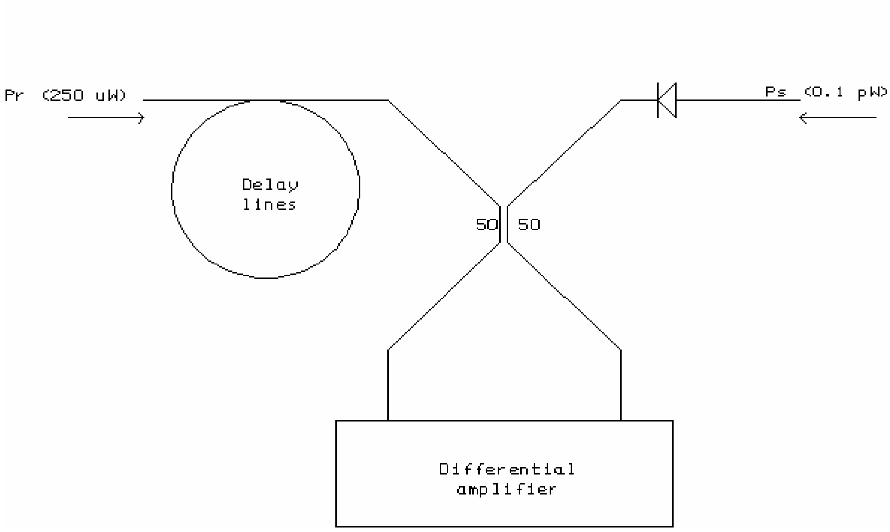
Manchester Metropolitan University,
Chester Street, Manchester, M1 5GD, UK

Mike.bennett@mmu.ac.uk

Optical head of system

- CW operation
- Bistatic
- OCT range resolution
- λ = 1.5 µm
- 50 mm optics
- 1W output
- Eye-safe

Mixing of signal and reference paths

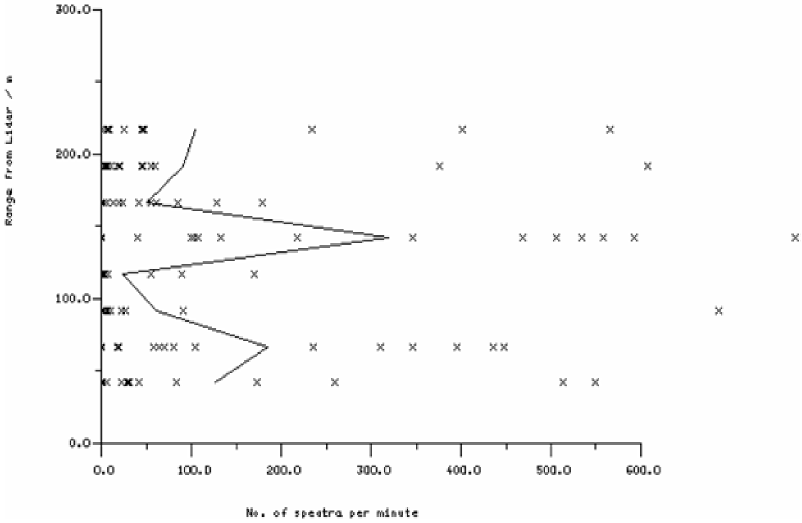


Nominal Performance

- Range resolution, $\Delta r = c/(2\pi.\Delta v)$ = 34.1 m
- Velocity resolution, $\Delta w \sim 0.39$ m s^{-1} (radial)
- Time resolution, $\Delta t = 0.25$ s (at single range)
- Ranges sampled, 40, 65, 90, … , 415 m
- Overall cycle time, $T_C = 16$ min

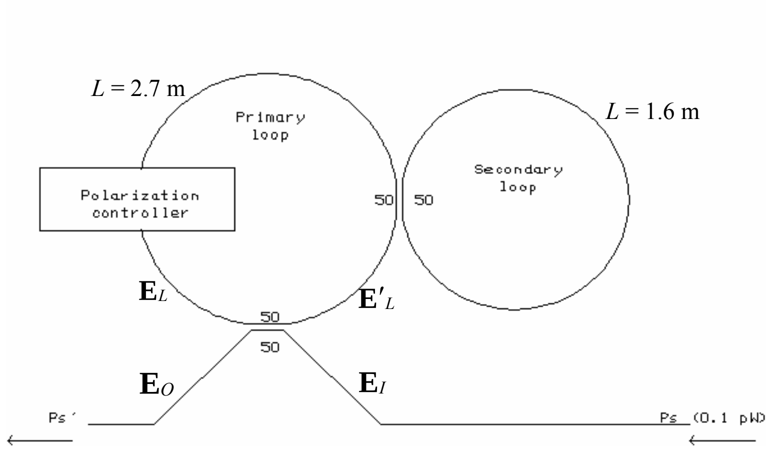
Large discrepancy between Δt and T_C arises from the need to cycle around ranges and also to keep the polarizations of signal and reference paths matched.

Rate of Lidar returns, 7/7/2003, from 0907z
No adjustment of polarization

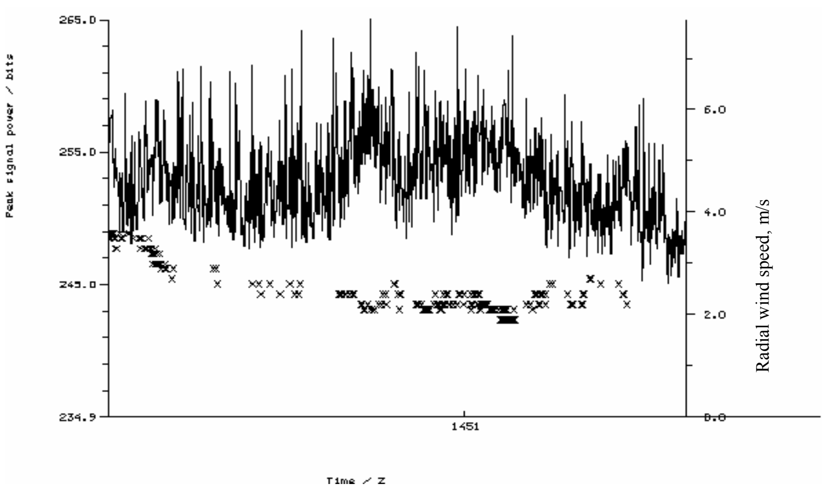


Manually adjusting the reference polarization

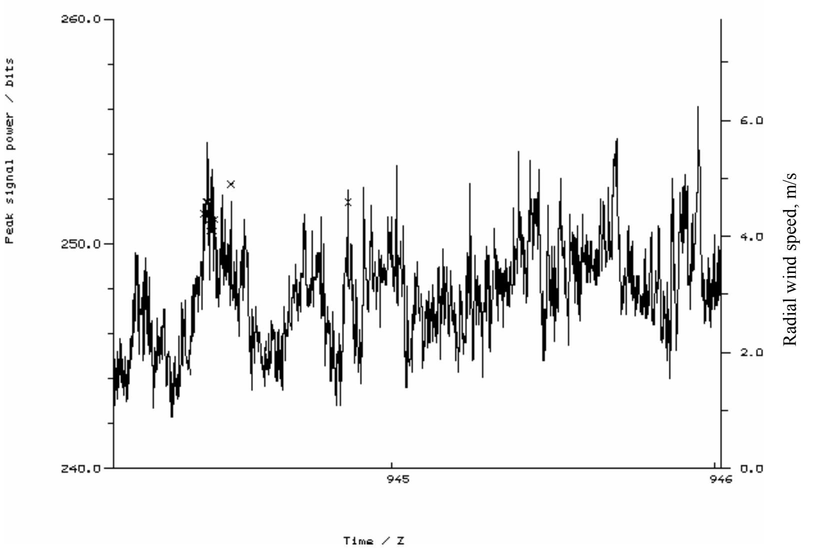
Polarization scrambling loops on signal path



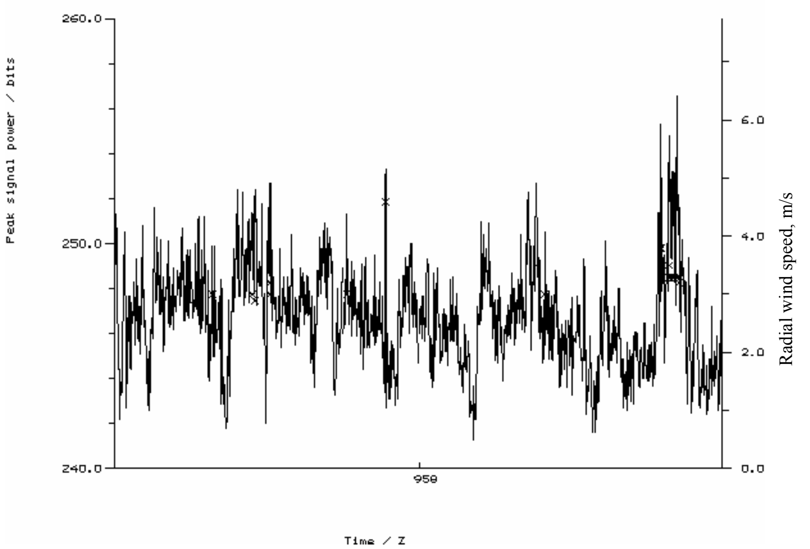
Peak power and radial wind speeds, manual polarization control, 14/7/2006



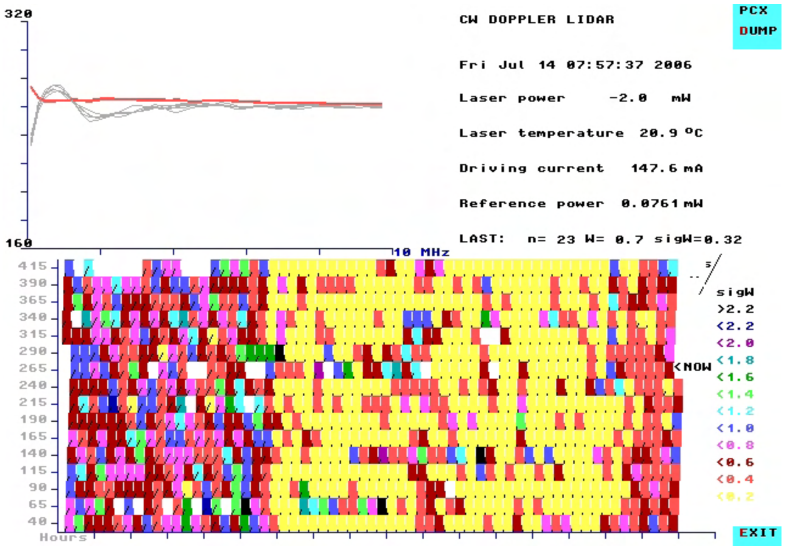
Peak power and radial wind speeds, single scrambler loop, 4/5/2006



Peak power and radial wind speeds, double scrambler loop, 4/5/2006

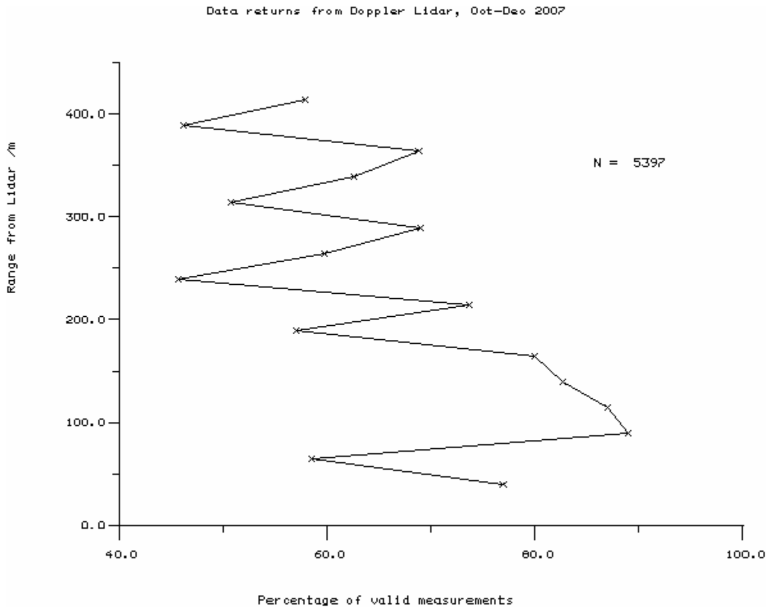


Overnight profiles – scrambled polarization

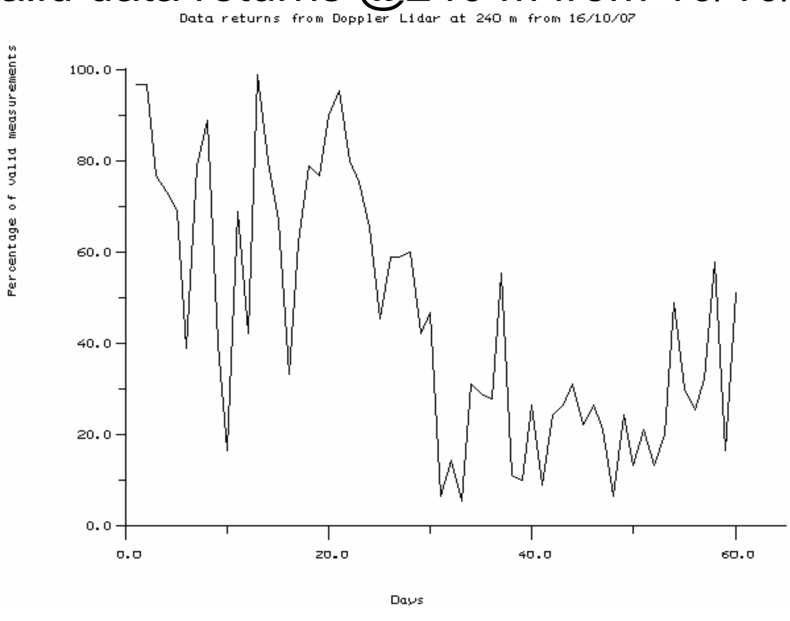


Sodar & Lidar in Manchester

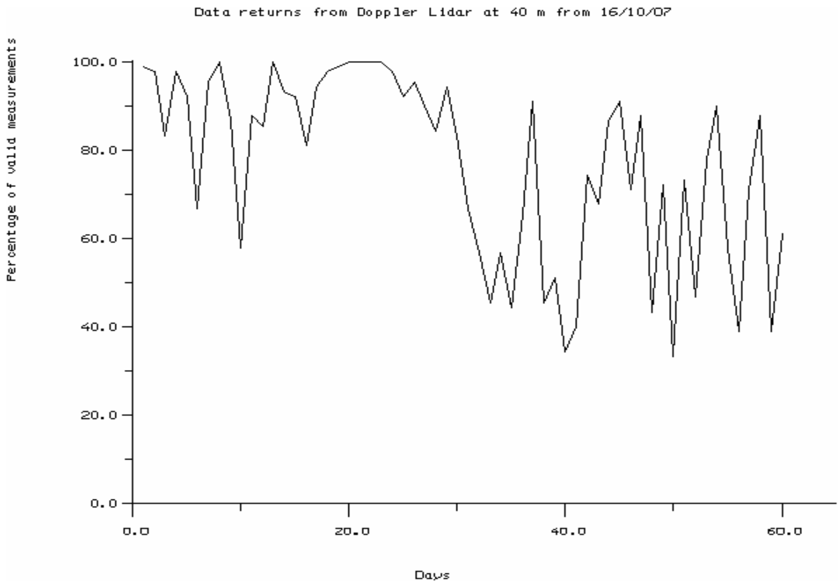
Valid data returns, Oct-Dec 2007



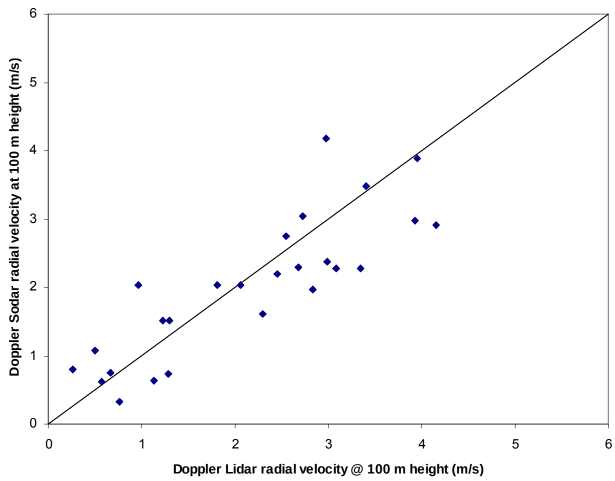
Valid data returns @240 m from 16/10/07



Valid data returns @40 m from 16/10/07



Comparison of Lidar with Sodar wind speeds, Manchester, July 2007



Performance in Practice

- Reliable measurements at optimal range for visibility <40 km.
- Returns are marginal from ranges where the bistatic optics are not optimal, particularly when the optics are wet.
- Polarization scrambling requires a 1 min sampling time at each range, implying a long cycle time around all ranges.

Multi-range processing

- Current OCT system relies on analogue processing. Polarization problems arise from the varying delay lines.
- If we could monitor the phase of the laser oscillator directly, then (a) we could simultaneously extract the beats signal from all ranges digitally; (b) the system would have fixed polarization; and (c) a monostatic arrangement might be possible.

Signal voltage for path delay of τ :

$$V(t,\tau) = V_0 \cos(\phi_0 + \Delta\phi(t,\tau) + 2\pi f_B t)\,,$$

Autocorrelation function :

$$R(t,t',\tau) = V_0^2 \cos(\phi + \Delta\phi(t,\tau) + 2\pi f_B t).\cos(\phi_0 + \Delta\phi(t',\tau) + 2\pi f_B t')$$

$$= \frac{1}{2} V_0^2 \{\cos(\Delta\phi(t,\tau) - \Delta\phi(t',\tau) + 2\pi f_B \overline{t - t'}\ )$$

$$+ \cos(2\phi_0 + \Delta\phi(t,\tau) + \Delta\phi(t',\tau) + 2\pi f_B \overline{t + t'})\}.$$

Orthogonality . . .

$$< \cos(\Delta\phi(t,\tau') - \Delta\phi(t',\tau')).R(t,t',\tau) >$$

$$= \ (V_0^2/4)\ \cos(2\pi f_B \overline{t - t'})\,, \quad |\tau - \tau'| < \tau_c\,,$$

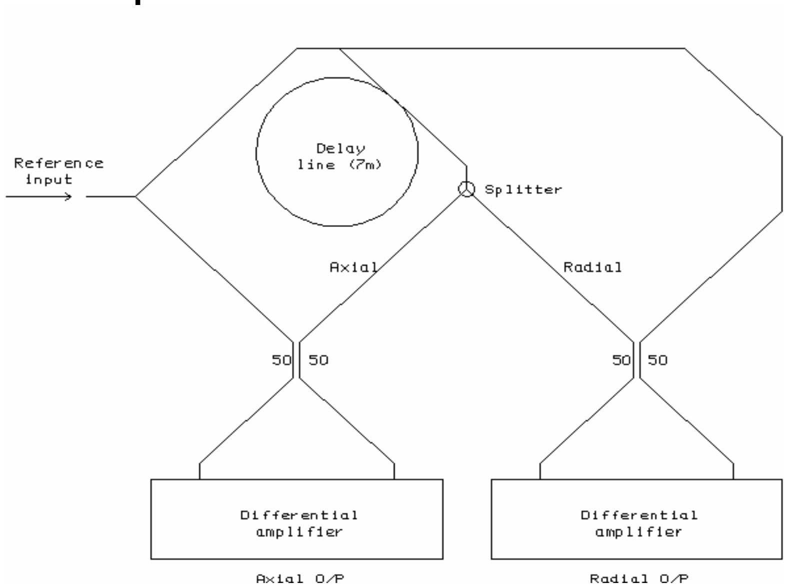
$$\approx\ 0\,, otherwise\,.$$

where

$$\Delta\varphi(t,\tau) = \varphi(t) - \varphi(t-\tau)$$

So we don’t have to measure the absolute phase:
we only have to monitor its drift with time

Fibre-optic arrangement to monitor phase drift of oscillator



Mathematically,

$$V_a(t,\varepsilon) = V_{a,\max}\cos(\Delta\phi(t,\varepsilon))$$

$$V_r(t,\varepsilon) = V_{r,\max}\sin(\Delta\phi(t,\varepsilon)).$$

where ε is the delay around the loop. Hence

$$\Delta\phi(t,\varepsilon) = \tan^{-1}(V_r/V_{r,\max},\ V_a/V_{a,\max})$$

and

$$\Delta\phi(t,\tau) = \sum_{k=0}^{k<\tau/\varepsilon} \Delta\phi(t - k\varepsilon, \varepsilon).$$

Computational requirements

- Present system operates at 60% of real time at a single range with a 1.3 GHz processor.
- Multi-range system operating at 8 ranges simultaneously would need 20X as much computation.
- Choice 1 Use 4 GHz processor; grab signal for 250 ms; report every 2-3 s.
- Choice 2 Wait until 2011; purchase 45 GHz processor; run in real time.
- Choice 3 Wait until 2013 ; purchase 90 GHz processor; run in real time for 16 ranges.

Introducing WindCube$_{tm}$

An innovative and compact pulsed Lidar for the Wind Energy

L.Sauvage and R.Parmentier

LEOSPHERE
Lidar Environmental Observations
The Netherlands & France

23 – 24 January 2007
IEA RD&D Wind, Annex XI meeting, RISOE

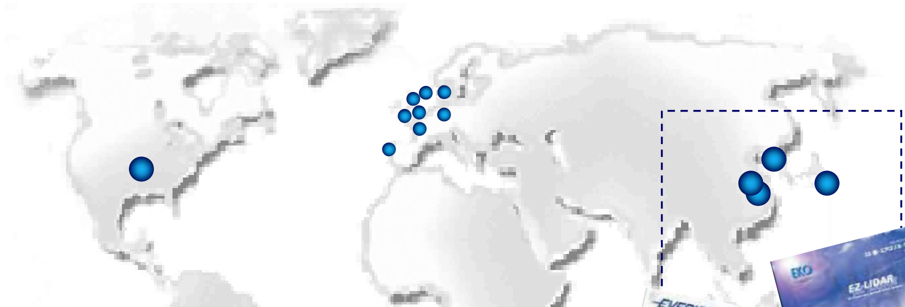
Leosphere at a glance

Our vision : become an European Leader in Lidar Environmental Observations

Wind and turbulences

Cloud, aerosol and humidity

Corporate ID



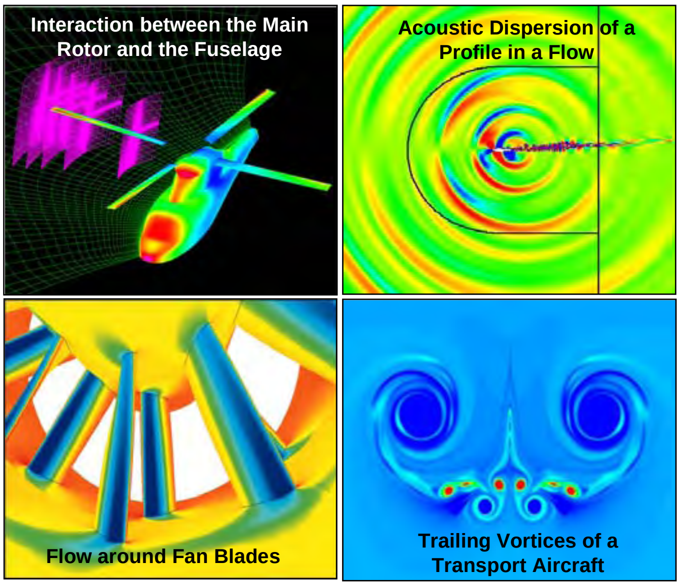
- **15 people**

  Optoelectronics / Atmospheric Physicians / Software engineers
- **Turnover : 1M€ '06 / 2.6m€ est.'07**
- **90% non domestic sales**

Where does that technology comes from?

ONERA

French Aerospace Research Agency



The need : both site assessment and Wind farm operations

- Power curve verification
- Model calibration
- Initial site assessment
- Micro siting
- Highly resolved wind profiles with max range above highest blades
- Impact of vertical profile and turbulences on turbine efficiency
- Circulation for complex site evaluation
- 3D mapping of wind
- Wind gust field upfront of wind turbines

The need for a discreet and reliable remote sensor

- « A device as reliable and cheaper than a met tower » (for bankers) but ...
- ... that can see further (for new wind turbines over 80m)
- in 3D (for complex terrain)
- Portable (for remote areas)
- easily deployable in less than one hour (for short term assessment)
- Silent (for use in areas with population)
- Discreet (for anti-windfarm demonstrators)
- self protective

Wind³Cube

Functional specifications

FUNCTIONAL SPECIFICATIONS

Performances	
Rang min - max	35 to 150m
Accumulation time	1s
Data output frequency	1 Hz
Spatial resolution	26m (13m correlated)
Scanning cone angle	Dual 15° and 30°
Speed accuracy	0,2 m/s
Speed range	-30 to +30 m/s
Direction accuracy	2°
Data availability	95%

Upgradability	Extended range* : 400m (2007) and 2km (2008) 3D scanning

*by embedding a new laser source

Technical Specifications

OPERATIONAL SPECIFICATIONS

Parameters	
Wind profile	Yes
Turbulences	Advanced analysis
Electrical	
Power supply	100/240V AC 50-60 Hz**
Power consumption	120W
Environmental	
Temperature range	-10°c to +40°c
Operating humidty	IP65
Rain protection	Windshield wiper
Compacity	portable (2 persons)
Optics & electronics	
Laser	1,54 µm
Eyesafety	IEC 60825-1
Dimensions	
Size	800x550x550 mm
Weight	45 kg
Data	
Data format	ASCII / binary
Data transfert	GSM / LAN / TCP-IP

** Autonomous power supply solution under development

Key operational Benefits

- Instant outdoor set up (EZ lidar™ concept) : 45kg – Plug and Play
- Silent and discreet, robust and self-protecting, unattended.
- Ultra-extensive range (1km), 2/3D capable.
- Steady high-resolution and availability of data whatever the height
- User friendly graphical interface for measurement settings
- Both data storage (built-in hard disk drive > 1 month) and data transfer through Ethernet / GPRS (ASCII/Binaries)
- Eye-Safe (EN-60825-1)

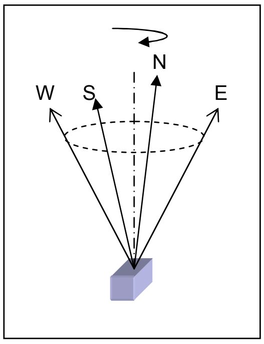
Technological breakthrough

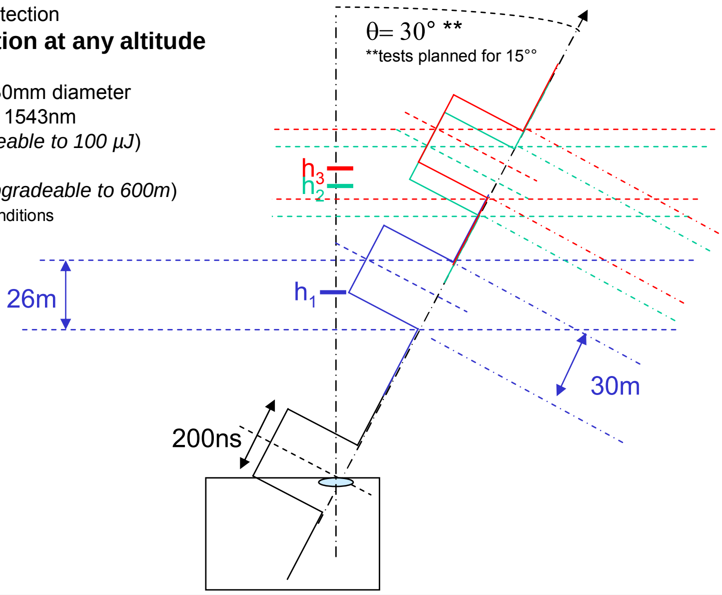
- Pulsed Doppler heterodyne detection

→ **constant space resolution at any altitude**
- Low beam divergence

→limited beam cross-section : 30mm diameter
- Robust Fiber laser source, λ = 1543nm
- Pulse Energy = 10 µJ (*upgradeable to 100 µJ*)
- minimum altitude: 35 m
- maximum altitude: >150m* (*upgradeable to 600m*)

*depends on weather conditions





Technological breakthrough

- Optimized data processing
  - → Based on instrument modelling
  - → Real-time (1Hz) Wind coordinates u, v, w
  - → Radial wind speed variance
  - → Signal-to-Noise Ratio
  - → 1min / 10min horizontal wind speed + direction average
  - → turbulence data (cross-products)

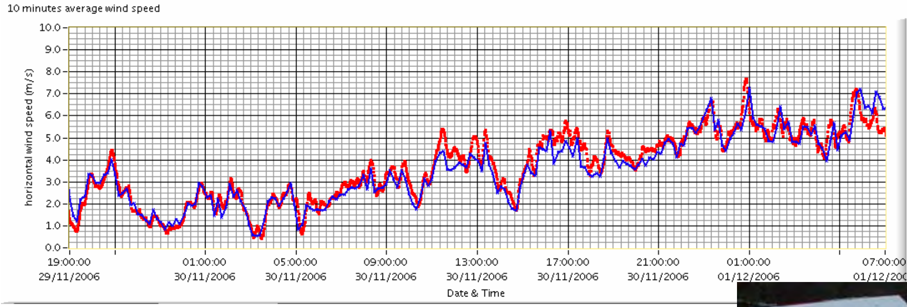
    Frehlich et al., Bound Lay.Met, 1998
- More than 10 user-defined altitudes

Measurements at the Orly airport, France, December 2006.

Unattended 24/24 7/7 Validation campaign

Measurement performed on ***CEA / Saclay*** site with meteorological tower : 60m / 100m USA-1

Example of 36 hours of unattended wind speed measurement
Comparison with ultrasonic anemometer at 60 m



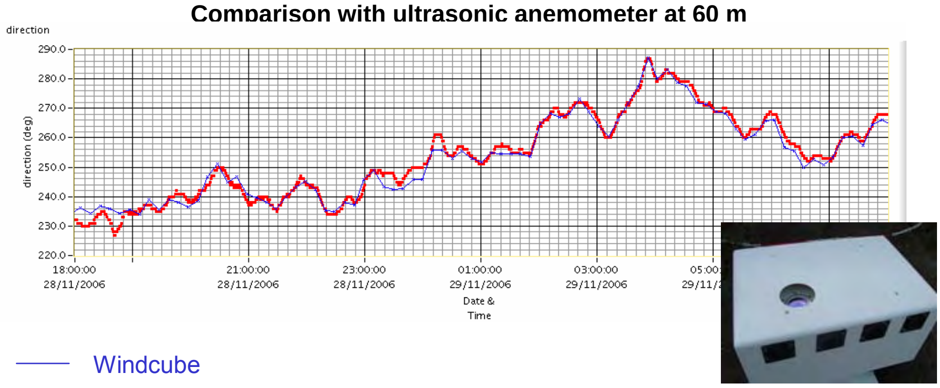
—— Windcube

—— USA-1

Unattended 24/24 7/7 Validation campaign

Measurement performed on ***CEA / Saclay*** site with meteorological tower : 60m / 100m USA-1

Example of 14 hours of unattended wind direction measurement
Comparison with ultrasonic anemometer at 60 m

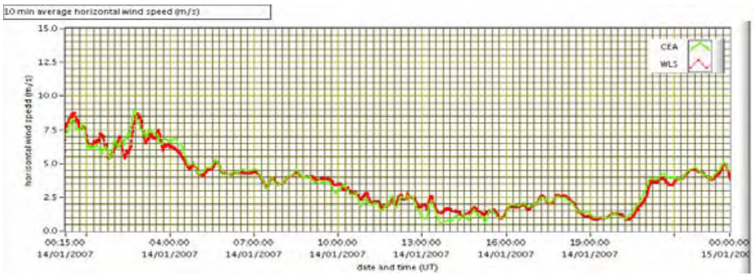


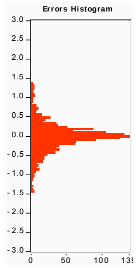
—— Windcube

—— USA-1

January 2007 campaign

Measurement performed on **CEA / Saclay** site with meteorological tower : 60m / 100m USA-1



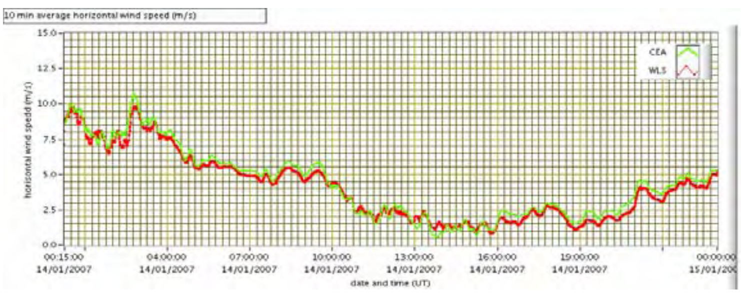


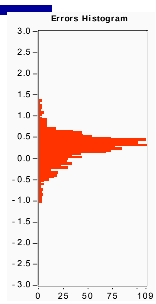
14/01/2007 – 60m
Data availability = 98% over 24 hours
Absolute mean error = -0.02 m/s
Standard deviation = 0.3 m/s

Weather : sunny.

January 2007 campaign

Measurement performed on **CEA / Saclay** site with meteorological tower : 60m / 100m USA-1



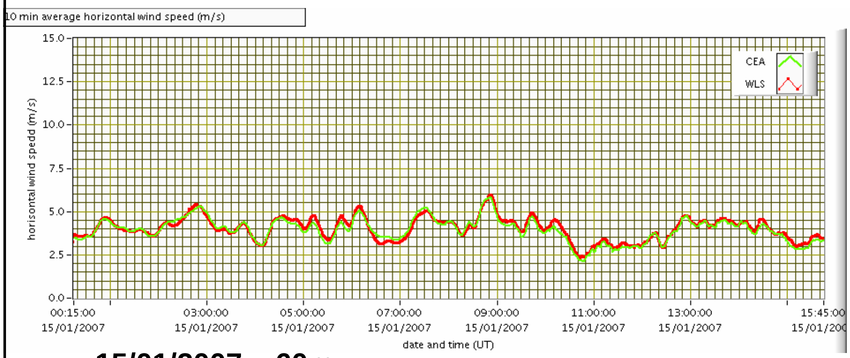


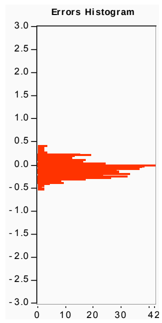
14/01/2007 – 100m
Data availability = 98% over 24 hours
Absolute mean error = 0.25 m/s
Standard deviation = 0.3 m/s

Weather : sunny.

January 2007 campaign

Measurement performed on ***CEA / Saclay*** site with meteorological tower : 60m / 100m USA-1





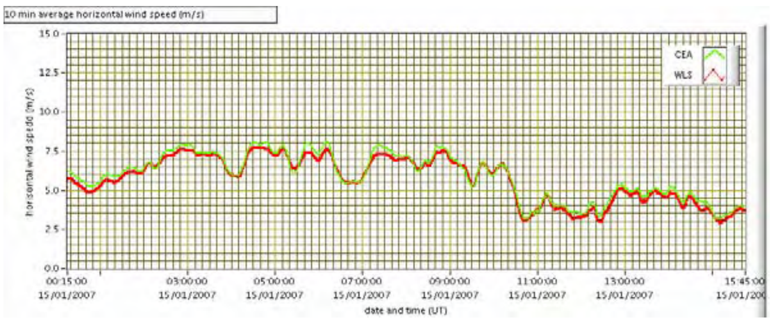
15/01/2007 – 60m

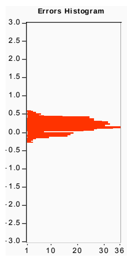
Data availability = 100% over 15.5 hours
Absolute mean error = -0.1 m/s
Standard deviation = 0.2 m/s

Weather: cloudy

January 2007 campaign

Measurement performed on ***CEA / Saclay*** site with meteorological tower : 60m / 100m USA-1

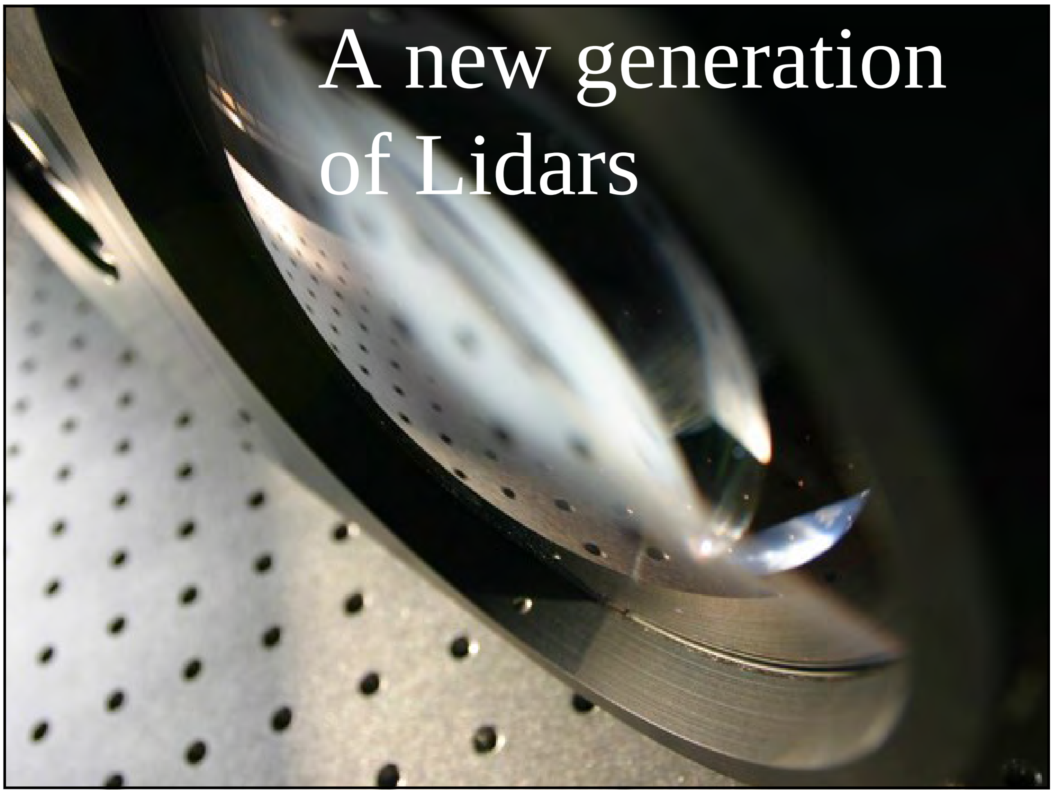




15/01/2007 – 100m

Data availability = 100% over 15.5 hours
Absolute mean error = -0.1 m/s
Standard deviation = 0.2 m/s

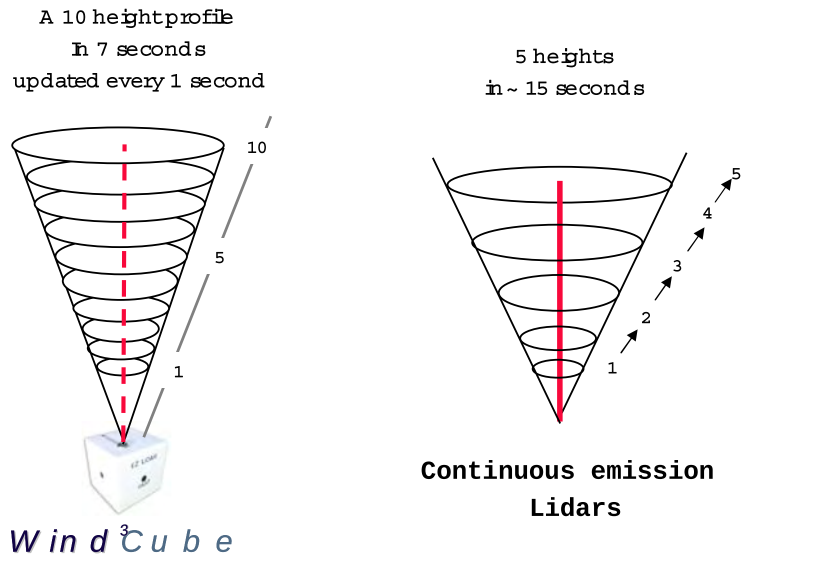
Weather: cloudy



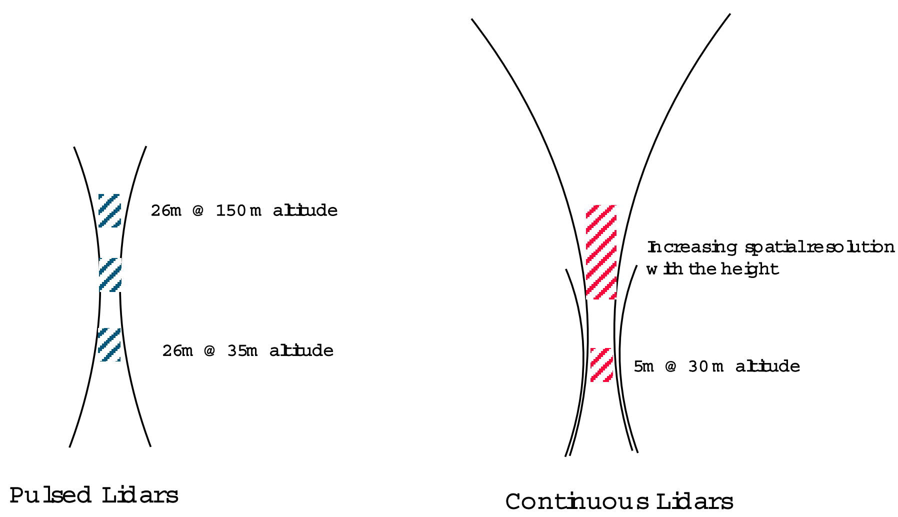
A new generation of Lidars
What does WindCube brings to existing Lidar technologies ?

- WindCube is a pulsed Lidar :
  - Simultaneous measurement at any height
  - Steady performances whatever the height
- WindCube is upgradable:
  - 600m detection
  - 3D windflows
- WindCube is adapatable to reach higher ranges
- WindCube has a 15° scaning angle
- WindCube is robust

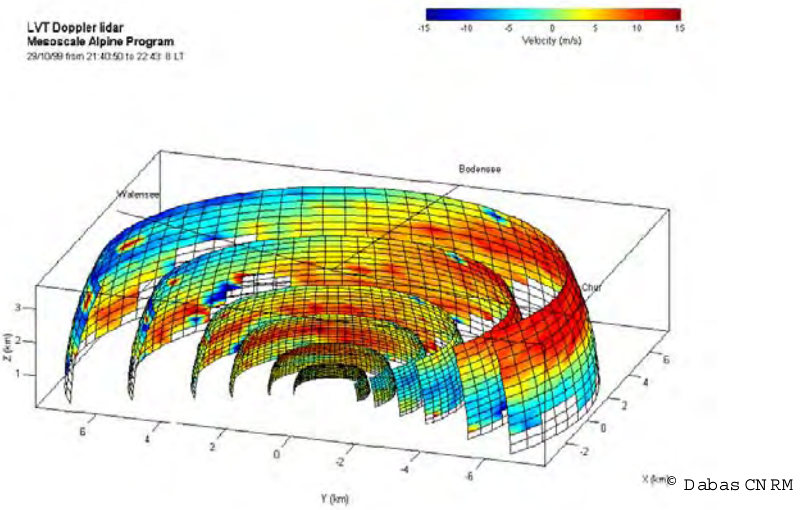
Simultaneous measurement at any height



Pulsed vs. Continuous detection



Upgradability : 3D wind mapping



FURTHER WORK

- New intercomparison campaign with CNRM (versus PA2 Remtech sodar, radial wind speed statistics versus USA-1 at 10m)
- RISOE validation campaign (Feb. 07)
- Enhanced range (600m obtained from various measurements at Orly airport)
- Turbulence calculation incorporated into the commercial software
- Complete autonomous system (independant power supply provided)


Thank you
www.leosphere.com

Summary of IEA RD&D Wind – 51st Topical Expert Meeting on

State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites

January 2007, Risø, Denmark

Background

Wind power is moving towards the installation of wind farms in complex terrains, off-shore, in forests, and at high levels in the atmosphere. Marketing of large, multi-MW wind turbines is in continued growth. At the same time our basic knowledge on winds in these challenging environments is inadequate.

The method traditionally used for accredited measurements for wind energy purposes is to mount cup anemometers on met masts. As turbines grow in height, mast instrumentation, erection and maintenance have become expensive; prices increase with height and building permits can be time-consuming. At the same time the discrepancies between the measured wind at the rotor centre and the turbine performance have increased the need for determining the wind over the whole turbine rotor.

Successful development of wind power should be based on sound information on winds in each location. To achieve this it is important to place emphasis on new observation methods and strategies. Most promising are the new (for wind energy purposes) remote sensing techniques: Sodar, Lidar and satellite. Sodar is based on sound propagation, Lidar on laser doppler and satellite on microwave scatterometry and Synthetic Aperture Radar (SAR) methods. Advantages and limitations of the various techniques will be described and discussed.

SODAR

Sodar (SOund Detection And Ranging) provides a method for wind speed measurements. The instrument is ground-based and emits a short pulse of sound at a certain frequency to the atmosphere. The sound propagates upwards, while at the same time a part of the sound is reflected back. The Doppler frequency shift of the received signal is proportional to the wind speed aligned to the transmission sound path. By combining three or five of these pulses, usually one along the vertical and two or four inclined to the vertical, the three-dimensional velocity field of both the mean values and the turbulent values is calculated.

LIDAR

Lidar is a remote sensing technique that offers the ability to determine wind speed and direction at substantial heights using a ground-based instrument. In this respect it is similar to Sodar, but operates via the transmission and detection of light rather than sound. The basic Lidar principle is to measure the Doppler shift of radiation scattered by natural aerosols carried by the wind. Typically, these are dust, water droplets, pollution, pollen or salt crystals. A new generation of fibre-based Lidar has emerged in recent years that operates close to the theoretical limit of sensitivity and typically only needs to detect one photon for every 10E+12 transmitted in order to measure wind speed. Since the Doppler-shifted frequency is directly proportional to line-of-sight velocity, the wind speeds obtained by a Lidar instrument seem not to need calibration. This however still remains to be documented by more measurements and by a full description of the whole measurement chain. As in the case of Sodar, the Lidar is also a new instrument, and its merits and limitations are neither fully documented nor known. In the case of the Lidar, the measurement of the wind speed takes place on the surface of a cone where the depth changes as a function of the focus distance. The measurement of the turbulence quantities using Lidar also remains to be documented.

Satellite remote sensing

Satellite remote sensing provides wind maps (snap-shot images) of the surface wind at 10 m above sea level. From a scatterometer, twice daily, wind maps at grid resolution of 25 km are available. The data series from July 1999 to present holds more than 5000 observations at most locations of the globe. Due to the resolution of 25 km, observations are not available close to the coastline (usually there is a void around 40 to 50 km distance offshore). In contrast, SAR wind maps cover the near coastal zone in which most wind farms are located. Far fewer SAR wind maps are available (e.g. a few hundred or less), but by using statistical treatment of a few samples, rough estimates of the wind resource can be obtained. The accuracy, around 1.1 m/s standard error, on a series of wind maps compared to offshore mast observations is useful in pre-feasibility studies and in decisions about the location of offshore masts (or LIDAR/SODAR). In addition, if high-quality met-observations are available within a mapped area, the relative differences in winds between different locations can be estimated with higher accuracy, possibly around 0.6 m/s.

Participants / Presentations

A total of 51 participants attended this meeting with representatives from Denmark, Finland, Germany, Ireland, Norway, Sweden, the Netherlands, UK and USA. The participants mainly represented National Research Organizations, utilities and entities performing measurements.

The large number of participants in the meeting reflected the interest in this research topic and application in wind turbine work. The number of participants was restricted due to the size limitations of the meeting facilities.

The number of presentations was 29, covering the following subjects:

General	8 presentations
Sodar	10 presentations
Lidar	9 presentations
Satellite	2 presentations

Discussion

A discussion was held at the end of the meeting. Some of the discussions are summarized below. These points should not be regarded as "truths" coming out of the discussions, but rather comments that participants gave.

General

- There was a common understanding that there is a need for more experience from remote sensing, especially comparing the performances of Lidar and Sodar.
- Lidar and Sodar will complement each other for a while. Both instruments will have a future in atmospheric science.
- Axel Albers: Both Sodar and Lidar have room for improvements. I researched Sodar since 1992. We never got the reproducibility we now see with the Lidar. The first QinetiQ Lidar give astonishing results. It will take a very long time before Sodar can replace met mast in terms of absolute wind speed. This will soon happen with Lidar.
- Andrew Tindal: For some time to come remote sensing will be used in conjunction with conventional anemometry. But, carefully, we should step towards the replacement, through understanding all the errors.

Sodar

- Sodar are commercially available from a number of different companies. Lidar on the other hand are for sale, but are not as developed and commercialized.
- Sodar are generally cheaper than Lidar. A price tag of the ZephIR is 100.000 GBP. Axel Albers commented that customers asking for measurements are not willing to pay rental for such expensive instruments.
- Sodar has fundamental limitations compared to Lidars. The wave length of the sound is large compared to that of light, implying bulkier sodar instruments. The speed of sound is much smaller than that of light, implying that the sound ray propagation in the atmosphere is considerably more complicated, e.g. beam drift. Given the recent development some argued that Lidar has a brighter future than that of Sodar.

Lidar

- Lidar has the disadvantage that the averaging volume increases with height, whereas the corresponding volume for the Sodar remains constant with height. Maybe the pulsed lidar technology will change that.
- Hans E. Jørgensen pointed out that we need to test the performance of Lidar in complex terrain: wind shear, turbulence intensity and flow inclination are issues here of great interest for developers.
- Troels Friis Pedersen: I believe a Lidar mounted on nacelles will be extremely useful for power performance measurements. Stefan Emeis: Maybe there is a difference in the needed accuracy between siting and power performance measurements. Sodar may be fine for wind profiles. J. Højstrup strongly

disagreed. We always need the same accuracy. Better accuracy implies lower financial and technical uncertainties. Albers: There are still a lot of uncertainties in site assessment.

Satellites

- Satellites always see the structure of the surface, e.g. SAR see the wind stress on the surface. Models are needed to transfer this information to hub height. Given the accuracy needed it may not be worthwhile.
- Space-borne Lidar are coming and they may be useful.
- Neil Douglas (Natural Power Consultants): Maybe accuracy is not always so important. For example satellites may be used for relative resource estimation.

There is a need for "best practices" on how to use remote sensing as siting devices, etc., as suggested by Kathleen Moore. More sodar /lidar/mast comparison needs to go to the literature. The initiative of Risø of a remote sensing test facility at Høvsøre is good!

Continuation

There was a common understanding that there is a need for more experience from remote sensing in order to increase the accuracy and the repeatability of measurements, especially comparing the performance of Lidar and Sodar with anemometers. The IEA-developed Recommended Practices for anemometry are available and could be used as a reference for developing similar documents for Lidar and Sodar. Participants pointed out that such documents are needed in a near-future time frame.

As a first step of continuation it was considered relevant to undertake initial work related to develop such practices. It was agreed to form two Ad-Hoc groups to put together proposals for the proper operation of a Sodar/Lidar. The ad-hoc groups should make to-do lists for improvements of the instruments.

- Sodar group: Kathleen Moore will take the lead. Participants: Gunter Warmbier, Mats Hurtig, Andy Oldroyd, Finn Nyhammer, Brian Hurley, Peter Clive, Sabine vonHunerbein, Ken Underwood, Stuart Bradley
- Lidar group: Ioannis Antoniou will take the lead, Axel Albers, Ian Locker, Detlef Kindler, Andreas Rettelmeyer, Brian Hurley

It was noted that there exists a general recommended practice for remote sensing. One in Germany (VDI 3786 Part 14, Verein Deutscher Ingenieure, Environmental meteorology, Ground-based remote sensing of the wind vector. Doppler Wind LIDAR, Dec. 2001) and elsewhere.

The results from the Ad-Hoc groups will be reported at the upcoming meeting of the IEA Wind Executive Committee by the Operating Agent of Task 11. This may result in further action within this field.

List of participants

IEA R&D Wind Task11, Topical Expert Meeting 51
State of the art of Remote Wind Speed Sensing Techniques using Sodar, lidar and Satellites
Risö, Roskilde, Denmark
23-24 January 2007

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