INTERNATIONAL ENERGY AGENCY

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

59th IEA Topical Expert Meeting

Remote Wind Speed Sensing Techniques using SODAR and LIDAR

October 2009, Boulder, CO, USA

National Renewable Energy Laboratory (NREL), USA

Organized by: CENER

Scientific Co-ordination:

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International Energy Agency

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

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

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

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

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

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

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

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

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

Two Subtasks

The task includes two subtasks. The objective of the first subtask is to develop recommended practices for wind turbine testing and evaluation by assembling an Experts Group for each topic needing recommended practices. For example, the Experts Group on wind speed measurements published the document titled "Wind Speed Measurement and Use of Cup Anemometry". A document dealing with Sodar measurements are presently under development.

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

Documentation

Since these activities were initiated in 1978, more than 60 volumes of proceedings have been published. In the series of Recommended Practices 11 documents were published and five of these have revised editions.

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

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European Commission	European Commission
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Unwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	CESI S.p.A. and ENEA Casaccia
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	POHANG University of Science and Technology - POSTECH
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	SenterNovem
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United States	The U.S Department of Energy -DOE

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1. INTRODUCTORY NOTE

Dennis Elliott (NREL), Félix Avia (Operating Agent Task 11, IEA Wind - CENER)

1.1 Background

An IEA Topical Expert Meeting on the Topic "State of the Art of Remote Wind Speed Sensing Techniques using SODAR, LIDAR and Satellites" was organized by and held at Riso National Laboratory in January 2007. This was the first and only IEA expert meeting on this topic.

There was a common understanding that there was 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.

It was decided to develop IEA Recommended Practices for LIDAR and SODAR. Participants pointed out such documents were needed in a near-future time frame. Two ad-hoc groups were formed to put together proposals for the proper operation of a SODAR/LIDAR. Draft documents are in preparation and are expected to be available at the end of the first quarter of 2010.

On the other hand, interest in and use of remote sensing measurements in wind energy applications have increased considerably, particularly as more data are required at increased heights where tall tower measurements become more difficult and expensive to establish. New and improved remote sensing technology has become available, presenting more opportunities to facilitate this technology. However, there are notable concerns over the reliability and accuracy of remote sensing measurements as compared to conventional measurements such as cup or sonic anemometers mounted on towers.

But even the conventional tower measurements are well known to have their issues such as tower flow effects on measurement accuracy.

After discussions with the leaders of ad-hoc groups, it was decided that the arrangement of a new topical expert meeting in these issues will be very useful and will help to improve the work being done.

1.2 Techniques

The two most common remote sensing techniques using ground-based systems are SODAR and LIDAR which are described in the document from the first IEA topical meeting. This meeting should focus largely on SODAR and LIDAR systems, because of the significantly increased use of these systems by the wind industry over the last couple of years.

The meeting should discuss remote sensing applications not only for wind resource assessment but also power performance and operations.

The use of remote sensing (including strength and weaknesses of each type) in different environments such as complex terrain, high surface roughness, and offshore should be addressed. The quality of remote sensing under different atmospheric conditions and at increased heights is also an important issue. Studies and methods to improve the quality of data are of great interest, especially relevant to creating bankable wind farm resource data sets.

1.3 Topics to be addressed

To hold a 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 SODAR and LIDAR systems.
- 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.
- Future options for wind energy using SODAR and LIDAR.

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

1.4 Expected outcomes

One of the goals of the meeting was to gather the existing knowledge on the subject and come up with suggestions and recommendations on how to proceed with the following:

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 this document was compiled containing:

- Presentations by participants
- Compilation of the most recent information on the topic

1.5 Audience

The national members invited 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.

Summary of IEA RD&D Wind – 59th Topical Expert Meeting

Dennis Elliott, NREL, Félix Avia and Paula Gómez, CENER

Background

An IEA Topical Expert Meeting (TEM) on the Topic "State of the Art of Remote Wind Speed Sensing Techniques using SODAR, LIDAR and Satellites" was organized by and held at Riso National Laboratory in January 2007. This was the first IEA expert meeting on this topic.

There was a common understanding that there was 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.

On the other hand, interest in and use of remote sensing measurements in wind energy applications have increased considerably, particularly as more data are required at increased heights where tall tower measurements become more difficult and expensive to establish. New and improved remote sensing technology has become available, presenting more opportunities to facilitate this technology. However, there are notable concerns over the reliability and accuracy of remote sensing measurements as compared to conventional measurements such as cup or sonic anemometers mounted on towers. But even the conventional tower measurements are well known to have their issues such as tower flow effects on measurement accuracy.

At the Riso TEM it was decided to develop IEA Recommended Practices for LIDAR and SODAR. Participants pointed out such documents were needed in a near-future time frame. Two ad-hoc groups were formed to put together proposals for the proper operation of a SODAR/LIDAR. Draft documents are in preparation.

After discussions with the leaders of ad-hoc groups, it was decided that the arrangement of a new topical expert meeting in these issues will be very useful and will help to improve the work being done.

Participants / Presentations

A total of 31 persons registered for this meeting. They represented the following countries: Denmark, Finland, Germany, Japan, Korea, Norway, Sweden, Netherlands, Spain, United Kingdom and the United States. A total of 21 presentations were given.

The participants represented a great variety of stakeholders related to the topic. Those were: research organizations, universities, consultants and some manufactures of equipments.

Presentations covered the following topics:

- 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 SODAR and LIDAR systems.

- 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.
- Future options for wind energy using SODAR and LIDAR.

A total of 25 presentations were given:

1. Félix Avia, CENER, OA Task 11 IEA Wind (FA)
2. Dennis Elliott, National Renewable Energy Laboratory, USA (DE)
3. Peter Clive, SgurrEnergy Ltd, UK (PC)
4. Xabier Comas, Acciona Energía, Spain (XC)
5. Michael Courtney, Technical University of Denmark-Riso National Lab for Sustainable Energy, Denmark (MC)
6. Yeongmi Ji, POSTECH, Korea (YJ)
7. Neil Kelley, National Renewable Energy Laboratory, USA (NK)
8. Thomas Nostrand, NRG Systems Manufacturer of Lidar Systems, USA (TN)
9. Julie Lundquist, Lawrence Livermore National Laboratory, USA (JL)
10. Rod Frehlich, University of Colorado, USA (RF)
11. Niels LaWhite, Second Wind Inc, USA (NL)
12. Mathew Filippelli, AWS Truewind, USA (MF)
13. Andreas Beeken, Dewi GmbH German Wind Energy Institute, Germany (AB)
14. Regina Deola, SANDIA Sandia National Laboratories, USA (RD)
15. Matthias Wächter, ForWind Center for Wind Energy Research, Germany (MW)
16. Jan Willem Wagenaar, ECN Unit Wind, Netherlands (JW)
17. Daniel Gustafsson, Vattenfall AB, Sweden (DG)
18. Nobuyuki Hayasaki , Itochu Techno-Solutions Corporation, Japan (NH)
19. Jeffrey Fine, Renewable Energy Systems-Americas, USA (JF)
20. Daniel Jaynes, Garrad Hassan America Inc., USA (DJ)
21. Kathleen Moore, Integrated Environmental Data, LLC, USA (KM)
22. David Schlipf, SWE am Institur Für Flugzeugbau Universität Stuttgart, Germany (DS)
23. Hyun-Goo Kim, Korea Institute of Energy Research, Korea (HK)
24. Fred Belen, Optical Air Data Systems - Catch The Wind Inc., USA (FB)
25. Kenneth Underwood, Atmospheric Systems Corporation, USA (KU)

Other participants were:

26. Jerry Crescenti, Iberdrola Renovables (JC)

27. Paula Gomez, CENER(PG)
28. Yoshiko Ito, Sonic Corp (YI)
29. John Obrecht, Siemens Energy – Wind Power (JO)
30. Joachim Reuder, University of Bergen – Geophysical Institute (JR)
31. Andrea Vignaroli, VTT Wind Energy (AV)

Discussion

Following the two days of presentations the floor was opened and a general discussion took place. A number of different topics were handled. However, it was decided to focus the discussion in the issue of "Best practices" for wind resource assessment using Remote Sensing Systems (RSS). There was a general consensus that Best Practices documents should be focussed on obtaining bankable data for resource assessment.

In particular, the following topics were discussed, in order to decide whether to include them in the Recommended Practices (RP) document, and which are the priorities:

- Validation of RSS vs tower measurements.
- Simple terrain vs complex terrain issue.
- Field practices
- Uncertainty and turbulence measurements
- Applications of RSS
- Structure of the RP documents
- Future actions

Validation of RSS vs tower measurements.

One of the first priorities to arise is the need to describe the design of measurement programs using best practices of meteorological towers and RSS in simple terrain (DE). There is a consensus among the meeting participants that there is no need to carry out new measurement campaigns. There are already many projects done (some of them presented in this meeting), which show that well designed measurement campaigns present very satisfactory performance of RSS in simple terrain.

Regarding the RSS to tower data comparisons, it was pointed out that a separation between the atmospheric component of the error, and the component associated with the instrument itself, has not been done. Such atmospheric error could be bounded, when necessary, from the tower data, by means of turbulence parameters (RF). The subject of turbulence as seen by RSS is discussed later on.

Simple terrain vs complex terrain issue.

According to the information presented for simple terrain, the confidence in the already existing procedures is very high, and correlation obtained between the measurements performed using remote sensing instruments versus the conditional cup anemometers is excellent.

The situation is different when making measurements in complex terrain; we have seen various results in complex terrain during these meeting, where RSS and towers present different levels of agreement. In some cases, even when the RS instrument is working correctly, the results can be misleading, if the terrain is too complex (DE). In such situations it's likely that the scatter presented

is dominated by atmospheric characteristics at the measurement site (including the terrain complexity as one of these) rather than by the instrument error (RF).

In relation to this, when comparing measured data using RSS versus data obtained using cup anemometers in complex terrain, it has to be taken into account that also cup anemometers can give not good data (CT). This can be considered under the uncertainty of assessment in complex terrain. It was previously shown in KU's presentation that even well-designed meteorological towers can show important discrepancies in complex terrain (DE).

It was stated that a classification of the terrain (simple, complex, etc) in terms of remote sensing is not defined, but is necessary (MC).

It was also expressed that more knowledge is required about site characterization; that should be done in coordination with the IEC T88 WG (DE).

The conclusion of this part of the discussion is to focus on simple terrain when elaborating the first versions of the recommended practices. It is agreed that the accuracy of RSS can be verified in simple terrain, but this doesn't mean RSS should not be used in complex terrain (DE).

Field practices

It was pointed out that there is a need for guidelines on what the recommended field practices are. For instance, recommendations for location of the RSS, because (the usual) installation in the vicinity of a meteorological mast may not be the best location, and that is normally chosen for inter-comparison purposes (FB).

It was also suggested that it should be clear in the RP document what are acceptable uses and deployments of RSS and which are not (DJ). Key issues are to operate and maintain the instruments correctly.

Uncertainty and turbulence measurement

There is a consensus that resource assessment is bankable at the present state of the art using RS instruments; but uncertainty analysis is necessary in order to achieve bankability in wind resource assessment.

It was remarked that the key point is to have a procedure to assess the uncertainty of measured data, classified according the site and specific parameters of the measurement campaign, not depending on the instruments (DJ).

It was discussed how typical wind energy metrics, such as the turbulence intensity (σ_u/u), can be used to classify the measurement uncertainty of the data collected by RS instruments. On the one hand, one could define new sets of turbulence metrics based on RSS (JC). But, on the other hand, as each RSS measures turbulence in a different way, it'd be better to remain with the conventional definition of turbulence (MC). Turbulence seen by RSS can be related to the standard definition of TI, by means of investigating the physics inherent to each RSS device, and establishing the connection between both (RF). Deriving a new turbulence metric, common for all RSS, could be put in the list for future R&D activities, but it is agreed not to be a priority at this point (DE). General opinion is that we are not in the stage of coming up with recommended practices regarding turbulence.

A large number of experts are already studying an analyzing how to assess the uncertainty. And it is not high priority to launch new research project to assess the uncertainty, due to the fact that enough information is already available on it.

Applications of RSS.

Although it was prioritized to focus on the use of RSS for resource assessment, other applications such as power curve measurements, operation and forecasting were discussed.

It was commented that high accuracy requirements are more restrictive for resource assessment purposes than for use in control strategies (DJ). It is important to remark that the availability of data (quantity) should be a priority in addition to the quality (DE).

The RSS measurement is complementary to the cup anemometers measurements and help to have a better picture of the real situation (JC). For instance, in the new IEC Document of Power Curve Standard, the measurement of the vertical profile is going to be included (MC).

It was commented about why not including in the RP also the study on the power performance of Wind Turbines (JW). **I**ntroduction of RSS in the measurement of power curve procedure is already being taken care of by the 12-1 revision group (MC).

It was agreed that other applications different from resource assessment should be mentioned in the RP, but main focus should remain in resource assessment.

Structure of the RP documents

A consensus is reached about elaborating a RP document that, basically, would describe under which conditions data from RSS can be bankable, what are the parameters to check that, and how parameters can be measured (DE)

PC's suggestion that the recommended practices document should be technology specific (lidar or sodar), but not be instrument specific, is agreed by the group. A scheme for the RP is proposed, according to which a general verification protocol could be carried out (common for both lidars and sodars), followed by best practices for lidars and sodar, and finally different documents instrument-specific. This called "Boulder Protocol" document could be integrated with the draft RP documents (PC).

A classification identifying the advantages and disadvantages of some instruments versus other types according the necessities could be done (FB), but as it may lead to discussion of one instrument over the other, it is agreed to focus in the advantages of using RSS complementary with tower masts (JC).

Parameters that should be included in the documents are the bias number and the random error number. Some procedures should be developed, and specified by manufacturers, to evaluate them. Manufactures should provide reference values of both.

The acceptable (atmospheric) error depends on the application. (RF)

Future actions under the umbrella of IEA Wind

The participants in the meeting were very interested in continuing the efforts in this area, and reiterated the necessity of elaborate the RP on best practices to use remote sensing equipments. Some of the participants will collaborate to the preparation of the RP.

It is suggested by FA that is more convenient to have a small group of people elaborating the draft RP that later on would be passed on to the rest of the members to comment on or complete. In particular, the two ad-hoc groups to deal with sodar and lidar (respectively) are:

- Kathleen Moore & Jerry Crescenti for SODAR RP
- Dan Jaynes and Rod Frehlich for LIDAR RP.

It is also agreed that the next meeting will be held between the operating agent and the components of these two groups, and later on a general, plenary meeting. It is suggested, as tentative, to have drafts of the RP in 6-month time.

The existing documents on sodar RP (also available at www.iedt.com/sodar.html) and PC's suggestion for protocol will be distributed to the assistants to the meeting. It was also suggested (JC) that a web site is created so that the participants in this meeting

The International Energy Agency Implementing Agreement for
Co-operation in the Research, Development, and Deployment of Wind Energy System

TEM on REMOTE WIND SPEED SENSING TECNIQUES USING SODAR AND LIDAR

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NREL-NWTC- October 15-16, 2009

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National Renewable Energy Laboratory
Innovation for Our Energy Future

Introductory Note

IEA Topical Expert Meeting 59
"Remote Wind Speed Sensing Techniques Using Sodar and Lidar"

Dennis Elliott

National Renewable Energy Laboratory – Golden, Colorado USA

October 15-16, 2009

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

Instrumentation Available for Wind Energy Technology

- Tower / in situ – traditional, and **The** accepted Reference
- Remotely Sensed
  - **Acoustic**
    - **Sodar**
  - **Optical**
    - **Lidar**
  - Radio Frequency
    - Radar wind profiler

2

National Renewable Energy Laboratory — Innovation for Our Energy Future

Need for Remotely Sensed Measurements

- Impractical = in-situ measurements of wind characteristics at heights of current (80-120 m) and future wind turbine rotors (200 m)
- Details of vertical boundary-layer structure over candidate sites and operating wind farms:
  - Important from both a resource and operational viewpoints
- Regional as well as local measurements are required to meet the needs of resource assessment, R&D, and operational numerical weather prediction
- Reliable, autonomous, and cost effective remote sensing instrumentation is needed

3

National Renewable Energy Laboratory Innovation for Our Energy Future

Background for this Meeting

The first IEA Topical Expert Meeting on Remote Sensing at Risoe National Laboratory in January 2007 recommended:

- Need for more experience from remote sensing
  - To increase the accuracy and the repeatability of measurements
  - Especially comparing the performance of Sodar and Lidar with tower measurements
- Development of IEA Recommended Practices for Sodar and Lidar
  - Two ad-hoc groups were formed to put together proposals for the proper operation of Sodar and Lidar
  - Draft documents are in preparation
- Arrange a new expert meeting to discuss pertinent issues and new research on this topic

National Renewable Energy Laboratory Innovation for Our Energy Future

Important Issues to Discuss

- Significantly increased use of Sodar and Lidar systems by the wind industry over the last couple of years (but no best practices)
- Use of remote sensing in a variety of applications including:
  - Resource assessment
  - Power performance
  - Operations
  - Wind forecasting
- Performance (including strengths and weaknesses) in different environments - complex terrain, high roughness, offshore, etc
- Quality of data in different atmospheric conditions and at increased heights
- Studies to improve quality of data, especially relevant to creating bankable wind resource data sets

National Renewable Energy Laboratory Innovation for Our Energy Future

Topics to be Addressed

- Overview of existing knowledge and experience on Sodar and Lidar technical issues
- Calibration of Sodar and Lidar systems
- Accuracy and reliability of the different systems and comparisons with point measurement techniques
- Development of a “good measurement practice” using remote sensing equipment
- Future options for wind energy using Sodar and Lidar

National Renewable Energy Laboratory Innovation for Our Energy Future

Commercially-Available Sodars

Representative Examples of Mini-Sodars

Second Wind
Triton

ASC
4000

ART
VT-1

Scintec
SFAS

	Mini-Sodars	Mid-Range Sodars
Nominal operating frequency	4500 Hz	2000 Hz
Measurement range	15-200 m	30-1000 m
Minimum vertical resolution	5-10 m	20 m
Averaging times	2 to 60 minutes	2 to 60 minutes
Claimed accuracy	0.3 to 0.5 m/s	0.3 to 0.5 m/s

7

National Renewable Energy Laboratory — Innovation for Our Energy Future

Commercially-Available Lidars for Wind Energy Applications

Examples

Continuous Wave (CW) Lidar

QinetiQ
Zephyr

Pulsed Coherent Lidars

Wind Profiling Lidar

NRG/Leosphere
WindCube

Catch the Wind
Vindicator

Scanning Lidars

Lockheed-Martin
WindTracer

HALO
Photonics

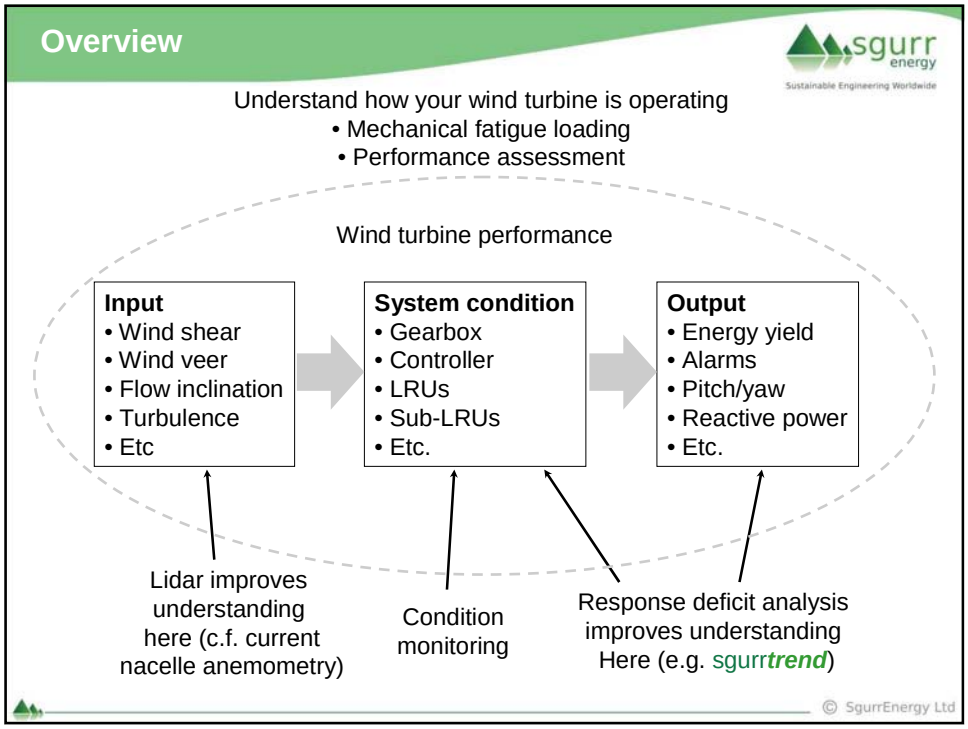
8

National Renewable Energy Laboratory — Innovation for Our Energy Future

Welcome to NREL's National Wind Technology Center
Have a successful meeting

National Renewable Energy Laboratory Innovation for Our Energy Future

Lidar and Wind Regime Analysis
Peter Clive
Technical Development Consultant
sgurr energy
Sustainable Engineering Worldwide


Overview
sgurr energy
Sustainable Engineering Worldwide
Understand how your wind turbine is operating
• Mechanical fatigue loading
• Performance assessment
Wind turbine performance
Input
• Wind shear
• Wind veer
• Flow inclination
• Turbulence
• Etc
System condition
• Gearbox
• Controller
• LRUs
• Sub-LRUs
• Etc.
Output
• Energy yield
• Alarms
• Pitch/yaw
• Reactive power
• Etc.
Lidar improves understanding here (c.f. current nacelle anemometry)
Condition monitoring
Response deficit analysis improves understanding Here (e.g. sgurrtrend)
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Lidar community

Labs
Risø DTU
NREL
CRES
CIRCE?
etc.

Users
Developers
DD/PIAs
Utilities
PPAs
NIAs
Collaborative Networks
etc.

Providers
SgurrEnergy
Leosphere
NRG
Lockheed Martin
QinetiQ
Natural Power
Michigan Aerospace
CatchTheWind
etc.

OEMs
Siemens
Vestas
etc.

Committees
IEA TEM
UpWind FP7
LAG
IEC 61400-12-1 MT
MeasNet
etc.

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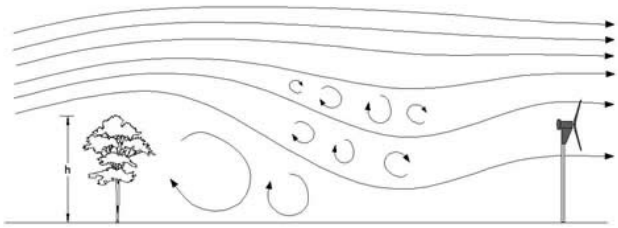
Not Just Wind Speed & Direction

- Turbulence
- Wind shear
- Wind veer
- Flow inclination



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Remote Sensing Technologies

- Lidar and Sodar devices are now available for measurement of wind characteristics.
- Lidar arguably most promising.
- Relatively new to Wind Engineering

  Used in;
  - Atmospheric Science applications
  - Airport Monitoring

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Lidar

Mature technology, new application

Compact and portable for rapid and easy deployment

Acquires wind speed, direction, shear, veer, TI, and inclination data

Measures at proposed turbine locations and operational assets

Wind resource assessment and model validation

Performance monitoring and assessment of operational turbines

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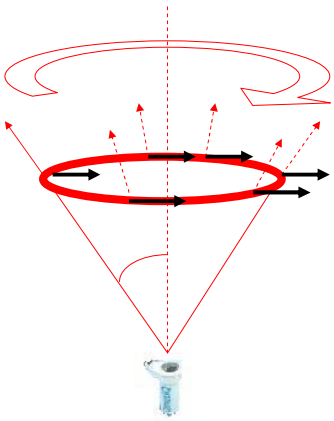
Conventional VAD Scans



contents

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VAD (1)

A laser is shone upwards and light reflected by microscopic airborne particulates is detected.

Emitted laser beam inclined to vertical by a wedge

Beam swept around cone by rotating wedge, scanning the air

contents

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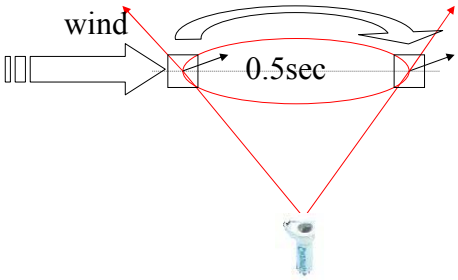
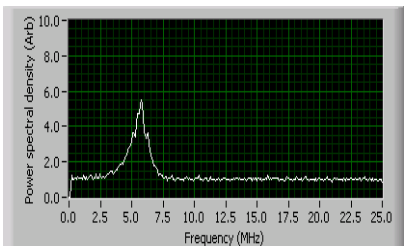
VAD (2)

1: The laser is scanned around a cone to give a series of values from which the wind velocity is derived.



2: The reflected light is detected at 50 positions around the cone.

3: For each of these 50 positions the spectrum of the reflected light is measured.



4: The Doppler shift indicates the radial velocity of the particulates and hence the wind carrying them.

Data from "Measurement of Turbulence with a CW Lidar: Effects of Conical scanning and Probe Volume", Torben Mikkelsen and Hans E. Jørgensen, IEA Remote Sensing Experts Meeting, Risø, January 2007

contents

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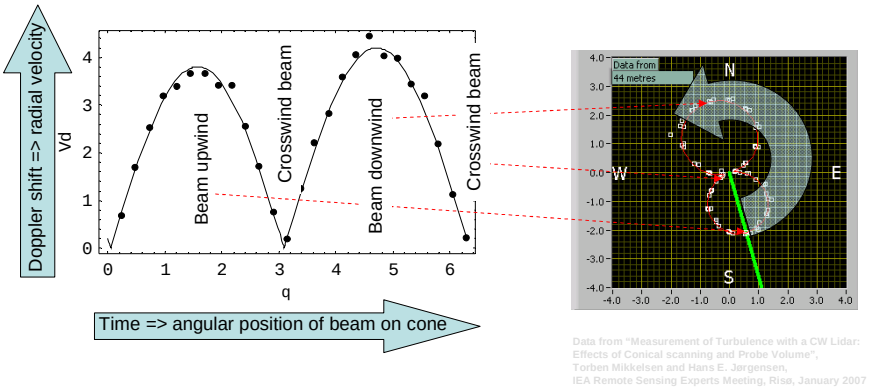
VAD (3)

A polar plot of 50 radial velocities per 1 second scan produces a characteristic "figure of 8" plot or VAD ("Velocity Azimuth Display") aligned in the wind direction. All three wind velocity components, u, v and w, can be obtained from this.



Data from "Measurement of Turbulence with a CW Lidar: Effects of Conical scanning and Probe Volume", Torben Mikkelsen and Hans E. Jørgensen, IEA Remote Sensing Experts Meeting, Risø, January 2007

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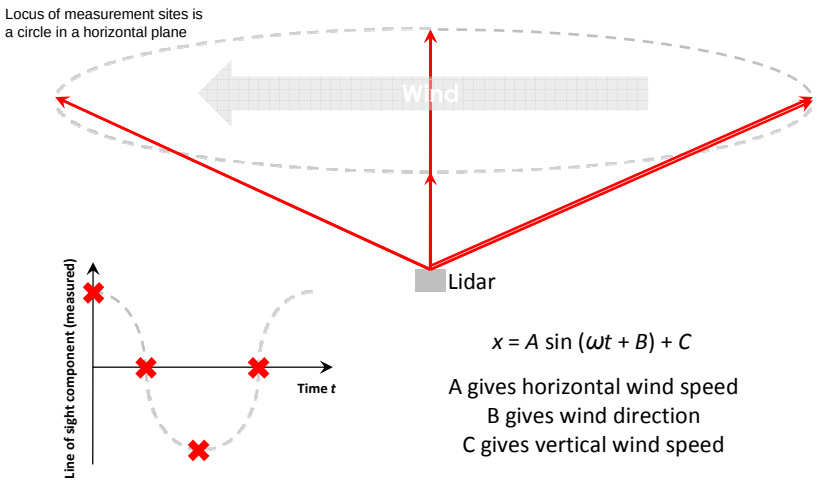
Conventional scan geometry

VAD scan geometry



$x = A \sin(\omega t + B) + C$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

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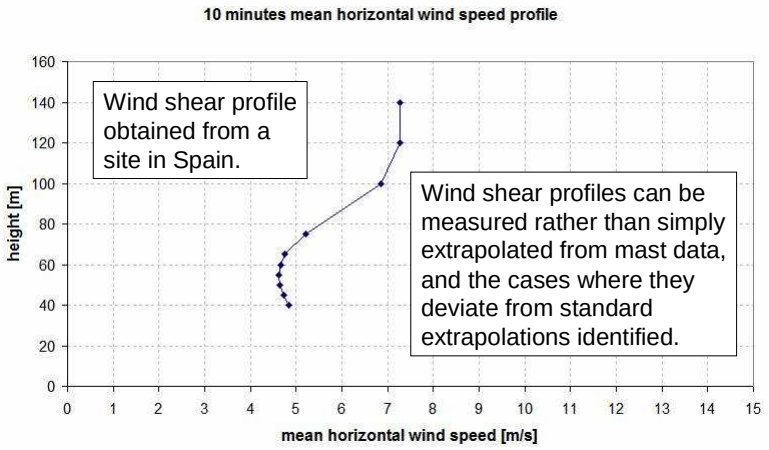
VAD - wind shear profiling



Wind shear profile obtained from a site in Spain.

Wind shear profiles can be measured rather than simply extrapolated from mast data, and the cases where they deviate from standard extrapolations identified.

Data courtesy of Remy Parmentier, Leosphere

contents

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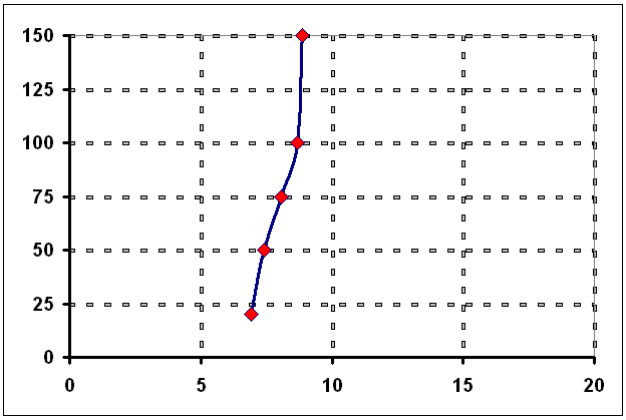
VAD - wind shear profiling



contents

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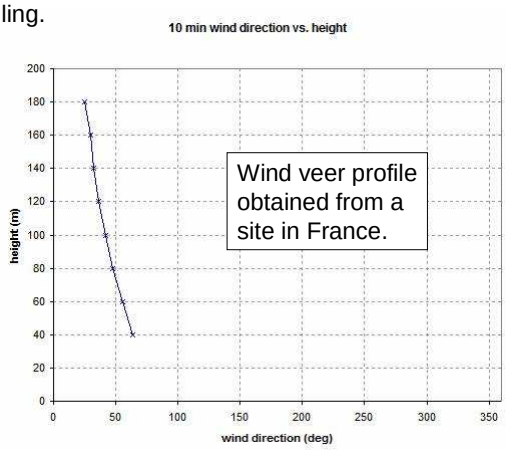
VAD - wind veer profiling

Lidar allows easy wind veer profiling.

Wind directions change with height. As hub heights increase effects such as the Ekman Spiral begin to become significant.

Wind veer representing a variation in wind direction of 20º across the rotor diameter has been measured, which seriously impacts predictions of turbine performance.



Data courtesy of Remy Parmentier, Leosphere

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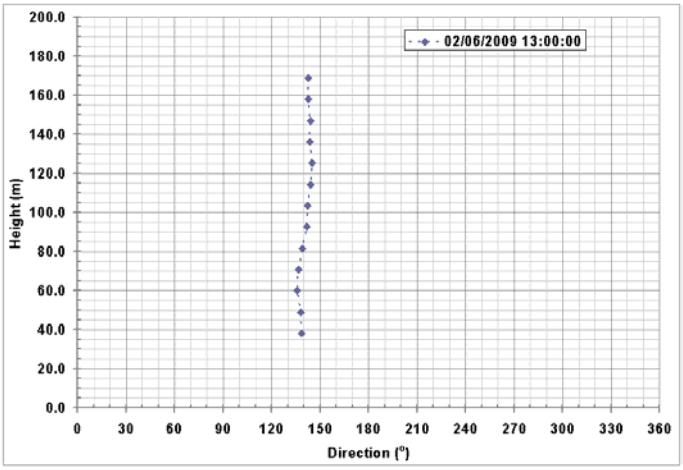
VAD - wind veer profiling



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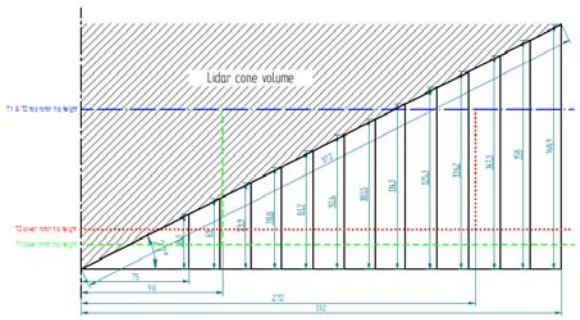
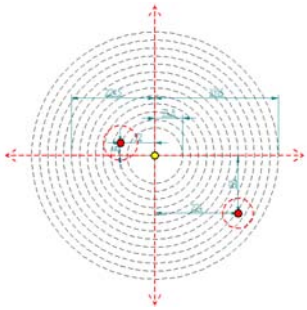
VAD - wind veer profiling





Need for freestream conditions throughout measurement volume

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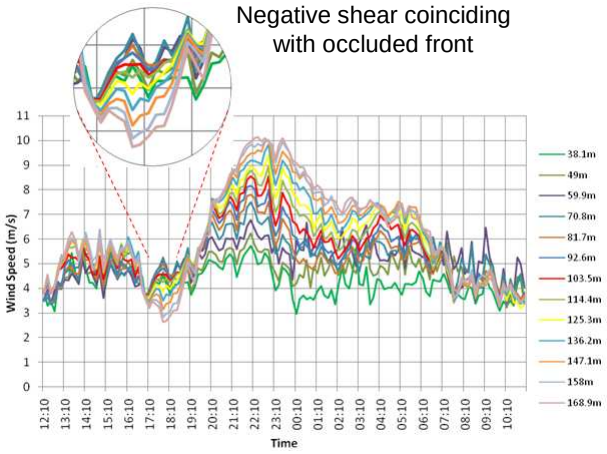
VAD - wind shear profiling

Negative shear coinciding with occluded front



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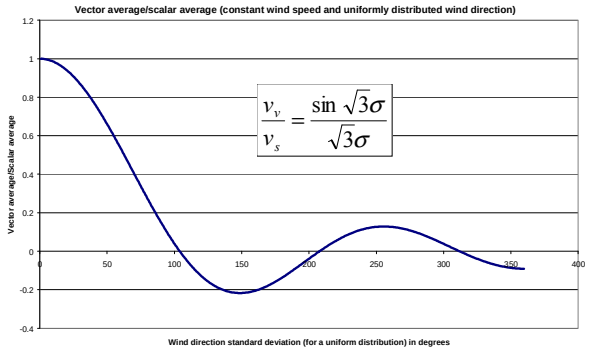
Veer (1)

Cup anemometers acquire a scalar average of wind speed at a point…
Remote sensing devices such as SODAR and Lidar find averages of radial velocity vectors in given directions, from which the wind vector is obtained. These methods can produce different results. An extreme example would be if the wind blew with constant speed *V* half the time from the north and half the time from the south during an averaging interval. The scalar average as seen by a cup would be *V*, but the vector average as seen by the remote sensing device would be *zero*. In general the vector average will be less than the scalar average as a result of the variation in wind direction during the averaging interval.



The ratio of scalar to vector average, assuming a uniform direction distribution and constant wind speed, as a function of wind direction standard deviation σ_{dir} (a measure of how much the wind direction varies during the averaging interval), is the Bessel function shown above…

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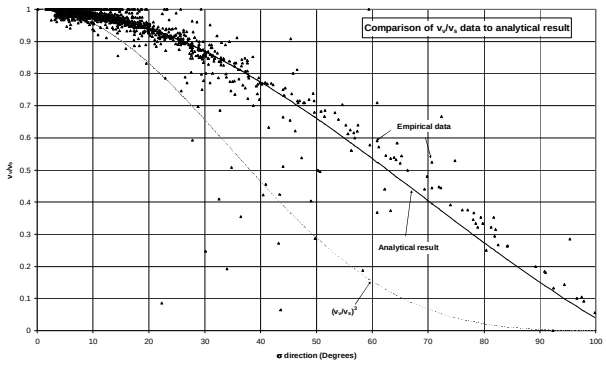
Veer (2)

Empirical results agree reasonably well; $R^2 = 0.86$



(Empirical data obtained from a prop and vane instrument courtesy of Kathy Moore)

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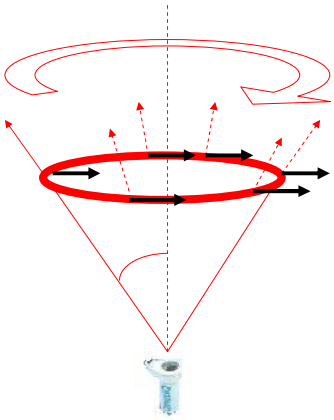
Issues with VAD Scans



contents

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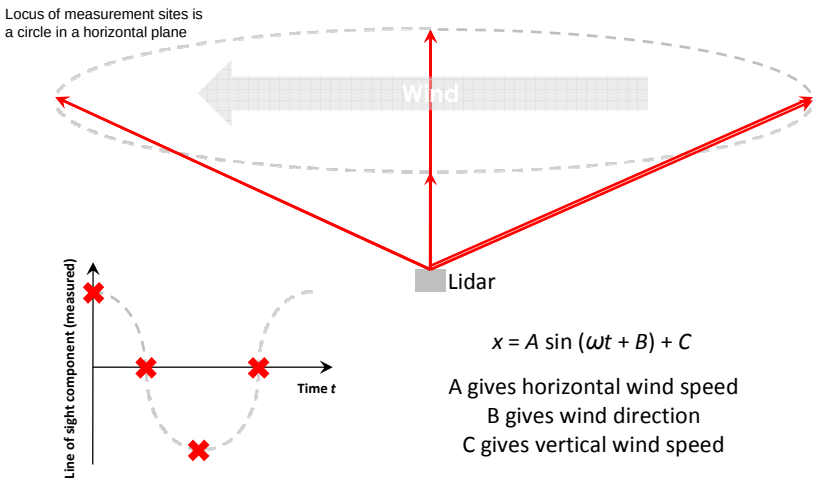
Data rates

VAD scan geometry



$x = A \sin(\omega t + B) + C$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

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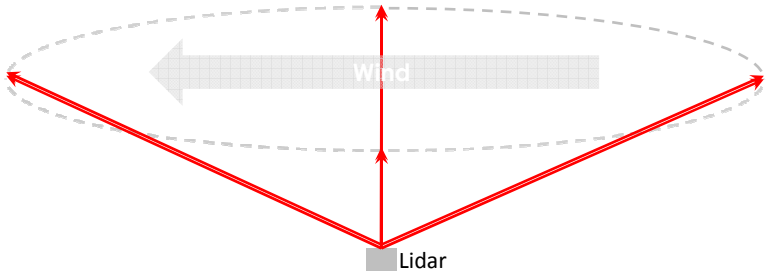
Data rates

Statistically equivalent
data refresh rates



Beams used

Beam	1	2	3	4	5	6	7	8
Scheme A				✓	✓	✓	✓	✓
Scheme B				✓				✓

✓ = wind parameters recorded

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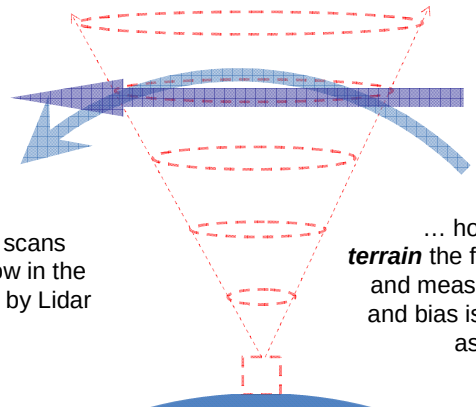
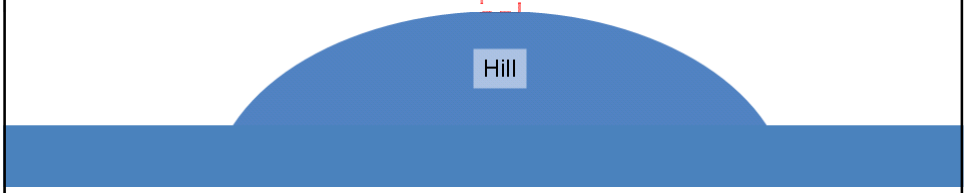
Variable flow inclination (1)



Conventional VAD scans assume uniform flow in the volume penetrated by Lidar measurements …

… however in ***complex terrain*** the flow is ***not*** uniform, and measurement ambiguity and bias is introduced by the assumption that it is.



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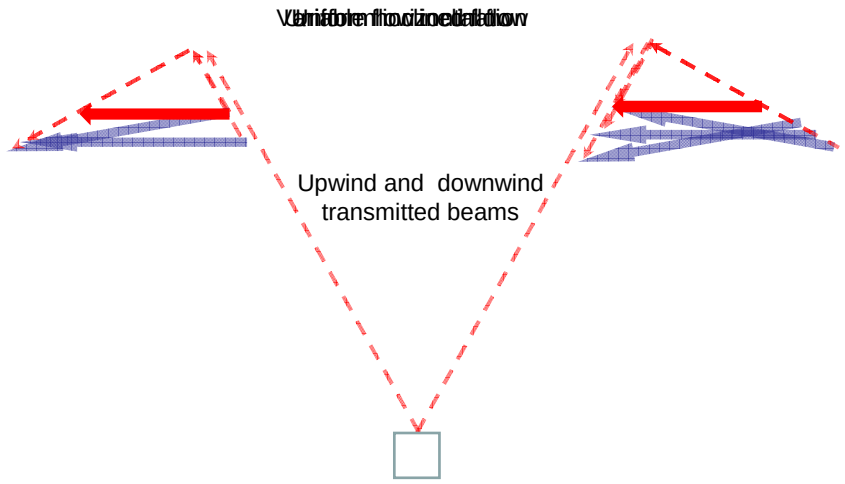
Variable flow inclination (2)



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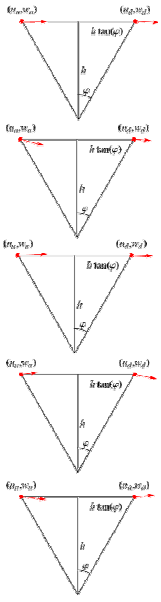
Turbulence (Jakob Mann)



We ignore sample volume averaging

$$
\begin{aligned}
v_{up} &= (-\sin\varphi, \cos\varphi)\cdot(u_u, w_u) \\
&= -u_u \sin\varphi + w_u \cos\varphi \\
v_{down} &= (\sin\varphi, \cos\varphi)\cdot(u_d, w_d) \\
&= u_d \sin\varphi + w_d \cos\varphi
\end{aligned}
$$

$$
\begin{aligned}
u_{lidar} &= \frac{v_{down} - v_{up}}{2\sin\varphi} \\
&= \frac{(u_d + u_u)\sin\varphi + (w_d - w_u)\cos\varphi}{2\sin\varphi} \\
&= \frac{1}{2}(u_d + u_u) + \frac{1}{2}(w_d - w_u)\cot\varphi
\end{aligned}
$$

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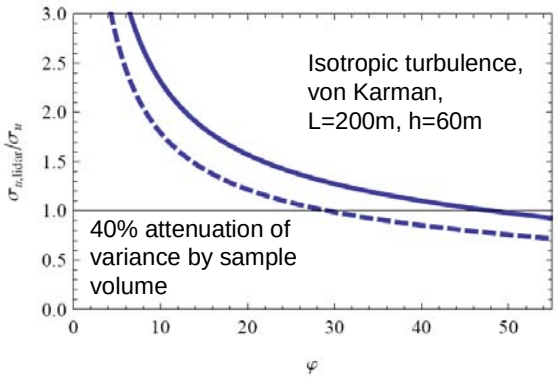
Turbulence (Jakob Mann)

turbulence is homogeneous and $R_{uw}(x)$ is symmetric

$$\sigma^2(u_{lidar}) = \frac{1}{2}\left(\sigma_u^2 + R_{uu}(2h\tan\varphi)\right) + \frac{1}{2}\cot^2\varphi\left(\sigma_w^2 - R_{ww}(2h\tan\varphi)\right)$$



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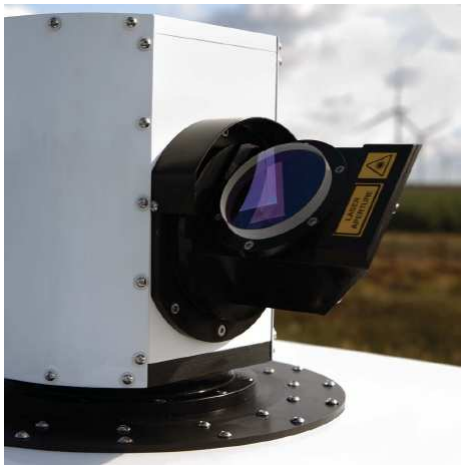
Galion

© SgurrEnergy Ltd

Galion

Galion™



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Galion

- "Next generation"
- A range of 2km, multiple measurements from a single deployment
  - Not limited to measuring directly above the unit
- Pulsed

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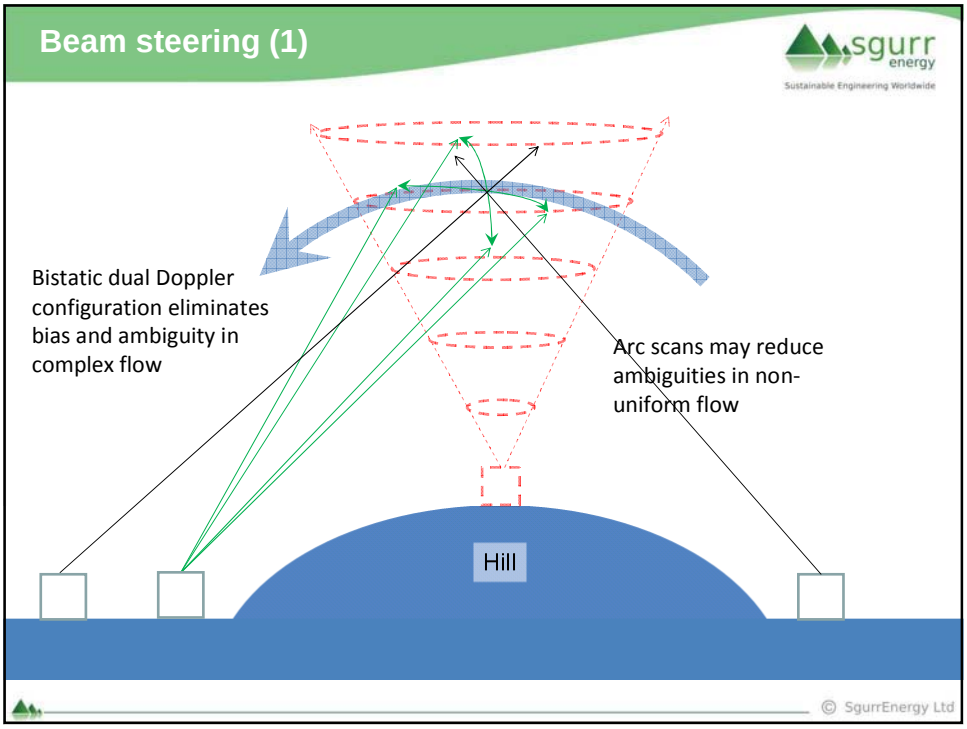
Beam steering (1)



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Some data …

Date/time	Height/range	Hsp	Vsp	Wdir	Turb	Mean intensity
12/08/2009 06:29:52	60	6.368	-0.596	266.155	0.113	3.402
12/08/2009 06:29:52	70	6.436	-0.653	259.913	0.139	2.982
12/08/2009 06:29:52	80	6.575	-0.516	255.097	0.265	1.999
12/08/2009 06:29:52	85	6.583	-0.375	255.423	0.344	1.619
12/08/2009 06:29:52	90	6.446	-0.199	255.264	0.383	1.427
12/08/2009 06:29:52	100	6.475	0.017	256.110	0.537	1.343
12/08/2009 06:29:52	110	6.810	0.062	258.718	0.765	1.207
12/08/2009 06:29:52	120	7.202	0.096	264.966	0.669	1.211
12/08/2009 06:29:52	130	7.909	0.306	269.134	0.489	1.268
12/08/2009 06:29:52	140	8.120	0.295	272.291	0.425	1.207
12/08/2009 06:29:52	150	8.201	0.289	275.378	0.338	1.097
12/08/2009 06:29:52	160	8.146	0.363	277.349	0.290	1.035
12/08/2009 06:29:52	170	7.958	0.539	279.887	0.193	1.012
12/08/2009 06:29:52	180	7.382	0.386	277.980	0.029	1.004
12/08/2009 06:29:52	200	7.023	0.533	289.316	0.002	1.000
12/08/2009 06:30:16	60	5.049	-0.267	282.108	0.002	2.847
12/08/2009 06:30:16	70	5.276	-0.306	279.127	0.023	2.609
12/08/2009 06:30:16	80	5.633	-0.318	277.491	0.039	2.022
12/08/2009 06:30:16	85	5.871	-0.329	277.187	0.043	1.831
12/08/2009 06:30:16	90	6.057	-0.358	276.965	0.041	1.674
12/08/2009 06:30:16	100	6.237	-0.488	277.553	0.047	1.463
12/08/2009 06:30:16	110	6.422	-0.460	281.041	0.169	1.364
12/08/2009 06:30:16	120	6.927	-0.352	281.088	0.333	1.515
12/08/2009 06:30:16	130	7.139	-0.244	280.477	0.523	1.730
12/08/2009 06:30:16	140	7.194	-0.238	279.015	0.646	1.712
12/08/2009 06:30:16	150	7.259	-0.289	277.844	0.579	1.368
12/08/2009 06:30:16	160	7.303	-0.204	276.311	0.450	1.164
12/08/2009 06:30:16	170	7.213	-0.238	275.981	0.270	1.091
12/08/2009 06:30:16	180	7.027	-0.278	277.401	0.161	1.069
12/08/2009 06:30:16	200	6.803	-0.403	281.000	0.285	1.014

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Some data …

Filename: c:\[some directory structure]\XXXXXX_XXXXXXXX.vad
Campaign code: Sample arc scan
Rays in scan: 3
Start time: HH:MM:SS

Height	Doppler	Intensity	Ray time	Az	El
43	-5.185388	1.063760	12:13:02	20.0	25.0
60	-6.509156	1.162066	12:13:02	20.0	25.0
77	-7.265595	1.407929	12:13:02	20.0	25.0
94	-6.603711	1.500995	12:13:02	20.0	25.0
111	-6.320046	1.247592	12:13:02	20.0	25.0
129	-6.414601	1.099703	12:13:02	20.0	25.0
146	-6.698266	1.036109	12:13:02	20.0	25.0
163	-7.454704	1.013726	12:13:02	20.0	25.0
180	-7.076485	1.003100	12:13:02	20.0	25.0
197	-9.156692	1.004086	12:13:02	20.0	25.0
214	-7.171040	0.987200	12:13:02	20.0	25.0
231	-6.225491	0.981878	12:13:02	20.0	25.0
248	-7.360150	0.986212	12:13:02	20.0	25.0
43	-4.807169	1.088273	12:13:10	50.0	25.0
60	-5.752717	1.236650	12:13:10	50.0	25.0
77	-5.279943	1.636607	12:13:10	50.0	25.0
94	-1.686859	1.758928	12:13:10	50.0	25.0
111	-2.159633	1.362204	12:13:10	50.0	25.0
129	-3.767066	1.149870	12:13:10	50.0	25.0
146	-3.199736	1.059805	12:13:10	50.0	25.0
163	-4.428949	1.025258	12:13:10	50.0	25.0
180	-5.090833	1.009761	12:13:10	50.0	25.0
197	-4.523504	1.009095	12:13:10	50.0	25.0
214	-5.279943	0.994285	12:13:10	50.0	25.0
231	-5.563607	0.998960	12:13:10	50.0	25.0
248	-5.752717	0.989357	12:13:10	50.0	25.0
43	-2.254188	1.072573	12:13:17	80.0	25.0
60	-2.065078	1.217146	12:13:17	80.0	25.0
77	-1.686859	1.612764	12:13:17	80.0	25.0
94	-1.592304	1.681203	12:13:17	80.0	25.0
111	-2.443297	1.371780	12:13:17	80.0	25.0
129	-3.105181	1.152750	12:13:17	80.0	25.0
146	-2.254188	1.066050	12:13:17	80.0	25.0
163	-2.348742	1.027679	12:13:17	80.0	25.0
180	-1.875968	1.007692	12:13:17	80.0	25.0
197	-1.403194	0.999794	12:13:17	80.0	25.0
214	-4.712614	0.992695	12:13:17	80.0	25.0
231	-0.835865	0.986730	12:13:17	80.0	25.0
248	-1.308639	0.991706	12:13:17	80.0	25.0

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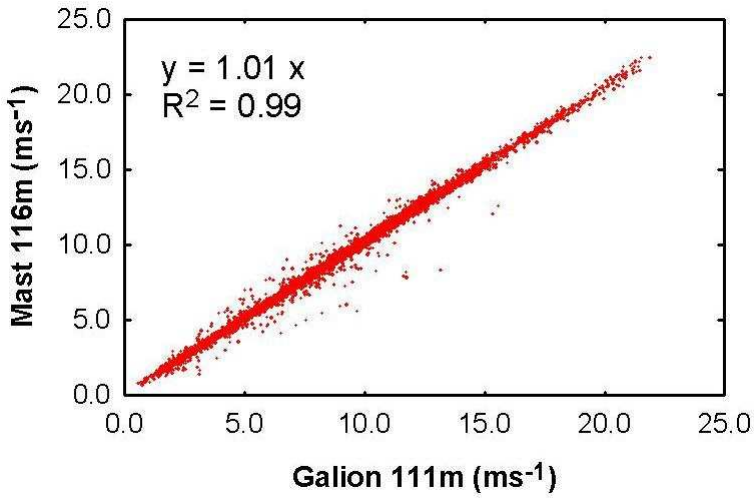
Recent results (1)



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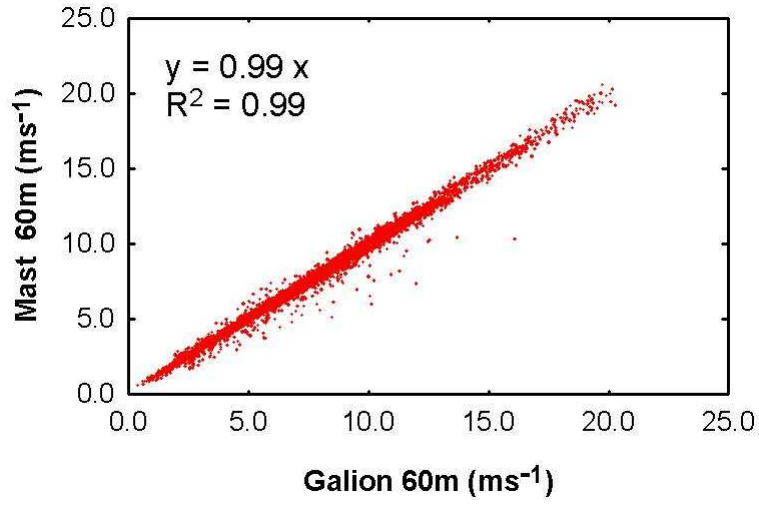
Recent results (2)



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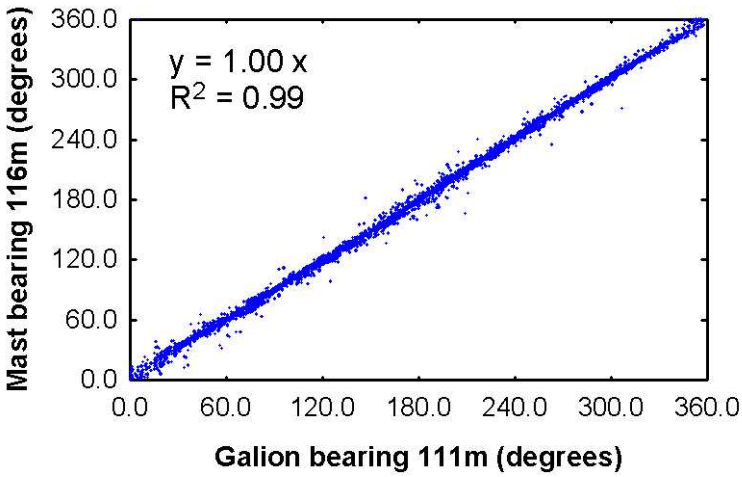
Recent results (3)



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Independent verification

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DTU

Verification of the SgurrEnergy Galion lidar using mast-mounted instruments

Risø DTU
National Laboratory for Sustainable Energy

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Independent verification

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Independent verification

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Independent verification

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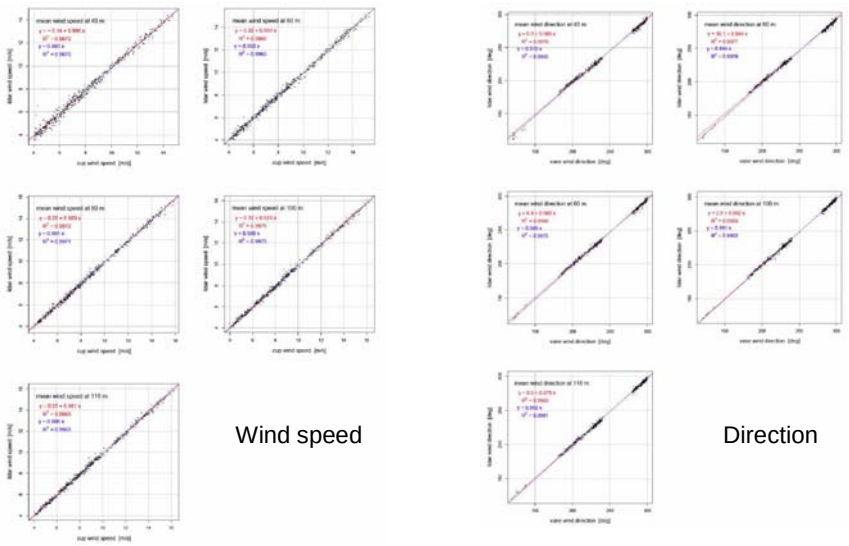

Wind speed

Direction

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Independent verification

Wind speed

Height [m]	C [m/s]	k [-]	R2	m [-]	R2
40	-0.14 (±.04)	0.998 (±.005)	0.9872	0.983 (±.002)	0.9870
60	0.02 (±.02)	0.991 (±.003)	0.9960	0.993 (±.001)	0.9960
80	0.07 (±.02)	0.983 (±.002)	0.9972	0.991 (±.001)	0.9971
100	0.12 (±.02)	0.976 (±.002)	0.9975	0.988 (±.001)	0.9973
116	0.07 (±.02)	0.981 (±.002)	0.9969	0.988 (±.001)	0.9969

Direction

Height [m]	C [deg]	k [-]	R^2	m [-]	R^2
40	5.3 (±.6)	0.960 (±.002)	0.9970	0.980 (±.000)	0.9965
60	10.1 (±.5)	0.944 (±.002)	0.9977	0.984 (±.000)	0.9959
80	6.4 (±.4)	0.962 (±.002)	0.9980	0.988 (±.000)	0.9975
100	2.5 (±.4)	0.982 (±.002)	0.9983	0.991 (±.000)	0.9982
116	3.5 (±.4)	0.978 (±.002)	0.9983	0.992 (±.000)	0.9981

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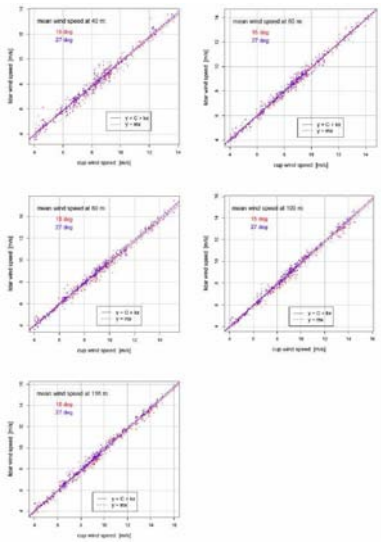
Dual cone



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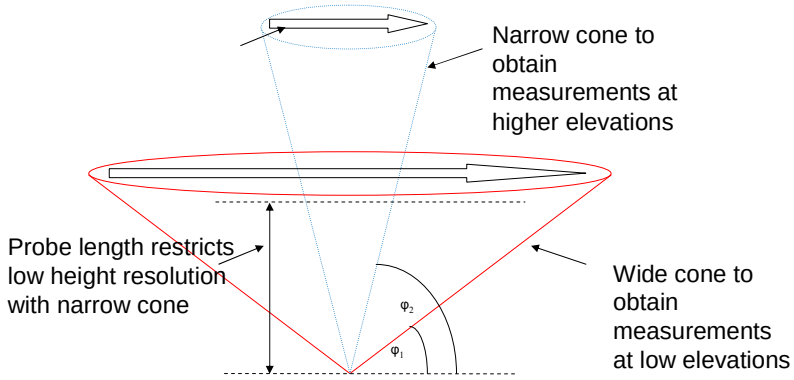
Dual cone



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Probe length (1)

Height resolution

Pulsed lidars have constant height resolution ~20 m determined by pulse length

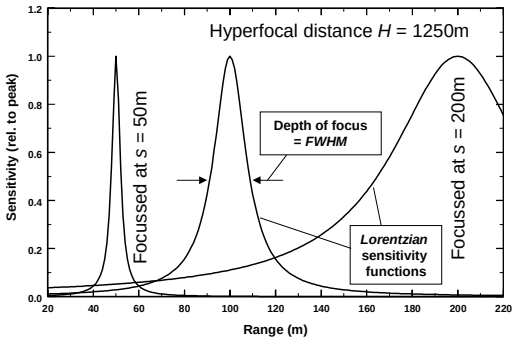
CW (continuous wave) lidars rely on focus of detector optics to resolve height.

Depth of focus (~ *FWHM*) varies with height, altering the *effective probe length*.

$$FWHM \approx \frac{2Hs^2}{H^2 - s^2}$$

Finite height resolution with non-linear wind profiles can lead to bias e.g. as wind speeds vary more in the lower half of the height range over which wind speed is integrated (averaged) than in the upper half.

Sensitivity of cw lidar to reflected signal for three different height/focus settings



Data from "Wind lidar evaluation at the Danish test site at Høvsøre", David A Smith, Michael Harris *et al.*

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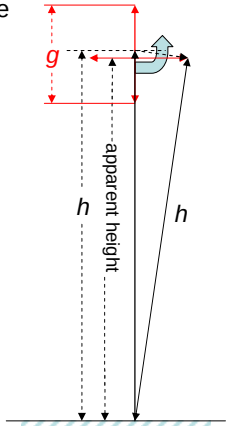
Probe length (2)

Volume average bias resulting from logarithmic wind profile and effective probe length ***can be corrected***

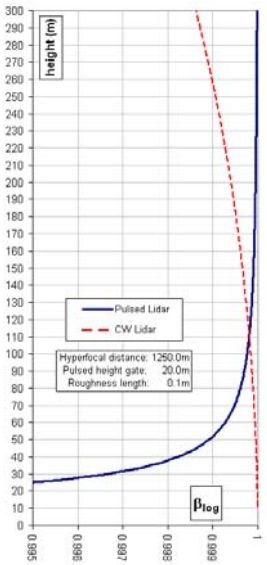
$$\beta_{\log} = \frac{\left[\frac{h}{g}\ln\left(\frac{h+\frac{1}{2}g}{h-\frac{1}{2}g}\right)+\ln\left(\frac{\sqrt{h^2-\left(\frac{1}{2}g\right)^2}}{z_0}\right)-1\right]}{\ln\left(\frac{h}{z_0}\right)}$$

Assuming neutral stability
Neglecting zero-plane displacement

- z_0 = roughness length
- h = height
- g = height gate size
  i.e. *effective probe length*
  (pulse length or depth of focus)
- $\beta_{\log}$ = ratio of volume and point values (for log profile)
  i.e. *measure of bias*



Geometric interpretation



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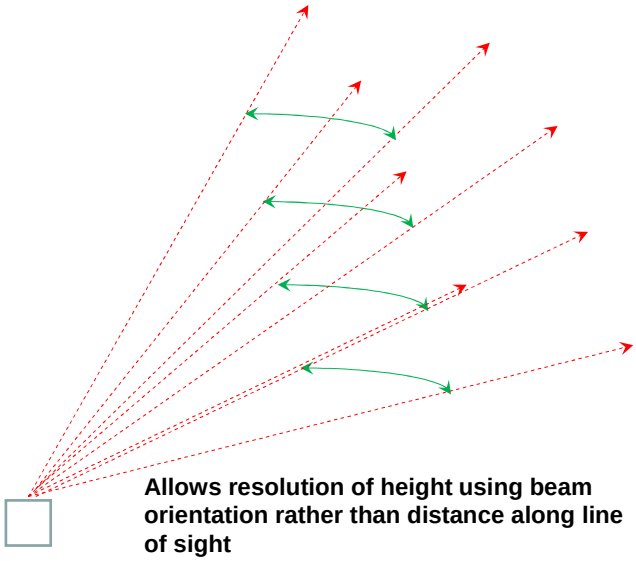
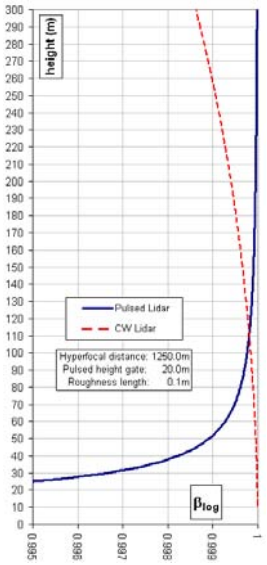
Arc scanning



Allows resolution of height using beam orientation rather than distance along line of sight



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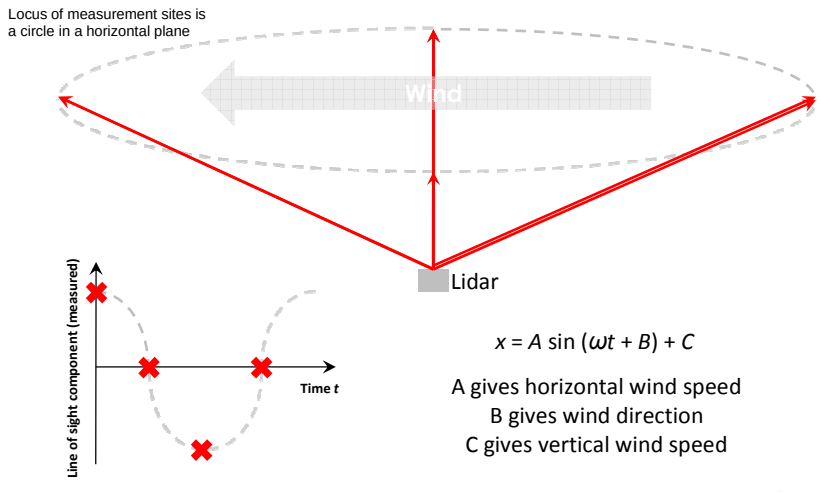
Arc scanning

VAD scan geometry



$x = A \sin(\omega t + B) + C$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

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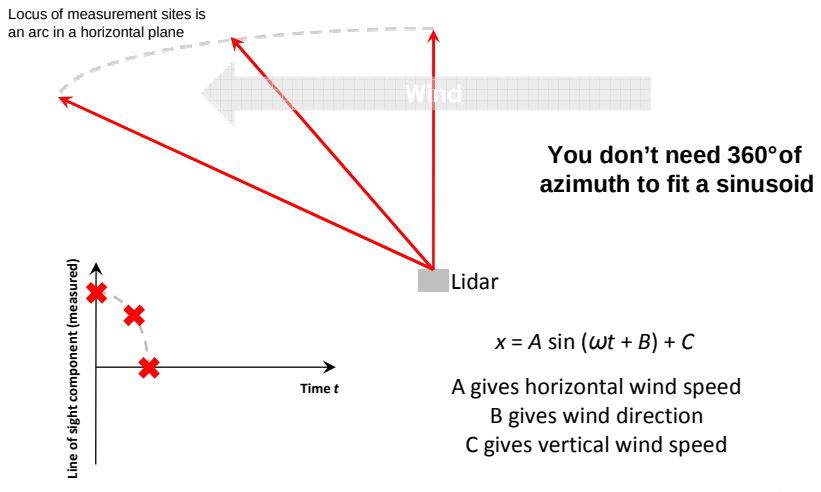
Arc scanning

Arc scan geometry



You don't need 360° of azimuth to fit a sinusoid

$x = A \sin(\omega t + B) + C$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

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Arc scan issues

Turbulent decorrelation

- We want scan induced variation in Doppler values ($\sin\theta - \sin(\theta+\delta)$) to exceed TI induced variation in Doppler values
- Timescale issues for small values of δ
  - Average rays might be needed
  - Large value of δ (>45°) might be needed

Non-linear bias

- Again, larger arcs, dual Doppler configurations, and average rays might be required

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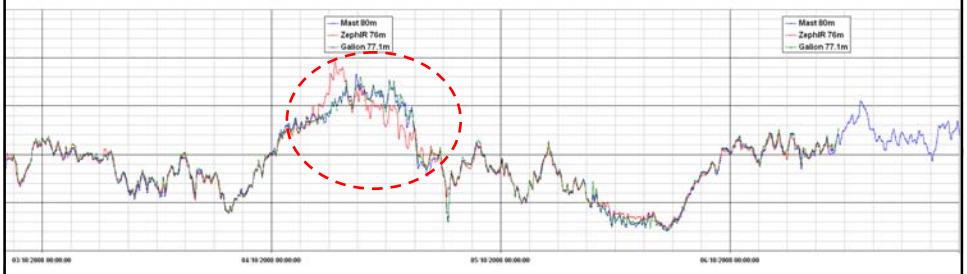
Comparison study (1)



Time series

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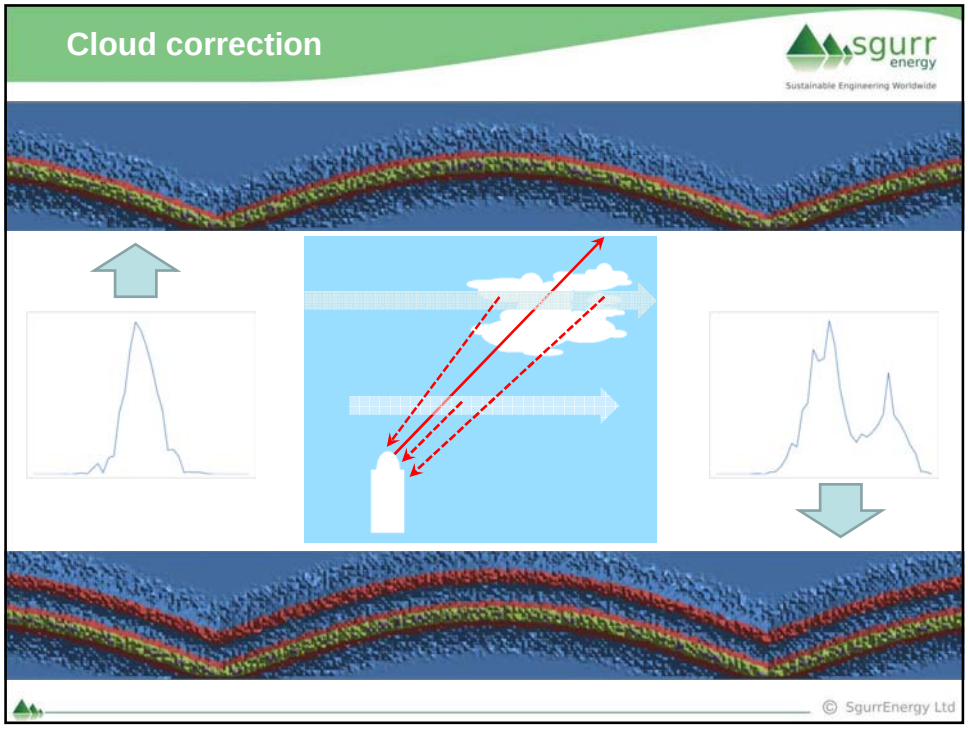
Cloud correction
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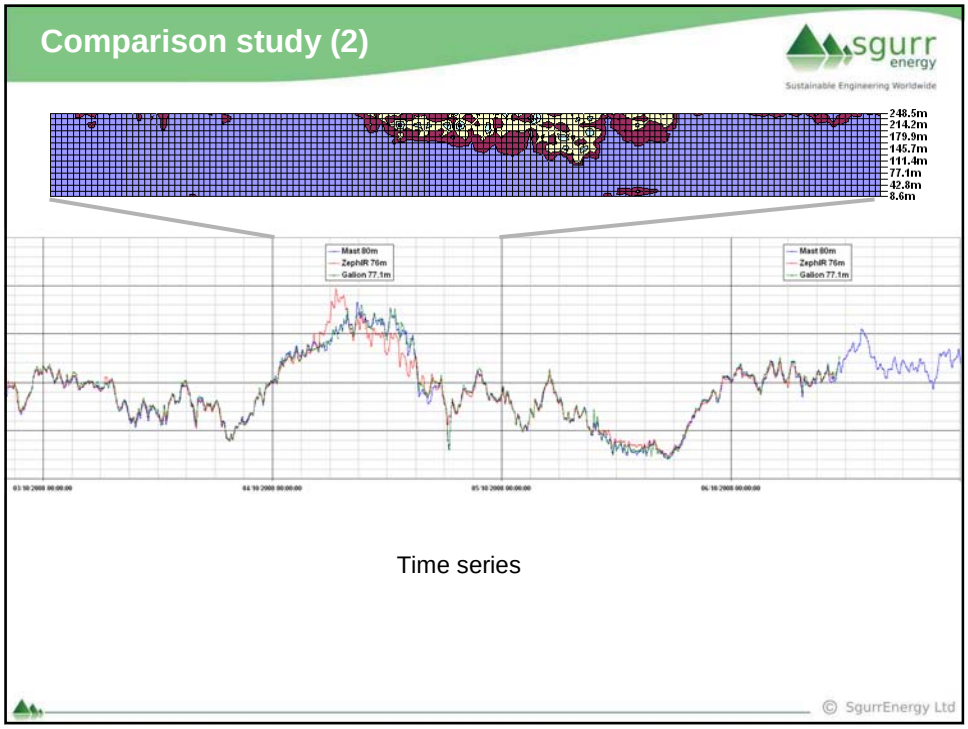
Comparison study (2)
sgurr energy
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248.5m
214.2m
179.9m
145.7m
111.4m
77.1m
42.8m
8.6m
Mast 80m
ZephIR 76m
Gallon 77.1m
Mast 80m
ZephIR 76m
Gallon 77.1m
Time series
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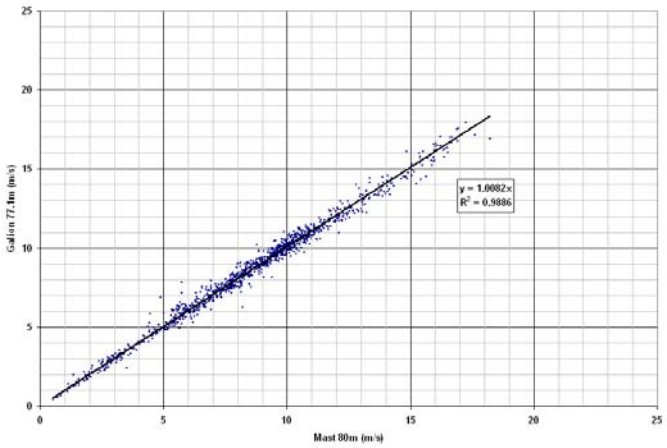
Comparison study (3)

Linear regression – Galion v Mast



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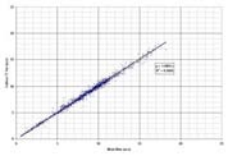
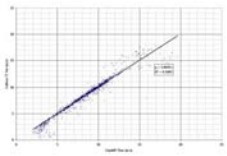
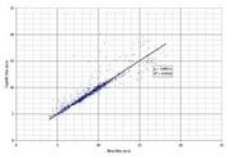
Comparison study (4)



Galion v Mast



Galion v ZephIR



ZephIR v Mast

$$\sigma^2_{G,M} = \sigma^2_G + \sigma^2_M$$

$$\sigma^2_{G,Z} = \sigma^2_G + \sigma^2_Z$$

$$\sigma^2_{Z,M} = \sigma^2_Z + \sigma^2_M$$

Solve for σ^2_G

Rerun regression with Λ factor. Most of the observed scatter in the regression of Galion data on mast data is due to the real differences in conditions 110m apart.

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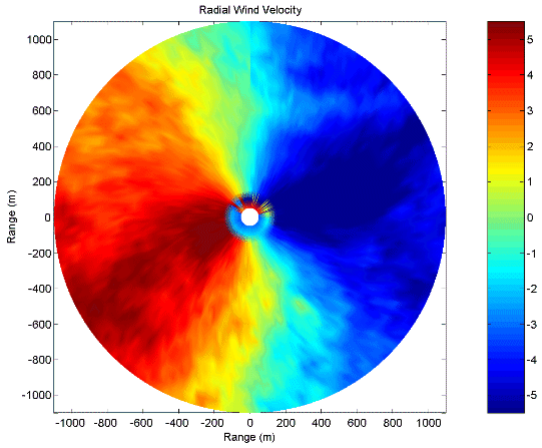
Galion: All sky scanning



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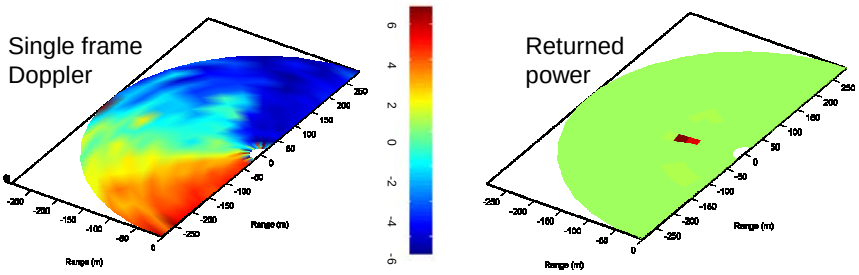
Wake monitoring (1)

Single frame Doppler

Returned power



NEG Micon 900kW turbine at Myres Hill

Date: 28/11/08
Start: 12:01 Finish: 13:44
Elevation angle = 25⁰ 49 sec per frame
5 sec between frames 112 frames
19m range gates
Beam is at hub height on an arc of radius ~175m

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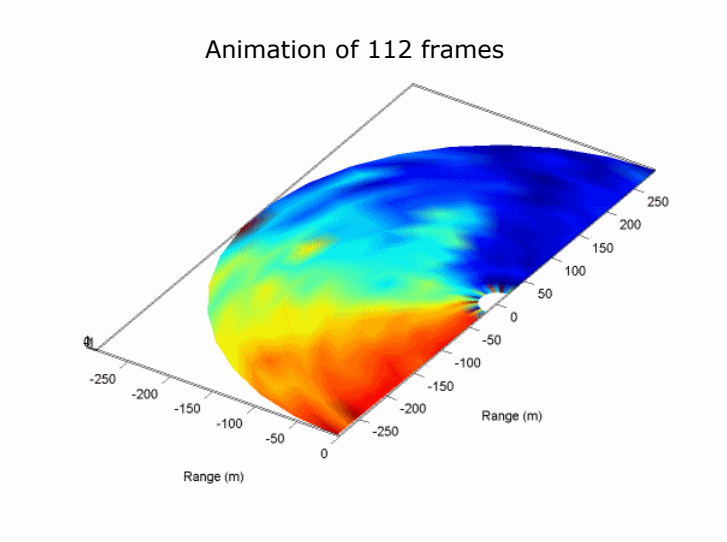
Wake monitoring (2)



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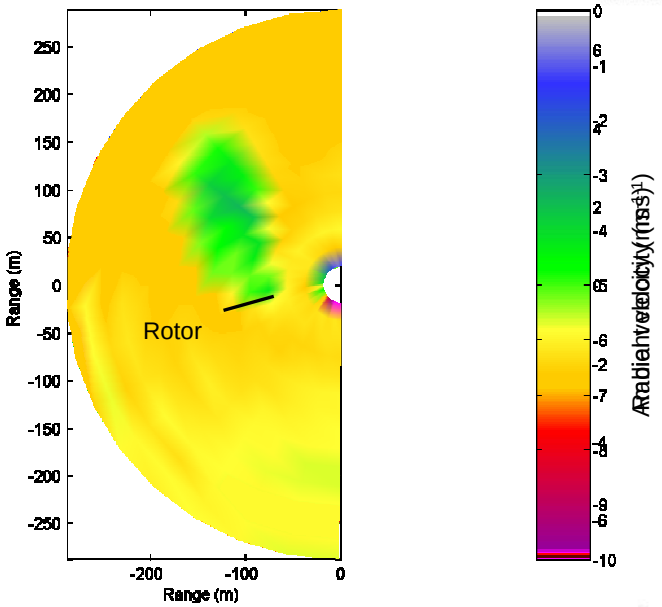
Wake monitoring (3)



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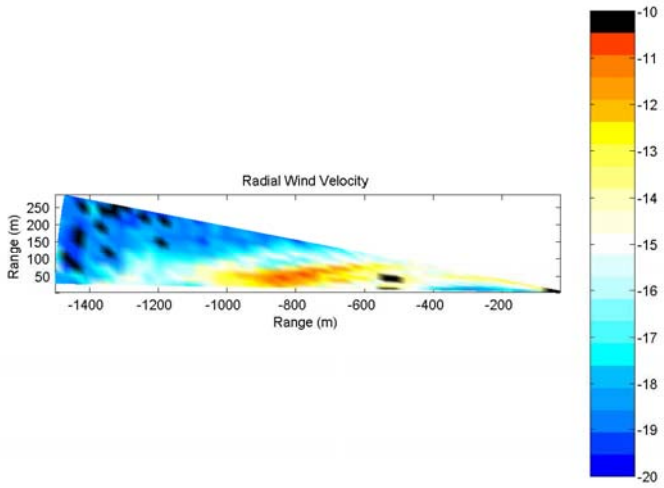
Wake monitoring (4)



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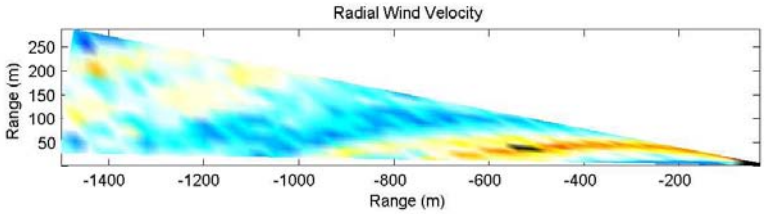
Wake monitoring (5)



Scan position 1 – all scans with range at 1500m
1: Basic VAD scan to establish conditions
2: Horizontal arc scan, constant elevation 3.8 degrees Az from 271 to 281 degrees in 1 degree incriments. Looking approx upwind towards 2 turbines, with hope that wakes from both will be visible. Closest turbine around 500m from Galion, further around 1250m upwind. From 12:45 to 12:56 approx
3: Horizontal arc scan as above, except from 269 to 279 degrees, elevation 3.7 degrees. From 13:02 to 13:16 approx
4: Horizontal arc scan as above, except from 267 to 277 degrees, elevation 3.6 degrees. From 13:18 to 13:30 approx
Basic VAD scan as before from 13:35 to 13:45 – Note North rays of these VADs may interfere with flight of nearby turbine blade

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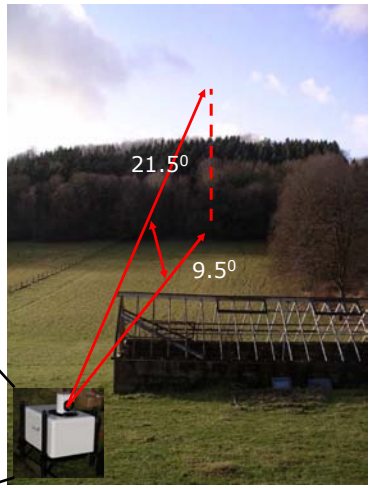
Forestry (1)

- Fixed azimuth (260⁰), elevation scanned
- Each frame: 13 rays, 1 degree step, 30 sec per scan
- 16 frames
- Wind coming towards lidar over trees
- Clouds were scudding along but it was relatively calm down at the lidar



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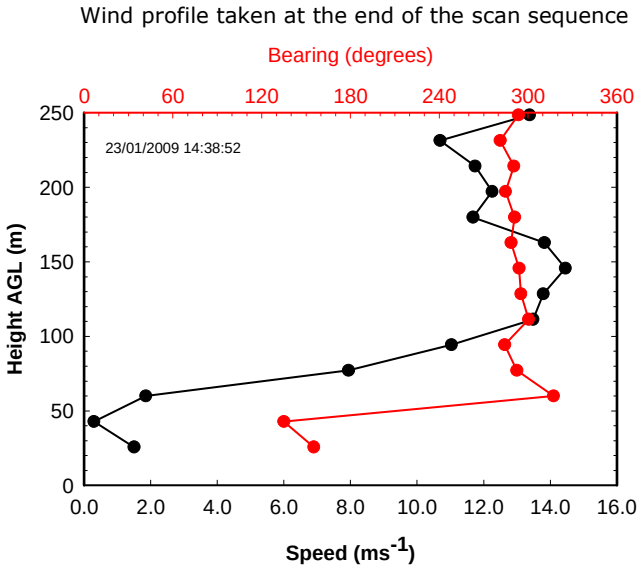
Forestry (2)



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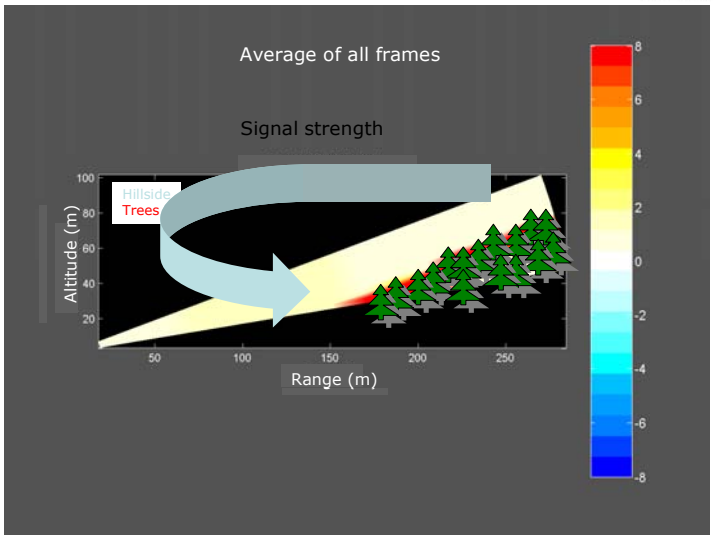
Forestry (3)



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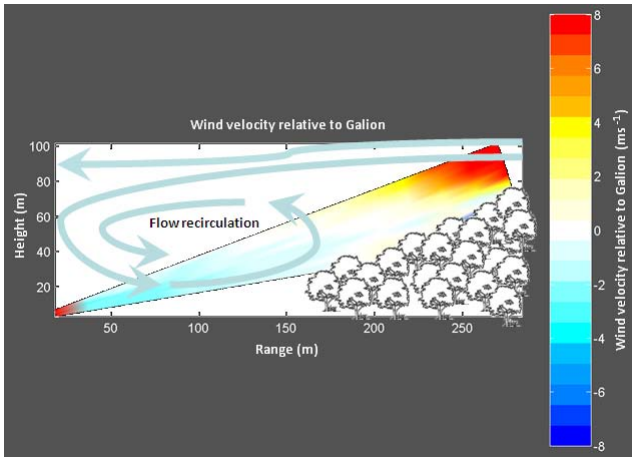
Forestry (4)



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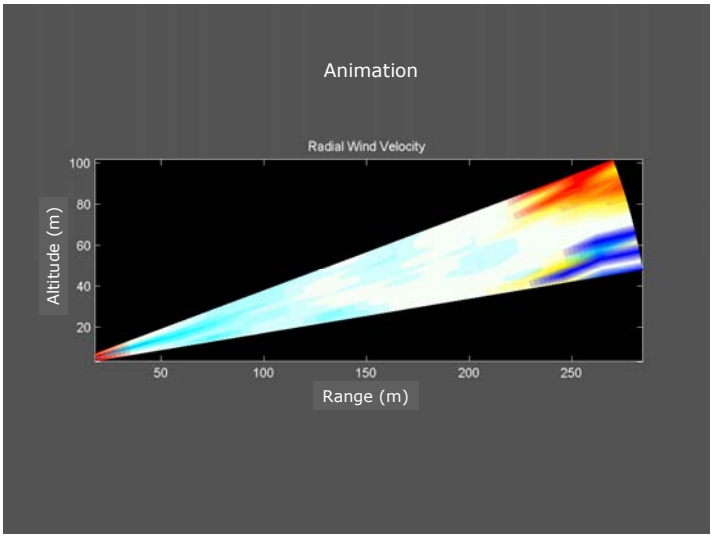
Forestry (5)



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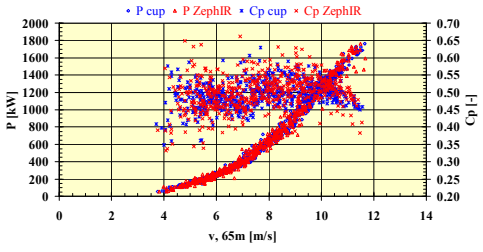
Power curve measurement

Lidar can be deployed where masts cannot, for example in operational wind farms to investigate turbine power performance

Windguard power curve measurement using cup and lidar anemometry



Data from "Our Results Gained with Lidar, and How we Interpret the Status", Axel Albers, IEA Remote Sensing Experts Meeting, Risø, January 2007

Note that the uncertainties associated with the lidar derived power curve are less than those associated with the cup. This suggests that the lidar introduces less uncertainty into the analysis, i.e. lidar is *better* than cup anemometry

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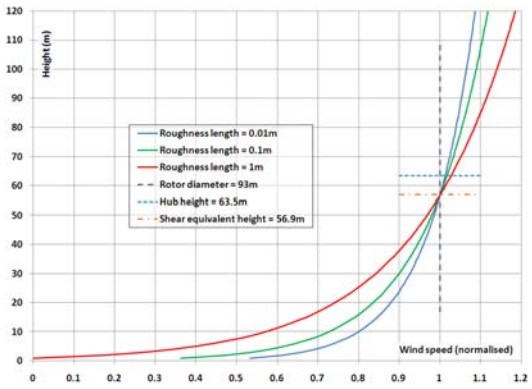
Equivalent height (1)

The height at which the spatial average of the wind speed across the rotor occurs is always the same for logarithmic wind shear regardless of the degree of that wind shear. For hub height h, rotor diameter $d = 2r$:

$$< u_z >= \frac{u_0}{2r}\int_{h-r}^{h+r} \ln\frac{z}{z_0}\,dz = \frac{u_0}{2r}\left[z\ln\frac{z}{z_0} - z \right]_{h-r}^{h+r} = u_0\left\{ \frac{h}{2r}\ln\frac{h+r}{h-r} + \ln\frac{\sqrt{h^2-r^2}}{z_0} - 1 \right\}$$

so $< u_z >= u_0 \ln\frac{h_{eq}}{z_0}$

where $h_{eq} = \sqrt{h^2-r^2}\, e^{\frac{h}{2r}\ln\frac{h+r}{h-r}-1}$



This means power curves obtained using wind speeds measured at the wind shear equivalent height of the rotor, h_{eq}, will have scatter due to the impact of different wind shear profiles on turbine performance, but not due to its impact on hub height wind speed. These effects cannot be discriminated in power curves acquired using hub height wind speeds. This enables better turbine performance assessment .

Lidar is required to acquire wind speeds at equivalent height h_{eq}. Nacelle and hub mounted anemometry cannot.

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Equivalent height (2)

- **Equivalent height presented for interest**
- **Principal approach may be**
  - **Equivalent speed**
  - **Multivariate approach**
- **If rotor area averaged approach taken, should weighting also reflect torque delivered to hub by each blade element?**

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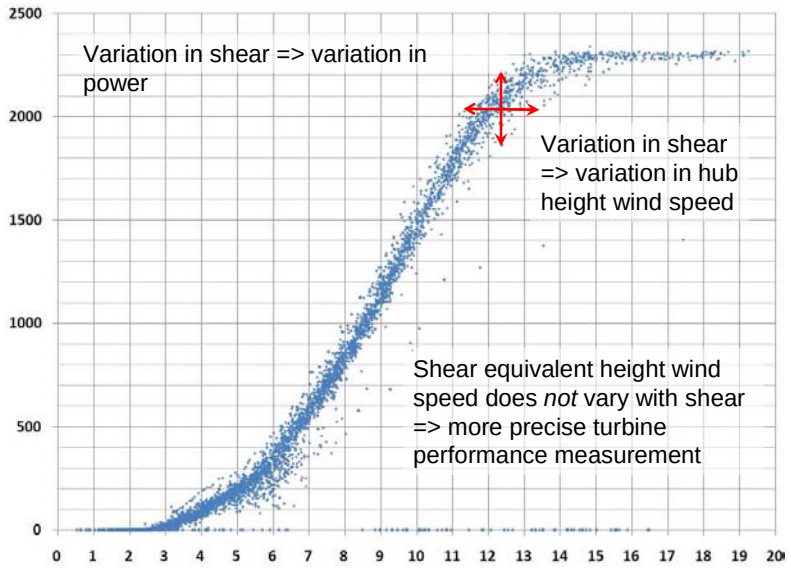
Equivalent height (3)



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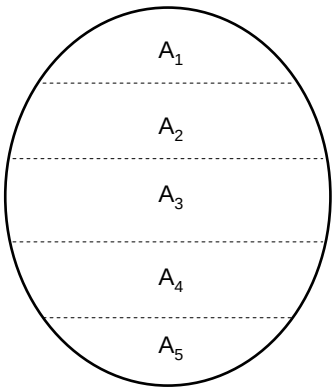
Equivalent speed

Rotor area A



$$v_{eq,1} = \frac{1}{A}\sum_i A_i v_i$$

$$v_{eq,2} = \frac{1}{A}\sum_i A_i v_i \cos^{\beta}\theta_i$$

$$v'_{eq,1} = \sqrt[3]{\frac{1}{A}\sum_i A_i v_i^{3}}$$

$$v'_{eq,2} = \sqrt[3]{\frac{1}{A}\sum_i A_i v_i^{3}\cos^{\beta'}\theta_i}$$

$$v_{eq,3} = \frac{1}{A}\sum_i A_i \sqrt[3]{\frac{1}{n}\sum_{j=1}^{n}\left(v_{ij}\cos^{\beta}\theta_{ij}\right)^3}$$

$$v'_{eq,3} = \sqrt[3]{\frac{1}{A}\sum_i A_i\left(v_i + 3TI_i^{2}\right)^3}$$

Kinetic energy flux formulation

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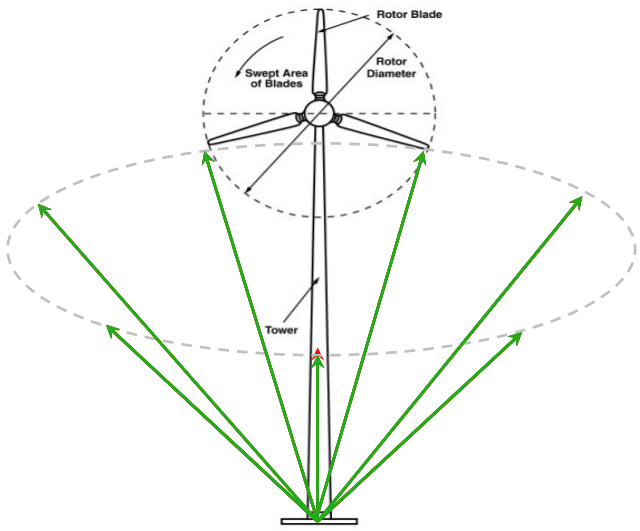
7-point VAD



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3VCR

1. The performance of the device has been independently verified by comparing measurements made using it with concurrent and co-located measurements of the same wind flow parameters made using other reference instruments which would have been deemed acceptable for conducting the aforesaid quantitative assessment of wind resource;

2. The measurement campaign in which the device is operated to acquire data for the aforesaid quantitative wind resource assessment is conducted according to the methodology adopted during instrument verification;

3. The uncertainty analysis on which energy yield percentiles are based is robust and adequately represents the uncertainty introduced by the instruments used during the measurement campaign;

4. The wind conditions prevailing during the quantitative resource assessment measurement campaign are considered sufficiently similar to those prevailing during the verification period that a divergence in the performance of the device from the performance of the reference instruments would not be expected.

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Conclusions

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- Lidar is useful for measuring shear, veer, and flow inclination, profiles.
- Available devices have not converged on single optimal solution.
- Galion is leading device on ground of:
  - Performance
  - Flexibility
  - Deployability
- Forthcoming results.
  - Wind veer and shear.
  - Arc scans.

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Any questions?
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IEA Wind Task 11: Remote Wind Speed Sensing SODAR and LIDAR

Xabier Comas Blanco (xcomas@acciona.es)

Boulder Colorado, 15 & 16 October 2009

ACCIONA Energy

- **A.E.** is a world leader in the renewables sector.
- It is the largest developer and constructor of windfarms in the world.
- It´s installed capacity in this field was 7,291 MW at 30 June 2009. It has implemented 252 windfarms with 6,947 turbines located in fourteen countries on the five continents.
- It is also present in other electric power generation technologies based on renewable energy sources (solar thermal, photovoltaic, and biomass) and the manufacture of wind turbines (designed in-house) and the production and marketing of bio fuels.

Boulder Colorado, 15 & 16 October 2009

AE experience in remote wind speed sensing

Equipments

4 LIDARs

– 1 ZephIR Natural Power (QINETIQ) Continuous laser

Energy Resource dept.

– 3 Windcube™ (LEOSPHERE) Pulsed laser

2 in Energy Resource dept.

1 in Monitoring of Production dept.

2 SODARs (preliminary stage)

– 2 Triton (SECONDWIND)

Both in Energy Resource dept.

Boulder Colorado, 15 & 16 October 2009

AE experience in remote wind speed sensing

Objetives:

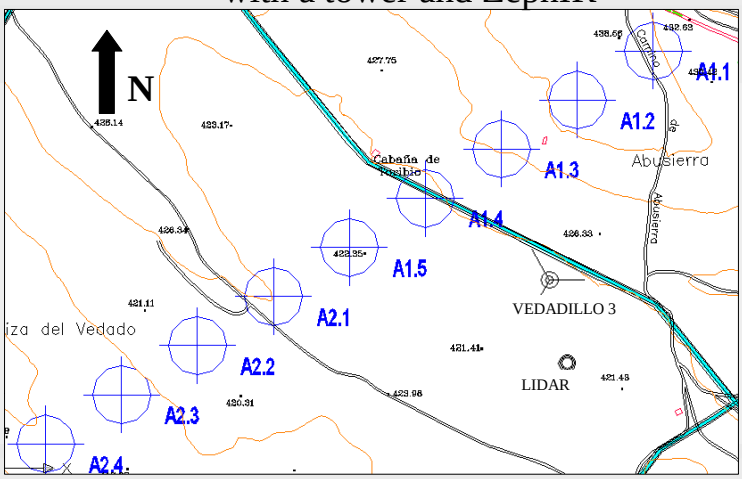
– Confirm the wind shear in the upper heights nearby a met tower.

– To map the wind flow on complex and difficult sites where the uncertainty for vertical and horizontal extrapolation is too high (it is applicable for a non complex terrain)

– Wind turbine power curve monitoring

Boulder Colorado, 15 & 16 October 2009

Example: Flat terrain inside windfarm measuring with a tower and ZephIR



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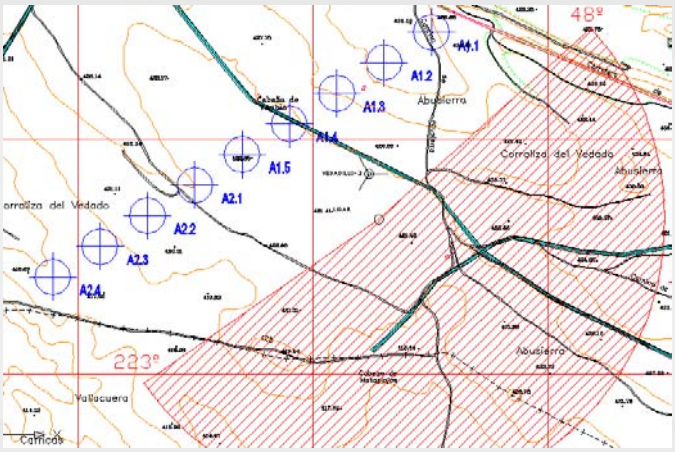
AE experience in remote wind speed sensing

NON DISTURBED MEASURING SECTOR



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AE experience in remote wind speed sensing

DATA COVERAGE

HEIGHT	# DATA	# GOOD DATA	# DATA NON DISTURBATED SECTOR	COVERAGE
40	9246	8791	2590	95,1%
60	9246	8623	2581	93,3%
80	9650	8872	2890	91,9%
100	9246	8476	2517	91,7%
120	9240	8470	2506	91,7%

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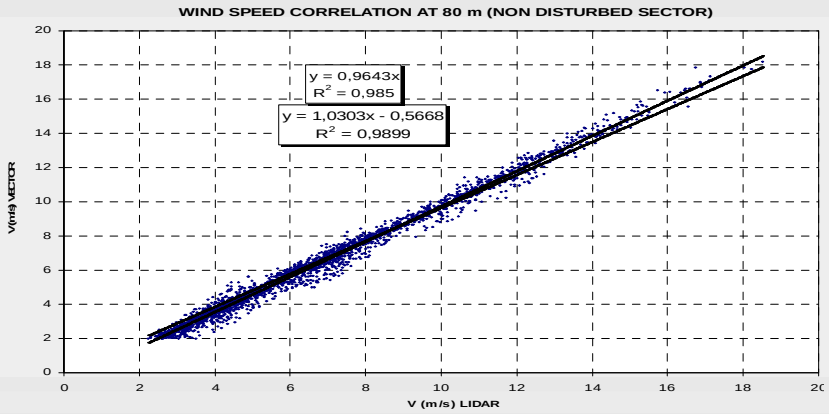
AE experience in remote wind speed sensing

Correlations (non disturbed sector) Wind speed



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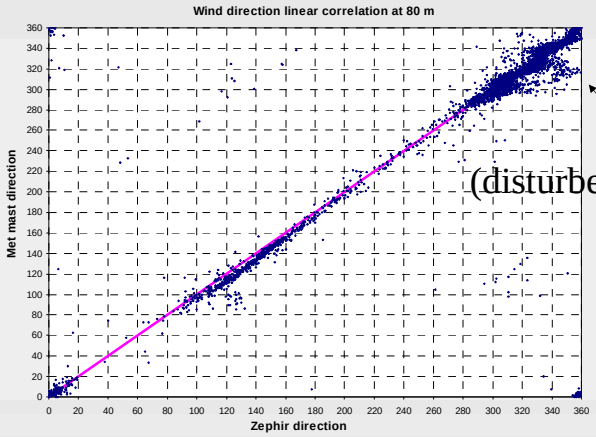
AE experience in remote wind speed sensing

Wind direction Correlation



(disturbed sector)

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AE experience in remote wind speed sensing

Complex terrain general result (4 campaings Zephir and 1 campaing windcube)

- Coverage: 70-80% falling in higher levels
- Wind speed: Discrepancy. In some cases overestimates (ZephIR)
- Good correlations but it must be improved.

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AE experience in remote wind speed sensing

Windfarm acceptance test (internal use) with Windcube in a German wind farm (flat terrain). Aims:

- Calculation of flow distortions parameters in the nacelle anemometer position in the monitored wind turbines.
- Evaluation of the power curve efficiency in the measured wind turbine.
- Extrapolation of the speed up effect to the rest of the wind turbines of the wind farm.

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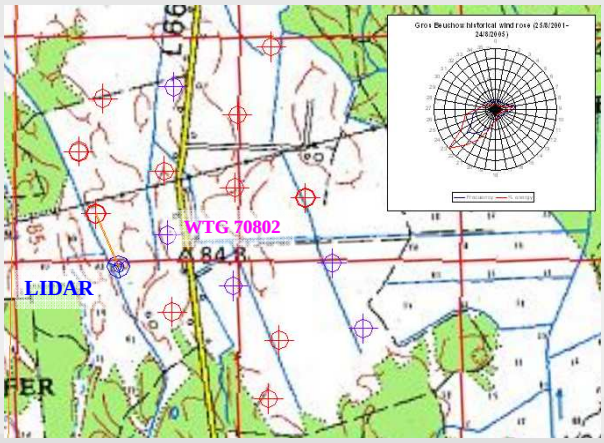
AE experience in remote wind speed sensing

Windfarm acceptance test with Windcube



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Windfarm acceptance test with Windcube

- 96.2 % of data coverage.
- Only common free sectors for this study.
- A..

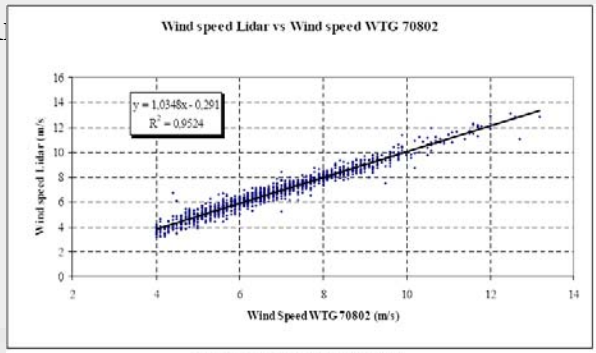

Figure 5.2.3.1- Speed up in WTG 70802

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Windfarm acceptance test with Windcube

The obtained power curve compared with the guaranteed and measured power curve by WindTest. Rayleigh 6.5 m/s distribution used to obtain AEP.

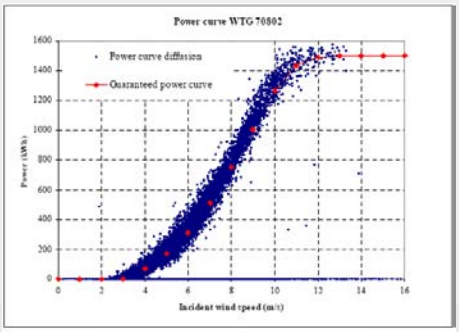

Figure 5.2.4.1.1- Diffusion power curve in WTG 70802

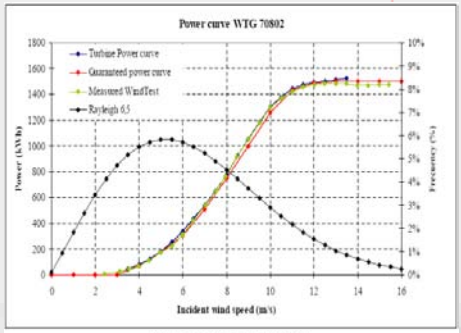

Figure 5.2.4.2.1- Power curve in WTG 70802

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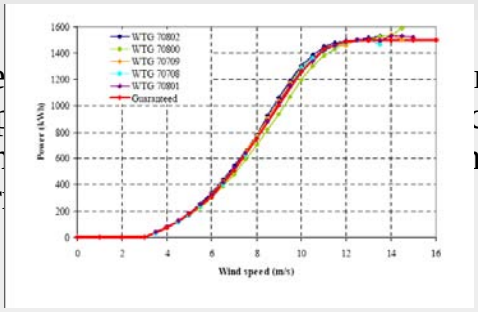
Windfarm acceptance test with Windcube

- The efficiency of the monitored wind turbine is:
- 103.8%
- With the r curve and the p culated for each win ncy of the wind far



- The efficiency of the wind farm is 100.7%.

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Conclusions

ZephIR	Windcube
• Very slow data download ☹	• Easy to install. Attention must be paid to level out ☺
• Less energy consumption than other devices (150W) ☺	• Friendly software and fast data download ☺
• Good result in flat terrain ☺	
• In complex terrain still under study	

•In complex terrain still under study

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Conclusions

- Short lidar campaigns (over typically 3 months) in combination with reference met mast (50-60 m) are a valuable solution for many site assessment purposes.
- Maintenance is easier and more comfortable than met tower.
- The power s icaps of these devices as th 0-300W. The most suitable equi el generator, a charge contr ll mounted on a trailer. Howe e if it exists in the area (250-50 source such as a one of a hou

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FUTURE

- More lidar and sodar campaigns.
- How to compare Turbulence Intensity with traditional cup anemometer?
- Lidar's T.I. is marked by the spatial character of the measurement and may not be directly comparable to that of Cup anemometers.

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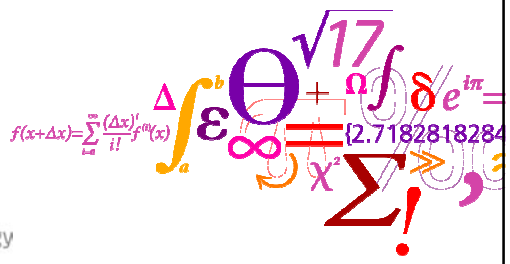
Lidar R+D activities in Denmark

Michael Courtney

Risø DTU – Wind Energy Division, Denmark

IEA Topical Experts Meeting,
NREL, October 2009



Risø DTU
National Laboratory for Sustainable Energy

Who am I?

- Senior Scientist in the Test and Measurements program, Wind Energy Division, Risø DTU.
- Member of Risø DTU 'Team Lidar' together with Jakob Mann, Torben Mikkelsen, Petter Lindelöw-Marsden, Ferhat Bingol, Rozenn Wagner, Mikael Sjöholm, Julia Gottschall,..
- Main research interests: Lidar testing and Windscanner
- WP leader for Remote Sensing in EU projects UpWind and SafeWind
- Lidar testing in EU NorseWind
- Involved in remote sensing aspects of IEC 61400-12-1 revision

The state of play

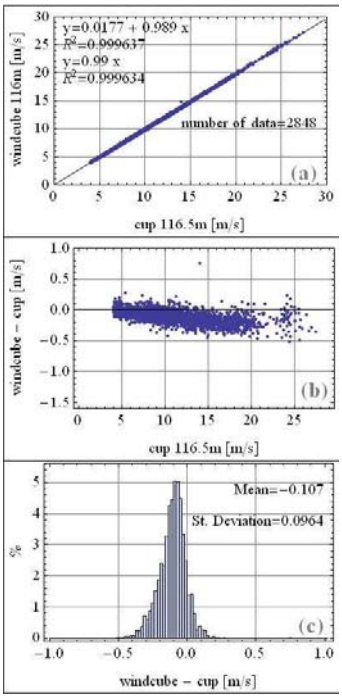
- 70-80? ZephIRs
- 50-60? Windcubes
- Galion and Vindicator entering the market

- Used mainly for resource assessment
- Some offshore
- Many in complex terrain

Risø DTU, Technical University of Denmark

Good lidars are getting accurate in flat terrain!

- Best lidars are within ±1.5% of traceable cup (for the heights we can test).
- Very low noise
- We are approaching the limit of what we can verify with mast-mounted cup anemometers.



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Reliability is a big issue

- MTBF is months not years
- Much improvement but accelerating market may cause new problems
- Service and warranty conditions are very important

Availability is also an issue

- Pulsed lidars at longer ranges (heights) are dependant on sufficient aerosol.
- At the moment, 50% availability at 300m at Høvsøre, 95% availability at 100m.
- This can be improved by changes in design – longer pulses, more powerful lasers.
- Need more knowedge about aerosol statistics (UpWind).

Are Lidar data bankable?

- Probably yes, if you work together proactively with the bankers consultant.
- Mast verification before and preferably after the field campaign are highly desirable.
- The lidar may not survive a longer measurement campaign without some problems. Think about this **before** you start.
- Need for Recommended Practices

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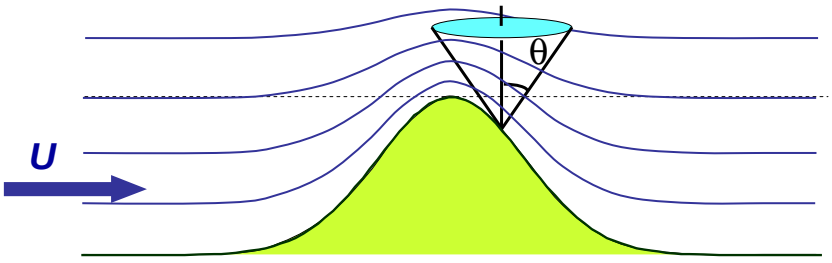
Complex Terrain & Conical Beams



Different parts of cone sample different winds

Example: Dimitri Foussekiss Cres

$V_{LIDAR} = 0.9995\ V_{MAST} + 0.0194$ in flat terrain

$V_{LIDAR} = 0.8753\ V_{MAST} + 0.4519$ in complex terrain

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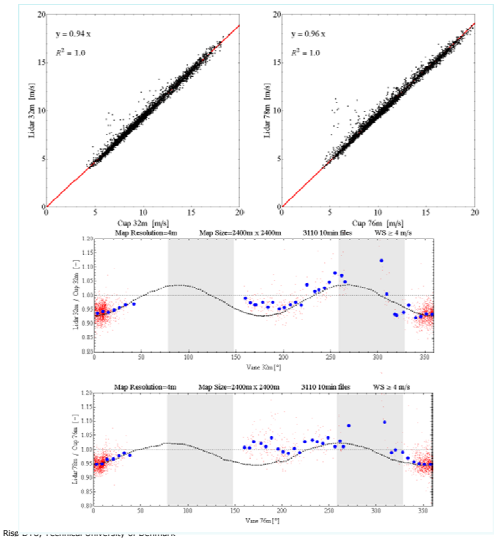
Simulating lidar errors in complex terrain using flow models (WAsP Engineering)



Contact:
Ferhat Bingöl
febi@risoe.dtu.dk

Recent complex terrain results show:

- No difference between 15˚ and 30˚ cone angle for mean speed
- Significant difference in measured standard deviation for 15˚ and 30˚ cone angle
- Significant difference between flat terrain and complex terrain cup/lidar turbulence ratio.

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Complex terrain research issues

- Find sensible limits (classification) for 'flat terrain'
- Find the limit of error prediction with flow models
- Integrate radial speeds directly in flow models
- Look at how to minimize uncertainty by choosing where to measure (slopes better than peaks)
- More advanced scanning patterns? (Still needs assumptions with one beam)
- Bistatic or 3-beam (Windscanner) systems

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Testing LIDARs at Høvsøre

Høvsøre Large Wind Turbine Test Facility

- West coast of Denmark, flat terrain, wide range of horisontally homogeneous wind speed.
- Site equipped with rain and cloud sensors
- **28** lidars tested
- **70** months of comparison with class 1 cup anemometers @ 40-116 m (160 m)

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Reasons for testing lidars

- Accuracy is getting quite good (1.5% speed and 5m altitude error)

BUT

- Individual lidars still vary too much (cone angles, focus, ..?)
- Lidars can deterioate over time
- We still find imperfections (non-linearities, cloud and mist sensitivity)
- Testing required to make the data bankable
- New types need development and verification

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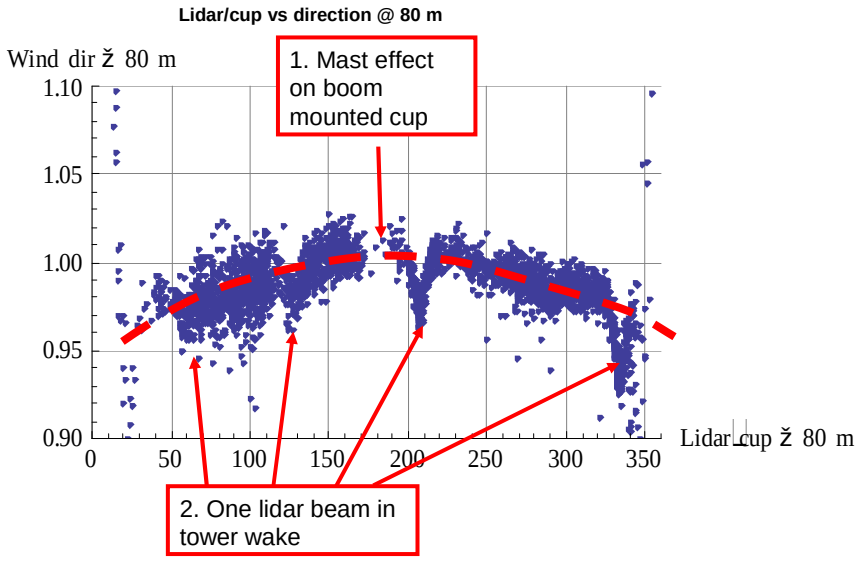
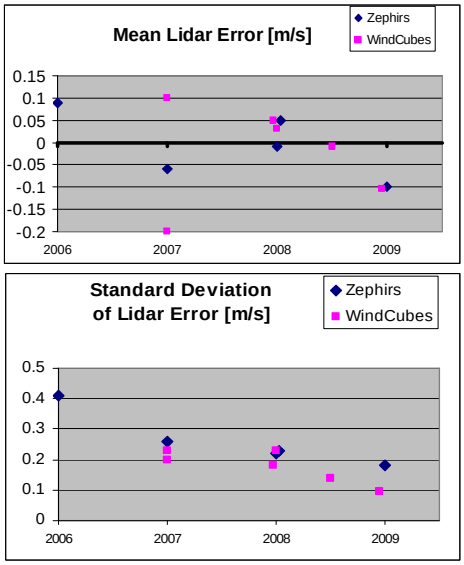
As lidars get better, the testing gets more demanding



Development of Wind Sensing Lidars



2006: Zephir commercial model introduced. Hardware issues.

2007: Ceilometer installed, screening on clouds: positive bias and σ reduced, availability drops. Leosphere introduces Windcube.

2008: Cloud correction: availability increases. Cone angle accuracy: bias reduced.

2008.5: Cone angle accuracy Estimator improved: nonlinear problems reduced.

2009: Improved test conditions, lower RIN. Improved test conditions.

Vindicator and Galion commercial

Mean < ~±0.05 m/s σ ~0.20

Mean < ~±0.05 m/s σ ~0.10

Testing and Verification issues

- Reducing lidar uncertainty (manufacturers job!)
  - More consistent physical specs (cone, focus, pulse, sig. proc...)
  - Correction for predictable shear effects (e.g. range gate distortion)
- Reducing cup anemometer uncertainty
  - Tighter, more consistent calibrations?
  - Better understanding and documentation of side boom effects
  - Inclusion of cup turbulence under/over speeding
- Standardised verification procedure
  - Underway as part of IEC 61400-12-1 revision (Risø DTU/Windguard/others?)
- Classification
  - Also required as part of IEC 614-12-1 revision

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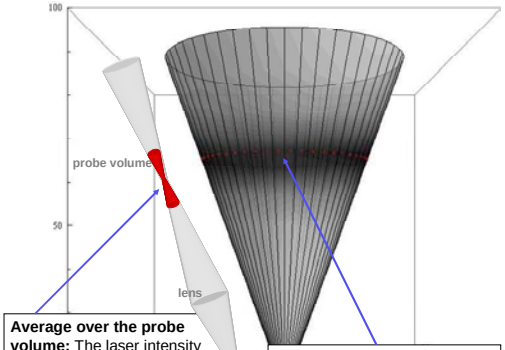
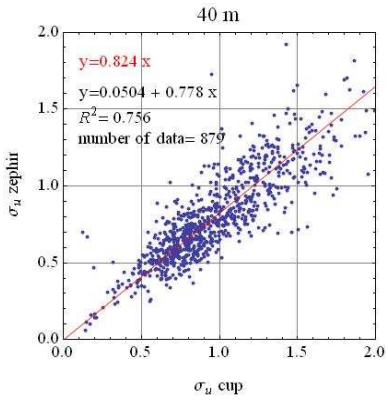
Turbulence measured by a lidar is not the same as that measured by a point sensor



Average over the probe volume: The laser intensity is distributed along the beam with a distribution that has its maximum at the focus point. Each radial speed is obtained from backscattered signals averaged over the probe volume.

Average over the circular path: The laser beam scans conically measuring 50 radial speeds per rotation equally distributed over the circular path. The wind speed vector is calculated from the 50 (for a lidar scanning for 1second, 150 if it scans for 3 seconds) radial speeds.



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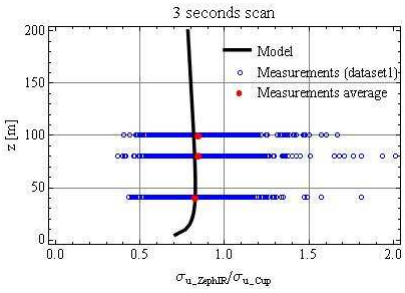
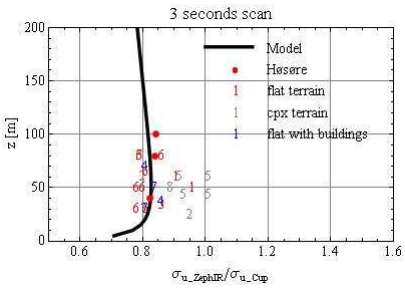
Comparison of model with experimental results



Høvsøre



6 different sites

Thanks: M.Harris, Natural Power

Risø DTU, Technical University of Denmark

How does the turbulence measured by a lidar compare with that from a cup?

- It is attenuated by the volume averaging
- Lidar TI about 80% of a cup TI on flat terrain with standard 30˚ cone

BUT

- Lidar turbulence is a mix of all 3 components

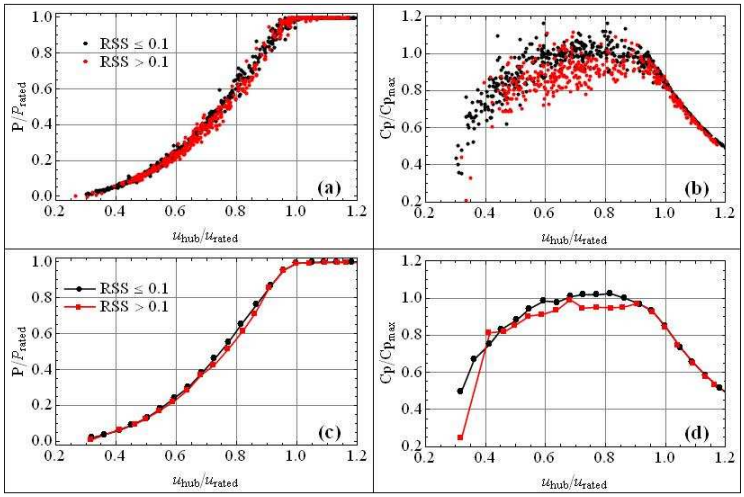
CONSEQUENTLY, the lidar/cup TI ratio depends on:

1. Lidar geometry (cone angle)
2. Measuring height
3. Terrain type
4. Atmospheric stability
5. Lidar scanning pattern ?

Turbulence issues – relating σ_{U_lidar} to σ_{U_cup}

- Better models to include the effects of the vertical turbulence on the observed horizontal turbulence.
- Ditto in complex terrain.
- Do we need to know the vertical turbulence (vertical beam necessary)?
- Is σ_{U_lidar} good enough?
- Empirical corrections?

Power curve measurements – the effect of ignoring wind shear

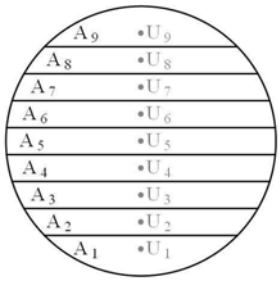


→ 2 different power curves for the 2 groups of profiles

Equivalent wind speed

$$KE_{prof} = \frac{1}{2}\sum_i \rho \langle u_i \rangle^3 A_i$$

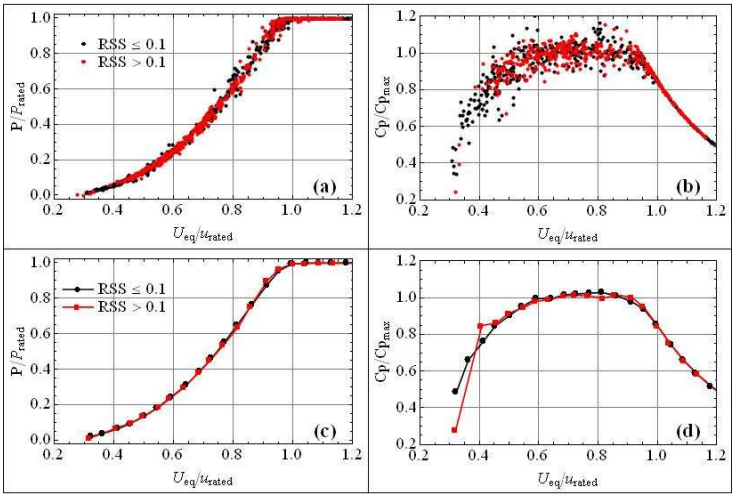
$$= \frac{1}{2}\rho U_{eq}^3 A$$



with $$U_{eq} = \left(\sum_i \langle u_i \rangle^3 \frac{A_i}{A} \right)^{1/3}$$

Then $$C_p = \frac{P}{\frac{1}{2}\rho U_{eq}^3 A} = \frac{P}{KE_{prof}}$$

Power curve using the equivalent wind speed

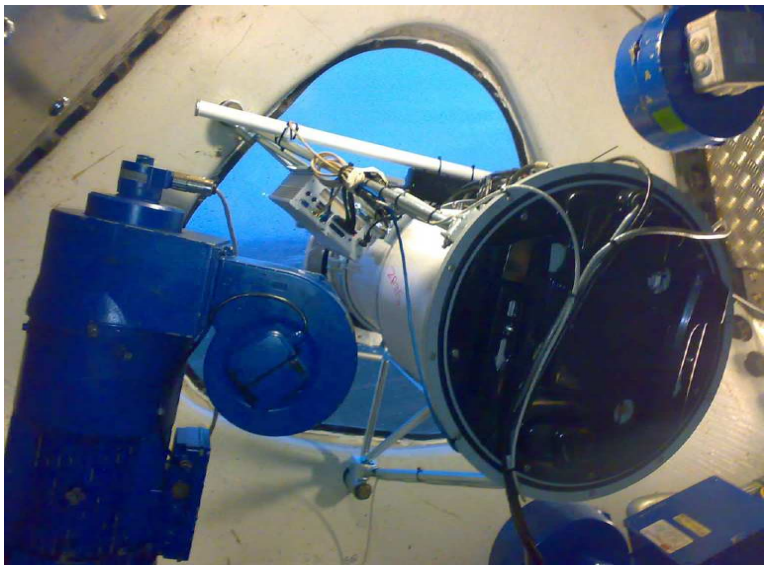


→ Same power curve for the both groups of profiles

Efforts to introduce RS in IEC61400-12-1

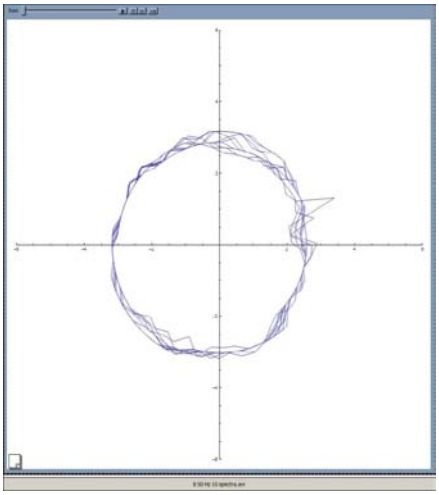
- Scope of the revision should allow for shear measurements
- Under the present scope, a mast will still be required
- Lidar Acceptance Group (LAG) formed to try to 'stretch' the revision to stand-alone lidars
- Procedures for lidar verification
- Classification scheme
- Equivalent wind speed method
- Uncertainty re-visited

Nacelle mounted lidar



Risø DTU, Technical University of Denmark

Radial wind speeds measured from a rotating CW spinner lidar



Risø DTU, Technical University of Denmark

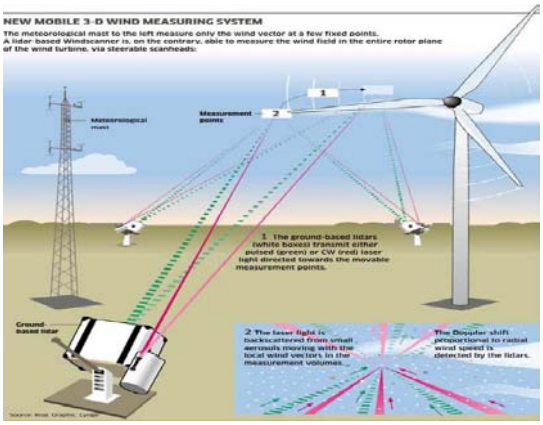
Nacelle lidar research areas

- Power curve measurements (probably pulsed systems)
- Control aspects (pulsed or CW)
  - Load alleviation
  - Power optimisation
- Rotor induction studies
  - What range do we need for accurate power curves?
- Wakes (continued)

Risø DTU, Technical University of Denmark

Windscanner

- 3 Modified ZephIR heads
- New Ripley prism scan head
- Scanning up to 500Hz
- About 100m x 100m
- Prototype testing scan head



Risø DTU, Technical University of Denmark

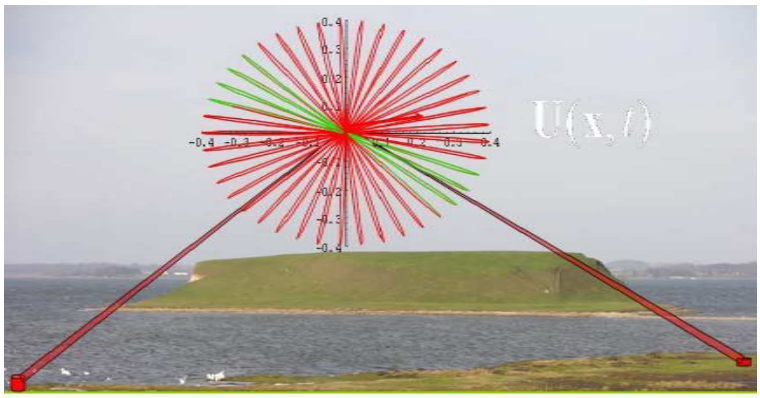
Musketeer II – Testing the optimised optics

The finished design will be more elegant!

Risø DTU, Technical University of Denmark

Long range Windscanner

- 3 X Pulsed or maybe 2P + CW
- Flexible scan head (like Galion)



Full Scale Laser Wind Scanner

Risø DTU, Technical University of Denmark

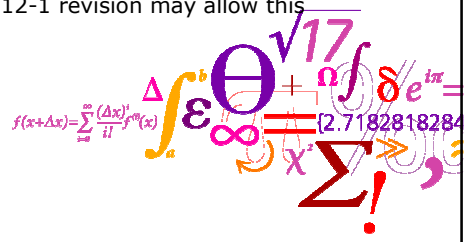
Technical University of Denmark

Conclusions

- Lidars are getting better – a good lidar in flat terrain may well have less uncertainty than a boom mounted cup?
- Complex terrain remains an issue – flow models are one way forward.
- Recommended Practices are required but it remains unclear how to tackle complex terrain.
- Lidar turbulence measurements are not easy to understand – more work needed!
- Lidars can measure good and ultimately better (site and season independant) power curves. IEC 61400-12-1 revision may allow this within a couple of years.

Thank you

mike@risoe.dtu.dk



Remote Sensing at POSTECH

2009.10.15
POSTECH
Graduate school of Wind Energy

Ji Yeongmi

Contents

1. Introduction

2. Overview of measurement
   - 2.1 Measurement – Set-up, Location, test site
   - 2.2 Principle

3. Result and analysis
   - 3.1 Overall - Recovery rate, time series, correlation,
   - 3.2 A day data- Wind profile, analysis

4. Conclusion

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1. Introduction

- Test of remote sensing instruments
- Intercomparison between SODAR and LIDAR
  - Evaluation of the availability and quality of non flat terrain measurement

POSTECH GWE

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2. Overview of measurement

POSTECH GWE

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2.1 Measurement – Set-up

- Instrument:

REMTECH PA0

LEOSPHERE Wind Cube

- Duration: 09-8-20 ~ 09-9-28
- Location: Pohang Accelerator Laboratory
- Measurement Heights:

  40m, 50m, 60m, 70m, 80m, 90m, 100m, 110m, 120m & 130m
- Data collection: every 10-minute on average

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2.1 Measurement - Location

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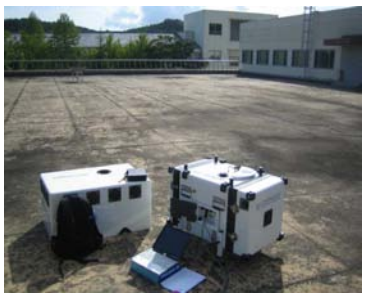
2.1 Measurement –Test site



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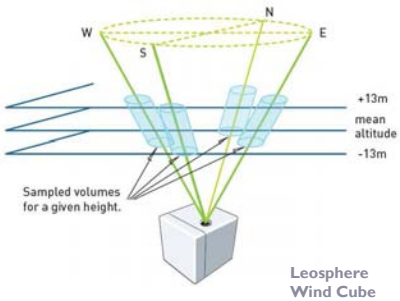
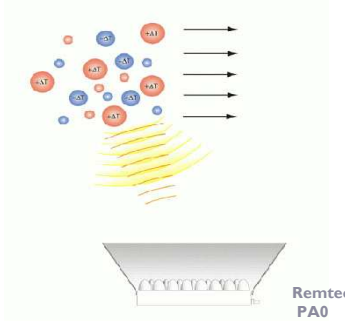
2.2 Principle



Leosphere
Wind Cube



Remtech
PA0

	Wind Cube	PA0
Method	Volume average using Doppler effect	
Vertical Resolution	20m	~15m
Sampling Time	~1 sec	~3 min
Tilt Angle	30°	30°

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3. Results and Analysis

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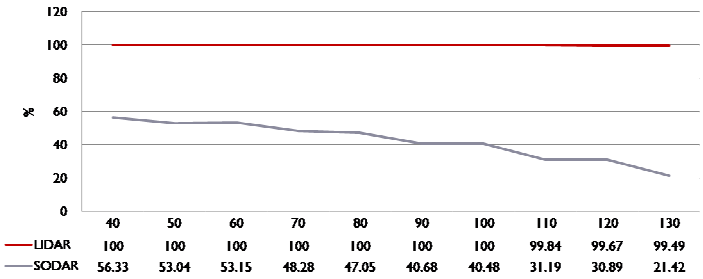
3.1 Overall - Recovery rate



Influence Factor

- High level
- Rain
- Ambient noise in daytime (about 52dB)

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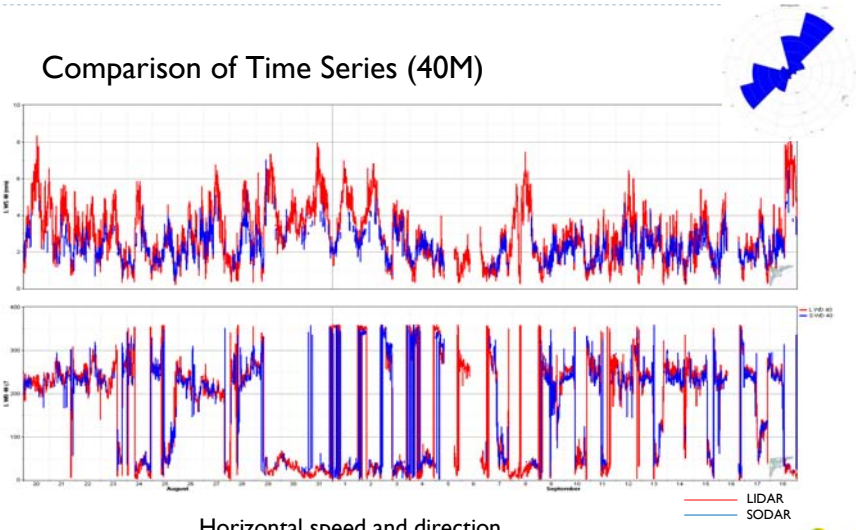
3.1 Overall - Time series

Comparison of Time Series (40M)



Horizontal speed and direction

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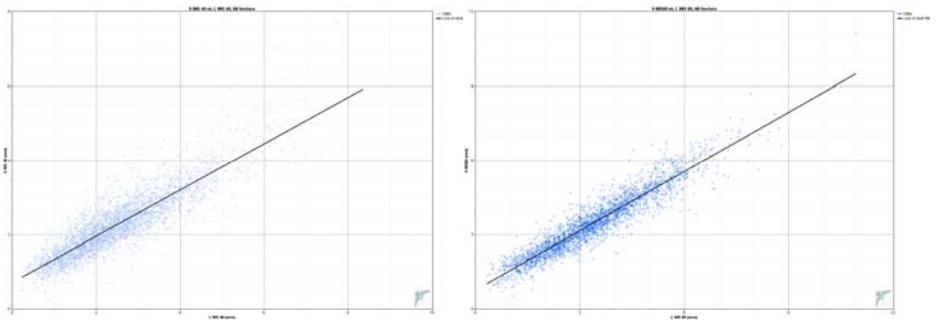
3.1 Overall - Correlation



y=0.705+0.625x
R^2=0.794

y=0.754+0.800x
R^2=0.885

Horizontal wind speed at 40m, 80m, (SODAR Vs LIDAR)

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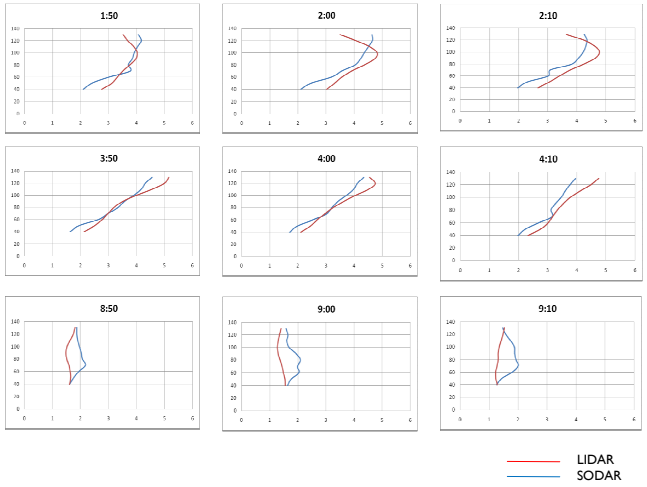
3.2 A day data - Wind profile



Unstable
in high wind speed

Stable

Unstable
in low wind speed

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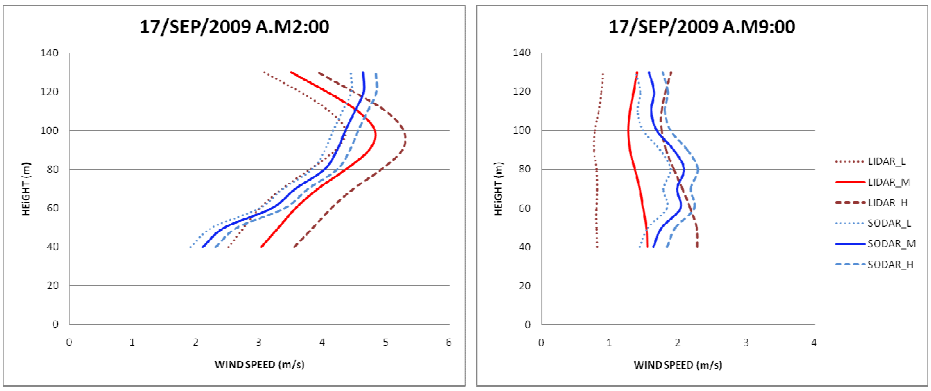
3.2 A day data - Analysis



SODAR : with speed accuracy
LIDAR: with deviation

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4. Conclusion

- Measurements in the range of height from 40m to 130m using SODAR and LIDAR
- Intercomparison
  - Low Availability of data from SODAR : less than 60%
  - Different wind profile of SODAR and LIDAR in unstable layer condition
  - Due to the difference in sampling rate
  - Decreasing reliability of data from SODAR In complex terrain or unstable wind profile
  - For evaluate reliability clearly, to be tested with a met mast

POSTECH GWE

National Renewable Energy Laboratory
Innovation for Our Energy Future

Sodar & Lidar Activities at NREL

IEA Topical Expert Meeting

"Remote Wind Speed Sensing Techniques Using Sodar and Lidar"

Neil Kelley, NWTC

October 15-16, 2009

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

OUTLINE

Applications of Remote Sensing at the NWTC

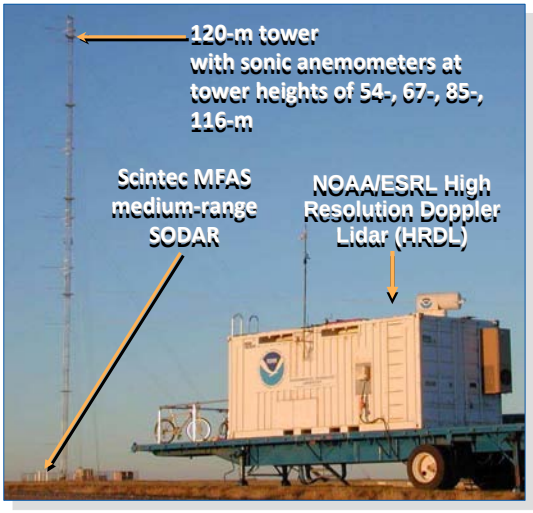
- Wind Flow Characteristics Research
  - Low-Level Jet Research
    - Sodar
    - Scanning Lidar
  - Turbulence Scaling Parameters
    - Sodar
    - Scanning Lidar
- Evaluation of Remote Sensing Technologies to Provide Local Atmospheric Conditions for Mesoscale Modeling Initialization
  - Sodar

Wind Flow Characterization Research

Lamar Low-Level Jet Program

Objective: To develop an understanding of the influence of nocturnal low-level jets on the inflow turbulence environment of multi-megawatt wind turbines

Cooperative Program with
Enron (GE) Wind
NOAA/ESRL
DOE/NREL



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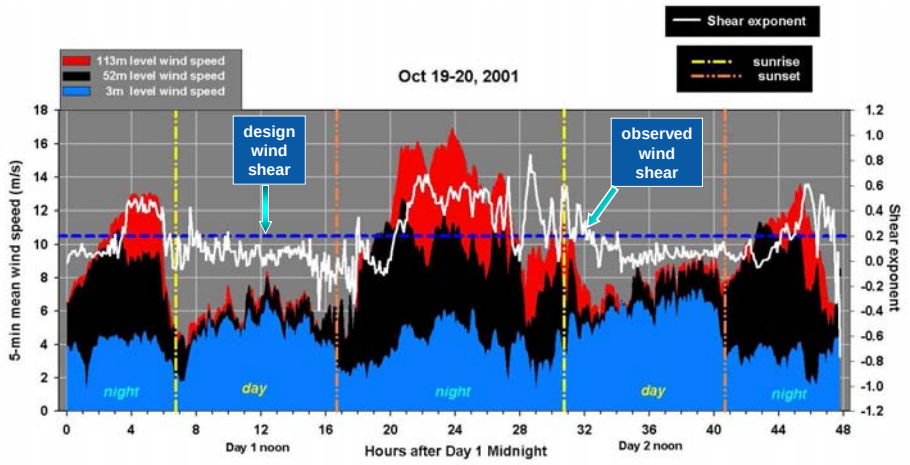
Why Worry About Low-Level Jets?

Typical Diurnal Variation in Turbine Inflow on the Great Plains



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Sodar & Applications

Scintec Sodar

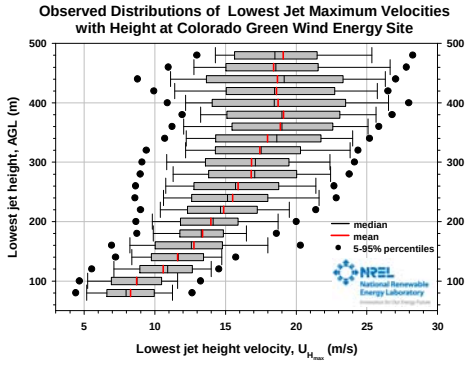
– **Operating characteristics**

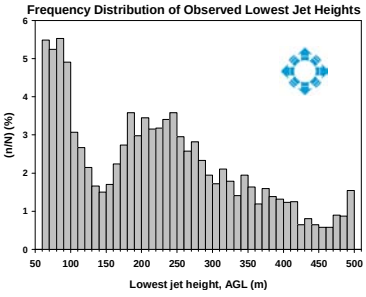
- 30 to 500 m height range
- Single and multi-frequency operation
- 20-min averaging 10-min records
- Operated 24/7 during “warm” season for low-level jets (April – September)

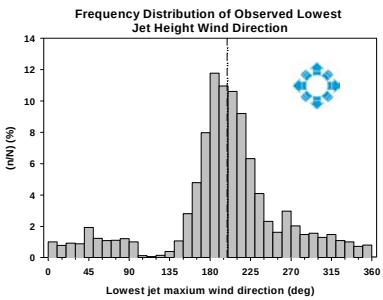
– **Measurement Objectives**

- Determined frequency, height, and intensity of low-level jets that have been included in the NREL TurbSim Stochastic Inflow Simulator Great Plains Spectral Model
- Documented intensity of vertical shears from 30 to 200 m
- Provided vertical wind direction profiles for alignment of NOAA HDRL Lidar

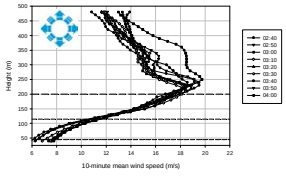
Examples of Results Derived from Sodar



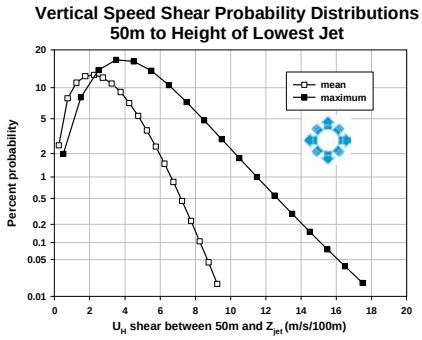


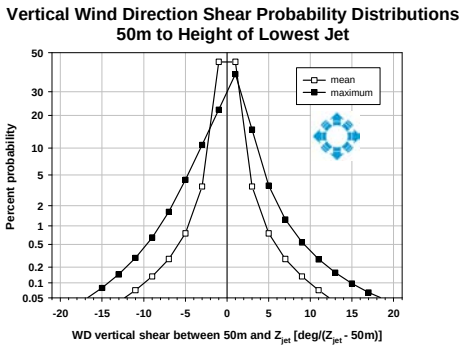


Low-Level Jet Wind Speed Profile



What About Shears Below the Jets?





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Volumetric Scanning Lidars Used

NOAA/ESRL Pulsed Doppler Coherent Research Lidar

HRDL technical parameters#	
Wavelength	2.02 µm
Pulse energy	1.5 mJ
Pulse rate	200/s
Range resolution	**30 m**
Velocity resolution	**~ 0.1 m/s**
Time resolution	**0.25 s**
Minimum range	**0.2 km**
Maximum range	**3 km**
Beam width range	6 to 28 cm

#as configured for the NREL Lamar Low-Level Jet Program

Lockheed-Martin/CTI Pulsed Doppler Coherent Lidar

WindTracer® technical parameters#	
Wavelength	2 µm
Pulse energy	2 mJ
Pulse rate	500/s
Range resolution	**80 m**
Velocity resolution	**0.1-0.6 m/s**
Time resolution	**0.1 s**
Minimum range	**0.4 km**
Maximum range	**8-10 km**
Beam width	8 cm

#~as deployed at the NWTC, currently available model has somewhat different specifications

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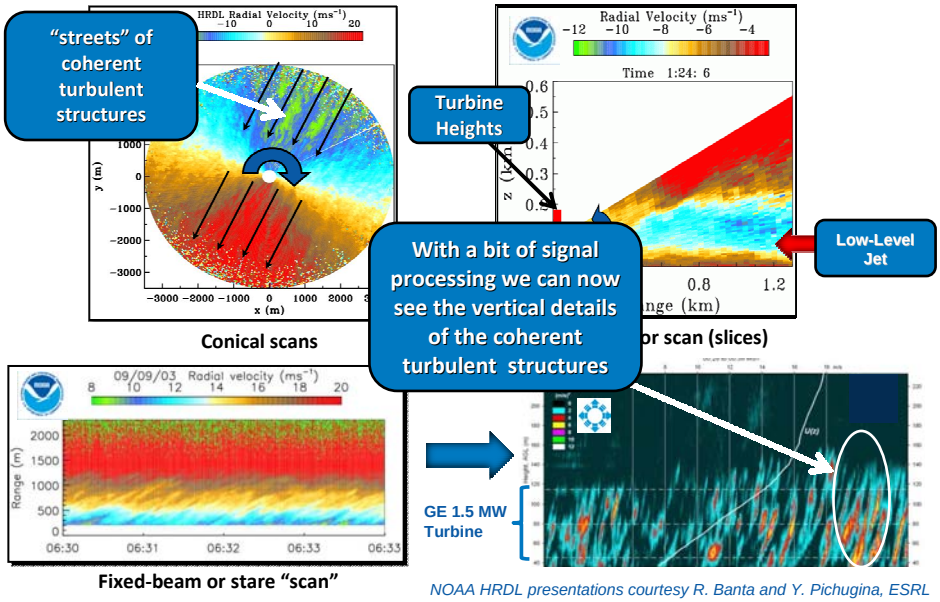
Examples of Results Derived from HDRL Lidar Using Different Scanning Modes During Lamar Experiment



NOAA HRDL presentations courtesy R. Banta and Y. Pichugina, ESRL

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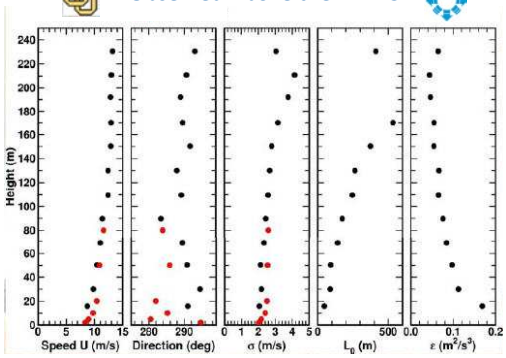
Examples of Results Derived from the WindTracer Lidar at the NWTC Using a Volume Scan

Profiles of Turbulence Scaling Parameters Observed Above the NWTC



Frehlich, R. and Kelley, N., 2008

● LIDAR ● NWTC TOWER

Very useful for determining initial conditions for NWP

National Renewable Energy Laboratory — Innovation for Our Energy Future

Evaluation of Remote Sensing Technologies for NWP Initialization

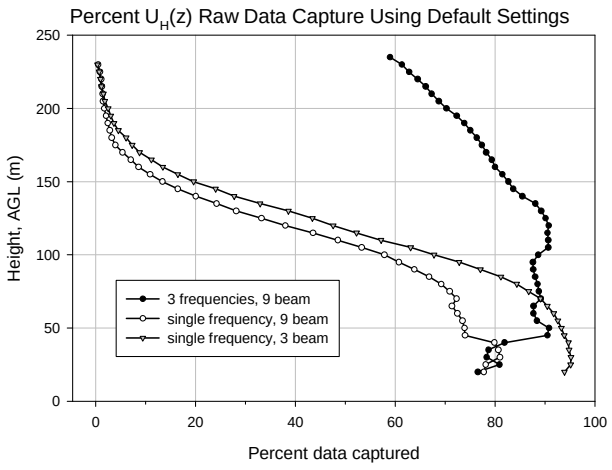
Sodar

- The NWTC presents a challenging environment for sodar observations particularly if a high data capture is desired for wind speeds within a overall wind turbine operating range of 3 to 25 m/s.
- Because the wind industry is using low-range or “mini-sodars”, we have been evaluating a Scintec SFAS sodar because of its high degree of flexibility including user-selected multi-frequency and multi-beam operation.
- We conducted an experiment last winter in which the SFAS sodar was operated over a desired height range of 20-235 m in three separate configurations:
  - 3 frequencies (2549, 3386, and 4479 Hz using 9 radiated beams
  - Single frequency (4479 Hz) using 9 radiated beams
  - Single frequency (4479 Hz) using 3 radiated beams

National Renewable Energy Laboratory Innovation for Our Energy Future

Maximum Altitude Performance Example with high S/N Ratio

10-Minute Averaging



National Renewable Energy Laboratory Innovation for Our Energy Future

References

Banta R.M., Y.L. Pichugina, N.D Kelley, B.J. Jonkman, and W.A. Brewer, 2008: Doppler lidar measurements of the Great Plains low-level jet: Applications to wind energy. *14th International Symposium for the Advancement of Boundary layer Remote Sensing,* 23-25 June, Risø National Laboratory, DTU, Roskilde, Denmark, pp.4

Kelley, N., M. Shirazi, D. Jager, S. Wilde, J. Adams, M. Buhl, P. Sullivan, and E. Patton, 2004: Lamar Low-Level Jet Project Interim Report, NREL/TP-500-34593.

Frehlich, R., Kelley, N., 2008: Measurements of Wind and Turbulence Profiles with Scanning Doppler Lidar for Wind Energy Applications, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* **1**, 42-47.

Global Partners in Lidar Wind Technologies

Lidar value for wind energy

October '09 - IEA

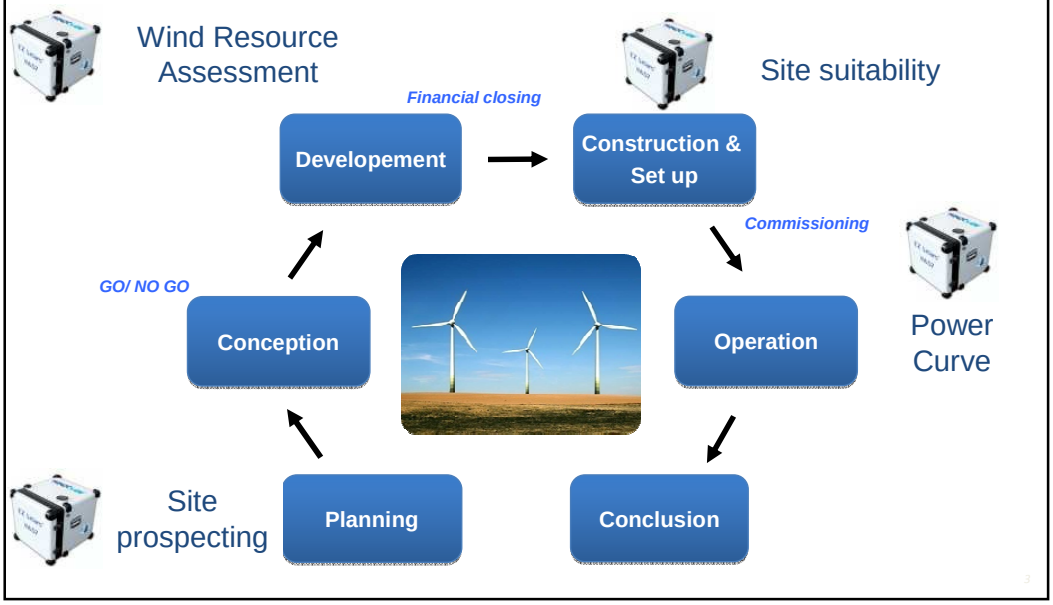
Global Partners in Lidar Wind Technologies

Agenda

- Lidar applications for wind energy
  - Site prospecting
  - Site assessment
  - Site suitability
  - Power performance verification
  - Good practices
- Introducing the Windcube™
  - The state-of-the-art on Lidar measurement accuracy
  - Advanced measurements
  - Challenging complex terrain
  - Potential sources of measurement bias
  - Quality and traceability
  - Feedback on Windcube™ reliability
- Quantitative measurements and bankability

2

Lidar Applications in Wind Farm Projects



Pre-construction benefits

- Site prospecting
  - Easy to deploy
  - Construction permit not required
  - Discreet
- Wind resource assessment
  - Hub height wind speed true measurement
  - Easy to move for better site flow characterization

4

Operational benefits

- Site suitability
  - Whole rotor shear measurement
  - Whole rotor veer measurement
  - Inflow angle
  - Turbulence Intensity
- Operational measurement
  - Power curve measurement (IEC being revised to include RS for PC)
  - Wake

5

Good measurement practices when using a Lidar

- Use with a Met Tower to provide initial relative accuracy of Lidar (Verification at flat non complex site within the project footprint)
- Instrument siting location is known and understood
  - Good documentation of siting before the campaign
  - Surface roughness
  - Complex Terrain
- Use Met Tower to correlate with Lidar data to determine that the proper

  data coverage (speed range, directional bins and seasonal effects) has been acquired at a site.
  - Depending on site complexity, the closest Met Tower should be placed not farther than 2km (flat terrain) or 0.5km (mountains)

6

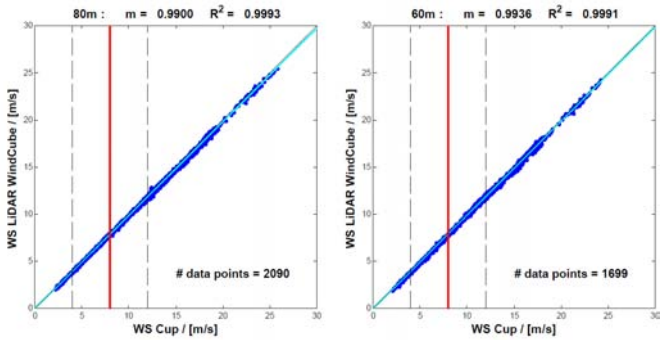
The Windcube™: state-of-the-art of Wind Remote Sensing

- Key features:
  - 200m 3D wind profile
  - 10 simultaneous programmable measurement heights
  - 1Hz data rate
  - Constant accuracy at all heights
  - Portable, flexible, easy to use
  - Ready to use data (automatic data filtering)
  - Built for all weather conditions including offshore

7

Horizontal wind speed accuracy

Norsewind Project:Evaluation of Windcubes™

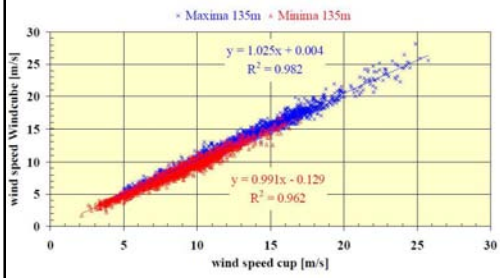


Comparison of horizontal wind speed (10-minute average) as measured by Windcube and cup anemometer at 80m and 60m heights (onshore 1st phase of the Norsewind Project)

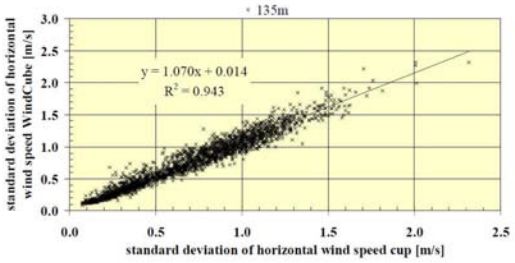
Source: Testing and calibration of various lidar remote sensing devices for a 2-year offshore wind measurement campaign, A. Oldroyd, M. Courtney, Detlef Kindler, presented at EWEC 2009 Conference, Marseille, France.

8

Advanced Measurements



Comparison of extreme values of horizontal wind speed at 135m height



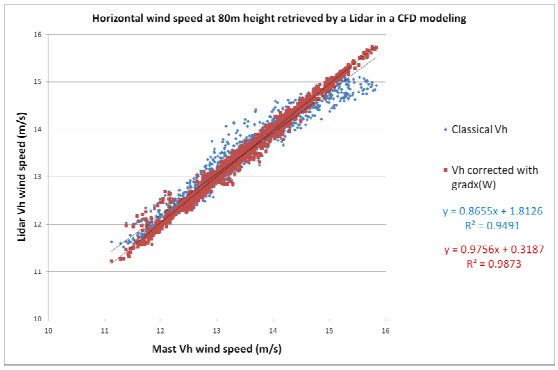
Comparison of standard deviation of horizontal wind speed at 135m height

Source: Comparison of Lidars, German test station for Remote Wind Sensing Devices, A. Albers, A.W. Janssen, J. Mander, Deutsche Windguard Consulting GmbH, Paper presented at DEWEK 2008 Conference, Bremen, Germany.

9

Complex terrain

- Observed bias from -5% to +5% coming from flow inhomogeneity
- Good understanding of wind flow distortion effect on Lidar measurement
  - A geometrical problem that effects all RS
  - Reducing the scanning cone angle is not the magical solution
  - Radial velocities are not biased, a model based correction is possible
  - WAsP Engineering correction is being tested



CFD simulation:
biased Lidar in blue
corrected Lidar in red

10

High data recovery at all times

- constant availability days & nights
- constant accuracy under diversity of climates
- same accuracy and availability over 0 to 45 m/s wind speed range

All weather operation since 2006

- IP-65 Casing
- Optional thermal insulation blanket for cold climates
- Window de-icing system
- Automatic wiper system

11

Potential sources of bias

- LOS velocity measurement:
  - laser wavelength drift
  - zero wind speed reference frequency offset characterization
  - sampling frequency drift
  - zero distance time reference (triggering error)
  - optical telescope focusing distance (through range gate distortion)
- 3D wind velocity reconstruction:
  - Averaging over pulse probed volume (~20m FWHM)
  - Scanning cone angle error (wind speed proportional error)
  - Spatial and time averaging through the use of 4 sequential LOS (flow inhomogeneity)

12

Traceability and internal acceptance process of Windcubes™

- For all Windcube™ production units:
  - all components serial numbers and test data sheets stored in the Windcube™ file.
  - manufacturing calibration process results stored
  - minimum 1 week comparison with the **Golden Windcube™** → from 40m to 200m: CNR, Horiz. wind speed, STD, Vertical wind speed, wind direction
  - acceptance threshold for each parameter
- Internal report automatically filed in each S/N folder
- Several Units shipped upon customer's request to DTU/RISO and Deutsche WindGuard GmBH for verification against a tall mast

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Reliability feedback based on North America experience

- Needs to be more Robust (Early units only)
  - Shipping Damage
    - Resolved through product improvements
    - Shock and Vibration monitoring during shipping
  - Optical Alignment
    - Enhance locking mechanisms of all optics
    - Advanced techniques to minimize effects
  - Improved Product
    - Continuous improvement through product test and inspection

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Bankability

Global Partners in Lidar Wind Technologies

- Qualitative and **Quantitative** measurement accepted
  - Increasing amount of information (validation reports, best practice guides…)
  - Wind energy consultants, developers, operators and bankers are more and more confident in Lidar performance
- Business cases
  - Alpha Wind (Denmark) (wind resource assessment based on stand alone Windcube™)
  - EDF EN (France): 5 months of Windcube™ use experienced significantly increase of P50 (+2%) and P90 (+5%)
  - General confidence in Lidar has increased in North America (GH US, AWS Truewind, Helimax-GL, GEC-DNV, Genivar, Padoma…)

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Windcube™ specifications

Global Partners in Lidar Wind Technologies

Technical Specifications

Electrical	
Power supply	24V DC or 100/240V AC 50-60 Hz
Power consumption	111W to 375W
Environmental	
Temperature range	- 30°c to +40°c (with winter package)
Operating humidity	IP65
Rain protection	Wiper
Compactness	Portable
Optics & Electronics	
Laser Class	1 - 1,54 µm
Eye safety	IEC 60825-1
Dimensions	
Size	800x550x550 mm
Weight	60 kg
Data	
Data format	ASCII / binary
Data transfer	GSM / GPRS / LAN / TCP-IP

Software	
Standard WINDSOFT	- Instrument control - Data acquisition - Data storage - Data processing - Manual data transfer (TCP/IP)
Optional Expert	- raw data (spectra data) - signal-to-noise ratio - calibration data
Optional Windcube Anywhere	- Automatic remote data transfer (GSM/GPRS) - Sendmail:email data sending - System remote control - Remote alarm by sms or email
GPS tracking	-GPS tracking

Performance Specifications

Specifications	
Range min - max	40 to 200m
Accumulation time	0.5s
Data output frequency	1 Hz
Probe depth	20m
Number of measurement heights	10
Scanning cone angle	Dual 15° or 30°
Speed accuracy	0.2 m/s
Speed range	0 to 45 m/s
Direction accuracy	1.5°
Parameters	
Output data	- 1s/10min horizontal & vertical wind speed, min & max, direction - Signal-to-Noise Ratio - Horizontal & vertical wind speed standard deviation

17

SODAR Insights on Wind Turbine Power Curves

Julie K. Lundquist, Sonia Wharton (LLNL)
Mike Zulauf, Justin Sharp, Jerry Crescenti (IRI)

2009 IEA Topical Expert Meeting 59,

Remote Wind Speed Sensing Techniques Using Sodar and Lidar

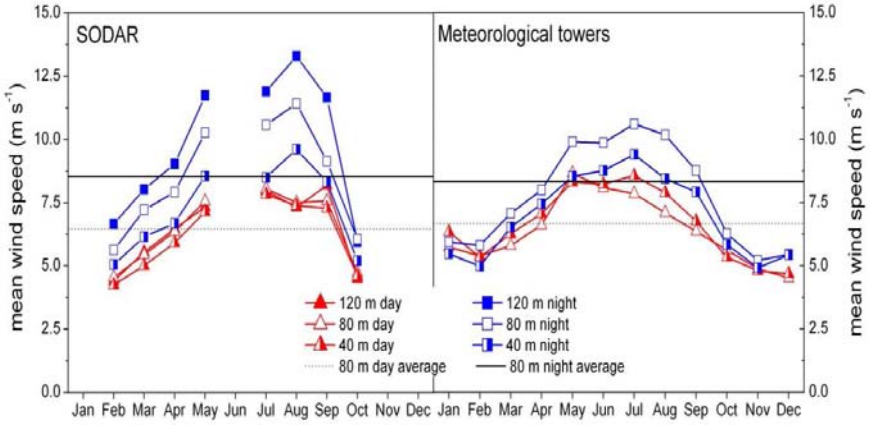
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PRES-414238

Lawrence Livermore National Laboratory

SODAR and conventional *in situ* measurements are available at an operating wind farm to assess impacts of atmospheric variability on power curves

- Measurements taken from a “West Coast North America” operating wind farm with tens+ of turbines
- Terrain of gently rolling hills
- SODAR observations available for ten months
- Met tower and nacelle cup anemometer measurements available for same time period
- Do turbine power curves demonstrate the influence of atmospheric stability?

SODARS and cup anemometers see similar seasonal patterns; differences due to measurement approach (volume v. point) and data availability



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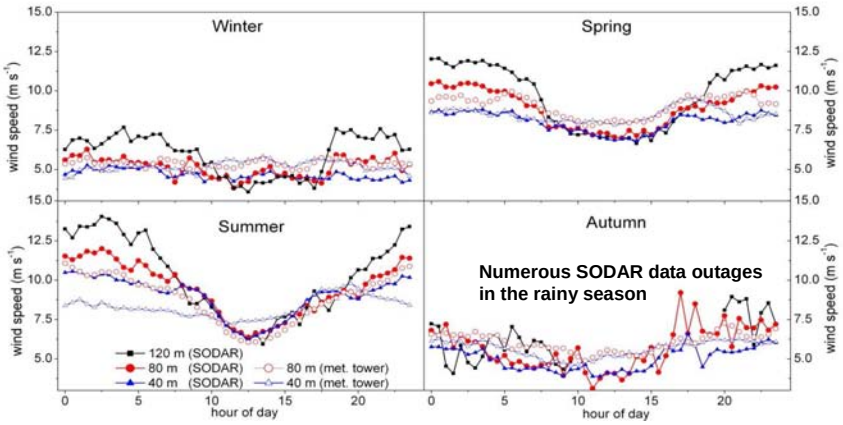
SODAR reports stronger diurnal variability as compared to cup anemometers



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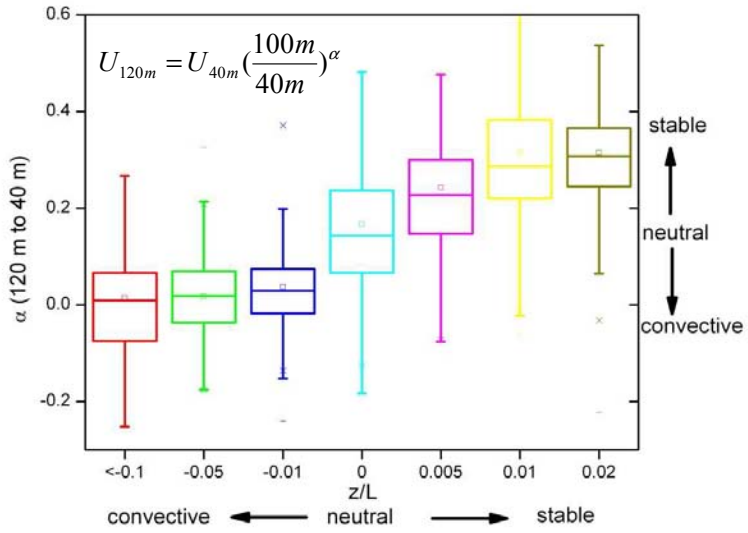
In comparison to local surface-based stability measurements, shear, as measured by the SODAR, does not segregate stability classes



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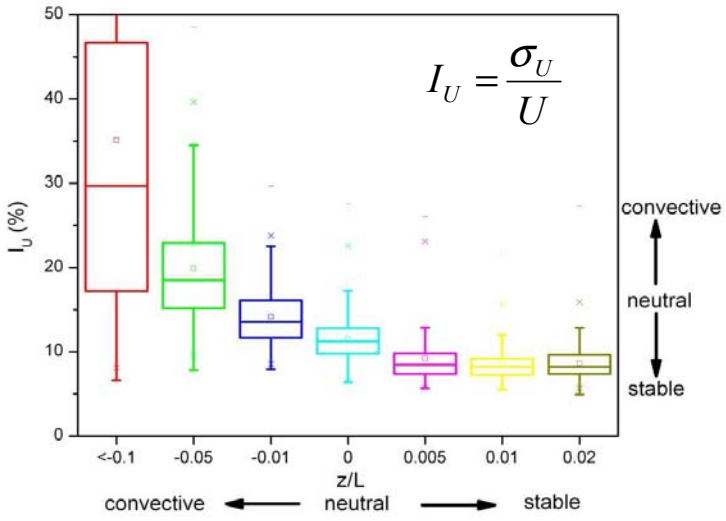
5

In comparison to local surface-based stability measurements, turbulence intensity, as measured by the SODAR, can distinguish stability classes



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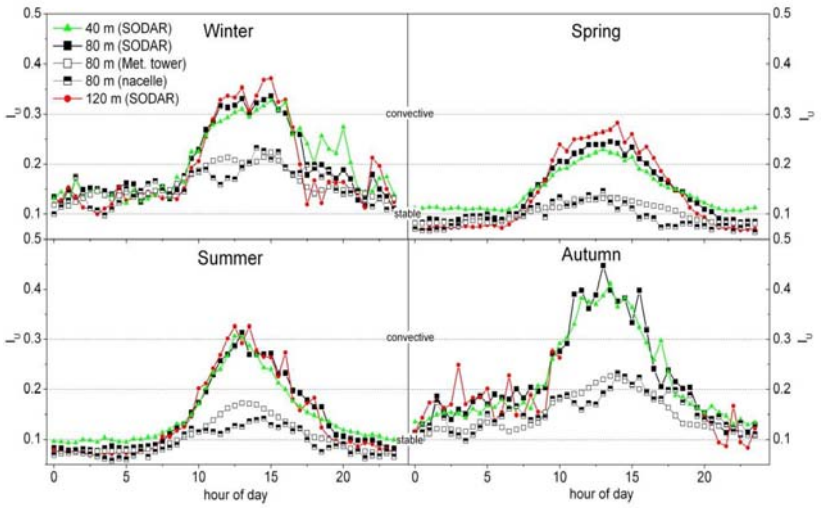
SODAR discerns stronger variations in turbulence intensity than cup anemometers



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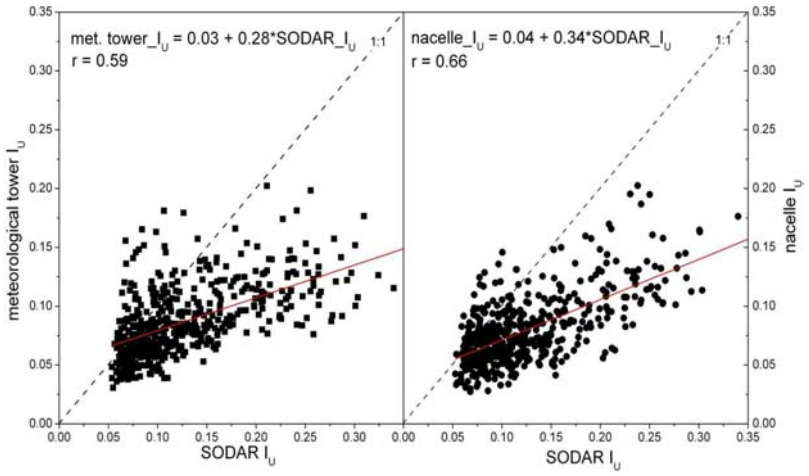
7

Comparison of SODAR and cup anemometers turbulence intensities over five consecutive days show significant differences at high I_U



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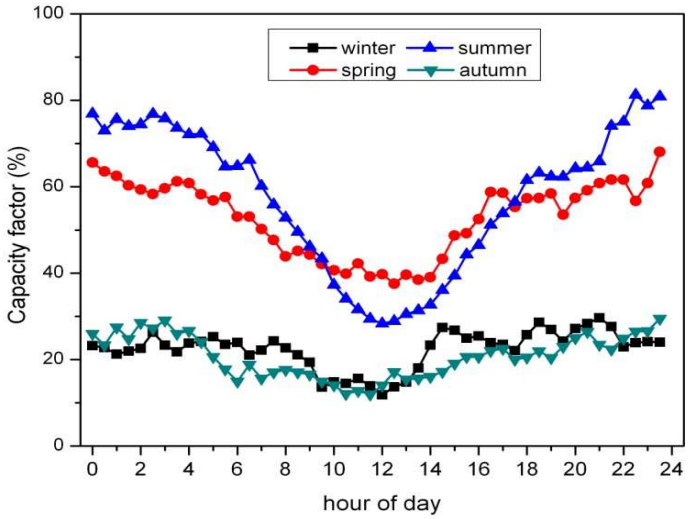
8

Seasonal variability in winds is reflected in turbine capacity factor



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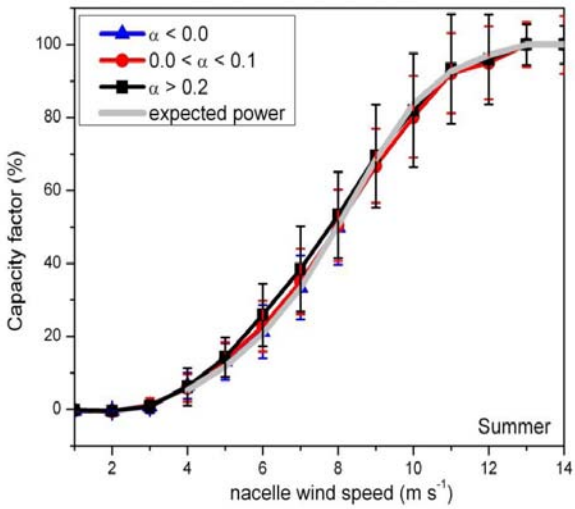
9

Power curves segregated by SODAR shear do not show a strong dependence on atmospheric stability



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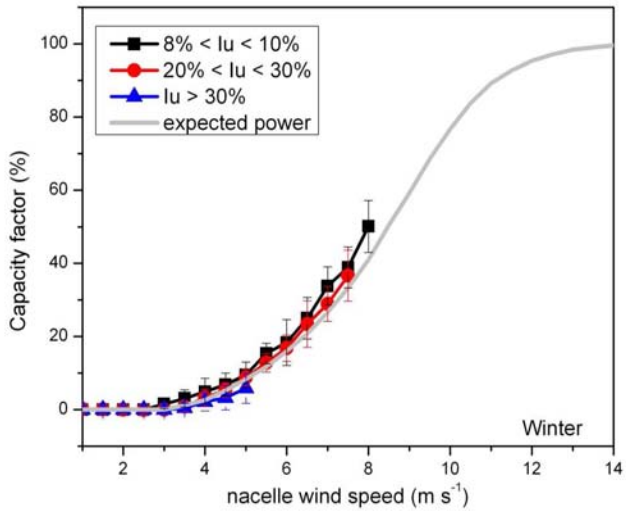
10

In winter, power curves segregated by SODAR turbulence intensity I_U show only a slight dependence on atmospheric stability



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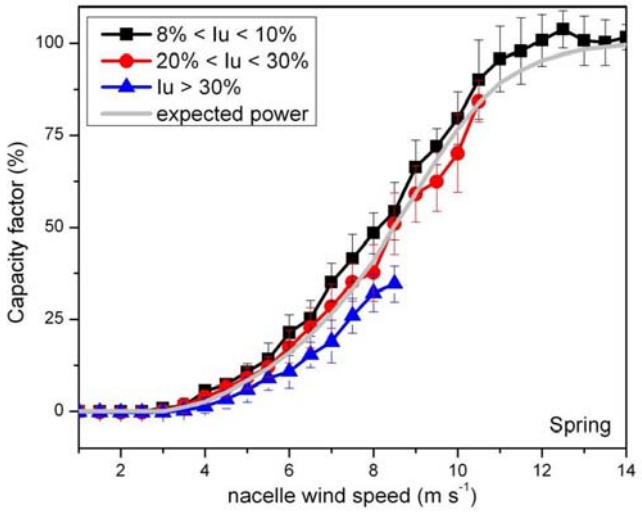
11

In spring, power curves segregated by SODAR turbulence intensity I_U show a significant dependence on atmospheric stability



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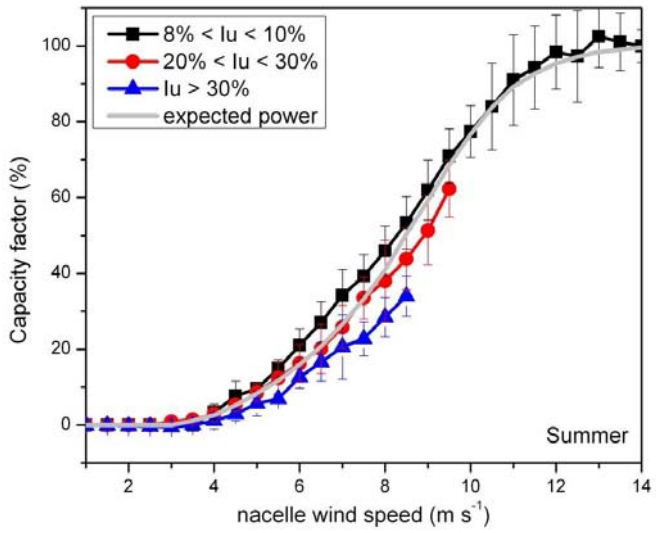
In summer, power curves segregated by SODAR turbulence intensity I_U show a significant dependence on atmospheric stability



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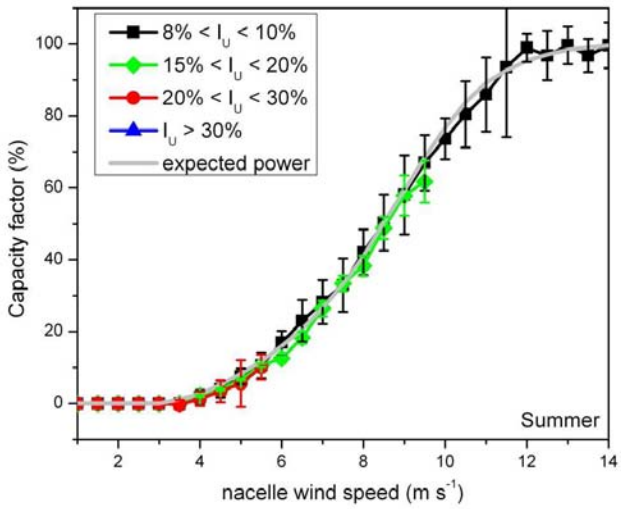
That strong dependence of power on turbulence intensity is not apparent when using cup anemometer measurements of I_U



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In summary:

- Although SODAR and cup anemometers show similar trends at this location, SODAR measures higher wind speeds and much higher turbulence intensities
- Turbulence intensities from SODAR reflect direct measurements of atmospheric stability (Monin-Obukhov length) from a nearby research station, while those from cup anemometers overpredict stable conditions
- SODAR measurements of turbulence intensity can explain turbine power curve variability – while SODAR measurements of shear or cup anemometer measurements of I_U cannot
- SODAR measurements of wind profiles and turbulence intensities can yield useful insight to wind turbine power curves

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Questions?

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Dept. of Atmospheric and Oceanic Sciences
University of Colorado at Boulder

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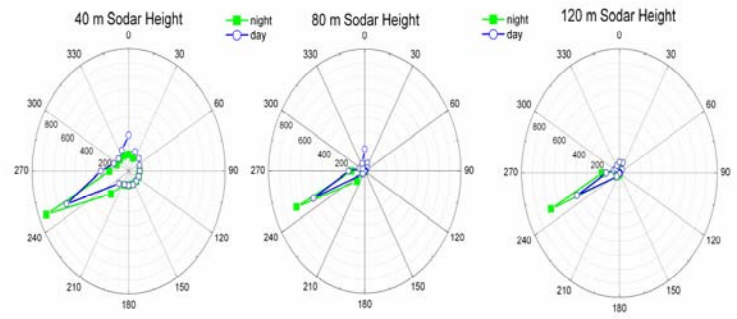
At this site, variation of wind direction with height is not a consideration



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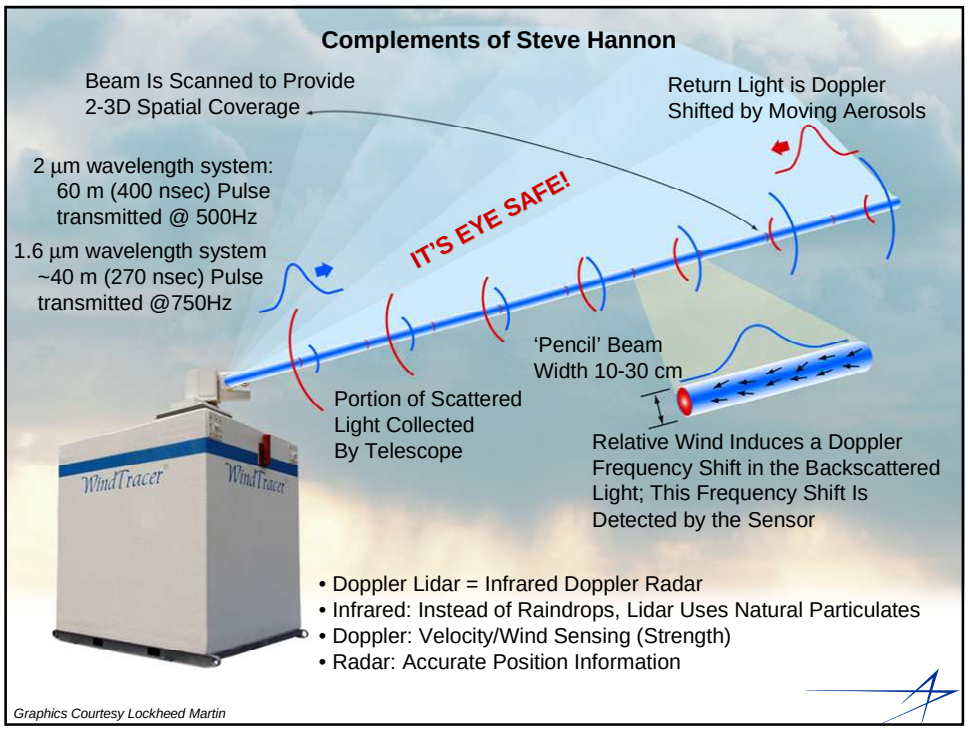
17

Wind and Turbulence Measurements with Scanning Doppler LIDAR

Rod Frehlich

University of Colorado, Boulder, CO

Supported by DOE, NSF, and ARO



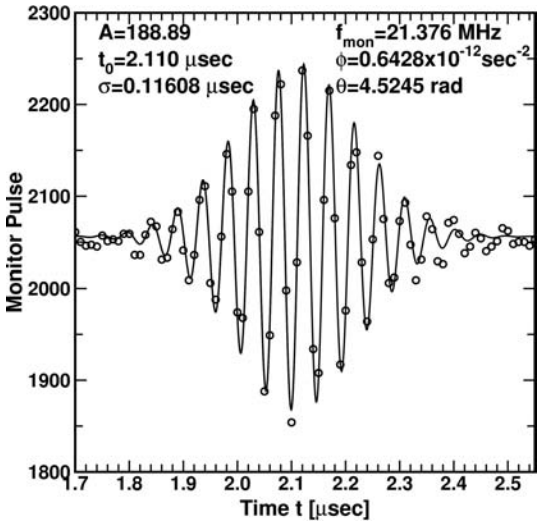
Coherent Doppler Lidar Properties

- Direct measurement of Doppler shift from aerosol particles
- Doppler shift 1 MHz for 1 m/s (2 μm)
- Accurate radial velocity estimates with little bias
- Eye safe operation

Monitor Pulse

Frehlich, Hannon, Henderson 1994

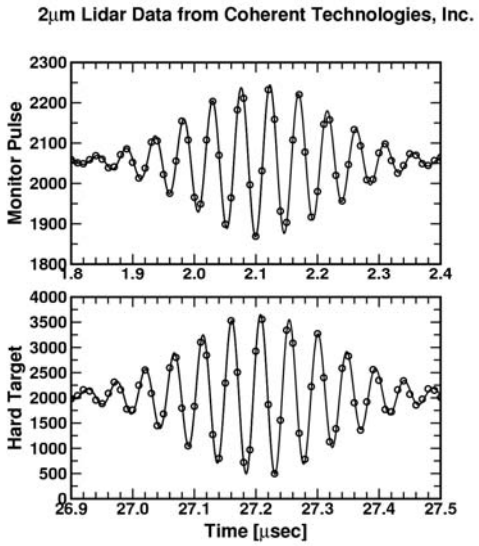
- Velocity calibration from monitor pulse
- Solid-state lidar approximately Gaussian transmitted pulse
- Frequency is reference for zero velocity



Hard Target Data

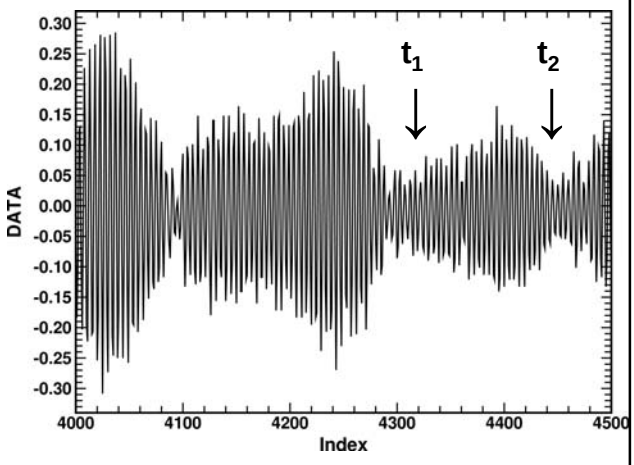
Frehlich, Hannon, Henderson 1994

- Velocity bias determined from hard target data
- Bias is typically less than 2 cm/s
- New lidars are even better



Raw Atmospheric LIDAR Data

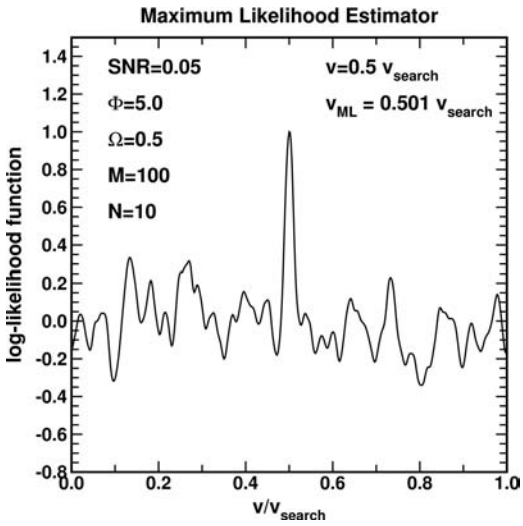
- Lidar signal is a narrow band Gaussian random process
- Range-gate defined by processing time interval t_1-t_2



Estimation of Velocity

Frehlich and Yadlowsky 1994; Frehlich 1996

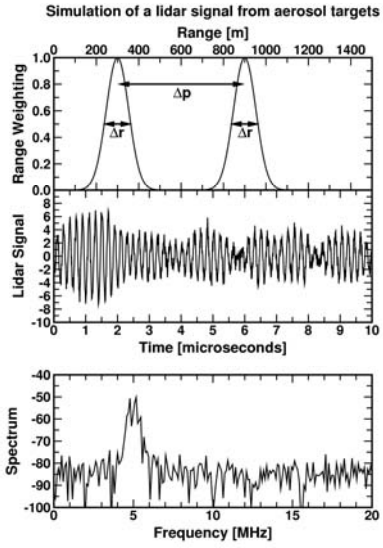
- Data from multiple pulses N improves performance
- Spectral based estimators
- Maximum Likelihood has best performance



Doppler LIDAR Range Weighting

Frehlich 1997; Banakh and Smalikho 1997

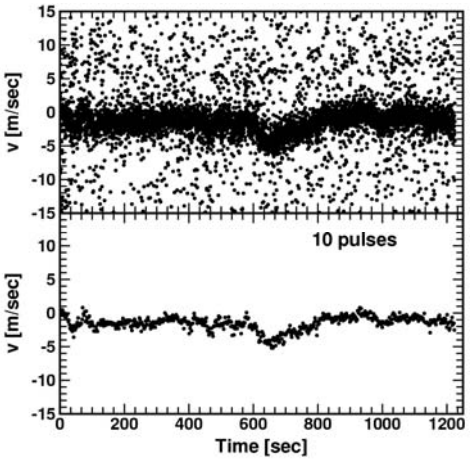
- Time of data maps to range (1 μs = 150 m)
- Pulsed lidar velocity measurements filter the random radial velocity $v_r(z)$
- Pulse width Δr
- Range gate length defined by processing interval Δp
- Spectral velocity estimate



Multiple Pulse Estimates

Frehlich, Hannon, Henderson 1994

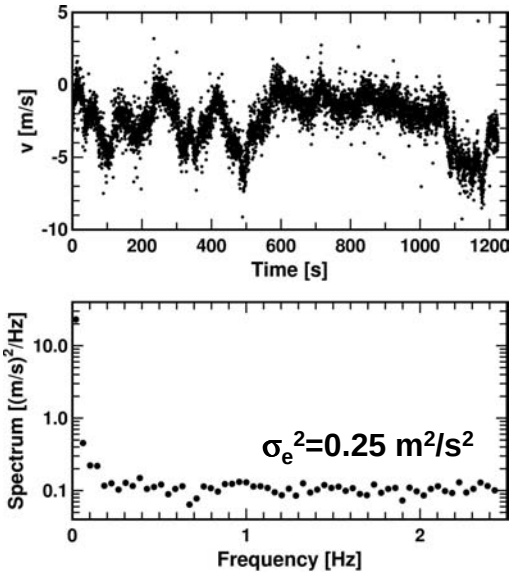
- Single pulse data has random outliers
- Pulse accumulation removes outliers
- Data rate is less with multiple pulses



Estimates of Random Error

Frehlich, Hannon, Henderson 1994; Frehlich 2001

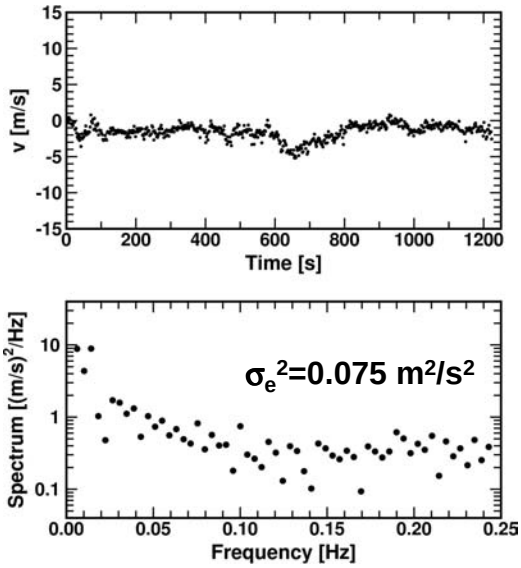
- Radial velocity error variance σ_e^2 can be determined from data
- Spectral noise floor is proportional to σ_e^2
- Low frequency is atmospheric signal (turbulence)



Estimates of Random Error-cont.

Frehlich, Hannon, Henderson 1994; Frehlich 2001

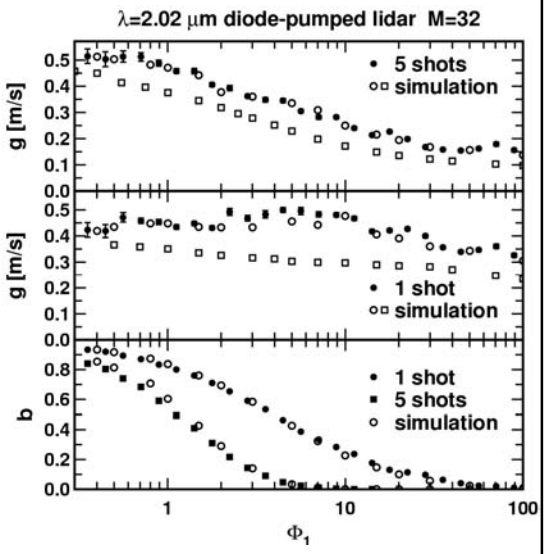
- Multiple pulse data has a smaller region for the noise floor
- The atmospheric signal must in the low frequency region



Verification of Accuracy

Frehlich, Hannon, Henderson 1997

- Velocity random error depends on signal energy
- Accuracy is very good with multiple shots
- Agrees with theoretical predictions if turbulence is included (o)



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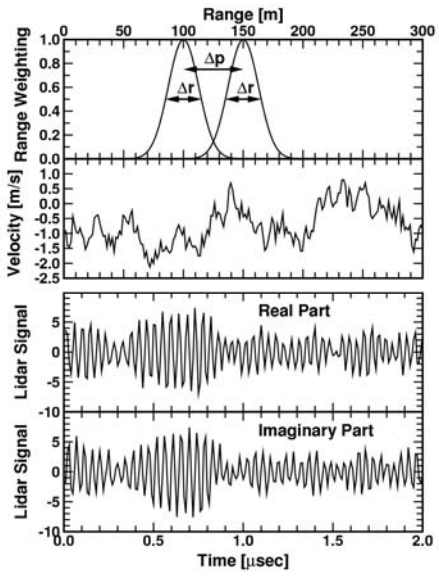
- Time of data maps to range (1 μs = 150 m)
- Pulsed lidar velocity measurements filter the random radial velocity $v_r(z)$
- Pulse width Δr
- Range gate length defined by processing interval Δp
- Range weighting W(r)



LIDAR Data and Turbulence

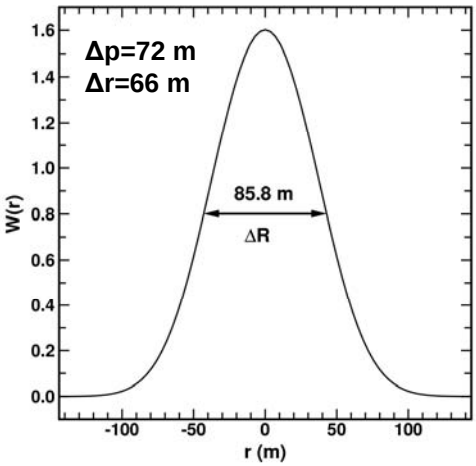
Frehlich 1997, 2008; Banakh and Smalikho 1997; Frehlich 2008

- LIDAR radial velocity estimates at range R

  $v(R) = v_{wgt}(R) + e(R)$
- $v_{wgt}(R)$ pulse weighted velocity
- e(R) estimation error

$$v_{wgt}(R)=\int v_r(z)W(R-z)\,dz$$

- $v_r(z)$ random radial velocity
- W(r) range weighting



Scanning Lidar

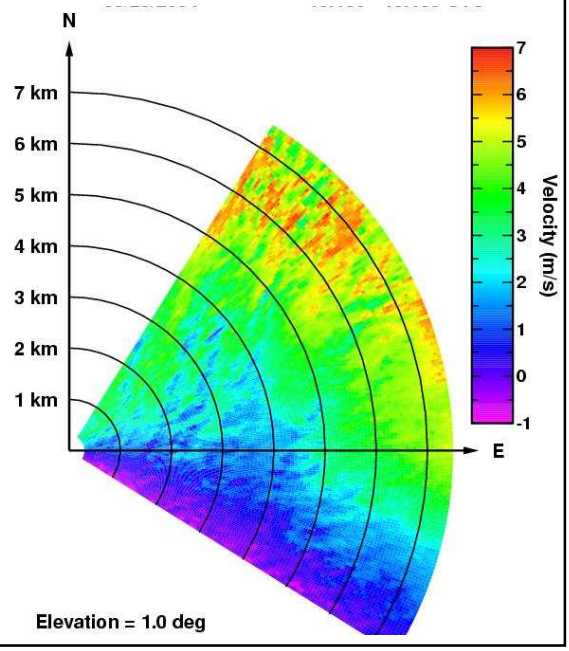
Frehlich et al. 2006, 2008; Lenschow, Mann, Kristensen 1994

- **High-resolution profiles of wind speed and turbulence statistics**
- **Highest statistical accuracy from large number of independent samples**
- **Rapid update rates compared with tower derived statistics**
- **Can provide profiles at multiple locations**
- **Ideal technology for wind energy applications**

LIDAR Radial Velocity Map for 1º

Frehlich et al. 2006

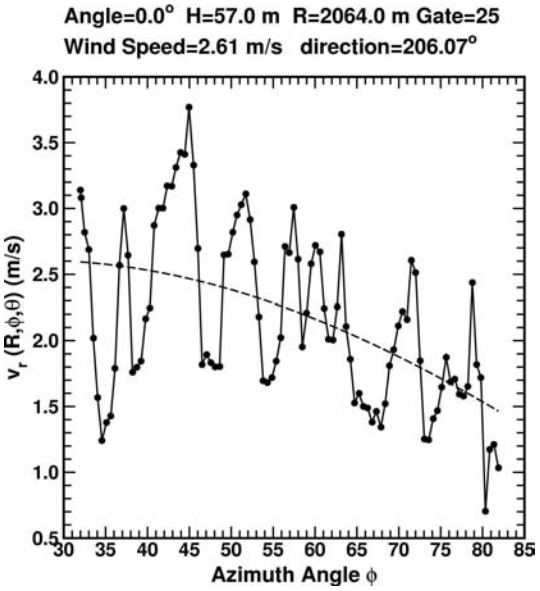
- **Range-gate 72 m**
- **100 range-gates along beam**
- **180 beams (Δφ=0.5 degree)**
- **10 radial beams per second**
- **18 seconds per azimuth scan**
- **Δh=R Δφ << Δp for R<2km**



Wind Speed and Direction

Frehlich et al. 2006

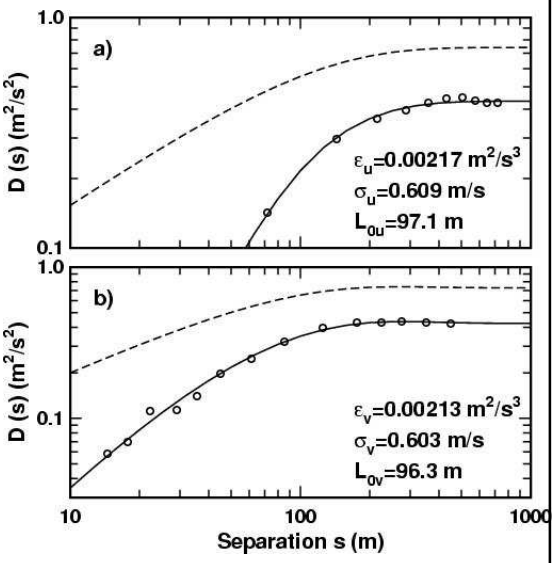
- **Best-fit wind speed and direction at R=2064 m**
- **Fluctuations are turbulence**
- **Spatial extent of fluctuations is outer scale of turbulence L_0**



Turbulence Estimates from Lidar

Frehlich et al. 2006

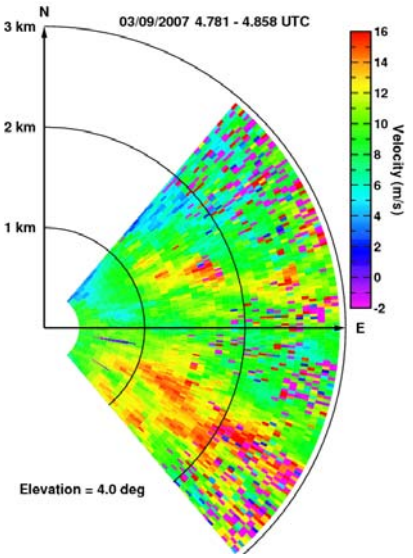
- **Structure function of radial velocity in range a)**
- **Best fit produces estimates of σ_u, ε_u, L_{0u}**
- **Structure function in azimuth b)**
- **Best fit produces estimates of σ_v, ε_v, L_{0v}**



Doppler Lidar at NREL

Frehlich and Kelley 2008

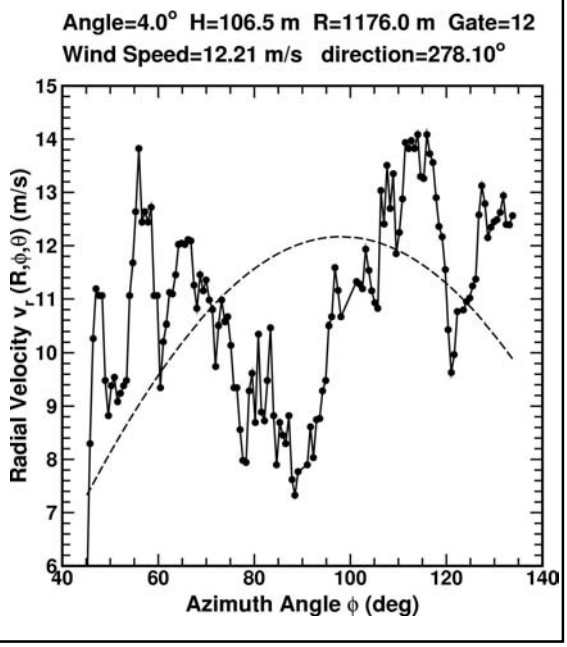
- Large turbulent eddies
- Large velocity variations
- 3D sampling required for accurate estimates
- Most challenging conditions for wind energy applications



High Turbulence

Frehlich and Kelley 2008

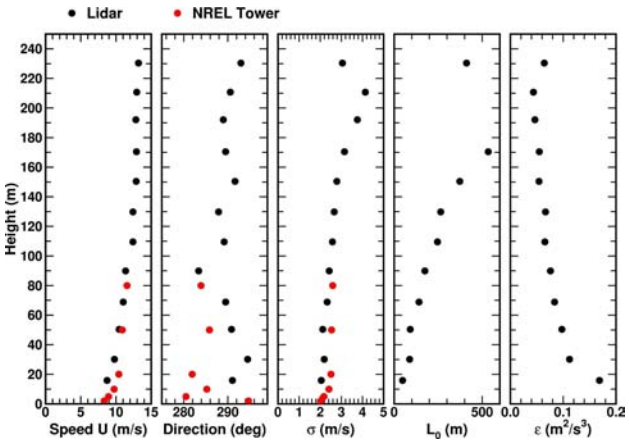
- Large fluctuations about the best fit wind speed
- 3D average increases the number of independent samples for more accurate statistics



Atmospheric Profiles

Frehlich and Kelley 2008

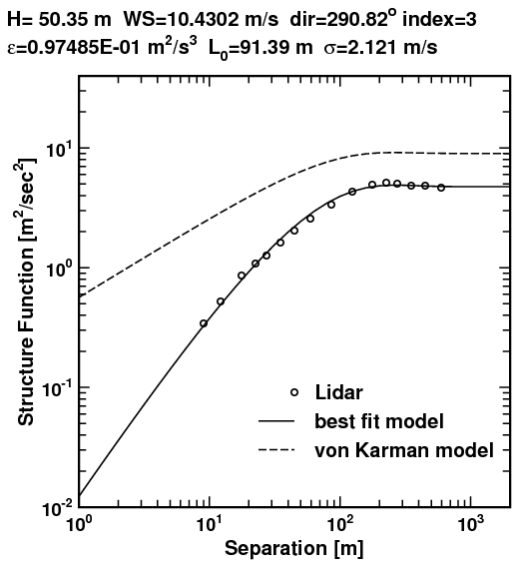
- Accurate profiles produced
- Most complete description of wind and turbulence available over turbine blade height
- High turbulence



Azimuth Structure Functions

Frehlich and Kelley 2008

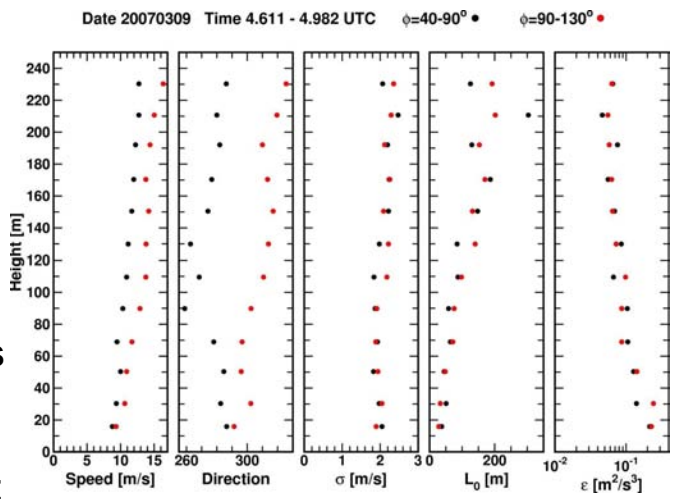
- Azimuth structure functions resolves turbulence scales
- Best fit model produces accurate estimates of the three turbulence statistics
- Profiles produced from 3D volume scan by binning data into height intervals



Profiles from Two Angular Sectors

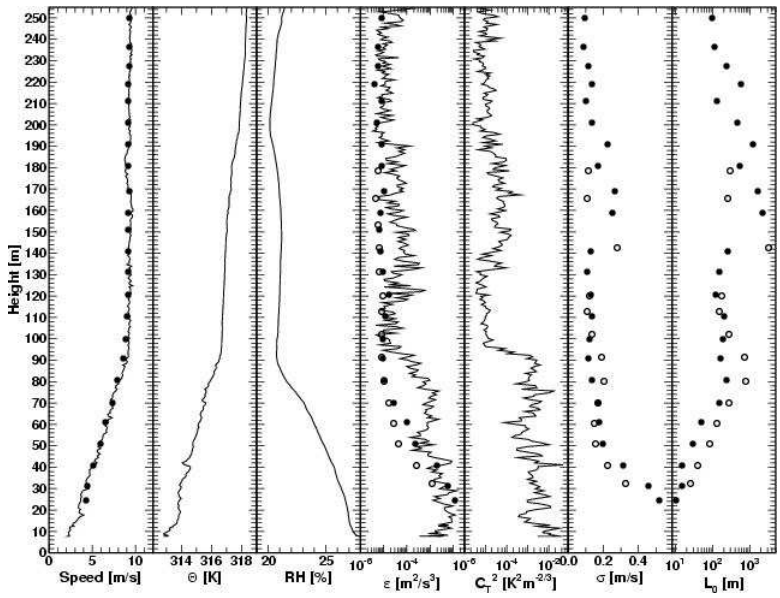
Frehlich and Kelley 2008

- Differences in wind speed and direction
- Turbulence profiles similar
- Implications for site resource assessment



Lidar and TLS Profiles

Frehlich et al. 2008; Frehlich 2008



Summary

- Doppler lidar has low bias and small random error
- Suitable for resource assessment and operations
  - Towers are expensive and limited in height coverage
  - Compact Doppler lidar can measure wind profile
  - Scanning Doppler lidar can monitor large areas
- Autonomous lidar (WindTracer)
  - Airports
  - Homeland security DC

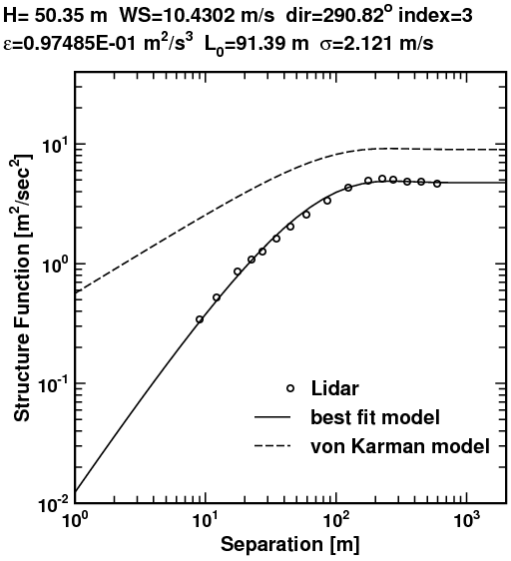
Future Work

- Optimize Lidar design, signal processing, and scanning patterns
- Extend spatial filter correction to two dimensions for faster scanning and larger maximum range
- Extend maximum measurement range to 30 or 40 km for improving short-term wind power forecasts (ramp events)
- More data required for wind energy applications

Azimuth Structure Functions

Frehlich and Kelley 2008

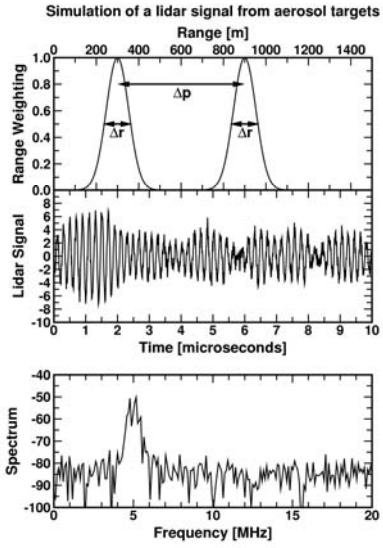
- Azimuth structure functions resolves turbulence scales
- Best fit model produces accurate estimates of the three turbulence statistics
- Profiles produced from 3D volume scan by binning data into height intervals



Doppler LIDAR Range Weighting

Frehlich 1997; Banakh and Smalikho 1997

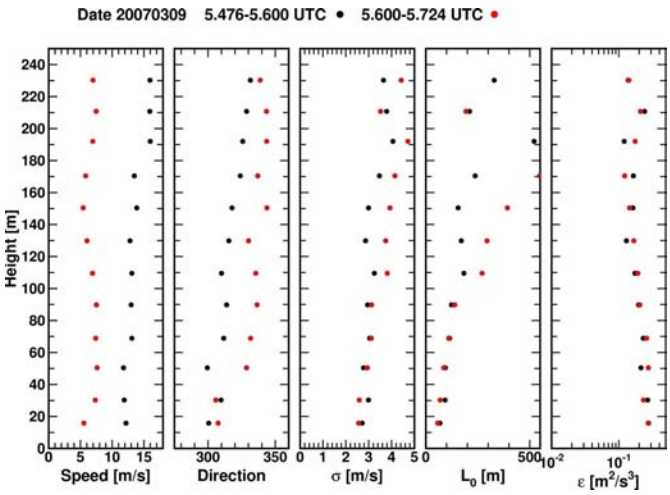
- Time of data maps to range (1 μs = 150 m)
- Pulsed lidar velocity measurements filter the random radial velocity $v_r(z)$
- Pulse width Δr
- Range gate length defined by processing interval Δp
- Spectral velocity estimate



Rapid Evolution in 7 Minutes

Frehlich and Kelley 2008

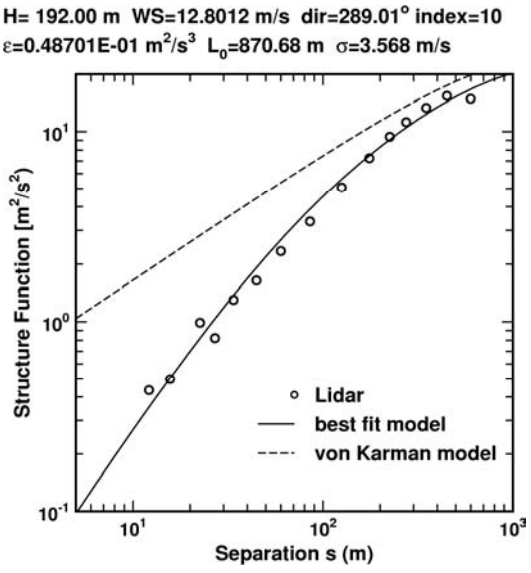
- Rapid change in wind speed
- Turbulence levels are not reduced with lower winds
- 3D scanning required for short time averages



Large Turbulent Length Scale

Frehlich and Kelley 2008

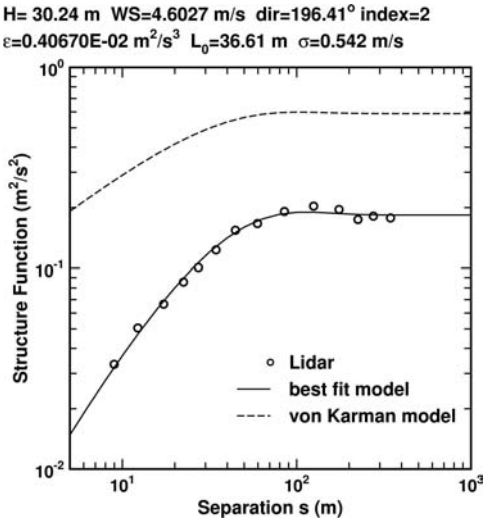
- Difficult to separate turbulence and larger scale processes
- Similar to free troposphere and boundary layer data
- Violates Cartesian approximation of the analysis at large lags
- Small scales are correct (ε)



Small Turbulent Length Scale

Frehlich and Kelley 2008

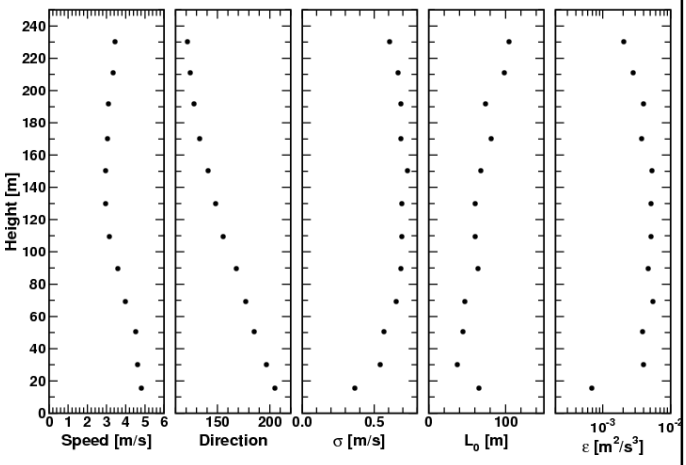
- Large corrections for spatial filtering
- Requires shorter lidar pulse and more accurate corrections
- Critical for lower altitudes



Directional Shear

Frehlich and Kelley 2008

- Large shear in wind direction
- Typically at night with light winds
- More data required for wind energy applications



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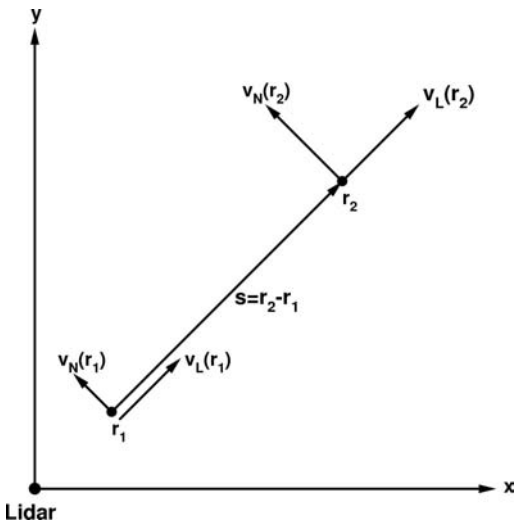
Statistics of Turbulence

- **Longitudinal velocity**
- **Transverse velocity**
- **Longitudinal structure function**

$$D_{LL}(s)=<[v_L(r_2)-v_L(r_1)]^2>$$

- **Transverse structure function**

$$D_{NN}(s)=<[v_N(r_2)-v_N(r_1)]^2>$$



Horizontal Isotropic Turbulence

Frehlich, Hannon, Henderson 1998; Frehlich et al. 2008

- **Universal description - longitudinal**

$$D_{LL}(s) = 2\,\sigma_u^2 \Lambda(s/L_{0u})$$

- **σ_u – longitudinal standard deviation**
- **L_{0u} – longitudinal outer scale**
- **$\Lambda(x)$ – universal function (von Karman)**
- **$s << L_{0u}$**

$$D_{LL}(s) = C_K\,\varepsilon_u^{2/3}\,s^{2/3} \qquad C_K \sim 2.0$$

- **ε_u = energy dissipation rate**

Horizontal Isotropic Turbulence

Frehlich et al. 2006, 2008

- Universal description - transverse

$$D_{NN}(s) = 2\,\sigma_v^2 \Lambda(s/L_{0v})$$

- σ_v – transverse standard deviation
- L_{0v} – transverse outer scale
- $\Lambda(x)$ – universal function (von Karman)
- $s << L_{0v}$

$$D_{NN}(s) = C_J\,\varepsilon_v^{2/3}\,s^{2/3} \qquad C_J \sim 2.67$$

- ε_v = energy dissipation rate

Lidar Structure Function (Radial)

Frehlich, Hannon, Henderson 1998; Frehlich et al. 2006, 2008; Frehlich and Cornman 2002

- Corrected longitudinal structure function

$$D_{wgt}(s) = D_{raw}(s) - 2\,\sigma_e^2(s)$$

- $D_{raw}(s)$ – raw structure function
- $\sigma_e^2(s)$ – correction for estimation error
- Theoretical relation ($\Delta h << \Delta p$)

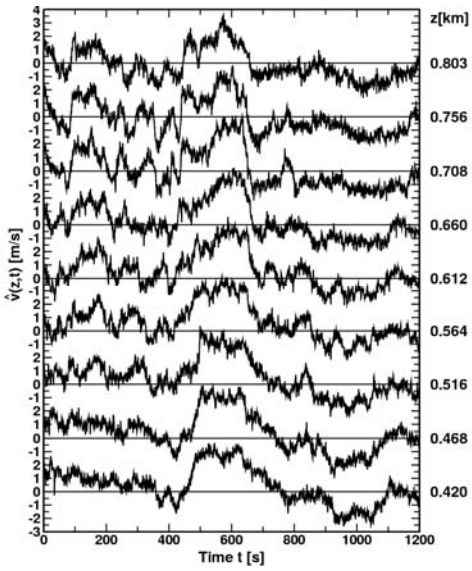
$$D_{wgt}(s) = 2\,\sigma_u^2\,G(s, L_{0u}, \Delta p, \Delta r)$$

- Best-fit to data produces estimates of $\sigma_u, L_{0u}, \varepsilon_u$

Non-Scanning Lidar Data

Frehlich, Hannon, Henderson 1998

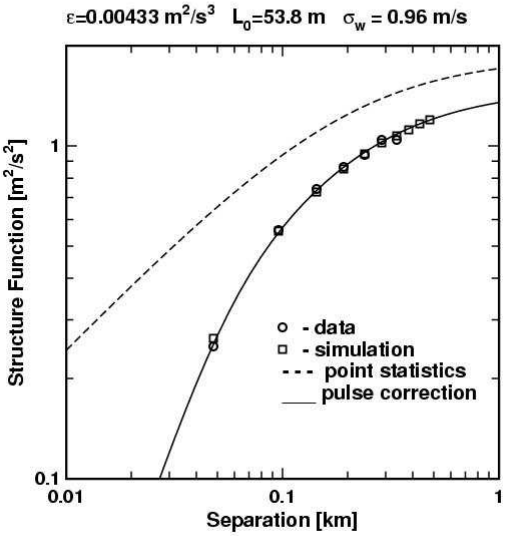
- Vertically pointed beam
- Time series of velocity for various altitudes z
- High spatial and temporal resolution
- Resolves turbulence



Turbulence Statistics

Frehlich, Hannon, Henderson 1998

- Calculate corrected structure function
- Determine best-fit to theoretical model
- Best-fit parameters are estimates of turbulence statistics ε_u, L_{0u}, σ_u



Lidar Structure Function (Azimuth)

Frehlich et al. 2006, 2008; Frehlich and Kelley 2008

- **Corrected azimuth structure function**

$$D_{wgt}(s) = D_{raw}(s) - 2\,\sigma_e^2(s)$$

- $D_{raw}(s)$ – raw structure function
- $\sigma_e^2(s)$ – correction for estimation error
- **Theoretical relation ($\Delta h << \Delta p$)**

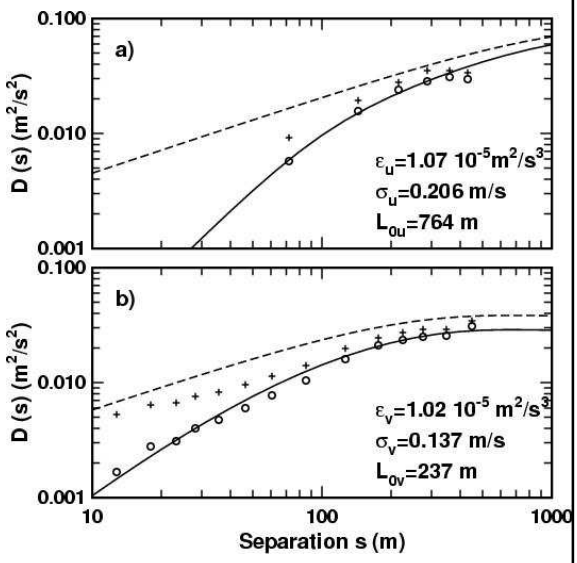
$$D_{wgt}(s) = 2\,\sigma_v^2\, G_\varphi(s, L_{0v}, \Delta p, \Delta r)$$

- **Best-fit to data produces estimates of $\sigma_v, L_{0v}, \varepsilon_v$**

Turbulence Estimates H=80 m

Frehlich 2008; Frehlich et al. 2008

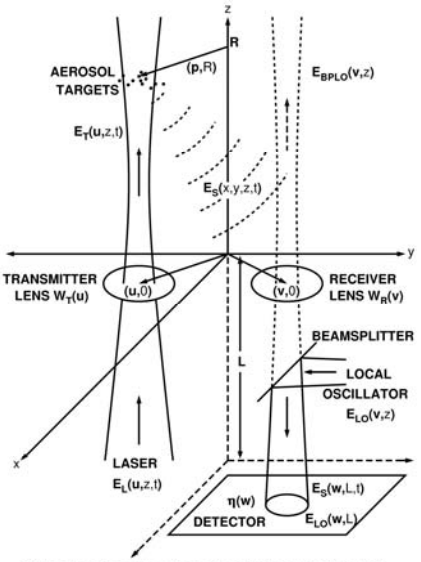
- **Best fit for noise corrected structure function (o)**
- **Raw structure functions (+)**
- **Radial structure function (a) has small elevation angles (<= 4º)**
- **Structure function in azimuth b)**
- **Best agreement in ε_u and ε_v (isotropy)**



Optical Design Issues

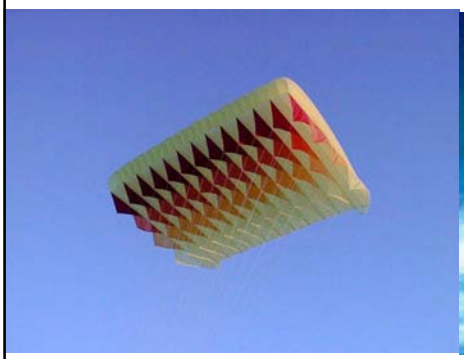
Frehlich and Kavaya 1991

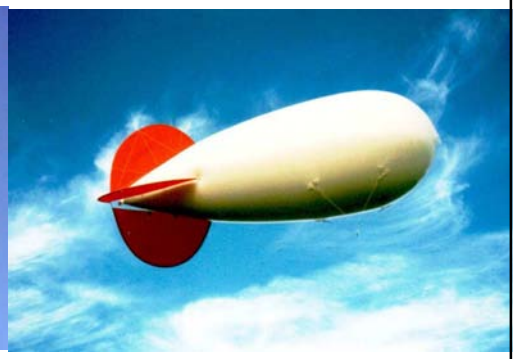
- Frequency stable reference laser (Local Oscillator- LO)
- High quality transmit and LO laser field
- Small collimated transmit beam (5-30 cm diameter)
- Careful beam alignment (μ radian)
- High quality laser pulse



Schematic of a Coherent Doppler Lidar

CIRES Tethered Lifting System (TLS): Hi-Tech Kites or Aerodynamic Blimps for Verification Profiles





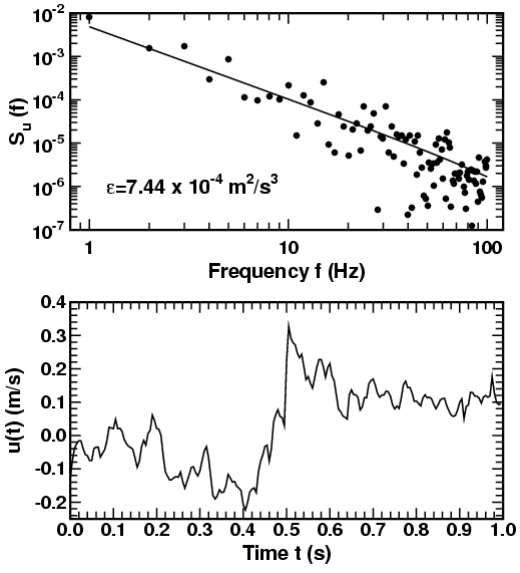
High Resolution Profiles from TLS Data

- TLS instrumentation used as “truth” for turbulence profiles
- Hot-wire sensor for small scale velocity
- Cold-wire sensor for small scale temperature

Velocity Turbulence

Frehlich et al. 2003

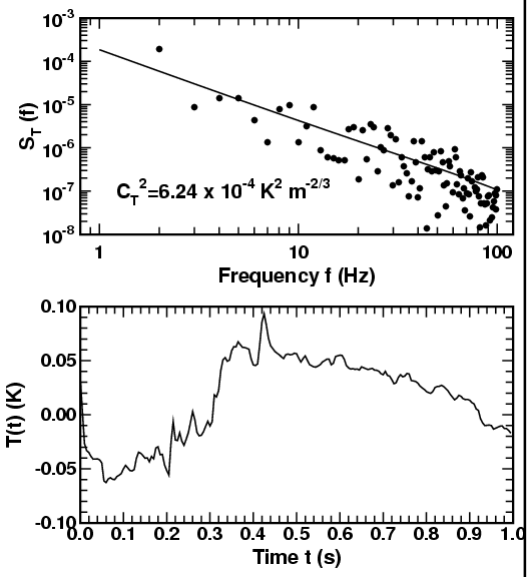
- Along-stream velocity u(t)
- Spectrum $S_u(f)$
- Taylors frozen hypothesis
- Energy dissipation rate ε
- 15% random error



Temperature Turbulence

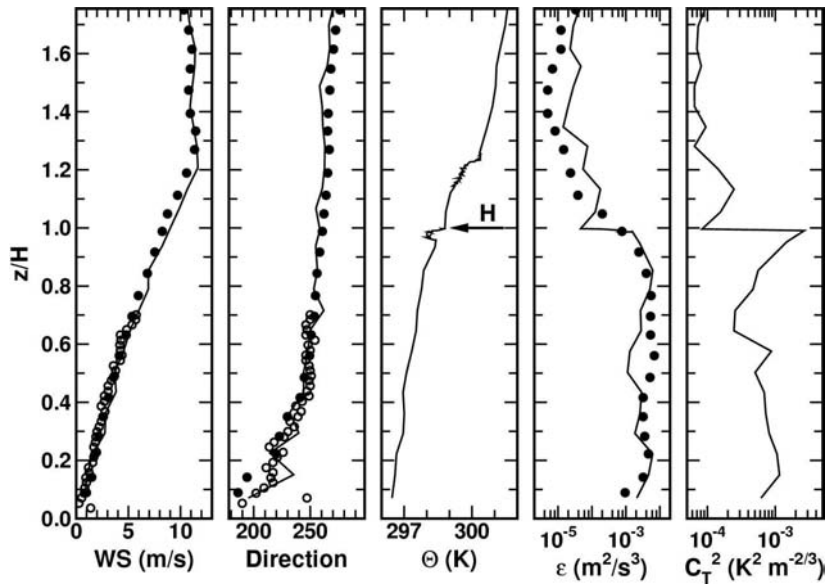
Frehlich et al. 2003

- Along-stream temperature T(t)
- Spectrum $S_T(f)$
- Taylors frozen hypothesis
- Temperature structure constant C_T^2
- 15% random error



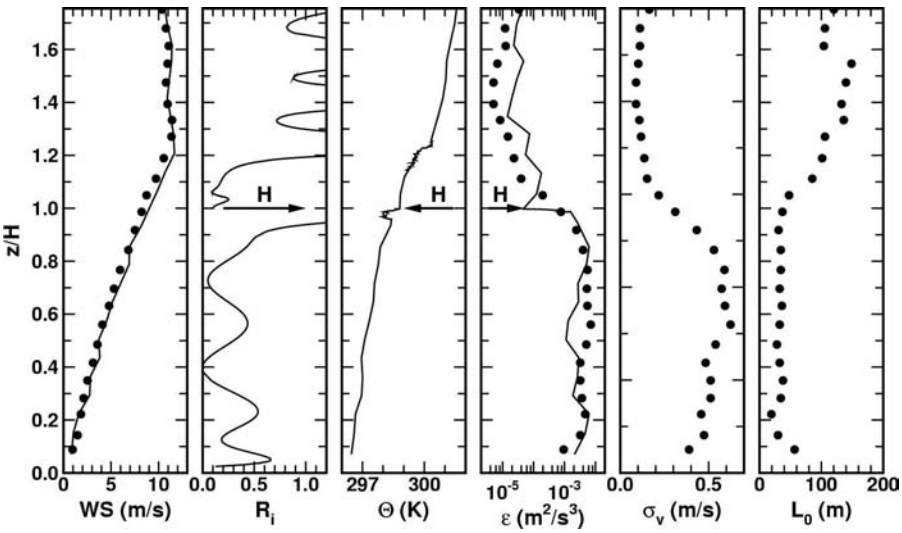
LIDAR (●), SODAR (o) and TLS

Frehlich et al. 2006



LIDAR (●) and TLS

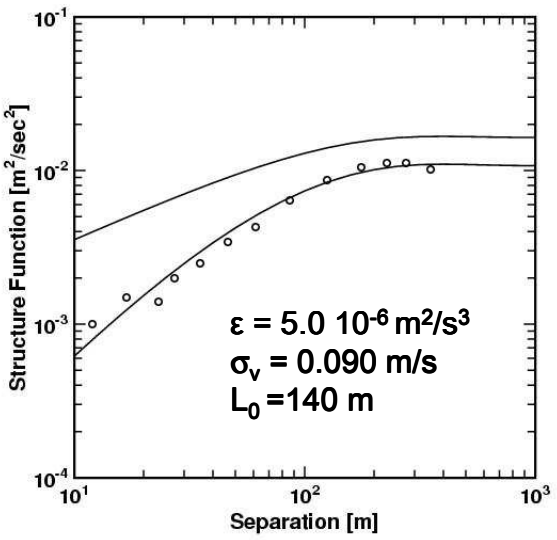
Frehlich et al. 2006



Low Turbulence Data

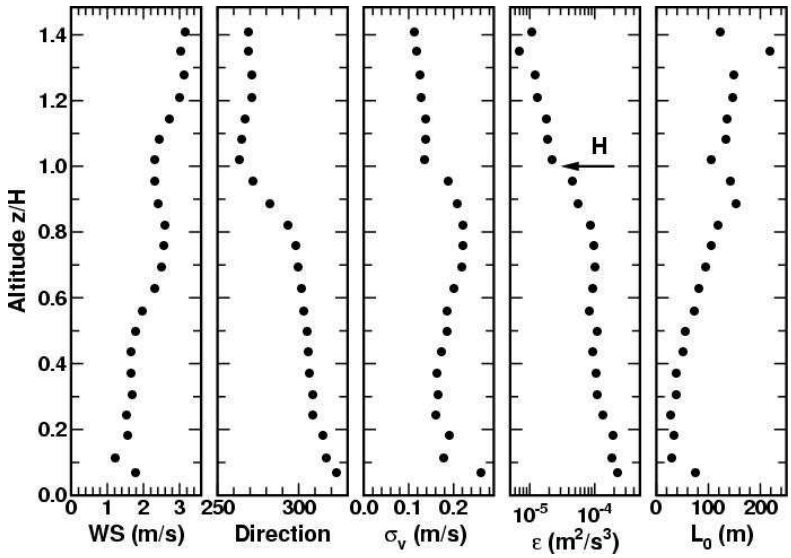
Frehlich et al. 2006

- **Accurate corrections for pulse filtering required**
- **Correct turbulence model for spatial statistics**



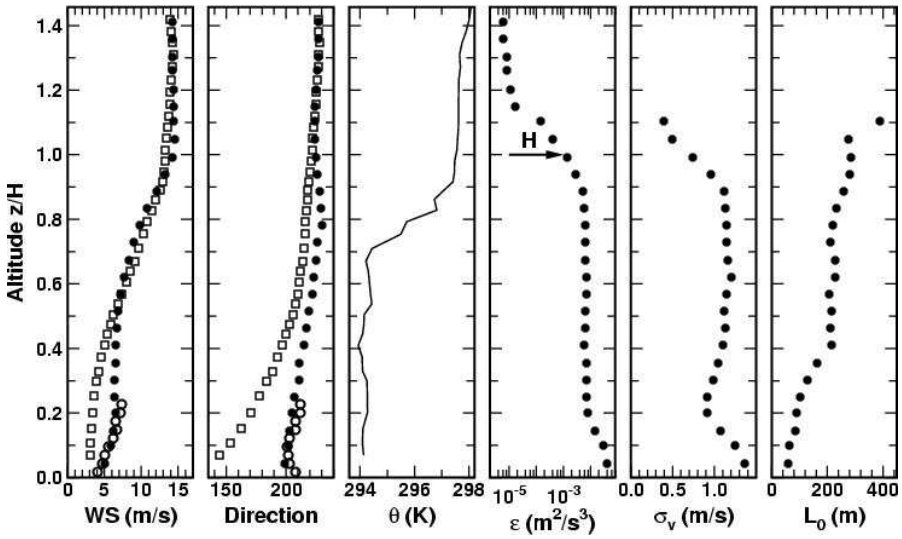
Low Turbulence Conditions

Frehlich et al. 2006



Convection

Frehlich et al. 2006



Lafayette Campaign Frehlich et al. 2008

Triton Sonic Profiler

Fleet Overview and Performance

IEA Topical Expert Meeting on
Remote Wind Speed Sensing Techniques
Using Sodar and Lidar

Niels LaWhite
October 15-16, 2009

SECONDWIND

Outline

- Specifications
- Defining Characteristics
- Fleet Performance Overview
- Validation Data
- Current Research

SECONDWIND

Specifications

- Monostatic, 3-beam, phased array sodar, 4 – 4.5KHz.
- Measurement heights:
  - 40, 50, 60, 80, 100, 120, 140, 160, 180, 200m
- Satellite communications
- Self powered:
  - » 7 Watt Load, 170 Watt Solar
  - » 2 Week Battery Life
- Weather resistant
- Heater option for snow melting

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Defining Characteristics

- Designed for Resource Assessment
  - » Low Power
  - » Autonomous Operation
- Array Performance
  - » Hex Packing, Reduced Side Lobes
  - » Symmetrical Beam Pattern
- Ease of Deployment
  - » Compact, Rugged
  - » Orientation (Tilt) correction
  - » GPS Location/Time Stamp
- Real-Time Data and Performance Statistics
- Remote Administration and Monitoring

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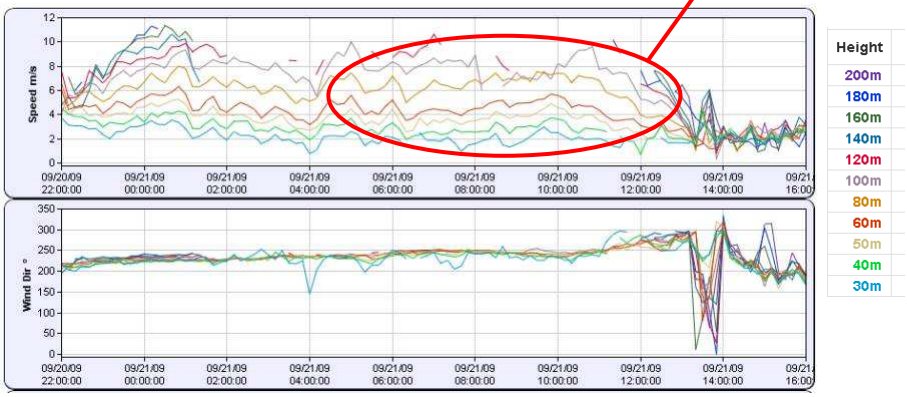
SkyServe

- Web Based Hosting Standard For All Tritons
- ~Real-Time Data Stream with Graphical UI



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Fleet Performance Overview

- 85 Commercial Units Deployed in 17 Countries
- 400K Hours (~45 Years) of Accumulated Data
- 98% Average Uptime (Rising)
- Average Data Availability (Percent Valid Data) Decreases with Height
  - » Main Focus: Maximize Availability at 80 m and Below
  - » Secondary: Exceed 80% Availability at 120 m

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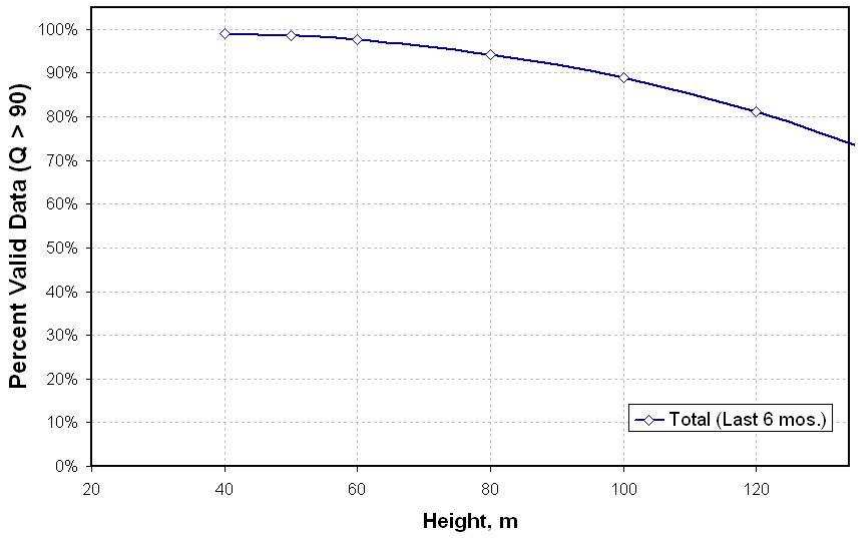
Average Data Recovery



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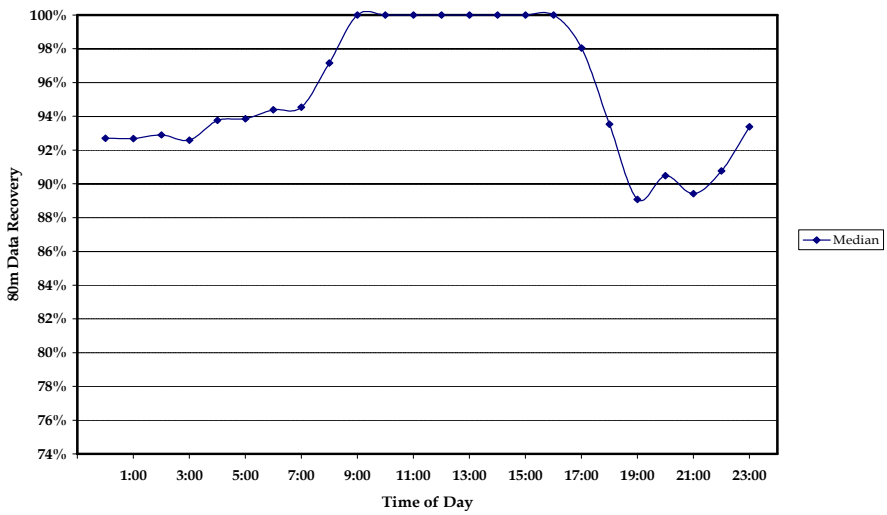
Average 80 m Diurnal Performance Trend



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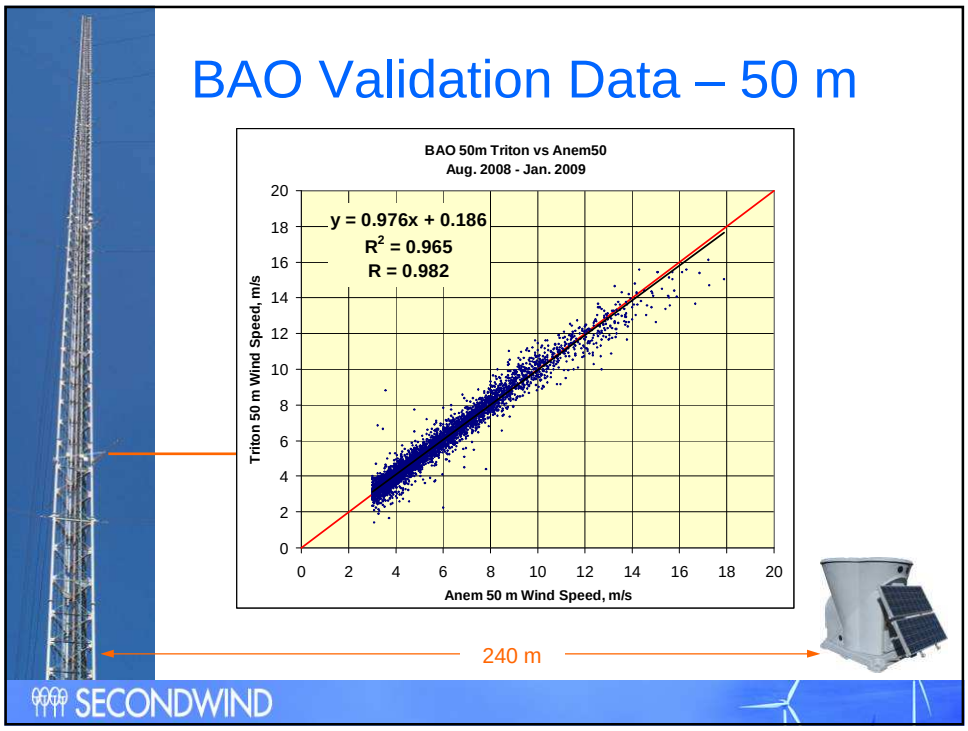
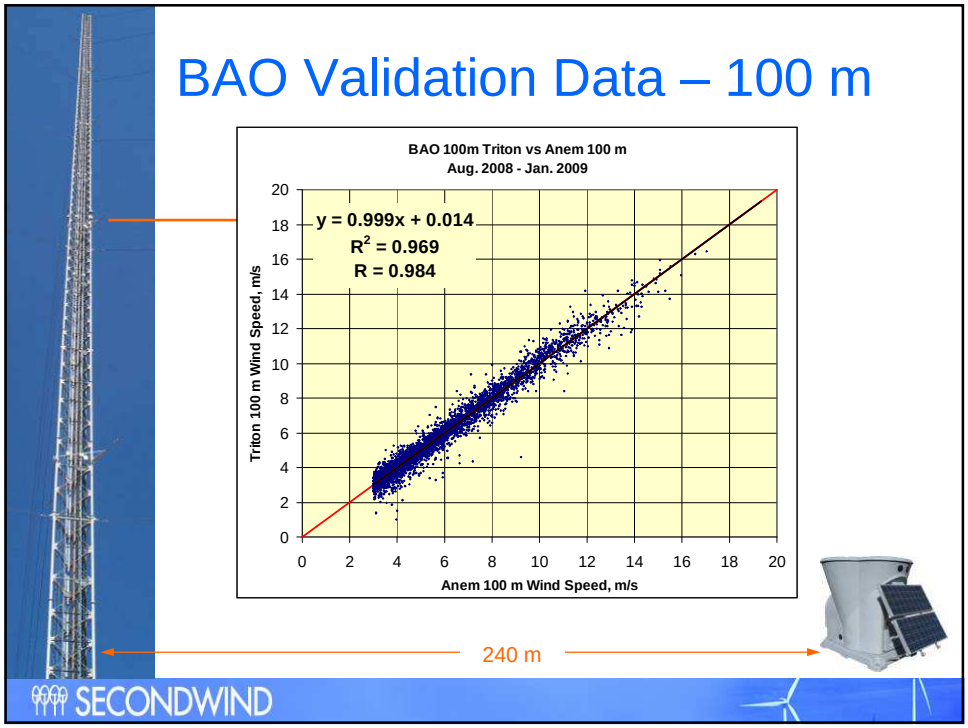
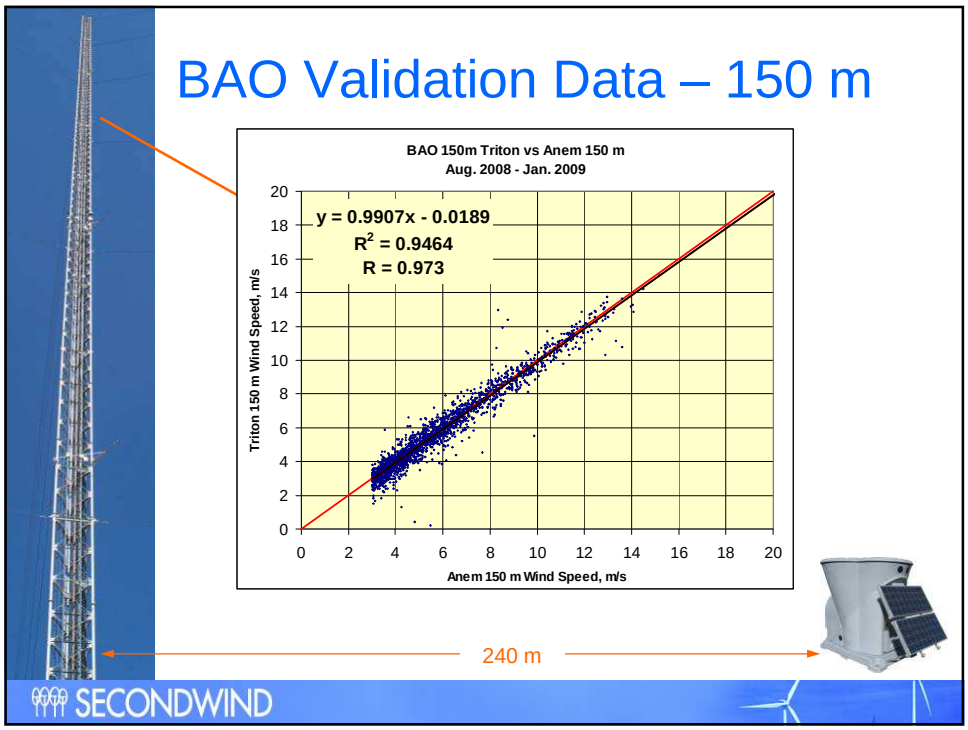
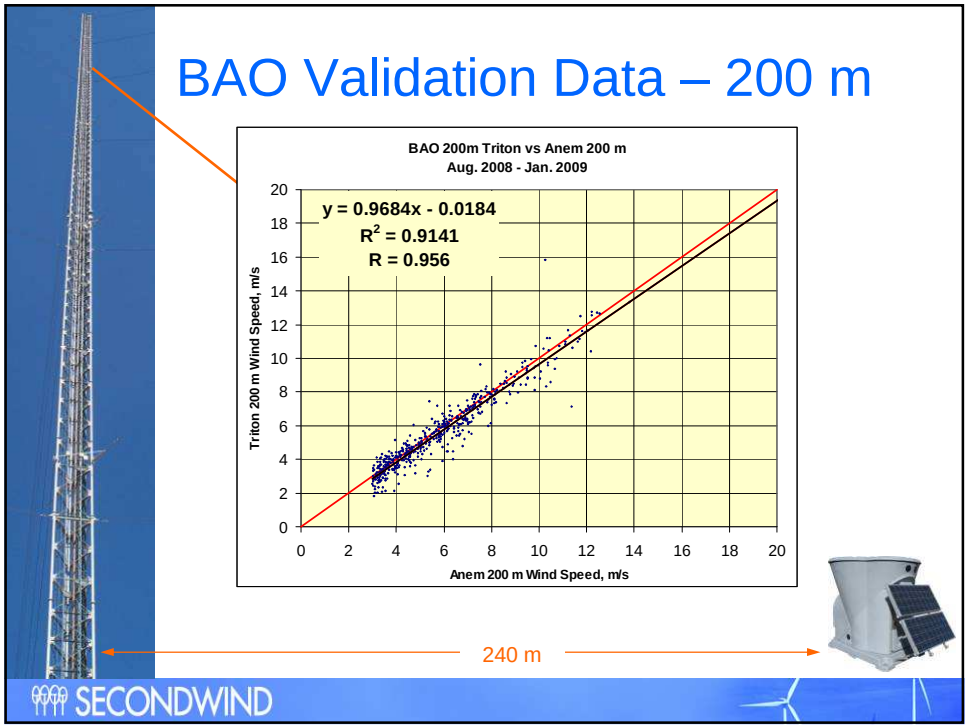
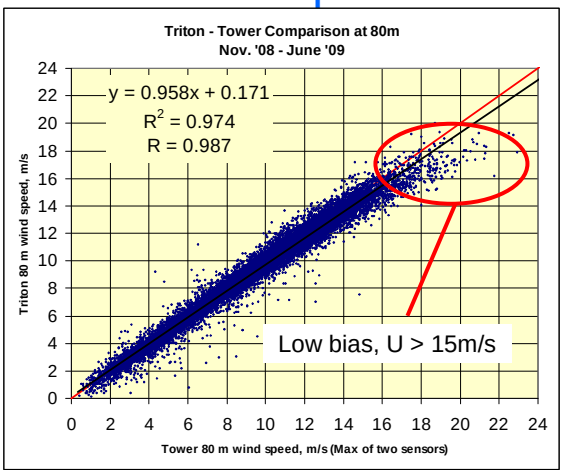

BAO Validation Data – 50 m
BAO 50m Triton vs Anem50
Aug. 2008 - Jan. 2009
y = 0.976x + 0.186
R² = 0.965
R = 0.982
Triton 50 m Wind Speed, m/s
Anem 50 m Wind Speed, m/s
0 2 4 6 8 10 12 14 16 18 20
240 m
SECONDWIND


BAO Validation Data – 100 m
BAO 100m Triton vs Anem 100 m
Aug. 2008 - Jan. 2009
y = 0.999x + 0.014
R² = 0.969
R = 0.984
Triton 100 m Wind Speed, m/s
Anem 100 m Wind Speed, m/s
0 2 4 6 8 10 12 14 16 18 20
240 m
SECONDWIND


BAO Validation Data – 150 m
BAO 150m Triton vs Anem 150 m
Aug. 2008 - Jan. 2009
y = 0.9907x - 0.0189
R2 = 0.9464
R = 0.973
Triton 150 m Wind Speed, m/s
Anem 150 m Wind Speed, m/s
0 2 4 6 8 10 12 14 16 18 20
240 m
SECONDWIND

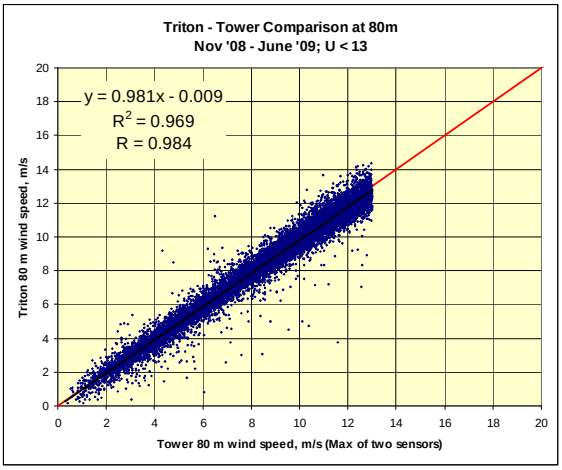

BAO Validation Data – 200 m
BAO 200m Triton vs Anem 200 m
Aug. 2008 - Jan. 2009
y = 0.9684x - 0.0184
R2 = 0.9141
R = 0.956
Triton 200 m Wind Speed, m/s
Anem 200 m Wind Speed, m/s
0 2 4 6 8 10 12 14 16 18 20
240 m
SECONDWIND

IEC Compliant Tower 80m Comparison



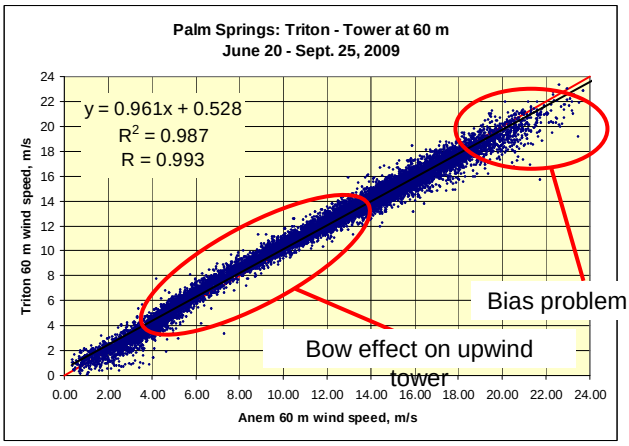
SECONDWIND

80m Comparison, U<13 m/s



SECONDWIND

High Wind Performance



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Current Research

- R&D Triton Fleet – 7 Units
  - » Co-Located, Interleaving Studies at Two Sites
  - » Two Units for Industry Collaboration
  - » One Heater Unit for Study - Awaiting Snow
- New Features and Enhancements
  - » Self Test
  - » Rain Filter
  - » Extended Pulse Length
- Under Investigation
  - » Atmospheric Absorption vs. Temperature Profiles
  - » Turbulence Validation
  - » Performance in Complex Terrain

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Thank You

- Thanks to Dan Wolfe, NOAA for use of the BAO Tower
- For more information, contact **niels@secondwind.com**

SECONDWIND

IEA Topical Meeting: Remote Wind Speed Sensing Techniques using Sodar and Lidar
NREL - Boulder, Colorado – October 15-16, 2009

AWS Truewind

Multi-technology Remote Wind Speed Sensing Evaluation: Initial Lidar Results

Matthew Filippelli – AWS Truewind
Dr. Kathleen Moore – Integrated Environmental Data

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AWS Truewind

Discussion Outline

- Overview of AWS Truewind
- Summary of Recent Remote Sensing Research
- Presentation of Initial Lidar Results
- Practical and Data Performance Discussion
- Current and Future Lidar Work

AWS Truewind

Integrated Services Supporting the Complete Project Lifecycle

Resource Modeling → Energy Assessment → Project Engineering → Due Diligence → Performance Evaluation → Forecasting

- Industry Leader & Consultant for 30,000+ MW
- Project roles in over 60 countries
- Established in 1983; 100+ employees

Headquarters: Albany, NY
Southwest Office: Austin, TX

Joint Venture Partner: Barcelona, Spain

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Remote Sensing

Extensive experience integrating remote sensing into comprehensive site assessments

Sodar Experience:
- Long time proponent of sodar for resource assessment
- Evaluation of 200+ sodar deployments across North America
- 8+ years of wind energy application experience
- 3 AWST owned units; support of numerous client-owned units
- On-, near- and offshore operational experience

Lidar Experience:
- Proponent of lidar for on- and offshore resource assessment
- Growing experience with multiple deployments across the US
- Experience with 3 commercially available models
- Several planned collaborative and evaluation efforts for remainder of 2009 and 2010

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AWS Truewind Research

Purpose: assess the potential value of sodar and lidar in resource and operational assessment

- While these devices can provide valuable measurement of the 3D flow field across a turbine's rotor plane, their acceptance has been limited by a perceived lack of performance validation
- Advancement of sodar and lidar acceptance – conceivably to the point of bankable stand-alone use – requires additional performance studies and an agreed-upon framework of requirements
- This work addresses these needs through robust multi-unit field studies

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AWS Truewind Research

This study presents the initial results of multi-unit remote sensing deployments across North America, with a focus on lidar performance

- The measurements cover a variety of operating environments and terrain conditions
- Remote sensing data sets are compared with measurements from existing meteorological masts
- The performance of both commercial and near-production lidar units are evaluated and compared with standard wind resource assessment equipment
- Qualitative and quantitative assessments of performance are presented and potential sources of error and bias are identified

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Objectives

The focus areas of this presentation are:

- Inter-comparison of field data and practical experiences from multiple Lidar and Sodar units at established wind monitoring sites
- Qualitative description and Quantitative estimates of potential sources of error and biases
- Enhance the discussion and experience base for advancing the acceptance of Sodar and Lidar in wind resource and project energy assessment

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Approach

The field evaluation was conducted in two phases:

- Duration of each phase: 4 to 6 weeks
- Concurrent data were collected at two active wind resource assessment sites by multiple remote sensing devices
- Pre-existing meteorological towers on both sites for reference
  - Equipped with industry-standard cup anemometers.
  - Each tower was serviced prior to testing the remote sensing units, and the primary anemometers replaced with calibrated sensors.
- Practical performance of the units was evaluated
- Output from each of the devices was compared with the tower data
  - Time series
  - Wind speed correlations
  - Wind rose output.

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Approach

Several models of commercially available and prototype remote sensing devices were examined.

- Lidar devices:
  - Natural Power ZephIR
  - Leosphere / NRG Windcube
  - Catch the Wind Vindicator
- Sodar devices:
  - ART VT-1
  - Scintec SFAS

The anemometers employed for primary comparison were calibrated NRG #40's.

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Instrumentation - Lidars

Leosphere / NRG Windcube (left) and Natural Power ZephIR lidars, commercial units

Fixed-focus Catch the Wind Vindicator lidar, prototype

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Instrumentation - Sodars

ART VT-1 trailerized sodar, commercial unit

Scintec SFAS flat array sodar, commercial unit

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Instrumentation – Existing Met Tower

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Phase 1 Setup

Phase 1 was conducted at an active upstate New York wind development site from early-December, 2008 through mid-January, 2009.

- **Reference tower**:
  - 50 m NRG tube, 3 monitoring levels (30, 40, & 49 m AGL)
  - Redundant NRG #40 at each level; Primary anemometers not affected by vibratory degradation
- **Test Equipment**:
  - ZephIR 0148, Windcube 0020, Vindicator & VT-1 108
- **Site:** Rolling Farmland; N to S slope on site; ZephIR and Windcube sited about 125 m NNE of tower, ART sited about 120 m NNW; Vindicator sited about 60 m WNW

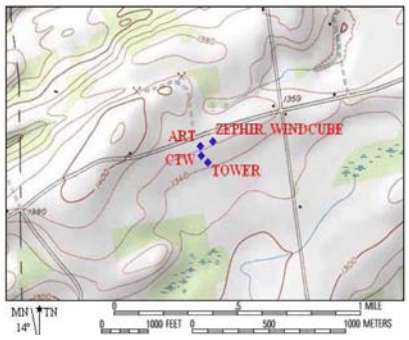

Figure 5: Topographical layout of Phase 1 site, upstate NY

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Phase 1 Conditions

A severe ice storm occurred during the Phase 1 evaluation.

- Significant ice accumulation on the equipment
- Loss of grid power at the monitoring site for several days
- Screening necessary to treat suspect measurements during data analysis

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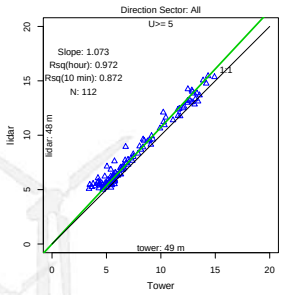
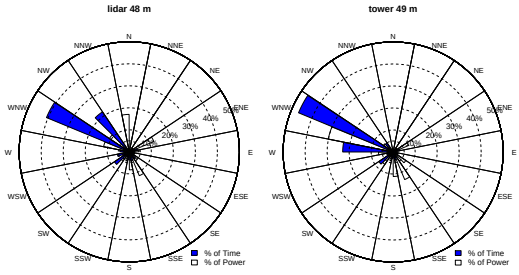
Phase 1 Results - ZephIR



Speed Correlation at with tower at 49 m



Wind Rose comparison with tower at 49 m

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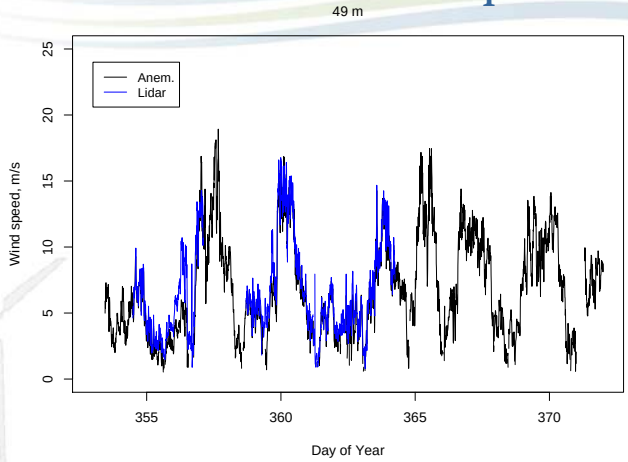
Phase 1 Results - ZephIR



Time Series of 10-min Speed measurements – Tower and ZephIR at 49 m

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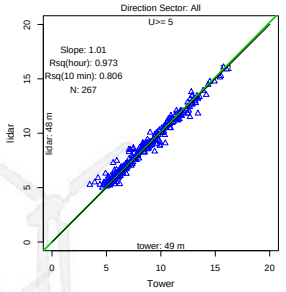
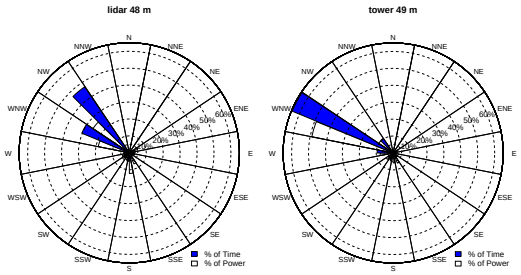
Phase 1 Results - Windcube



Speed Correlation with tower at 49 m



Wind Rose comparison with tower at 49 m

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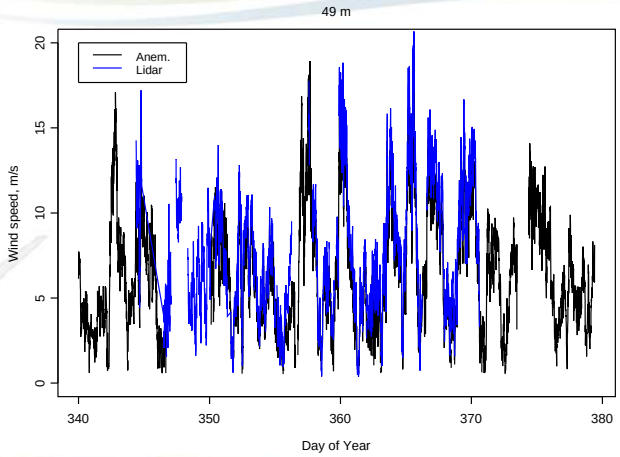
Phase 1 Results - Windcube



Time Series of 10-min Speed measurements – Tower and Windcube at 49 m

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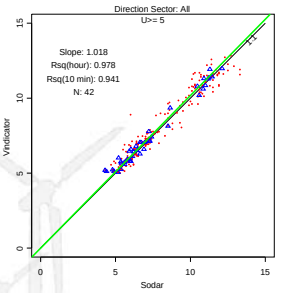
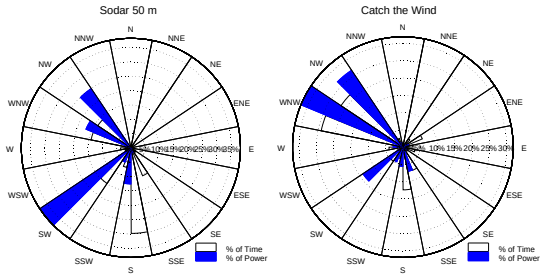
Phase 1 Results – Vindicator



Speed Correlation with the ART Sodar at 50 m



Wind Rose Comparison with ART Sodar at 50 m

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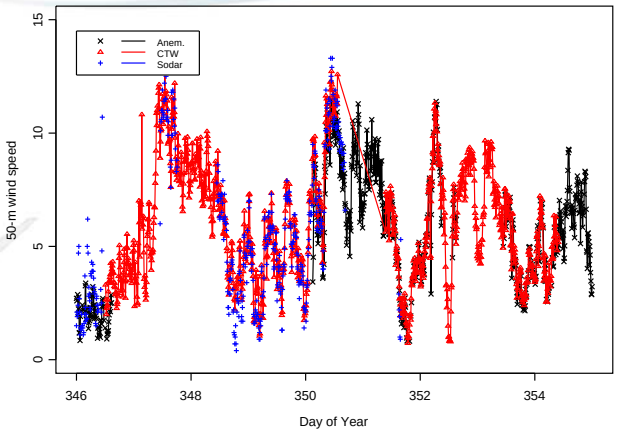
Phase 1 Results – Time Series



Time Series of 10-min Lidar, ART Sodar and Tower Measurements at 50 and 49 m, respectively

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Phase 2 Setup

Phase 2 was conducted at a wind resource research station in northern Iowa from mid-February through late-March, 2009.

- **Reference tower**:
  - 200 m lattice comm. tower; 4 monitoring levels (53, 102, 157, & 193 m AGL)
  - Calibrated NRG #40 primary sensors (post-December 2008 units); Calibrated NRG IceFree III redundant sensors
- **Equipment**:
- ZephIR 0145, Windcube 0020, & SFAS 0021
- **Site:** Nearly flat farm land, no crops; All devices located 140 m SW from tower; No elevation difference

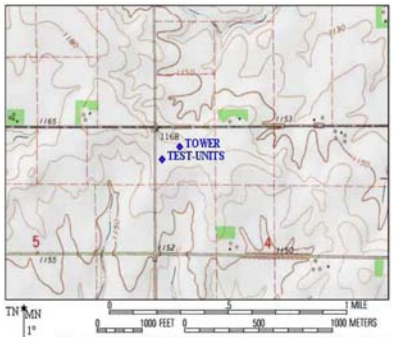

Figure 6: Topographical layout of Phase 2 site, northern Iowa

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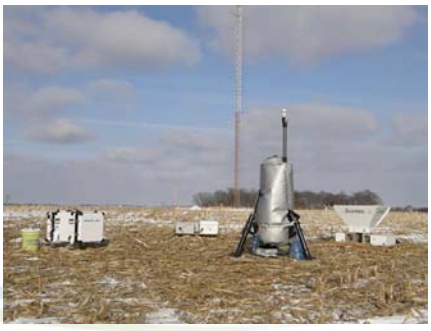
Phase 2 Conditions

- Phase 2 provided an excellent opportunity to correlate the remote sensing measurements with anemometry at heights well above typical met masts. Advantages included:
  - Tall reference mast with sensors at approximately 50, 100, 150 and 200 m AGL
  - Relatively flat terrain and minimal surface roughness



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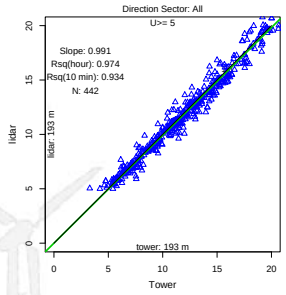
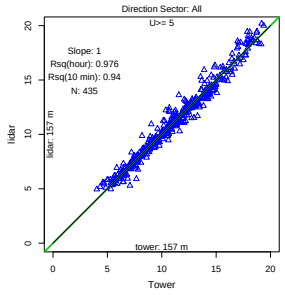
Phase 2 Results - ZephIR



Speed Correlation at 193 m



Speed Correlation at 157 m

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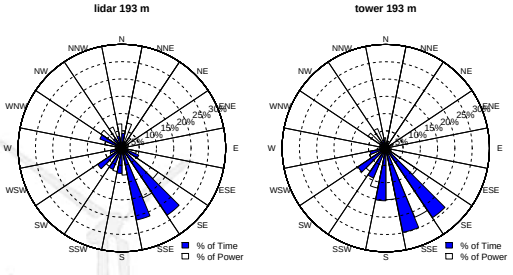
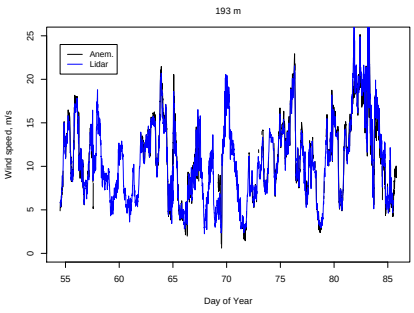
Phase 2 Results - ZephIR



Wind Rose Comparison at 193 m



Time Series of 10-min wind speed Data at 193 m

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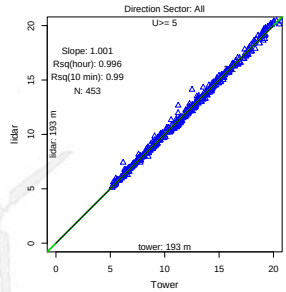
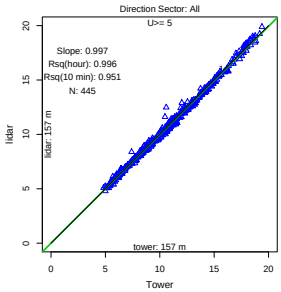
Phase 2 Results - Windcube



Speed Correlation at 193 m



Speed Correlation at 157 m

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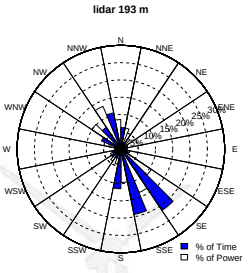
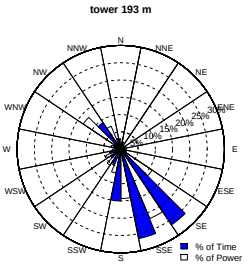
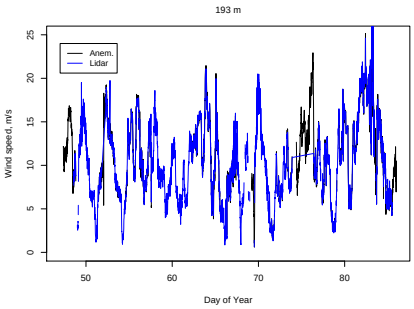
Phase 2 Results - Windcube





Wind Rose Comparison at 193 m



Time Series of 10-min wind speed Data at 193 m

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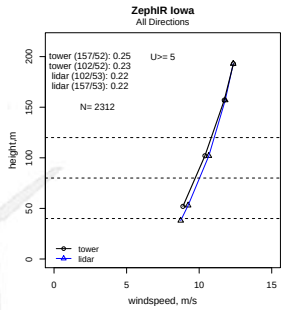
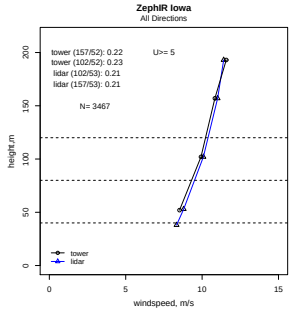
Phase 2 Results – ZephIR Profile Comparison



Wind Shear Profile Comparison vs. NRG #40



Wind Shear Profile Comparison – NRG IceFree III

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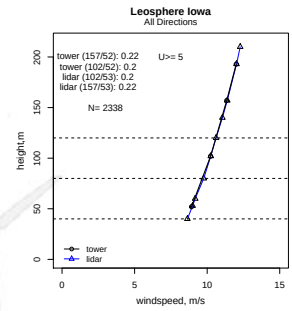
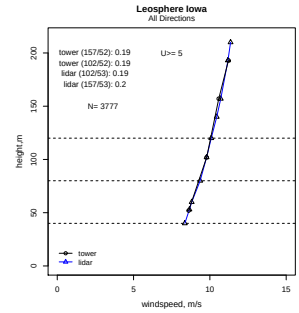
Phase 2 Results – Windcube Profile Comparison



Wind Shear Profile Comparison – NRG #40



Wind Shear Profile Comparison – NRG IceFree III

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Performance Discussion

- Brief observations on each lidar unit's performance in Phases 1 and 2 are presented below.
  - ZephIR unit 145 demonstrated good correlations with high-elevation reference anemometry in Phase 2. Equipment and environmental issues in Phase 1 limited measurements for comparison, but data recovery in Phase two was near 100%.
  - Weather and equipment issues affected portions of Windcube's Phase 1 data record. In spite of this, overall performance of unit 0020 was generally good at both locations.
  - The Vindicator ® LWS was the only device to operate continuously throughout the Phase 1 ice storm. However, other data gaps severely limited comparison opportunities with the tower. Overall performance against other remote sensing devices was good.

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Current Work

- Execution of lidar validation and monitoring campaigns private clients
- Building and proposing on- and offshore lidar monitoring and validation programs
- Interaction with several manufacturers on product development and collaborative evaluations

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Future Work

- Continuing work on this topic includes the following efforts to reach the project's overall objectives:
  - Additional detailed analysis of full field data sets from Phases 1 and 2. Efforts will include inter-comparison of remote sensing data sets and examination of weather- and terrain-induced effects.
  - Quantitative estimates of potential sources of error and biases for each of the technologies tested.
  - Drafting a framework for advancing the acceptance of Sodar and Lidar in wind resource and project energy assessment

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Acknowledgements

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- The Natural Power Consultants, Ltd.
- Leosphere
- NRG Systems, Inc.
- Catch the Wind, Inc.
- Iowa Energy Center
- Sustainable Energy Developments, Inc.

Research efforts and analysis led by Matthew V. Filippelli, Senior Engineer of AWS Truewind and Dr. Kathleen Moore of Integrated Environmental Data

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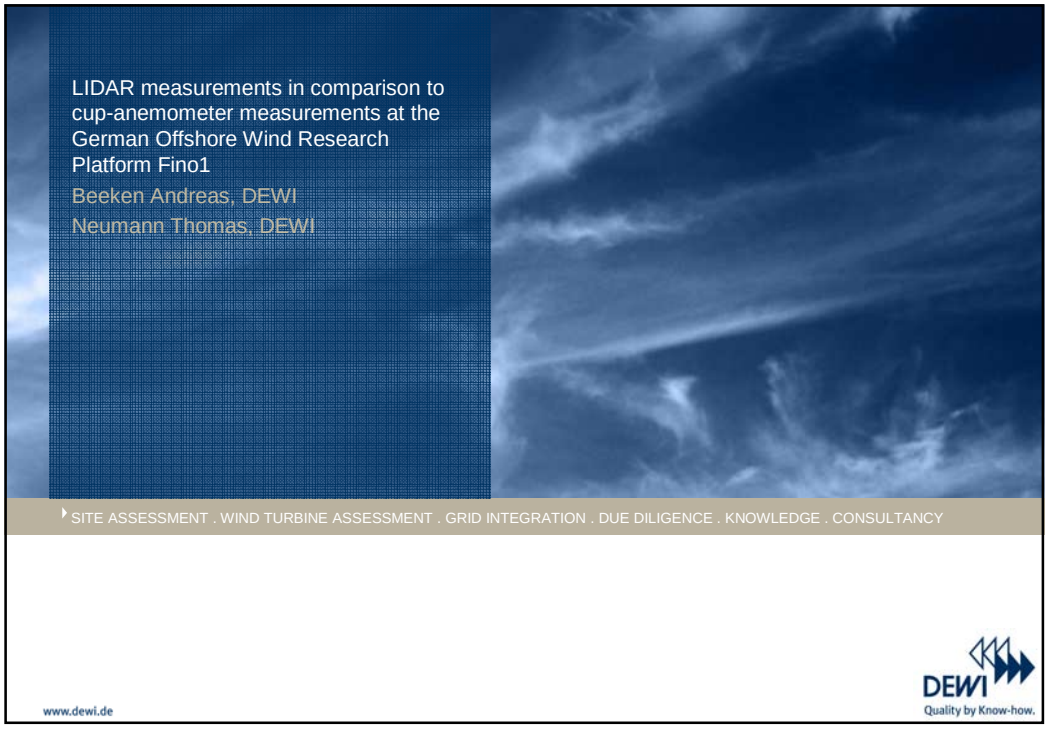
LIDAR measurements in comparison to cup-anemometer measurements at the German Offshore Wind Research Platform Fino1
Beeken Andreas, DEWI
Neumann Thomas, DEWI
SITE ASSESSMENT . WIND TURBINE ASSESSMENT . GRID INTEGRATION . DUE DILIGENCE . KNOWLEDGE . CONSULTANCY
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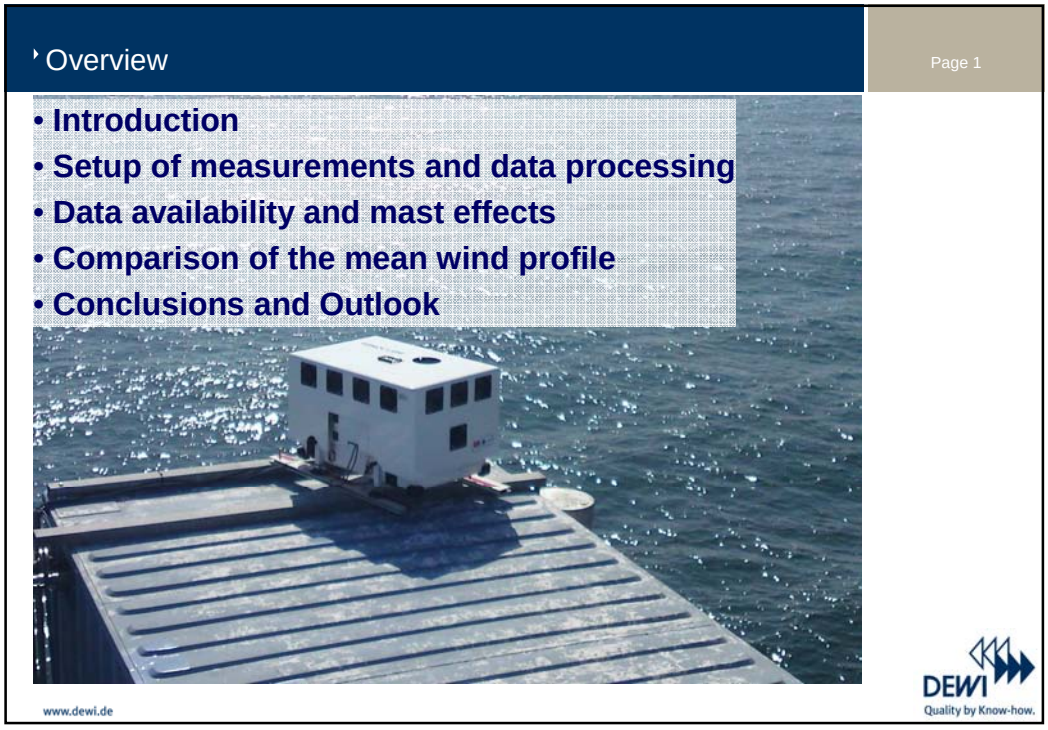
Overview
Page 1
• Introduction
• Setup of measurements and data processing
• Data availability and mast effects
• Comparison of the mean wind profile
• Conclusions and Outlook
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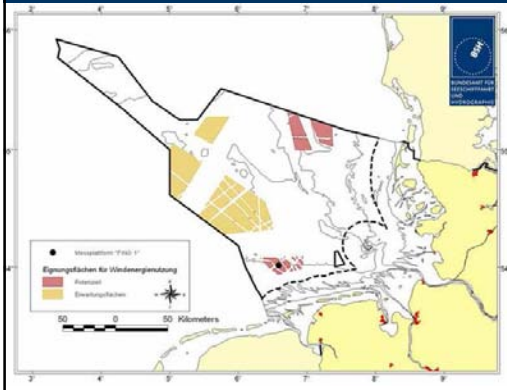
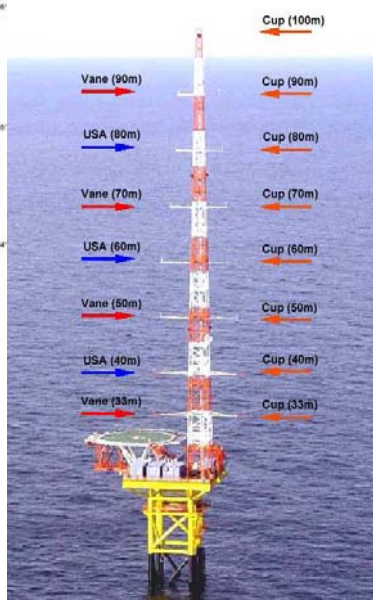
Fino1- Platform





- Meteorological measurements
- Hydrological measurements
- Structural and dynamic measurements
- Ecological observations

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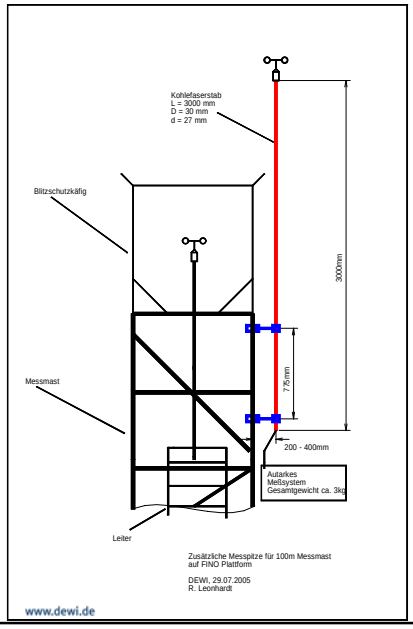
DEWI Quality by Know-how.

Lightning Protection Cage at the top of Fino1

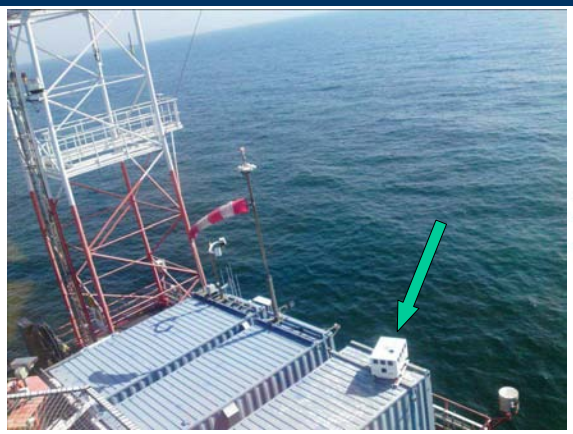


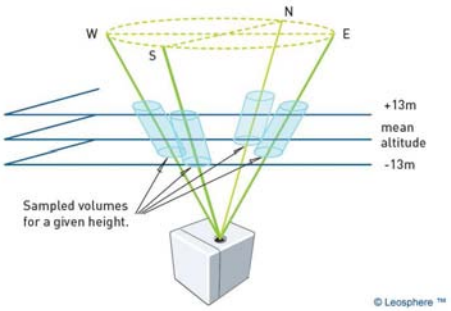
- Vanes and cup anemometers mounted on booms
- At 80 m and 90 m boom lenghts are equal
- 70 m boom is larger then the two above
- 100 m cup-anemometer surrounded by lighting protection cage
- In 2006 and since December 2008 an additional top anemometer is installed

DEWI Quality by Know-how.

LIDAR system - Leosphere WindCube

Page 4





- WindCube mounted on a container at north-west edge of Fino1 – Platform
- approx. 10 m distance to Met Mast
- 10 measurement heights from 70 m up to 250 m
- Directional offset towards north ~10°

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DEWI Quality by Know-how.

Data processing

Page 5

- **Period of measurements from 16.07.2009 (13:20) till 05.10.2009 (9:00)**
- **Total number of 10-minute mean values: 11638**
- **Excluding wind directions influenced by mast effects**
- **Wind speed > 4 m/s**

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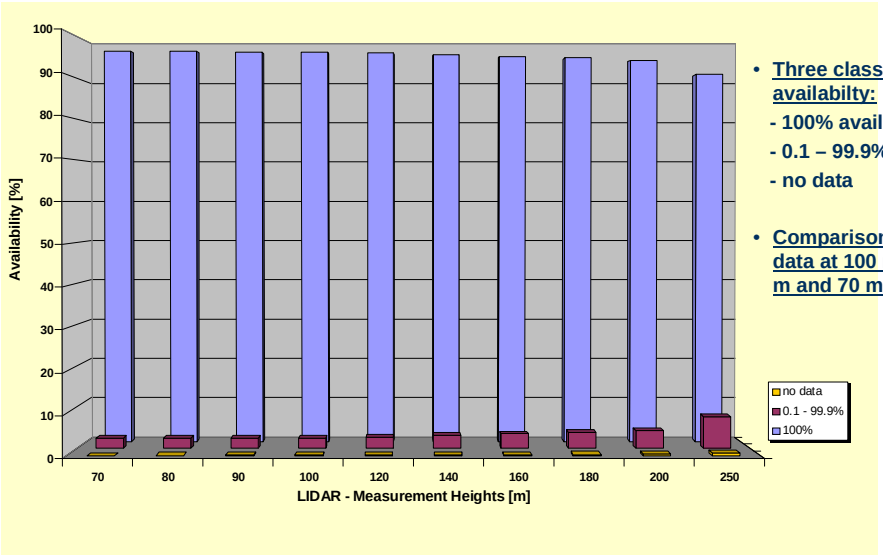
DEWI Quality by Know-how.

LIDAR Data Availabilty at Fino1 - Platform

Page 6



- **Three classifications of availabilty:**
  - 100% availabilty
  - 0.1 – 99.9% availability
  - no data
- **Comparison to Fino1 data at 100 m, 90 m, 80 m and 70 m height**

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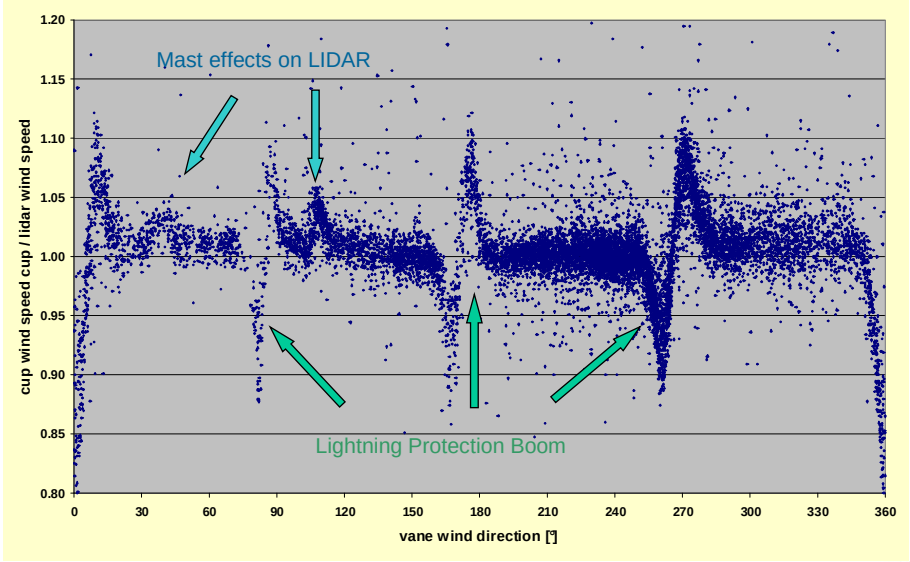
DEWI Quality by Know-how.

Ratio cup wind speed / lidar wind speed at 100 m height

Page 7



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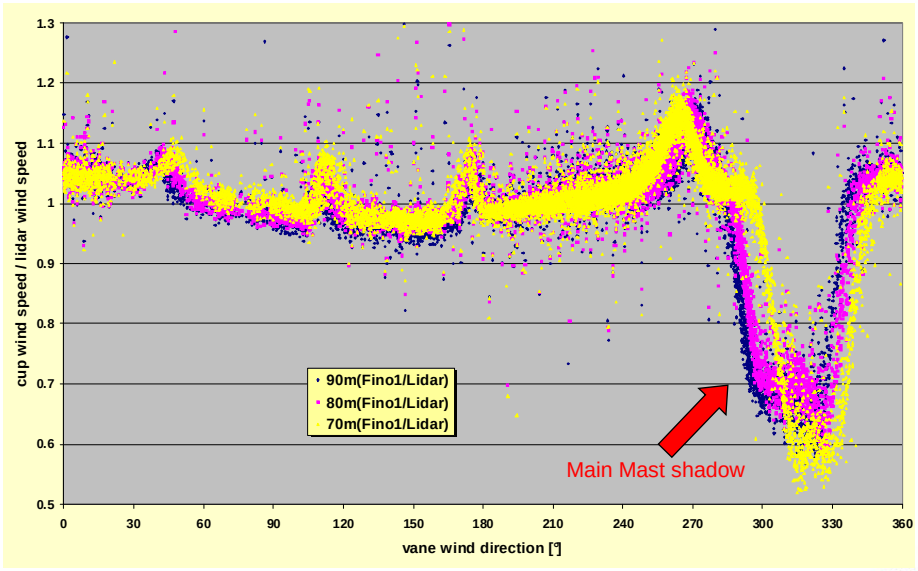
DEWI Quality by Know-how.

Ratio cup wind speed / lidar wind speed at 70 m, 80 m and 90 m height

Page 8



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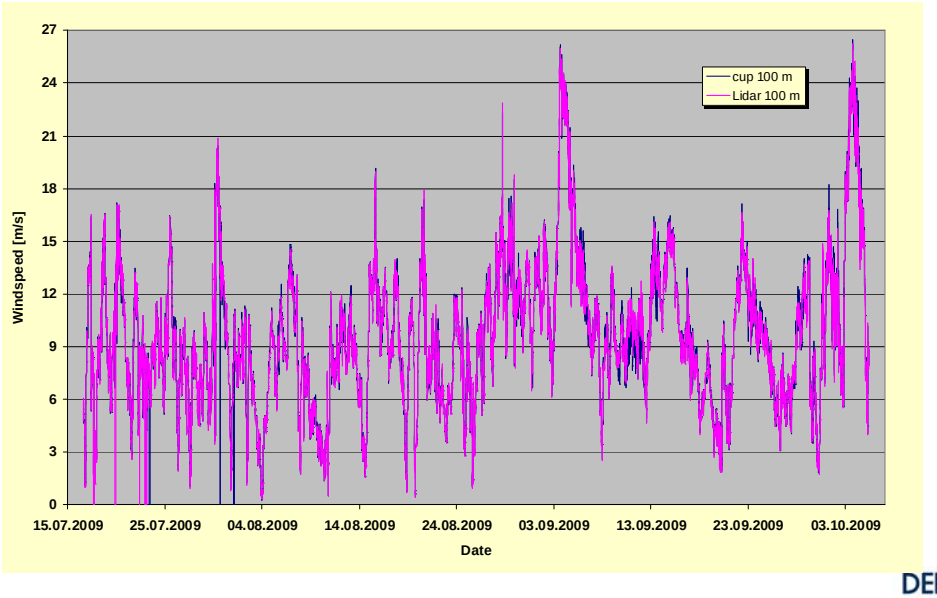
DEWI Quality by Know-how.

Comparison wind speed time series: Lidar – cup at 100 m height

Page 9



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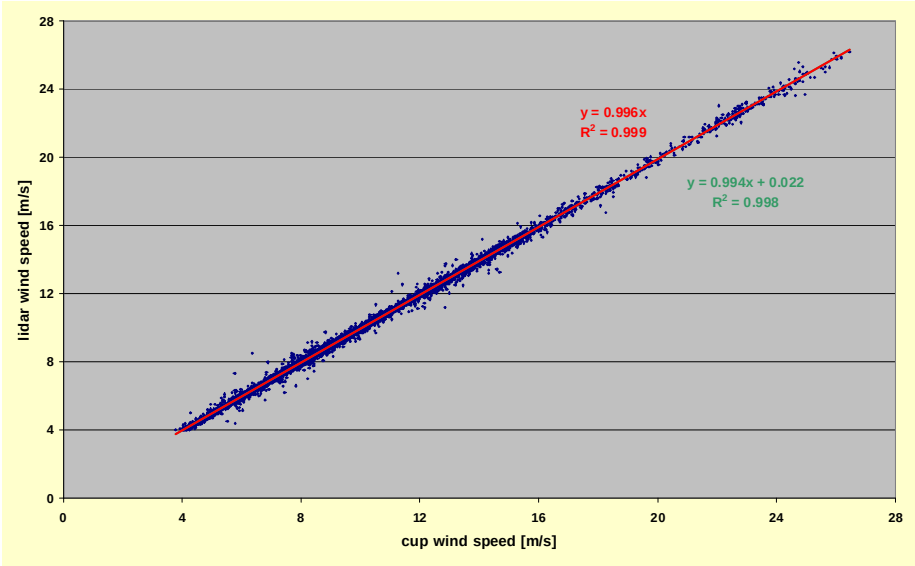
DEWI Quality by Know-how.

Illustration of standard regression analysis for horizontal wind speed at 100 m height

Page 10



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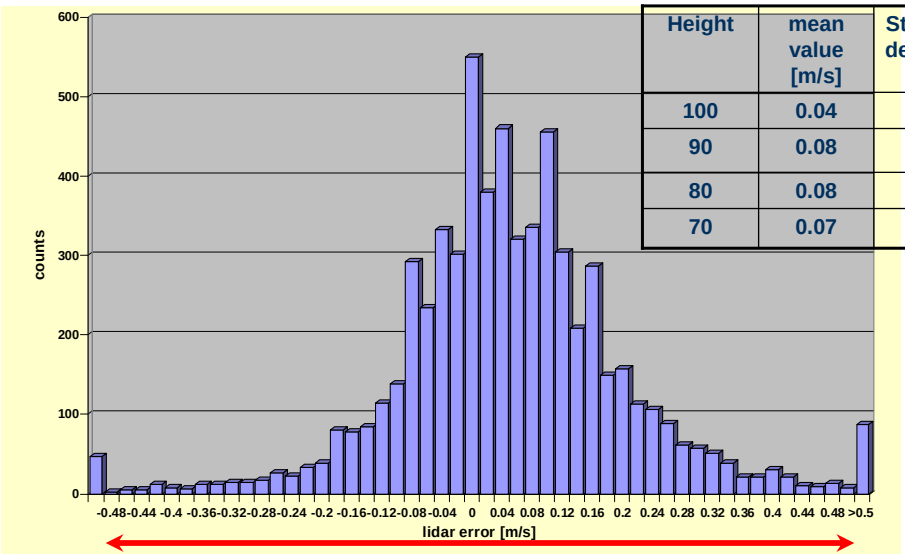
Statistics of LIDAR error (cup – lidar)

Page 11



Height	mean value [m/s]	Standard deviation [m/s]
100	0.04	0.18
90	0.08	0.33
80	0.08	0.28
70	0.07	0.27

1 m/s

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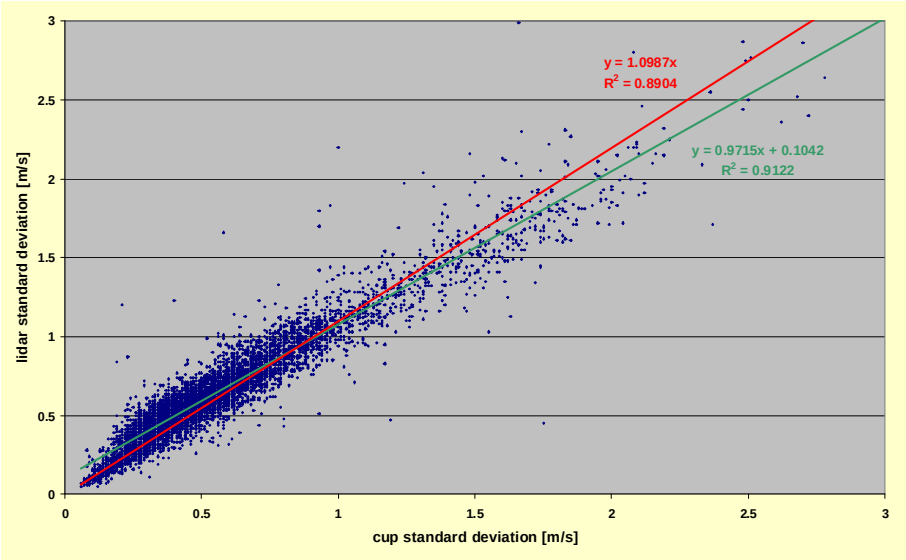
Illustration of standard regression analysis for standard deviation of horizontal wind speed at 100 m height

Page 12



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Standard regression analysis for standard deviation of horizontal wind speed at 100 m height

Page 13

Possible reasons for a larger dispersion for wind speed standard deviation are:

- **Comparison of volume measurements to point measurements**
- **Different influences caused by the mast**
- **Different calculation routines at computation of the wind speed standard deviation**

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Comparison wind direction time series: Lidar – vane at 90 m height

Page 14

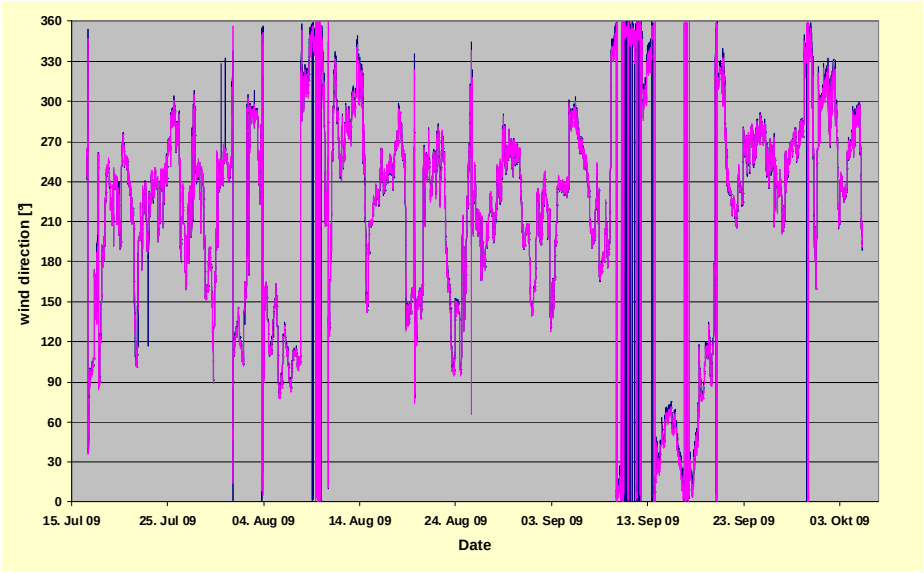

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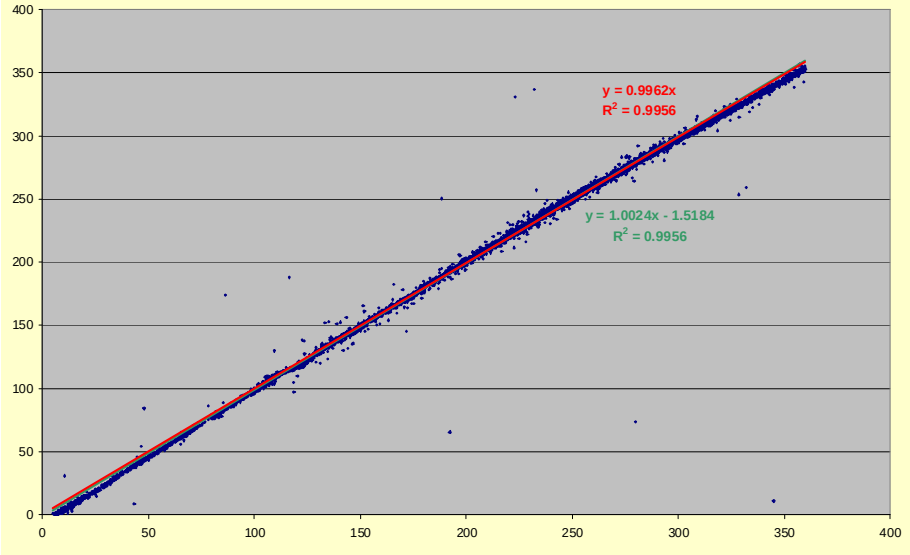
Illustration of standard regression analysis for wind direction at 90 m height

Page 15



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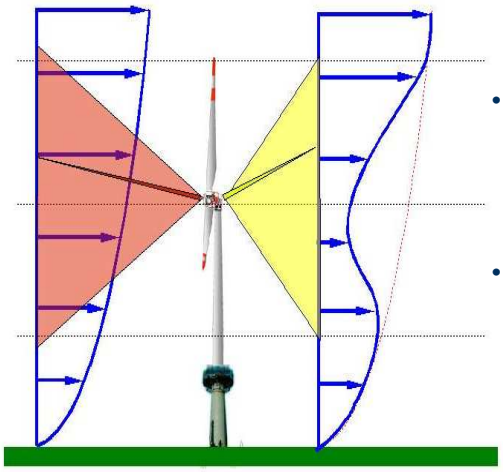
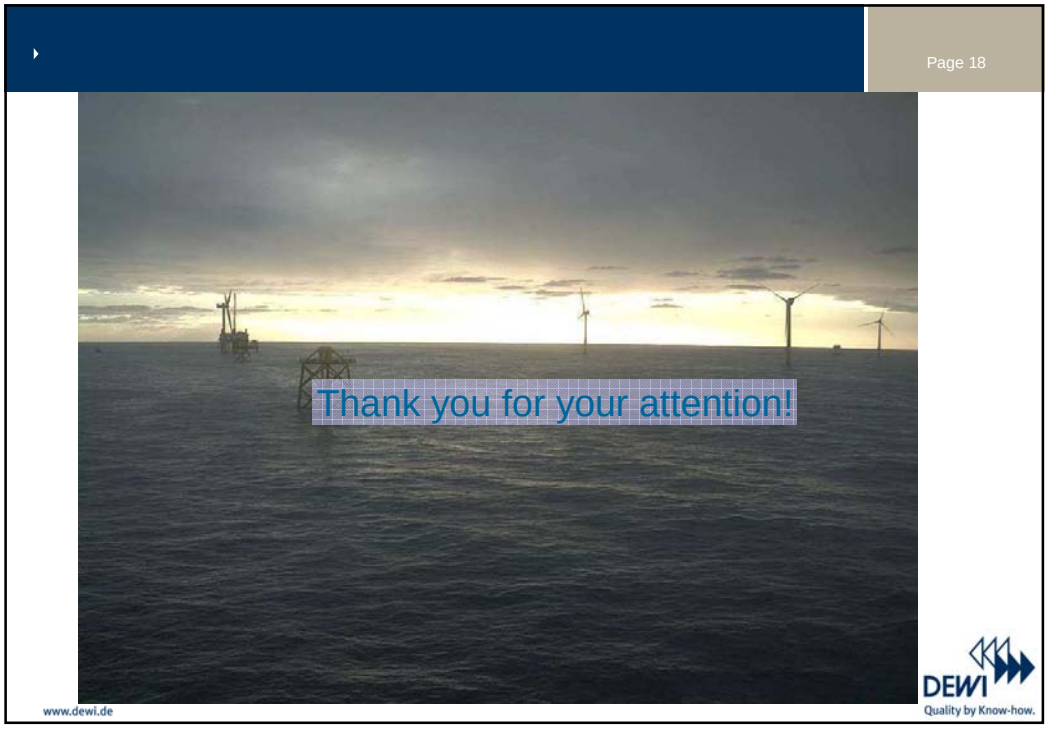
Conclusions

- Overall good experiences with the WindCube during the three month measuring campaign
- High data availabiltity in all heights: between >97% and >91%, depending on the definition of availability
- Reasonable correlation to 10-minute mean values measured with cup-anemometers or vanes
- The wind speed standard deviation shows a larger scatter, further investigation is necessary
- Additional analyses will follow (e.g. wind shear, thermal stratification…)

Outlook



- Measurement campaign in preparation for RAVE-LIDAR project
- Horizontal scanning of inflow and wake from the top of two 5MW turbines from Multibrid GmbH and REpower AG
- Project Partners:
  - SWE Endowed Chair of Wind Energy
  - ForWind
  - DLR, German Aerospace Center
  - Multibrid GmbH
  - Federation of German Windpower (FGW)


Page 18
Thank you for your attention!
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Quality by Know-how.

SODAR Data Evaluations for use in the Wind Industry

Gina Deola
Wind & Water Power Technologies Department
Sandia National Laboratories

radeola@sandia.gov

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

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Objectives

- Data review of some results of a recent Tower/SODAR Comparison
- Data review from a Complex Terrain Site
- Summarize a few points on developing Good Measurement Practices when using a SODAR

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Tower/SODAR Comparison

- **Texas Tech University 200 meter tower**
- **ART VT-1 SODAR owned by SNL**
- **Co-located approximately 3 months**
  - Roughly 400 meters spatial separation
  - SODAR upwind of tower predominant direction
- **Initial Filters**
  - Omitted data when tower winds were in tower shadow
    - For this case…omitted directions between 89.5 and 143.5
  - Omitted data when winds at each location were < 1 m/s
  - Omitted data when SODAR valid samples per 5 minute averaging interval were less than 30* (<50% returned valid signals)
    - * Consider sampling frequency when trying to compare discrete values

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Field Orientation Overview

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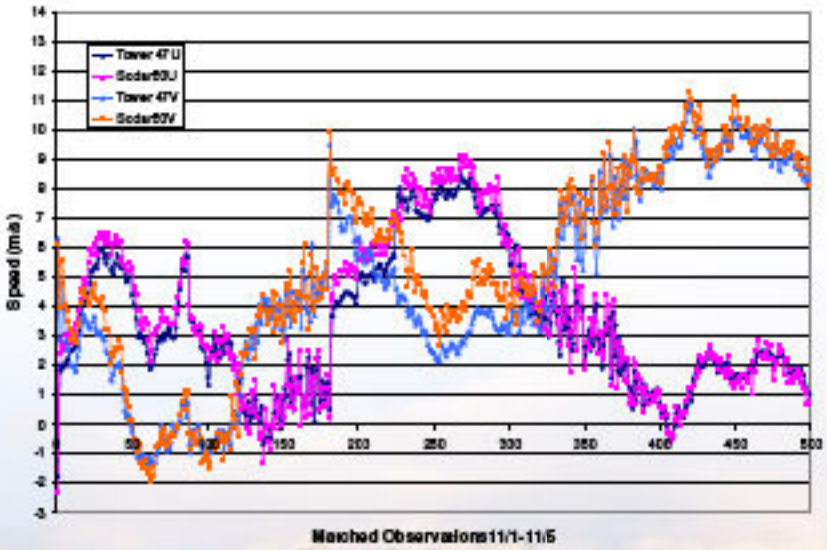
Tower/SODAR First Look

50m Level U and V Components



Matched Observations 11/1-11/5

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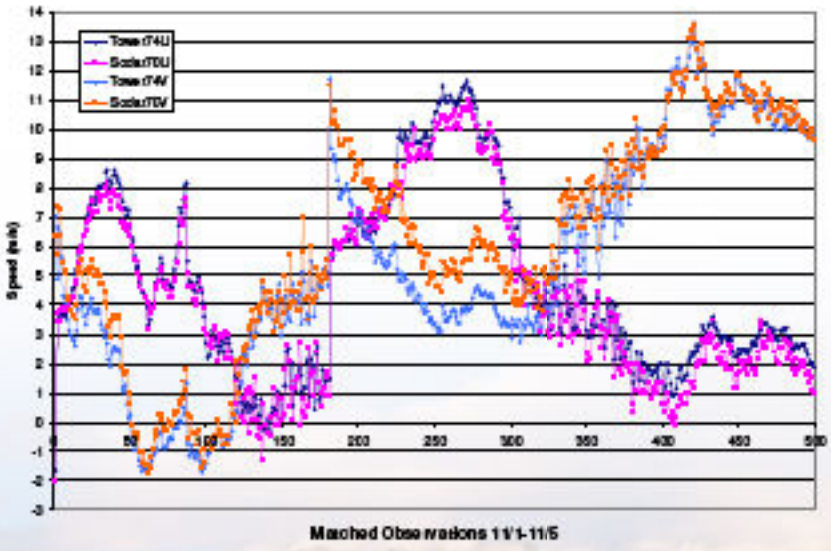
Tower/SODAR First Look

75m U and V Components



Matched Observations 11/1-11/5

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Tower/SODAR First Look

- **Previous figures indicate**
  - Discrete component data match well at times, and other times not as well.
  - Seem to be a larger problem with V component data for the initial look.
    - Root cause most likely not the SODAR
      - SODAR bias should tend to be more systematic, not occasional and not only on one component
- **Refined filters will be needed if discrete component data are to match better**
  - Looked at potential off-axis instrument response errors since using Gill UVW sensors
    - V oriented 166 degrees and U oriented 256 degrees true N

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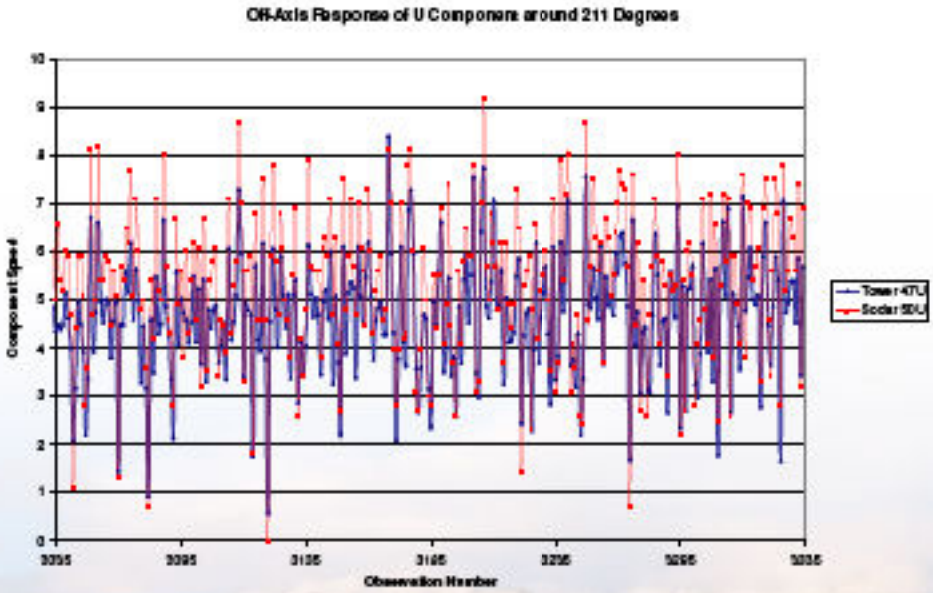
Off-Axis Comparison U ~ 211 degrees



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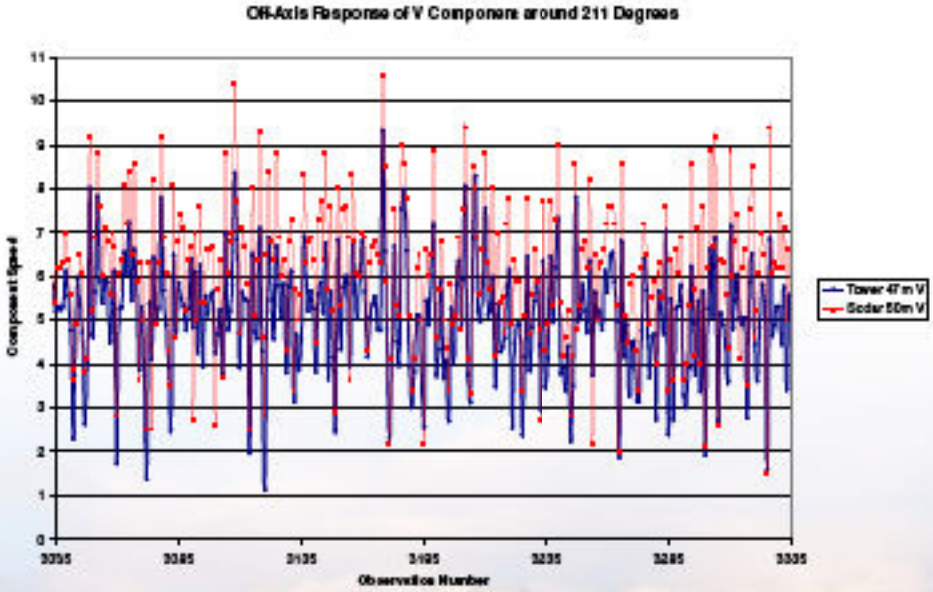
Off-Axis Comparison V ~ 211 degrees



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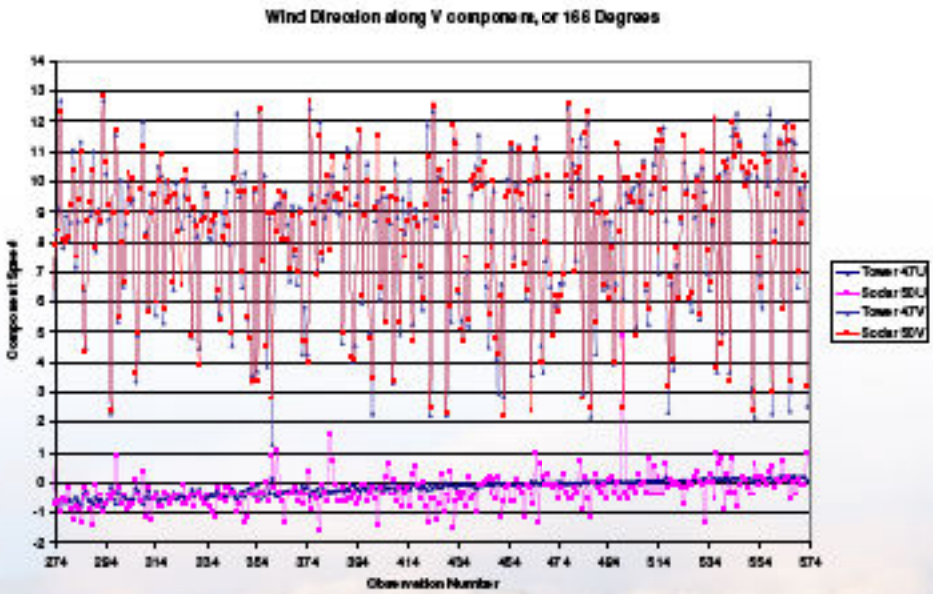
On-Axis Comparison V ~ 166 degrees



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Filters used for Discrete Data Comparisons

- **For Tower**
  - Shadow Effects
    - This case omitted WD between 89.5 and 143.5 degrees
  - Boom Arm Effects
    - This case omitted WD between 301 and 121 degrees
  - Instrument Off-Axis Effects
    - This case omitted 188.5 through 233.5 and 278.5 through 301 degrees
  - Low Wind Speeds
    - This case less than 1.0 m/s
- **For SODAR**
  - Low Wind Speeds (less than 1.0 m/s)
  - Required minimum percentage of valid samples
    - Omitted data that had less than 50% good samples in averaging interval

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Summary Data

(after filters applied, 3377 observations)

Component	Mean	SE Mean	Minimum	Q1	Median	Q3	Maximum
Sodar 50U	3.96	0.0741	-3.50	0.30	2.80	7.70	17.80
Tower 47 U	3.82	0.089	-2.45	0.33	2.62	7.33	19.09
Sodar 50V	4.51	0.0747	-4.30	0.60	4.00	8.60	15.20
Tower 47V	4.29	0.0737	-4.38	0.46	3.45	8.53	14.26
Sodar 50 WS	8.09	0.0483	1.40	6.00	8.40	10.25	17.90
Tower 47 WS	7.77	0.0465	1.20	5.78	8.13	9.77	19.15
Sodar 70U	4.57	0.0835	-3.80	0.50	3.10	8.95	17.10
Tower 75U	4.94	0.0909	-2.89	0.97	3.38	9.10	20.24
Sodar 70V	4.82	0.0828	-3.80	0.60	4.20	9.40	16.10
Tower 75V	4.33	0.0896	-5.29	-0.18	3.45	8.44	15.11
Sodar 70 WS	9.00	0.0537	1.00	6.70	9.40	11.40	17.10
Tower 75 WS	9.07	0.0535	1.25	6.79	9.53	11.42	20.35
Sodar 110U	5.69	0.0994	-7.90	0.90	3.80	11.00	20.70
Tower 116U	5.73	0.0991	-4.36	0.88	3.60	11.04	21.13
Sodar 110V	5.31	0.0994	-9.40	0.70	4.60	10.65	17.80
Tower 116V	5.22	0.101	-6.48	0.43	4.20	10.79	17.12
Sodar 110 WS	10.61	0.0664	1.00	7.80	11.10	13.40	21.20
Tower 116 WS	10.65	0.0658	1.21	7.91	11.16	13.44	21.20

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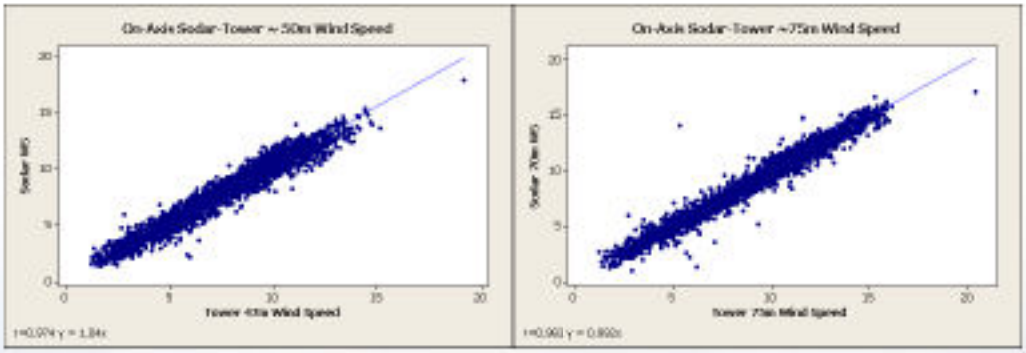
Discrete Data



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Rotor Plane Characterization

- SODAR and Lidar…full rotor plane characterization
- Following figures and results use larger dataset (~10,750 points)
  - Data includes only winds > 4.0 m/s (based on SODAR 50m level)
    - 92% of the possible valid matched observations (11637)
- Results of SODAR and Tower Data Comparison and Analysis
  - Identified strong speed shears, directional shears and vertical motions coincident with each other.
- While discrete data may differ, does each measuring platform capture essence of site?

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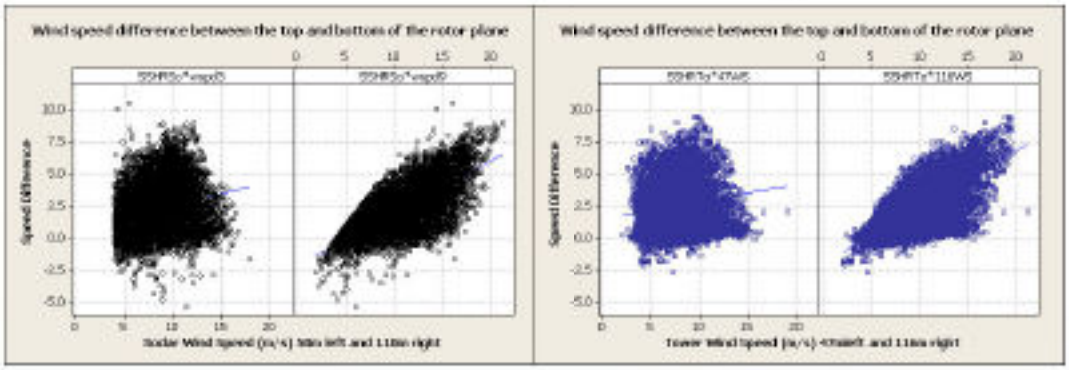
Speed Shear



- **Top (~110m) and bottom (~50m) speed to ID rotor plane speed difference**
  - Large differences in speeds between the top and bottom
  - Similar characterization of the site for these observations
    - SODAR does seem to have more observations of negative shear
      - Generally weak, not significant
      - Possibly related to decrease of returned signal at 110 meter level

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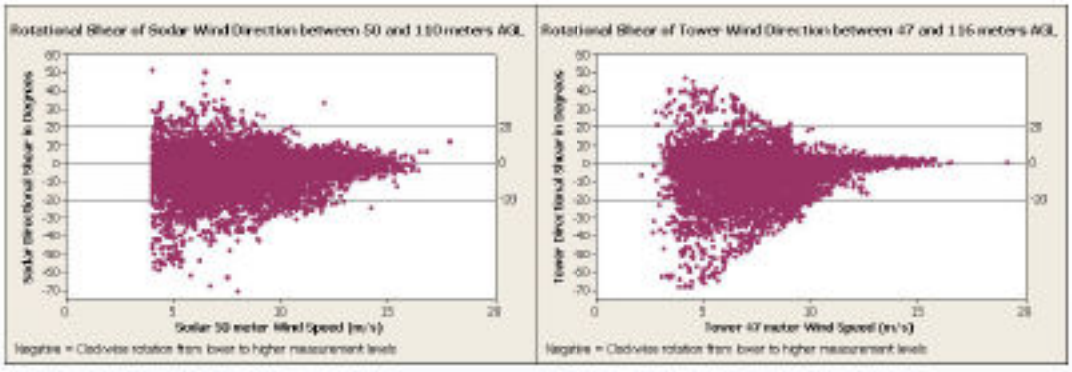
Directional Shears



- **Large directional shears are evident at this site**
- **Tower distribution seems more scattered in this case**
  - Possible tower/boom effects, or SODAR volume averaging

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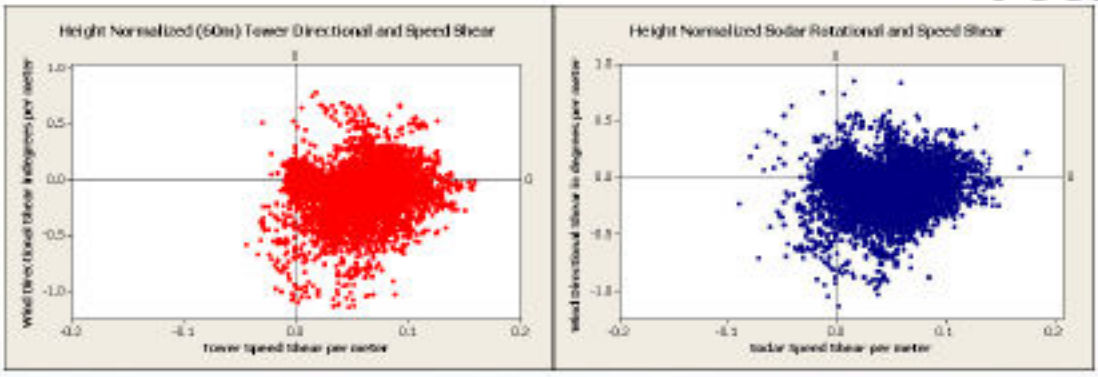
Tower and SODAR Shears and Veers



- **Normalized speed and directional shears (shear/rotor plane depth in meters)**
- **Generally good agreement**
  - Some kind of positive speed shear is usually present at this site
  - A few stray SODAR points, and more points with negative speed shear
    - This is consistent with other figures

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Complex Terrain Site

- **Data Collected mid-July through beginning of October**
- **Behind Four Hills Area on DOE lands**
  - Minimum screening, using all data marked valid with default QA such as a minimum 7.5 SNR, 100 Hz frequency shift of return signal, no rain.
    - 92 percent data recovery
    - For winds > 4.0 m/s somewhere in the rotor plane (50-110 m)
      - Data reduced to 46% of full data (5146 points)

Four Hills	50m WS	80m WS	110m WS	140m WS	Alpha Plane	Alpha Bottom	Alpha Top
All data (92%)	4.09	4.37	4.58	4.85	0.144	0.140	0.149
1 level WS>4.0 *	6.07	6.50	6.80	7.05	0.155	0.162	0.148
50&80 WS>4.0	6.82	7.25	7.51	7.73	0.121	0.129	0.110

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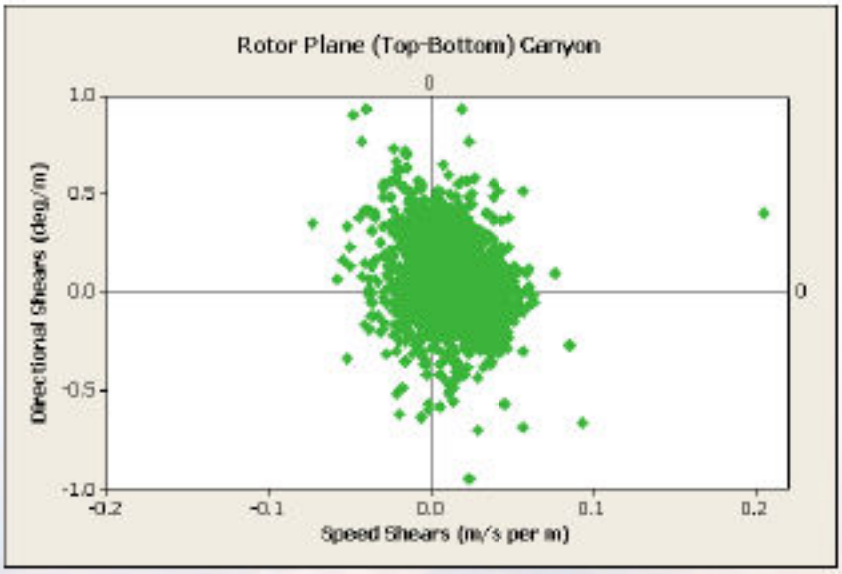
Shears and Veers Four Hills



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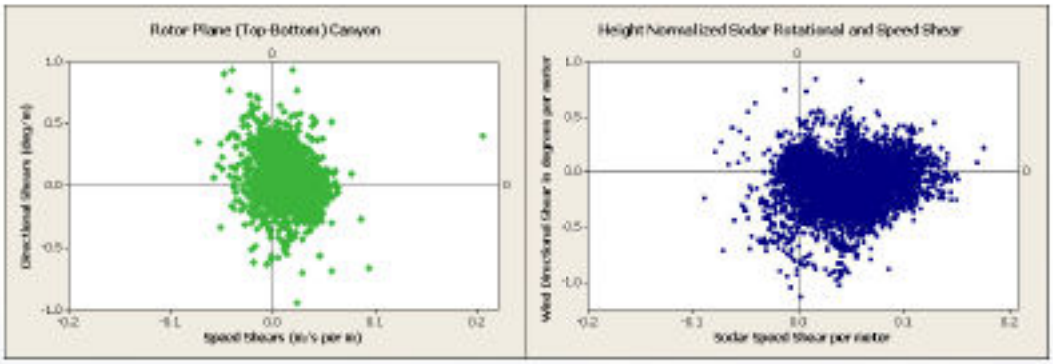
Comparison of Simple Terrain and Complex Terrain Shears



- **Figures indicate:**
  - An absence of large speed shears in this complex terrain site
  - Greater percentage of negative speed shears
  - More evenly distributed directional shears

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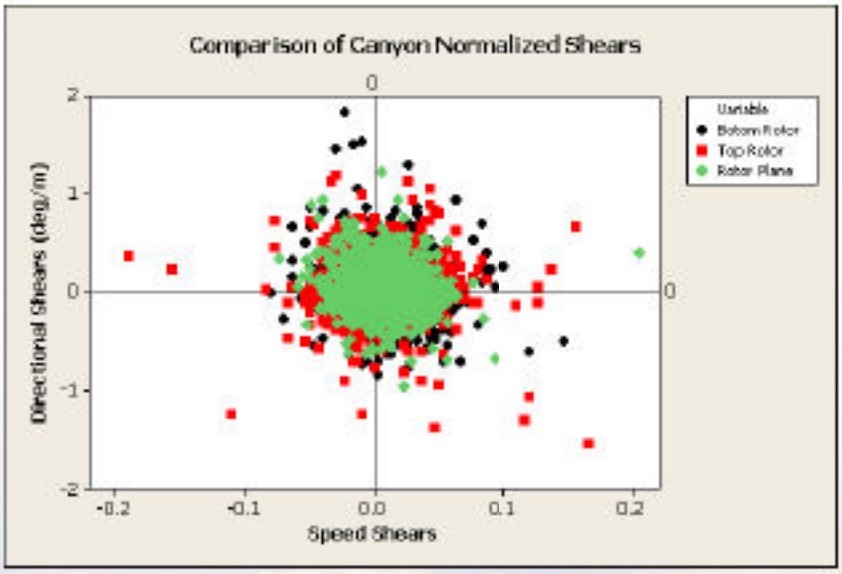
A look at individual rotor levels



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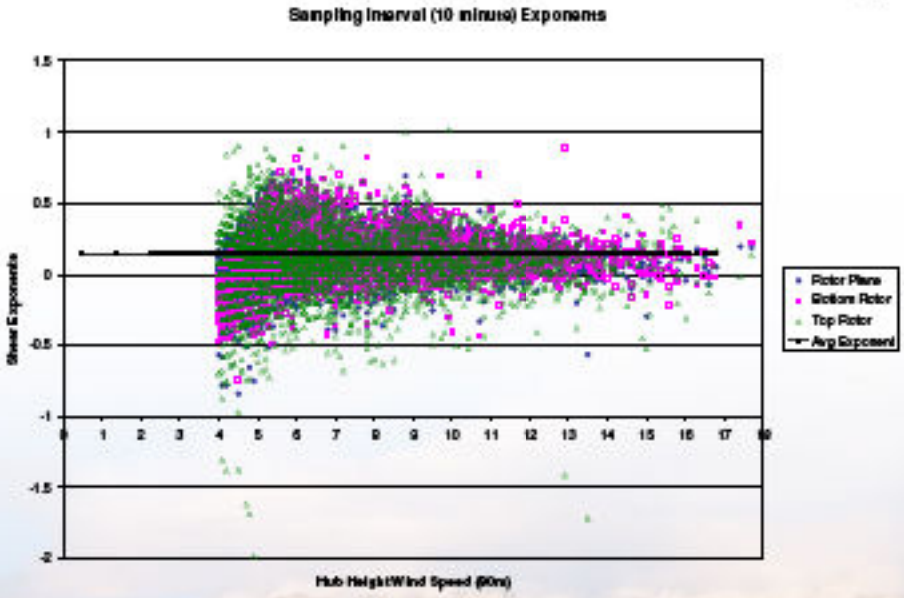
Sampling Interval Alpha Exponents



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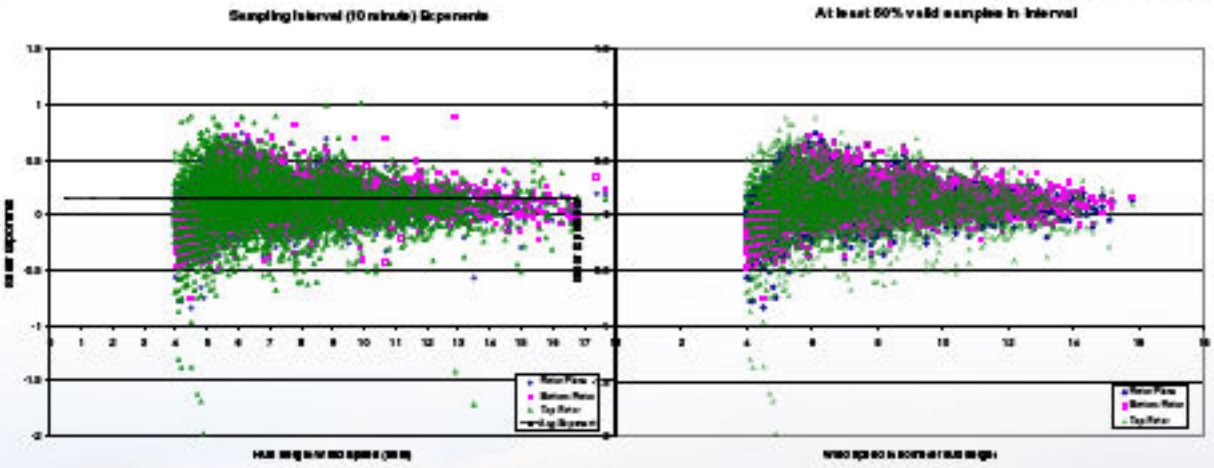
Additional Screening

(used 50% valid returned criteria...omitted 10% ~350 observations)



- To minimize larger shears, used ~ 3960 data points....WS>4.0 at both 50 and 80 meter levels
- Only a few "outlier exponents" were omitted, many data points that were most likely good and valid data were omitted from figure on the right.
  - Example shows that trying to removing spurious data points using broad-brush approach may remove valid data

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Good Measurement Practice Development Considerations

- **Many general good measurement practices apply to remote instruments, with added practices**
  - Good routine maintenance supports good measurement practices.
    - VT-1 Operations and Maintenance Manual identifies activities
  - Becoming familiar with terrain is an important aspect of good practices
    - deeper layer of measurements/varied locations may change our "reference".
  - May need more frequent review of remote sensing instrument operation.
    - Nocturnal ambient noise may be similar to operating frequency.

- **Specific data use objectives may require different levels of scrutiny/QA criteria**
  - Discrete data comparisons may have more filtering requirements, but not different measurement practices.
  - For general wind characterization, less filtering may be required, except for when looking at/for extremes.
    - May not want to use same filtering techniques as with discrete comparisons, as many good data points may be omitted.
  - Information contained in some of these graphs can be used as a starting point if looking at "ranges of acceptable/unacceptable data".

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Questions

- Somewhere in Southern Texas
- Compliments of Barry Neal

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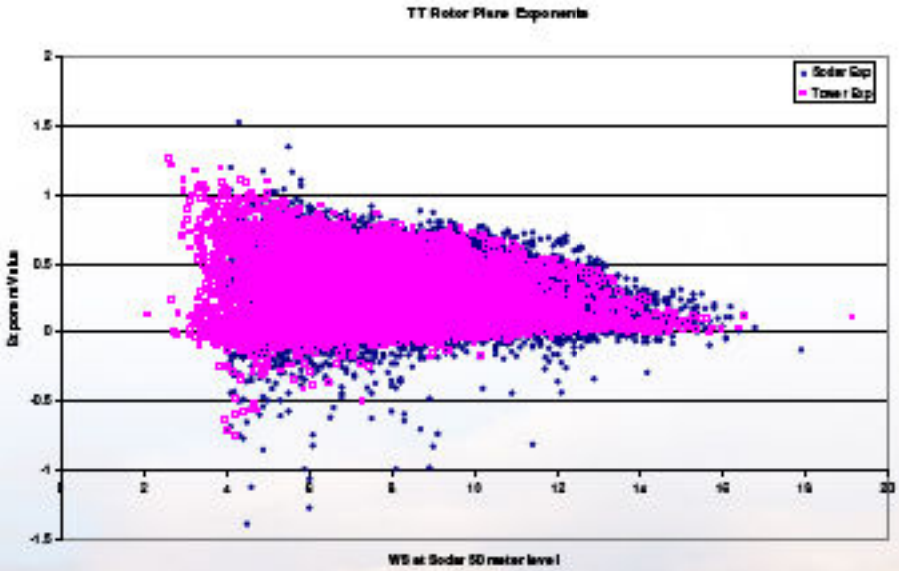
Spare Slide



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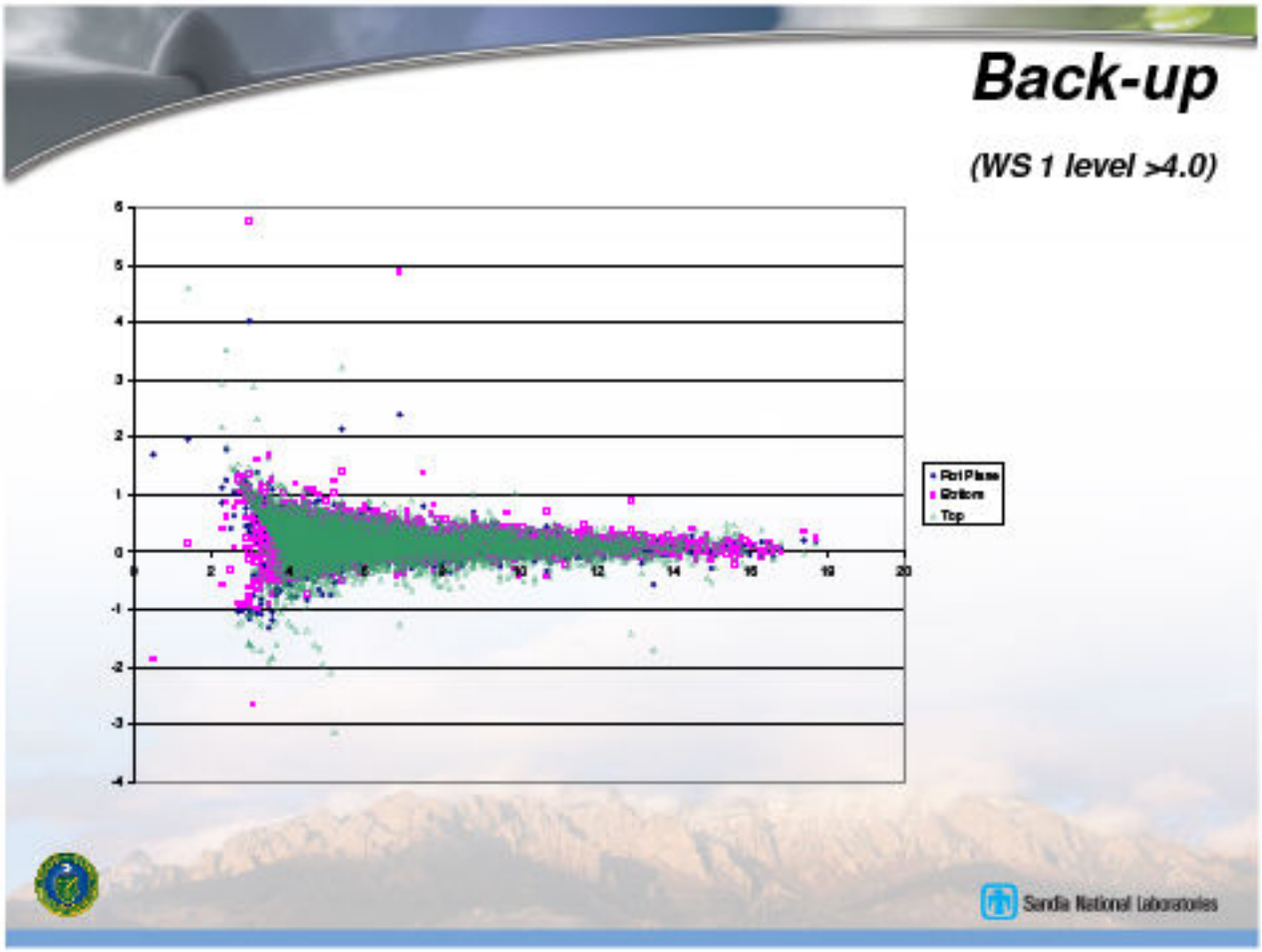
Back-up
(WS 1 level >4.0)
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ForWind
Center for Wind Energy Research

Langevin Power Curve Estimation using LIDAR, Cup, and Sonic Anemometers

Matthias Wächter[1], Andreas Rettenmeier[2], Joachim Peinke[1]

[1] ForWind Center for Wind Energy Research, Oldenburg University
[2] Endowed Chair of Wind Energy (SWE), Stuttgart University

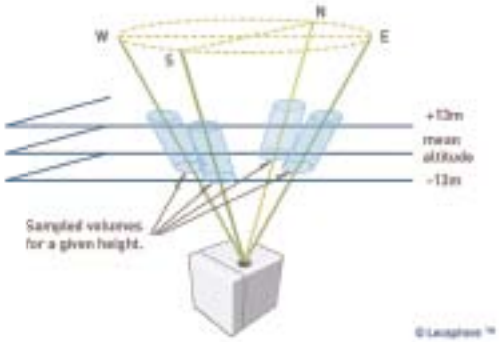
IEA Topical Expert Meeting "Remote Wind Speed Sensing"
NREL NWTC, Boulder, 15./16. October 2009

Introduction

- Work within the RAVE project: „Development of LIDAR Measurements for the Offshore Test Field"
- Here: Measurement campaign at Bremerhaven, Germany
  - Power curve measurement, especially using the LIDAR

LIDAR technology

- **LIDAR: LI**ght **D**etection **A**nd **R**anging
- Leosphere Windcube: Pulsed laser Doppler anemometer for wind speed measurements
  - 4 measurements ⇒ 3D wind vector, every 1.5 s
  - 10 height levels simultaneously, up to 200 m



Wächter e.a.: **Power Curves** TEM Boulder 2009 3 ForWind

LIDAR technology

- **LIDAR: LI**ght **D**etection **A**nd **R**anging
- Leosphere Windcube: Pulsed laser Doppler anemometer for wind speed measurements
  - 4 measurements ⇒ 3D wind vector, every 1.5 s
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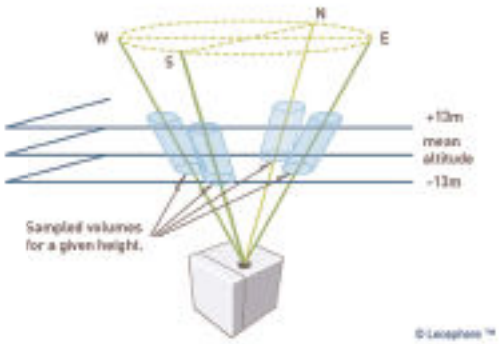
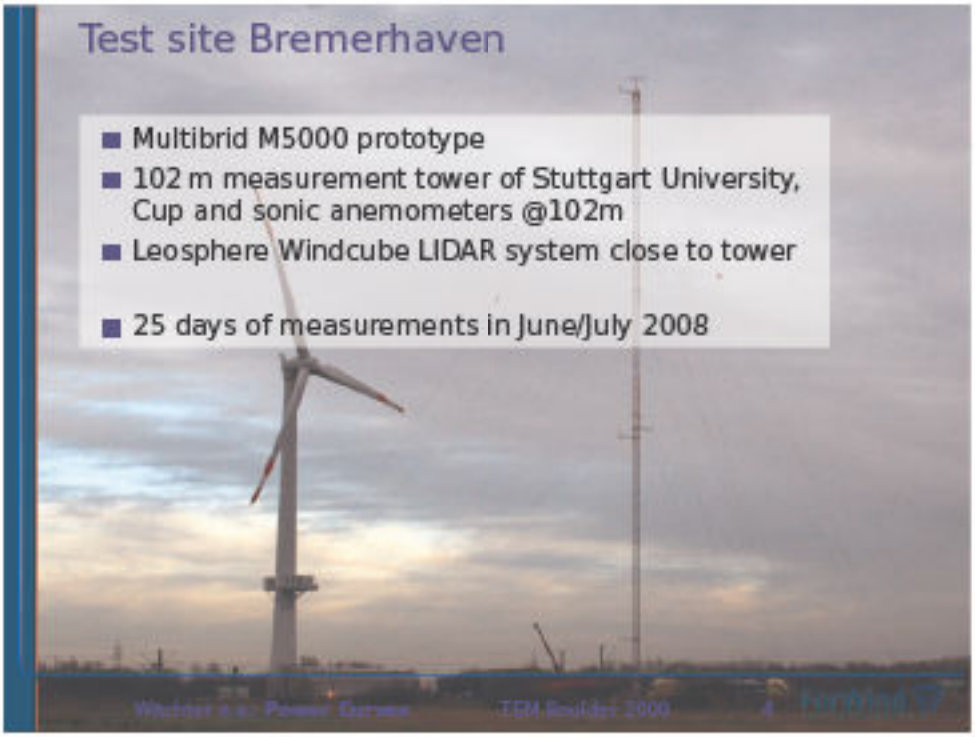


How does it perform?

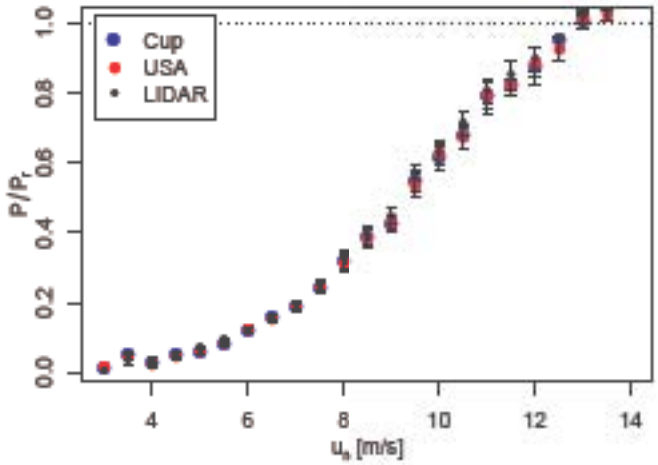
Wächter e.a.: **Power Curves** TEM Boulder 2009 3 ForWind

Test site Bremerhaven


Test site Bremerhaven
Multibrid M5000 prototype
102 m measurement tower of Stuttgart University, Cup and sonic anemometers @102m
Leosphere Windcube LIDAR system close to tower
25 days of measurements in June/July 2008

Power curves after IEC 61400-12-1

10 min averages of *u* and *P*
⇒ power characteristic of turbine at site



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Power curves after IEC 61400-12-1

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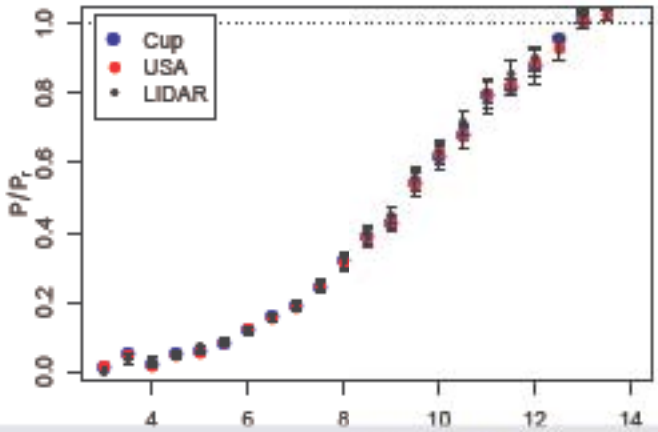
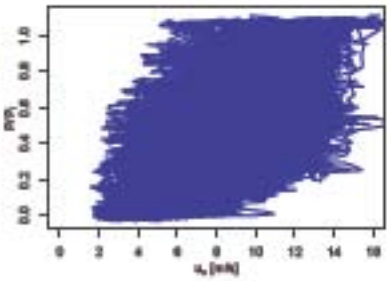


LIDAR agrees well with cup and US anemometer

Wächter e.a.: **Power Curves** TEM Boulder 2009 5 ForWind

Langevin power curve estimation

High frequency power data:
Highly dynamical system
on 1 s time scale

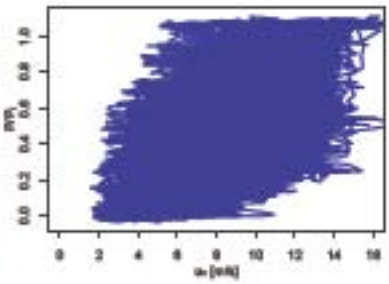


Wächter e.a.: **Power Curves** TEM Boulder 2009 6 ForWind

Langevin power curve estimation

High frequency power data:
Highly dynamical system
on 1 s time scale

turbulent wind leads to
„turbulent" power fluctuations



Wächter e.a.: **Power Curves** TEM Boulder 2009 6 ForWind

Langevin power curve estimation

High frequency power data:
Highly dynamical system
on 1 s time scale

turbulent wind leads to
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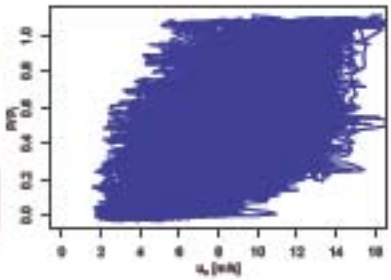
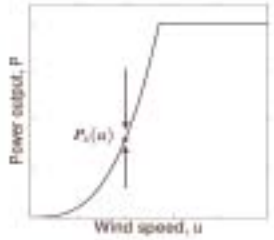


Langevin power curve:

- For fixed u,
  power relaxes to $P_S(u)$
- Find stable fixed points $P_S(u)$



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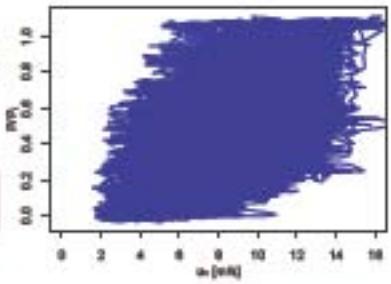

Langevin power curve:

- For fixed u,
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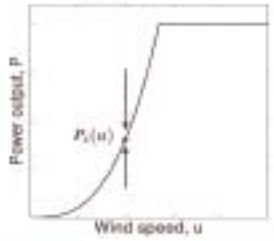
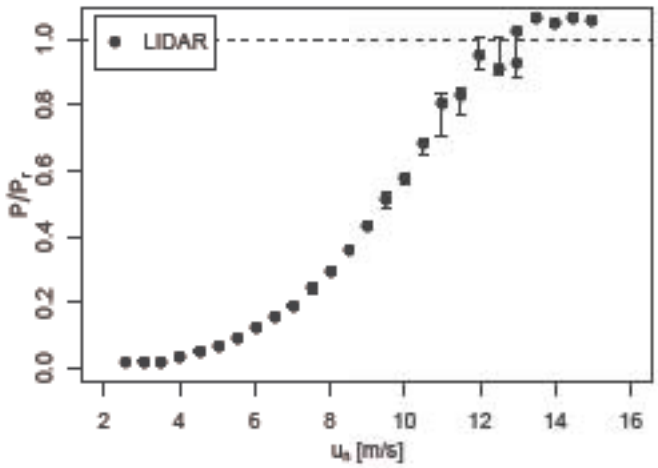
- Find stable fixed points $P_S(u)$

⇒ Power „for constant u"



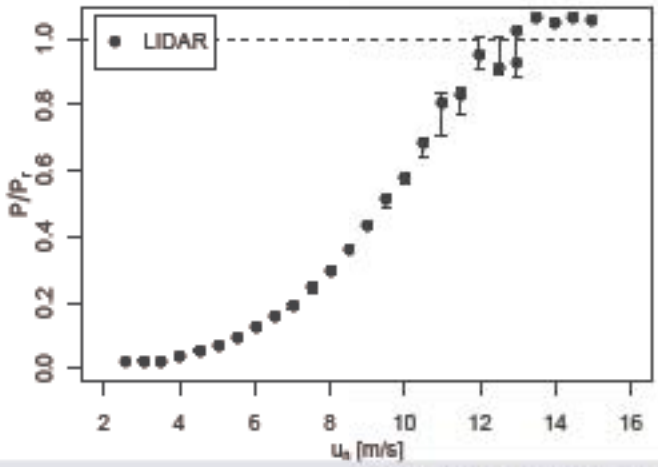
Wächter e.a.: Power Curves TEM Boulder 2009 6 ForWind

Langevin power curves



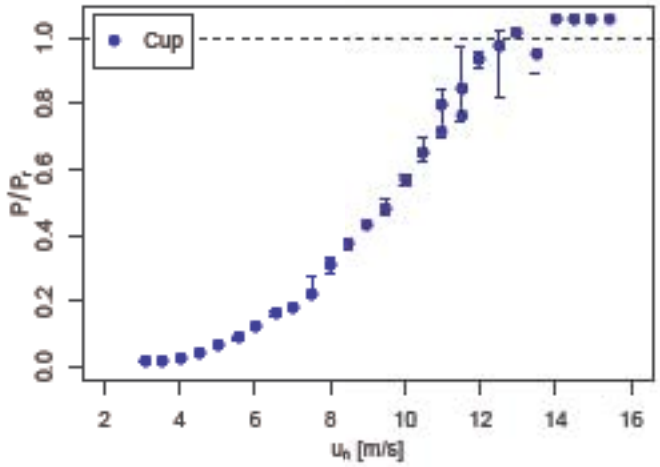
- Multiple fixed points possible

Langevin power curves



LIDAR well applicable for Langevin power curves

More Langevin power curves



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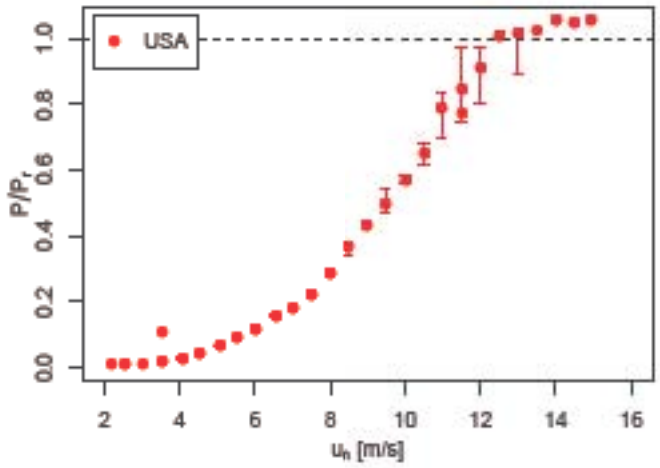
More Langevin power curves



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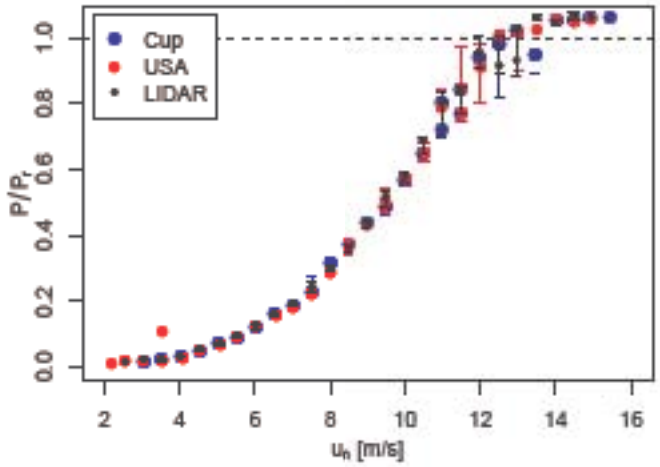
More Langevin power curves



- Multiple fixed points possible

Features of Langevin power curves

- Use of high frequency data:
  - Allows short measurement periods
  - Analyzes short time dynamics
- Site independent
- No averaging effects
- Shows multiple stable states

⇒ **Tool for turbine monitoring**

Further reading:

Anahua e.a., Wind Energy **11**, 219 (2008)
Gottschall e.a., J. Phys.: Conf. Ser. **75**, 012045 (2007)
Gottschall e.a., Environ. Res. Lett. **3**, 015005 (2008)

Conclusions

- LIDAR well applicable for wind measurements
- Good correspondence of power curves for cup, USA, and LIDAR
- LIDAR is slower than cup and USA, but still captures short time dynamics of power conversion

Thanks to:

- Edgar Anahua
- Julia Gottschall
- SWE, U. Stuttgart
- German Environment Ministry (funding)

Conclusions

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Thank you for your attention!

Wächter e.a.: Power Curves TEM Boulder 2000 10 ForWind

ECN

Energy research Centre of the Netherlands

SODARs and WISE guys

J.W.Wagenaar

www.ecn.nl

ECN

Outline

- Introduction
- WISE
- ECN's Power Performance
- Other Experiences

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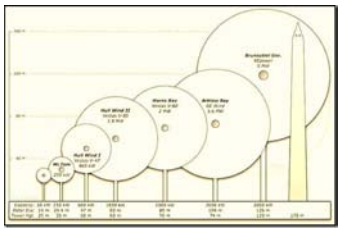
ECN

Introduction

- Increasing size turbines
  -> increasing size meteo masts (costs, permits)
- Possible solution: SODAR
  - pros: less expensive, portable, off the shelf, ...
  - cons: WE appl stricter requirements, fixed echoes, atmospheric conditions, ...



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ECN

ECN's SODAR

Model 3000, AeroVironment, with AV4000 speaker array

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ECN

WISE: WInd energy Sodar Evaluation

- Energy research Centre of The Netherlands, ECN (NL) (Co-ordinator)
- National Laboratory, RISØ (DK)
- WINDTEST Kaiser-Wilhelm-Koog GmbH (DE)
- University of Salford (UK) / University of Auckland (NZ)
- IMK-IFU Forschungszentrum Karlsruhe (DE)
- DEWI German Wind Energy Institute (DE)

ECN RISØ WINDTEST THE UNIVERSITY OF SALFORD DEWI

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WISE project (2000 - 2005):

- Theory of SODAR Measurement technique
- Sodar calibrations for WE applications
- Operational characteristics
- Power Performance measurements with SODAR
- Application in difficult circumstances

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ECN

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ECN-C--05-041 ECN-C--05-044

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ECN

'ECN Windturbine Testveld Wieringermeer' EWTW

- Flat agricultural terrain
- 5m below sea level
- Main wind SW
- Lake "IJsselmeer" 2km eastwards
- ECN – EWTW approx 40km

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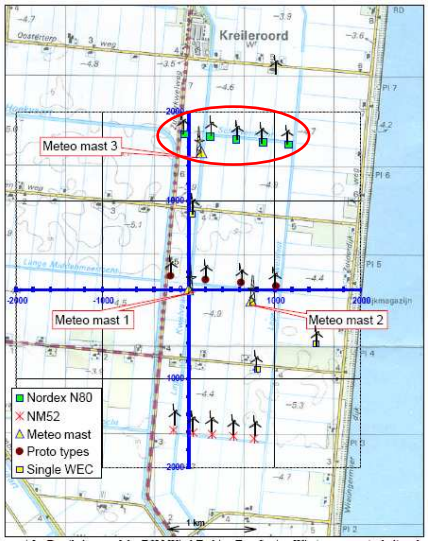
ECN

EWTW

- 5 Research Turbines



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ECN

EWTW

- 5 Research Turbines
- 4 Prototype Turbines

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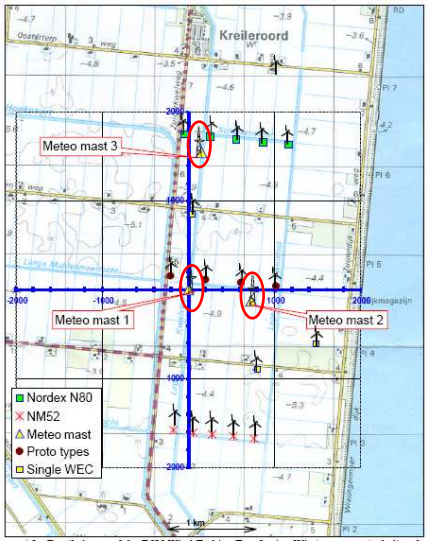
ECN

EWTW

- 5 Research Turbines
- 4 Prototype Turbines
- 3 Meteo masts



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EWTW

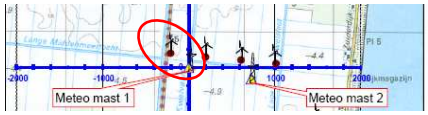
- 5 Research Turbines
- 4 Prototype Turbines
- 3 Meteo masts
- Scaled Wind Farm
  - 10 turbines
  - 14 meteo masts

ECN

EWTW + SODAR

- **Meteo Mast**: booms at 70m, 45m etc. with cups and vanes (ISO- 17025)
- **Turbine**:
  - Rotor diameter D=92m
  - Hub height H=70m
- **SODAR**: Model 3000, AeroVironment, with AV4000 speaker array
- **Distances**:
  - Mast–Turbine: 2.96D
  - SODAR-Turb: 3.45D

  (IEC-61400-12)



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ECN

Power Performance

- Applying recommended settings (WP1) + filter settings

General
- Data availability
- Precipitation
- Measurement sector
- U,V,W stand dev
- Signal to Noise ratio (SNR)

PV
- Max difference SODAR-cup
- Min wind speed cup

- ECN Database structure
- Power Performance and AEP
- 'Stand alone' SODAR + calibrated SODAR + cup

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ECN

Stand alone SODAR

Not comparable with cup:

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Stand alone SODAR

Not comparable with cup:

- Overestimation wind speed 10%-12%, offset -0.3m/s to -0.6m/s

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ECN

Stand alone SODAR

Not comparable with cup:

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- Underestimation of PV and AEP

ECN

Stand alone SODAR

Not comparable with cup:

- Overestimation wind speed 10%-12%, offset -0.3m/s to -0.6m/s
- Underestimation of PV and AEP
- SODAR AEP’s outside uncertainty boundaries cup

ECN

Calibration: small mast

SODAR calibrated against mast of 45m (WP3)

Meaning:

Simultaneous calibration against cup anemometer at 45m mast

Extrapolation to 70m.

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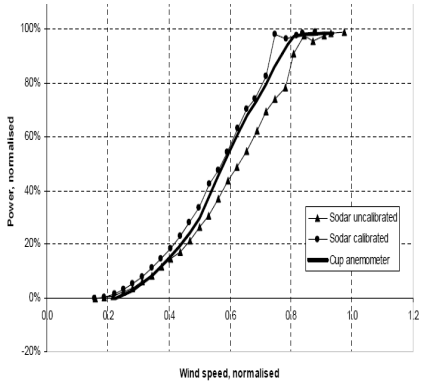
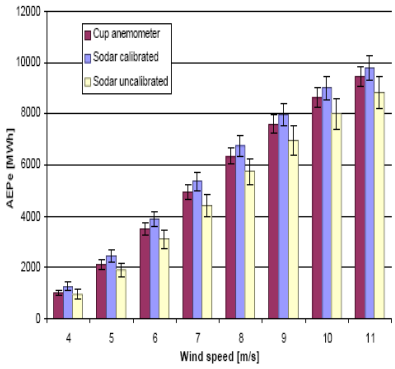
ECN

Calibration: small mast

SODAR calibrated against mast of 45m (WP3)





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ECN

Calibration: small mast

- Differences with cup power curve reduced

ECN

Calibration: small mast

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- Overestimation of PV and AEP

ECN

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- Differences with cup AEP higher then uncertainty (ws<10m/s)

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- Much better then ‘Stand alone’

ECN

Calibration: small mast

- Differences with cup power curve reduced
- Overestimation of PV and AEP
- Differences with cup AEP higher then uncertainty (ws<10m/s)
- Much better then ‘Stand alone’
- Not many high wind speeds

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ECN

Pre-calibrated + Stand alone SODAR

- Overestimation PV and AEP
- Differences AEP higher then uncertainty
- Calibration less effective

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ECN

Pre-calibrated + Stand alone SODAR

- Overestimation PV and AEP
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⇒ **Simultaneous calibration against small mast**

ECN

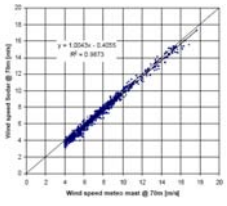
Pre-calibrated + Stand alone SODAR

- Overestimation PV and AEP
- Differences AEP higher then uncertainty
- Calibration less effective

⇒ **Simultaneous calibration against small mast**

Note:

- Not many high wind speeds
  Calibration successful ?
- No equal regression parameters found



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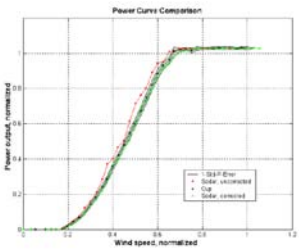
Side Remarks:

- *SODAR's wind profile (non complex terrain) to comparable accuracy as cup*
- *Power Performance in other test fields slightly better*



- *Data filtering increases measuring period considerably*

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Other Experiences

- Various measurements AeroVironment (smaller projects)
- Other/newer SODAR measurements @ EWTW (commercial project)
- LIDAR measurements @ Cabauw (commercial project)

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Vattenfall's experience in remote wind speed sensing

The use of AQ500 sodar technology
NREL, 15-16 Oct 2009
Daniel Gustafsson, Vattenfall Vindkraft AB

1

VATTENFALL

Background

2

VATTENFALL

Measurement campaign (in Sweden)

- **Met masts**
  - About 30 own or instrumented telecom mast
  - Cup and sonic anemometers
- **Sodar**
  - 17 AQ500 WindFinder
  - 2 years of experience
- **Lidar**
  - 1 Windcube

3

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Sodar measurements – AQ500

4

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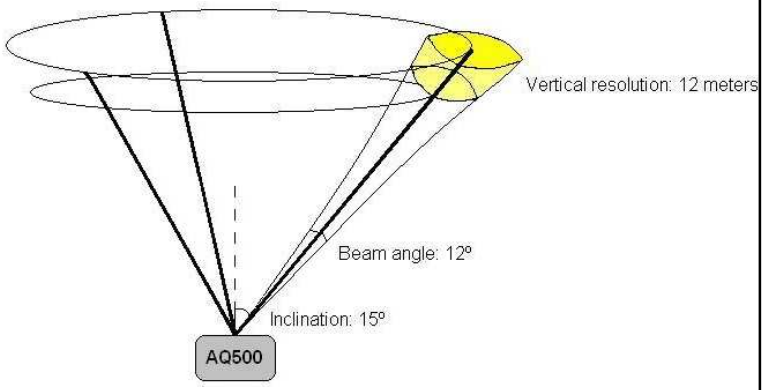
Sodar measurements – AQ500 features

- **Three-antenna configuration**



5

VATTENFALL

Sodar performance evaluation

6

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Initial AQ500 performance evaluation

- Measurements by 97 m met mast and sodar
- From December –07 until June –08
- Wind speed, wind shear and turbulence data
- Different sources of error

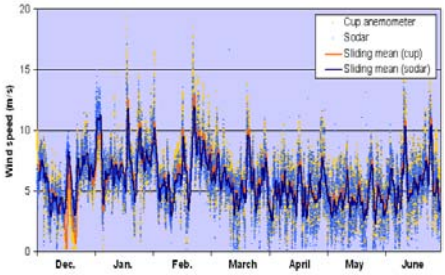
7

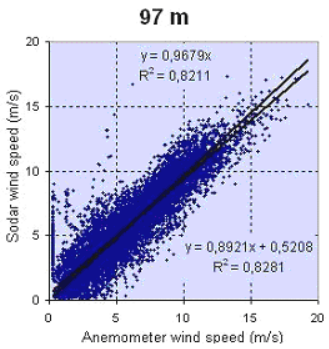
VATTENFALL

Sodar performance evaluation – wind speed

Unfiltered data

- Mean wind speed difference:
  - 0.12 m/s at 97 m





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Sodar performance evaluation – sources of error

- Under speeding due to freezing
- Over speeding due to high turbulence
- Different sodar positions & incorrect positioning
- Wind direction dependence

9

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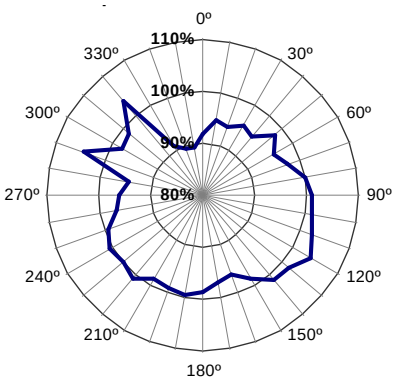
Sodar performance evaluation – sources of error

- Wind direction dependence
  - Different surroundings (micro-scale)
  - Met mast shading of anemometers
  - Met mast shading of sodar



Sodar / cup anemometer ratio for mean wind speed

10

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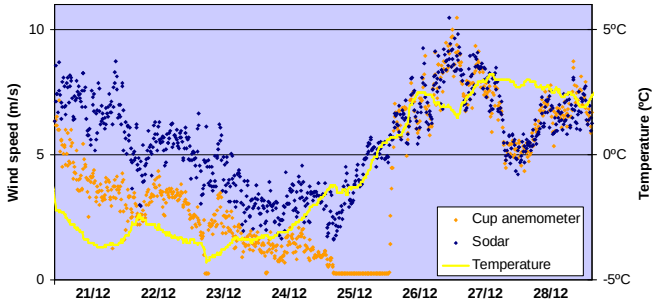
Sodar performance evaluation – sources of error

Under speeding due to freezing

- 1-3% of the data
- 0.06 m/s in mean wind speed



11

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Sodar performance evaluation – filtered data

Filtered data

- Mean wind speed difference:
  - 0.02 m/s at 97 m
- Correlation:
  - Improved to 0.90 from 0.80

12

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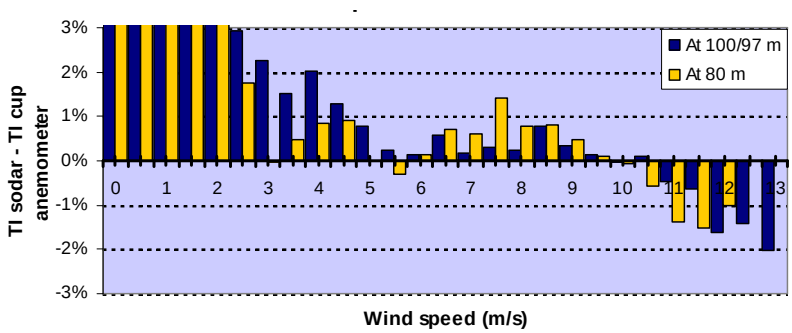
Sodar performance evaluation – turbulence

- Less than 1% difference at 5-12 m/s
  - Lower wind speed not important
  - Higher wind speed too few data



13

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Updated sodar analysis

14

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Reliability and extended comparisons

- Very high availability and reliability
  - Single problem with actual sodar unit (replaced in a week)
  - Few problems with power supply
  - Limited problems with fixed echoes
- Extending the comparative analysis to all relevant sodar units, presently own and operated by Vattenfall Vindkraft AB
  - Less time spent on each pair of measurement, but a larger, broader data source

15

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Wind speed, correlation and turbulence comparison

	Wind speed difference	Turbulence difference	Correlation		Comments
Sodar 3	-1.95%	+ 1.1%	0.88		150 m apart
Sodar 8 (site A)	-3.5%	-	0.92		400 m apart, short period
Sodar 12 (site A)	-3.1%	-	0.94		400 m apart
Sodar 12 (site B)	+1%	-	-		150 m apart

16

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Summary and future work

17

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Summary and future work

- AQ500 is an good substitute/complement for met masts
- 12 month met mast comparison has been started, the effect of scalar/vector averaging will be studied together with AQ System. Possibly also higher frequency comparisons with ultrasonic anemometers.

18

VATTENFALL

Discussions and further questions
19
VATTENFALL

IEA Topical Expert Meeting 59
Remote Wind Speed Sensing Techniques using Sodar and Lidar
2009-10-15,16

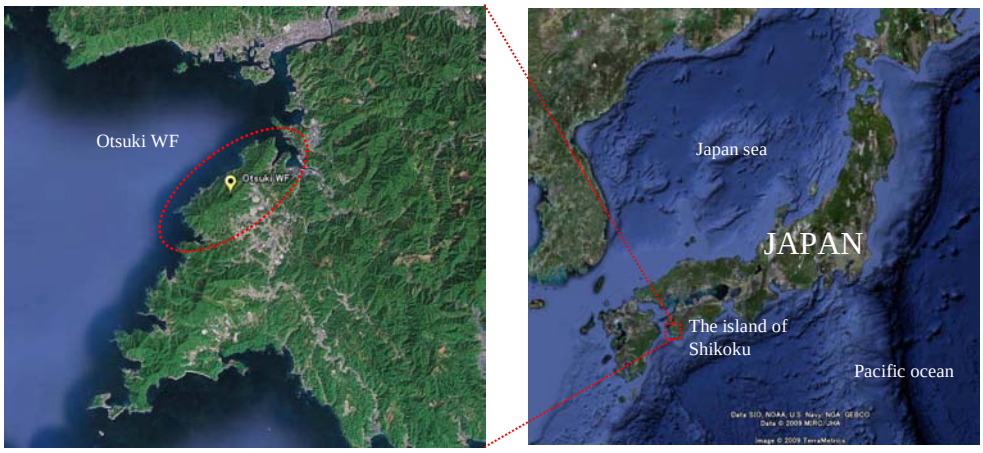
Analysis of SODAR Measurements over Complex Terrain in JAPAN

Nobuyuki HAYASAKI
ITOCHU Techno-Solutions Corporation, JAPAN
nobuyuki.hayasaki@ctc-g.co.jp

Yoshiki ITO
SONIC Corporation, JAPAN
yoshiki-ito@u-sonic.co.jp

Site Description

- The measurement site called Otsuki WF is located on the island of Shikoku
- The instruments were installed at a height of 280m asl along the mountain ridge.
- The prevailing wind directions are north-west (winter) and south-east (summer).



2

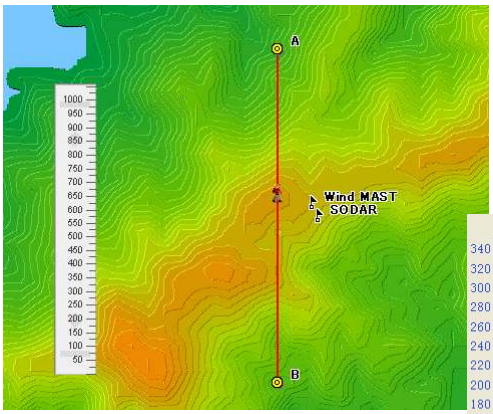
Site Description

- Otsuki WF is complex terrain and forested area.
- There is sea on the north side of Otsuki WF.

View from North side (Oct. 2009)

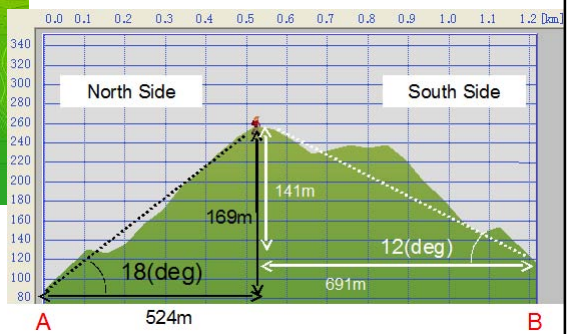
3

Site Description



Contour Map (10m interval)
By digital terrain data (50m grid)

- Otsuki WF has steep slope.
- Gradient Angle (A-B Cross section):
  - North side : 18(deg)
  - South side : 12(deg)

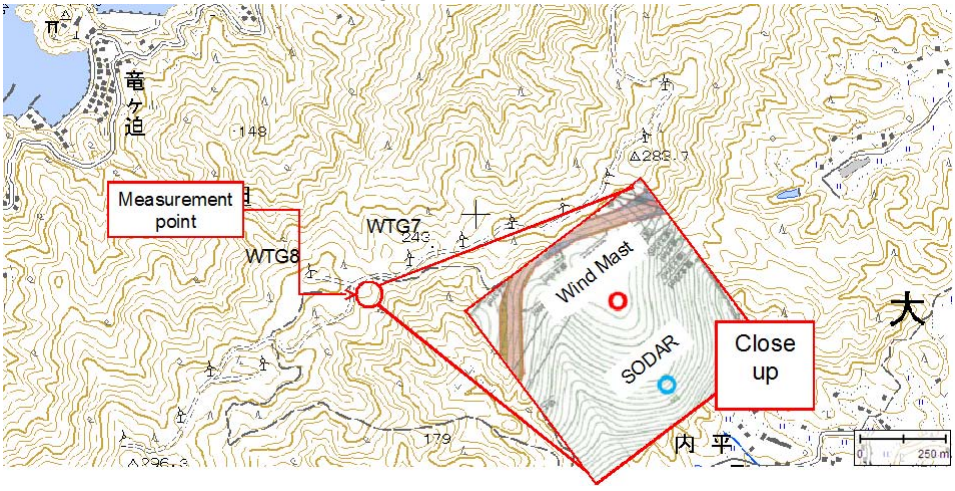


Vertical Cross Section

4

Site Description

- Wind flow is measured over complex terrain by SODAR.
- SODAR is located near the ridge line.
- Wind Mast which has 50m height is installed for SODAR validation.



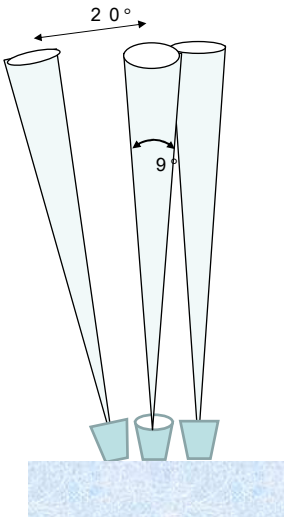
Terrain map around

5

Measurement configuration

- Mono-static SODAR (SONIC Corporation,AR410N)
  - Measuring method : Monostatic doppler sodar
  - Transmission frequency : 2400Hz
  - Transmission pulse length : 30msec
  - Beam width : 9deg
  - Angle of inclination : 20deg

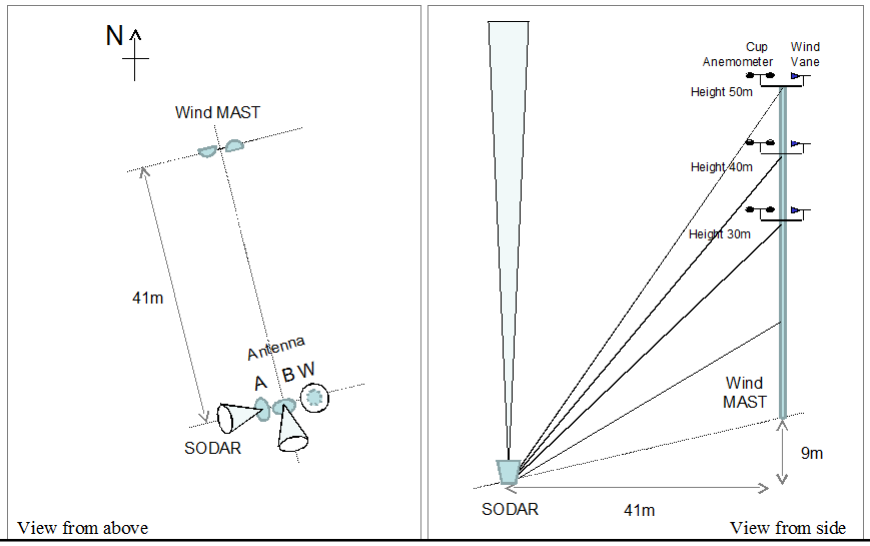
A B



6

Measurement configuration

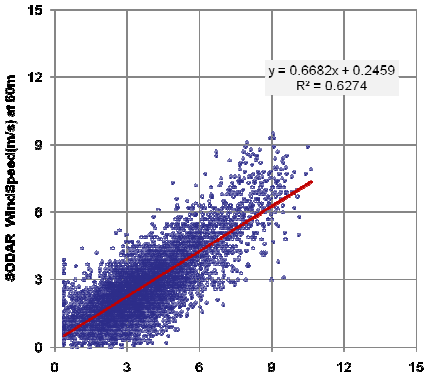
- Positional relationship between SODAR and Wind MAST
  - SODAR is 41m horizontal distance from Wind MAST.
  - There is 9m altitude difference between SODAR and Wind MAST

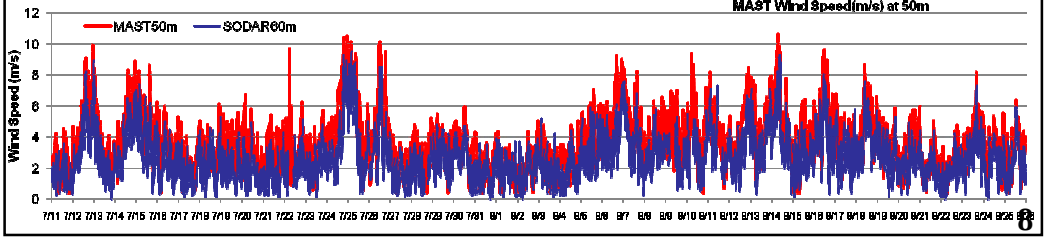


7

Comparison of the measured wind speed

- Comparison between cup anemometer and SODAR wind speed
  - The analyzed period started 11 July 2009 and ended 26 Aug 2009
  - The analyzed SODAR data that acquisition rate for 10min is over 80% is used.
  - Correlation coefficient between cup anemometer and SODAR is 0.792
  - Bias (SODAR – Cup Anemometer) is -0.99m/s
  - The 10min averaged wind speed of SODAR measurements is lower than that of cup anemometer

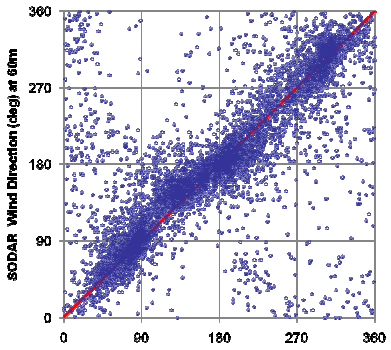


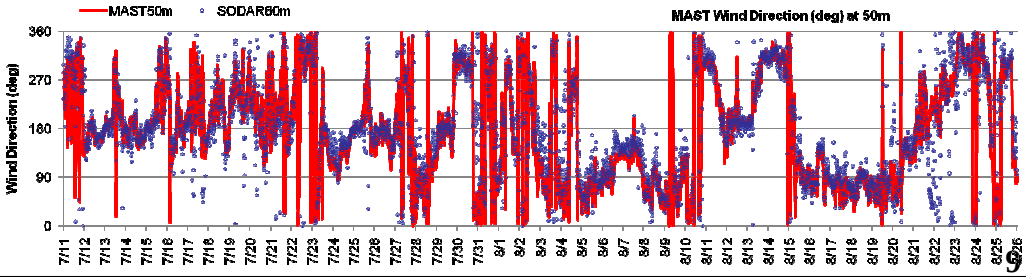


8

Comparison of the measured wind direction

- Comparison between wind vane and SODAR wind direction
  - Wind direction of SODAR is mostly coincided with that of wind vane
  - Low wind speed data is included.



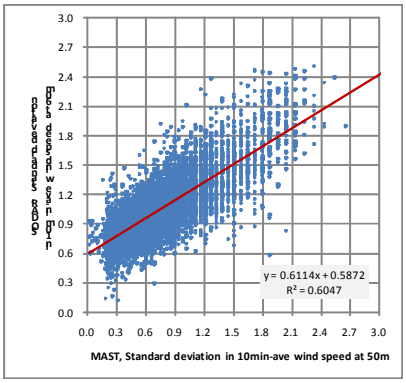


9

Comparison of the measured standard deviation

- Comparison of standard deviation for 10min-ave wind speed
  - Comparison between cup anemometer and SODAR
  - Standard deviation for SODAR tends to be higher than cup anemometer.
    - Average value of standard deviation (Cup anemometer) : 0.789
    - Average value of standard deviation (SODAR) : 1.067

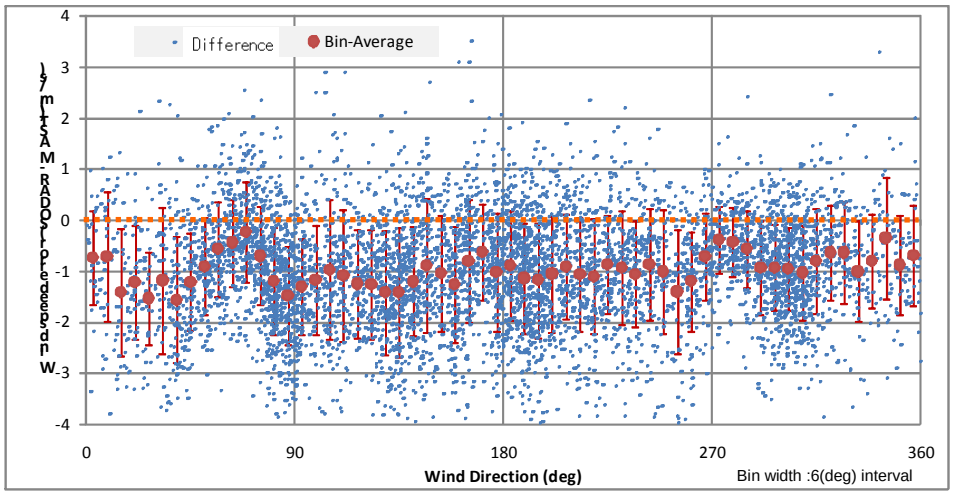
Correlation coefficient	0.778
Bias error	0.278
Average value of standard deviation (Cup anemometer)	0.789
Average value of standard deviation (SODAR)	1.067



10

Comparison of the measured data

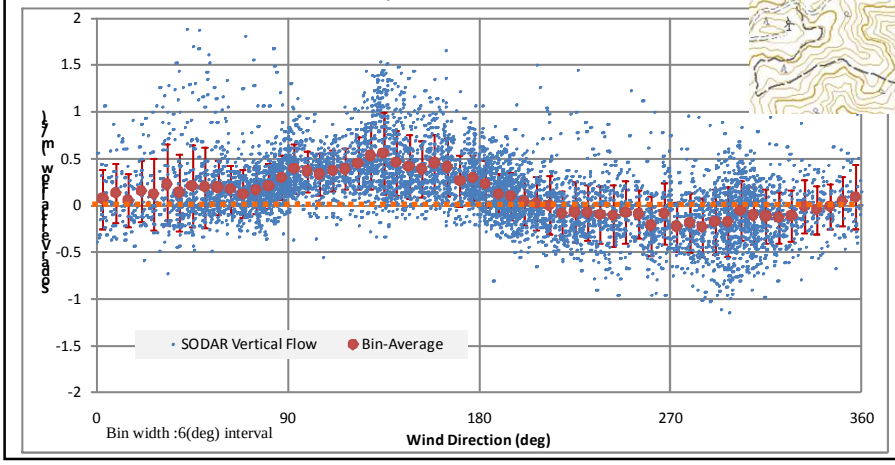
- Wind speed difference (SODAR – Cup Anemometer) for wind direction
  - Wind speed difference (SODAR - Cup Anemometer) depends on wind direction.
  - Wind speed difference (SODAR - Cup Anemometer) in bin-average varies from -0.2m/s to -1.5m/s.



11

Analysis of the SODAR measurements

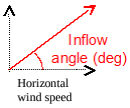
- Vertical wind speed for wind direction
  - Vertical wind speed varies for wind direction
  - In South East wind direction, Vertical wind speed is the highest.
    - South East slope is the highest.
  - The non-uniform of vertical wind speed may affect wind speed estimation of SODAR over complex terrain.

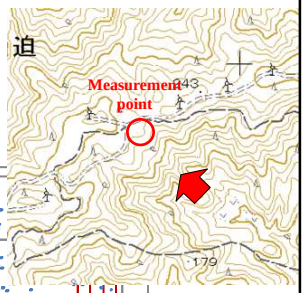


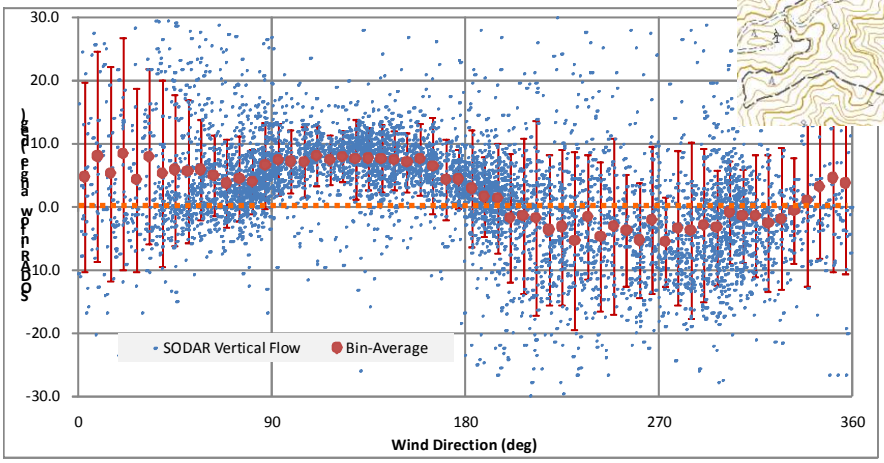
12

Analysis of the SODAR measurements

- Inflow angle for wind direction
  - In South East wind direction, inflow angle in Bin-average is the highest, 8(deg)
  - In the South East wind direction, inflow angle variability is the lowest.

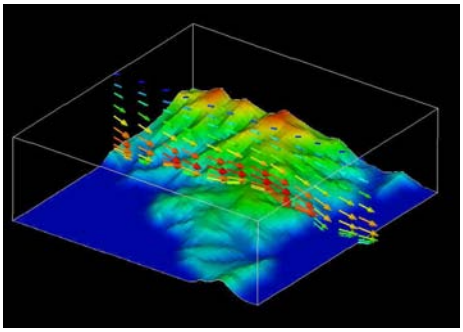






13

Speculation



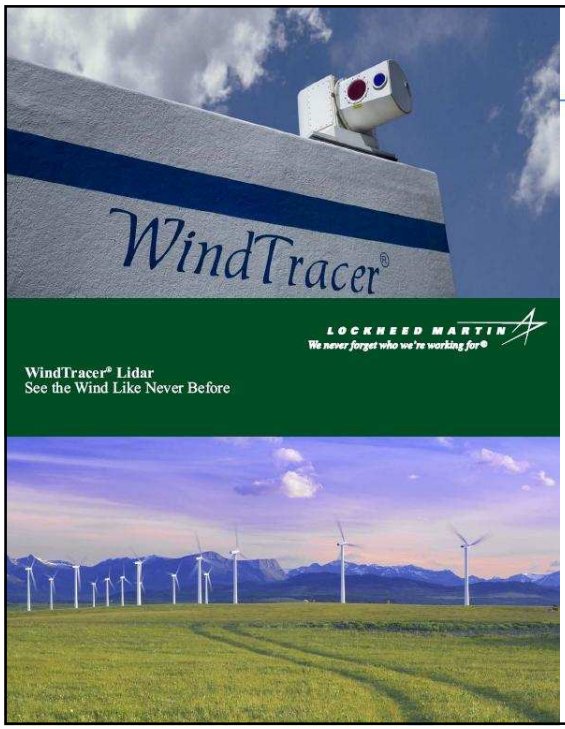
- We think the complex terrain in Otsuki causes the difference between SODAR and cup anemometer
  - Main assumption in SODAR is homogeneous for horizontal flow.
  - Flow distortion over complex terrain is larger than flat terrain.
  - Over revolution of cup anemometer in the complex terrain is possible.
  - We will simulate the wind condition by CFD techniques around this area.
  - We will examine the relationship between flow distortion estimated by CFD technique and SODAR measurement errors over complex terrain.

14

Summary and Future Plan

- Wind flow was measured over complex terrain by SODAR.
- The 10min averaged wind speed of SODAR measurements was systematically lower than that of cup anemometer
- We think the complex terrain in Otsuki causes the difference between SODAR and cup anemometer
- Future plan
  - We will simulate the wind condition by CFD (Computational Fluid Dynamics) techniques around this area.
  - We will examine the relationship between flow distortion estimated by CFD technique and SODAR measurement errors over complex terrain.

15



LIDAR

Cedar Point Experiment

June 2007

Jeff Fine

Measurements at RES Site

Large mesa-like site near Limon, Colorado

WindTracer® and 50 m fixed mast operated by RES

- One anemometer mounted on each side of tower to reduce shadow

One month of data collection during June 2007

Scanning Strategy

- Volumetric 360 deg scan with 10 minute revisit time
- 16 Tilts Utilized to ensure measurements between 70 and 90 meters Above Ground Level available at all viewable points within 6 km of lidar
- Resolution of 100 m radially, 2° in azimuth and in < 1° elevation
- Indicatively 100m resolution (x,y,z)

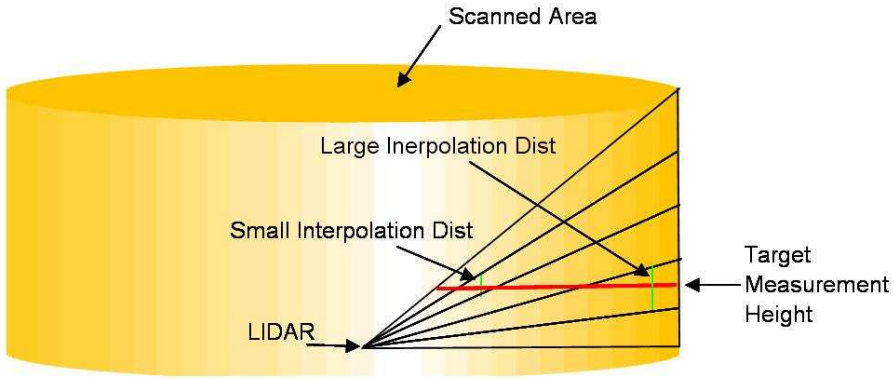
Goal

- 'Terrain-following' gridded output of wind speed and direction at 10 minute intervals

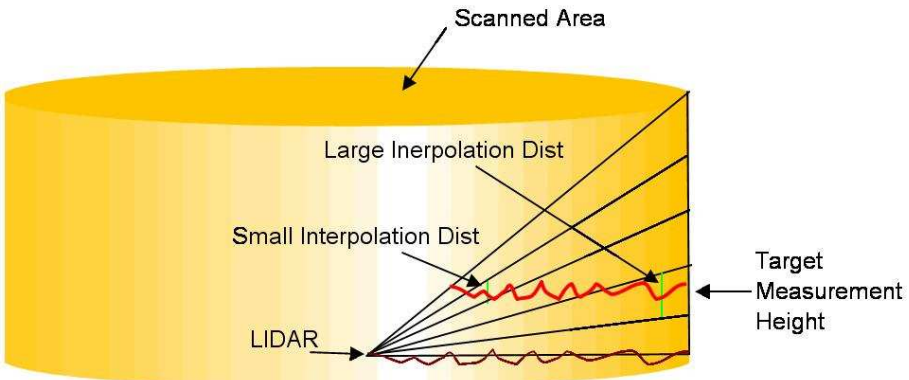
Test

- Extract the time series at the grid point closest to our mast location
- Plot the ratio of MAST Speed / LIDAR Speed by Wind Direction

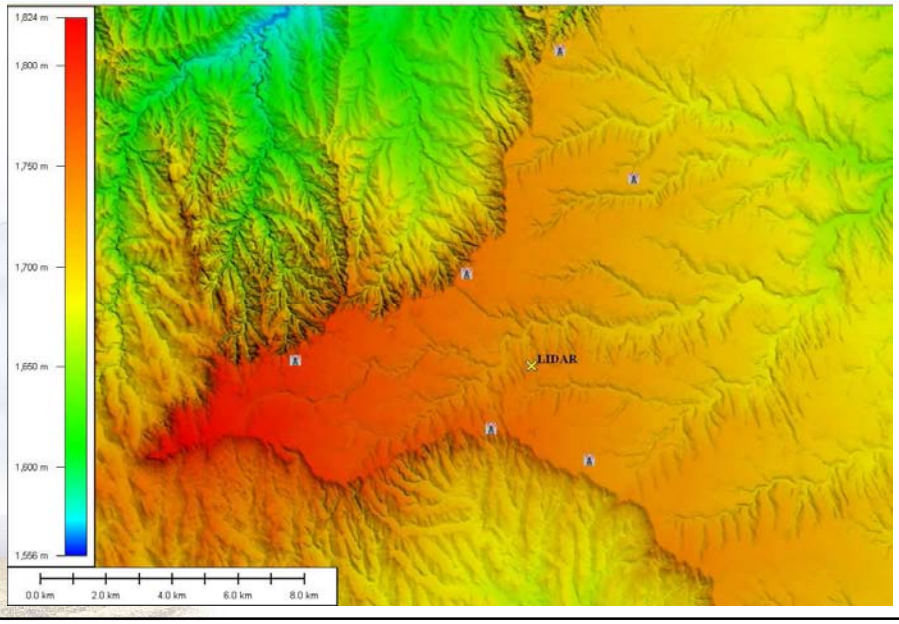
Scan Strategy



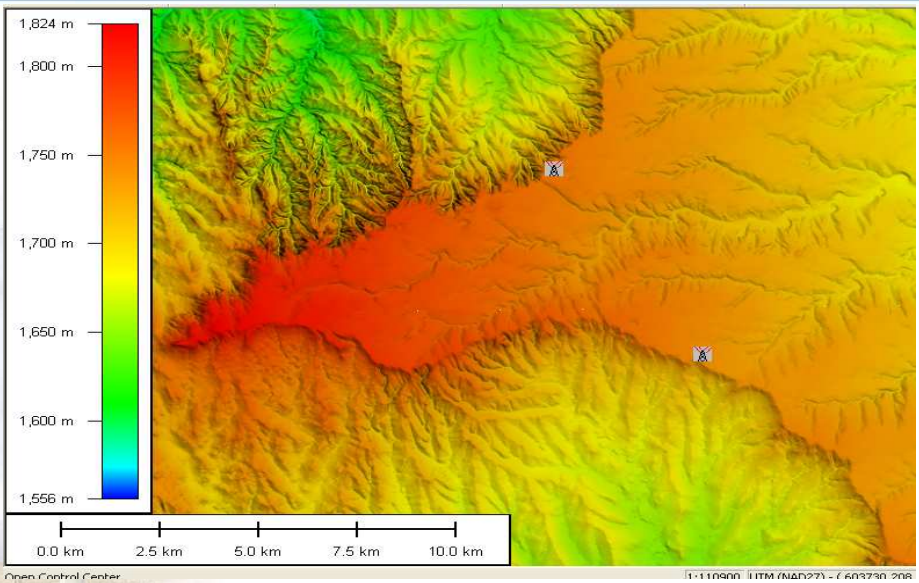
Scan Strategy With Terrain



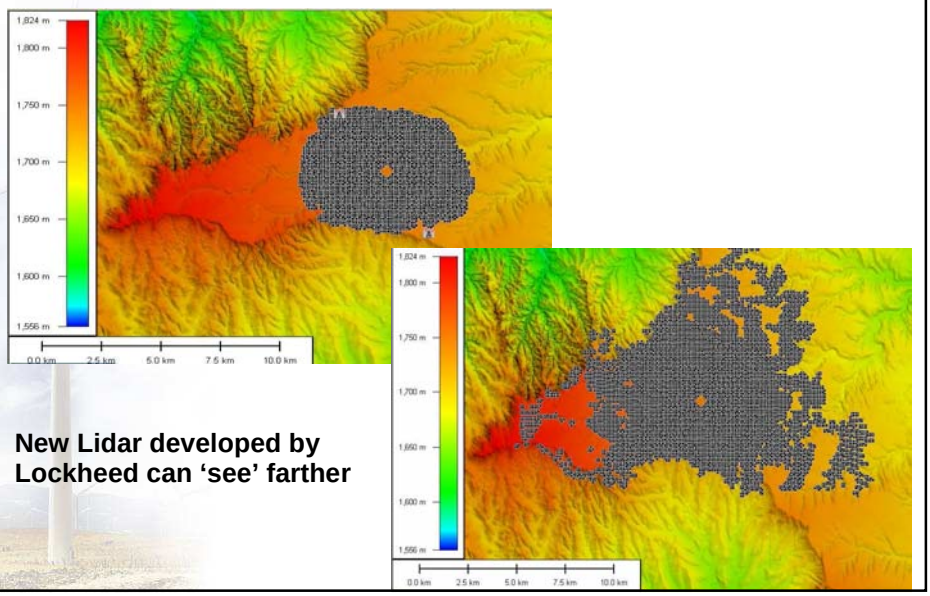
All Mast Locations



First Mast Locations Considered

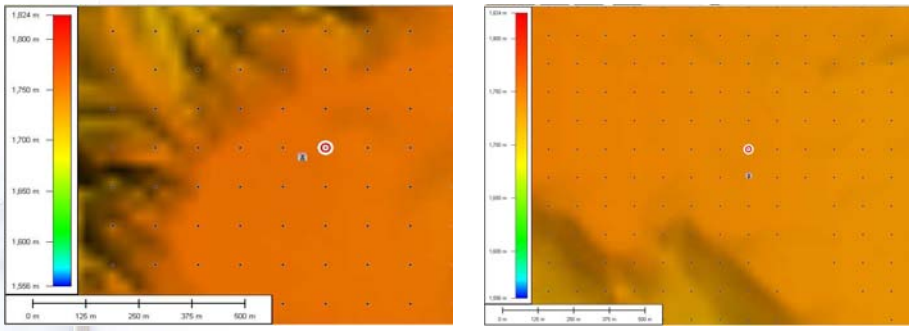


LIDAR Grid: Depends On Atmospheric Conditions



New Lidar developed by Lockheed can 'see' farther

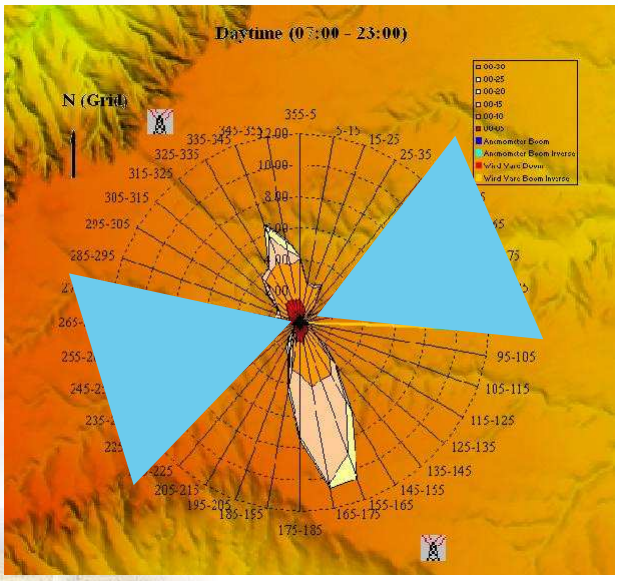
LIDAR Time Series



RES Mast

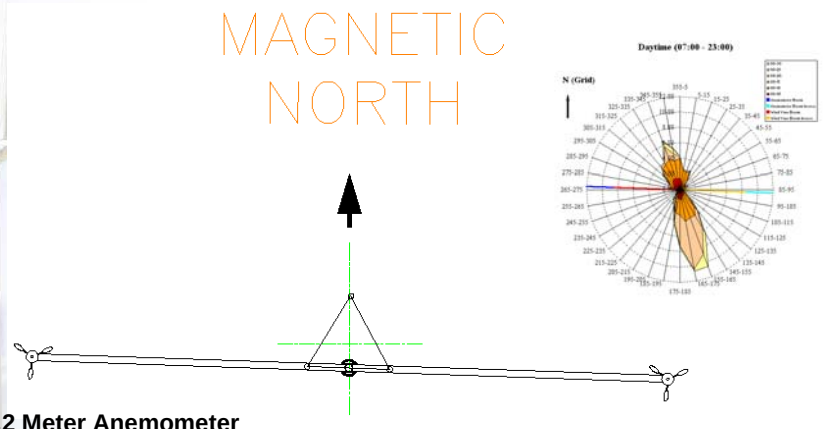
PPM Mast

Wind Rose



Expect Less Accuracy Perpendicular To Primary Directions

RES Boom Orientation



50.2 Meter Anemometer

Grid North Orientation: 272°

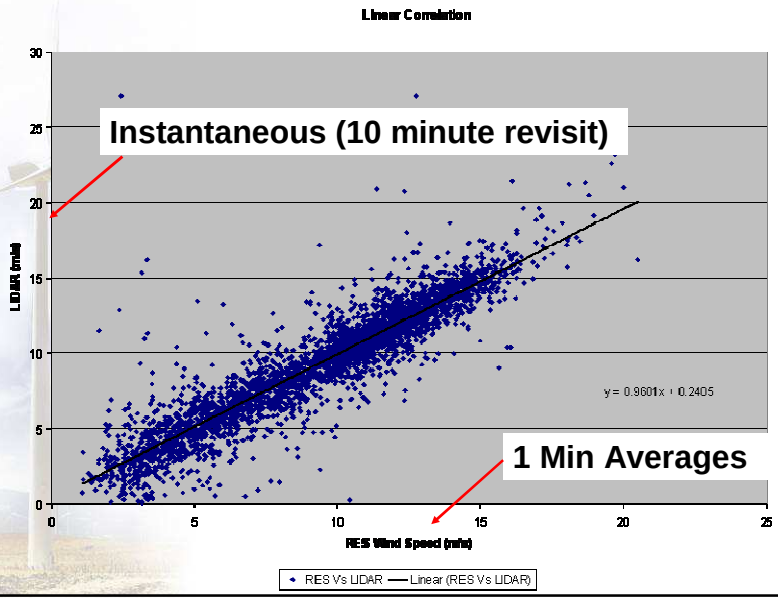
50.0 Meter Anemometer

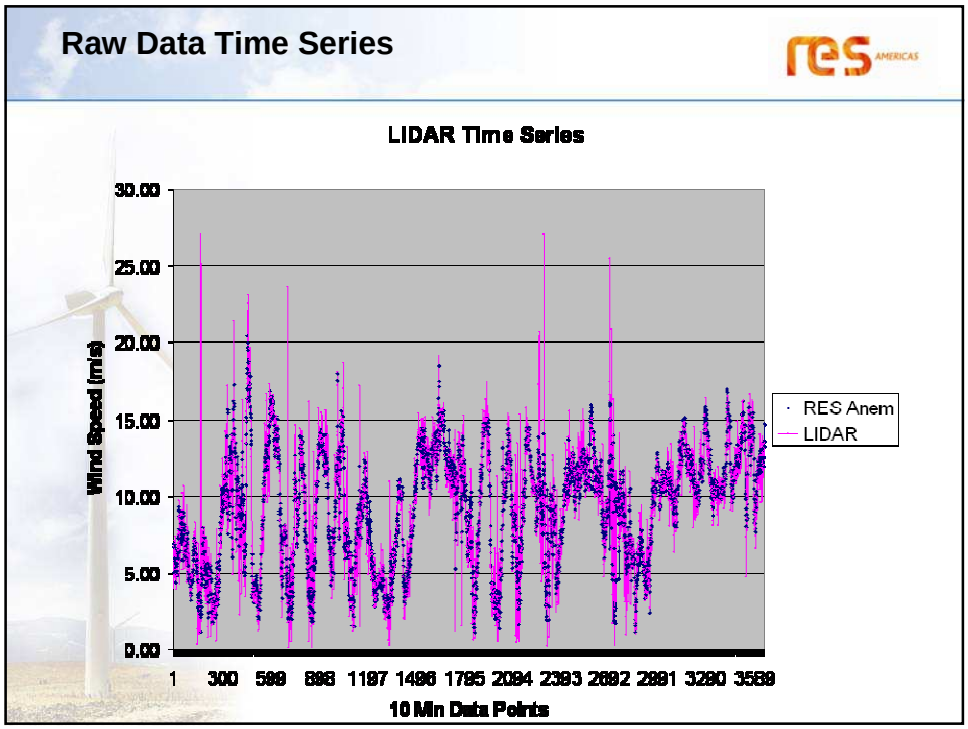
Grid North Orientation: 92°

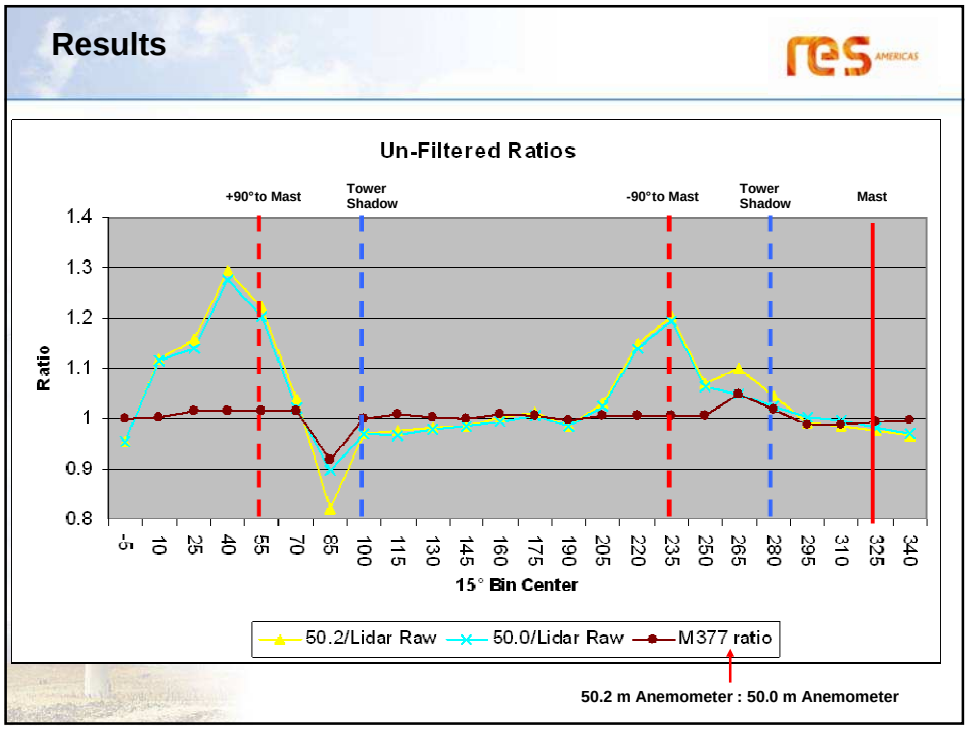
Results

- Overall Wind Speed Averages Of Time Series
  - RES 50.2m Anemometer = 9.25 m/s
  - LIDAR = 9.23 m/s
  - PPM Mast = 8.12 m/s
  - LIDAR = 8.06 m/s
- Excellent agreement!

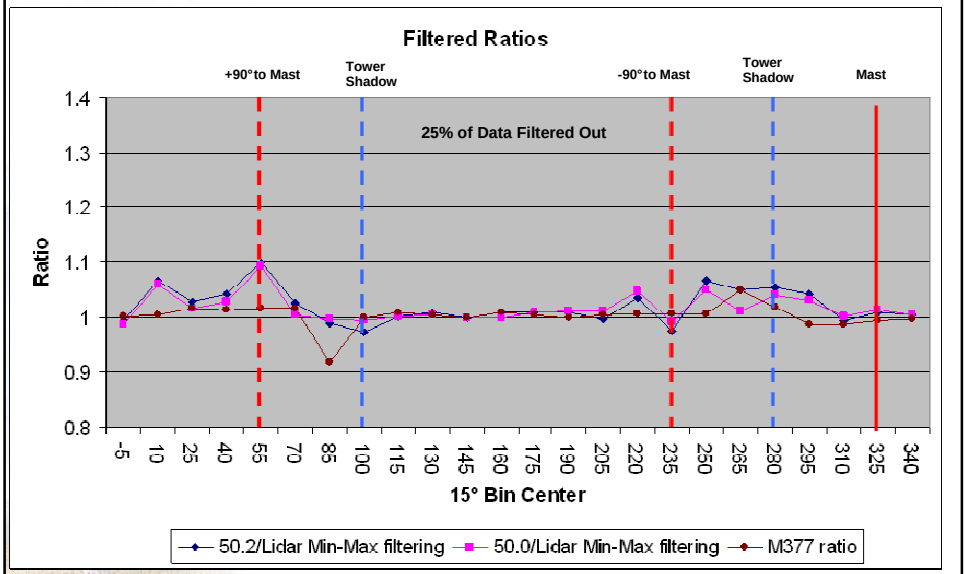
Scatter Plot



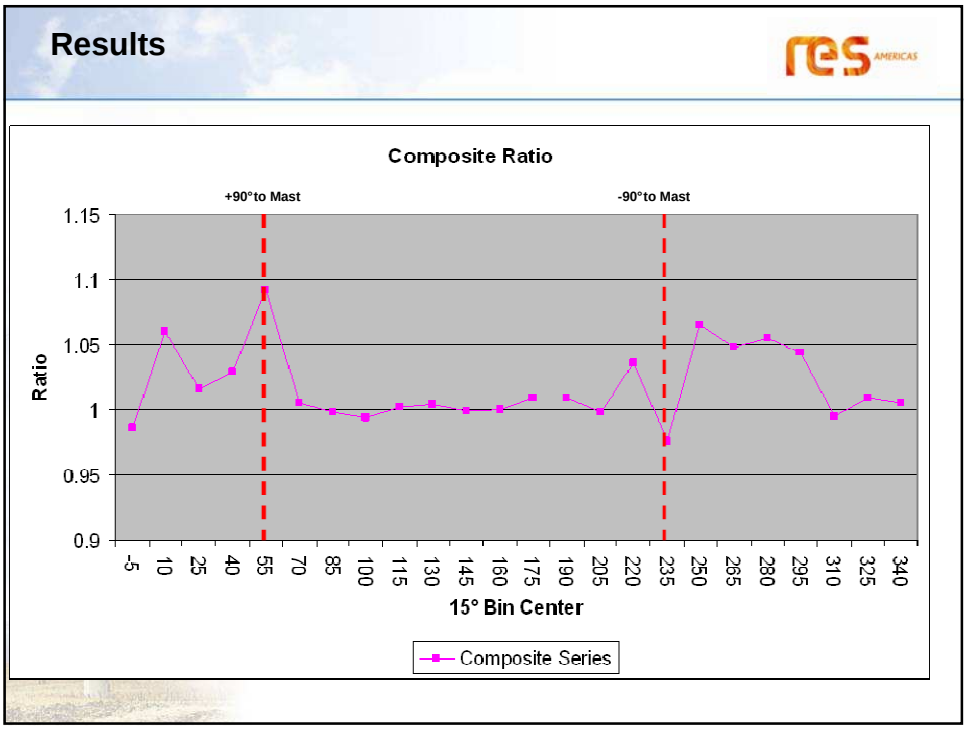

Raw Data Time Series
LIDAR Time Series
Wind Speed (m/s)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
300
599
898
1197
1496
1795
2094
2393
2692
2991
3290
3589
10 Min Data Points
RES Anem
LIDAR


Results
Un-Filtered Ratios
+90°to Mast
Tower Shadow
-90°to Mast
Tower Shadow
Mast
Ratio
1.4
1.3
1.2
1.1
1
0.9
0.8
-5
10
25
40
55
70
85
100
115
130
145
160
175
190
205
220
235
250
265
280
295
310
325
340
15° Bin Center
50.2/Lidar Raw
50.0/Lidar Raw
M377 ratio
50.2 m Anemometer : 50.0 m Anemometer

Results



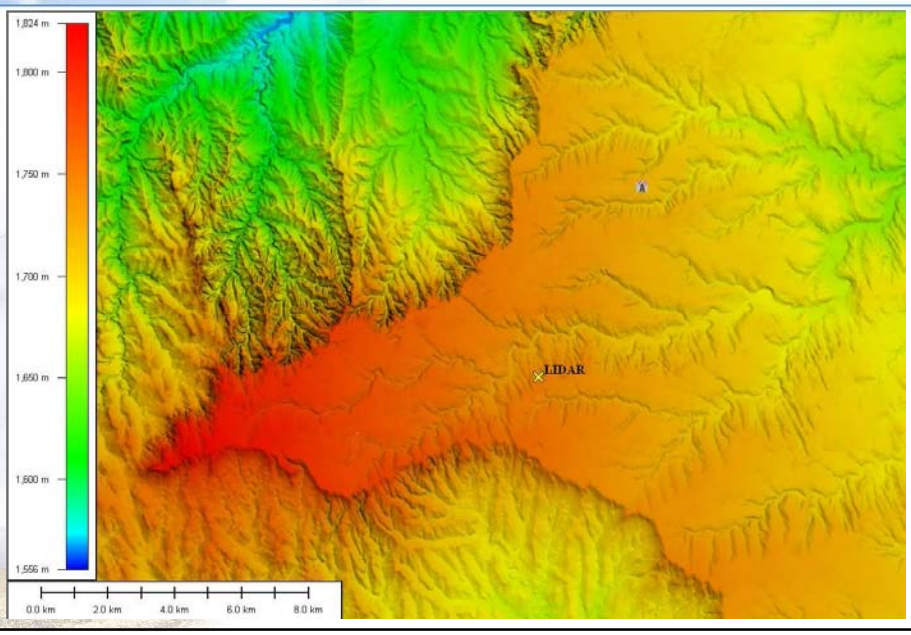
Results



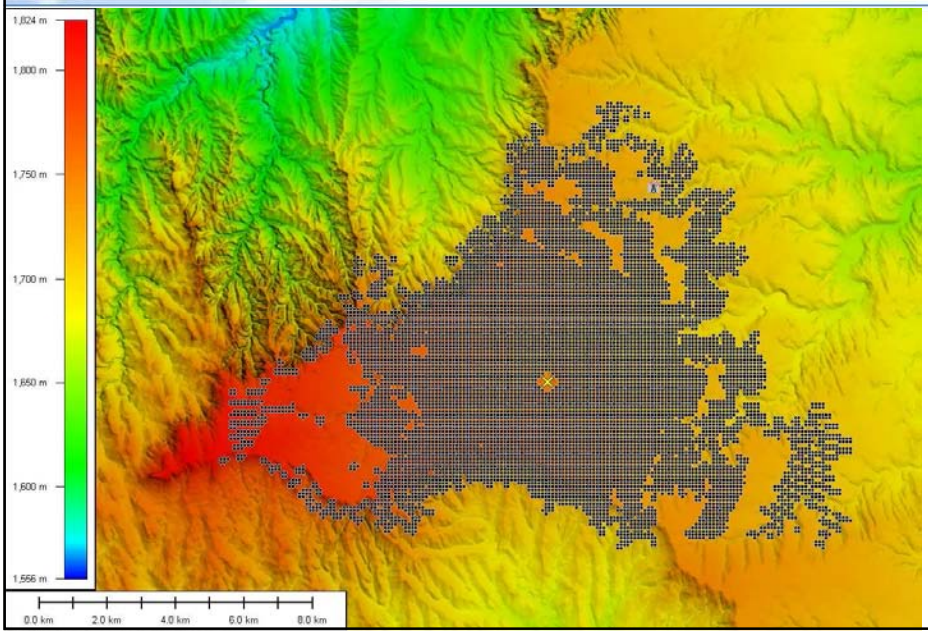
More Recent work

- Use concurrent periods between RES masts to develop a correlation
- Predict Mast data that would be concurrent to LIDAR data
- Compare time series ratios

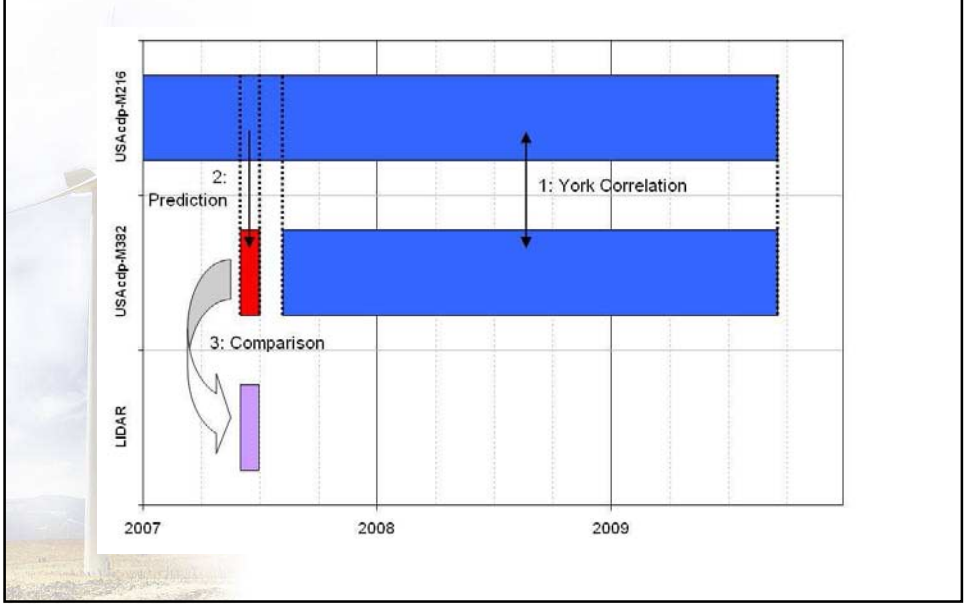
Mast Location



LIDAR Grid: Depends On Atmospheric Conditions



Prediction Method



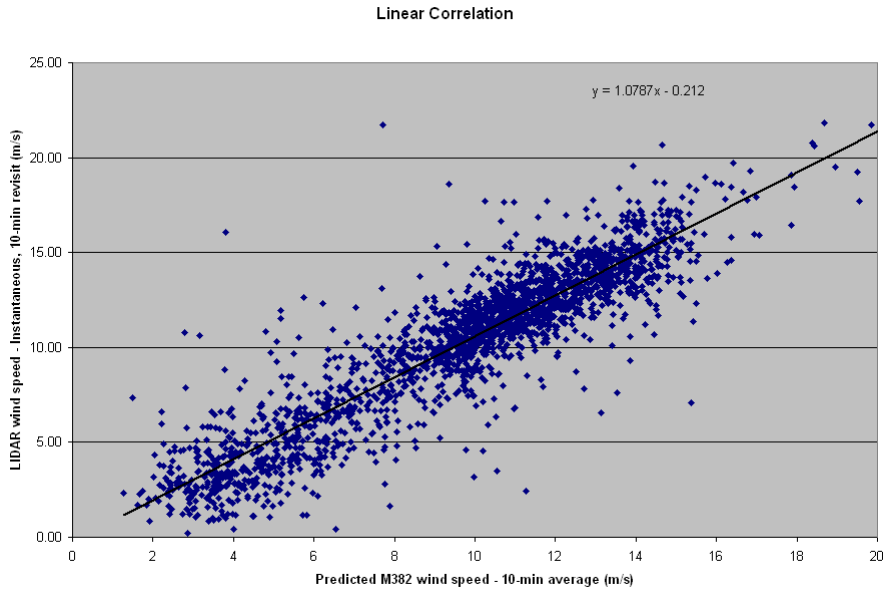
Results

•RES “Predicted Mast Data”

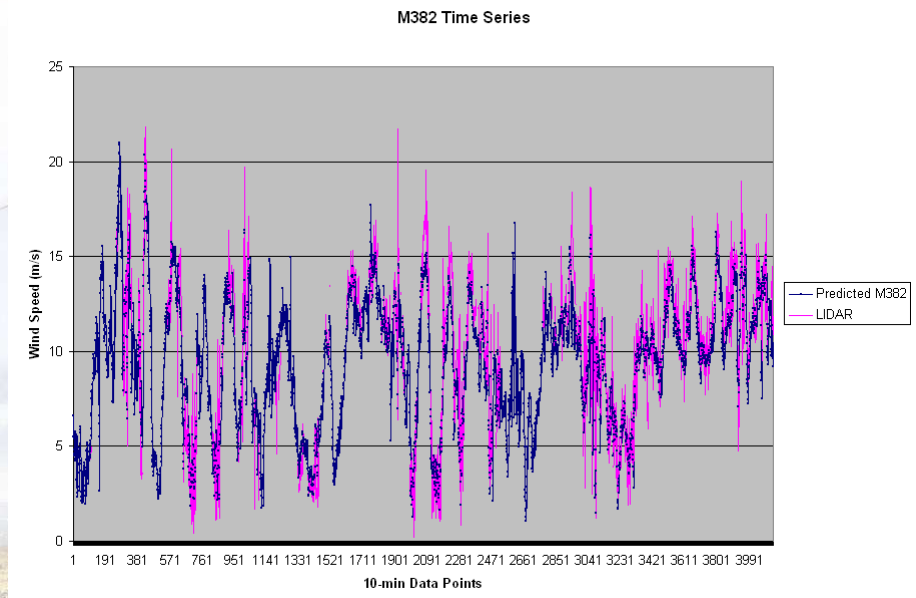
- Single Sector York = 9.92 m/s
- 12 Sector York = 9.71 m/s
- LIDAR = 10.26 m/s

•Prediction bias/error on such a short time-scale

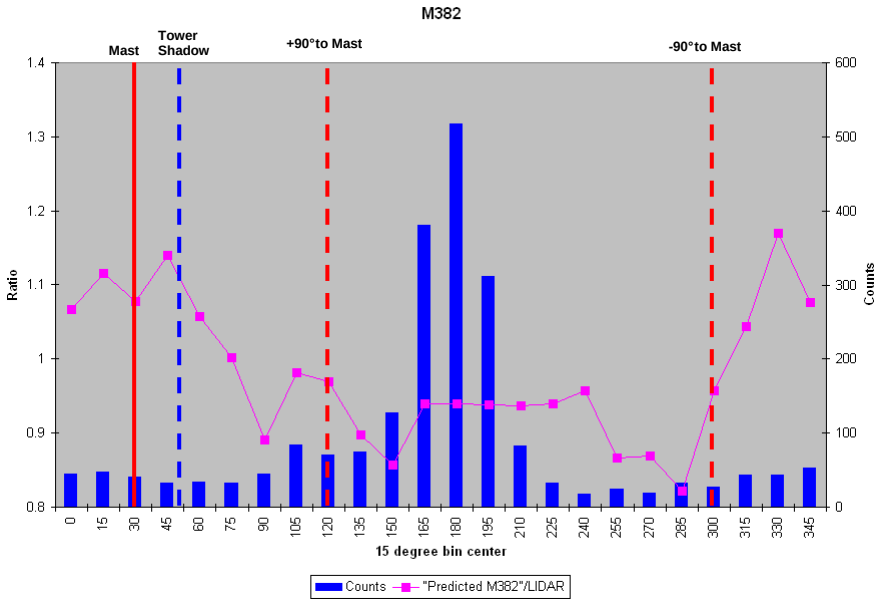
Scatter Plot



Raw Data Time Series



12 Sector York Result

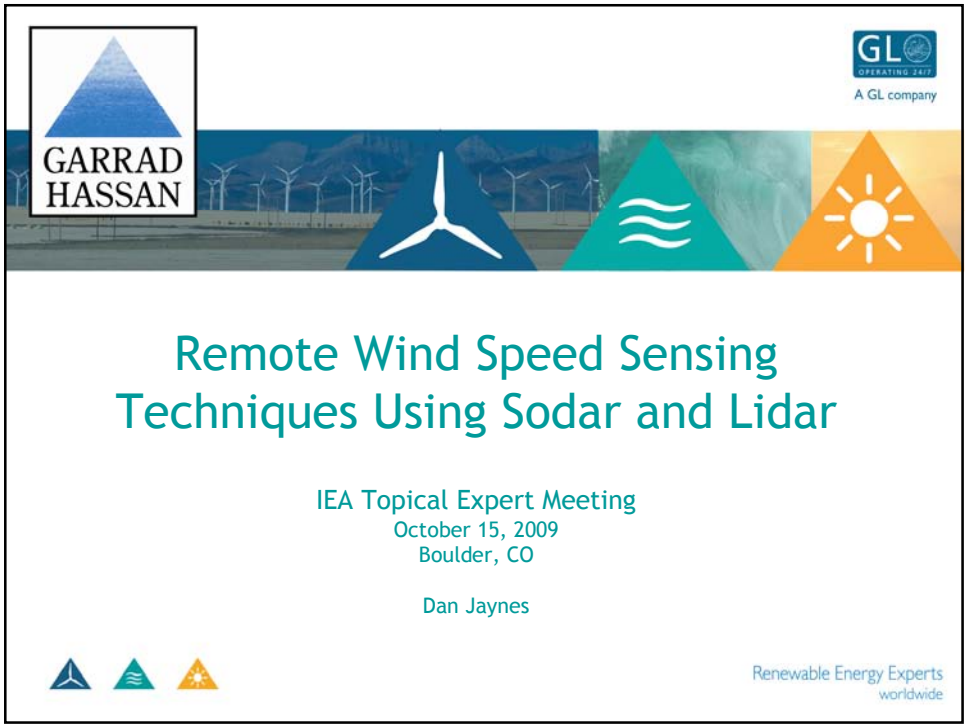


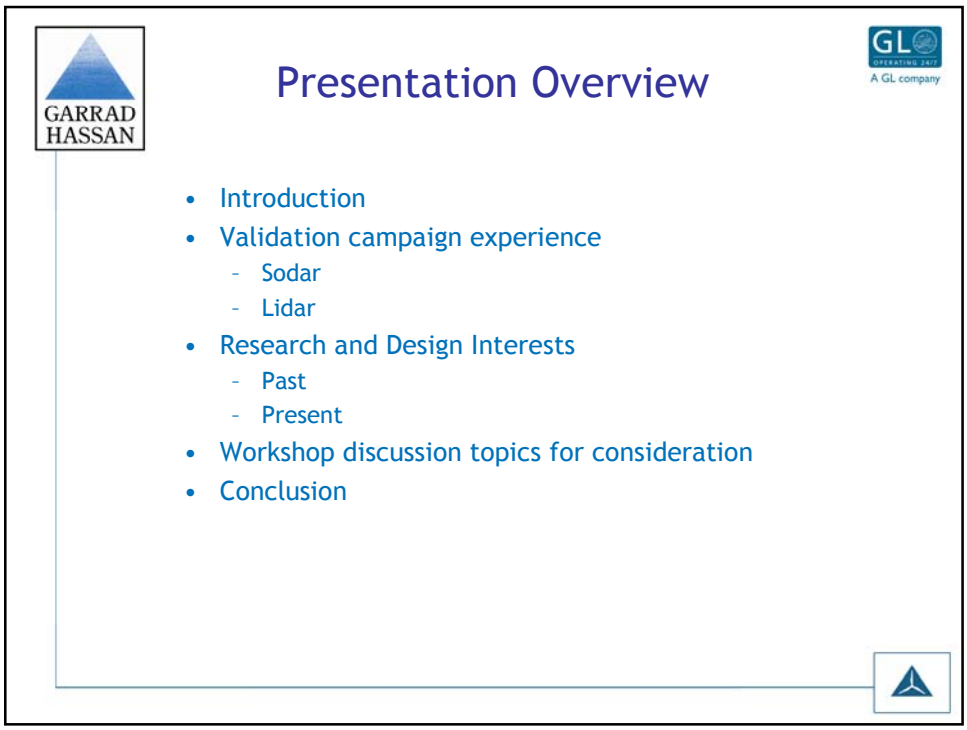
Conclusions

- Agreement with tower data was excellent on an overall average basis
- But accuracy by direction is highly dependent on site placement relative to the wind rose
  - Either need to use 2 or 3 in conjunction
  - Or move device a couple of times
- Need better understanding of limitations in more complicated terrain (we are trying to evaluate at a fixed height above ground
- Resolution is good in near field, but poor farther afield
- Needs to be used in conjunction with at least one meteorological tower
- Use only concurrent mast data as reference

Future Work

- Generate a methodology for site placement
- Create a template for data validation
- Achieve ‘Consultant Blessing’


GARRAD HASSAN
GL
A GL company
Remote Wind Speed Sensing
Techniques Using Sodar and Lidar
IEA Topical Expert Meeting
October 15, 2009
Boulder, CO
Dan Jaynes
Renewable Energy Experts
worldwide


GARRAD HASSAN
GL
A GL company
Presentation Overview
Introduction
Validation campaign experience
Sodar
Lidar
Research and Design Interests
Past
Present
Workshop discussion topics for consideration
Conclusion

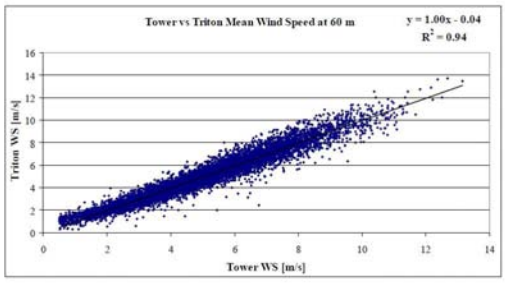
Introduction

- Presentation tone: Focus on discussion and collaboration
- Recent merger
  - Garrad Hassan Global Partners
  - Helimax
  - WINDTEST
  - Noble Denton

Happy Family

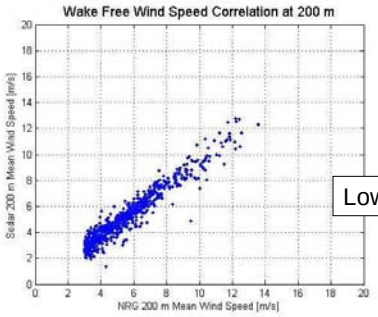
On-Shore Sodar Validation Experience

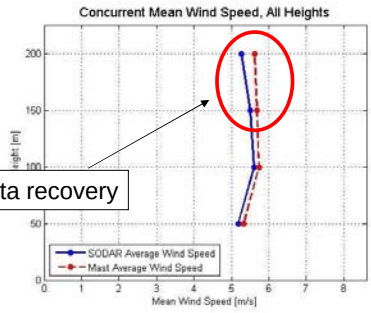
- Flat Terrain measurement campaigns - Second Wind Triton
- 60 m met mast located approximately 60 meters away at a site in KS



On-Shore Sodar Validation Experience

- Sodar Validation up to 200 m at Boulder Atmospheric Observatory
- Data provided by Second Wind
- Sodar comparison to uncalibrated SW C3 cup anemometers

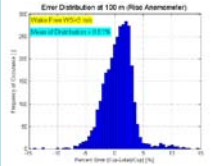


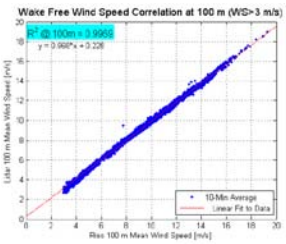


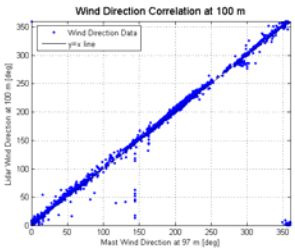
Low data recovery

On-Shore Lidar Validation Experience

- Simple terrain site in the Great Plains – Pulsed Lidar
- Collaboration with NRG Energy/Padoma Wind Power
- Lidar deployed next to a 100 m mast fitted with calibrated IEC anemometers

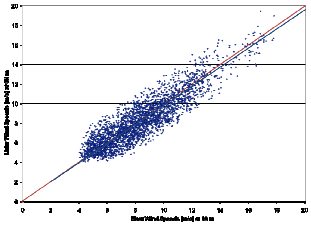


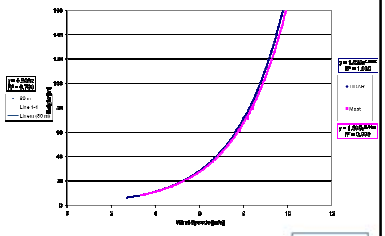




On-Shore Lidar Validation Experience

- Complex terrain site Northern Rockies – Continuous Wave Lidar
- Lidar deployed next to an 80 m met mast
- Helimax collaboration



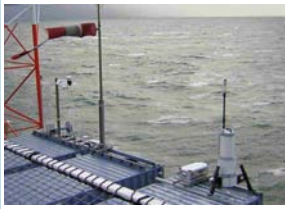


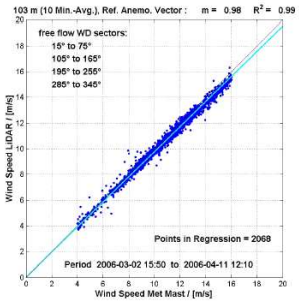
Lidar Measurement in Cold Weather

- Helimax Northern Canada deployment – difficult conditions
- ZephIR Lidar with stand-alone power supply

Offshore Lidar Validation

- WINDTEST, Natural Power, Oldbaum Services: ZephIR Measurement campaign on the FINO-1 platform in the North Sea





Kindler, D., A. Oldroyd, A. MacAskill, D. Finch, "An 8 month test campaign of the QinetiQ ZephIR system: Preliminary Results." J. of Wind Engineering and Industrial Aerodynamics Vol 95, Issue 12, Dec 2007.

Offshore Lidar Measurement Campaign

- Helimax CW Lidar deployment on an island in Lake Ontario
- Custom enclosure
- Deployed near tall tower
- Project finance applications
- Data not yet available

Ongoing R&D Efforts

- Sodar/Lidar Validation in flat and complex terrain
- Sodar/Lidar best practices for project finance applications:
  - Onshore: flat and complex terrain
  - Offshore
- Turbine power curve measurement and performance characteristics
- Sodar and Lidar head-to-head comparisons
- Sensitivity to vertical and lateral turbulence intensity
  - Implications to turbine loading
- Extreme wind speed analysis with remote sensing

R&D - NORSEWInD Project

- Collaboration between WINDTEST, Risø and Oldbaum Services
- Explore Lidar, satellite, mesoscale modeling and conventional met masts for wind resource characterization in high value areas
- Multiple Lidar validations at Høvsøre (pulsed and CW)

Workshop Discussion Topics

- Complex terrain error mitigation and modeling techniques
  - Risø work on WAsP script (Ferhat Bingöl)
  - Introduction of CFD analysis to compare with WAsP and other methods
- Turbine loading and relationship with volume averaged turbulence parameters provided by remote sensing instruments
  - IEC guidance required
  - Discussion on this topic would be useful

Workshop Discussion Topics

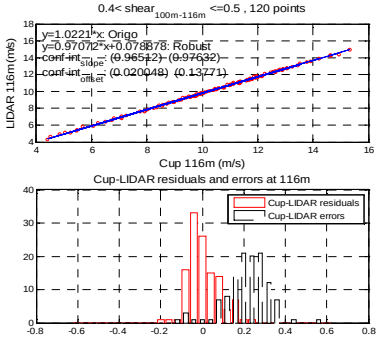
- Continued diligence on simple and complex terrain validation
  - Explore environmental variables that can induce measurement error:
    - Shear
    - Turbulence
      - Vertical
      - lateral
    - Aerosol distribution
      - including diurnal variations
    - Diurnal variation in temperature and turbulence characteristics
    - Investigation of changing speed of sound with respect to vertical temperature variation
    - Siting
      - Location
      - System level
- Power curve measurement
  - Influence of wind shear (R. Wagner)
  - Rotor flux AEP calculation approach (I. Antoniou)

Workshop Discussion Topics

- Lidar system stability
  - Causes
  - Correction approach
    - Status updates?
- Sodar echo rejection algorithm development
  - New developments?
- Investigation of the presence of the LLJ
  - Great plains (N. Kelly)
  - Other locations

Workshop Discussion Topics - Continued

- Presence of wind shear in remote sensing probe volume
  - Recent work presented by Ioannis Antoniou:



- Can bias associated with wind shear in the probe volume be accurately characterized and corrected?

Acknowledgements

- Second Wind
- Padoma Wind Power

- Colleagues at Helimax and WINDTEST
  - Dariush Faghani
  - Detlef Kindler

Thank you for your attention

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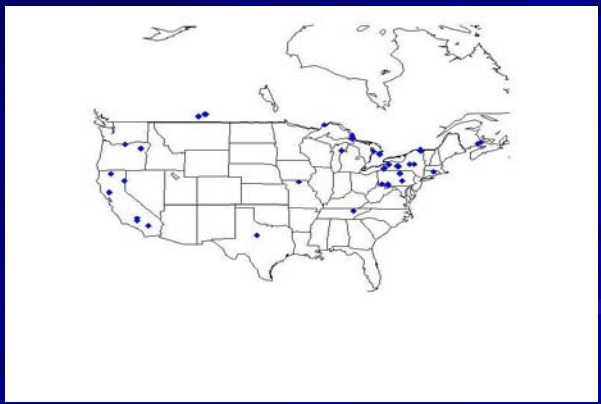
Sodar for Wind Resource Assessment

Kathleen E. Moore
Integrated Environmental Data, LLC

Acknowledgement

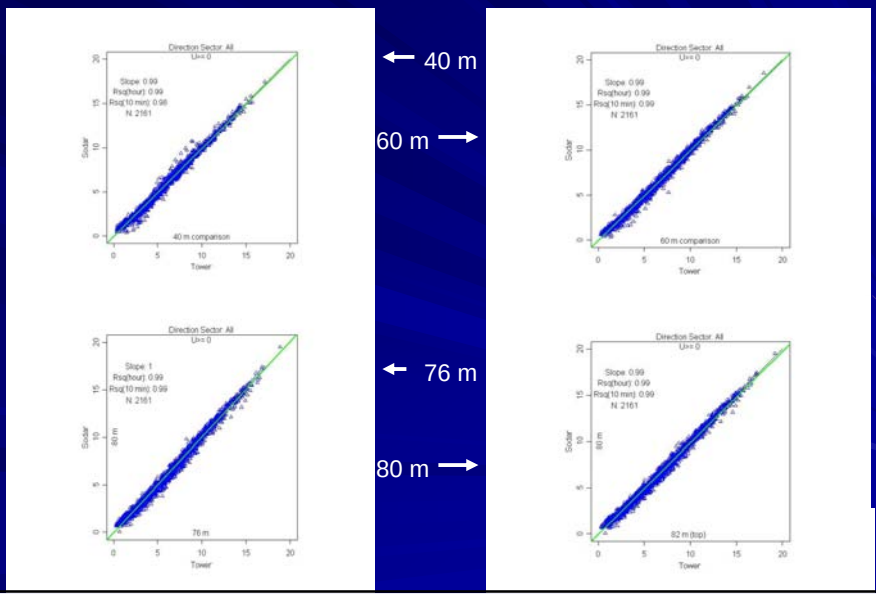
- AWS Truewind, LLC
- More than 200 campaigns with more than 20 sodars from 4 manufacturers

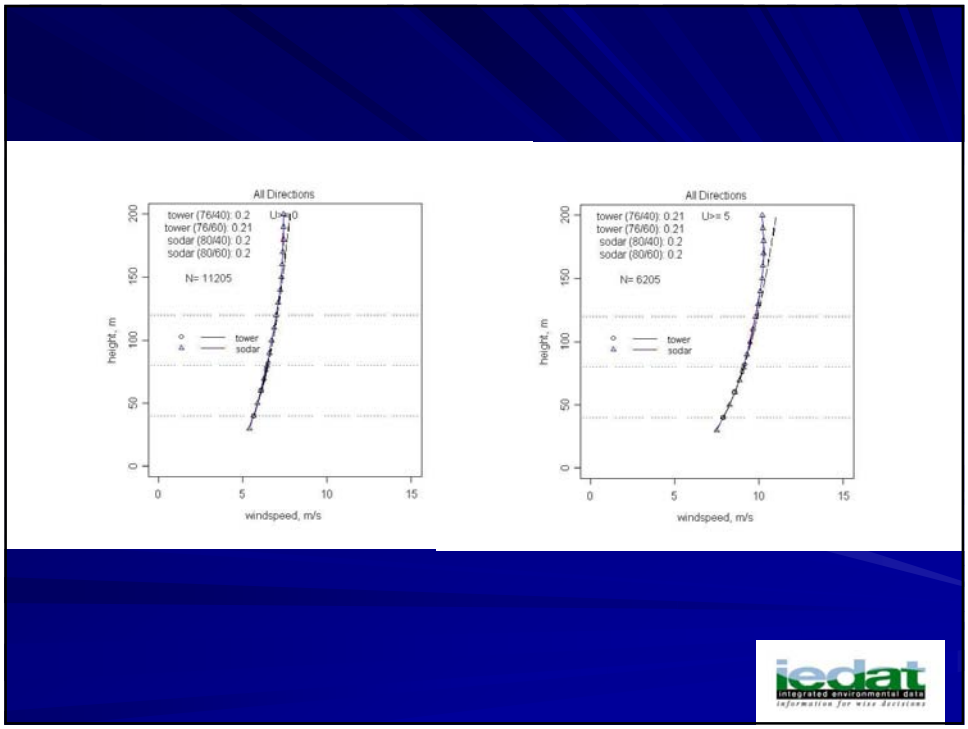
- Perspective of active user
- Used operationally for more than 200 sites
- Shear vs. mobile met. tower—always comparing to a tower

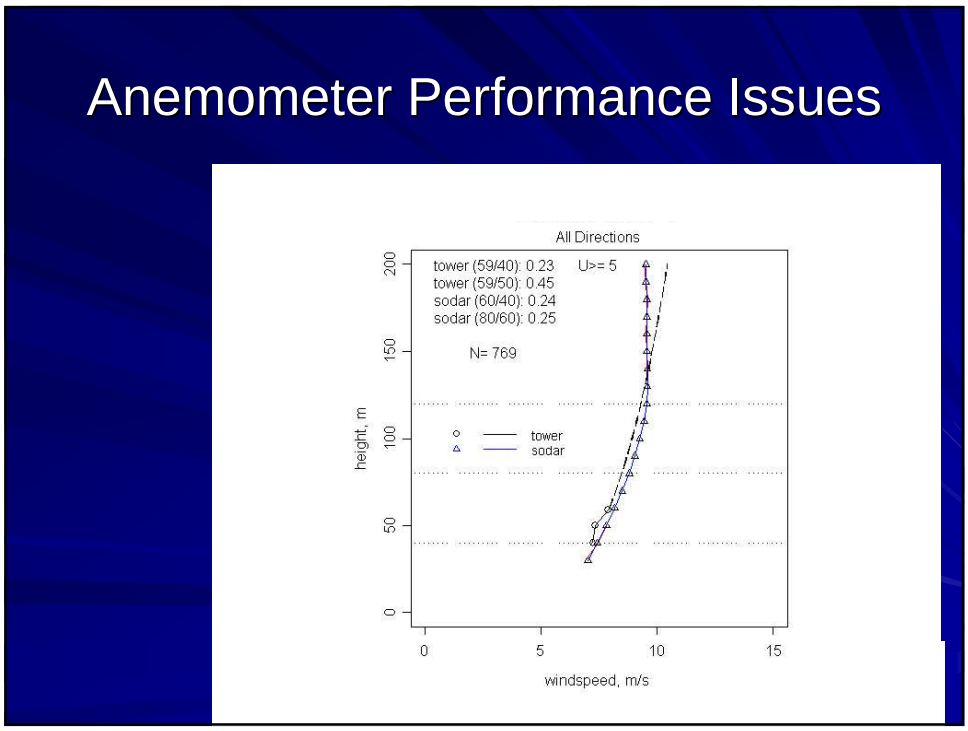


iedat
integrated environmental data
information for wise decisions

Comparison is excellent at all heights from 40 m to 80 m




All Directions
tower (76/40): 0.2
tower (76/60): 0.21
sodar (80/40): 0.2
sodar (80/60): 0.2
N= 11205
tower
sodar
height, m
windspeed, m/s
All Directions
tower (76/40): 0.21
tower (76/60): 0.21
sodar (80/40): 0.2
sodar (80/60): 0.2
U>= 5
N= 6205
tower
sodar
height, m
windspeed, m/s
iedat
integrated environmental data
information for wise decisions


Anemometer Performance Issues
All Directions
tower (59/40): 0.23
tower (59/50): 0.45
sodar (60/40): 0.24
sodar (80/60): 0.25
U>= 5
N= 769
tower
sodar
height, m
windspeed, m/s

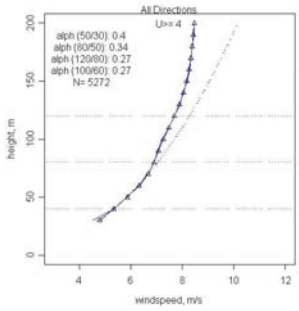
How Sodar Differs from Anemometers ….and what to do about it!

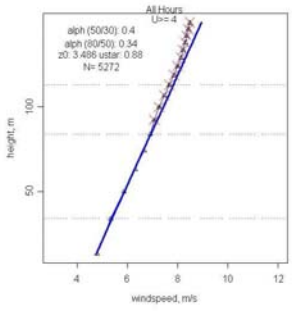
- Sodar beam tilt (temperature)
- Vector versus scalar wind speed (σ_w)
- Turbulence intensity and anemometer overspeeding (σ_w)
- Flow Inclination (w/U)
- Volume Averaging

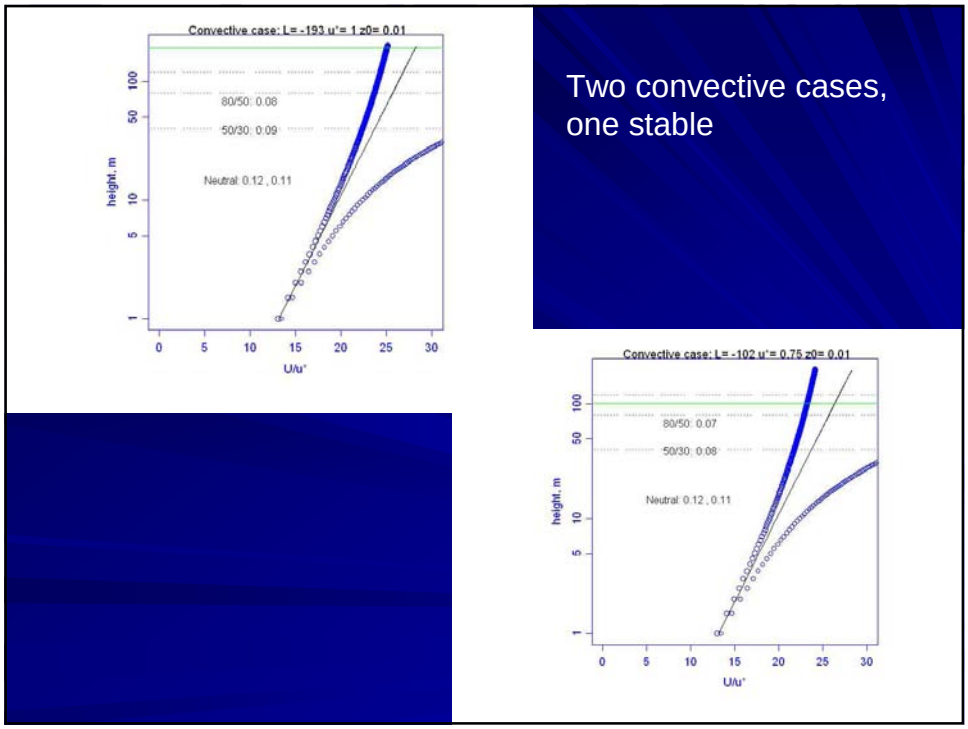
See Moore, K. E. and B. H. Bailey, 2005. Maximizing the Accuracy of Sodar Measurements for Wind Resource Assessment. AWEA, WindPower 2005.

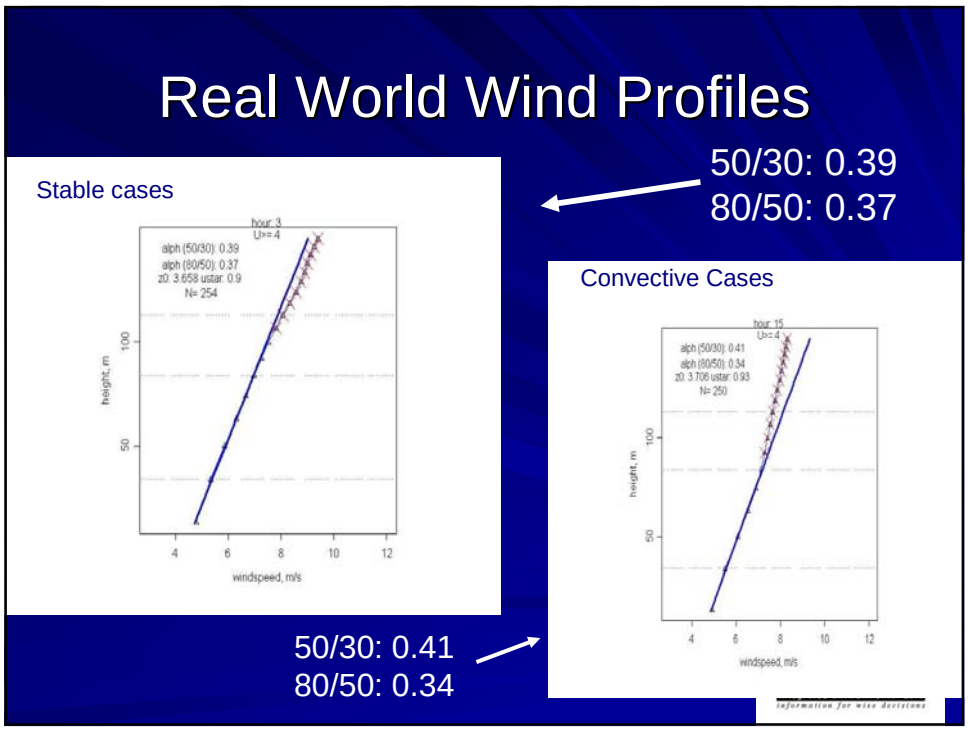
Linear vs. Logarithmic Profile

(There is often a limit to the logarithmic profile)



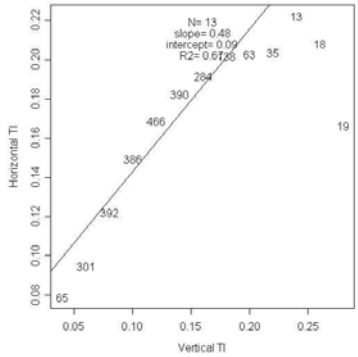


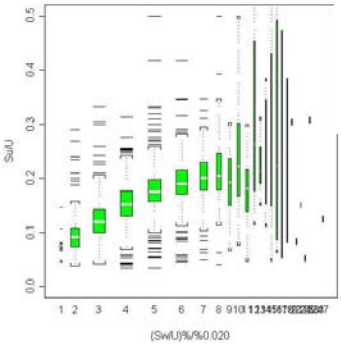

Convective case: L= -193 u*= 1 z0= 0.01
80/50: 0.08
50/30: 0.09
Neutral 0.12 , 0.11
height, m
U/u*
Two convective cases,
one stable
Convective case: L= -102 u*= 0.75 z0= 0.01
80/50: 0.07
50/30: 0.08
Neutral 0.12 , 0.11
height, m
U/u*


Real World Wind Profiles
50/30: 0.39
80/50: 0.37
Stable cases
hour: 3
U>= 4
alph (50/30): 0.39
alph (80/50): 0.37
z0: 3.658 ustar: 0.9
N= 254
height, m
windspeed, m/s
Convective Cases
hour: 15
U>= 4
alph (50/30): 0.41
alph (80/50): 0.34
z0: 3.706 ustar: 0.93
N= 250
height, m
windspeed, m/s
50/30: 0.41
80/50: 0.34

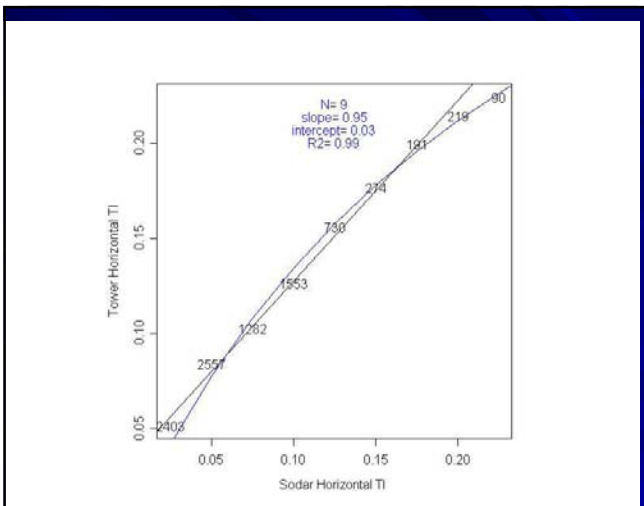
Tower horizontal TI vs. Sodar vertical TI

Weighted regression on the Medians by bin



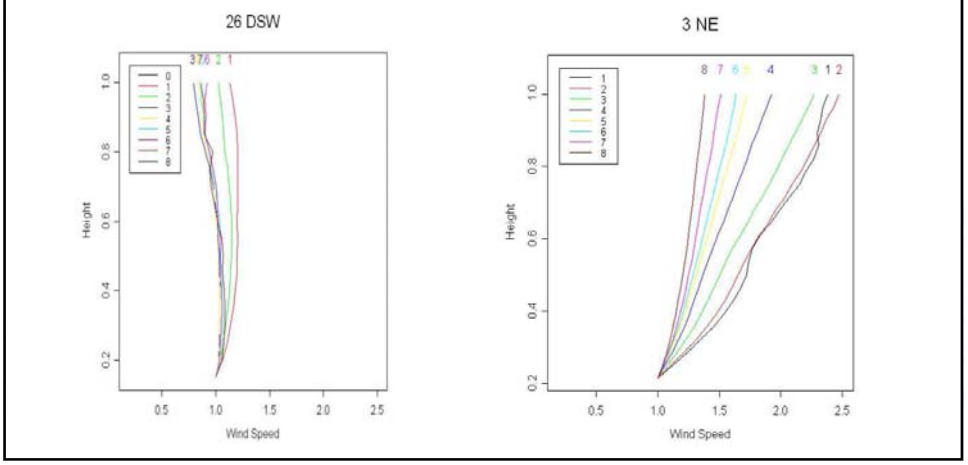


Boxplot (width of box proportional to number of observations)

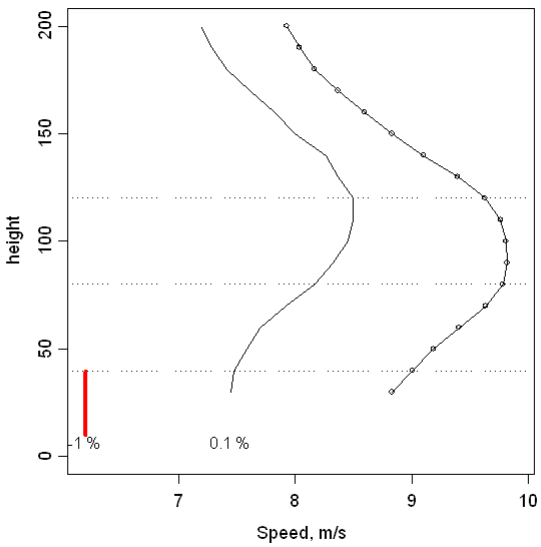


Triton Turbulence Intensity

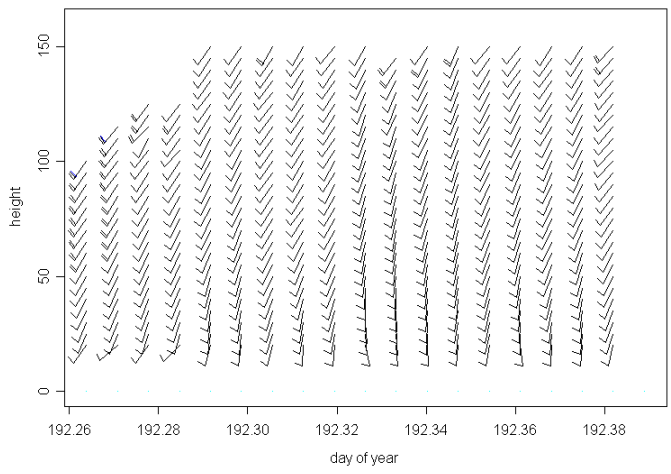
Shape of the wind profile is affected by vertical turbulence intensity (TI)



Downslope Sequence: 1.5 hours

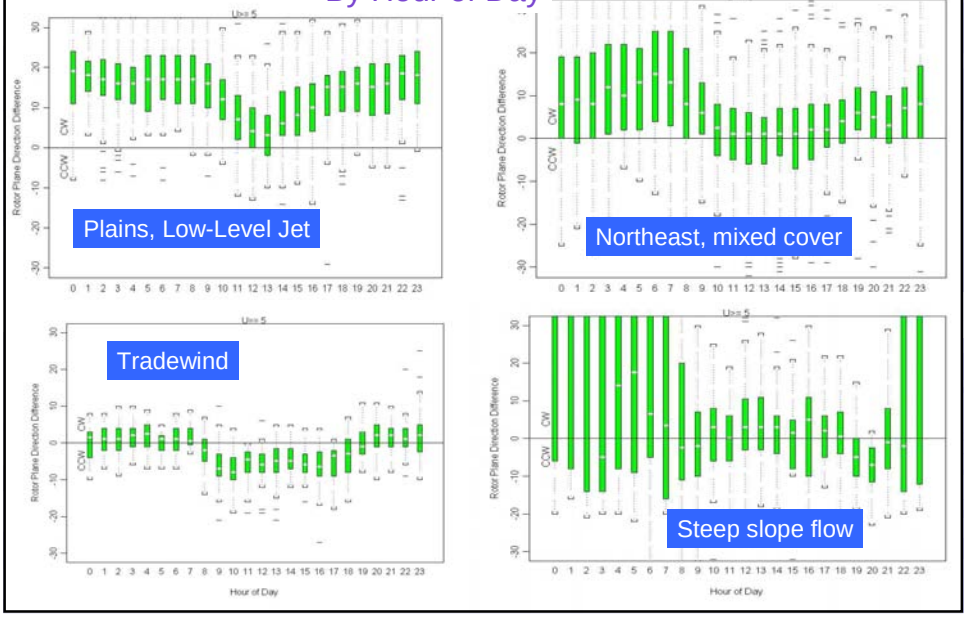


Directional Shear on a Mountain Slope



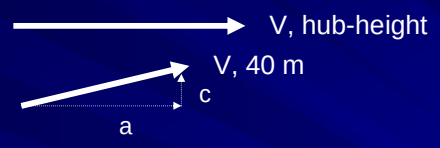
Change in Direction,40 m to 120 m

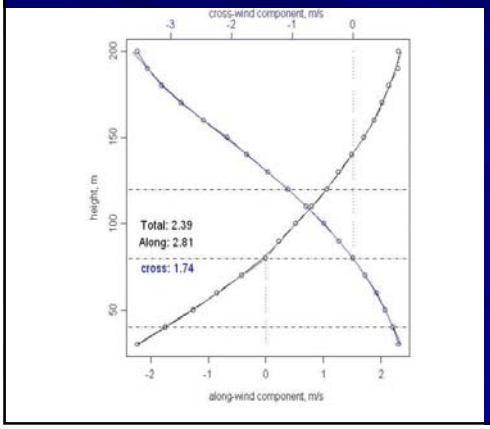
By Hour of Day



Wind vector at any height is the sum of two components:

- Parallel to hub-height wind vector (along-wind, a)
- Perpendicular to hub-height wind vector (cross-wind, c)





- Mid-latitude, flat site
- Directional shear= 14 deg. CW (40->120 m)
- U @ 80 m: 10.1 m/s
- Along-wind rotor-plane shear: 2.81 m/s
- Cross-wind: 1.74 m/s

Recommended Practices Guide

http://www.iedat.com/sodar.html (v. 4.0)

- Begun as “sodar best practices” in 2004
- Input from more than a dozen sodar users in the wind industry
- “Recommended Practices” further developed by ad hoc group formed at the IEA TEM in 2007
- Neutral with respect to any one technology
- Audit, calibration and test

Audit/Calibration

- Independent of anemometry
- Use traceable calibrated equipment (sound generator, oscilloscope)
- Challenge sodar with a series of known frequencies
- Verify outgoing pulse length and frequency
- Use a transponder function/device to verify timing and phase shift
- (also) verify that all speakers have correct phase and amplitude.

Conclusions

- Sodar an effective tool, especially when combined with anemometry
- Must account for differing physics between sodar and anemometry
- Sodar σ_s provide useful measure of turbulence
- Best practices would ideally recognize “calibration” (aka “audit”) using independent tone generation, transponder testing, etc.
- Sodar as stand-alone resource-assessment tool?

Thank You!

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Nacelle mounted pulsed LiDAR system

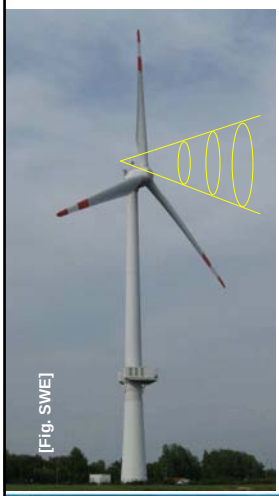
David Schlipf, Oliver Bischoff, Martin Hofsäß, Andreas Rettenmeier, Juan-José Trujillo, Martin Kühn

Endowed Chair of Wind Energy at the Institute of Aircraft Design,
Universität Stuttgart, Germany

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

Universität Stuttgart
Germany

A. Rettenmeier: "Experimental and numerical investigation of wind turbines operating in inhomogeneous inflow"



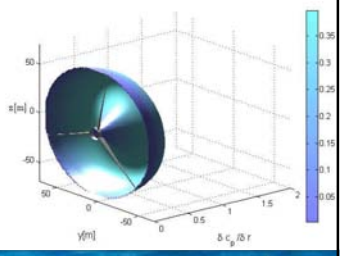
[Fig. SWE]

Nacelle-based LiDAR simulation and measurements of the inflow of wind turbines over the swept rotor area

Goal: determination of the effective wind speed for power curve and load measurements

Development & comparison of different weighting functions of

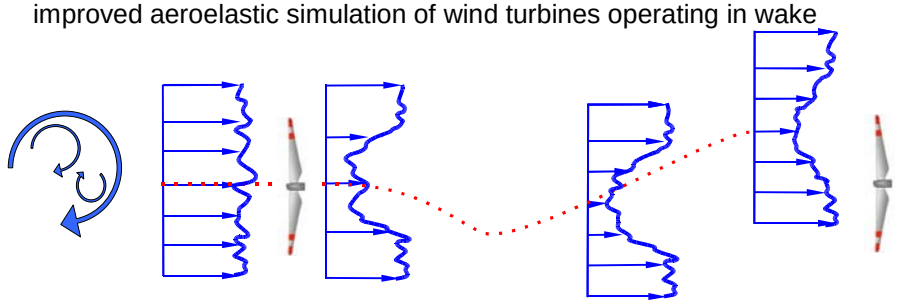
- Terrain or meteorological influences e.g. wind shear and wind profile
- aero-mechanical influences (turbine design)



3

J.J. Trujillo: “Dynamic Loading of Wind Turbines in Wake Operation“

The aim is to develop a model for far-wake dynamics that enables improved aeroelastic simulation of wind turbines operating in wake



Nacelle mounted pulsed LiDAR system
David Schlipf

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

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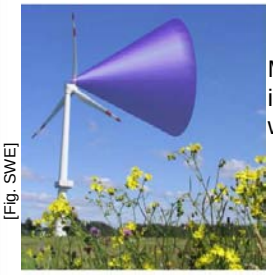
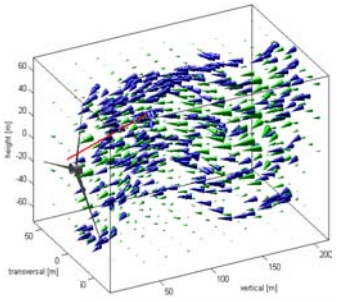
4

D. Schlipf: “Model Predictive Control of Wind Turbines with LiDAR Wind Measurement“



[Fig. SWE]

Measuring the incoming wind field with LiDAR technology



Interpolation of the measured data to a wind field model

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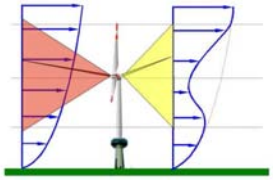
Nacelle mounted pulsed LIDAR system

Development of horizontal scanning device:
Scanning the wind field in high accuracy for different analyses of the inflow and wake



[Fig. SWE]

1. Using LiDAR simulator WITLIS for developing the most accurate scanning shape
2. Specification, design and construction of a scanning device for a Windcube®
3. Near-wake and far-wake measurements using LiDAR technology of Windcube® and DLR systems
4. Inflow measurements for power curve assessment and control

Nacelle mounted pulsed LiDAR system
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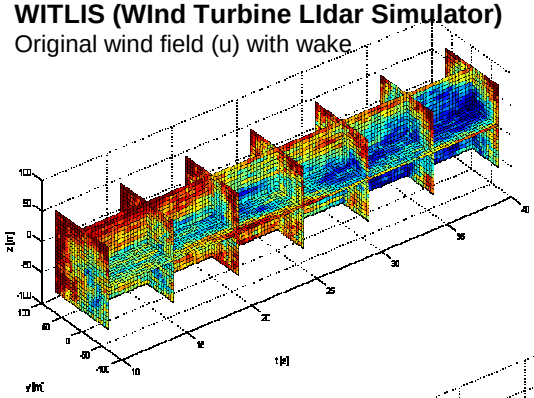
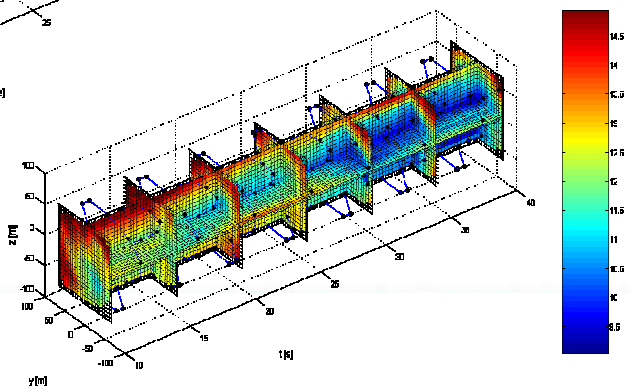
WITLIS (WInd Turbine LIdar Simulator)

Original wind field (u) with wake



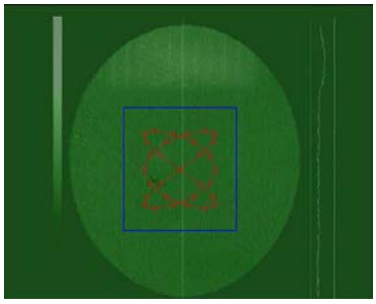
Interpolated wind field
- Real trajectories
- Volume measurement
- Turbine interference
- Direction correction (Cyclops Dilemma!)



- Trajectories can be optimized depending on application
- Main characteristics can be measured

7

Developed Scanner for nacelle mounted LiDAR system



High flexibility in trajectories with one mirror!

Here: Lissajous figure with 32 points in ~5s

Nacelle mounted pulsed LiDAR system
David Schlipf

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Installation on a Multibrid M5000

Nacelle mounted pulsed LiDAR system
David Schlipf

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9

Measurement environment

1st Class anemometer

Temperature sensor and 3D-sonic anemometry

Multibrid M5000 prototype

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

Measurement project

- Power curve and load measurement
- Met mast (102 m height)
- Meteorological sensors
- Data acquisition system
- LiDAR device

Nacelle mounted pulsed LiDAR system
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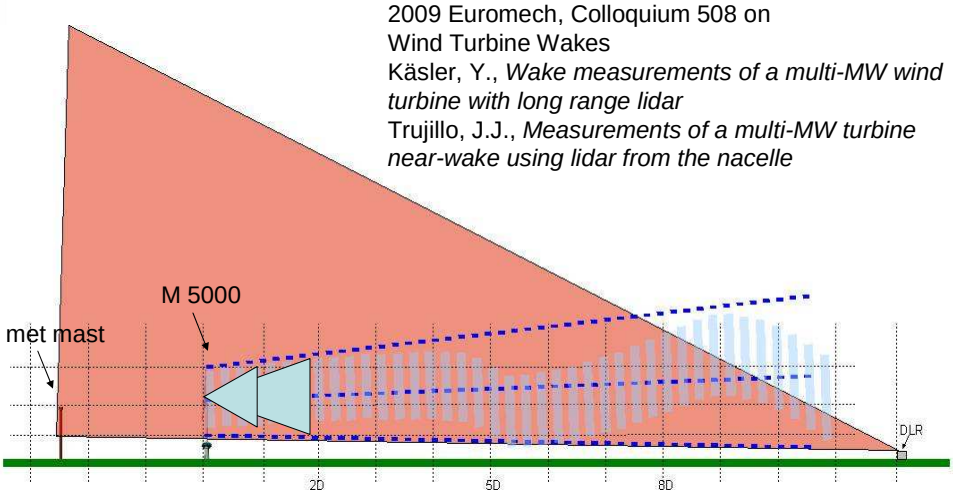
10

Campaign with DLR long range lidar and adapted Windcube

Detailed results at:
2009 Euromech, Colloquium 508 on Wind Turbine Wakes
Käsler, Y., *Wake measurements of a multi-MW wind turbine with long range lidar*
Trujillo, J.J., *Measurements of a multi-MW turbine near-wake using lidar from the nacelle*



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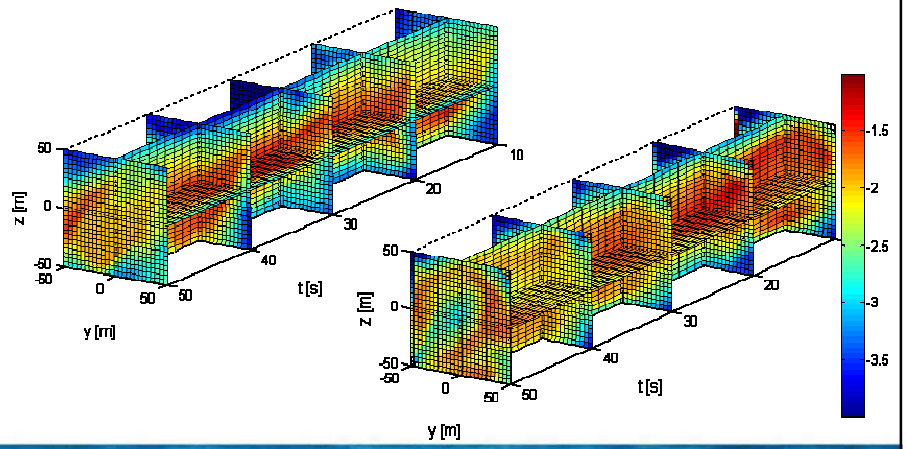
11

First measurements (2009-05-18)

evolution of near wake in 1.25D and 1D



Nacelle mounted pulsed LiDAR system
David Schlipf

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

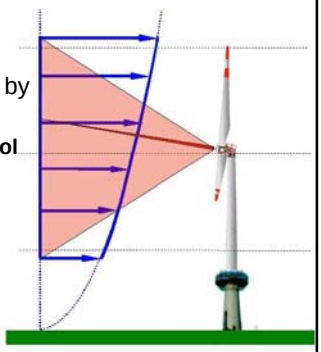
RAVE RESEARCH AT ALPHA VENTUS

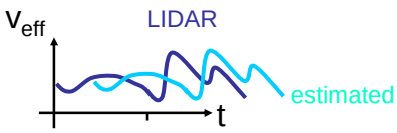
12

Planned inflow measurement

Goals

- verification of “Taylor’s Frozen Turbulence Hypothesis“
- behavior of inhomogeneous inflow for power production and loads
- comparison of wind characteristics for control measured by LIDAR and estimated from turbine data
  - effective wind speed for **collective pitch** and **speed control**
  - effective horizontal and vertical shear for **cyclic pitch**
  - effective wind direction for **yaw control**





Nacelle mounted pulsed LiDAR system
David Schlipf

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau

RAVE RESEARCH AT ALPHA VENTUS

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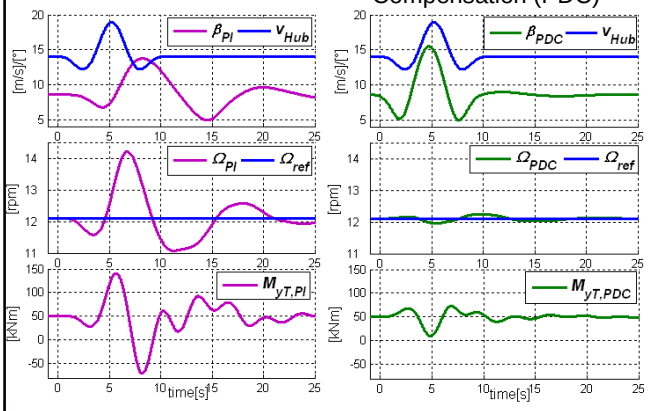
Outlook: Test LiDAR control, e.g. collective pitch

conventional (PI)

Predictive Disturbance Compensation (PDC)



- Simulation with WITLIS/Fast
- gust from IEC-Standard
- perfect measurement assumed

➢ better rotor speed regulation

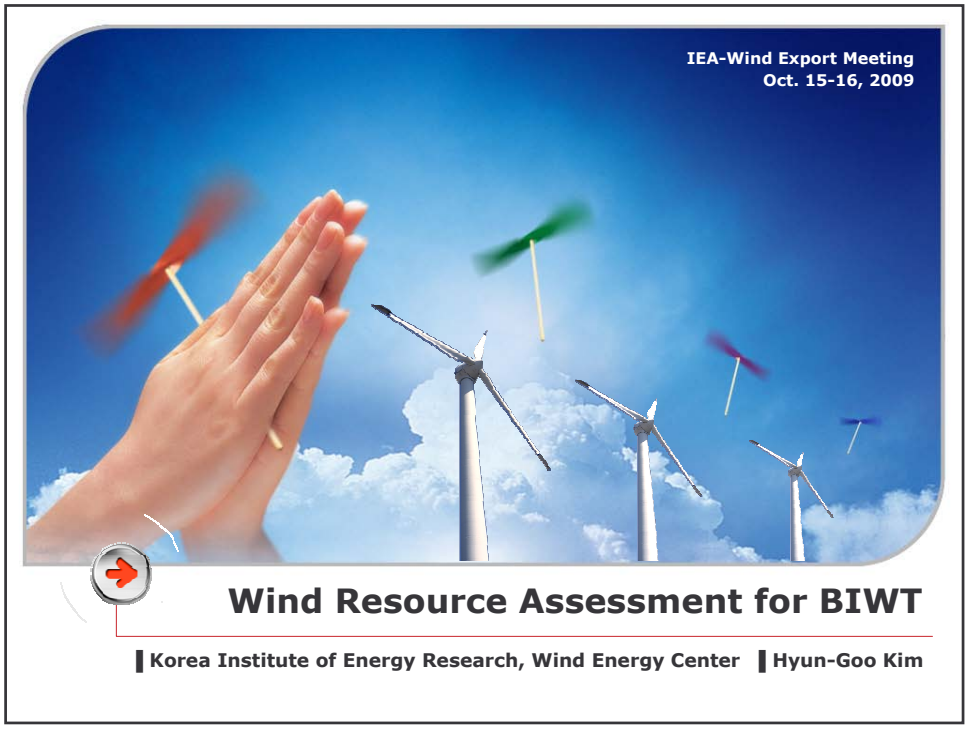
➢ less loads

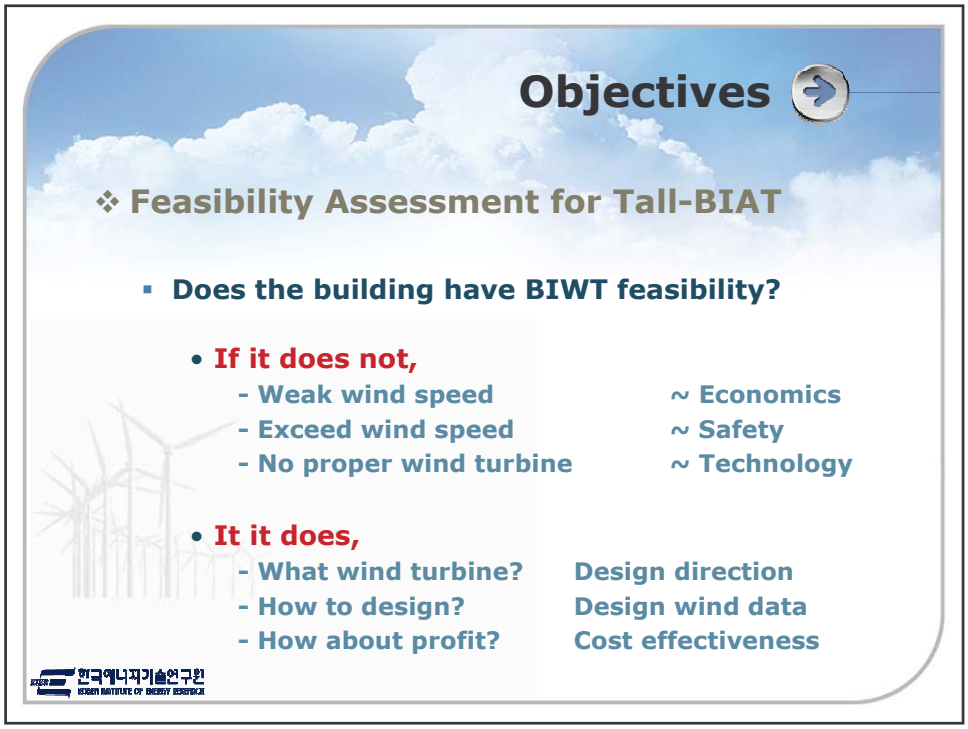
14

Thanks for your attention!

LIDAR group at the SWE

David Schlipf, Juan-José Trujillo, Prof. Dr. Martin Kühn (HoC), Andreas Rettenmeier, Martin Hofsäß, Oliver Bischoff


IEA-Wind Export Meeting
Oct. 15-16, 2009
Wind Resource Assessment for BIWT
Korea Institute of Energy Research, Wind Energy Center
Hyun-Goo Kim


Objectives
❖ Feasibility Assessment for Tall-BIAT
▪ Does the building have BIWT feasibility?
• If it does not,
- Weak wind speed ~ Economics
- Exceed wind speed ~ Safety
- No proper wind turbine ~ Technology
• It it does,
- What wind turbine? Design direction
- How to design? Design wind data
- How about profit? Cost effectiveness
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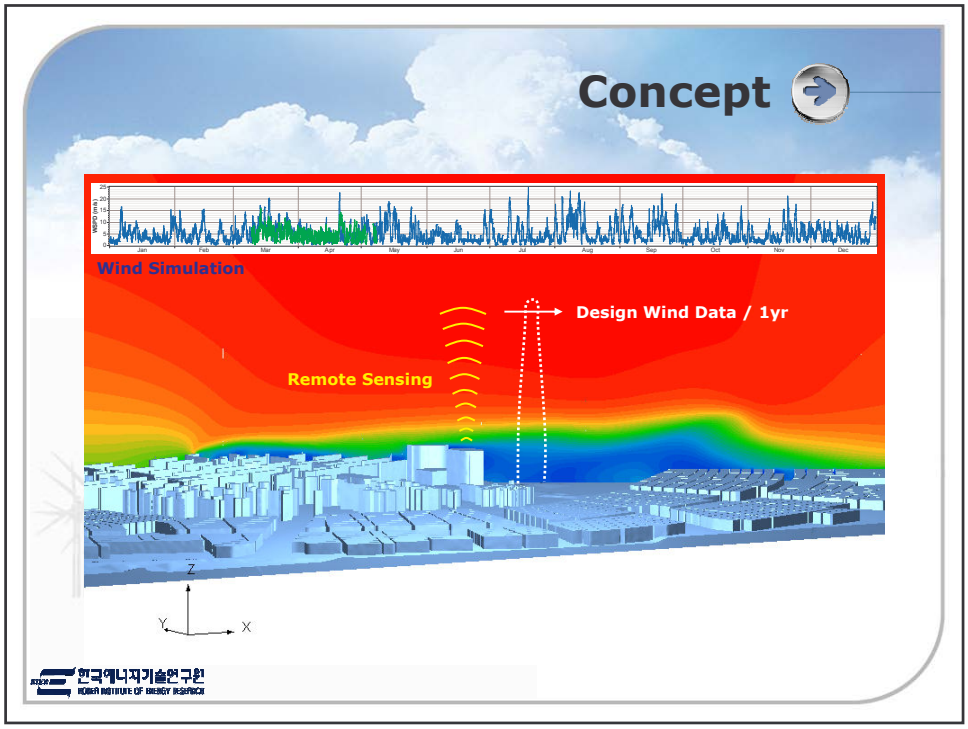
Concept
Wind Simulation
Design Wind Data / 1yr
Remote Sensing
Z
Y
X
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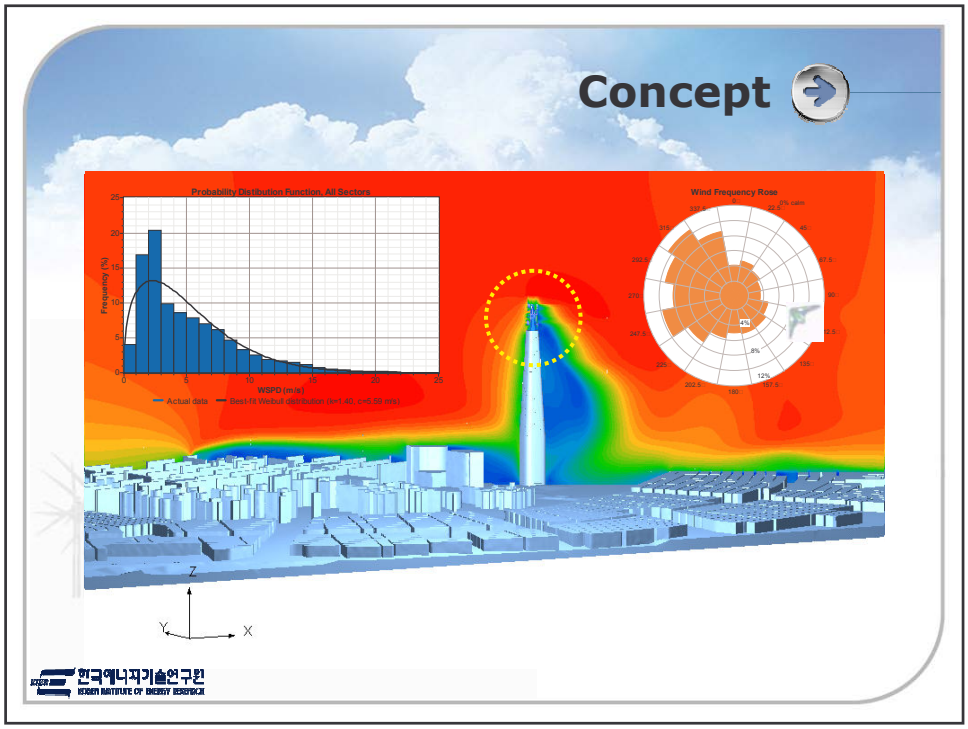
Concept
Probability Distibution Function, All Sectors
Frequency (%)
WSPD (m/s)
Actual data
Wind Frequency Rose
Z
Y
X
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Remote Sensing
LIDAR
SODAR
LOTTE WORLD
LOTTE WORLD
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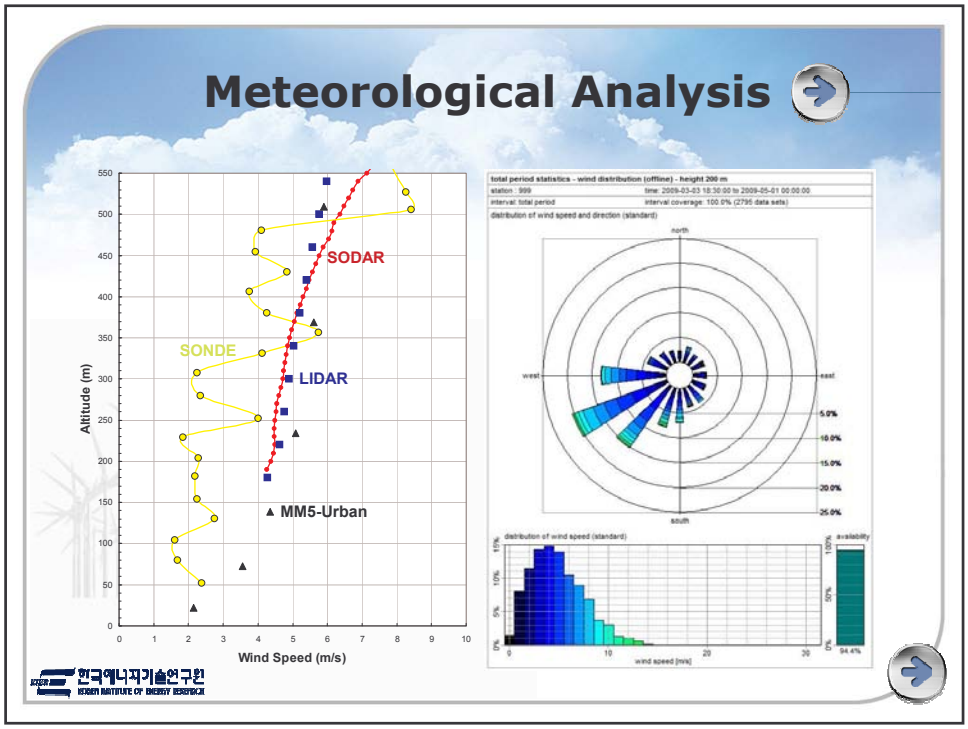
Meteorological Analysis
SODAR
SONDE
LIDAR
MM5-Urban
Altitude (m)
Wind Speed (m/s)
550
500
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
total period statistics - wind distribution (offline) - height 200 m
distribution of wind speed and direction (standard)
north
west
east
south
5.0%
10.0%
15.0%
20.0%
25.0%
distribution of wind speed (standard)
availability
wind speed [m/s]
94.4%
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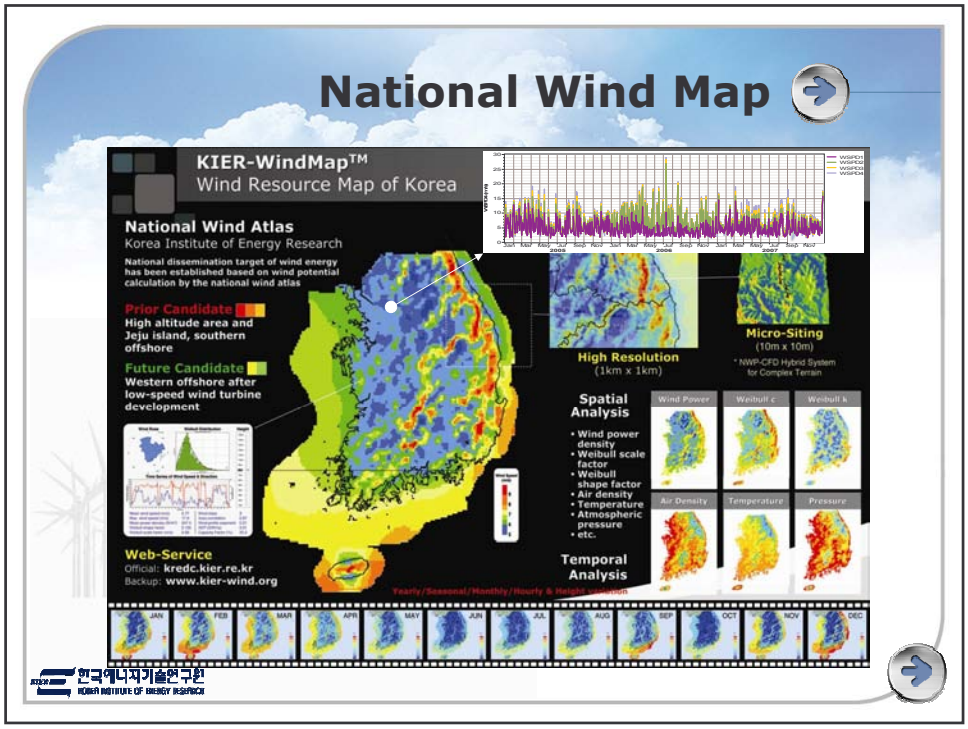
National Wind Map
KIER-WindMap™
Wind Resource Map of Korea
National Wind Atlas
Korea Institute of Energy Research
National dissemination target of wind energy has been established based on wind potential calculation by the national wind atlas
Prior Candidate
High altitude area and Jeju island, southern offshore
Future Candidate
Western offshore after low-speed wind turbine development
High Resolution
(1km x 1km)
Micro-Siting
(10m x 10m)
Spatial Analysis
• Wind power density
• Weibull scale factor
• Weibull shape factor
• Air density
• Temperature
• Atmospheric pressure
• etc.
Temporal Analysis
Web-Service
Official: kredc.kier.re.kr
Backup: www.kier-wind.org
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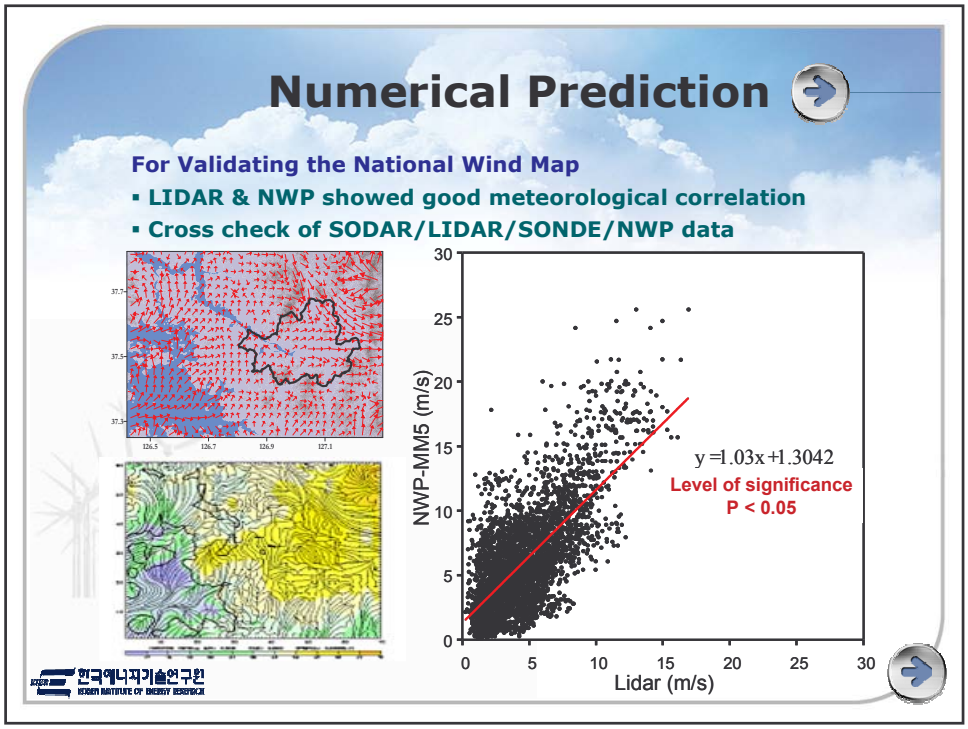
Numerical Prediction
For Validating the National Wind Map
▪ LIDAR & NWP showed good meteorological correlation
▪ Cross check of SODAR/LIDAR/SONDE/NWP data
NWP-MM5 (m/s)
Lidar (m/s)
y =1.03x +1.3042
Level of significance
P < 0.05
0
5
10
15
20
25
30
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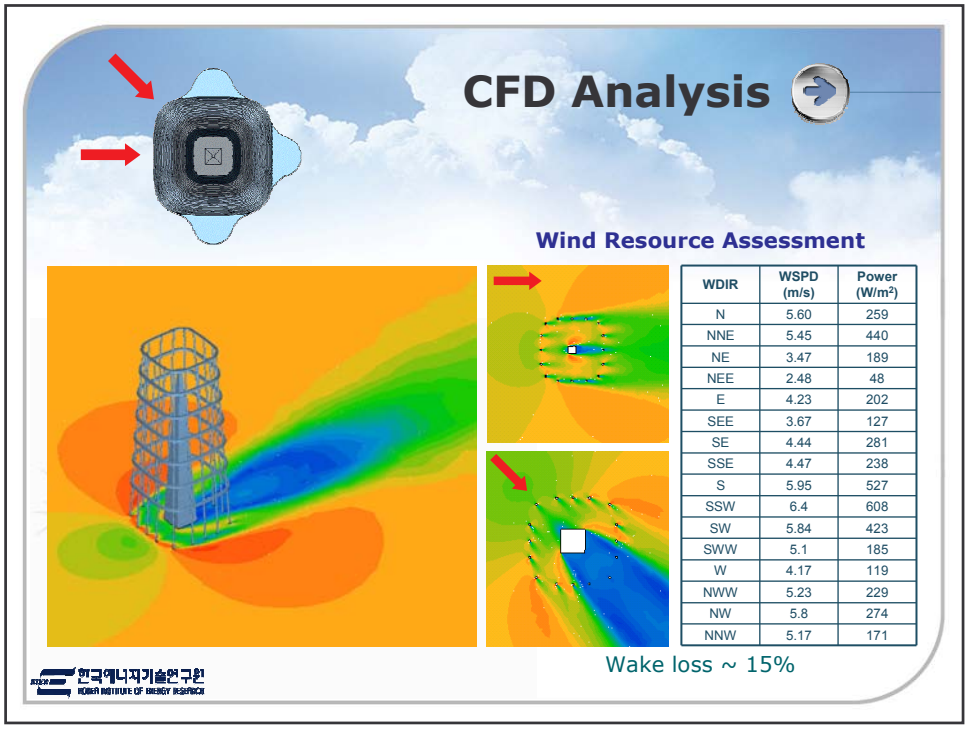
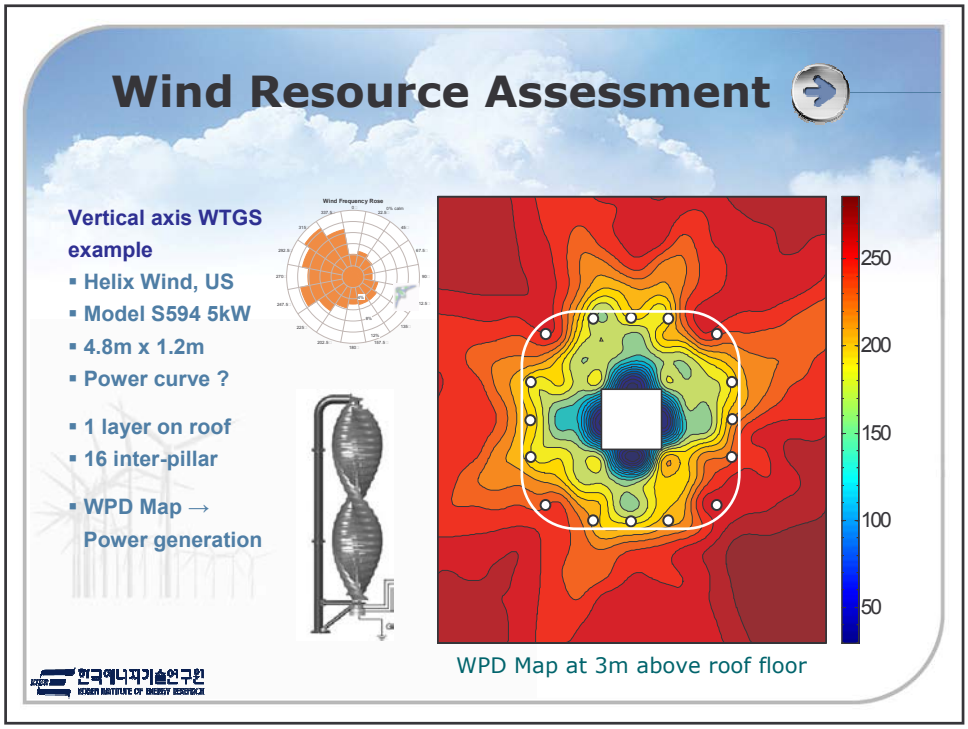

CFD Analysis
Wind Resource Assessment
WDIR | WSPD (m/s) | Power (W/m²)
N 5.60 259
NNE 5.45 440
NE 3.47 189
NEE 2.48 48
E 4.23 202
SEE 3.67 127
SE 4.44 281
SSE 4.47 238
S 5.95 527
SSW 6.4 608
SW 5.84 423
SWW 5.1 185
W 4.17 119
NWW 5.23 229
NW 5.8 274
NNW 5.17 171
Wake loss ~ 15%


Wind Resource Assessment
Vertical axis WTGS example
▪ Helix Wind, US
▪ Model S594 5kW
▪ 4.8m x 1.2m
▪ Power curve ?
▪ 1 layer on roof
▪ 16 inter-pillar
▪ WPD Map → Power generation
250
200
150
100
50
WPD Map at 3m above roof floor

Feasibility Assessment

AEP Prediction Example

- **Southwest Whisper 200, 16kW (1kW x 16) Installed**
- **Losses: Avail. 95%, Wake 15%, Icing 2%, Elect. 2%**

Month	Annual Mean Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Power Output (kW)	Mean Net Energy Output (kWh/yr)	Net Capacity Factor (%)	Gross Energy Output (MWh/yr)
Jan	4.25	44.22	1.21	0.1	100	13.4	1.60
Feb	4.43	44.94	1.49	0.2	108	16	1.73
Mar	6.88	14.92	2.82	0.3	244	32.8	3.90
Apr	3.98	43.33	0.14	0.1	77	10.7	1.23
May	5.74	35.89	3.49	0.3	194	26	3.10
Jun	3.62	58.61	0.42	0.1	72	10.1	1.15
Jul	4.26	57.26	0.67	0.1	104	14	1.66
Aug	6.56	38.04	4.7	0.3	217	29.2	3.47
Sep	6.43	33.61	4.17	0.3	208	28.9	3.33
Oct	3.88	54.7	0.81	0.1	91	12.3	1.46
Nov	4.72	44.31	1.53	0.2	125	17.4	2.00
Dec	4.95	34.01	0.94	0.2	140	18.8	2.24
Overall	4.98	41.93	1.87	0.2	1,681	19.2	26.88

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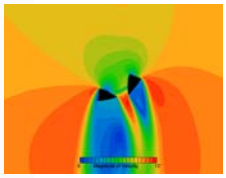
Oversea Case

Bahrein Int'l Trade Center

- **World first BAWT w/HAWT**
- **Height 240m, 50 storages**
- **225kW HAWT x3 = 675kW**
- **Blade diameter= 29m**
- **AEP= 1.3GWh**
- **Produce 13% consumption**
- **Capacity factor= 22%**



Venturi effect acceleration

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Application

- **Reflection of Building Top Design**
  - To Select wind turbine type
    - Type, Capacity, Manufacturer, Modification
    - No domestic company
  - To Determine installation layout
    - Structural, electricity design, safety, O&M
  - By design wind data & resource map
- **Environmental Impact Assessment**
  - For pedestrians, TMY + extreme cases
  - By wind environment analysis

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Thank you

Topics

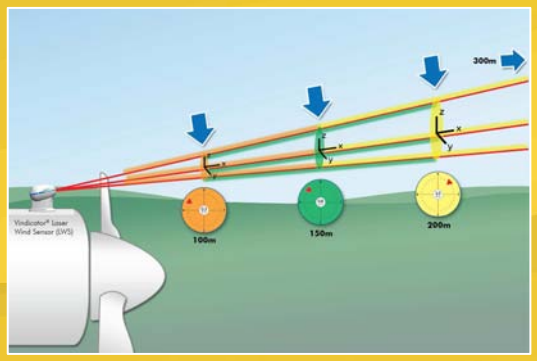
- Background
- Vindicator® Laser Wind Sensor
- Sensor Accuracy/Correlation Testing
- Wind Turbine Control Application
- Wind Resource Assessment Applications

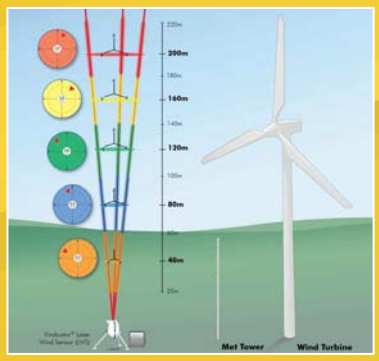
Background

- Catch the Wind Inc. Manufactures and Sells the Vindicator® Laser Wind Sensor (LWS)
  - Pulsed LIDAR
  - 3-D Wind Speed and Direction (single or multiple reporting)
  - All Fiber Optic
  - Unique Multi-channel Non-Scanning--Reporting Simultaneous Data
  - No Alignment or Calibration Issues
- Technology Licensed from Optical Air Data Systems, LLC
  - Derived from 20+ Years of US Government and Aerospace R&D
  - High Vibration and Attenuation Environments
  - Supported by 27 Patents

Vindicator® Laser Wind Sensor

Vindicator® Laser Wind Sensor





Nacelle-mounted Turbine Control Unit

- **Wind Speed Accuracy Better Than ±0.2 m/s**
- **Wind Direction Accuracy ±0.7º**

Wind Resource Assessment Unit

- **Range 300m**
- **Data Reported at 1hz or Higher**

LIDAR "Accuracy" Correlation

- Anemometer Calibrated in Wind Tunnel/Wind Tunnel Calibrated by LIDAR
- Volume "Averaged" Vector vs. Time Averaged Scalar Point Measurement with Anemometer
  - 3-D vs. 2-D Measurements
- LIDAR Overcomes Site, Mechanical and Blockage Limitations with Anemometers
- Spatial Correlation/Temporal Correlation
- Systemic Accuracy Set By System Parameters

WIND INDUSTRY NEEDS TO GET BEYOND COMPARISONS WITH ANEMOMETERS

The Dirty Truth

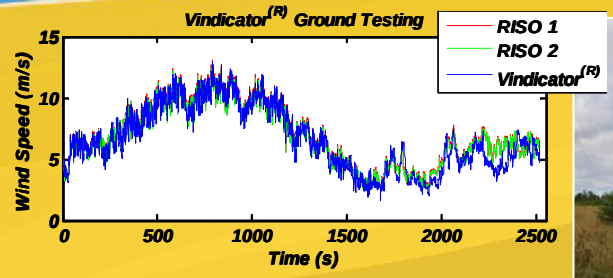
- Time-Averaging Wind Speed and Direction To Take Out Flow Dynamics
- Playing with Power Law Exponents to Curve Fit and Predict Shear Profiles
- Correction of Wind Data with Speed-Dependent Nacelle Transfer Functions
- Vertical Inflow Component in 2-D Wind Data
- Fatigue Life and Performance Below Predictions

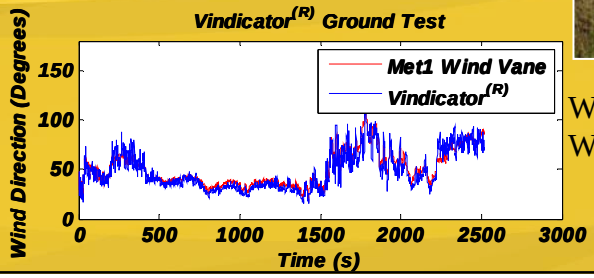
BETTER DATA FROM REMOTE SENSORS CAN ADDRESS THESE SHORTFALLS

Catch the Wind, Inc. Testing

- Truck Calibration Testing
  - Verified Accuracy at Full Range of Angles to Wind
  - Comparison with Vehicle Speed and Sonic Anemometer
- Long Term Testing (2 ½ years continuous)
- CTW Field Tests vs. DOE Met Towers
- Independent Field Tests
  - WEICan vs. Met Tower
  - AWS Truewind vs. Other Remote Sensors and Met Tower
- Maneuvering Platform vs. Ultrasonic Anemometer and GPS
  - Verified Motion Compensation

WEICan Correlation Testing





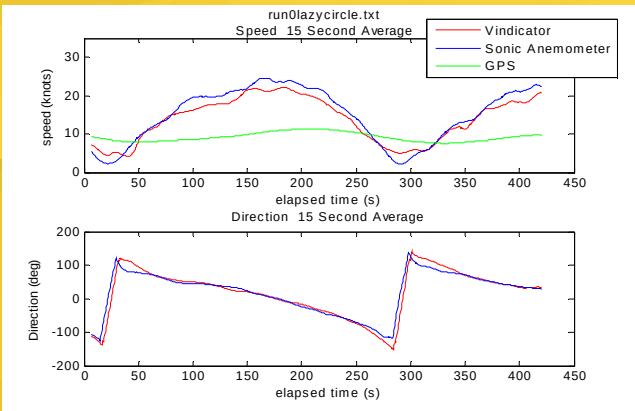
Wind Speed $R^2 = 0.9210$
Wind Direction $R^2 = 0.8914$

Cold Weather WRA Comparison

- Performed by AWS Truewind
- Results presented by AWS Truewind at CanWEA 2009 in Toronto
  - Phase I Correlation of Vindicator® LWS and SODAR ($R^2 = .941$)
  - "Vindicator® was the only device to operate continuously throughout the Phase I ice storm."
  - "Overall Performance Against Other Remote Sensing Devices Was Good"

Moving Platform Testing

- Tested in Maritime Environment on Maneuvering Power Boat
- Track Verification with GPS and Mast-mounted Ultrasonic Anemometer



Wind Turbine Control Sensor

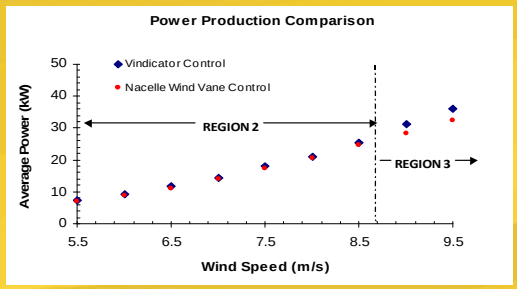
- Vindicator® LWS Was Originally Designed as a Sensor for Feed-Forward WTG Controls
  - Provides **3-D** Wind Speed and Direction 200-300 Meters Ahead of Wind Turbine
    - Can Report Multiple Range Points
  - **Undisturbed** In-Flow
  - Measurements **Prior** to Arrival Give Controls Time to be Pro-Active

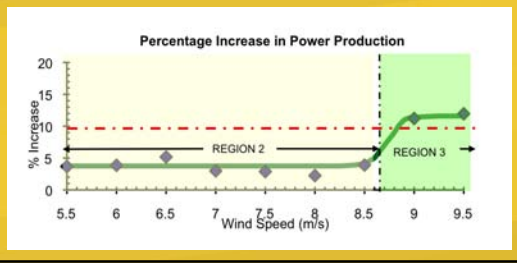
More Accurate *and* ***More Timely*** *Data for Control Decisions*

Progress in Wind Turbine Sensing

- Prototype Vindicator® LWS Installed on Wind Turbine at **WEICan** (PEI) for a Year
  - Comparisons with both Met Tower and Nacelle Wind Measurements
  - Confirmed Accuracy Improvements Over Nacelle Mounted Sensors
    - Results Presented at AWEA 09
  - Simple Yaw Control Algorithms
  - Power Output Data

WEICan Control Data

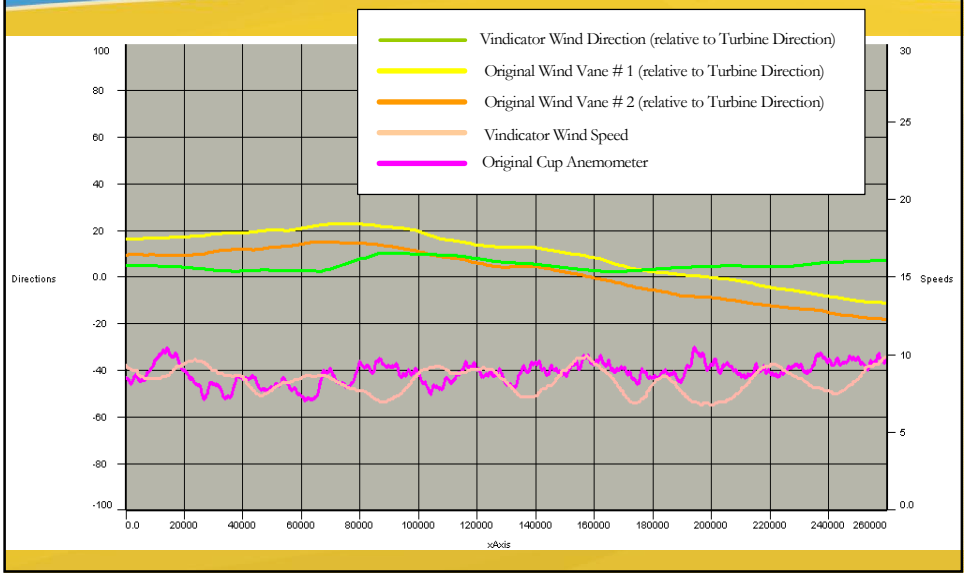




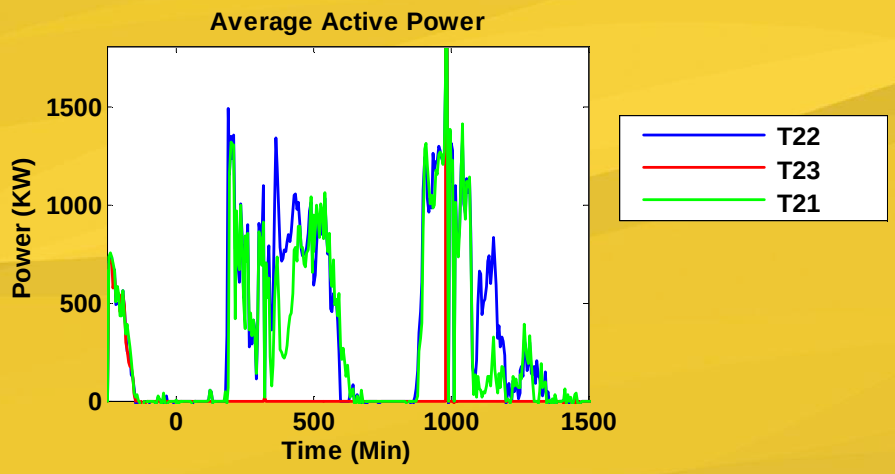
Progress in Wind Turbine Sensing

- Vestas V-82 Installation in July 09 at Nebraska Public Power District (NPPD)
  - Comparisons with Nacelle Anemometer and Wind Vane Measurements
  - Early Results Presented at CanWEA Sept 09
  - Continuing to Gather Accuracy and Power Production Data
  - Stress Wave Energy Data

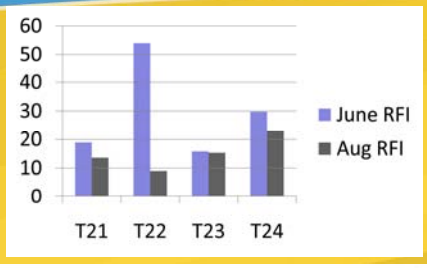
NPPD Preliminary Results



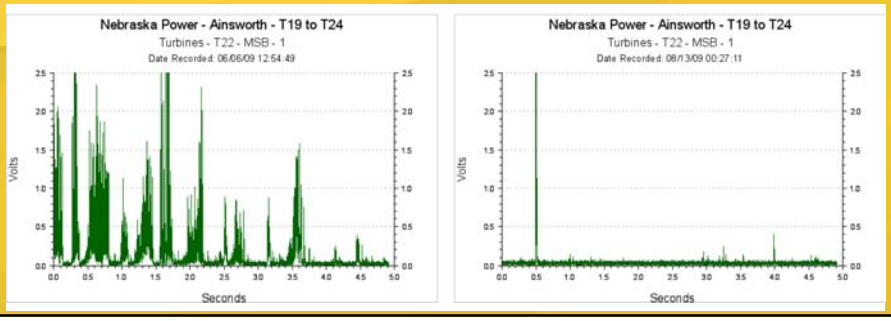
NPPD Preliminary Results



NPPD Stress Reduction



Vestas V-82 Turbine With SWANTech™ Condition Monitoring System



CRADA With NREL

- Catch The Wind Inc. Providing a Vindicator® LWS to Support Research in Feed-Forward Wind Turbine Controls
- Initial Installation On Two-Bladed Advanced Controls Research Turbine Planned

Canadian Hydro Developers

- Contracted for 8 Vindicator® LWS Installations Over the Next 6 Months
- Cowley Ridge (Alberta)
- NORDEX N60 (1.3 Mw)
- Gathering Comparative Power Output and Wind Measurement Data from Adjacent Wind Turbines

Offshore Wind Resource Assessment Application

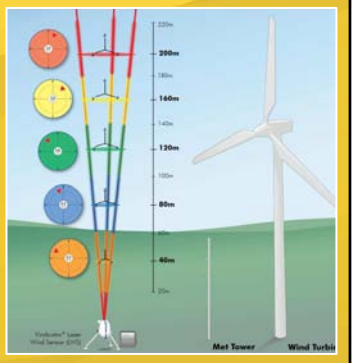
- Vindicator® LWS Supplied for Offshore WRA LIDAR Buoy
  - **AXYS Technologies Inc.** Has Completed Initial Motion Compensation Testing Ashore
  - WindSentinel™ Offshore Wind Resource Assessment Buoy Integration Nearing Completion
  - Buoy Testing Planned Off-Shore of British Columbia

Measurements Above Hub Height Without the Difficulty and Cost of Off-Shore Towers

AXYS WindSentinel™

On-Shore Wind Resource Assessment

- Helimax Vindicator® LWS Tests
  - Potential Terrestrial Wind Resource Assessment Product



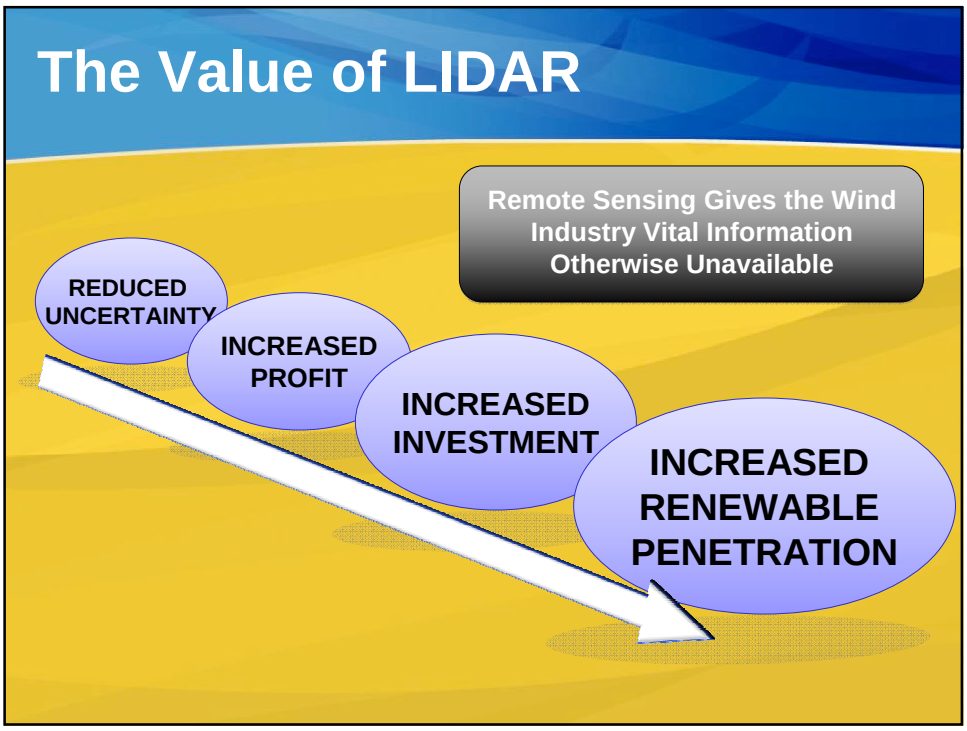
Summary

- Experience with LIDAR Wind Sensor In Support of Wind Industry Has Been Very Encouraging
- Wind Turbine Control and Wind Resource Assessment Applications of LIDAR Appear to Bring Significant Value to Wind Industry

Bottom Line

- LIDAR Is A Viable and Valuable Remote Sensor for Increasing Wind Turbine Operational Effectiveness and Reducing Assessment Uncertainty
- The Community Should Continue To Press for Full Acceptance

The Value of LIDAR



Questions?

Forward Looking Statements

Certain statements in this presentation may constitute "forward looking" statements which involve known and unknown risks, uncertainties and other factors which may cause our actual results, performance or achievements, or industry results, to be materially different from any future results, performance or achievements expressed or implied by such forward-looking statements. When used in this presentation, such statements use such words as "may", "will", "expect", "continue", "believe", "plan", "intend", "would", "could", "should", "anticipate" and other similar terminology. These statements reflect current assumptions and expectations regarding future events and operating performance and speak only as of the date of this presentation. Forward-looking statements involve significant risks and uncertainties, should not be read as guarantees of future performance or results, and will not necessarily be accurate indications of whether or not such results will be achieved. A number of factors could cause actual results to vary significantly from the results discussed in the forward-looking statements, including, but not limited to, the factors discussed under the "Risk Factors" section of the filing statement the Company filed with regulatory authorities on September 9, 2008 (the "Filing Statement"). Additional risk factor discussion can be found in the Company's continuous disclosure filings, reports and other filings with securities commissions and regulatory authorities in Canada and filed under the Company's profile on SEDAR at www.sedar.com. Although the forward-looking statements contained in this presentation are based upon what we believe are reasonable assumptions, we cannot assure that our actual results will be consistent with these forward-looking statements. We assume no obligation to update or revise these forward-looking statements to reflect new events or circumstances.

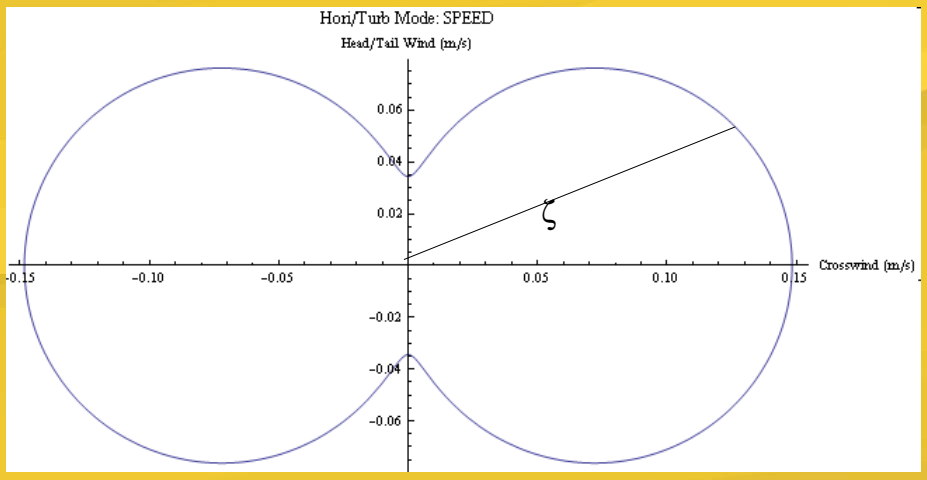
Vindicator® LWS Fit Check

Gamesa G8 Nacelle

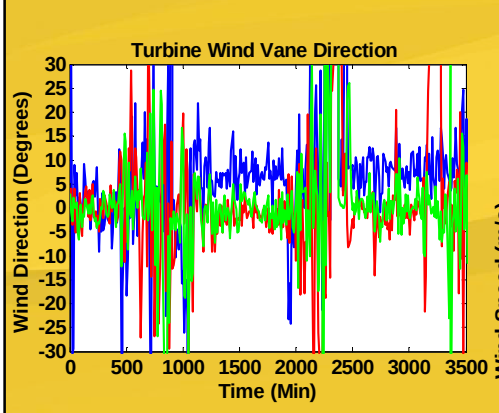
Non-scanning LIDAR

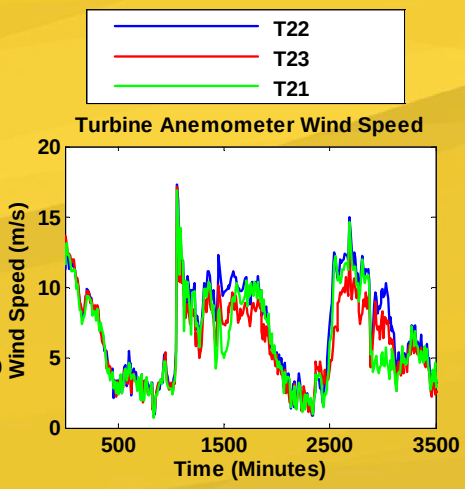
- Advantages of non-scanning LIDAR
  - No alignment issues, system maintains alignment and accuracy regardless of environmental and shipping conditions
  - Simultaneous measurements
    - All measurements correlated temporally
    - Motion-compensation capability

Systemic Accuracy



NPPD Preliminary Results





Future

- LIDAR Growth Potential
  - Real Time Turbulence, Shear/Vear, & Wake Measurements
  - Improved Wind Turbine Performance Assessment
  - Advanced Turbine Control Algorithms to Take Advantage of Advanced Wind Data and Spatial Data
  - Longer Range Wind Measurements Improve Forecasting and Enable Time for Smart Grid Integration

Atmospheric Systems Corporation

Kenneth H. Underwood, PhD, CCM
26017 Huntington Ln, Unit F
Santa Clarita, CA
91355

Who are we?

- May 2005, AeroVironment, Inc. completed the sale of the SoDAR product line to ASC.
- October 2005, ASC relocated from Monrovia, CA to Santa Clarita, CA
- ASC was established to manufacture, market, use and sell SoDAR systems. And to develop new SoDAR technologies to meet the market demands.

More History

- ASC staff pioneered the following advances (commercial):
  - Phased array speaker design for atmospheric wind profiling. The first commercial phased array speaker array was sold in 1986;
  - Reflector enclosures for use with the phased array speakers;
  - High acoustic frequency (4KHz or higher) monostatic (and bistatic systems);
  - Real time monitoring of speaker status (maintenance feature);
  - Real time remote operation and display of field data;
  - Correction for vertical motions in real time;
  - Battery powered, solar charged units with solar charging for extended field operations (first sold commercially in 2001)
  - First continually operated network installed in 1994 on a campus for emergency response monitoring
  - more

Comparison with an Instrumented Tower

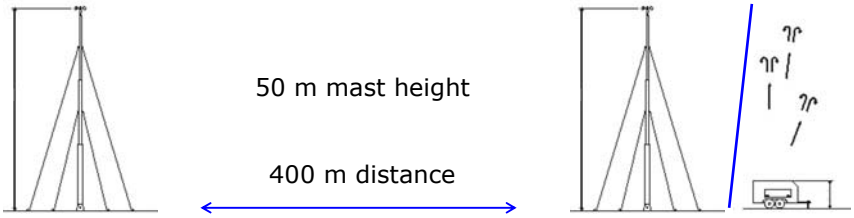
Verification of wind measurements

SODAR measurements with reference to meteorological masts

field experiment:

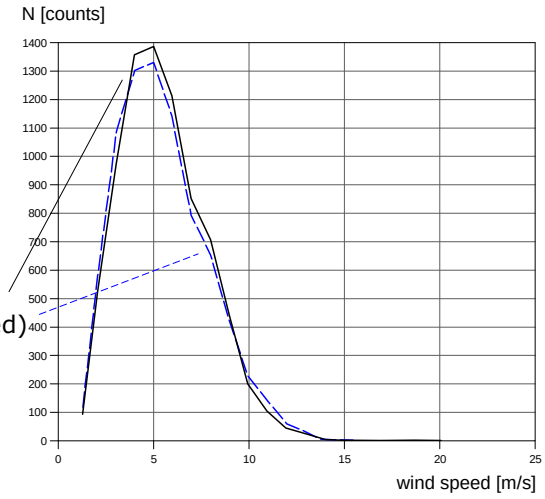
2 masts with (ultra)sonic anemometers – correlate sonic vs. sonic

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



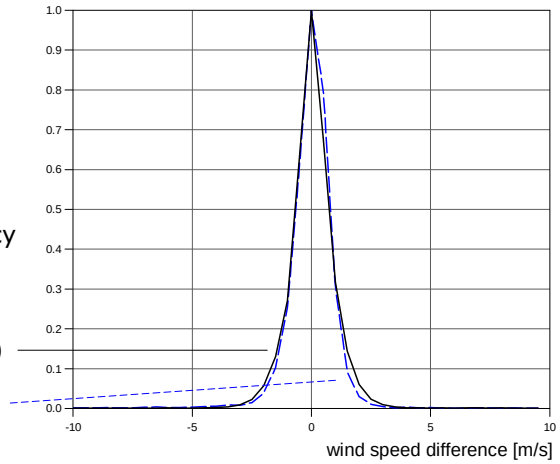
Verification of wind speed frequency distribution

frequency distribution
for sonic (black, solid)
and sodar (blue,dashed)
measurements
avg. speed
sonic 5.46 m/s
sodar 5.43 m/s

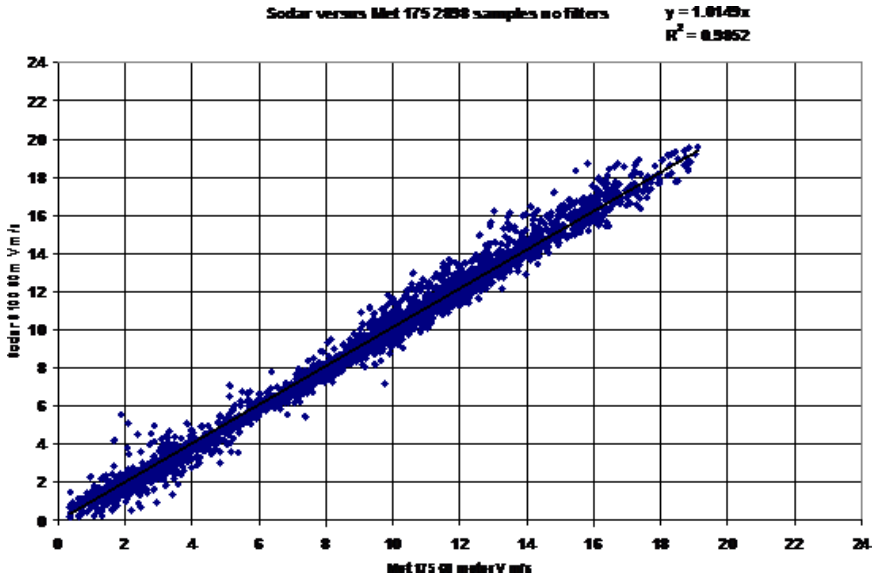


Verification of wind measurements

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

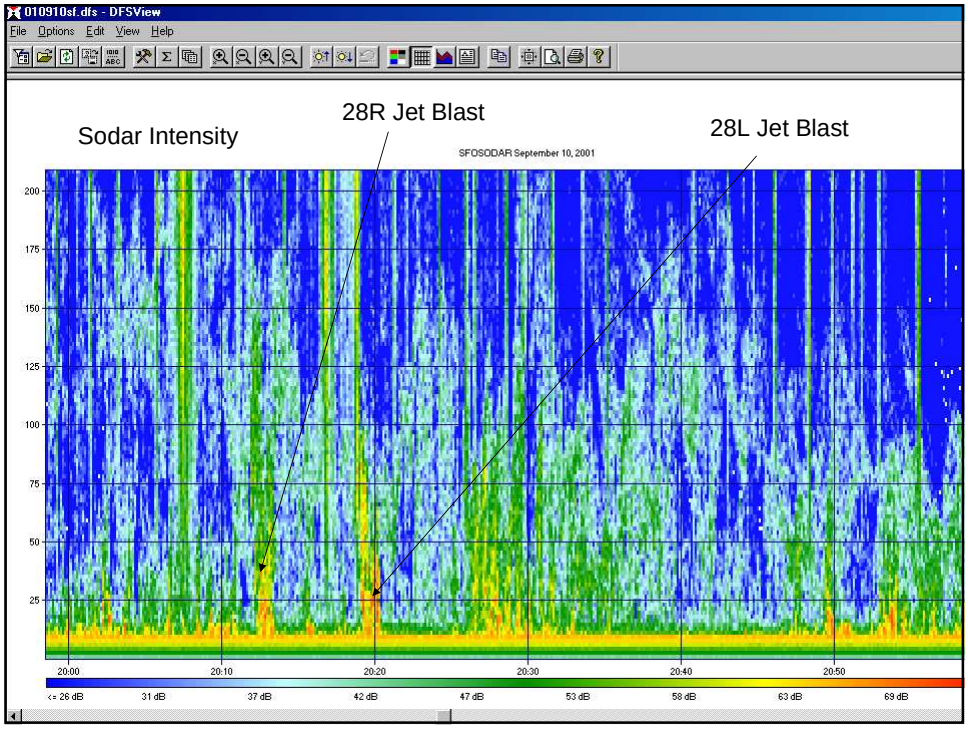


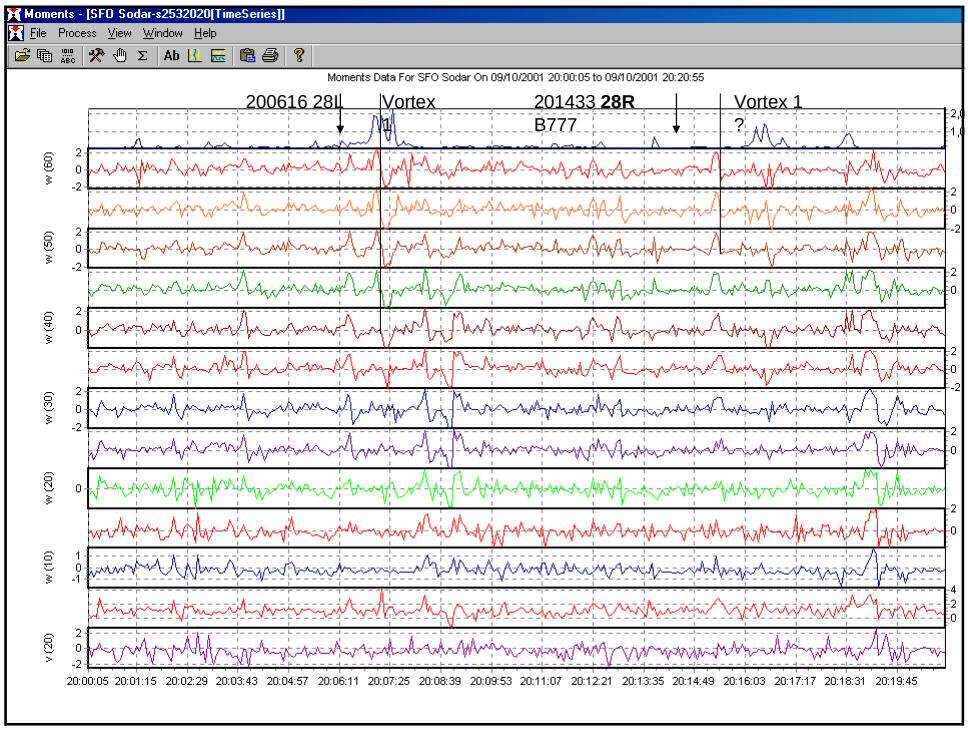
Wind Speed Comparison miniSoDAR & Cup anemometer



SL

Tennessee


010910sf.dfs - DFSView
File Options Edit View Help
Sodar Intensity
28R Jet Blast
28L Jet Blast
SFOSODAR September 10, 2001
200
175
150
125
100
75
50
25
20:00
20:10
20:20
20:30
20:40
20:50
<= 26 dB
31 dB
37 dB
42 dB
47 dB
53 dB
58 dB
63 dB
69 dB



Wind energy applications of sodars

WindExplorer (side view)

Atmospheric Systems Corporation

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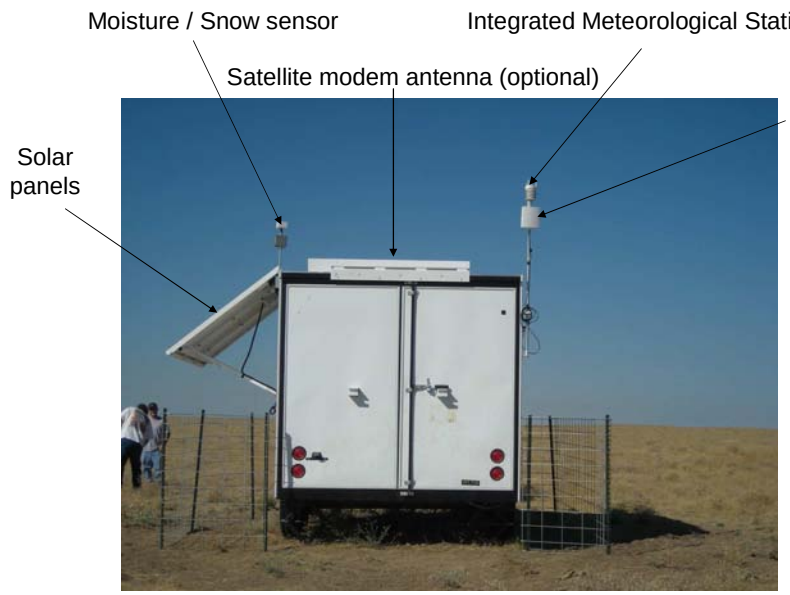
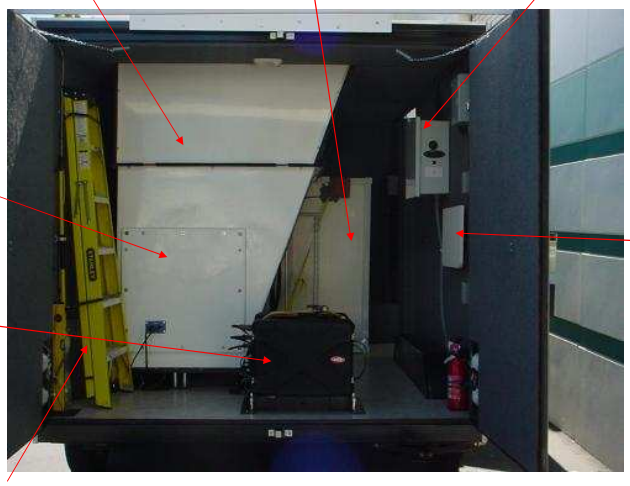


WindExplorer (rear view – closed doors)

Atmospheric Systems Corporation 17



WindExplorer (rear view – open doors)

Atmospheric Systems Corporation 18

WindExplorer Features

- Integrated Solar charging (400 W);
- Integrated gasoline generator (2.8 KW) with an integrated 25 gallon fuel tank;
- Integrated moisture / snow sensor;
- Integrated meteorological station;
- Dual axle trailer with mechanical surge brakes and 2” towing ball;
- Software packages (SodarView, PADS);
- Installation and training;
- Model 4000 enclosure base and cuffs;
- Acoustic Signal Processor;
- 32 speaker array and spares;
- Blanket heater for the reflector enclosure with thermistor controlled thermostat;
- 40 Amp AC battery charger
- 30 AMP solar controller & charger unit
- In-line Speaker Monitor Board status integrated as part of the standard wind table report;
- Satellite or cell modem communications.

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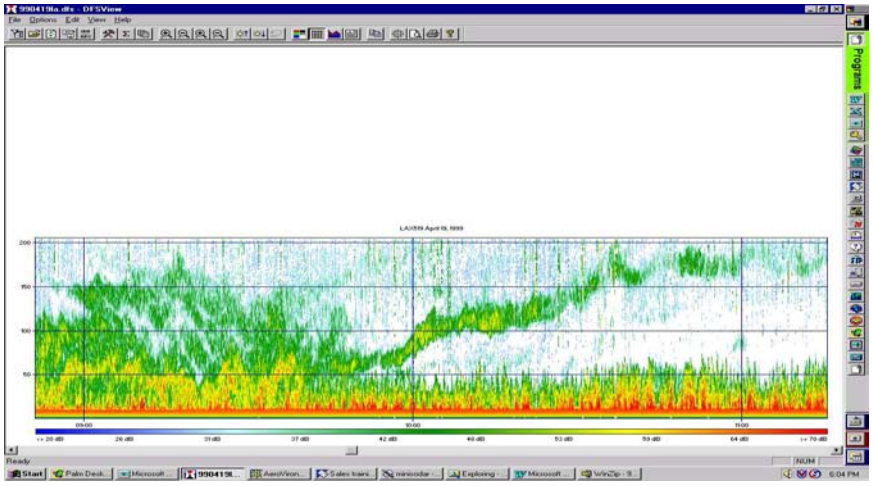
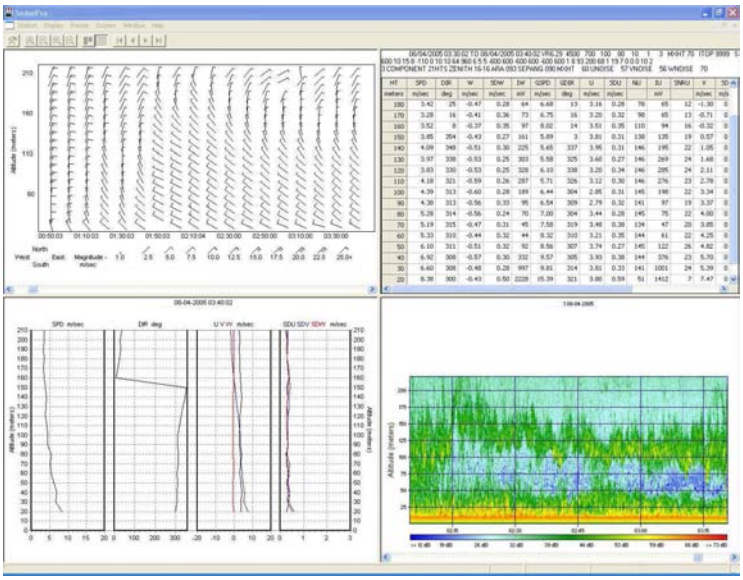
Vertical Beam Signal Amplitude Processing

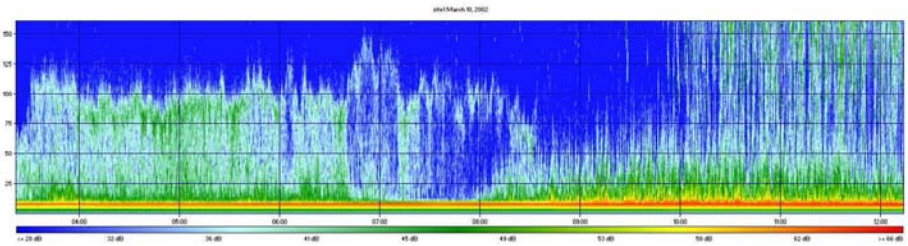
- Sampled directly (no transformation used)
- Generates the Facsimile Display
- Scaled in term of decibels - 20*LOG(V)
  - relative to a 1 millivolt signal
- Visualization of atmospheric stability
- Identifies significant scattering layers and wind shear regions
- Processed with DFSview™ software package

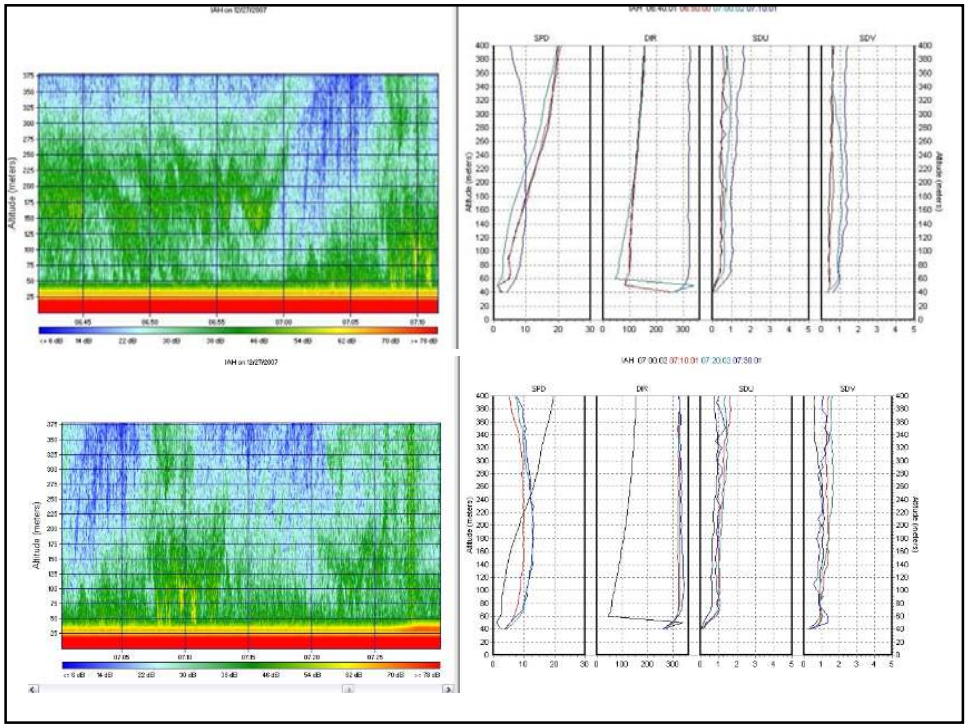
SoDAR signal intensity data or Facsimile Data





Lamar CO (3/10/2002)





Current Developments

- New computer and signal processing unit
  - Introduced in Jan 2007
  - Application of Facsimile data sets to atmospheric stability and wind resource forecasting
- Positive performance sodar operation
  - Speaker status and electronics hardware monitored
  - E-mail maintenance messages to operator
- Integrated, low power units
  - continuous improvement process
- Bistatic system configurations
  - Common volume sampling
- Triple monostatic configurations
  - Higher altitude performance
- Off shore applications

Atmospheric Systems Corporation (ASC)

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+1-661-294-9667 (f)

LIDAR activities at VTT

IEA Topical Expert Meeting on remote wind speed sensing techniques using sodar and lidar

NREL – Boulder 16.10.2009, Andrea Vignaroli

Business from technology

VTT Technical Research Centre of Finland

VTT IS

- the biggest multitechnological applied research organisation in Northern Europe

VTT HAS

- polytechnic R&D covering different fields of technology from electronics to building technology
- clients and partners: industrial and business enterprises, organisations, universities and research institutes

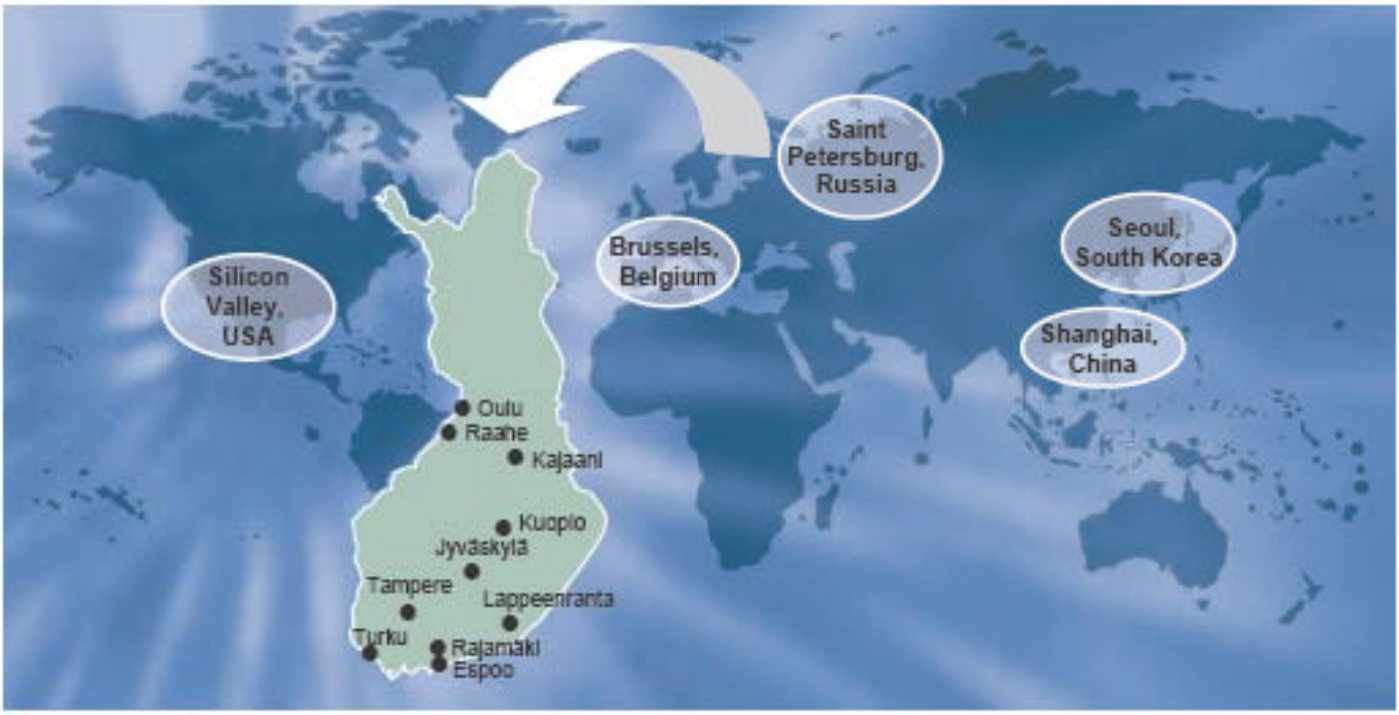
VTT CREATES

- new technology and science-based innovations in co-operation with domestic and foreign partners

- Turnover 245 M€
- Personnel 2,700
- 77% with higher academic degree
- 6,200 customers
- Established 1942
- VTT has been granted ISO9001:2000 certificate.

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

VTT on map



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VTT knowledge clusters

BIOTECHNOLOGY

MICRO-TECHNOLOGIES AND SENSORS

INDUSTRIAL SYSTEMS

ENERGY AND FOREST INDUSTRY

DIGITAL INFORMATION SYSTEMS

TELE-COMMUNICATIONS

MATERIALS AND BUILDING

4

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Wind Energy at VTT

Wind Turbine technology

We are developing technologies and solutions for cold climate and offshore applications for wind turbines.
To this end we have developed versatile modelling expertise from wind to electricity.
We are developing solutions enabling innovative control functions for future wind turbines based on new materials and their application in wind turbines.
This is supported by versatile laboratory and field testing facilities.

Wind Power in energy system

Our R&D into wind energy production includes wind energy market assessment and feasibility studies for wind energy in the energy market. The production and failure statistics of wind power in Finland are maintained at VTT.

VTT is a member of the IEA Implementing Agreement on RD&D of Wind Energy. We are developing and using energy system models for wind integration to assess the integration impact of wind power, as well as to minimise the cost of system integration.

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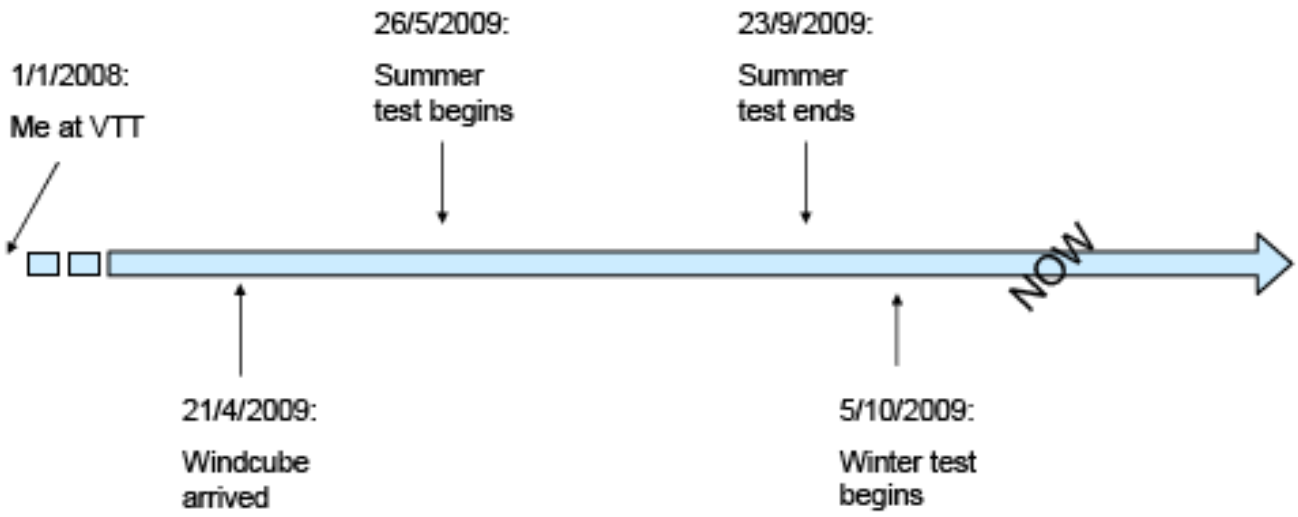
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

LIDAR activities at VTT



6

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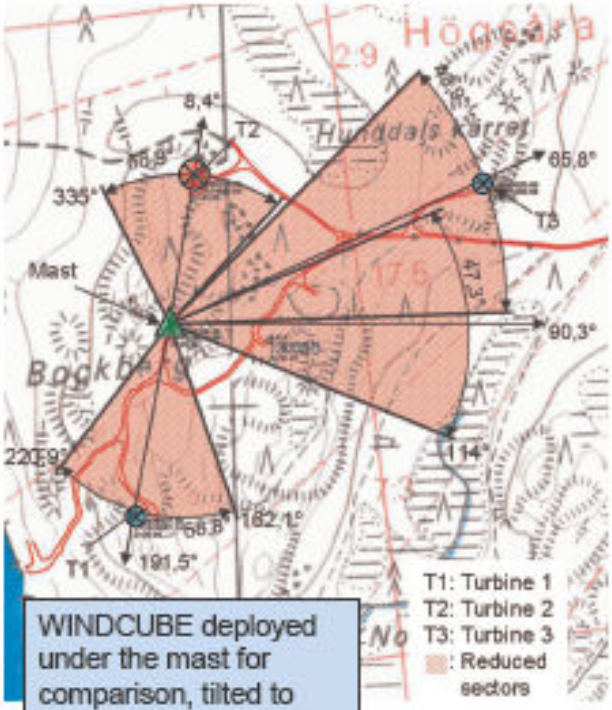
Summer test: Högsåra



WINDCUBE deployed under the mast for comparison, tilted to avoid obstruction form guy wires

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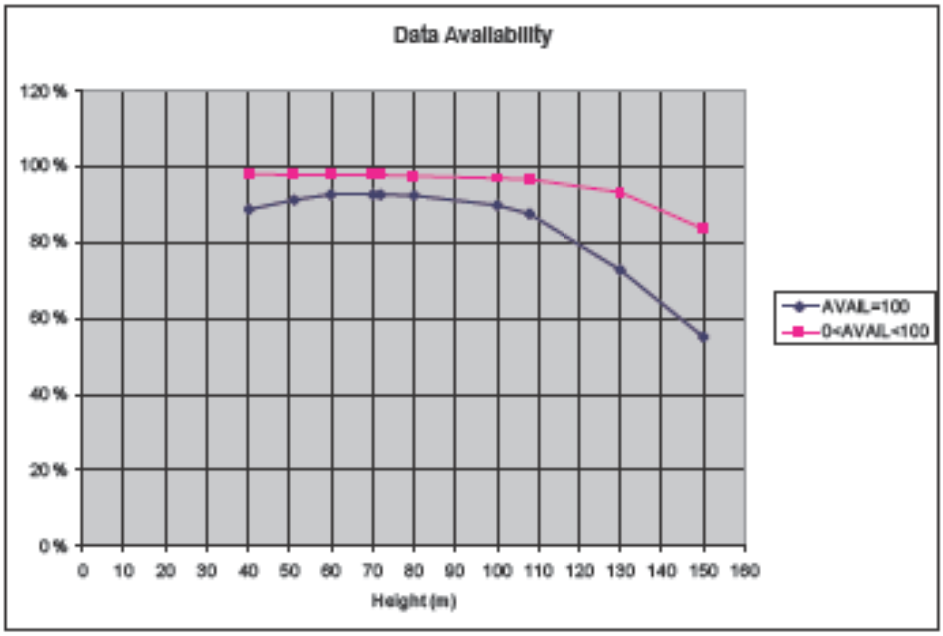
Measurement campaign lenght: 117 days

System availability: 82%



Summer Test: Filtering criteria

- Availability = 100%
- WS > 4,0 m/s &
- 221deg < WD < 335deg & 114deg < WD <162deg
  (Site Calibration sectors)

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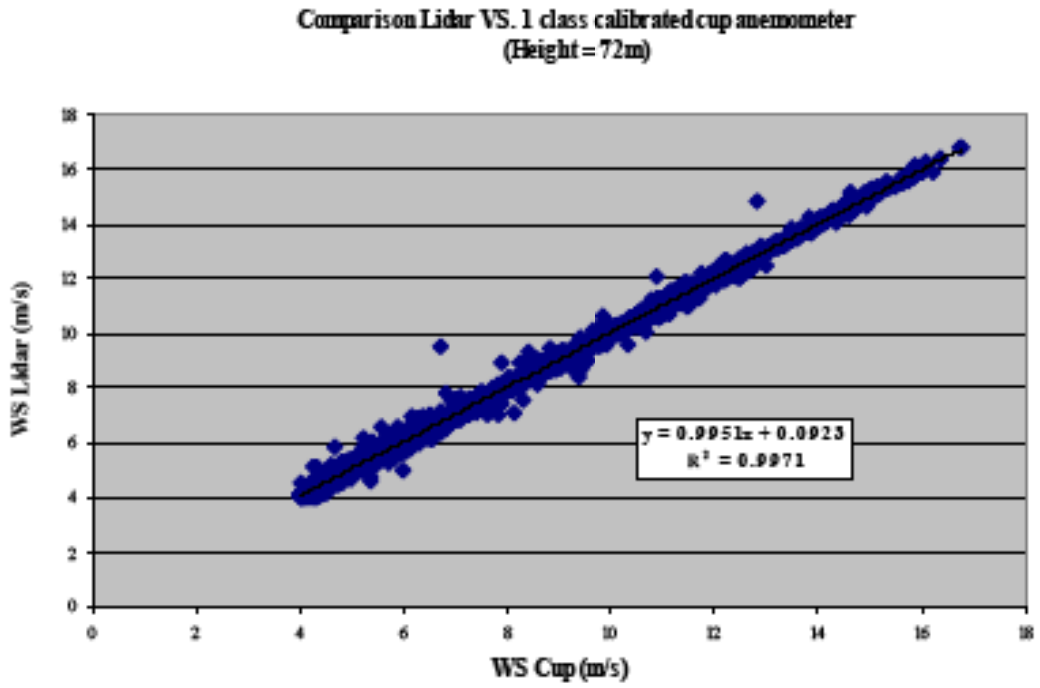
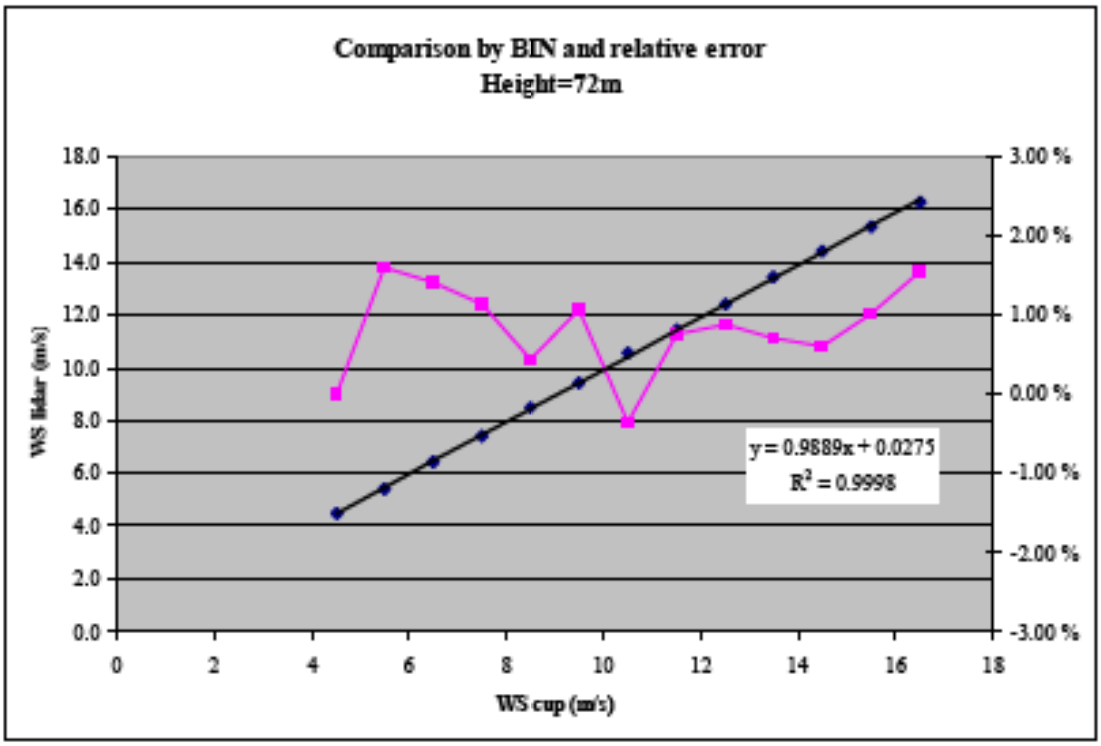
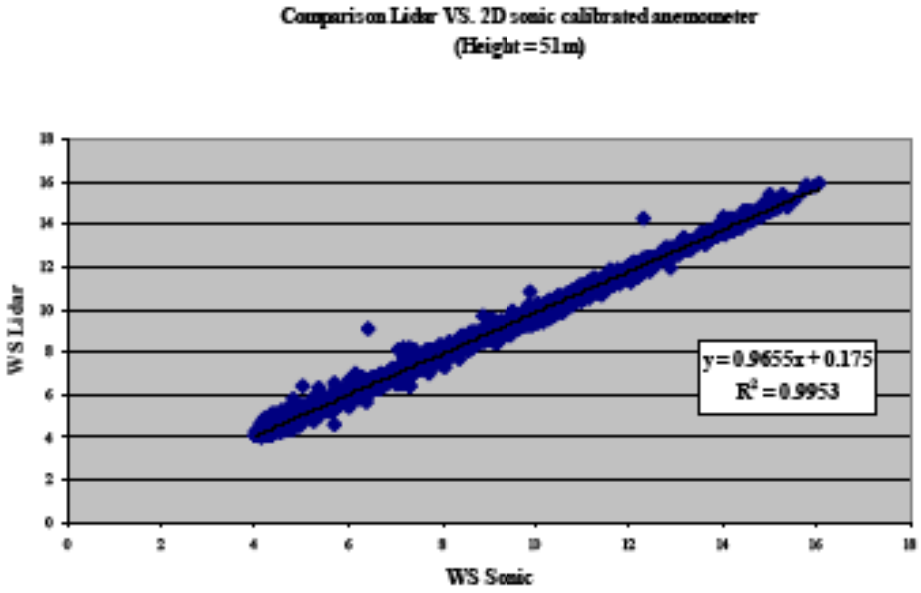



Comparison by BIN and relative error
Height=72m
WS lidar (m/s)
WS cup (m/s)
y = 0.9889x + 0.0275
R² = 0.9998
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
12
14
16
18
3.00 %
2.00 %
1.00 %
0.00 %
-1.00 %
-2.00 %
-3.00 %

11


Comparison Lidar VS. 2D sonic calibrated anemometer
(Height = 51m)
WS Lidar
WS Sonic
y = 0.9655x + 0.175
R² = 0.9953

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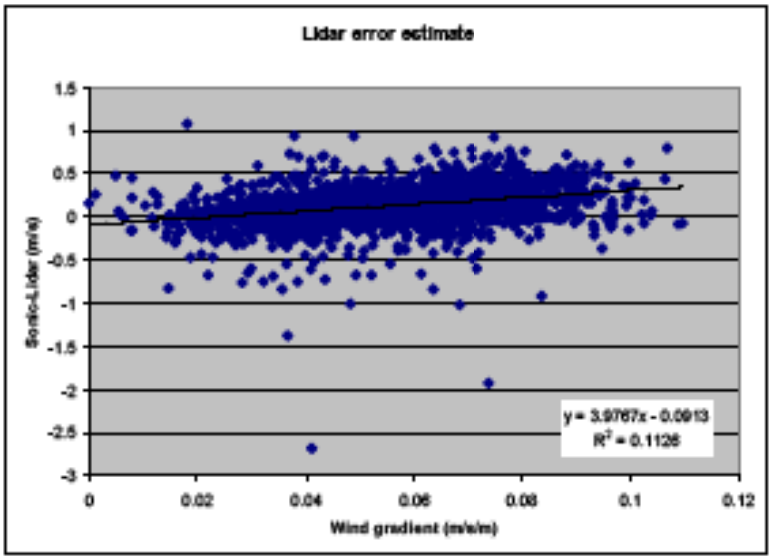
VTT TECHNICAL RESEARCH CENTRE OF FINLAND



Ave. Sonic – Ave. Lidar = 8.28 m/s – 8.16 m/s = **0.12 m/s**

Ave. Wind gradient = (WS mast 72m – WS mast 30m) / 42 m = **0.05**

- Lidar errors are proportional to the wind shear

- Results agree with others in licterature but behaviour emphasized due to the forest

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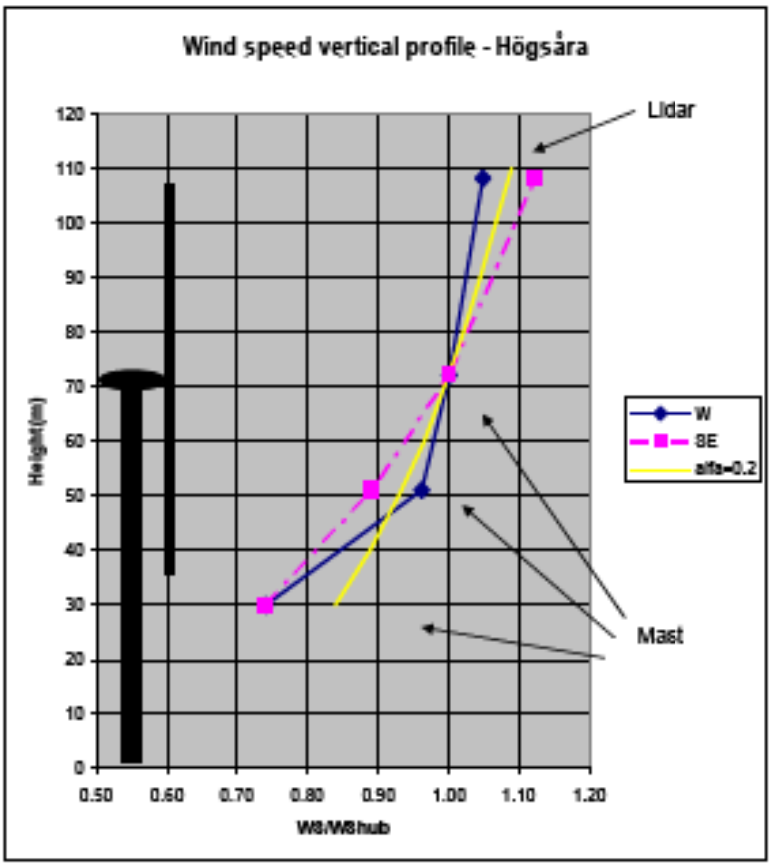

	W	SE
30	0.74	0.74
51	0.96	0.89
72	1.00	1.00
108	1.05	1.12

Not a big surprise:

There's the need to take into account the wind shear when measuring the power curve

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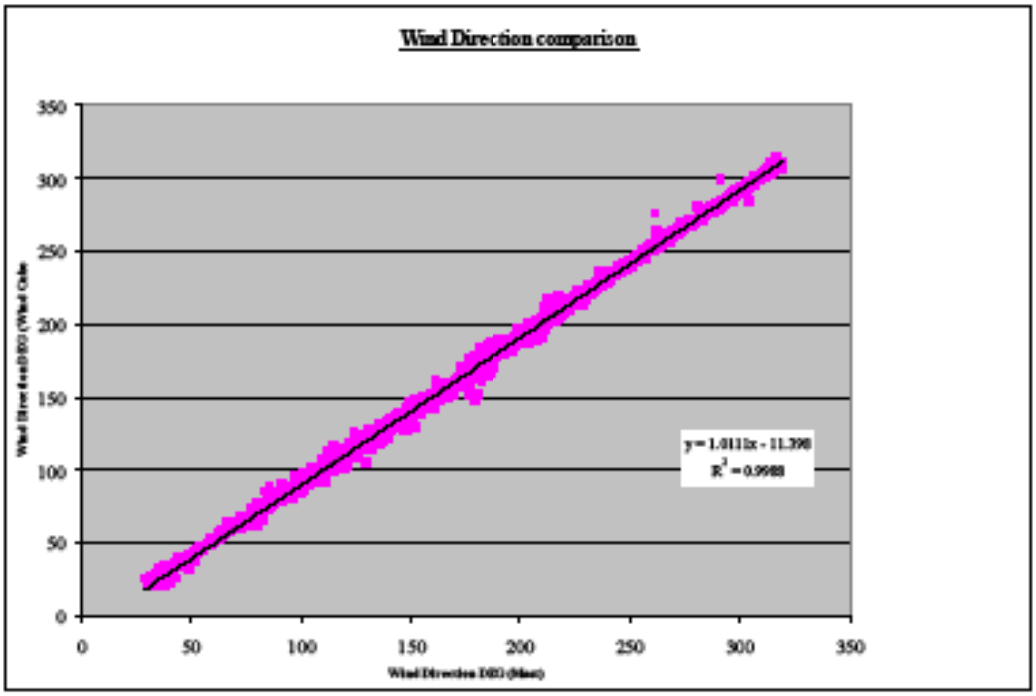

-11 deg offset: human error or inaccuracy of the lidar compass?

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What's in the TO-DO-LIST

- Lidar performances in function of rain and solar radiation measurements
- Comparison between turbulence measured by Lidar and Sonic over a forest
- Are lidar data still representative when changing CNR treshold and availibility criteria?

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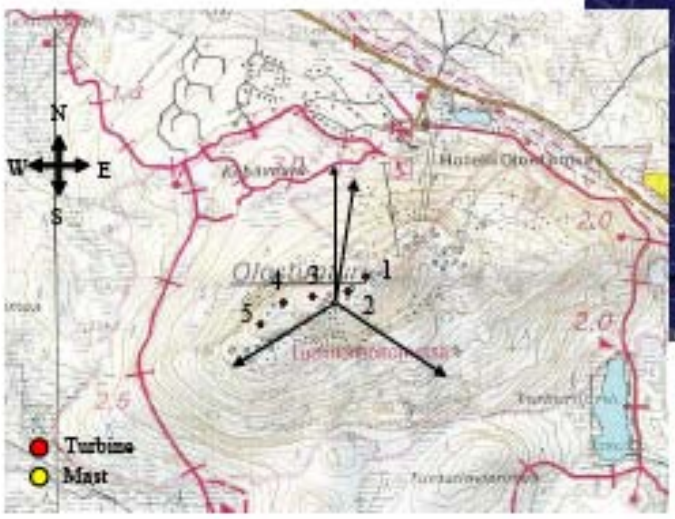
Winter Test: Olos



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Winter Test: Some first feelings

- Extreme clear sky events ecountered
- Wiper and pump issue
- Winter jacket ok
- Enough internal heat to melt some snow and ice on the window
- Temperature measurements of the volume of air over the window under planning

The key point is to keep the window ice free… let's see when conditions gets harsh!

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VTT TECHNICAL RESEARCH CENTRE OF FINLAND

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Wind Energy

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www.vtt.fi

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Download the free Upcode reading program to your mobile phone from ubibox.vtt.fi or www.upcode.fi

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* Technology developed by VTT

KIITOS!

TAKK!

THANK YOU!

GRAZIE!

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