INTERNATIONAL ENERGY AGENCY

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

61st IEA Topical Expert Meeting

"Wind Farms in Complex Terrain"

April 6-7, 2010

POSTECH's POSCO International Center (POSCOIC)

Organized by: CENER

POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

cener
centro nacional de energías renovables
national renewable energy centre

Scientific Co-ordination:

Félix Avia Aranda

CENER (Centro Nacional de Energías Renovables)

Urb. La Florida C/ Somera 7-9, 1ª

28023 - Madrid – Spain

Copies of this document can be obtained from:

CENER
Félix Avia Aranda
Urb. La Florida. C/ Somera 7-9, 1ª
C.P.: 28023 - Madrid – Spain
Phone: +34 91417 5042
E-mail: favia@cener.com

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

International Energy Agency

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

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

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. 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.

Operating Agent

CENER
Félix Avia Aranda
Urb. La Florida. C/ Somera 7-9, 1ª

C.P.: 28023 - Madrid – Spain E-mail:favia@cener.com
Phone: +34 91417 5042

COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Canada	National Resources Canada
Denmark	Risø National Laboratory - DTU
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
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	Uk Dept for Bussines, Enterprises & Regulatory Reform - BERR
United States	The U.S Department of Energy -DOE

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1. INTRODUCTORY NOTE

Prepared by POSTECH & KIER

1.1 INTRODUCTION

Korea is cordially hosting the first Topical Expert Meeting on "Wind Park Performance Assessment in Complex Terrain" of IEA Wind IA Task 11, which is also the first time held in Asian member country. This meeting might have a special meaning in the sense that more than 70% of the total area of Korea is covered by mountainous area. Therefore, for the development of new wind park, the "Complex Terrain" is nowadays one of the keen issues on seeking more reliable method of performance evaluation.

The recent years' macroscopic trend of wind farm development is gradually migrating from onshore to offshore. On the other hand, onshore development is heading from flat terrain having favorable wind condition to complex terrain in the vicinity and/or within forestry. This is because that the flat terrains where are relatively easy to develop the wind farms had already been occupied in the case of Europe and even many of late starter countries such as Korea, Japan and China typically with mountainous topography.

According to the report of vice president of CWEA(China Wind Energy Association) at GWEC 2008 in Beijing, more than half of wind farms constructed in complex terrain in China showed only 60% of designed electricity production. The main reason of the gap is presumably resulted by adopting the conventional engineering solution, modeled for simple or moderate complex terrain, which is more adequate for European countries.

Even though the International Electric Committee (IEC) has been devoting their efforts for preparing a standard for "Power Performance Measuring Techniques", however yet no concrete understandings and techniques is available for power performance predictions applicable on wind farm in complex terrain. Therefore, wind resource assessment and wind farm design in complex terrain still remains as the own risk of wind farm developers.

In these circumstances, this TEM is considered timely desirable to address not only for concerning technical discussions on wind resource prediction error and project risks caused by complex terrain effect but also for considering further the possibility of establishment of standard procedure or guidelines for wind resource assessment in complex terrain.

One of the goals of the meeting will be gathering the existing knowledge and experience on the subject and come up with suggestions and recommendations on how to proceed with the following:

1. Define complex terrain and identify prediction error due to complex terrain effects

2. Define a procedure of how should be the complex terrain assessed and modeled

3. Suggest next step for complex terrain consideration in terms of modeling - measurement and simulation, and wind farm design procedure or guidelines

Based on the above, a document will be compiled containing:

- Presentations by participants

- Compilation of the most recent information on the topic

1.2 TECHNIQUES

According to IEC61400-12, complex terrain is defined that terrain surrounding the site that features significant variations in topography and terrain obstacles that may cause flow distortion. It is well known that complex terrain accompanies terrain wakes or flow separation, flow channeling, flow accelerations over the crest of terrain features, augmentation of turbulent intensity, distortion of vertical wind profiles, etc. These nonlinear phenomena caused by complex terrain may result in not only AEP prediction error but also mis-selection of wind class of wind turbine, and the meeting should be addressed to these issues.

The meeting should also discuss consequences of complex terrain and forestry, how complex terrain can be assessed and mitigated, and how the modeling should be carried out in such circumstances. In modeling complex terrain, how to design and correct the field measurements, and the effectiveness of modeling methods such as RANS, LES, turbulence closure are to be discussed together, if allow, with sharing experiences from wind farm operation in complex terrain.

1.3 TOPICS 2010

To hold a meeting to discuss and gather information on:

- Definition of complex terrain

- Influence of topography; nonlinear and unsteady phenomena
- Influence of forestry
- Modeling in complex terrain
- Measurements in complex terrain
- Simulation in complex terrain; evaluation of CFD models such as RANS, LES, NWP, turbulence closure, etc.
- Guidelines for complex terrain
- Experiences from wind farm operation in complex terrain
- Best practice of wind farm design in complex terrain

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

1.4 PAPERS AND PRESENTATIONS

Experts who plan to attend the meeting are invited to write a paper and/or present their findings in the two day meeting. The presentation and paper should address one of the topics above and might answer one of the following questions:

1. *Process and policy*

- What standards are formulated by whom to safeguard the level of performance of air surveillance systems, and in what terms and definitions;
- How are these standards integrated in planning policies and institutions;
- What kind of tools are used to measure the standards, or the performance;
- Which policies meet the challenge to expand the energy system whilst maintaining required levels of air safety and national security;
- Which effects are acceptable and to what extent; can their impact on the mission of the radar-system be negligible;
- In what terms and how are the aim and expected results of the respective mission (ATC, Weather forecast, national security) formulated;
- For each country is there a process of formulating mission standards and what does this process look like;
- How can formulated safety standards be translated into a level of probability of detection;
- What effects influence the probability of detection most and when concurrently;
- Which effects occur with just one turbine and which effects occur for multiple turbines.

2. *Technical issues*

- How is energy system technology evolving with respect to stealth design, use of materials and sitting;
- What recent research has been done;
- How is radar system technology evolving with respect to data fusion, multi radar tracking, software, filters etc. and hardware;
- What kind of mitigating measures are effective and feasible;
- What questions have still to be answered by whom (further research).

AGENDA

Tuesday, April 6th

9:00 **Registration**. Collection of presentations and final Agenda

9:45 **Introduction by Host**
Prof. Hyunchul Park, Graduate School of Wind Energy, POSTECH

10:15 **Introduction by AIE Task 11 Operating Agent. Recognition of Participants**
Mr. Felix Avia, Operating Agent Task 11 IEAWind R&D

10:30 **Presentation of Introductory Note**
Dr. Hyun-Goo Kim, Korea Institute of Energy Research, Wind Energy Research Group

● *11:15 Coffee Break*

1st Session Individual Presentations:

11:45 **Complex Site Analyses**
Claude Abiven, Natural Power, UK

12:30 **Site assessment in Complex Terrain: Overview of Modelling Methodologies and Roadmap**
Javier Sanz Rodriguez, CENER, Spain

● *13:15 Lunch*

2nd Session Individual Presentations

14:30 **Multi-array turbine interactions in conjunction with complex terrain and atmospheric turbulence**
Mike Robinson, NREL, USA

15:15 **Analysis of SODAR Measurement over Complex Terrain in JAPAN**
Nobuyuki Hayasaki, ITOCHU Techno-Solutions Corporation, and Junsuke Murata, Mie University, Japan

● *16:00 Coffee Break*

16:30 **Complex Terrain in Finland: what you would not expect from a flat country**
Andrea Vignaroli, VTT – Technical Research Centre of Finland, Finland

● *17:15 Adjourn*

● *19:00 Dinner at Faculty Club (2nd floor, Sponsored by KEMCO)*

Wednesday, April 7th

3rd Session Individual Presentations

09:00 Presentation Title ?
Junsuke Murata, Mie University, Japan
09:45 Complex Terrain, 2nd Generation Lidar and Article 3 of the Boulder Protocol
Peter Clive, Sgurr Energy Ltd, Scotlant

●10:30 Coffee Break

11:00 Discussion
12:30 Summary of Meeting

●13:00 Lunch

●13:30 Meet at POSCOIC Lobby
- Excursion to Kyongju, the ancient city (40min. driving)

● 18:00 Dinner in Kyongju (Sponsored by Pohang Wind Energy Center)

Thursday April 8th

08:00 Meet at POSCOIC lobby

08:15 Technical Tour

09:00 Young-deok Wind Farm

11:00 Dong-guk S&C

12:00 Farewell Lunch (Korean Restaurant, Sponsored by the GWE)

14:00 Return to POSCOIC. Closing of the meeting

1.5 EXPECTED OUTCOME

One of the goals of the meeting will be gathering the existing knowledge and experience on the subject and come up with suggestions and recommendations on how to proceed with the following:

1. Define complex terrain and identify prediction error due to complex terrain effects
2. Define a procedure of how should be the complex terrain assessed and modeled
3. Suggest next step for complex terrain consideration in terms of modeling - measurement and simulation, and wind farm design procedure or guidelines

Based on the above, a document will be compiled containing:

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

1.6 INTENDED AUDIENCE

The national members will invite potential participants from research institutions, utilities, government 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 – 61st Topical Expert Meeting

Javier Sanz Rodrigo (CENER) and Félix Avia (CENER; OA Task 11 IEA Wind),

Background

Even though the International Electric Committee (IEC) has been devoting efforts for preparing a standard on "Power Performance Measuring Techniques", yet there are no specific standards for wind resources assessment and energy production estimation in complex terrain. Therefore, wind resource assessment and wind farm design in complex terrain still remains a mayor risk for wind farm developers.

Participants / Presentations

A total of 12 persons registered for this meeting. They represented the following countries: Republic of Korea, Japan, Finland, Spain, UK and the USA. A total of 9 presentations were given. The participants represented mainly research organizations, and universities.

Presentations covered the following topics:

- ✓ Definition of complex terrain
- ✓ Modelling in complex terrain
- ✓ Simulation tools
- ✓ Guidelines for development in complex terrain

The presentations were given by:

- ✓ *Dr. Hyun-Goo Kim, Korea Institute of Energy Research, POSTECH, Korea*
- ✓ *Claude Abiven, Natural Power, UK*
- ✓ *Javier Sanz Rodrigo, CENER, Spain*
- ✓ *Mike Robinson, NREL, USA*
- ✓ *Nobuyuki Hayasaki, ITOCHU Techno-Solutions Corporation, Japan*
- ✓ *Andrea Vignaroli, VTT – Technical Research Centre of Finland, Finland*
- ✓ *Chongwon Shin, Graduate School of Wind Energy, POSTECH, Korea*
- ✓ *Peter Clive, Sgurr Energy Ltd, Scotlant*

Discussion

Following the two days of presentations the floor was opened and a general discussion took place. A number of different topics were handled. The discussion was coordinated by Felix Avia.

In particular, the following topics were discussed:

- Definition of Complex Terrain
- CFD models validation
- Best practices
- Industry involvement

Definition of Complex Terrain

The first topic under discussion was the definition of complex terrain (CT) in the context of wind resource assessment. There was a general consensus between the participants about the necessity to have a clear definition of CT. The definition targets the limit of applicability of linear models, where CFD models would have to take over in order to reduce the uncertainty of linear models in the wind farm energy yield assessment. It is well known that linear models tend to overpredict the wind resource in complex terrain sites.

In the IEAWind R&D TEM #59 about remote sensing (RS) it also was stated that a classification of the terrain (simple, complex, etc) in terms of remote sensing is not defined, but is necessary. And same conclusion is detected for the working group of the IEC about power curve (PC) measurement.

However the definition of CT for RS may be not the same that for the annual energy estimation (AEE) of a WF, or for the PC measurement, but and effort should be done to unify the work in this issue. It was discussed that the limitations of linear models and remote sensing and somehow equivalent so, in this context, the definition of complex terrain would be the same.

It was also expressed that more knowledge is required about site characterization, that should be done in coordination with the IEC T88 WG (DE). For the time being there is a working group working on numerical site calibration, but there is not any work on changing the definition of CT. Depending of the subject there could be different approaches to the CT definition.

The general idea is that it should be possible to detect a set of parameters for definition of CT. However it was also commented that this definition should be done cautiously until CFD models are fully developed and validated. The definition of a limit for CT could create a distortion of the market because presently not all the participants in the wind sector, like financing enterprises, consulting companies or small and medium promoters, have access to CFD tools or know how to use them properly.

The general conclusion is that it should be clearly stated that for CT lineal models are not reliable and are prompt to overestimation of the AEE production. The complex terrain results of lineal models should be cross-checked with the results from CFD models both validated against data measured at onsite meteorological masts (when possible!).

CFD models validation

Another of the issues selected for discussion was the validation of existing models. A general consensus was reached, recognising that there is still a long way to run with CFD models for site assessment. The experts agree that the validation process in this moment is the most important issue.

It was clearly identified the necessity of developing user friendly models which are robust enough so that the user-dependency is minimized, in a similar way as lineal models do.

The best approach would be based on the definition of a fully validated benmarch CFD model that can be used as a reference for further developments in CFD. This would help monitoring the progress of new developments of CFD more than using the traditional comparison versus linear models, which always underperform in complex terrain.

Essential to CFD modelling is to properly validate the results versus onsite meteorological measurements (and even wind tunnel measurements using physical models!). When validating, the measurements have to be judged with care in order to assess the uncertainty associated to each measurement technique depending on the site installation.

A very useful output of this validation work is to produce a full description of the benmarch model, including specific guidelines on how to use CFD codes and the outputs of the model.

Best practices

The difficulty inherent to the use of CDF codes will be reduced if guidelines are available. How ever it is not and easy task, but something has to be done starting with a best practices document.

For CFD codes the user dependency is still a crucial aspect, especially if the codes are used in “black-box” mode.

The optimum situation is to have Guidelines defined by experts with strong experience in the use of CFD codes for assessment of wind resources in CT. Besides, several test cases with validation data and reference CFD simulations should be available together with the guidelines in order for the new users to verify their results.

Industry involvement

There are two levels of companies, the large corporations with their own R&D departments, that are capable of dealing with complex terrain assessments using advance modelling tools, and, in the other hand, a large number of small and medium enterprises that rely on the support from research centres in order to consider alternatives to their traditional methodologies.

The industry will be rapidly involved in the use of CFD models in order to reduce the risks of progressively larger investments.

In order to convince the industry to take a step ahead on the use of advance models, it is first necessary to gain confidence on the new models by introducing standardized methods. For the time being it is not only necessary to have the models but also to have experienced people, otherwise the results are too user-dependent. A major goal in the future will be to develop methodologies that can be traceable and reproducible because they rely on quality-checked procedures that have been validated in different wind regimes and topographical conditions. From this point it will be easier to think about developing “black-box” CFD models that can simplify the process as linear models do.

Future actions under the umbrella of IEA Wind

All the participants were in favour of the establishment of a new Task within the IEA’s R&D Wind, to compare and validate the CFD codes for the analysis of wind resource in complex terrain. The output of the study would be very useful for wind farm developers.

CENER will be the leader of the working group to put forward a proposal to set up the new task and to prepare the document to be distributed at the next Ex Co meeting.

Participants List - WIND FARMS IN COMPLEX TERRAIN
April 6-7, 2010 Pohang (KOREA)

	Name	Last Name	Job Center	Country	Address	Phone/Fax	E-mail
1	**Yunho**	**Park**	Korea Meteorological Administration	**KOREA**	1622-1 Hannam-ri, Namwon-eup, Seogwipo. Jeju 699-942	064-801-0228(016-770-0950) /064-805-0366	csat3@korea.kr
2	**Michael**	**Robinson**	NREL	**USA**	1617 Cole Blvd. MS 3811 Golden, CO 80401	303-384-6947 / 303-384-6999	Michael.robinson@nrel.gov
3	**Andrea**	**Vignaroli**	VTT-Technical Research Centre of Finland	**FINLAND**	Vvorimihentie 5, ESPOO , 02150	358-403-590-869 /	andrea.vignaroli@vtt.fi
4	**Peter**	**Clive**	Sgurr Energy Ltd	**SCOTLAND**	225 Bath Street, Glasgow G2 4GZ	44-141-227-1724	peter.clive@sgurrenergy.com
5	**Felix**	**Avia**	CENER - National Renewable Energy Center	**SPAIN**	Somera 7-9 28023 Madrid	34 91 417 50 42/ 34 91 556 63 00	favia@cener.com
5	**Javier**	**Sanz**	CENER - National Renewable Energy Center	**SPAIN**	Ciudad de la Innovacion, 7 - 31261 Sarriguren - Navarra	34 948 25 28 00 / +34 948 27 07 74	jsanz@cener.com
6	**Junsuke**	**Murata**	Mie University	**JAPAN**	1577 Kurimamachiya-cho-,Tsu, Mie - 514-0857	81-59-231-9658/81-59-231-1572	murata@mach.mie-u.ac.jp
7	**Claude**	**Abiven**	Natural Power	**UK**	Rue Goethe, 1 - 67000 -	33-388-161-402/33-369-208-044	claudea@naturalpower.com
8	**Nobuyuki**	**Hayasaki**	ITOCHU Techno-Solutions Corporation	**JAPAN**	Kasumigaseki Bldg. 3-2-5 , Kasumigaseki, Chiyoda-ku, Tokyo 100-680	81-3-6203-7556/81-3-3539-5175	nobuyuki.haysaki@ctc-g.co.jp
9	**Jun Young**	**Lee**	SAMSUNG Heavy Industries Co., Ltd.	**KOREA**	SAMSUNG Yeoksam Building, 647-9, Yeoksam-Dong, Kangnam-Gu, Seoul 135-080, Korea	82-55-630-6760/ 82-55-630-9788	juneyoung.lee@samsung.com
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11							
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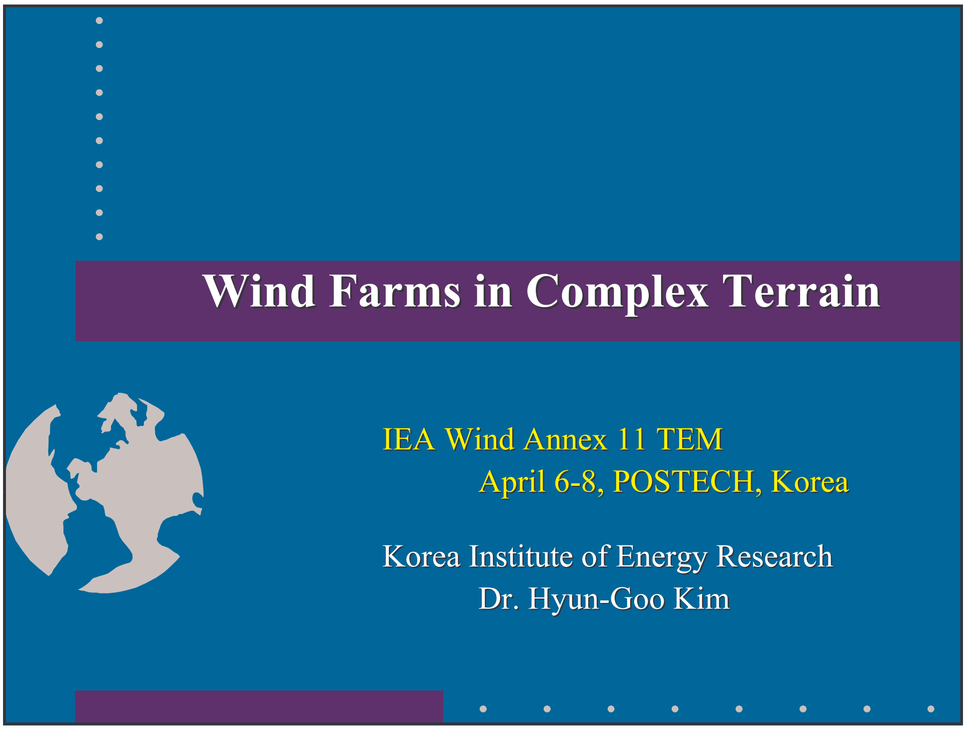
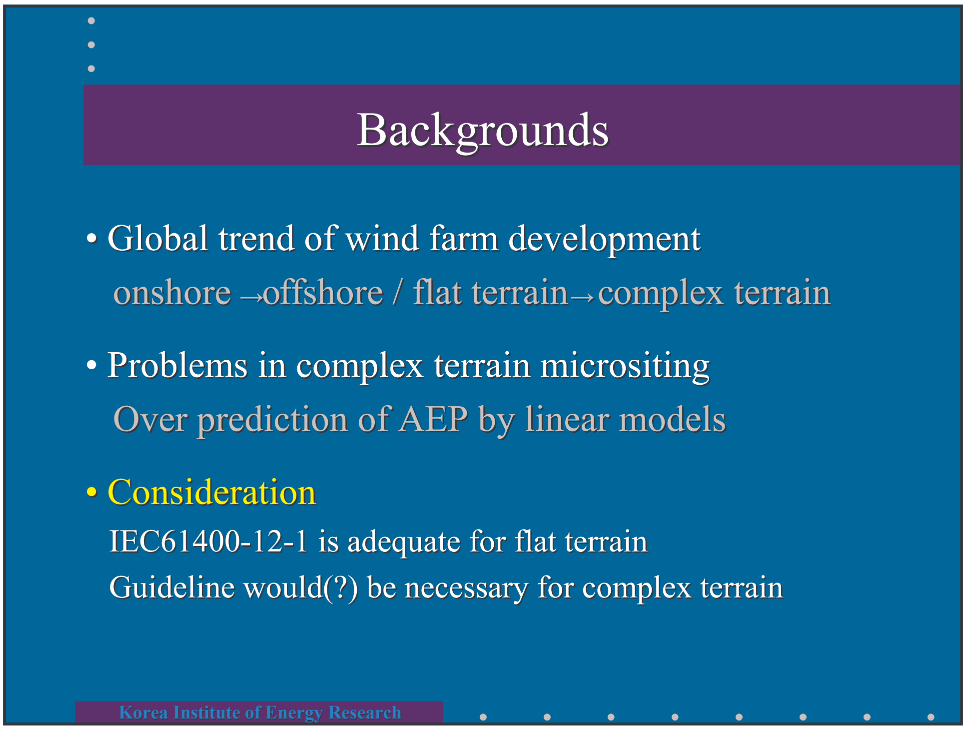
PRESENTATIONS

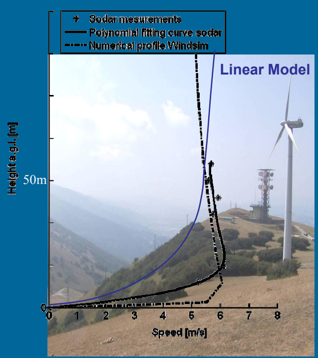

Wind Farms in Complex Terrain
IEA Wind Annex 11 TEM
April 6-8, POSTECH, Korea
Korea Institute of Energy Research
Dr. Hyun-Goo Kim


Backgrounds
• Global trend of wind farm development
onshore →offshore / flat terrain→complex terrain
• Problems in complex terrain micrositing
Over prediction of AEP by linear models
• Consideration
IEC61400-12-1 is adequate for flat terrain
Guideline would(?) be necessary for complex terrain
Korea Institute of Energy Research

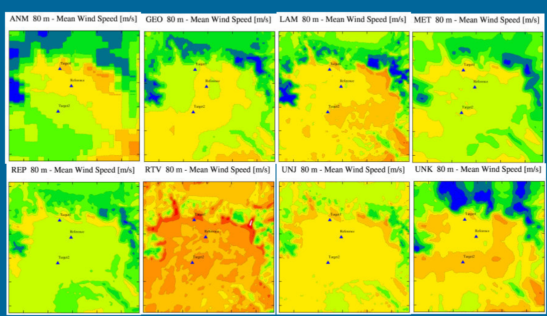
Complex Terrain

- What is the definition of complex terrain?
  hills and valleys, slope of terrain, RIX, etc.
- What is the characteristics of complex terrain?
  speedup, separation, transient, unsteadiness, etc.
- Point of views
  horizontal field, vertical profile,
  nonlinearity, turbulence, forestry, etc.

Complex Terrain

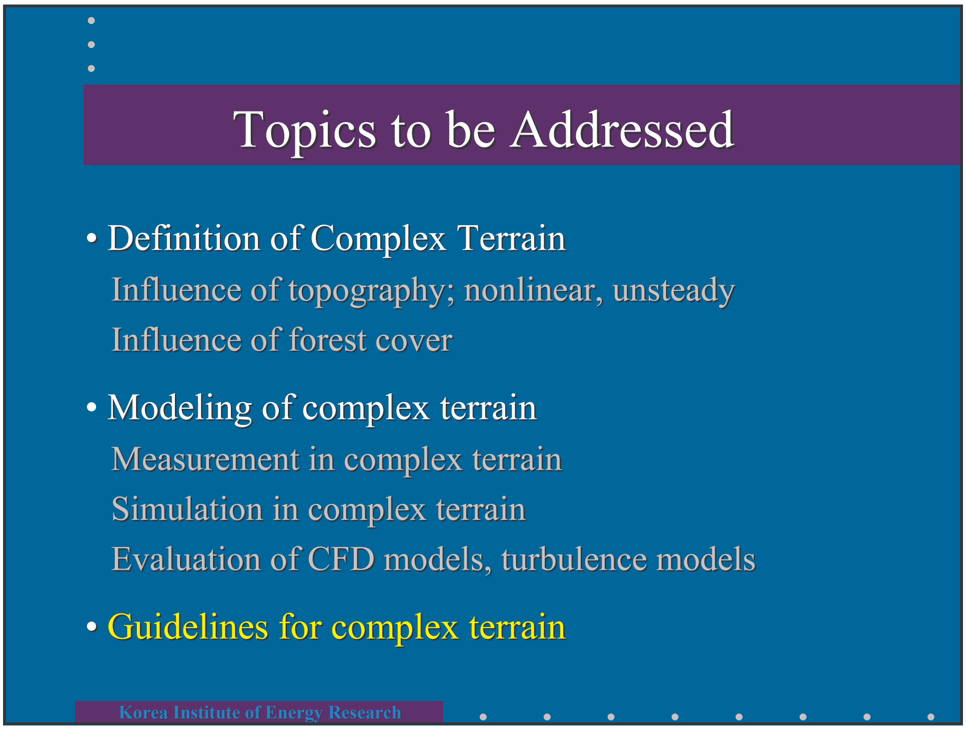


Hundhammerfjellet
wind farm, Norway



Micro wind mapping benchmark, DEWI(2007)

Korea Institute of Energy Research


Topics to be Addressed
• Definition of Complex Terrain
Influence of topography; nonlinear, unsteady
Influence of forest cover
• Modeling of complex terrain
Measurement in complex terrain
Simulation in complex terrain
Evaluation of CFD models, turbulence models
• Guidelines for complex terrain
Korea Institute of Energy Research

Test of Wind Mapping Solvers for the Wind Flow with Recirculation

IEA Wind Annex 11 TEM
April 6-8, POSTECH, Korea

Korea Institute of Energy Research
Dr. Hyun-Goo Kim

Motivation

- Issues on wind mapping
  steepness/roughness/complexity

- Korea, mountainous country
  where the terrain gets really rough

- Benchmark wind mapping software
  WAsP, WindSim, Meteodyn, In-house CFD

Korea Institute of Energy Research

Selected Field Experiments

- Well-defined geometry (numerical grid)
- Well-defined upstream conditions
- Reliability of the measurements
- Sufficient number of measuring locations

Terrain	*Height* H (m)	*Length* $4L$ (km)	*Slope* s	*Wind direction* ϕ	*Shape*	*Roughness* z_0 (cm)
Cooper's Ridge	115	1.6	0.143	270°	quasi-2D	3.0
Kettles Hill	105	2.4	0.1	245°, 260°	bell-shaped 3D	0.3~1.0
Askervein Hill	116	1.0	0.2	180°, 210°	elliptic 3D	3.0
Sirhowy Valley	200	1.8	0.4	90°, 270°	cyclic 2D	1.0

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Sirhowy Valley Experiment

- Located at South Wales, UK
  - Length 1.8km, Depth 200m
- Periodic Valley Terrain
  - Periodic boundary conditions were applied
- For Westerly(270°) and Easterly(90°) Winds

- Mason & King (1984), Mason (1987)

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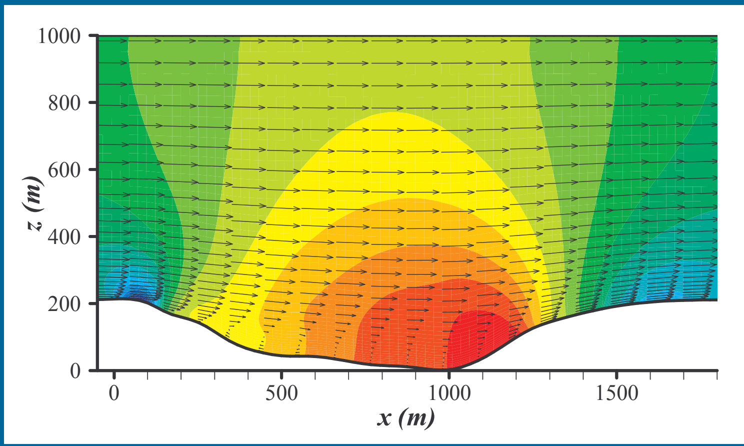
Separated Flow in Sirhowy Valley



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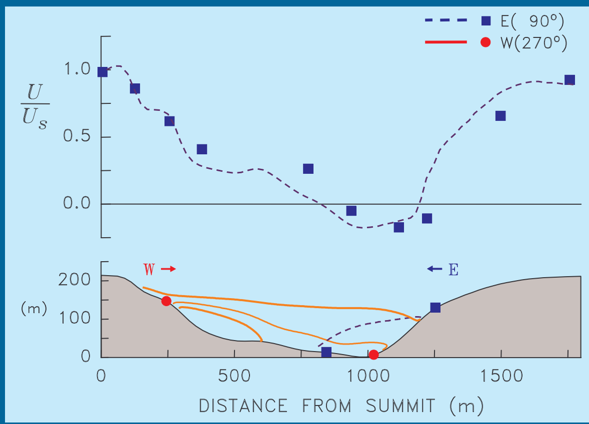
Separation and Reattachment Points

Wind directions	*Classification*	***Field data***	*$k-\varepsilon$ model*	*RNG model*	*Modified constants*
Westerly wind	Separation point (m)	**245**	293	270	156
	Reattachment point (m)	**1023**	596	1055	1197
	Length (m)	**778**	303	785	1041
Easterly wind	Separation Point (m)	**845**	870	800	675
	Reattachment Point (m)	**1254**	1205	1215	1250
	Length (m)	**409**	335	415	575

Korea Institute of Energy Research

Separation and Reattachment Points



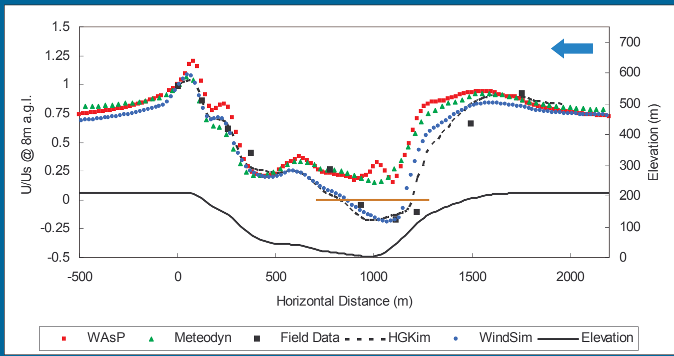
Constant

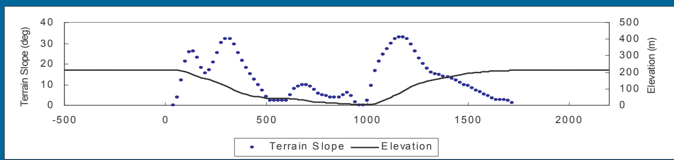
Benchmark Software

Software	Theory	Turbulence Model	Comments
WAsP	Linear	-	Easy & Fast Well known to WE industry
WindSim	CFD	k-ε Modified k-ε	Adequate for complex terrain Based on Phoenics, CHAM
Meteodyn	CFD	One-equation	Adaptive grid generation Stability consideration
H.G.Kim*	CFD	k-ε, k-ω, RNG k-ε	In-house code for R&D

* H.G. Kim and V.C. Patel (2000) Test of Turbulence Models for Wind Flow over Terrains with Separation and Recirculation, Boundary-Layer Meteorology

Easterly Wind Case





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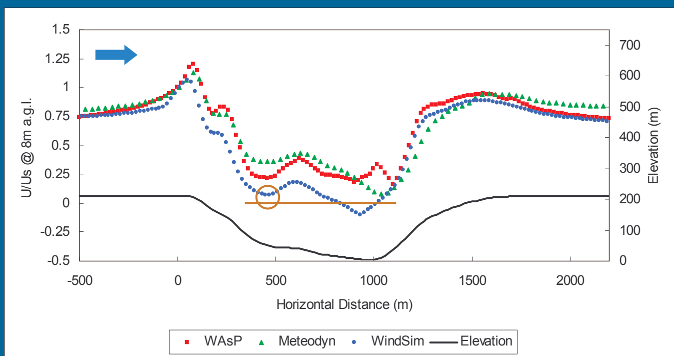
Westerly Wind Case



- Separation is expected over terrain slope 15 deg. (Wood, 1995)
- What else can we consider?

  Transient Flow, Three-dimensional effect, Periodic boundary conditions, etc.

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Conclusions

- WAsP does not predict recirculation
  WAsP is really a linear model (W = E)
- Meteodyn neither predict recirculation
  quite similar to WAsP prediction
- WindSim seems to be more improved
  RNG k-epsilon model is recommended
  Transient simulation may be necessary

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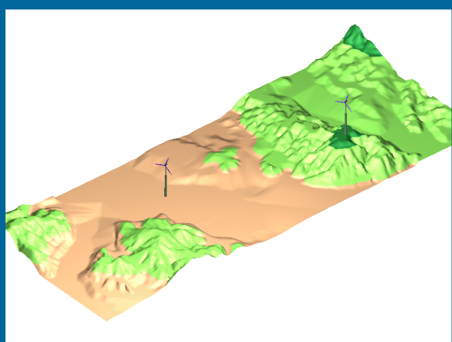
Thank you



hyungoo@kier.re.kr

http://www.kier-wind.org

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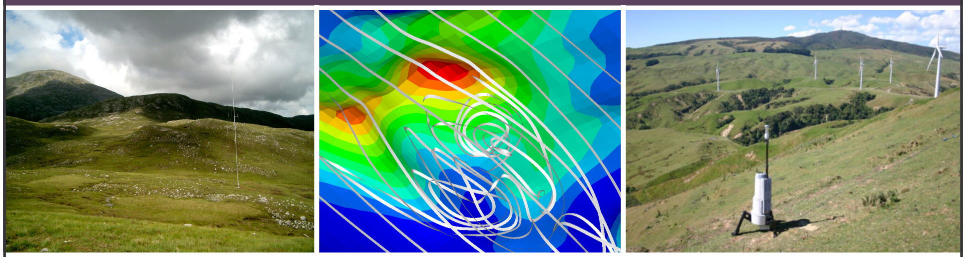

KEY FEATURES OF WIND FARM STUDIES IN COMPLEX TERRAIN

Claude Abiven   Pohang   7th April 2010

CONTENTS

1. Complex terrain assessment
2. Measurements
3. Site visit
4. Modelling
   - linear vs. CFD
   - forestry model (case study 1)
   - time-dependant analyses (case study 2)
5. Conclusions

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1. ASSESSING SITE COMPLEXITY

Site visualization (Google Earth)

RIX and land cover considerations (Natural Power applet)

VENTOS®

Windrose

If you have it, enter here the wind distribution (or paste it from an excel file for instance)

Paste from clipboard

Sector	Frequency
0	6.575
30	28.701
60	6.657
90	1.183
120	0.871
150	1.558
180	11.806
210	28.476
240	9.412
270	1.621
300	1.417
330	1.72

1 2 3 4 5

Next Step

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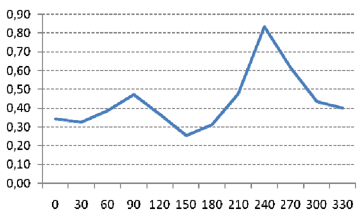
2. THE IMPORTANCE OF MEASUREMENTS

Measurements provide a first picture of flow conditions on site

- help assess site complexity
- provide useful information on the type of model to use



shear vs. direction in forested area

Large values of wind shear can be measured in forested areas

A canopy model might be necessary to reproduce the physics

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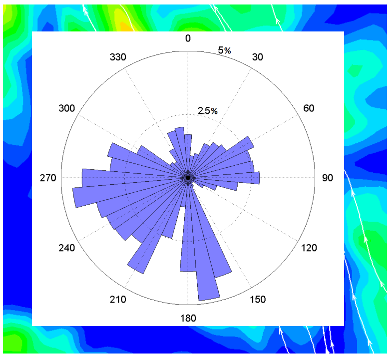
2. THE IMPORTANCE OF MEASUREMENTS



Holes in wind rose can imply that the wind is blocked by mountains in these directions

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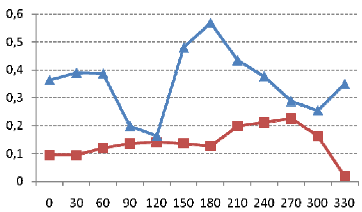
2. MEASUREMENTS ARE LOCAL BUT NECESSARY

However, values measured at the mast only reflect the local flow



Wind shear vs. direction measured at two masts 1.5km away from one another in complex forested terrain

☞ numerical models are used to estimate flow conditions at other locations

These models need to be calibrated with measurements

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3. SITE VISIT

A site visit can help:

- alert on specific features that need to be modelled such as steep slopes
- update/enhance forestry maps
- check mast configuration and obstacles

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4. MODELLING – CFD vs. LINEAR

CFD codes can solve the full time-dependent Navier-Stokes fluid equations:

mass conservation: $\nabla \cdot (\rho \mathbf{v}) = 0$

momentum conservation:

$$\rho\Big(\overbrace{\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}}^{\text{Inertia}}\Big) = \underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}} + \underbrace{\mathbf{f}}_{\text{Other forces}}$$

models turbulence (k-ε model here, but other schemes exist):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(P_k + C_{3\epsilon}P_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

LES (Large Eddy Simulation) can also be used but is computationally expensive

Linear models: *don't take into account the non-linear advection terms, don't include any turbulence model, don't include time-dependence*

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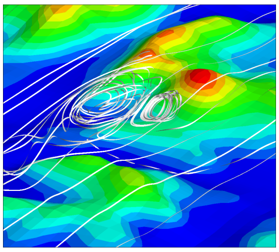
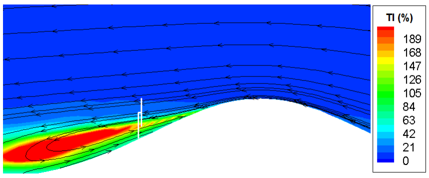
4. MODELLING – superiority of CFD models

Simplifications inherent to linear models imply that they:

- break down in case of steep slopes
- do not enable turbulence or inflow angle quantification
- cannot detect recirculation zones





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4. MODELLING FORESTED TERRAIN

In CFD models, trees are modelled in 3D, taking into account tree height and leaf density

In the transport equations additional terms are included in order to model what actually happens:

- momentum drag
- sink & source of turbulence

$$\rho\frac{\partial}{\partial\xi^j}\left(U_kU_i\beta_k^j\right) = -\frac{\partial}{\partial\xi^j}\left(P\beta_i^j\right) + \frac{\partial}{\partial\xi^j}\left[\left(\sigma_{ki}+\tau_{ki}\right)\beta_k^j\right] + \underbrace{JF_i}_{A},$$

$$\rho\frac{\partial}{\partial\xi^j}\left(U_kk\beta_k^j\right) = \frac{\partial}{\partial\xi^j}\left[\frac{1}{J}\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial\xi^m}\beta_k^m\beta_k^j\right] + J\left(\mathcal{P}_k - \rho\varepsilon + \underbrace{S_k}_{B}\right)$$

$$\rho\frac{\partial}{\partial\xi^j}\left(U_k\varepsilon\beta_k^j\right) = \frac{\partial}{\partial\xi^j}\left[\frac{1}{J}\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial\xi^m}\beta_k^m\beta_k^j\right] + J\left(\frac{C_1\varepsilon}{k}\mathcal{P}_k - \frac{C_2\rho\varepsilon^2}{k} + \underbrace{S_\varepsilon}_{C}\right)$$

Additional terms corresponding to:
- drag
- turbulence sink/source induced by the canopy

are included in the equations

Linear models model forests as a roughness value at the ground
do not model what actually happens

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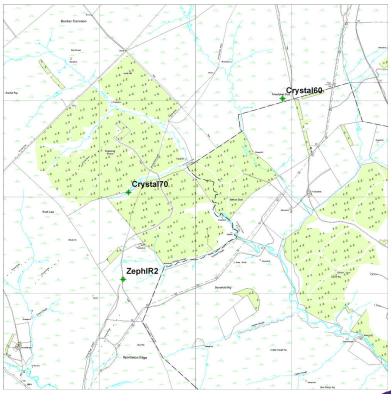
CASE STUDY 1 – roughness vs. canopy model

Site complexity:

- Topography within the limits of linearised flow solvers

- Large areas of forest

There are significant differences in average wind speeds predicted by WAsP and VENTOS®



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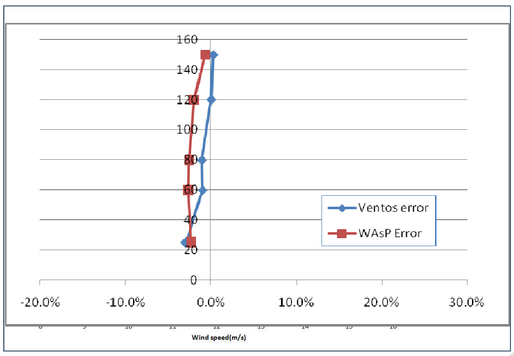
CASE STUDY 1 – Westerly winds

No forest upwind

WAsP is initialised from 70 m mast location to predict ZephIR location

Ventos results normalised to 70 m mast location

Max error 3%



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CASE STUDY 1 – North-north-easterly winds

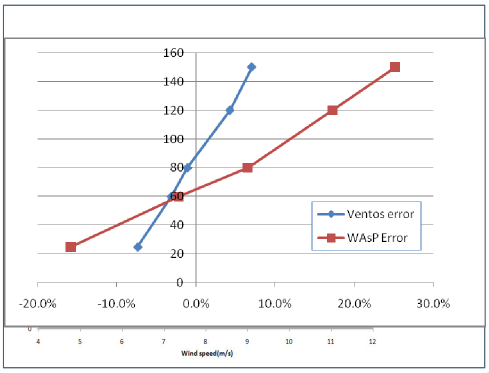
1500m of forest upwind

Significant differences between measured and modelled

WAsP overestimates by 0.6 m/s at 80m and 1.6 m/s at 120 m

Significant difference in shear over rotor compared to expected

VENTOS® underestimates by 0.1 m/s at 80m and overestimates by 0.4 m/s at 120 m



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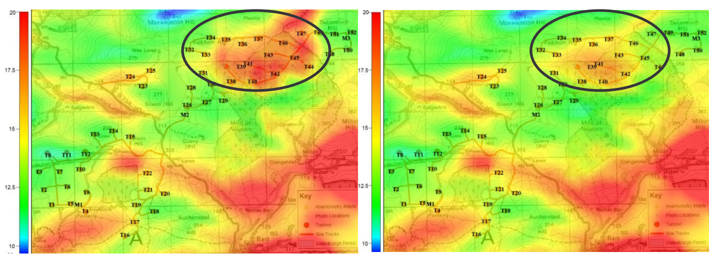
4. MODELLING – superiority of canopy models

The impact of forestry felling/growth can be assessed in terms of:
- wind shear
- turbulence intensity
- power production

This results in informed wind farm management decisions



Turbulence intensity modelled assuming current and future forestry

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4. TIME-DEPENDANT SIMULATIONS

CFD analysis is most often performed under the assumption of statistically averaged steady state solutions

mass conservation: $\nabla \cdot (\rho \mathbf{v}) = 0$

momentum conservation:

$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}\Big)}^{\text{Inertia}} = \underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}} + \underbrace{\mathbf{f}}_{\text{Other forces}}$$

models turbulence through the k-ε model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(P_k + C_{3\epsilon}P_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

This can be misleading, especially in complex terrain. Computer codes might show solutions that might not even exist

Time-dependant simulations and analyses can be necessary in complex terrain

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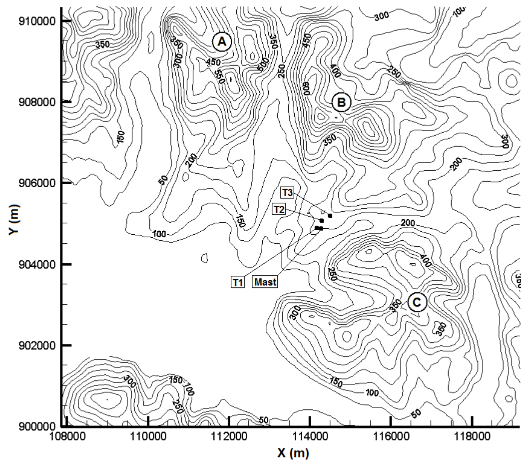
CASE STUDY 2 – TIME-DEPENDANT ANALYSES



Highly complex topography:

RIX of 12.8% on average

Oscillations detected from 1Hz wind measurements for Northerly winds

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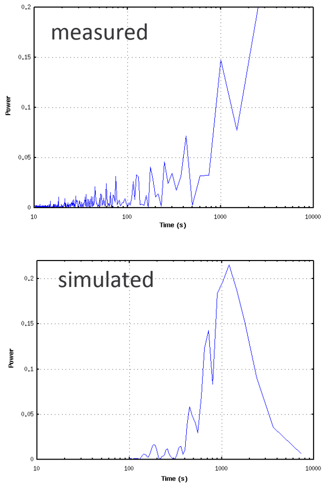
CASE STUDY 2 – POWER SPECTRUM



Measured and simulated peak positions are in good agreement T ≈ 1000s

☞ Simulations can help us understand the reason for these peaks

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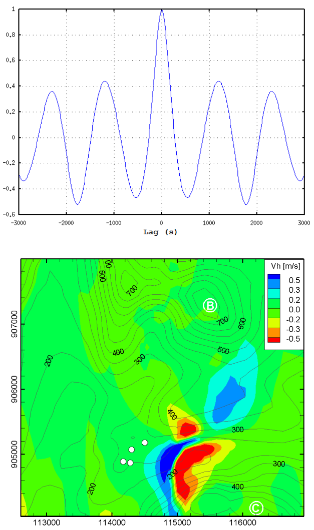
CASE STUDY 2 – EOF ANALYSIS (spatial spectral analysis)



The first EOF is associated with an oscillation of period ≈ 1000s

Most of the variability occurs downwind of the hill

Variations of the vortex located to the East are associated to variations downwind of this vortex.

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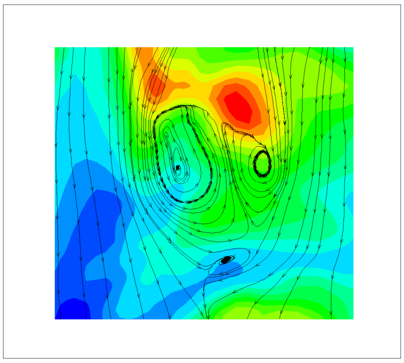
CASE STUDY 2 – FRAME BY FRAME ANALYSIS



Time-dependant simulations show that:

- vortices can break and reform

- flow variations are expected further downwind of the hill than shown by steady simulations

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CONCLUSIONS (1/2)

Steep slopes and forested terrain can imply:

- large values of turbulence, wind shear, inflow angle, recirculation zones

Which can lead to:

- underproduction, machine fatigue or failure

Key features of a wind farm study in complex terrain:

1. Site complexity assessment
2. Measurements (provide precious but local information on the flow)
3. Site visit
4. CFD modelling (not linear)

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CONCLUSIONS (2/2)

Advantages of CFD:

- ability to characterise turbulence, shear, inflow angle, recirculations
- forestry model
- time-dependant simulations

BUT CFD involves:

– heavy computations
– numerous parameters
– understanding of measurements
– a strong background in CFD & fluid dynamics
– a critical mindset
– knowledge and experience of a specific code
– experience of how an output translates into recommendations

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Site assessment in Complex Terrain: Overview of Modelling Methodologies and Roadmap

IEA Topical Expert Meeting #61: Wind Farms in Complex Terrain

Energía eólica

Javier Sanz Rodrigo
Daniel Cabezón
Bibiana García
Pohang, Korea, 8/04/2010
jsrodrigo@cener.com

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Contents

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Overview of site assessment methodologies

- State-of-the-art at operational level
- Prospects

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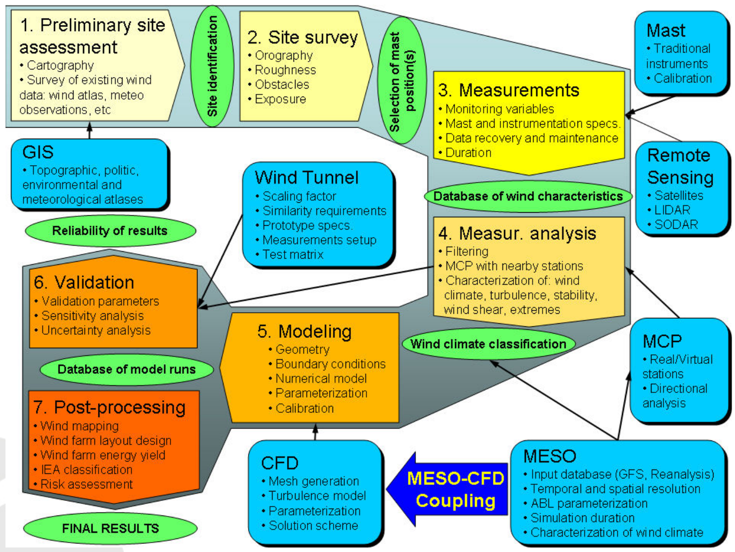
Wind Resource Assessment Process and Techniques



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State-of-the-art at operational level

- Measurements:
  - Mast based cup anemometry still the standard
  - Remote Sensing techniques booming but still far from operational in complex terrain
- Flow modelling
  - Linear-models still the standard for micrositing
  - CFD models emerging especially for complex terrain and wakes
    - User-friendly commercial software
    - Customized CFD models for experienced users
  - Mesoscale models for regional wind mapping (~3-5km resolution)
    - Downscaling to finer scales (~100m) with simplified microscale models
  - Wind tunnel site assessment not used
- Engineering models
  - IEC classification: V_{ref} and I_{eff}
  - MCP methods for long-term extrapolation
- Onsite field experience
  - Site selection

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State-of-the-art: Prospects

- Most developers rely on traditional methodologies based on engineering methods with a significant portion of field experience
- Lack of standardization of traditional methodologies creates "communication problems" between different end-users, e.g. developer vs manufacturer
- Migration to more sophisticated methodologies require important efforts in terms of training, organization, project management, etc
- CFD models show promising results but they are too user-dependent because of the large number of degrees of freedom → lack of standardized methodology or guidelines for good-use
- Commercial CFD solvers have been adapted for wind resource assessment in a user friendly environment but still requires a significant effort from the user (compared to traditional models)
- Lack of test cases for validation of numerical models
- Validation seems to be also "user-dependent"

→ Standardization of modelling and validation is required in order to make the transition to new wind assessment methods

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ABL modelling at CENER: CFDWind

- CFDWind 1.0
- CFDWind 2.0

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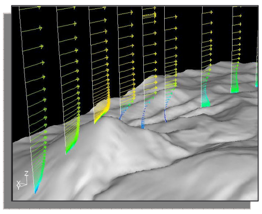
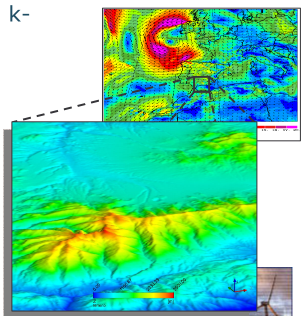
Modelling of the ABL at CENER

- Evolution of microscale models in the last three years:



1. EWEC-08: Surface boundary layer modelling based on Monin-Obukhov similarity theory implemented in CFD k-ε model
   - Most widely used model in wind resource assessment
   - Only valid in the first ~100m (neutral, unstable ABL)
   - Limited use in stable conditions (offshore) where ABL depth is ~10m
   - **CFDWind 1.0**
2. EWEC-09: ABL modelling with a limited-length-scale k-ε model
   - Coriolis effects included
   - Bounded eddy viscosity produces more realistic profiles at greater heights
   - ABL forced by geostrophic winds
   - **CFDWind 2.0**



3. EWEC-10: Downscaling of mesoscale with CFD
   - ABL classified according to geostrophic winds from mesoscale model
   - ABL modelled with CFDWind 2.0
   - **MESO-CFD**

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ABL modelling: CFDWind 1.0

- Based on Monin-Obukhov similarity theory for surface boundary layer (~ 10% of ABL height)
  - ❑ Constant turbulent fluxes, no Coriolis effects
  - ❑ Stationary and homogeneous
  - ❑ Scaling parameters

$$L = \frac{u_*^2 T_w}{\kappa g T_*};\quad u_* = \sqrt{\frac{\tau_w}{\rho}};\quad T_* = \frac{-q_w}{\rho C_p u_*}$$

- In flat terrain, under stationary homogeneous conditions, it has analytic solution, i.e. log-laws:

$$\frac{U}{u_*} = \frac{1}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right] \qquad \frac{\theta(z)-\theta_0}{T_*} = \frac{1}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_h\left(\frac{z}{L}\right)\right] \qquad k = \frac{u_*^2}{\sqrt{C_\mu}}\left[\frac{\phi_\varepsilon\left(\frac{z}{L}\right)}{\phi_m\left(\frac{z}{L}\right)}\right]^{\frac{1}{2}} \qquad \varepsilon = \frac{u_*^3}{\kappa z}\phi_\varepsilon\left(\frac{z}{L}\right)$$

- In complex terrain: k-ε standard turbulence model modified to match M-O similarity theory in flat terrain
  - ❑ Constants adapted to match M-O theory in flat terrain conditions

$$\sigma_\varepsilon \sqrt{C_\mu}\,(C_{2\varepsilon} - C_{1\varepsilon}) = \kappa^2 \qquad C_{\varepsilon 3}\left(\frac{z}{L}\right) = \sum_{n=0}^{5} a_n \left(\frac{z}{L}\right)^n$$

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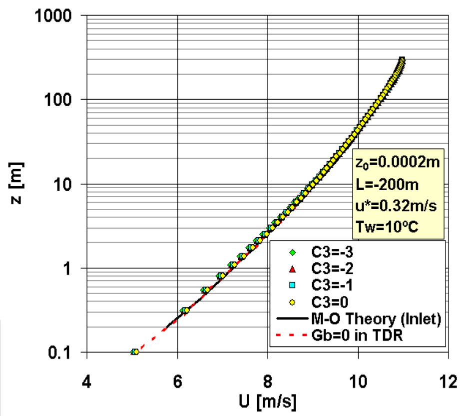
Validation CFDWind 1.0: Flat terrain

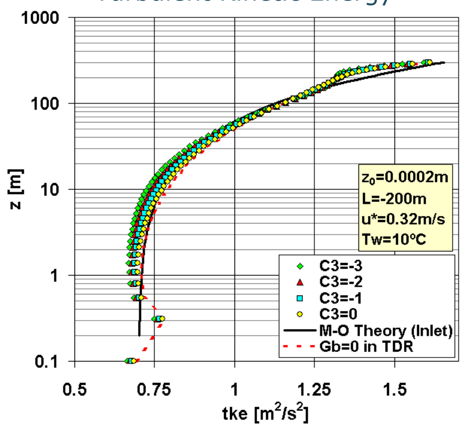
- Simulation in empty domain under various stability conditions

UNSTABLE

Velocity



Turbulent Kinetic Energy



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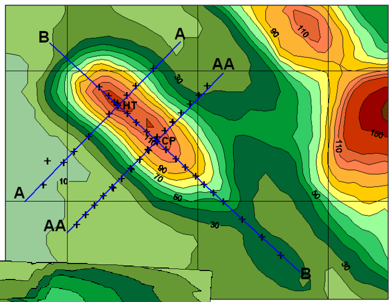
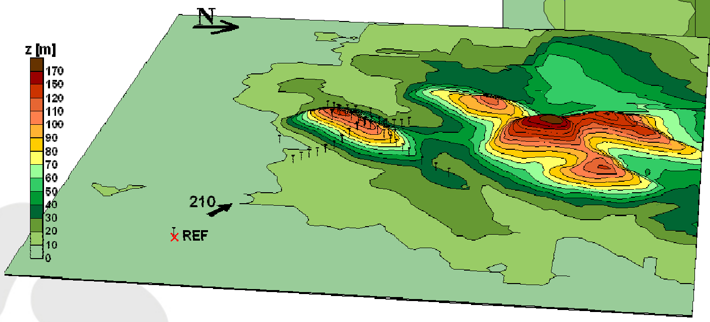
Validation CFDWind 1.0: Askervein

- Askervein hill
  - Most widely used (unique) test case for validation of flow models on topography
  - Field experiments (1982, 1983)
  - 10m masts along lines A, AA and B
  - 50m masts at reference sites upstream and at hilltop (HT y CP)
  - Kites, flights, etc





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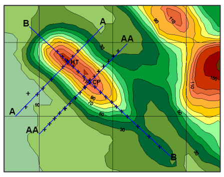
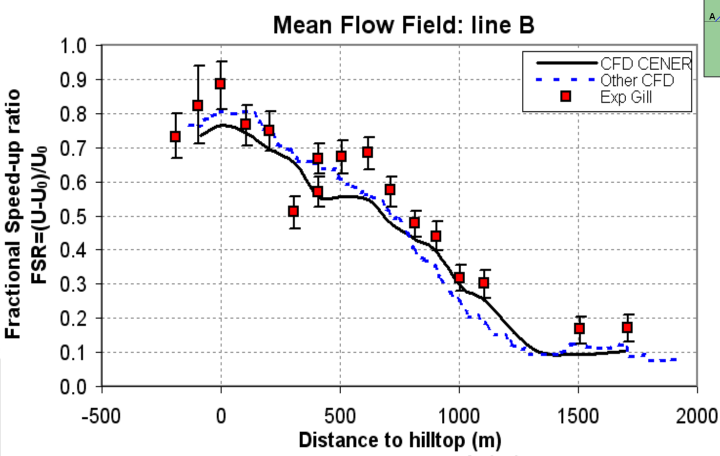
Validation CFDWind 1.0: Askervein

- Ideal conditions, not very challenging for flow models and not very representative of complex sites





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ABL modelling: CFDWind 2.0

- Assumptions:
  - Horizontally homogeneous conditions: d/dx→0, d/dy→0
  - Hydrostatic:

Geostrophic Wind: $\left(U_g, V_g\right) = \frac{1}{\rho f_c}\left(-\frac{\partial P}{\partial y}, \frac{\partial P}{\partial x}\right)$

Coriolis parameter $f_c = 2\Omega \sin\lambda$

- 1D Momentum and Energy equations:

$$\frac{\partial U}{\partial t} = f_c(V - V_g) - \frac{\partial \langle uw \rangle}{\partial z}$$

$$\frac{\partial V}{\partial t} = -f_c(U - U_g) - \frac{\partial \langle vw \rangle}{\partial z}$$

$$\frac{\partial \Theta}{\partial t} = -\frac{\partial \langle w\theta \rangle}{\partial z}$$

Kinematic momentum and heat fluxes

$$\left(\langle uw \rangle, \langle vw \rangle\right) = -\nu_t \left(\frac{\partial U}{\partial z}, \frac{\partial V}{\partial z}\right)$$

$$\langle w\theta \rangle = -\frac{\nu_t}{\sigma_t}\frac{\partial \Theta}{\partial z}$$

$$\nu_t = l_m \left(\sqrt{C_\mu} k\right)^{\frac{1}{2}} = C_\mu \frac{k^2}{\varepsilon}$$

- k-ε turbulence model with limited mixing length: $l_{max} = 0.00027 \frac{|U_g|}{f_c}$
- Boundary conditions: U_g, z_0, L, T_w

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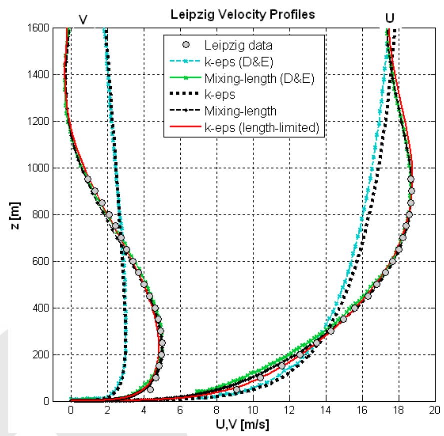
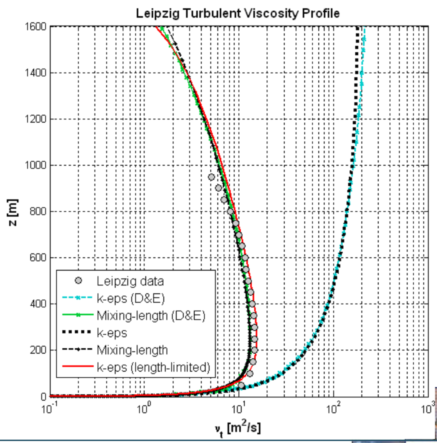
Validation CFDWind 2.0: Leipzig profile

- Leipzig wind profile: Neutral ABL (z_0=0.3m,u*=0.65m,U_g=17.5m/s)
  - Standard k-ε model produces a very deep ABL
  - Mixing-length and limited-length-scale k-ε model perform well





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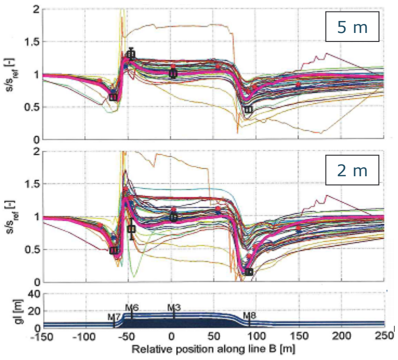
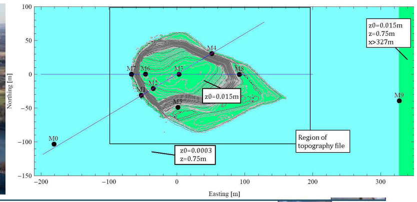
Validation CFDWind2.0: Bolund

- Bolund experiment carried out by RisoeDTU, co-financed by VESTAS
  - Nine 15-m masts equipped with cup and sonic anemometers
  - Controlled environment excellent for validation of flow models
- Blind comparison of 52 models (Dec-2009)
- CFDWind2.0 got among the best results according to "Risoe's ranking": 4% error in wind velocity at 5m level





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Downscaling mesoscale databases with CFD for high-resolution wind mapping

- MESO-CFD

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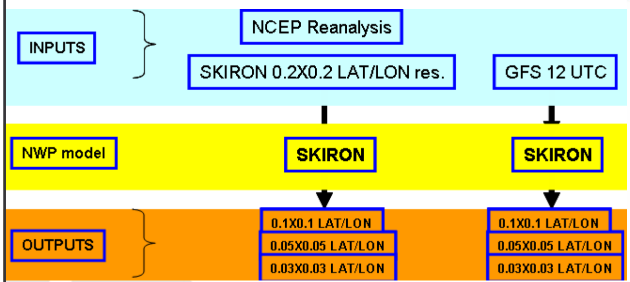
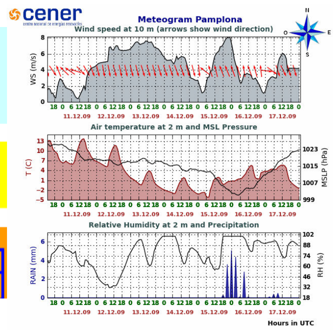
MESOscale modelling

- SKIRON mesoscale model developed by the Technical University of Athens (NKUA)
- Based on ETA forecasting model
- Operative wind power forecasting for whole Europe based on GFS forecasts at 0.1º resolution
- Wind Resource assessment based on reanalysis → GlobalWindMap





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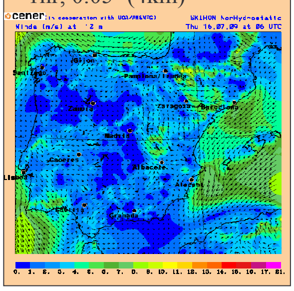
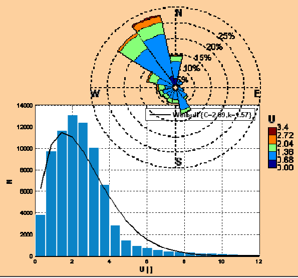
MESO-CFD modelling approach

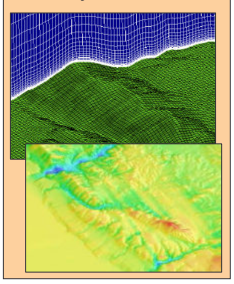
Mesoscale database
- 2003-2009
- 1hr, 0.05º (4km)



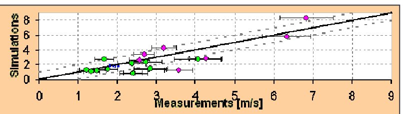
Wind Climate classification
- Wind speed, wind direction
- Stability, etc



CFD modelling
- Speed-up factors
- Steady-state, 100m



Validation/Calibration
- Collection of synoptic stations with surface winds
- Uncertainty analysis



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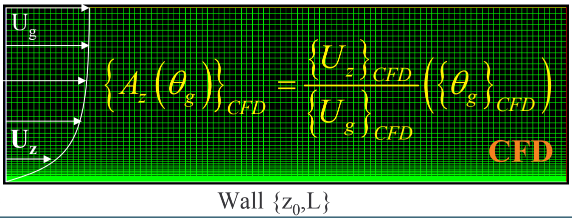
MESO-CFD Downscaling

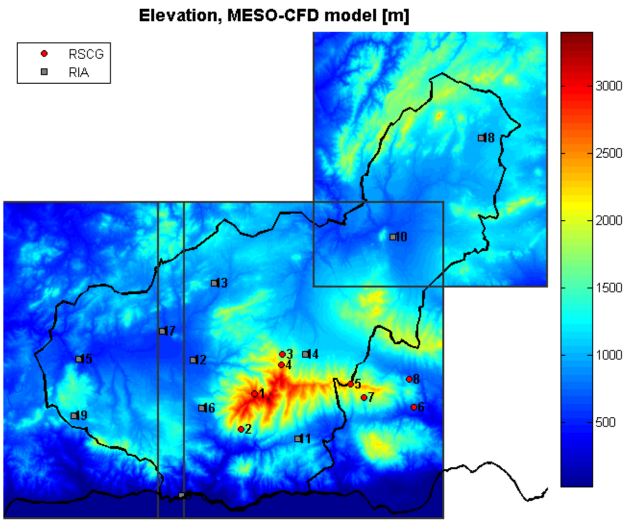
First approach to make use of two uncoupled models working in different regimes: MESO→time resolved, CFD→steady-state.

1. Run a mesoscale model for several years
2. Calibrate geostrophic pressure level based on synop observations
3. Classify the wind climate at geostrophic level → frequency tables of wind direction (wind speed and stability)
4. Divide the map in CFD subdomains
5. Run as many CFD runs (=wind climate classes) as possible
6. Scale down the geostrophic wind to surface conditions using speed-up ratios from CFD simulations
7. Merge maps and GIS integration

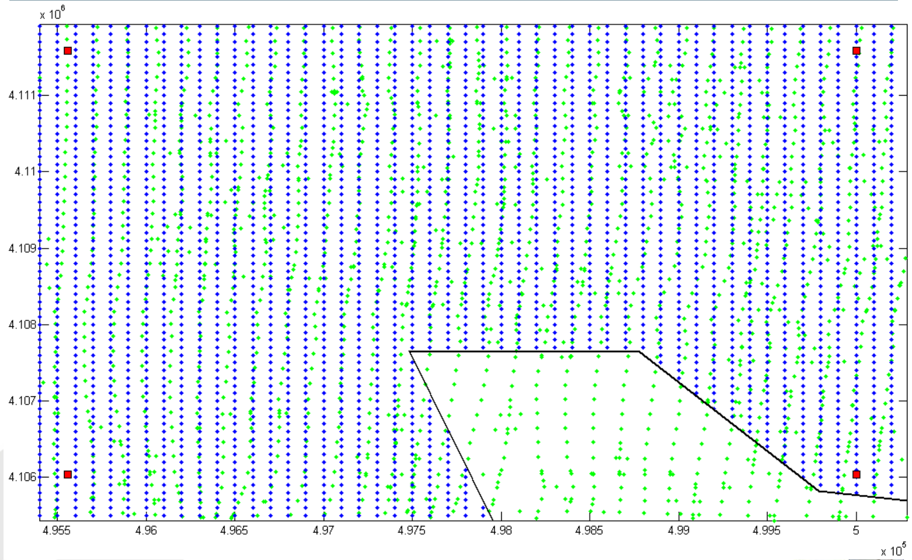


Test Case: Wind Map of Granada

- 3 domains conditioned by the presence of Sierra Nevada (3300m)
- 19 synop stations from two grids
  - RIA (simple terrain)
  - RSCG (complex terrain)
- Validation always compromised by the quality of the observations at hand



Grids: MESO, CFD, MESOCFD



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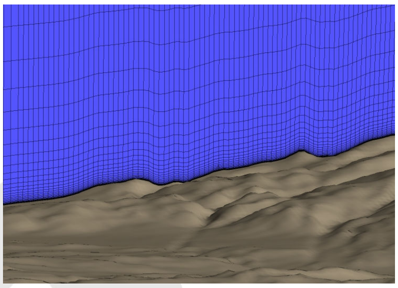
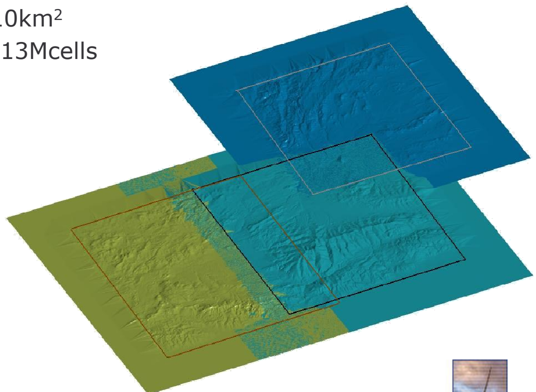
CFD configuration

- The region is divided in three CFD subdomains
  - Digital Elevation Model from SRTM (~90m resolution)
  - Roughness map from CORINE Land Cover (100m resolution)
  - Structured grid
  - Subdomain area ~110x110km^2
  - +20km buffer border = ~13Mcells
  - Overlapped subdomains





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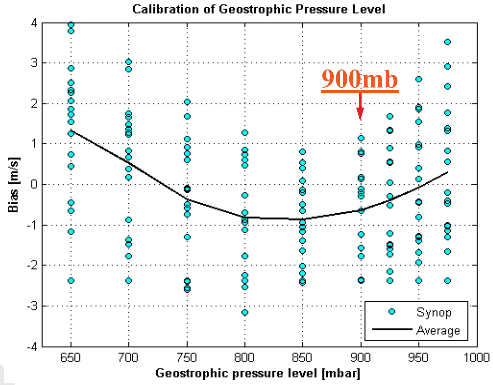
Geostrophic Level

- Simplest approach: constant pressure level wind at all times
  - Easiest implementation in scripts
  - Most efficient when the number of wind climate classes is low
    - In the present case: 12 wind direction classes
  - Requires surface measurements for calibration



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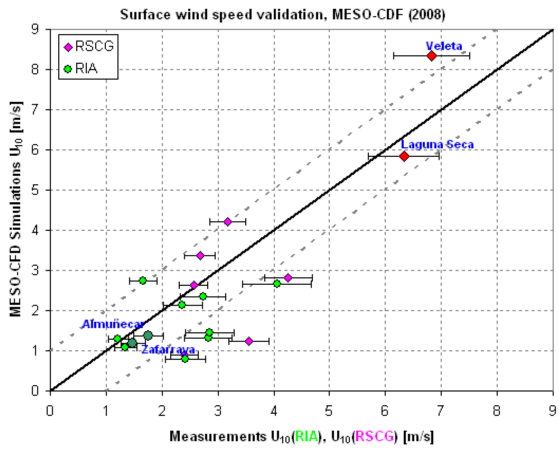
Validation

- Validation compromised to the (poor) level of the synop measurements. Overall validation ~ ±1m/s
- MESOCFD effectively corrects mesoscale simulations in complex terrain sites



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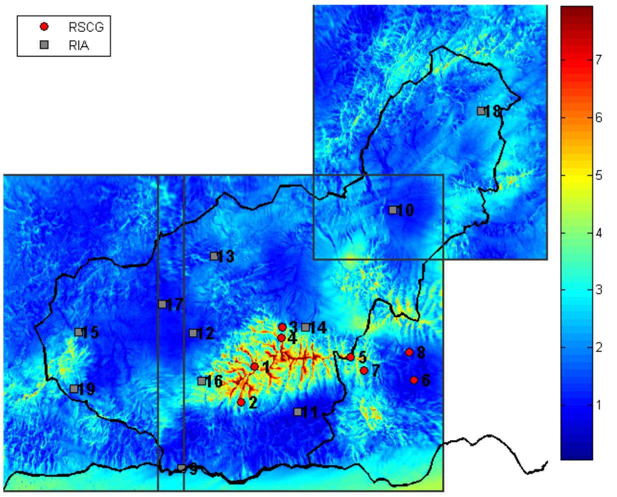
Wind Atlas: Wind velocity

- Geostrophic wind is downscaled to surface conditions with CFD speed-up factors
- 12 wind direction classes → 30º bins

Mean velocity at 10m, MESO-CFD model (2004-2009) [m/s]



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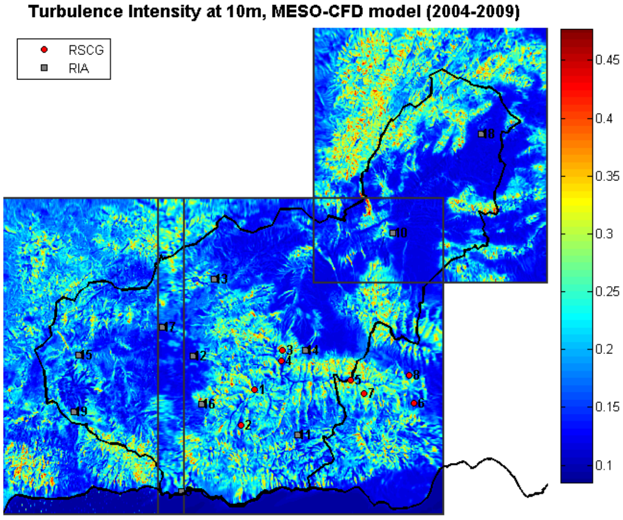
Wind Atlas: Turbulence Intensity

- Omnidirectional integration

$$I = \frac{\int_0^{360} I(\theta) f(\theta) d\theta}{\int_0^{360} f(\theta) d\theta}$$

Turbulence Intensity at 10m, MESO-CFD model (2004-2009)



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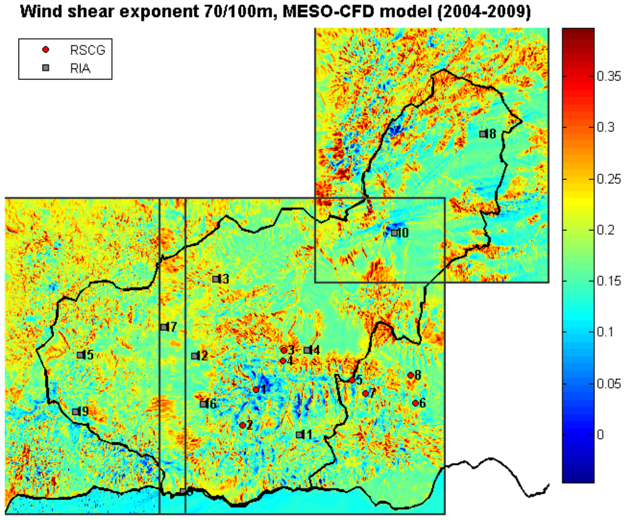
Wind Atlas: Wind Shear

- Power-law exponent

$$\alpha = \frac{\lg\left(\frac{U_2}{U_1}\right)}{\lg\left(\frac{z_2}{z_1}\right)}$$

- Omnidirectional



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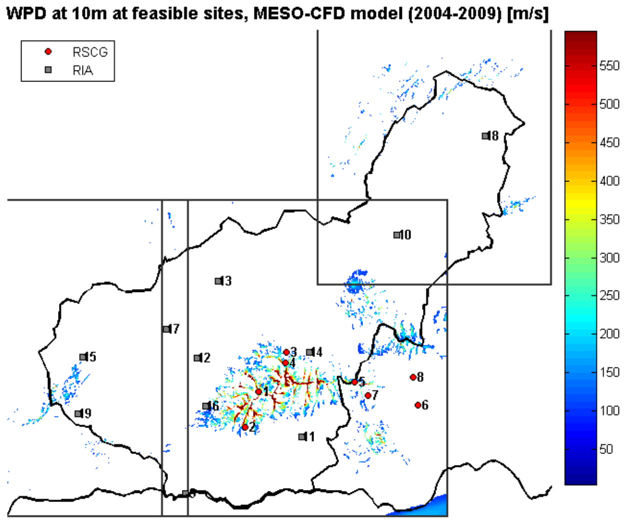
Wind Atlas: Wind Power Density

- Available wind power per unit of rotor area

$$WPD = \frac{1}{2}\rho U^3$$

- Feasibility maps
  - WPD>100W/m²
  - α<0.2
  - I<0.2



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Wakes modelling at CENER

- CFDWake

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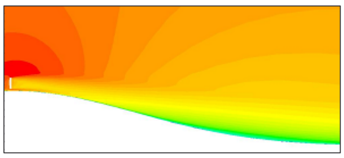
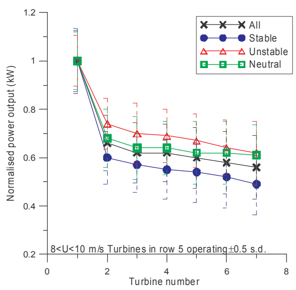
Wakes modelling



- Wakes inside wind farms influenced by
  - Background turbulence intensity
  - Wind speed and direction
  - Topography
- Traditional engineering models assume a terrain following wake with no wake-terrain interaction
- Effects of atmospheric stability underestimated
  - Especially important in offshore: slow wake decays in stable conditions
- Two types of CFD based models
  - Actuator disk: valid in far-wake conditions for wind assessment applications
    - Only requires rotor diameter and thrust curve
  - Full-rotor aerodynamics: time resolved flow-rotor interaction for design purposes
    - Requires blade geometry and aerodynamic coefficients



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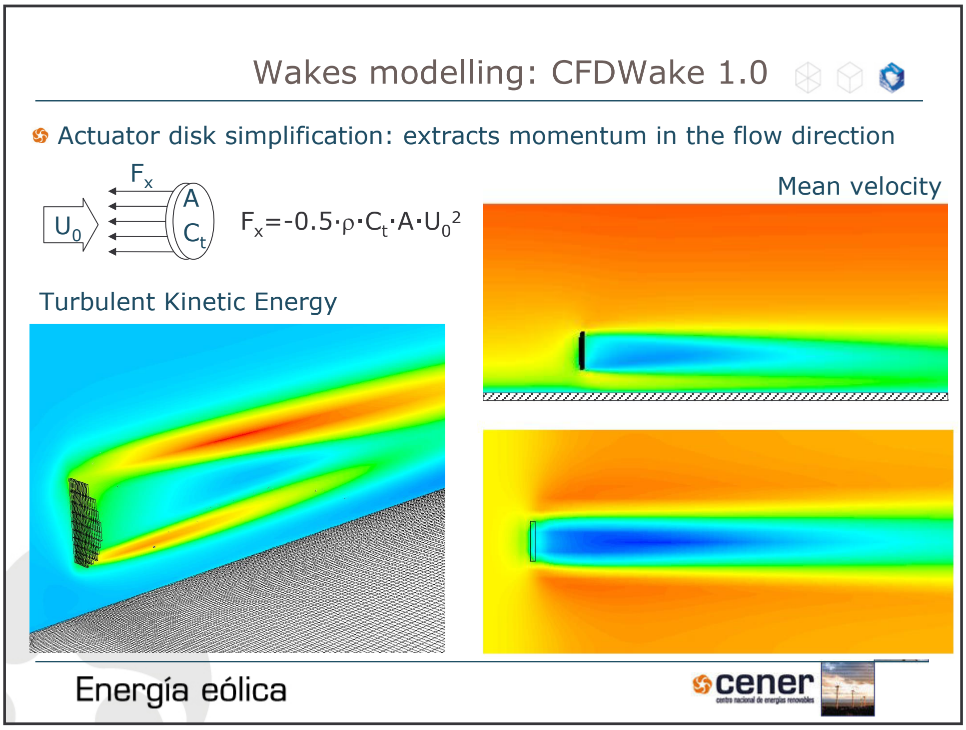
Wakes modelling: CFDWake 1.0
Actuator disk simplification: extracts momentum in the flow direction
F_x
A
C_t
U_0
$F_x=-0.5\cdot\rho\cdot C_t\cdot A\cdot U_0^2$
Mean velocity
Turbulent Kinetic Energy
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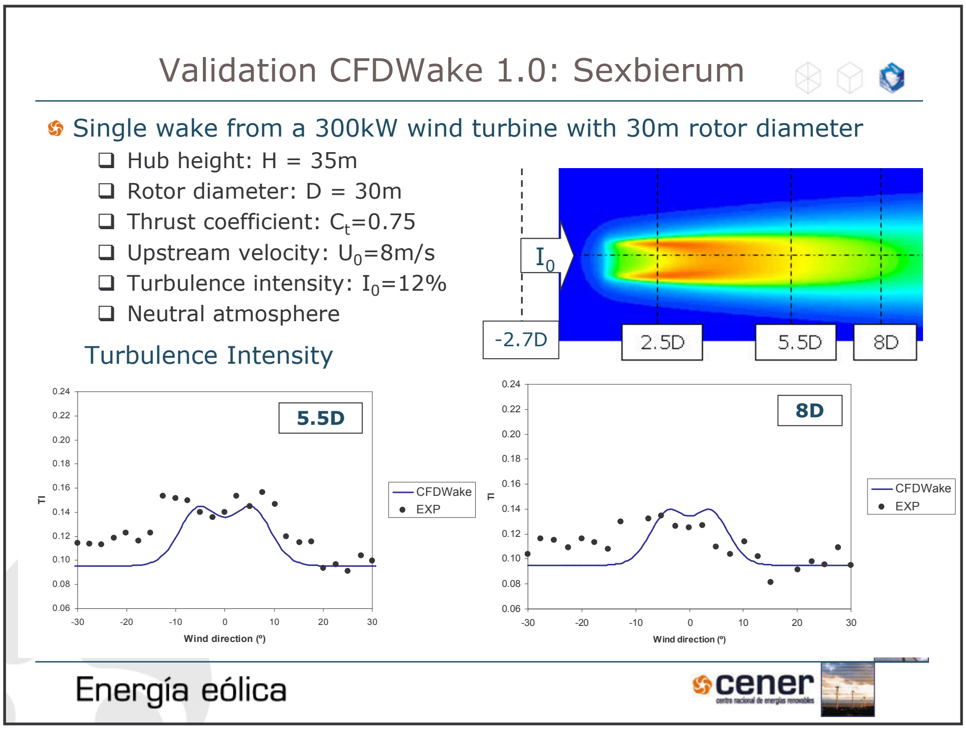
Validation CFDWake 1.0: Sexbierum
Single wake from a 300kW wind turbine with 30m rotor diameter
Hub height: H = 35m
Rotor diameter: D = 30m
Thrust coefficient: C_t=0.75
Upstream velocity: U_0=8m/s
Turbulence intensity: I_0=12%
Neutral atmosphere
I_0
-2.7D
2.5D
5.5D
8D
Turbulence Intensity
5.5D
8D
TI
Wind direction (º)
CFDWake
EXP
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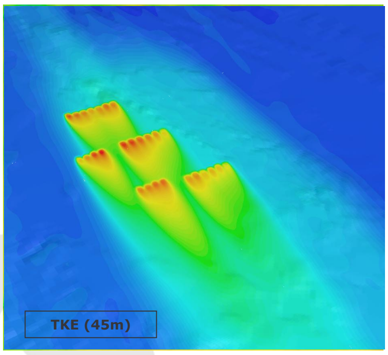
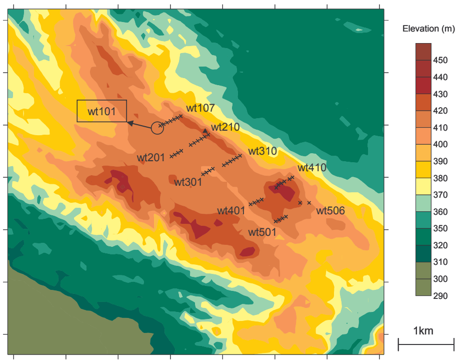
Validation CFDWake 1.0: Complex Terrain

- Multi-wake flow in complex terrain: 43 wind turbines in 5 rows
  - Hub height: H = 45/55m
  - Rotor diameter: D = 48.4m
  - Reference velocity: U_0=8±0.5m/s
  - Reference wind direction: 325±5º
  - Separation: 13x1.5D
  - Neutral atmosphere





UpWind
Finding design solutions for very large wind turbines

Project funded by EU-FP6

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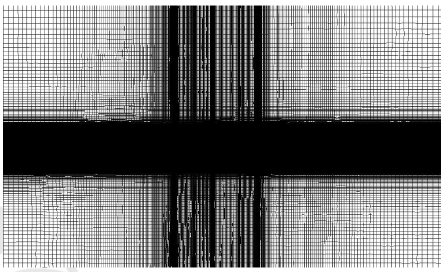
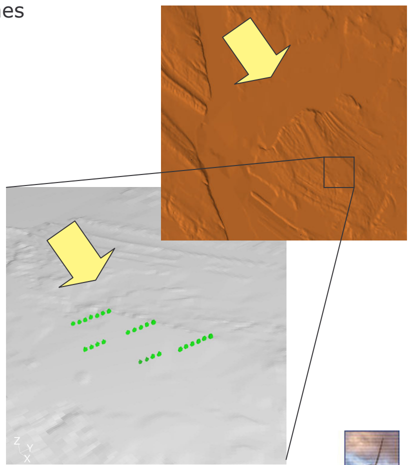
CFD Configuration: Mesh

- Mesh characteristics:
  - Domain size (km): 15 x 15 x 2
  - Structured mesh: 5 million Control Volumes
  - Refinement at rotor areas
  - Rotor thickness = 0.2D
  - 40 control volumes per rotor disk





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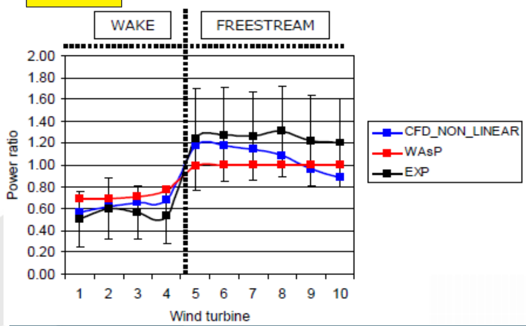
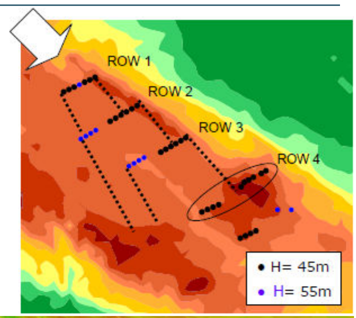
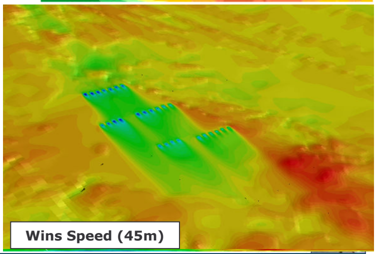
Validation CFDWake 1.0: Complex Terrain

- Flow model based on CFDWind 1.0
- Power ratio with respect to wt101
- CFD_LINEAR corresponds to a linear combination of terrain and wake effects (simulated in flat terrain)
- Overall error CFD: MAE=0.13, Bias=0.1

Row 4







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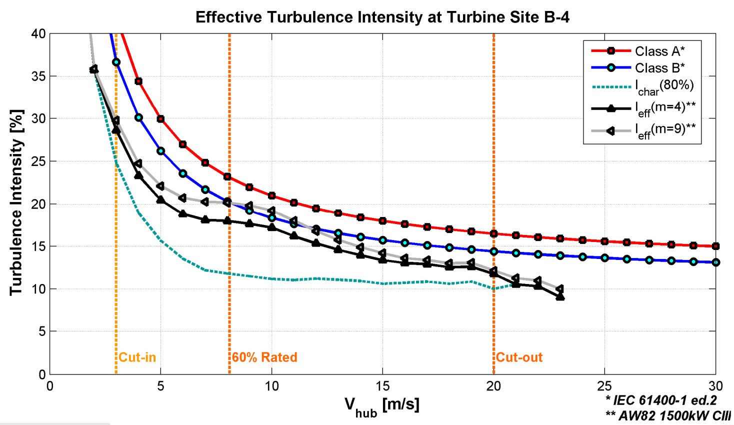
Site assessment: IEC 61400 classification

- Frandsen method using turbulence measurements from the reference met mast and added turbulence from CFD
- Still room for improvement for accurate CFD turbulence simulation



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CENER's Test Wind Farm in complex terrain

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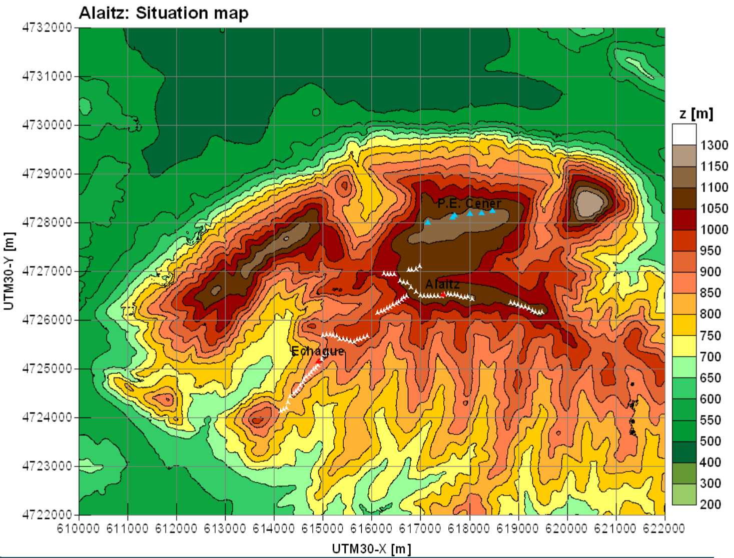
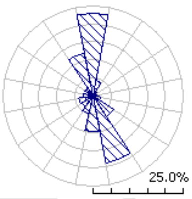
Alaitz Test Wind Farm: Site description





Measurements from Noain
(close to Pamplona)

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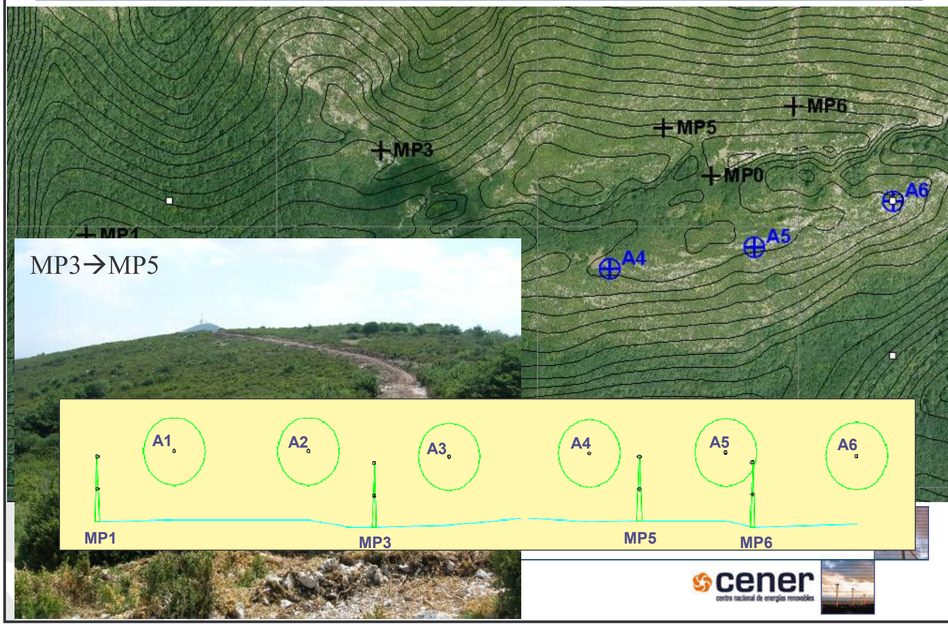
Alaiz Test Wind Farm: Aerial View



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Instrumentation

- Basic instrumentation compliant with IEC 61400-12-1 for power curve performance test for wind turbines up to 5MW
- Additionally, LiDAR-Zephic and sonic anemometers

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Site assessment within the EU Wind Energy Roadmap 2010-2020

- TPWind
- Wind Energy Roadmap

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TPWind

- European Wind Energy Technology Platform (**TPWind**): supported by the European Commission to bring together companies, research institutions, the financial world and regulatory authorities to define the strategic research agenda from 2008 to 2030
- Bottom up approach to mobilise national and EU public and private resources
- Definition of the Strategic Research Agenda 2008-2030 according to the following structure:
  - WG1: Wind Conditions
  - WG2: Wind Power Systems
  - WG3: Wind Energy Integration
  - WG4: Offshore Deployment and Operations
  - WG5: Wind Market and Economics
  - WG6: Wind Policy and Environment
  - Finance WG: Assessing and procuring sufficient R&D funds

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TPWind's '3% vision' in Wind Conditions

- TPWind's '3% vision': current techniques must be improved so that given the geographic coordinates of any wind farm, regardless of site conditions or data availability, predictions with an uncertainty of less than 3% can be made concerning:
  - the annual energy production ('resource')
  - the wind conditions that will affect the design of the turbine ('design conditions'); and
  - a short-term forecasting scheme for power production and wind conditions
- Research priorities
  - Siting of wind turbines in complex terrain and forested areas
  - Wakes in and between wind farms
  - Offshore meteorology
  - Extreme wind speeds
  - Wind profiles at heights greater than 100m
  - Short-term forecasting
- Two main tools: CFD and remote sensing
- Results integrated in a GIS based global wind atlas validated with experimental campaigns

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Siting in complex terrain and forested areas

- Objective: Reduce uncertainties in site assessment below 3% by 2030
- Research priorities:
  - Full-scale measurement campaigns ('Askervein II') in complex topography
    - Askervein has been the main test case for validation of flow models since the 1980s, although with many limitations (simple topography, lack of measurements above 10m, etc)
  - New measurement techniques based on remote sensing for high temporal and spatial resolution measurements and heights above 100m
  - Standards for wind resource assessment

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Wind Energy Roadmap

- TPWind developed the European Wind Initiative (EWI) with the European Commission, which published it as the **Wind Energy Roadmap** (October 2009).
- Objective: define EU wind energy research strategies for the period 2010-2020
- Included in the Strategic Energy Technology Plan (**SET-Plan**) as a key element for fighting climate change and helping EU Member States to meet the 2020 targets identified by the RES Directive.
- Total budget = 6000m€ (private and public resources) → 600m€/y
- Key areas
  - ❑ New turbines and components (2500m€);
  - ❑ Offshore technology (1200m€);
  - ❑ Grid Integration (2100m€);
  - ❑ Resource assessment and spatial planning (200m€)
- Current status: Definition of the Implementation Plan for the first three years (i.e. 2010 – 2012).

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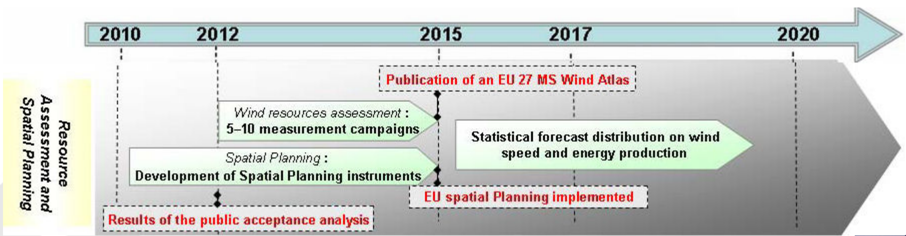
Resource Assessment and Spatial Planning

- Roadmap: Resource Assessment and Spatial Planning
- Key performance indicator: Wind resources and conditions predicted with an uncertainty of less than 3%
- Budget: 200 m€
  - ❑ Wind measurement campaigns
  - ❑ Database on wind data, environmental and other constrains
  - ❑ Spatial planning tools and methodologies for improved designs and production
- Actions:



Source: European Commission, "A Technology Roadmap" - SEC(2009) 1295

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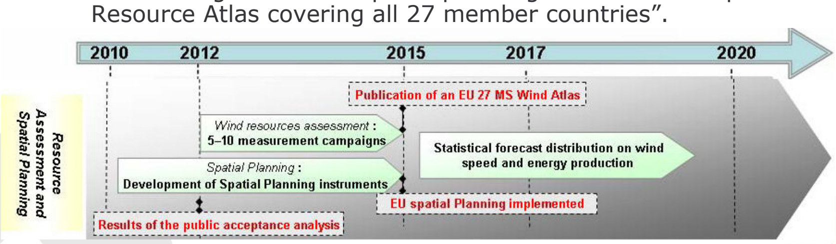
Resource Assessment and Spatial Planning: Actions

- Several large-scale measurement campaigns will be launched in complex terrain, at forested and near shore / offshore sites across Europe
- The resulting database will be made available to the research and industrial community
- 2010-2012
  - ❑ Identifying the sites and measurement techniques enabling to launch such large-scale measurement campaigns
  - ❑ European Handbook for Integrated Spatial Planning of Renewable Energy resources: Part I Wind Energy resources. Towards establishing " Tools for spatial planning and a new European Wind Resource Atlas covering all 27 member countries".



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References

[1] Cabezón D., Sanz Rodrigo J., van Beeck J., 2007, Sensitivity analysis of turbulence models for the ABL in complex terrain, EWEC-07 scientific proceedings, Milan, Italy (May) 2007.

[2] Sanz Rodrigo J., Cabezón D., Martí I., Patilla P., van Beeck J., 2008, Numerical CFD modelling of non-neutral atmospheric boundary layers for offshore wind resource assessment based on Monin-Obukhov theory, EWEC-08 scientific proceedings, Brussels (Belgium), April 2008.

[3] Sanz Rodrigo J., Cabezón D., Lozano S., Martí I., Parameterization of the atmospheric boundary layer for offshore wind resource assessment with a limited-length-scale k-ε model, EWEC-09 proceedings, Marseille (France), March 2009

[4] Cabezón D., Sanz Rodrigo J., Martí I., Crespo A., CFD modelling of the interaction between the Surface Boundary Layer and rotor wake, EWEC-09 proceedings, Marseille (France), March 2009

[5] Sanz Rodrigo J., García B., Cabezón D., Lozano S., Martí I., Downscaling mesoscale simulations with CFD for high resolution regional wind mapping, EWEC-10 proceedings, Warsaw (Poland), April 2010

[6] Cabezon D., Hansen K.S., Barthelmie R., Analysis and validation of CFD wind farm models in complex terrain. Effects introduced by topography and wind turbines, EWEC-10 scientific proceedings, Warsaw (Poland), April 2010

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Avda. Ciudad de la Innovación, nº 7
31621 Sarriguren. Navarra (España)
Tel. +34 948 25 28 00
Fax. +34 948 27 07 74
Email. info@cener.com
www.cener.com
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NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Multi-Array Windfarm Modeling Program Initiative

IEA Wind Task 11:

Wind Farms in Complex Terrains

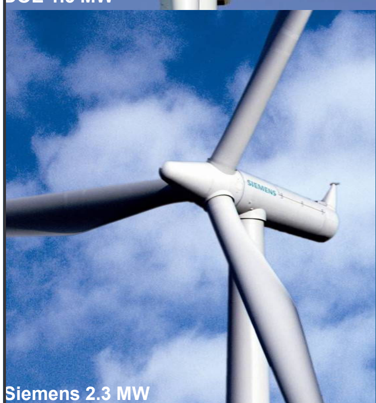
April 6-8, 2010

Michael Robinson, PhD
Deputy Director

NREL's National Wind Technology Center

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

Multi-MW Turbines at the NWTC



DOE 1.5 MW GE Turbine:

- Model: GE 1.5SLE
- Tower Height: 80 m
- Rotor Diameter: 77 m
- Custom elevator and observation platform
- DOE owned; used for research and education

Siemens 2.3 MW Turbine:

- Model: SWT-2.3-101
- Tower Height: 80 m
- Rotor Diameter: 101 m
- Custom service lift
- Siemens owned and operated
- Multi-year R&D CRADA; aerodynamics and rotor performance

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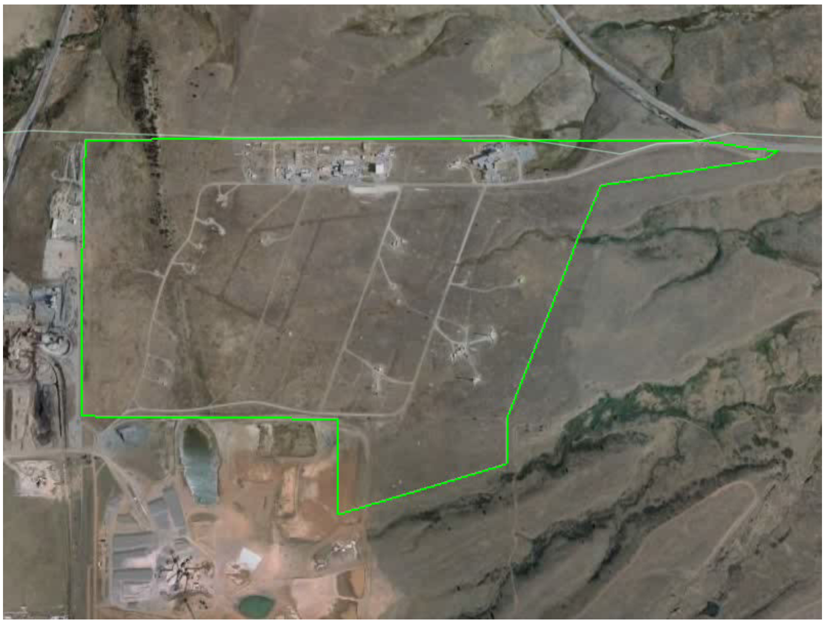
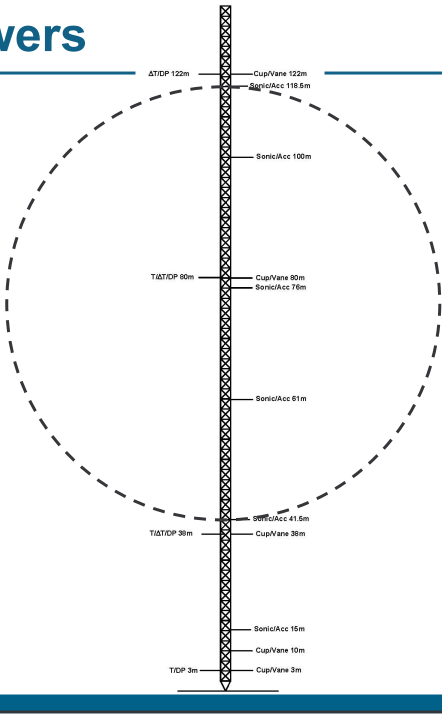
NWTC Field Testing Capability



135 Meter Met Towers



Met Tower Instruments:

- Sonic anemometers
- Accelerometers
- Cup anemometers
- Direction vanes
- Temperature and ΔT
- Barometric pressure
- Dew point
- Precipitation

Administration's National Renewable Goals

Double renewable energy capacity by 2012

10% renewable energy by 2012

25% renewable energy by 2025

Create 5 million new green jobs

80% GhG reduction (from 1990 levels) by 2050

Informed by “20% wind energy by 2030” landmark report issued by DOE in May 2008

5

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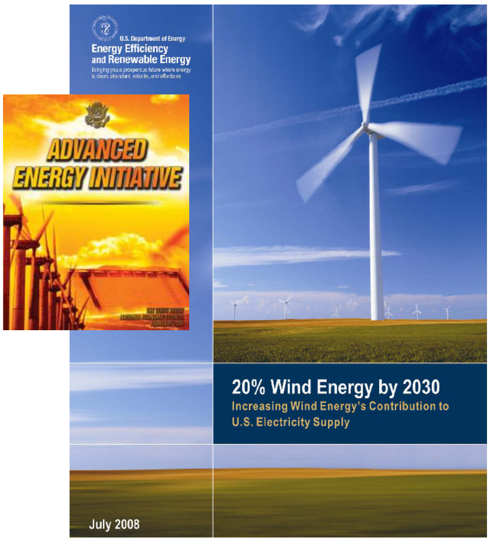
Critical Elements for 20% Scenario

300 GW by 2030

- 80% Land 20% Offshore
- Improved Performance
  - 10% reduction in capital cost
  - 15% increase in capacity factor
  - Address Wind Farm underperformance
- Mitigate Risk
  - Reduce O&M costs by 35%
  - Foster the confidence to support continued 20% per year growth in installation rates from now until 2018
- Enhanced Transmission System (AEP)
  - $60 billion cost estimate over 20 yrs
  - 19,000 mi of line
  - Supports 200-400 GW addition
- Policy, Communication & Outreach
- Infrastructure Development



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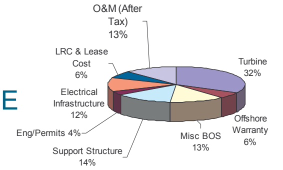
Remaining Technology Challenges

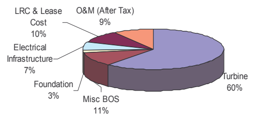
Needs Improvement:

- Gearbox performance
- Operating expenses to high
- Capital expenses still exceed DOE performance goals
- Rotor stretching strategy
- Wind plants under-performing 10%

Why:

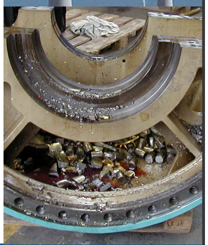
- Bearing failures; inaccurate internal loads?
- Unscheduled maintenance, low reliability, lack O&M automation
- Fatigue load & deflection control required
- Tower clearance limit, materials, aeroacoustics limiting tip speed, dynamic stability?





Existing design codes & tools should achieve 20 year life & reliable power performance predictions;

What are we missing?



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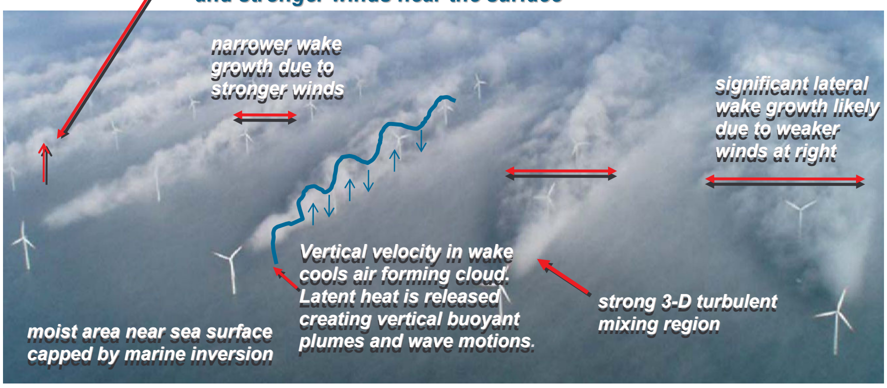
Complexity of Multi-Array Wakes

buoyant plume:
entraining dryer air, as a result of downward momentum, temperature, and moisture fluxes and stronger winds near the surface

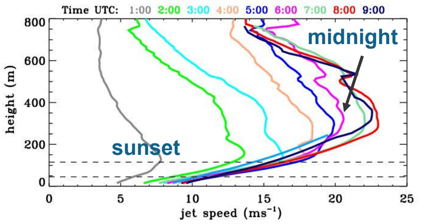


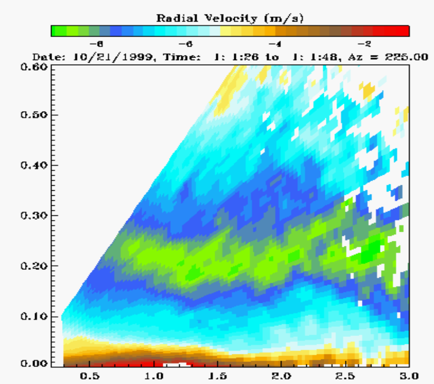
stronger winds — *horizontal wind speed gradient?* — *weaker winds*

NREL

conceptual analysis by N. Kelley, NREL

Planetary Boundary Layer (PBL)



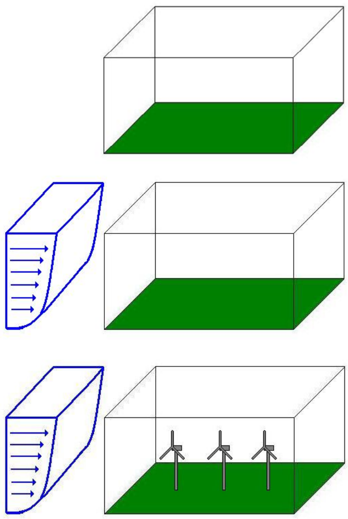


- Turbine, wind farm, PBL; similar dimensional scales
- Farm / inflow interactions not quantified
- Characterization & prediction remain an issue
- Detailed inflow information required for turbine design and optimized control
- Diurnal variation
- Growing concerns include:
  - Quality of the downwind resource
  - Microclimatology changes
  - Agriculture impacts
  - Permitting

Technical Approach

High Resolution CFD methodology:

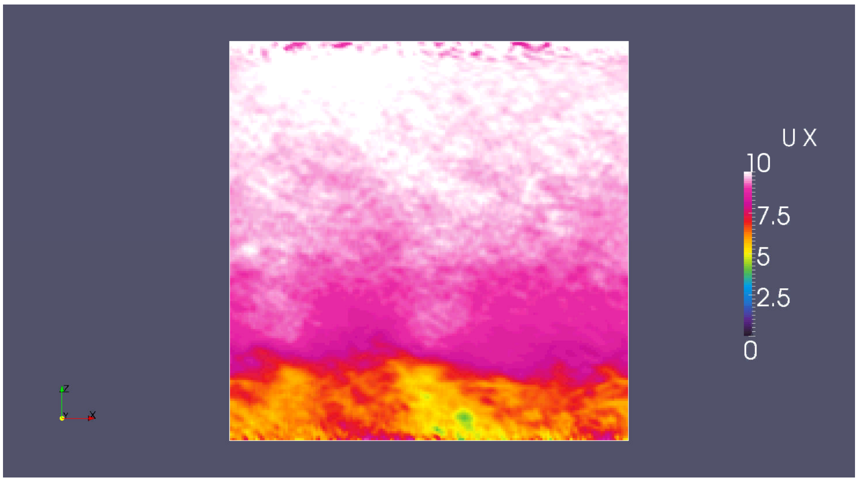
- OpenFOAM finite volume solver:
  - Large Eddy Simulation (LES) – computationally expensive.
  - Reynolds Averaged Navier Stokes (RANS) – less expensive.
- Precursor simulation - Create realistic atmospheric boundary layer (ABL):
  - Neutral boundary layer only to date.
  - Quality checks vs. known ABL behavior.
- Turbine wake simulation:
  - Two turbines interact in ABL.
  - Modeled as actuator disks.
  - Spacing effect.
  - Aligned and skewed flow.
- Data validation & model comparison:
  - Power production loss in wake.
  - Mean velocity profiles.
  - LES, RANS, & PARK models.



Dr. Pat Moriarty &
Dr. Matt Churchfield
NREL

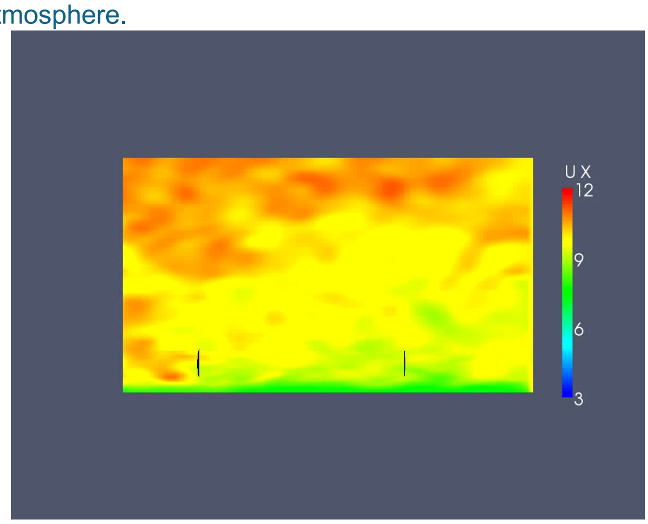
Accomplishments / Progress / Results

- **Atmospheric flow successfully modeled:**
  - Neutral ABL only.



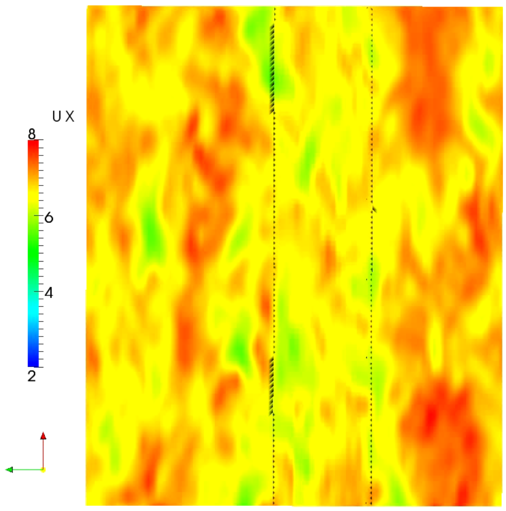
Accomplishments / Progress / Results

- **Wind Turbine Wake Modeling**:
  - Successful simulation of two turbines interacting with realistic atmosphere.



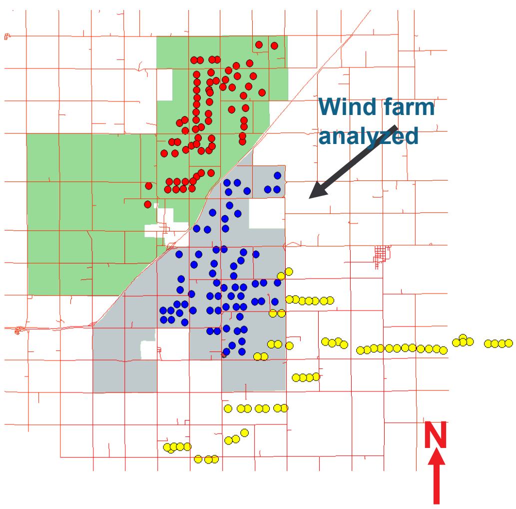
Accomplishments / Progress / Results

- Skewed flow common within wind farms.



Technical Approach

- Wind farm data analysis:
  - Data from May 09 onward.
  - Onshore wind farm in Midwest.
  - CRADA partner Xcel energy.
- Quality check of data:
  - Eliminate faults and data anomalies.
  - Eliminate neighboring farm sectors.
- Create power curves for turbines:
  - Use as a check of met mast data.
- Identify wake effects:
  - Different turbine spacing.
  - Different atmospheric conditions.



Proposed Next Steps

Project plans for the rest of FY 2010 and future:

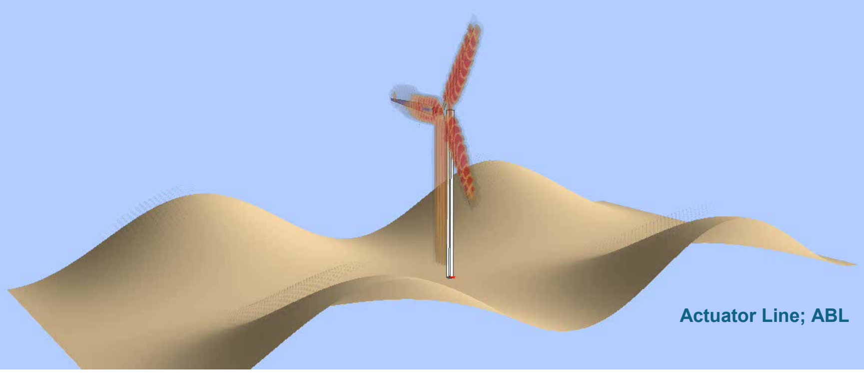
- Continue improving and validating models:
  - Non-neutral atmospheric conditions.
  - Higher fidelity turbine model – actuator line.
- Continue wind farm data analysis to examine onshore wind farm behavior.
- Develop IEA Annex for turbine wake model validation.
- Code release to greater community.
- Horn's Rev model

Other critical needs for industry:

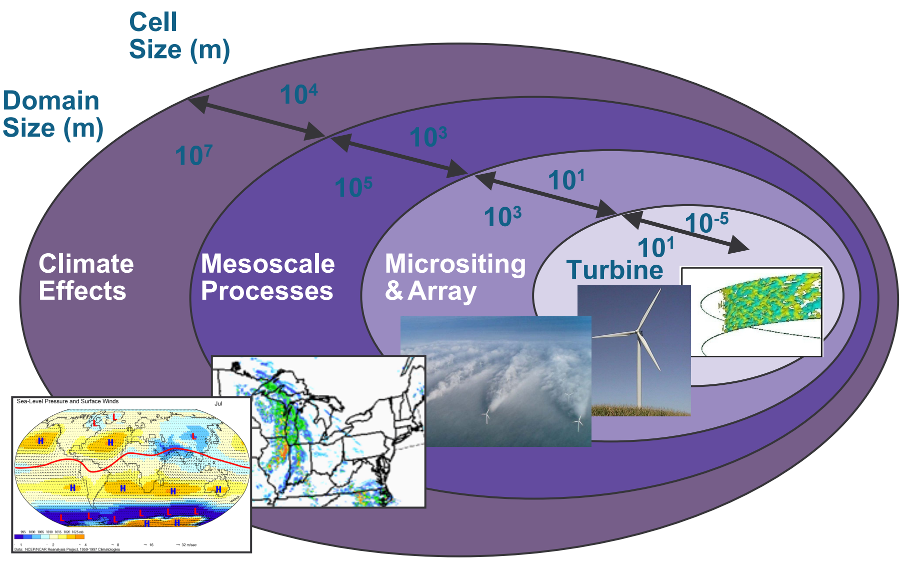
- Include effects of terrain and vegetation
  - Many wind farms not build in flat terrain
- Couple aeroelastic code to wind farm simulations:
  - Could predict loads
  - Estimate maintenance impacts
- Couple with mesoscale models:
  - Large wind farms
  - Interactions between wind farms
- Higher resolution validation data
- Better lower fidelity models:
  - LES may be too computationally intensive for industry
- National integrated working group:
  - Coordinate similar efforts around country at universities and other labs

LANL Complex Terrain (HIGRAD)

Dr. Rod Linn &
Dr. Eunmo Koo
Los Alamos National Laboratory



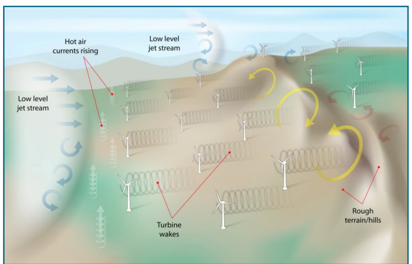
Computational Modeling Scales



RD&D Requirements for Multi-Arrays

Technology Challenges:

- Wind farm underperformance
- Component Failures; Gearbox, Blades
- Loads exceeding design parameters
- Excessive O&M Costs
- Optimized turbine & plant control
- Inflow / wind farm interaction
  - Microclimatology changes
- Downstream characterization:
  - Downwind resource
  - Impacts on agricultural



What's Needed:

- Detailed field measurement campaign
  - Simultaneous inflow / turbine / wake data; advance measurement capability
  - Multiple locations, varying topography
  - Pre & post quantification
- Fully coupled numerical simulation code development; CFD based
  - Terrain, turbines, atmospheric stability, surface cover
- Updated Codes & Standards
- Collaborative including industry, universities, national laboratories
  - International participation

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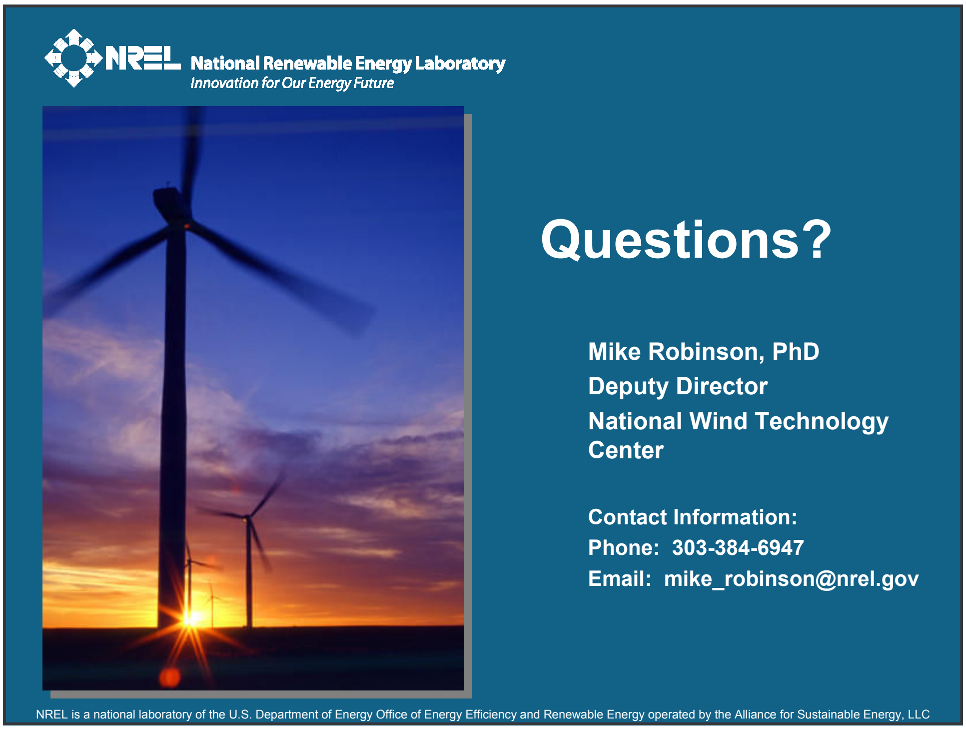

National Renewable Energy Laboratory
Innovation for Our Energy Future
Questions?
Mike Robinson, PhD
Deputy Director
National Wind Technology Center
Contact Information:
Phone: 303-384-6947
Email: mike_robinson@nrel.gov
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

IEA Task11 Topical Expert Meeting
Wind Farms in Complex Terrain
2010-4-6,7

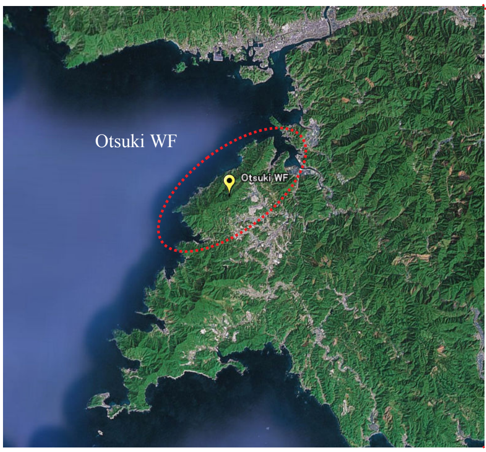
Analysis of SODAR Measurement over Complex Terrain in JAPAN

Nobuyuki HAYASAKI
ITOCHU Techno-Solutions Corporation (CTC), JAPAN
http://www.engineering-eye.com/en/index.html
nobuyuki.hayasaki@ctc-g.co.jp

Junsuke Murata
Mie University,Japan
http://www.mie-u.ac.jp/en/

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).



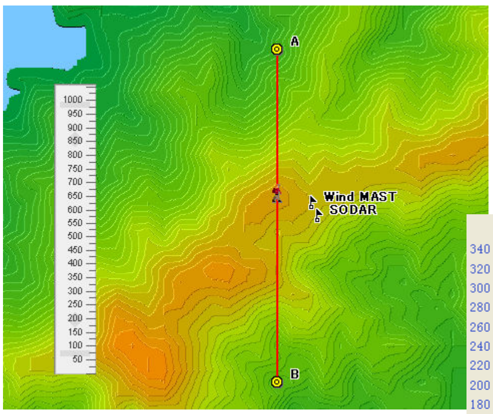
2

Site Description

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

3

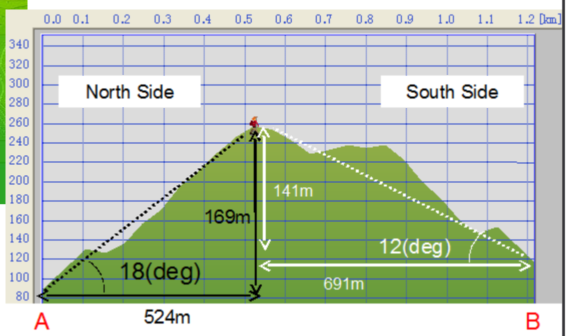
Site Description



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)



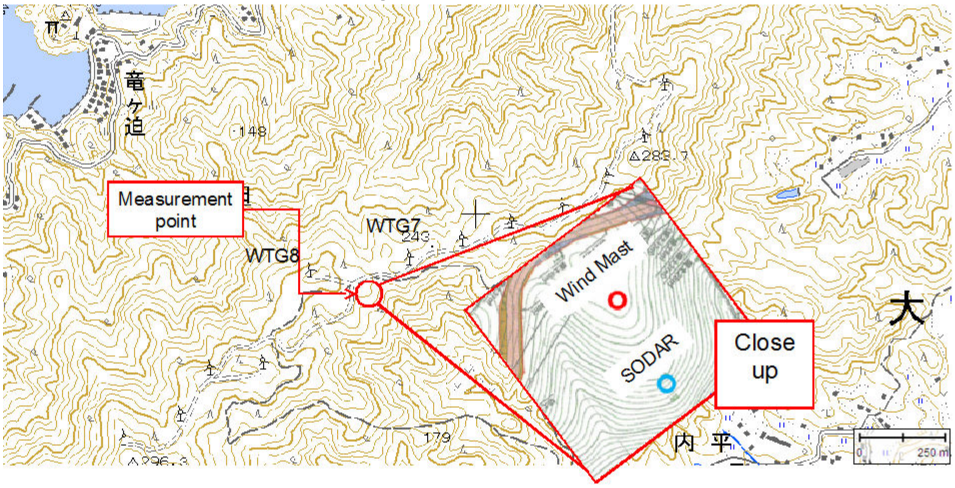
Vertical Cross Section

4

Site Description

CTC

- 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 Otsuki WF

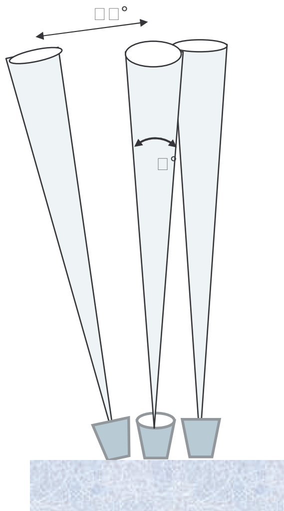
5

Measurement configuration

CTC

- 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

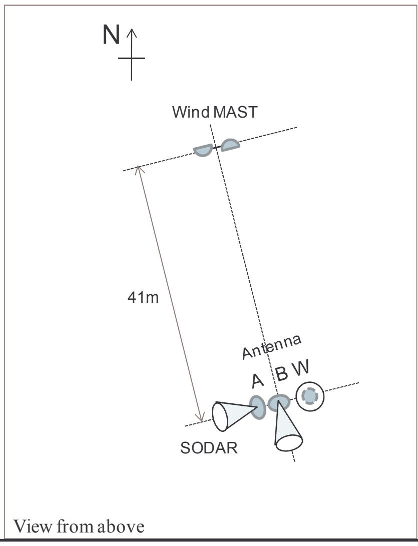
A B W

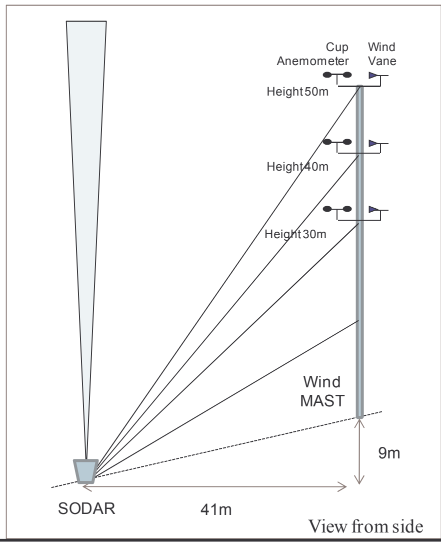


6

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

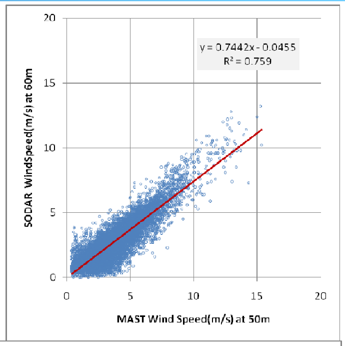


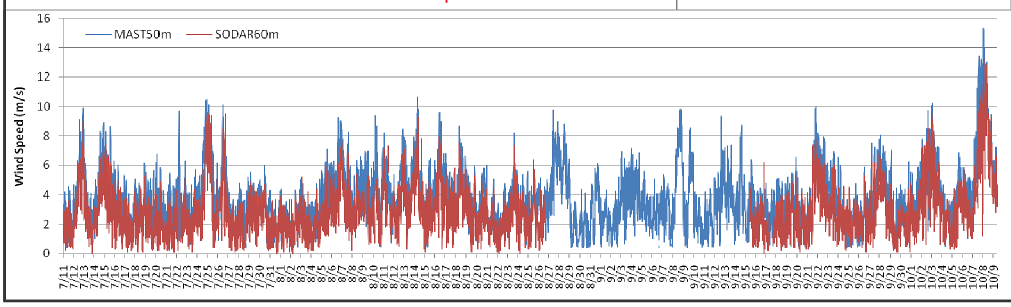


7

Comparison of the measured wind speed

- Comparison between cup anemometer and SODAR wind speed
  - The analyzed period started 11 July 2009 and ended 9 Oct 2009
  - The analyzed SODAR data that acquisition rate for 10min is over 80% is used.
  - Correlation coefficient between cup anemometer and SODAR is 0.871
  - Bias (SODAR – Cup Anemometer) is -1m/s
  - The 10min averaged wind speed of SODAR measurements is lower than that of cup anemometer



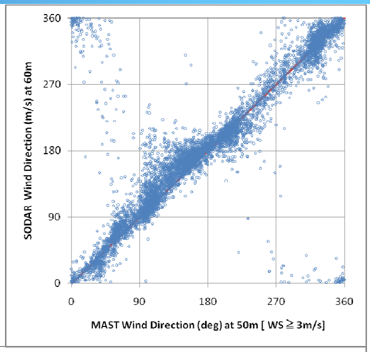


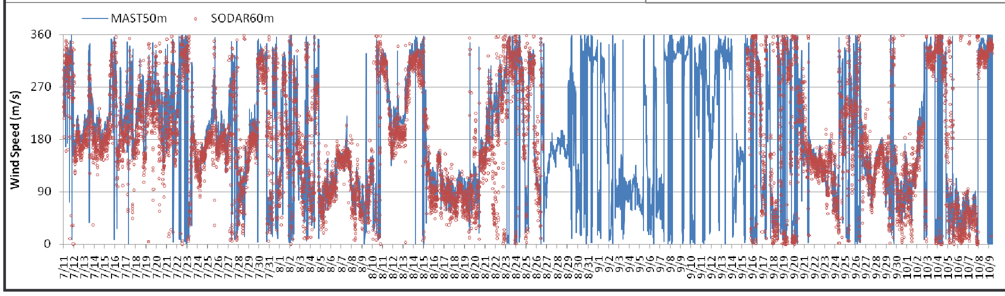
8

Comparison of the measured wind direction

CTC

- 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 excepted. (WS>=3m/s)



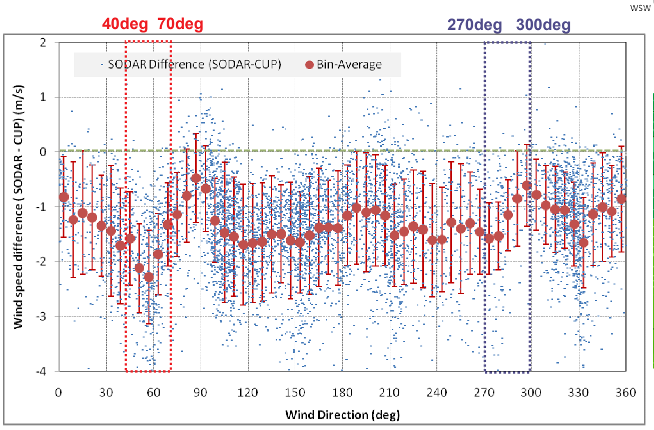


9

Comparison of the measured data

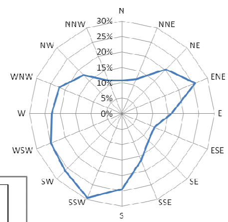
CTC

- Wind speed for wind direction
  - Wind speed difference (SODAR - Cup Anemometer) depends on wind direction.
  - Wind speed difference (SODAR - Cup Anemometer) in bin-average varies from -0.5m/s to -2.2m/s.

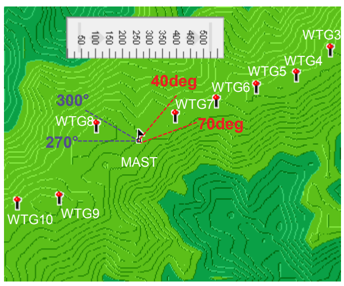


Wind speed difference for wind direction (WS>=3m/s)

Red circle: bin average for wind speed difference, Red line: standard deviation, Bin width: 6deg interval



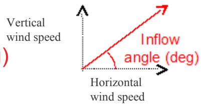
Turbulence intensity (WS>=3) Measured by cup anemometer



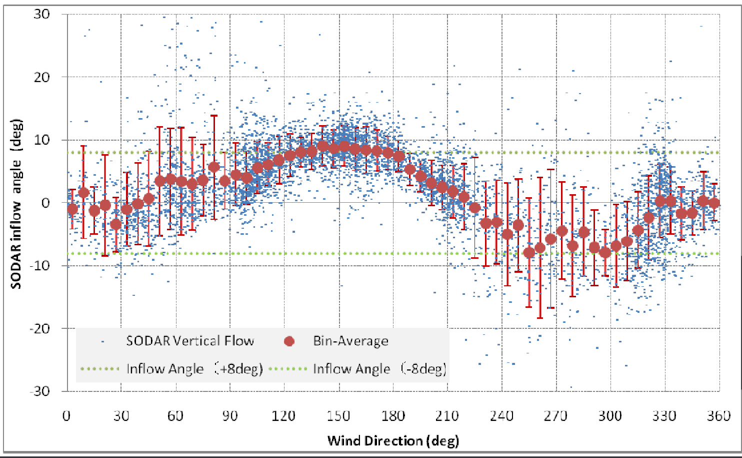
10

Analysis of the SODAR measurement

- 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.



Topography map around measuring point

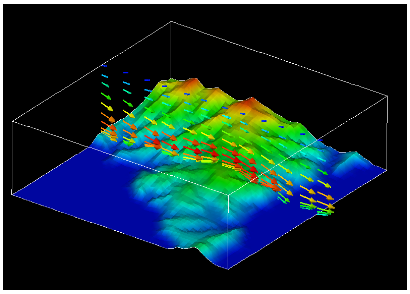


Inflow angle distribution for wind direction (WS>= 3m/s)

Red circle: bin average for wind speed difference, Red line: standard deviation, Bin width: 6deg interval

11

Speculation

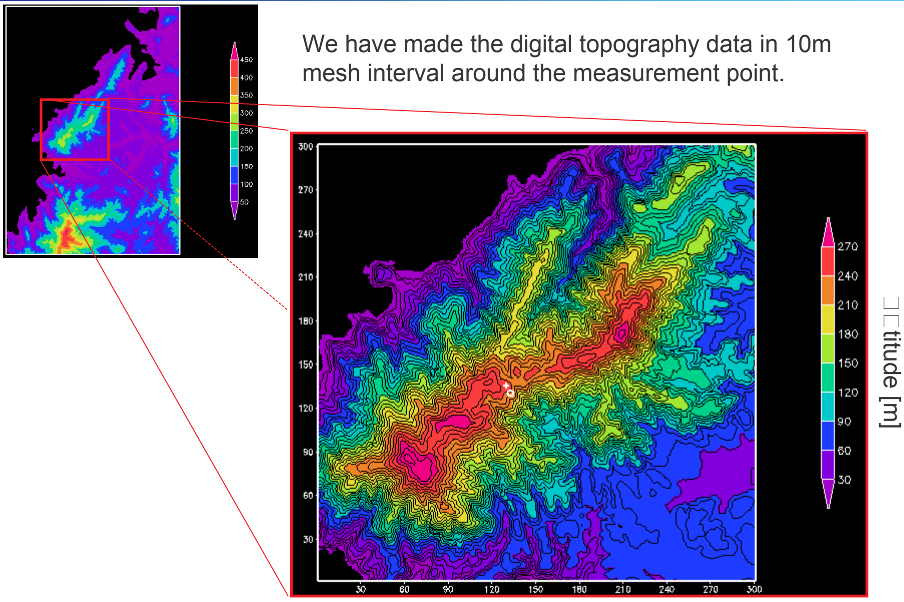


- We think such flow distortion over complex terrain causes the difference between SODAR and cup anemometer
  - Main assumption in SODAR is homogeneous for horizontal flow.
    - But such assumption doesn't work over complex terrain due to flow distortion
  - Flow distortion for the spatial control volume of SODAR measurement can be estimated by CFD simulation.
  - In order to remove the effect of flow distortion, we have simulated the wind condition by CFD techniques around this area.

12

CFD simulation of flow over complex terrain

We have made the digital topography data in 10m mesh interval around the measurement point.



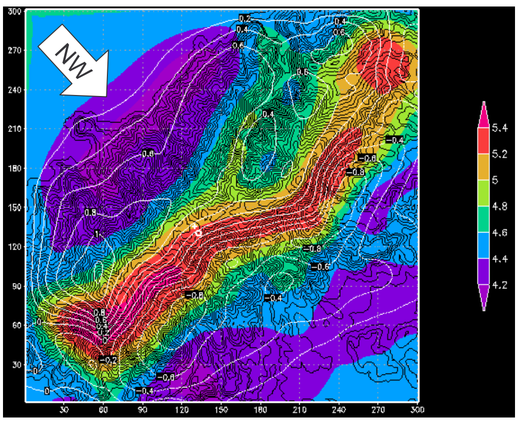
Digital Topography data around measuring point (10m mesh interval)

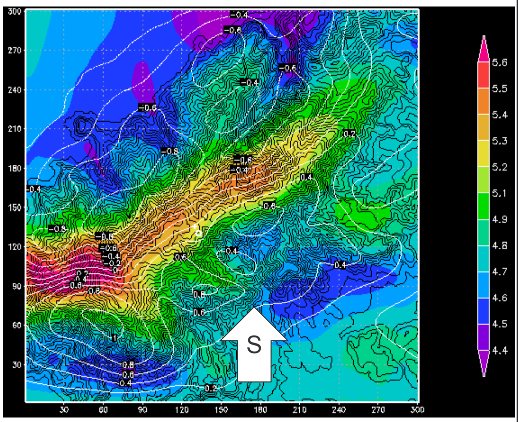
13

CFD simulation of flow over complex terrain

Results of CFD simulation (k-e model) in 10m-mesh

- Wind speed measured by wind mast is used as input wind speed of CFD simulation.
- Examples of respective wind direction are as follows (NW, S wind direction)





Example of the CFD result for respective wind direction sector (NW,S wind direction)
Color line: Wind speed[m/s], White line: Vertical wind speed [m/s], Black line: Altitude[m]

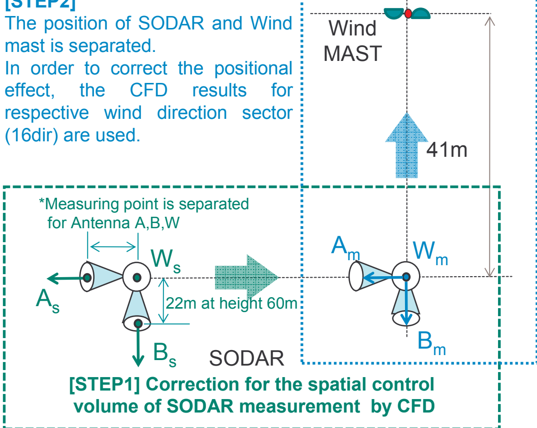
14

Method to correct SODAR measurement by CFD

[STEP1]
In order to correct the inhomogeneous of spatial control volume, Eq.(1)-(3) and CFD results for respective wind direction sector (16dir) are used.

[STEP2]
The position of SODAR and Wind mast is separated.
In order to correct the positional effect, the CFD results for respective wind direction sector (16dir) are used.

[STEP2] Correction for the distance between SODAR and Wind mast



[STEP1] Correction for the spatial control volume of SODAR measurement by CFD

$$C_A(dir) = A_m^{CFD}(dir) / A_s^{CFD}(dir)$$
$$C_B(dir) = B_m^{CFD}(dir) / B_s^{CFD}(dir)$$
Eq.(1)

$$A_m = C_A(dir) \cdot A_s$$
$$B_m = C_B(dir) \cdot B_s$$
$$W_m = W_s$$
Eq.(2)

$$V_x = \{A_m \cos\theta_B - B_m \cos\theta_A + W_m \cos\alpha(\cos\theta_A - \cos\theta_B)\} / \sin\alpha \sin(\theta_B - \theta_A)$$
$$V_y = \{A_m \sin\theta_B - B_m \sin\theta_A + W_m \cos\alpha(\sin\theta_A - \sin\theta_B)\} / \sin\alpha \sin(\theta_B - \theta_A)$$
$$WS = \sqrt{V_x^2 + V_y^2}$$
$$WD = \tan^{-1}\left(\frac{V_x}{V_y}\right)$$
Eq.(3)

θ_A : Azimuthal angle of SODAR, A
θ_B : Azimuthal angle of SODAR, B
α : Zenith angle of SODAR

[A_s□B_s□W_s]
Wind speed for SODAR beam direction(A,B,W) measured at SODAR observation point.
[A_m□B_m□W_m]
Wind speed for SODAR beam direction(A,B,W) converted into the center of SODAR observation point.
[$A^{CFD}(dir)$, $B^{CFD}(dir)$]
Wind speed for SODAR beam direction (A,B) estimated by CFD results for respective wind direction sector.

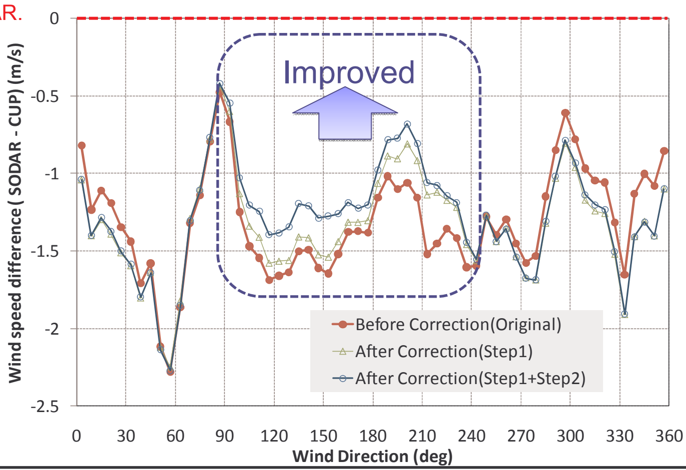
15

Results for correction of SODAR data

We checked the improvement of wind speed difference for wind direction

- Accuracy got better for the wind direction from 90deg to 240deg.
- Accuracy got worse for the wind direction from 0deg to 30deg, and from 270deg to 360deg.

Results show that this correction method still has problems to resolve.
We think the grid interval (10m) needs to set smaller to simulate the flow distortion for control volume of SODAR.



16

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 have simulated the flow over complex terrain by CFD
  - We corrected the SODAR measurement by CFD simulation in 10m-mesh digital topography data.
  - We confirmed the wind speed difference between SODAR and Cup anemometer got better in some wind direction sectors, but got worse the other wind sectors.
- We will study the correction method for remote wind sensing measurement over complex terrain more precisely by using more advanced CFD techniques.

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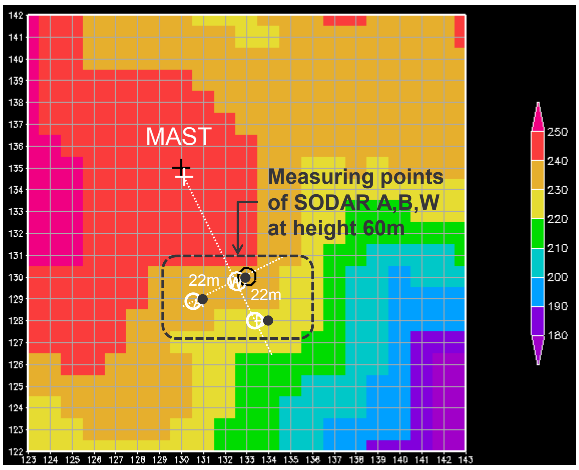
APPENDIX

CFD simulation of flow over complex terrain

Angle of inclination for SODAR	20 (deg)
Measuring height	60 (m)
Horizontal distance from SODAR installation	21.8 (m)



Color : Altitude(m)

Simulation area around measuring point (Simulated by 10m mesh topography data)

19

Business from technology

Complex Terrain in Finland: what you don’t expect from a flat country

IEA Wind Task 11 – Topical Expert Meeting on ”Wind Farms in Complex Terrain”
Andrea Vignaroli
VTT Technical Research Centre of Finland

Outline

- VTT introduction
- The Finnish Archipelago
- Measurements and modeling in Högsåra island
- Conclusions

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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.

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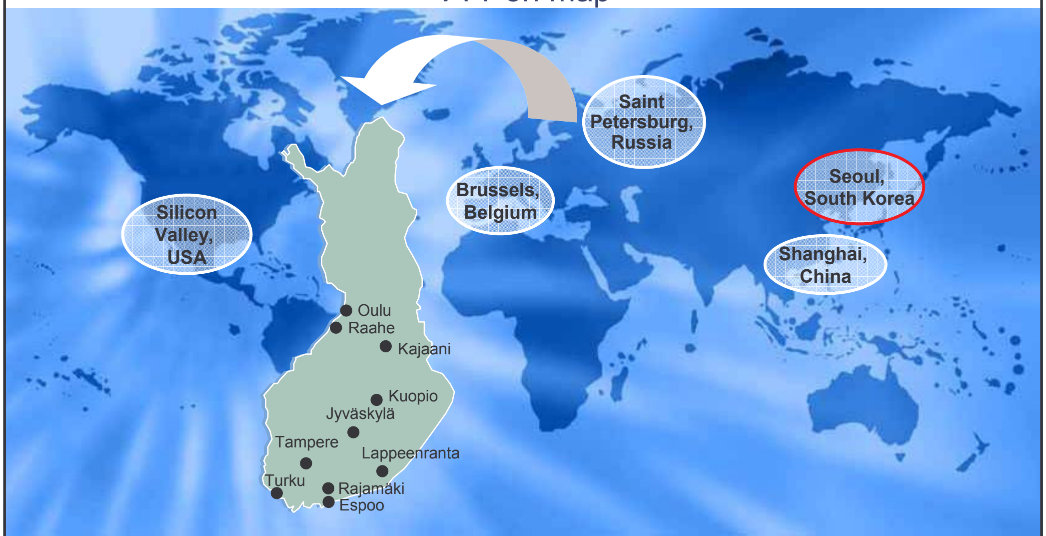
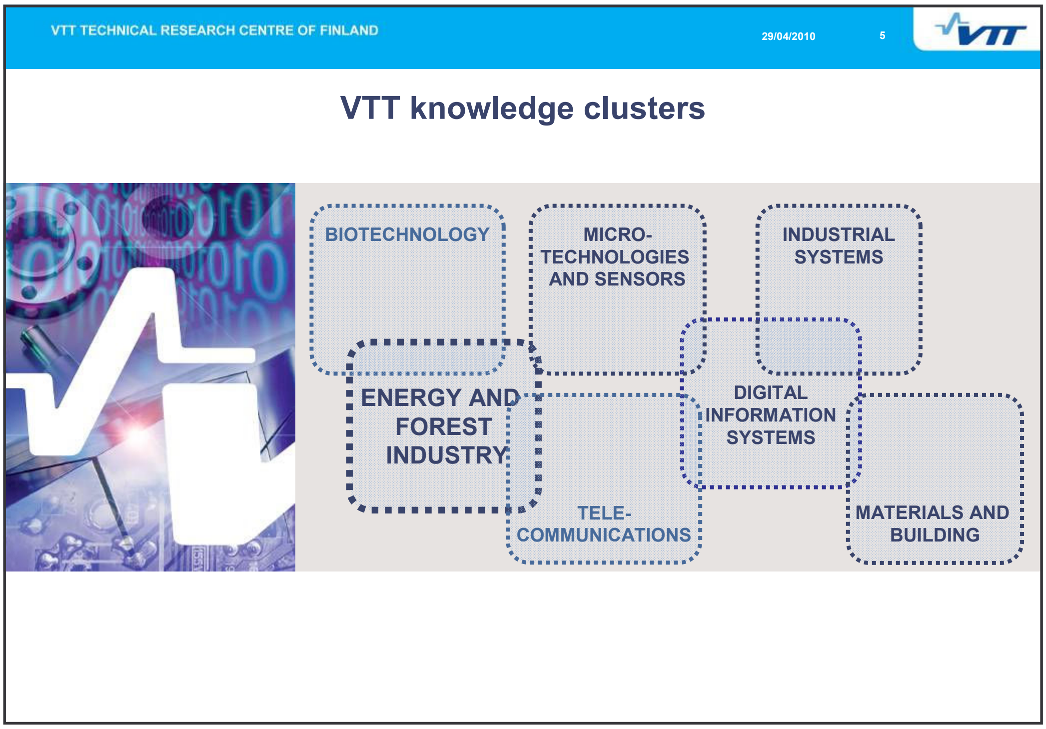
VTT on map

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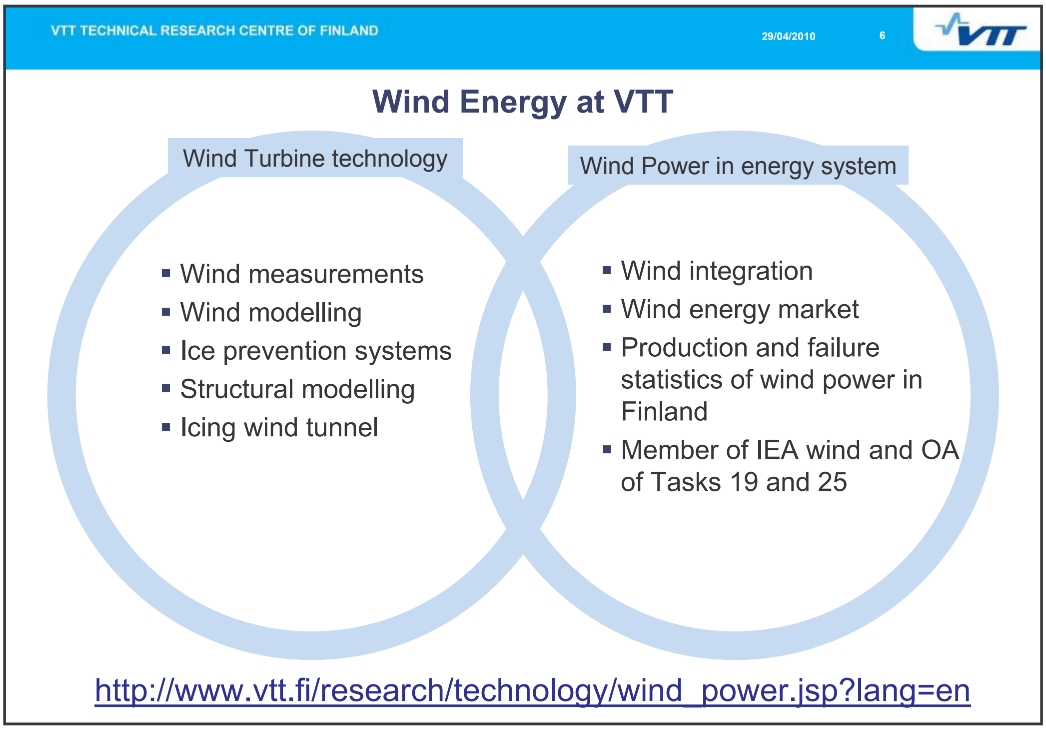
VTT knowledge clusters
BIOTECHNOLOGY
MICRO-TECHNOLOGIES AND SENSORS
INDUSTRIAL SYSTEMS
ENERGY AND FOREST INDUSTRY
DIGITAL INFORMATION SYSTEMS
TELE-COMMUNICATIONS
MATERIALS AND BUILDING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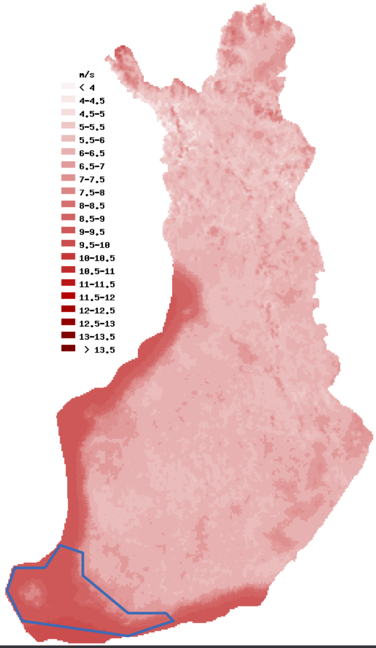
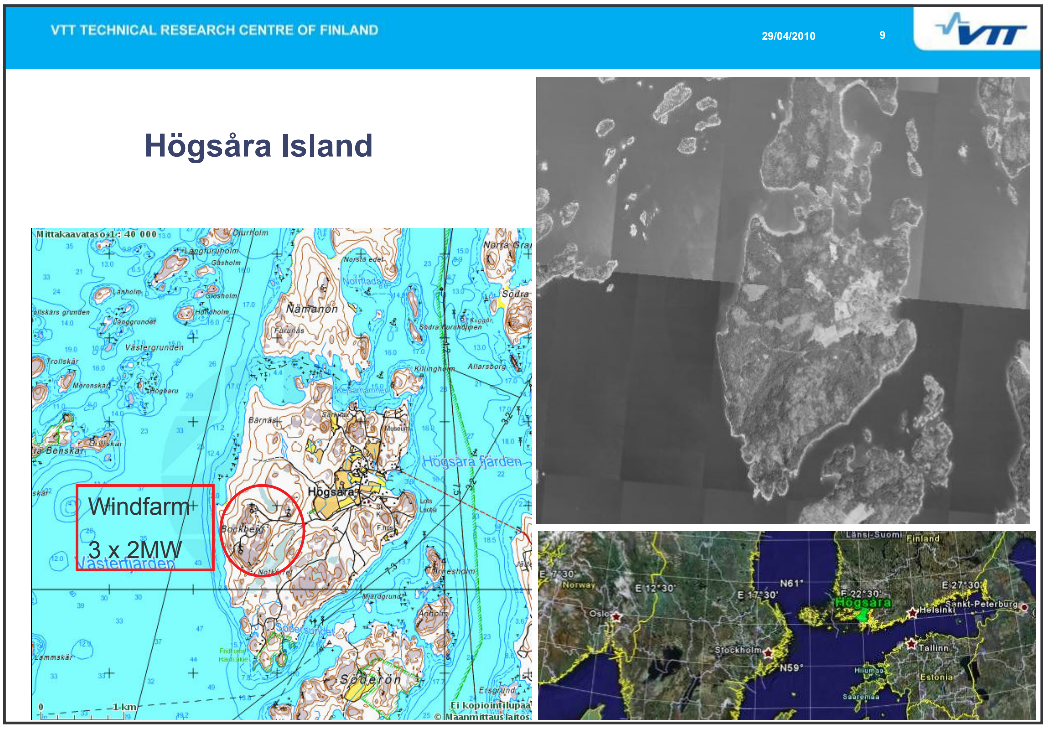
VTT
Wind Energy at VTT
Wind Turbine technology
▪ Wind measurements
▪ Wind modelling
▪ Ice prevention systems
▪ Structural modelling
▪ Icing wind tunnel
Wind Power in energy system
▪ Wind integration
▪ Wind energy market
▪ Production and failure statistics of wind power in Finland
▪ Member of IEA wind and OA of Tasks 19 and 25
http://www.vtt.fi/research/technology/wind_power.jsp?lang=en

The Finnish Archipelago

- The Finnish Wind Atlas identifies the southern Finland archipelago as an area with very good potential
  (~ 8.5 – 9.0 m/s average windspeed at 100m)
- ~ 18000 islands > 0.5ha (100m x 100m)
- Area ~ 8300 Km^2 where ~ 2000 Km^2 land
- Rock (granite)
- Shallow water



The Finnish Archipelago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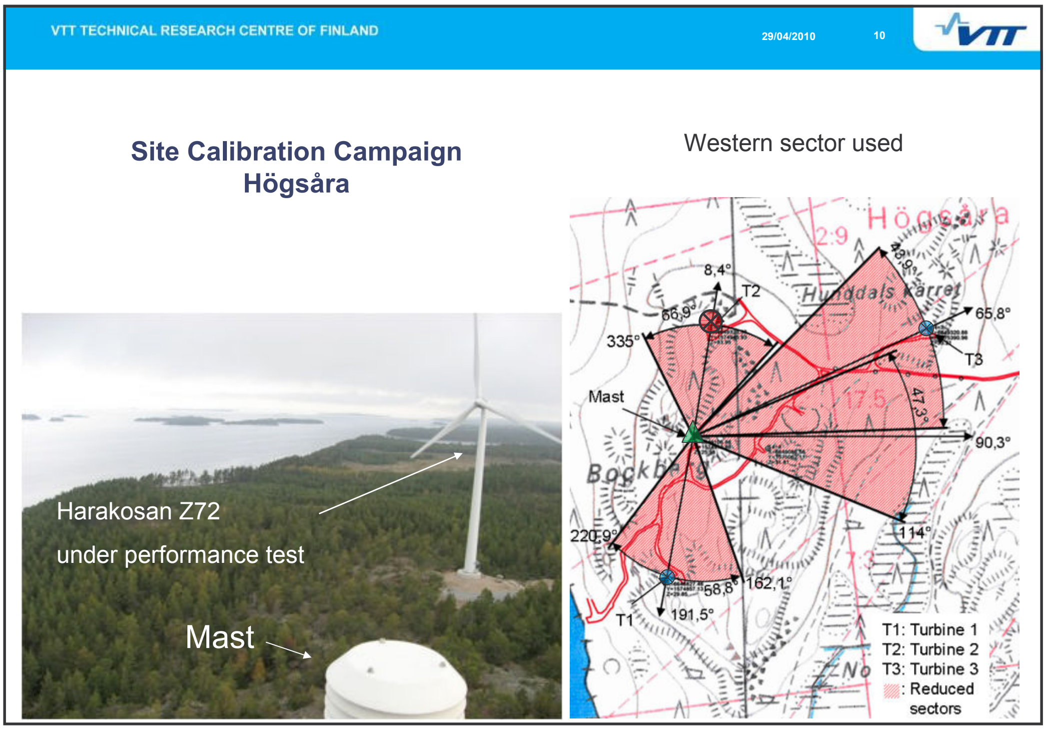
Högsåra Island
Windfarm
3 x 2MW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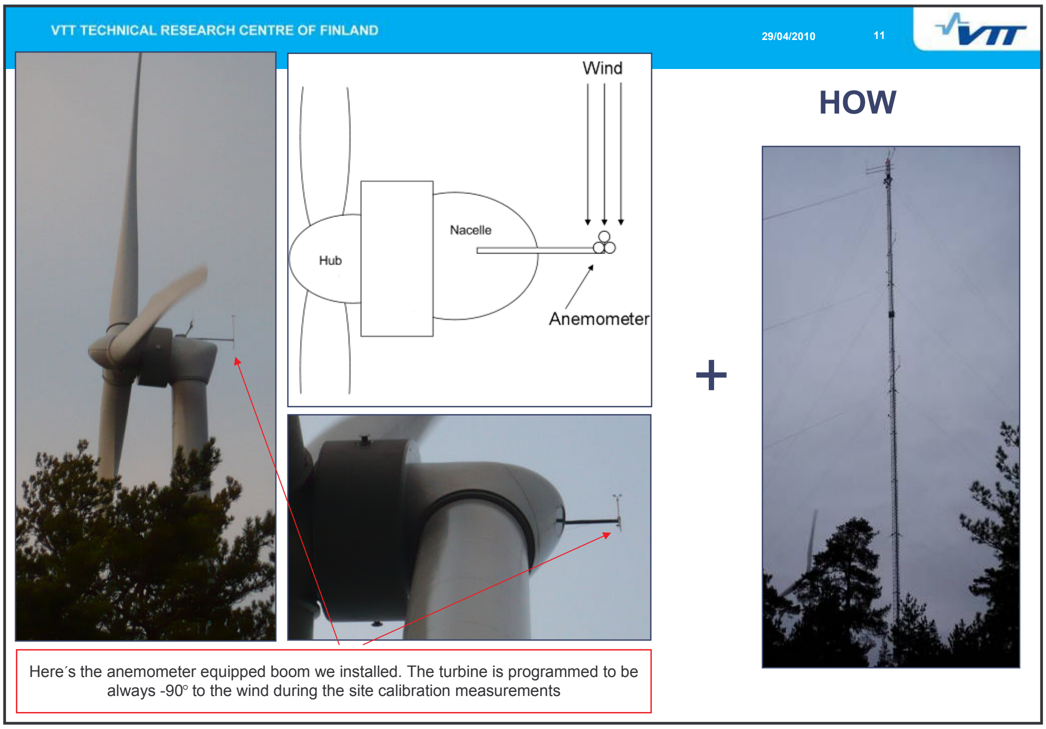
Site Calibration Campaign
Högsåra
Western sector used
Harakosan Z72
under performance test
Mast
8,4°
T2
66,9°
65,8°
335°
T3
Mast
47,3°
90,3°
114°
220,9°
58,8°
162,1°
T1
191,5°
T1: Turbine 1
T2: Turbine 2
T3: Turbine 3
: Reduced
sectors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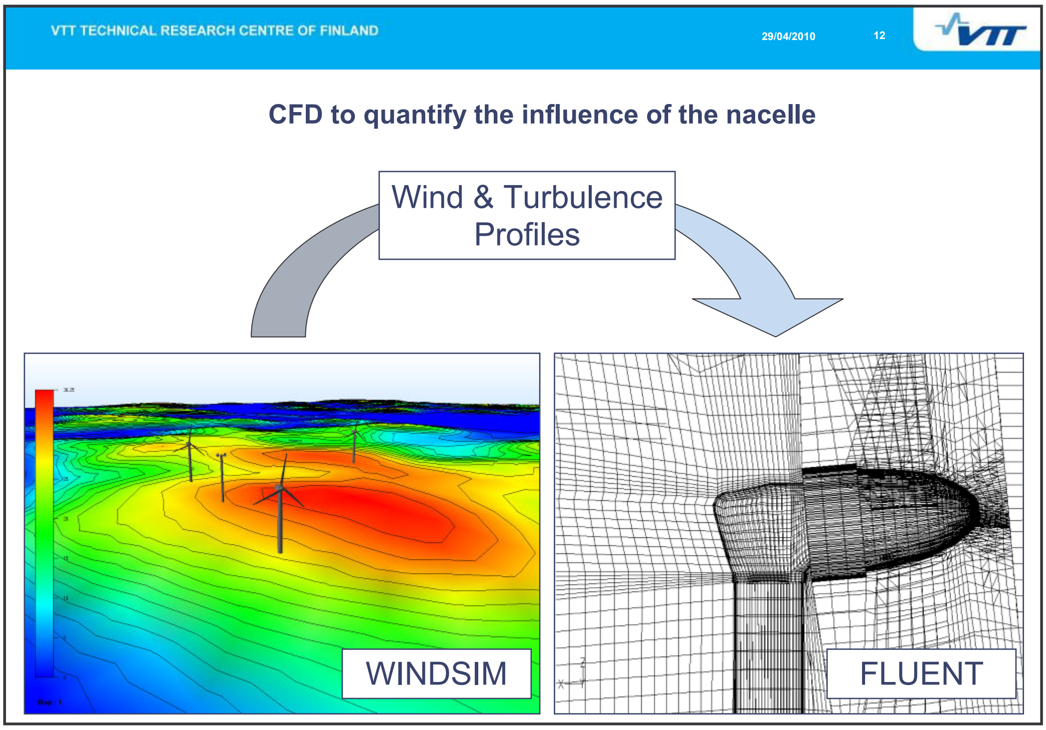
VTT
HOW
Wind
Nacelle
Hub
Anemometer
+
Here´s the anemometer equipped boom we installed. The turbine is programmed to be always -90° to the wind during the site calibration measurements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VTT
CFD to quantify the influence of the nacelle
Wind & Turbulence Profiles
WINDSIM
FLUENT

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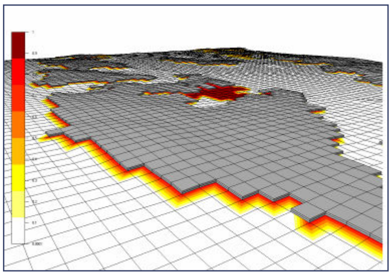
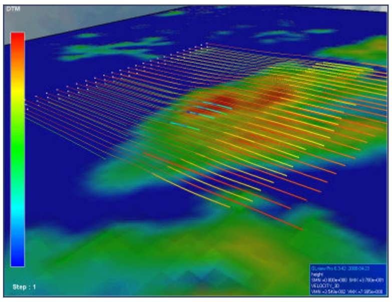
Some Windsim settings

Terrain



Windfield



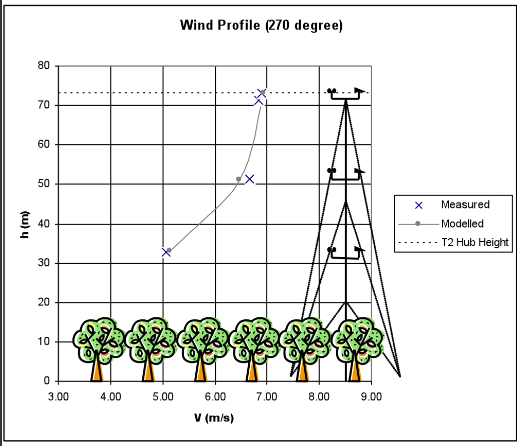
Forest Height	15m
Forest Porosity (1 = fully blocked)	0.3
C1(force proportional U, S1 = -ρ C1 U)	0.002
C2 (force proportional to U², S2 = -ρ C2 U|U|)	0.003
Forest cells along Z	2

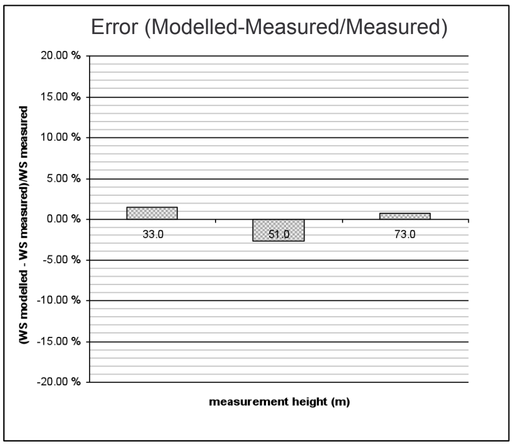
Direction	270°
Height of Boundary Layer	480 m
Speed ABL	7.9 m/s
Turbulence model	Standard k-e

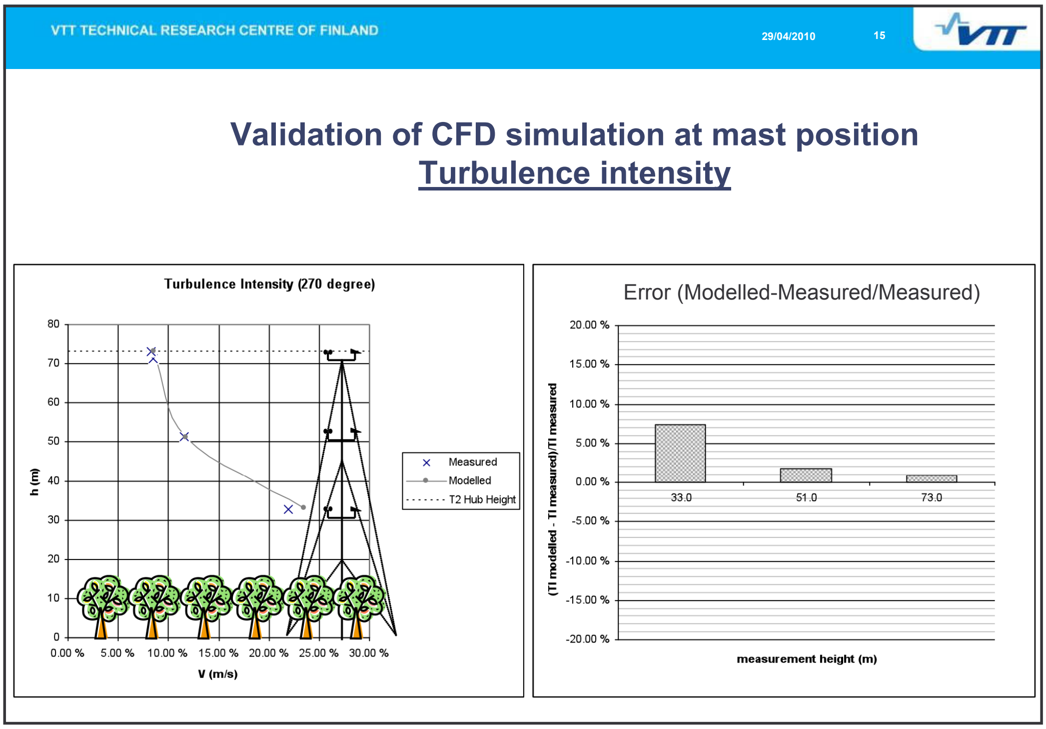
VTT TECHNICAL RESEARCH CENTRE OF FINLAND 29/04/2010 14

Validation of CFD simulation at mast position

Vertical Profile



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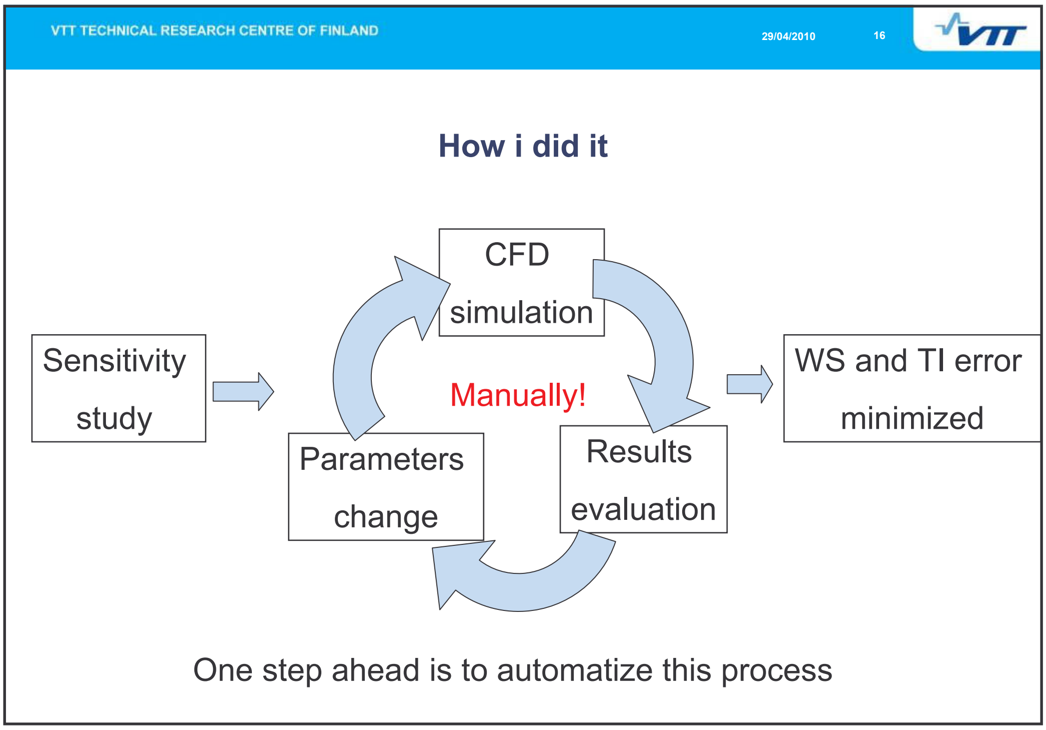
Validation of CFD simulation at mast position
Turbulence intensity
Turbulence Intensity (270 degree)
h (m)
V (m/s)
Measured
Modelled
T2 Hub Height
0.00 %
5.00 %
10.00 %
15.00 %
20.00 %
25.00 %
30.00 %
Error (Modelled-Measured/Measured)
(TI modelled - TI measured)/TI measured
measurement height (m)
33.0
51.0
73.0
20.00 %
15.00 %
10.00 %
5.00 %
0.00 %
-5.00 %
-10.00 %
-15.00 %
-20.00 %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29/04/2010
16
VTT
How i did it
Sensitivity study
CFD simulation
Manually!
Parameters change
Results evaluation
WS and TI error minimized
One step ahead is to automatize this process

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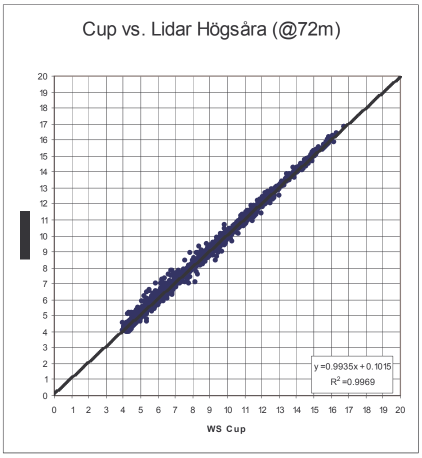
Lidar Measurements at Högsåra



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

- Lidar needs omogenous flow in the probed volume
- No big flow distortion measured on the horizontal plane

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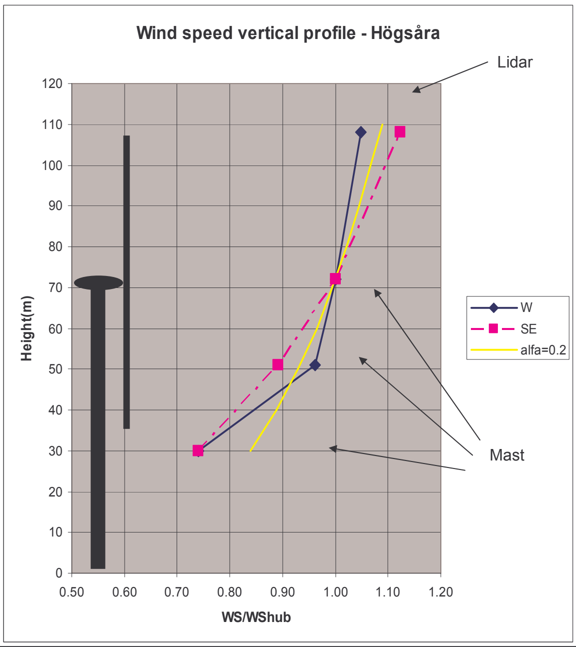

Normalized vertical profile

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

Interesting differences in the vertical profile between the two site calibration sectors

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Rankings by VTT for accurate wind distribution and profile estimation at hub height

Costs ↑

1. Tall Mast + Lidar + CFD
2. Short Mast + Lidar + CFD
3. Tall Mast + CFD
4. Short Mast + CFD

↑ Accuracy

Measurements always used also to calibrate the model

…and what about You?

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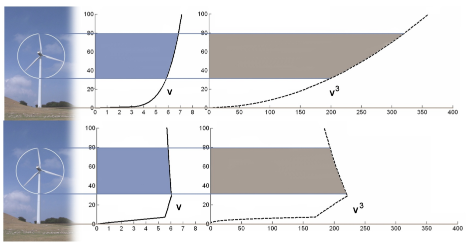
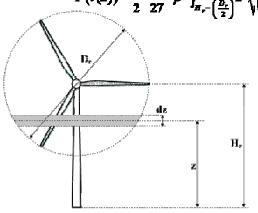
Also the Customization of the power Curve can help for a better enegy yield assessment
Ref.: Castellani et al. (2005) – University Of Perugia - Italy



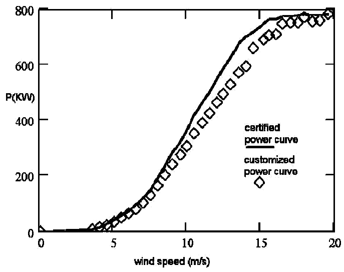
$$P(v(z)) = \frac{1}{2}\cdot\frac{16}{27}\cdot\rho\cdot\int_{H_r-\frac{D_r}{2}}^{H_r+\frac{D_r}{2}} 2\cdot\sqrt{\left(\frac{D_r}{2}\right)^2-(H_r-z)^2}\cdot v(z)^3\,dz$$



$$R = \frac{P(\text{numerical profile})}{P(\text{exponentiaial profile})}$$

$$P_{cus}(v,m) = R(v,m) * P_{ce}(v)$$

v = wind speed
ρ = air density



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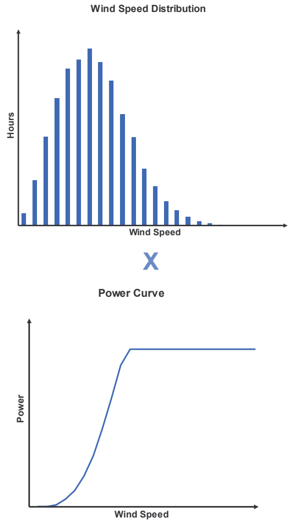
Conclusions

- Complex terrain can be encountered also at sea level
- CFD is a good tool to deal with complex terrain and forest
- Measurements could be used also to tune the CFD modeling
- Lidar is a promising answer for feasible micrositing and model tuning
- Power curve customization for sites that deviates greatly from a test site

better

better



= accurate energy yield assessment in complex terrain

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For info and questions:

Andrea Vignaroli
Research Scientist, MSc Tech
Wind Energy

Tel. +358 20 722 4514
Mobile +358 40 359 0869
Fax +358 20 722 7048
Email andrea.vignaroli@vtt.fi

VTT TECHNICAL RESEARCH CENTRE OF FINLAND
Biologinkuja 3-5, Espoo
P.O. Box 1000
FI-02044 VTT, Finland
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KIITOS!

THANK YOU!

GRAZIE!

22

VTT creates business from technology


Sensitivity Analysis of
WindSIM in Complex Terrain
April 6th, 2010
Chongwon Shin
POSTECH
GWE
Graduate school of wind energy


iea wind
Contents
1. Objective
2. Procedure
3. Result Part 1
4. Result Part 2
5. Conclusion

Objective

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➢ To analyze how the changes in the following parameters effect Annual Energy Production (AEP) in complex terrain with the software, WindSim.

✓ Parameters : Reference Velocity
Roughness
Resolution (Cell Size)

✓ Advantages of WindSim
- Based on CFD instead of Linear Theoretical Method (WAsP)
  - More Precise Vertical Wind Profile
  - Less Standard Deviation of Predicted Error than WAsP

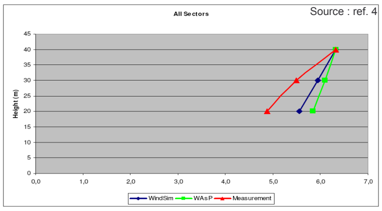

Figure : Vertical profiles in complex terrain

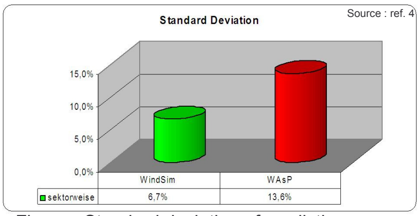

Figure : Standard deviation of prediction error

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Site Description

iea wind

- Mountainous Area with Many Slopes and Valleys
- Mostly Covered by Small Trees
- Longitude / Latitude : 129° 25’ / 36° 25’

POSTECH GWE

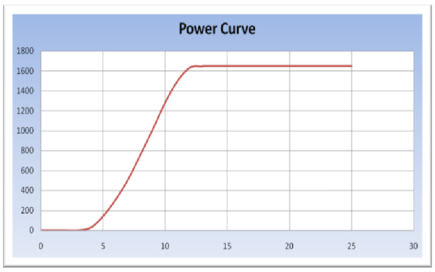
Procedure

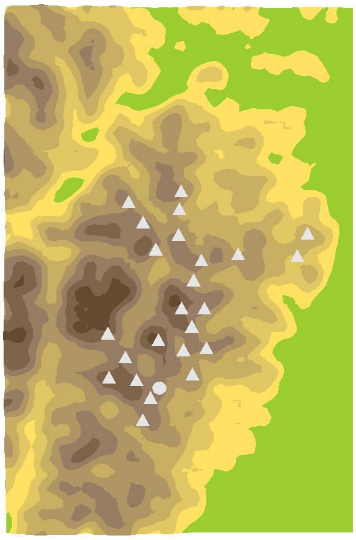
iea wind

Given Data

Wind Turbine (V82)

- ✓ Rate Power : 1650 kW
- ✓ Hub Height : 80m
- ✓ Rotor Diameter : 82m
- ✓ 24 Sets





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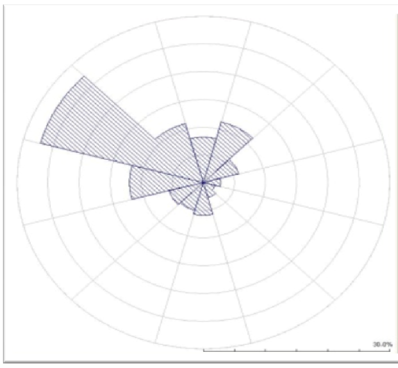
Procedure

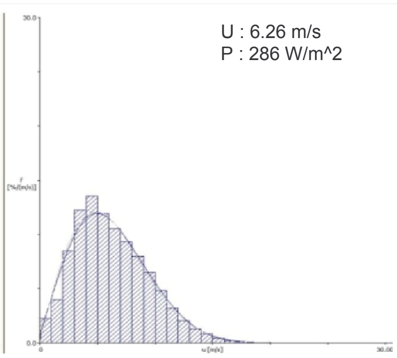
iea wind

Given Data

Met Mast (KIER)

- ✓ 36° 24’ 40” / 129 °25’00’’
- ✓ height : 205.7m(sea level)
- ✓Pole height : 30m
- ✓ 2000, 7, 6 ~ 2002, 12, 6





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Procedure

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Parameters

Assumption

- ✓ Height above terrain : 1500m
- ✓ Total Domain Size : 3378m x 5571m
- ✓ Height Distribution Factor : 0.01
- ✓ Number of Cells in Z-direction : 20
- ✓ Wind Direction : 12 different sectors
- ✓ Height of Boundary Layer : 500m
- ✓ Turbulence Model : Standard k-ε

Variables

Reference Velocity (m/s)	Roughness Length (m)	Grid Size (m)
10	0.01	72 x 72
15	0.02	66 x 66
20	0.03	60 x 60

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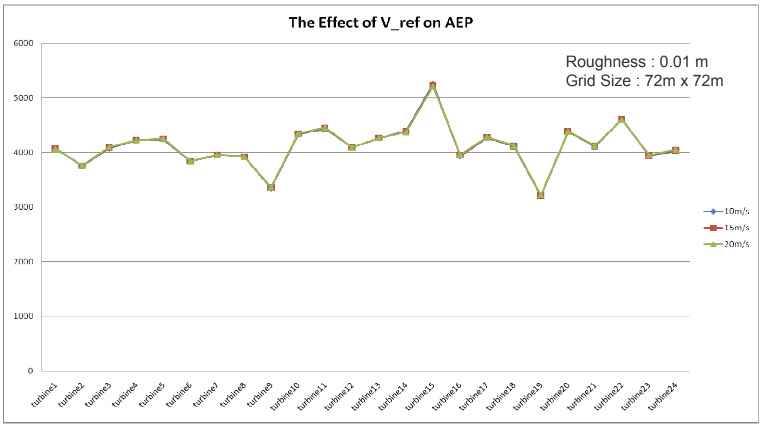
Result Part 1

iea wind

Conditions

- ✓ Fixed : Roughness & Grid size
- ✓ Variable : **Reference Velocity**



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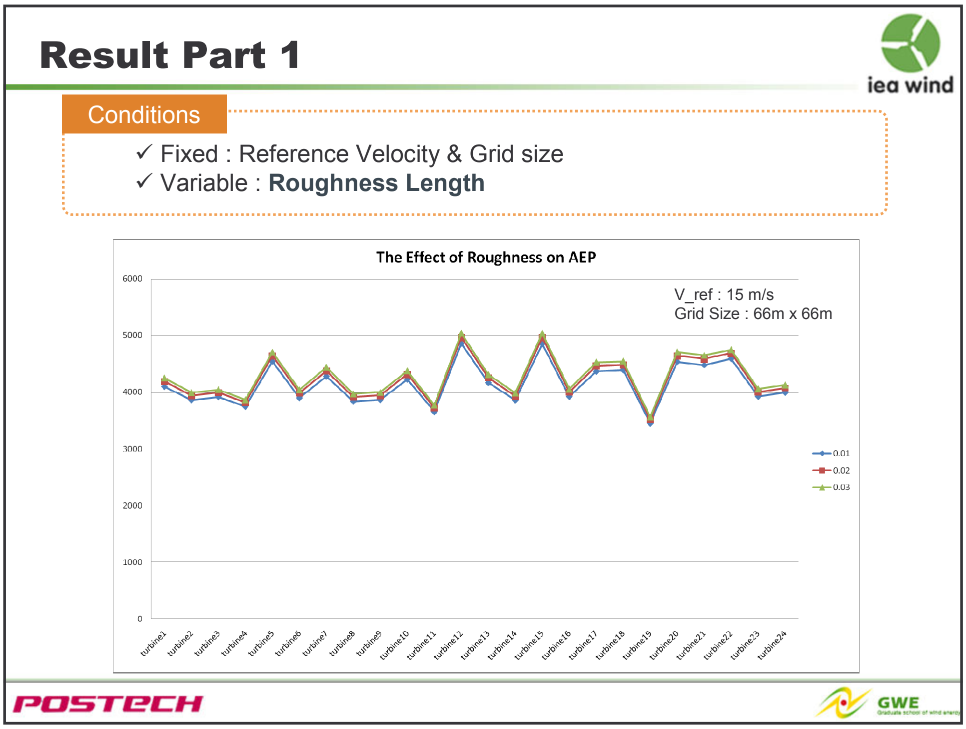
Result Part 1
iea wind
Conditions
✓ Fixed : Reference Velocity & Grid size
✓ Variable : Roughness Length
The Effect of Roughness on AEP
V_ref : 15 m/s
Grid Size : 66m x 66m
6000
5000
4000
3000
2000
1000
0
0.01
0.02
0.03
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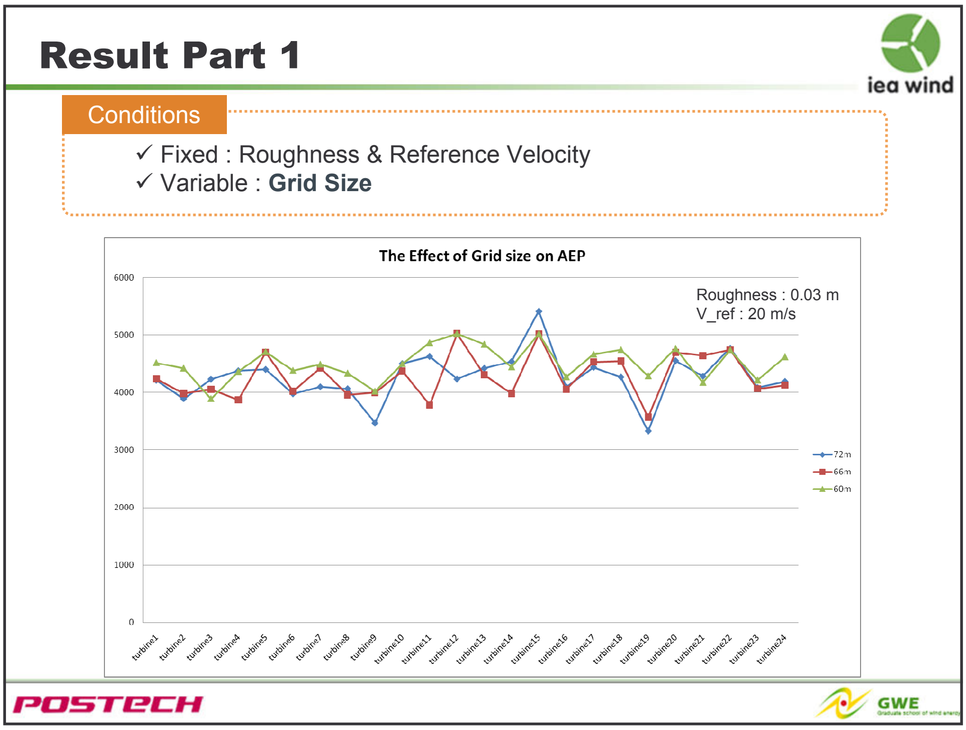
GWE


Result Part 1
iea wind
Conditions
✓ Fixed : Roughness & Reference Velocity
✓ Variable : Grid Size
The Effect of Grid size on AEP
Roughness : 0.03 m
V_ref : 20 m/s
6000
5000
4000
3000
2000
1000
0
72m
66m
60m
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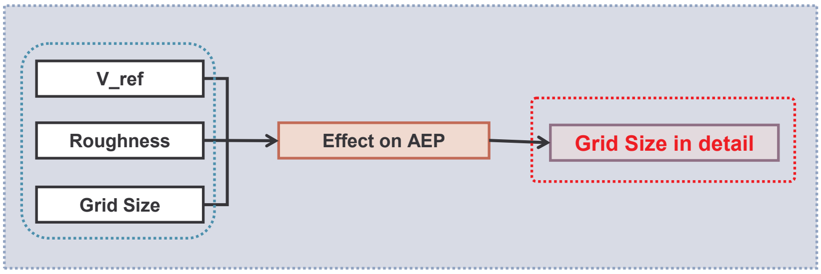
Result Part 1

iea wind



- V ref: almost no effect on AEP
- Roughness: slight effect on AEP
- Grid Size: greatest effect on AEP

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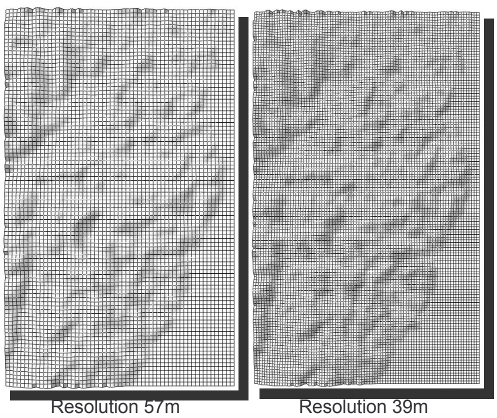
Result Part 2

iea wind

- By setting the max. grid numbers, we attained the corresponding grid sizes
- 39 m by 39 m is the smallest grid size allowed in the system

Case	Grid	Size (m^2)
1	114460	57 x 57
2	127720	54 x 54
3	143880	51 x 51
4	162400	48 x 48
5	184500	45 x 45
6	211200	42 x 42
7	244240	39 x 39



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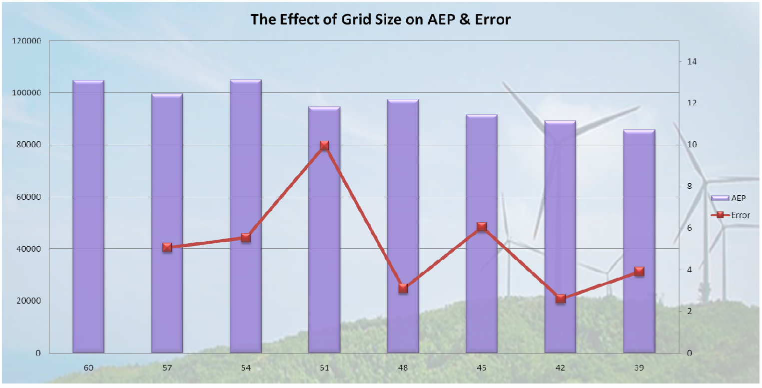
Result Part 2

iea wind

- As the grid size decreases, the fluctuations in AEP and error become smaller.
- We may anticipate that the AEP value becomes more precise, as the grid size decreases even further.



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Conclusion

iea wind

- ✓ Grid Size has the most effect on AEP, while V ref and Roughness Length have slight or no effect on it.
- ✓ As the Grid Size decreases, there exists tendency that fluctuations in AEP and error become smaller.
- ✓ Areas for Improvement
  - ➢ Increase Domain Size
  - ➢ Increase the number of variables in each parameter

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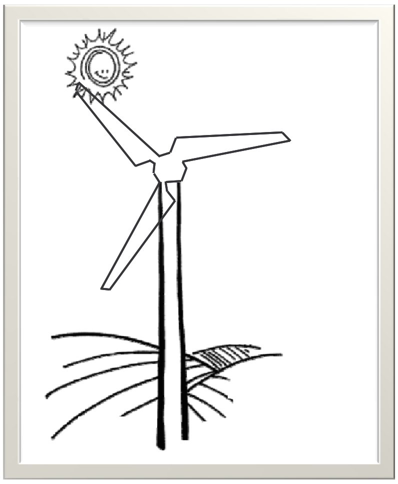

Thank you for your attention!

POSTECH GWE

Reference

iea wind

1) Bowen, A .j. and Mortensen, N. G., WAsP Prediction Errors Due to Site orography, Risoe, 2004
2) Seok-Woo Kim, Hyun-Goo Kim, Sensitivity Analysis of Wind Resource Micrositing at the Antarctic King Sejong Station, KIER, 2007
3) A. Llombart, A.Talayero, A. Mallet, E. Telmo, Performance analysis of wind resource assessment progrmas in complex terrain.
4) Albrecht, C. and Klesitz, M., Three-Dimensional Wind Field Calculation Above orographic Complex Terrain in Southern Europe, European Wind Energy Conference, Athens, 2006

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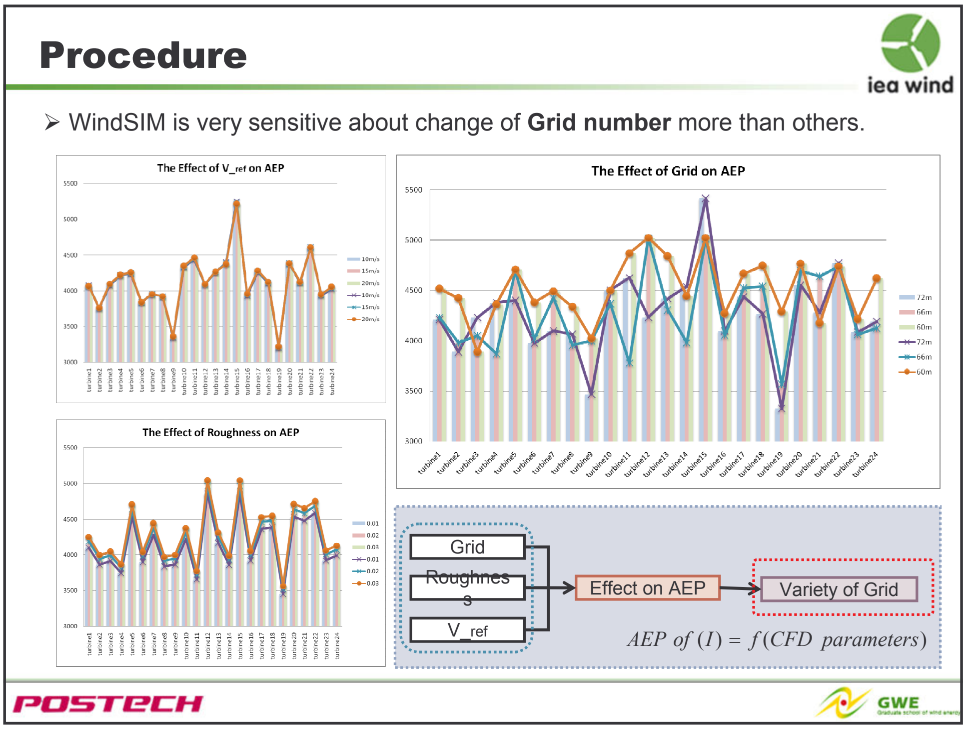
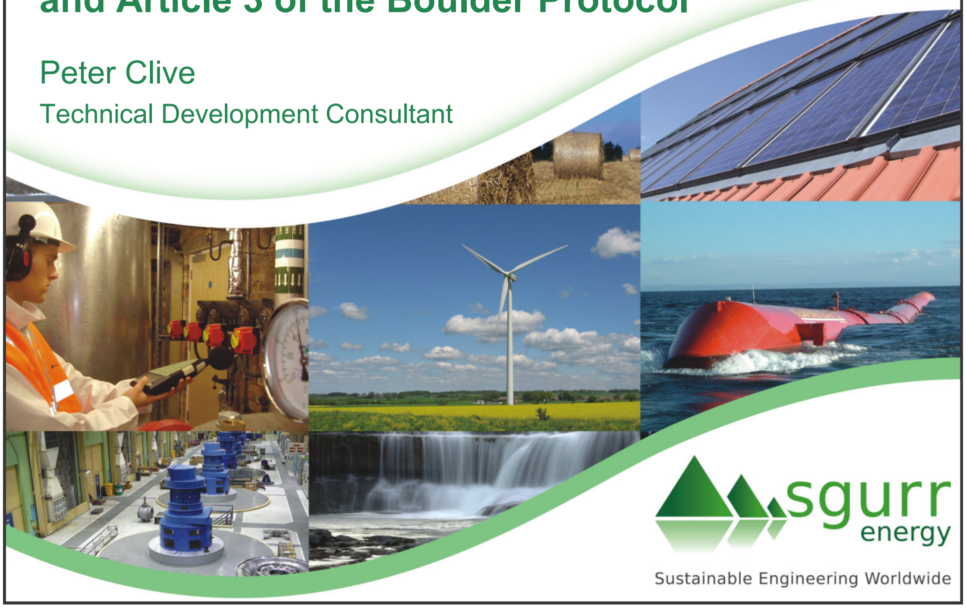

Procedure
iea wind
➢ WindSIM is very sensitive about change of **Grid number** more than others.
The Effect of V_ref on AEP
The Effect of Grid on AEP
The Effect of Roughness on AEP
Grid
Roughness
V_ref
Effect on AEP
Variety of Grid
AEP of (I) = f(CFD parameters)
POSTECH
GWE

Complex Terrain, 2nd Generation Lidar and Article 3 of the Boulder Protocol

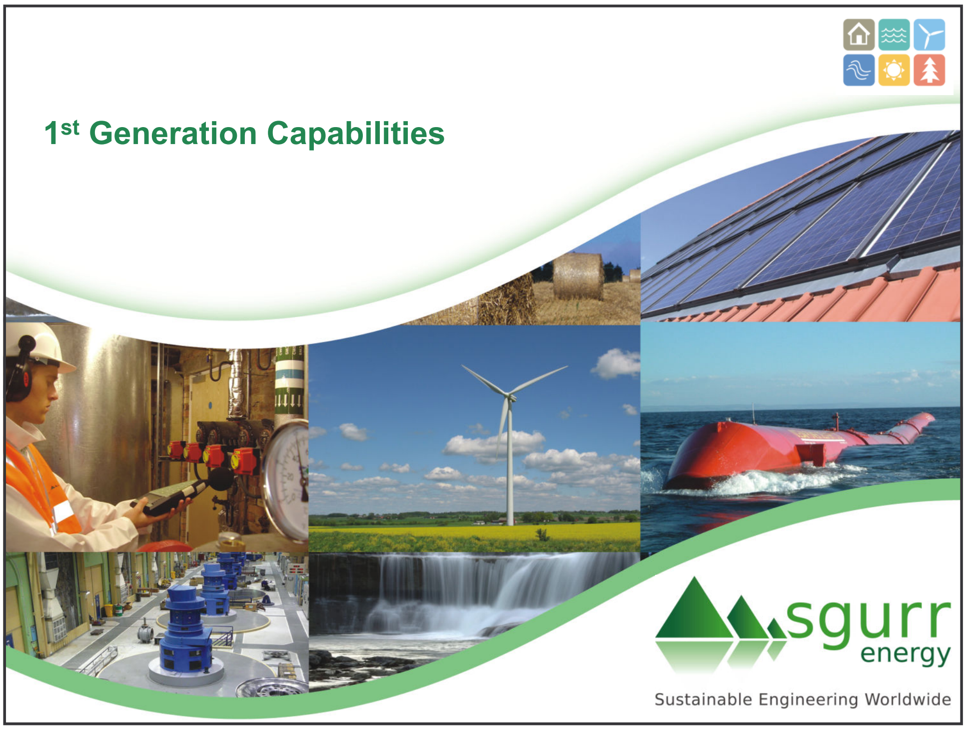
Peter Clive
Technical Development Consultant

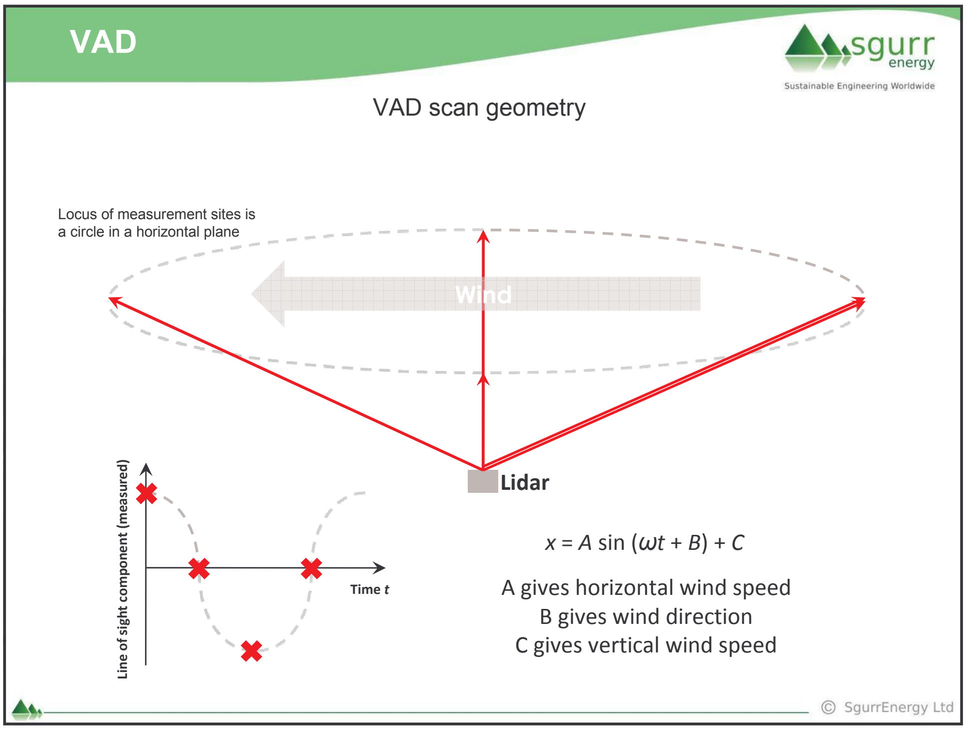


sgurr energy
Sustainable Engineering Worldwide

Contents

- 1st generation capability (single degree of freedom)
  - VAD: Velocity Azimuth Display
  - Issues in non-uniform flow
- 2nd generation capabilities (two degrees of freedom)
  - Including the zenith
  - Volumetric/flow imaging techniques
    - PPI: Plane Position Indicator (constant elevation)
    - RHI: Range Height Indicator (constant azimuth)
- The Boulder Protocol
  - Example: Arc scans
  - Example: Convergent beam techniques (u,v,w at a point)
- Conclusions – designing measurement campaigns


1st Generation Capabilities
sgurr
energy
Sustainable Engineering Worldwide


VAD
sgurr
energy
Sustainable Engineering Worldwide
VAD scan geometry
Locus of measurement sites is
a circle in a horizontal plane
Wind
Lidar
Line of sight component (measured)
Time t
x = A sin (ωt + B) + C
A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed
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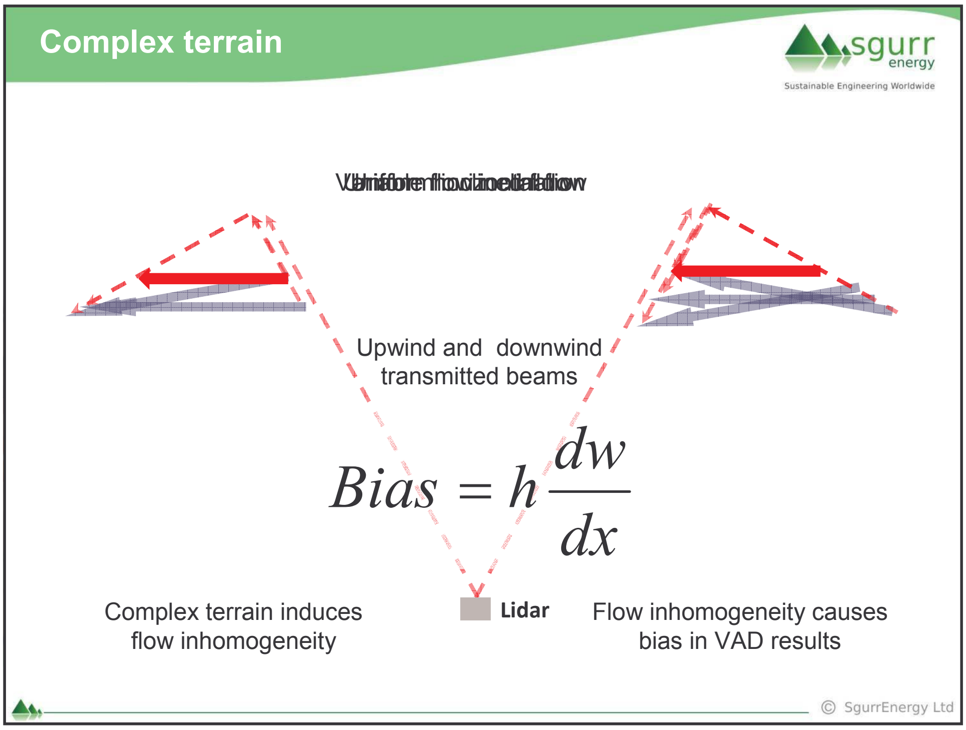
Complex terrain
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Upwind and downwind transmitted beams
$Bias = h\frac{dw}{dx}$
Complex terrain induces flow inhomogeneity
Lidar
Flow inhomogeneity causes bias in VAD results
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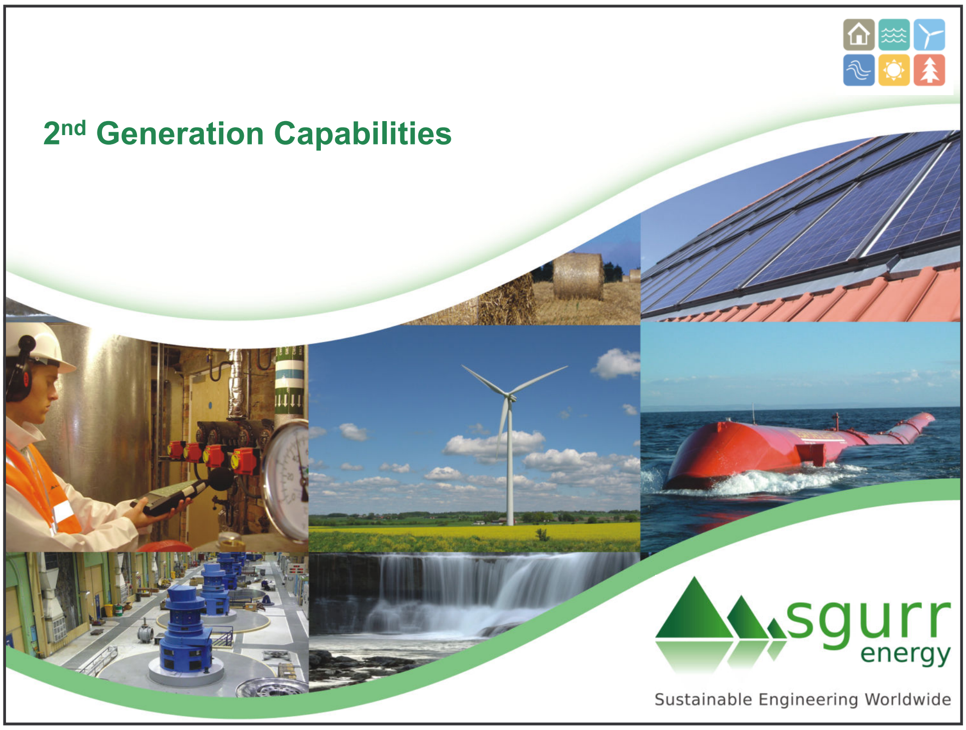
2nd Generation Capabilities
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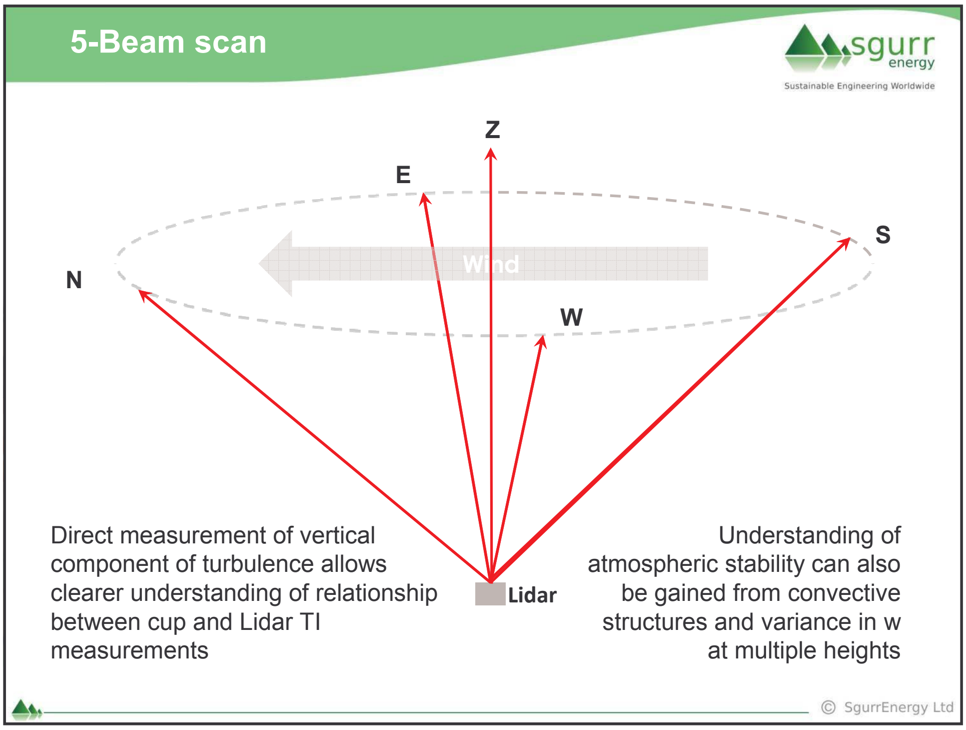
5-Beam scan
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Z
E
S
N
W
Wind
Lidar
Direct measurement of vertical component of turbulence allows clearer understanding of relationship between cup and Lidar TI measurements
Understanding of atmospheric stability can also be gained from convective structures and variance in w at multiple heights
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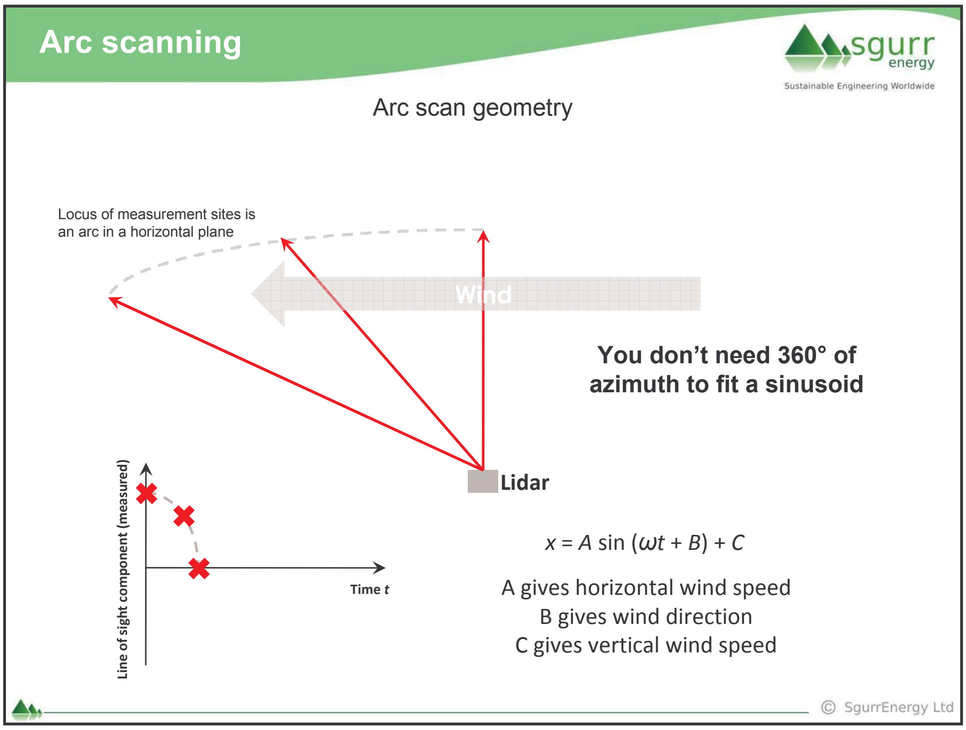
Arc scanning
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Arc scan geometry
Locus of measurement sites is an arc in a horizontal plane
Wind
You don't need 360° of azimuth to fit a sinusoid
Lidar
Line of sight component (measured)
Time t
x = A sin (ωt + B) + C
A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed
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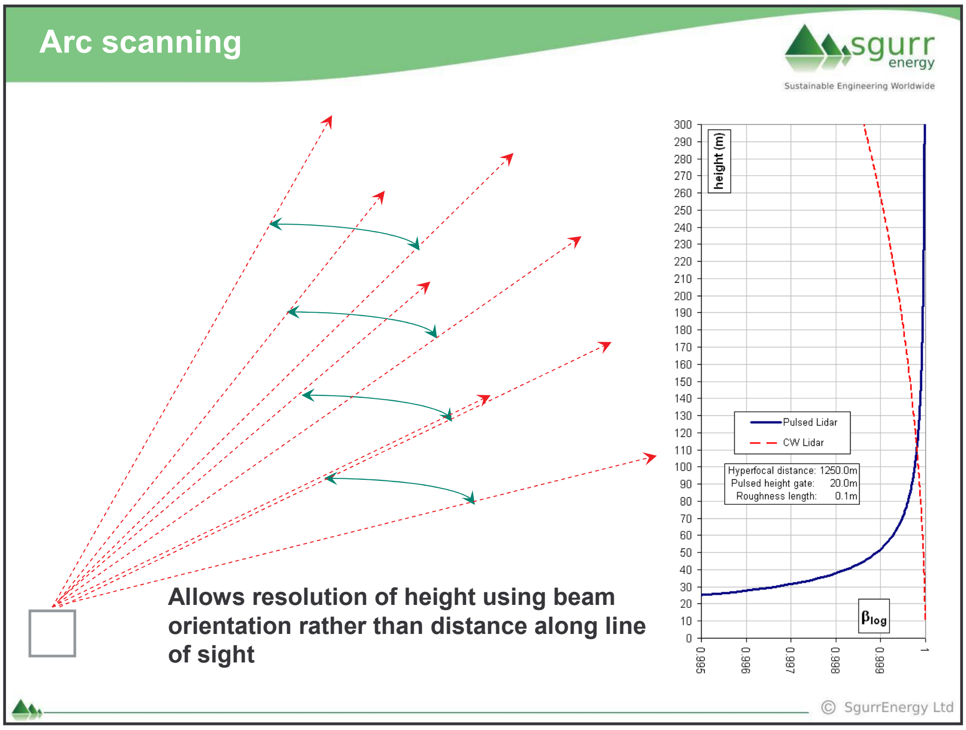
Arc scanning
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Allows resolution of height using beam orientation rather than distance along line of sight
height (m)
Pulsed Lidar
CW Lidar
Hyperfocal distance: 1250.0m
Pulsed height gate: 20.0m
Roughness length: 0.1m
βlog
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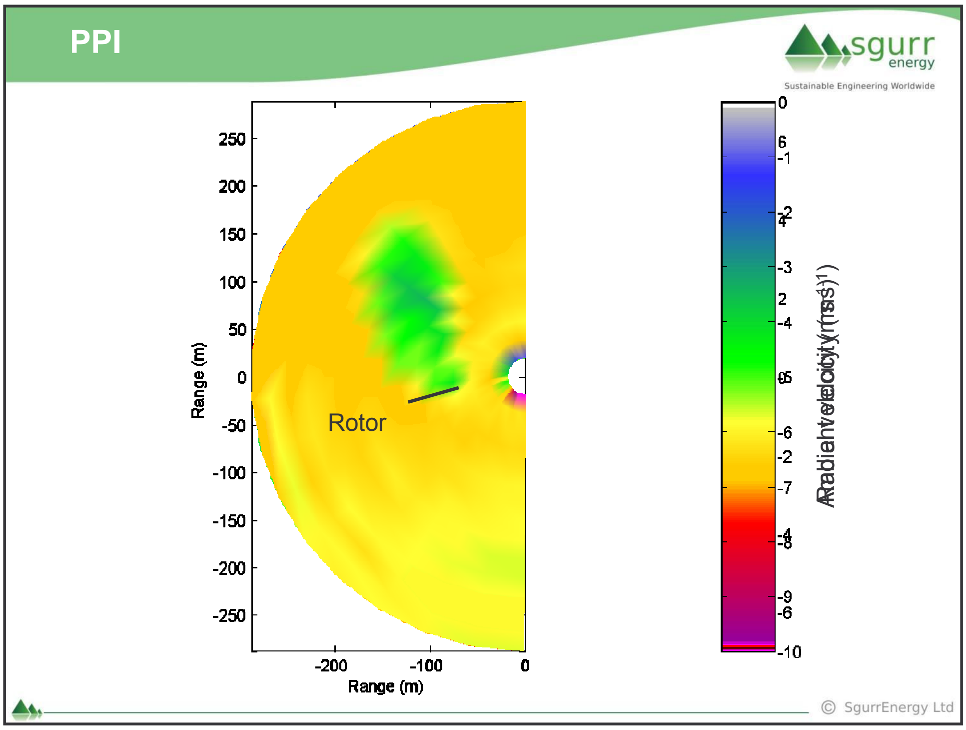
PPI
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Range (m)
Rotor
Range (m)
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PPI

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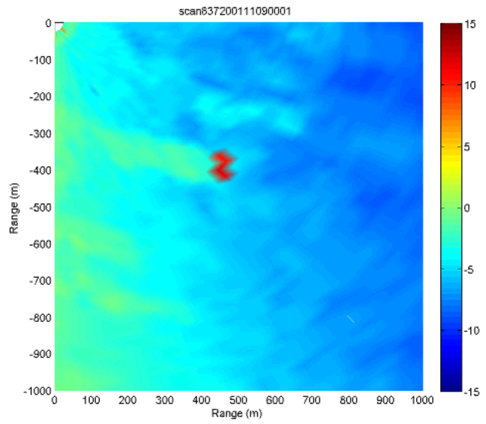

Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI

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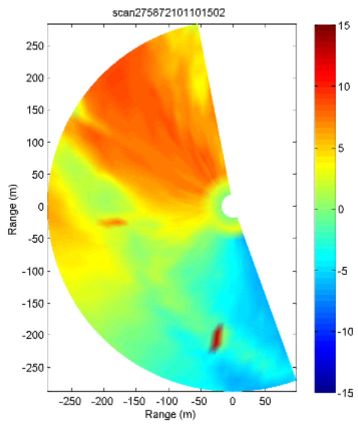

Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI

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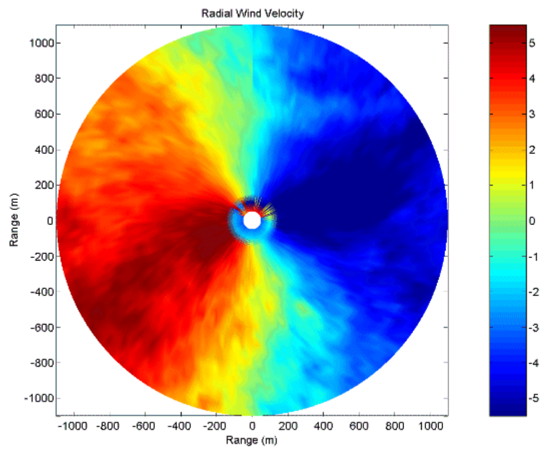

RHI

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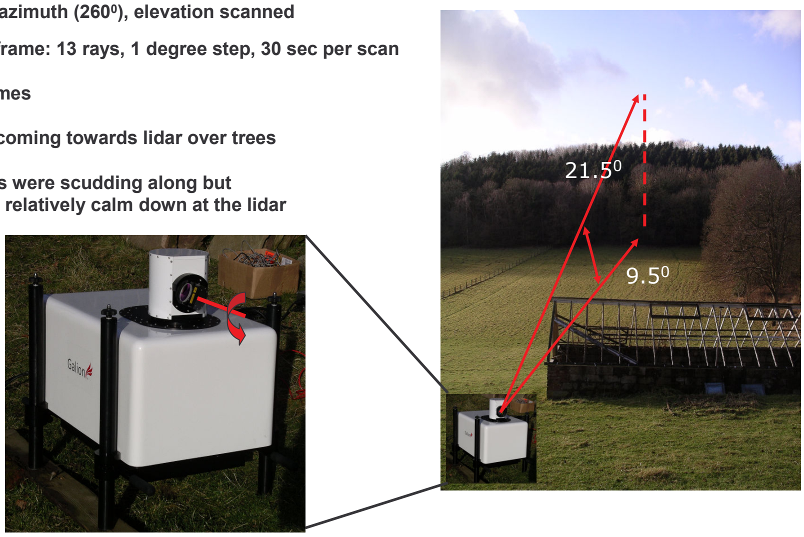
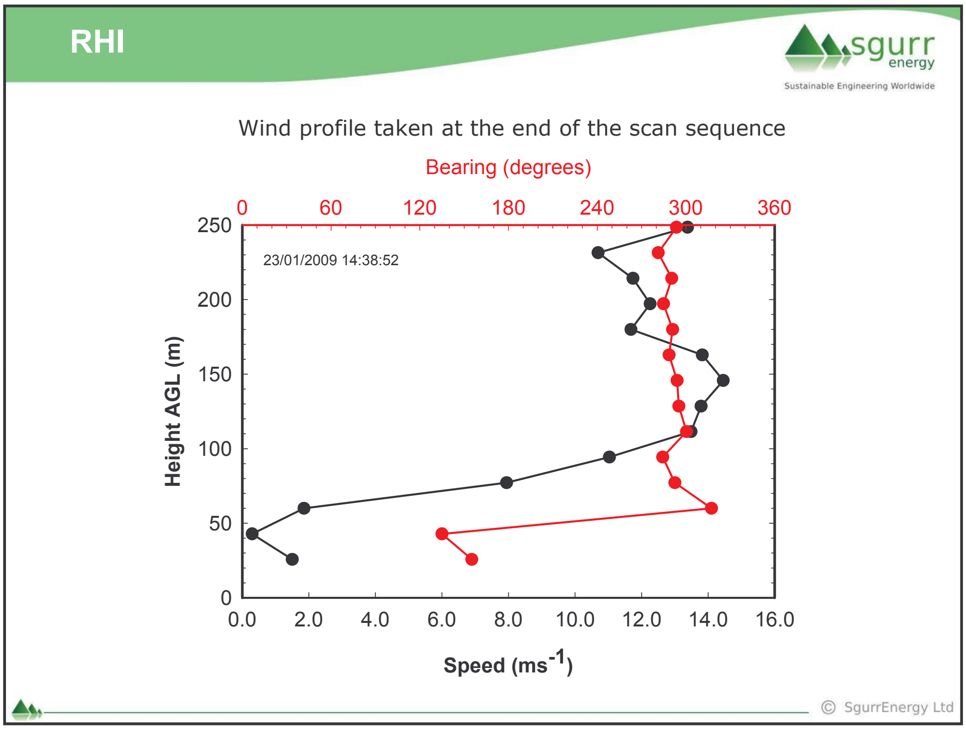
- Fixed azimuth (260^0), elevation scanned
- Each frame: 13 rays, 1 degree step, 30 sec per scan
- 16 frames
- Wind coming towards lidar over trees
- Clouds were scudding along but it was relatively calm down at the lidar




RHI
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Wind profile taken at the end of the scan sequence
Bearing (degrees)
0 60 120 180 240 300 360
23/01/2009 14:38:52
Height AGL (m)
250 200 150 100 50 0
0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0 16.0
Speed (ms-1)
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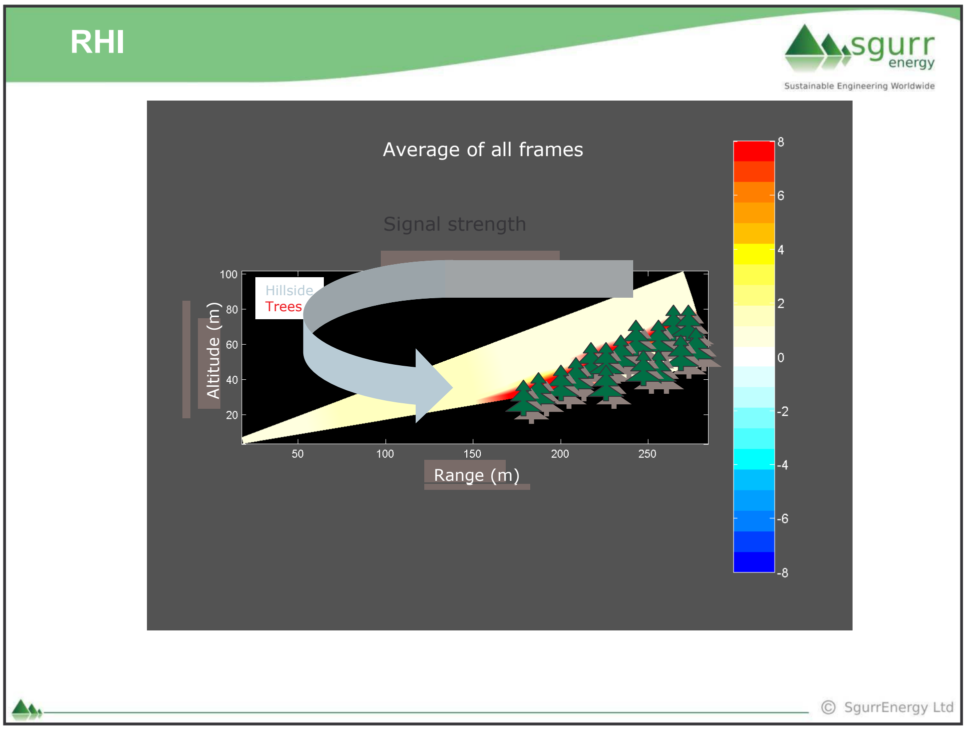
RHI
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Average of all frames
Signal strength
Hillside
Trees
Altitude (m)
100 80 60 40 20
50 100 150 200 250
Range (m)
8 6 4 2 0 -2 -4 -6 -8
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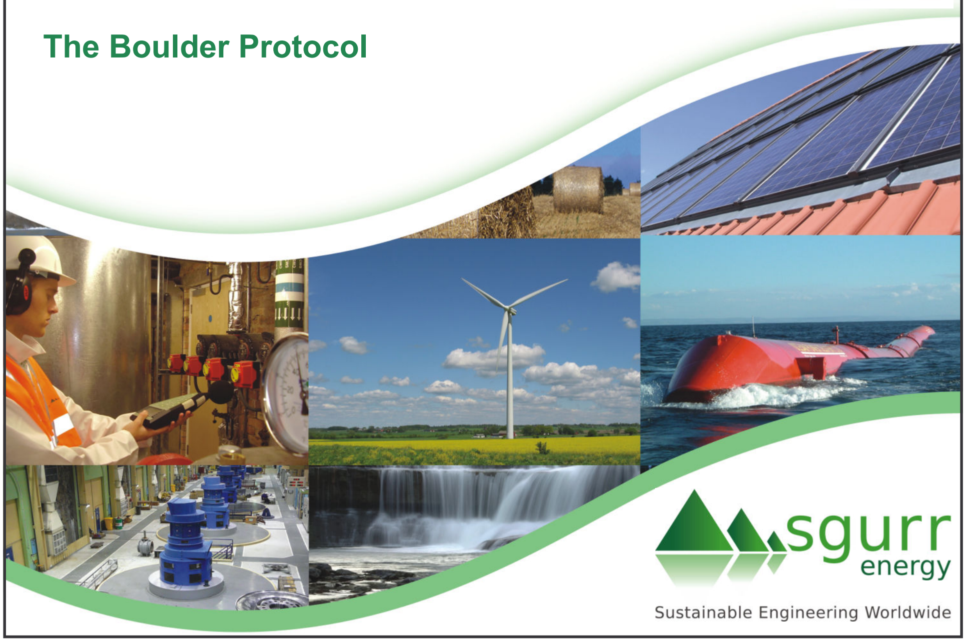
The Boulder Protocol



Boulder Protocol: preamble

Memorandum: Remote Sensing Data Acceptability Criteria
Remote sensing devices, including commercially available Sodars and Lidars developed for wind power applications, are considered to be an acceptable source of data for use in a wind power investigation such as, but not limited to

• undertaking a quantitative assessment of wind resource to which reference may be made when setting the terms for raising finance for a project to exploit that wind resource for power generation;
• acquiring wind inflow information in relation to the assessment of the performance of operational wind power assets in response to inflow conditions;

under the following conditions. All stated examples are illustrative only.

0: General Requirements
A preliminary requirement is that the data is acquired during a measurement campaign that in all respects additional to those pertaining specifically to remote sensing is well designed and is fit for purpose. For example, compliance with relevant standards and guidelines has been observed, the campaign is of sufficient duration to achieve the necessary seasonal balance in the dataset and/or stipulated data coverage and convergence requirements, and the measurements are acquired in locations appropriate for the project.

Boulder Protocol: article 1

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1: Verification of Performance
The performance of the remote sensing 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 reference instruments which would have been deemed acceptable for conducting the wind power investigation.

1.1: The use of reference instruments will support traceability of device performance as a result of the routine calibration of the reference instruments using repeatable and adequately documented methods in conformance with relevant standards and guidelines at facilities that are inspected and certified as compliant with national standards, and adequate recording of the manufacturing processes and provenance of the reference instruments and their components.

1.2: The manufacturing processes and provenance of the remote sensing device and its components will also be adequately documented to support traceability.

1.3: The degrees of concurrency and co-location are those that enable the most precise and well understood relationship between the device and reference measurements to be determined. So, for example,

- The same averaging intervals are used for the device and reference datasets being compared;
- Regression methodologies accommodate errors in all instruments;
- The device is sited and analysis of the measurements conducted in a manner that minimises extraneous influences such as
  - flow perturbations;
  - fixed echoes;
  - real variations in the flow between the device and reference instrument measurement locations;
  - divergent levels of data coverage within averaging intervals.

1.4: The verification exercise has been conducted recently enough for its results still to be valid.

Boulder Protocol: article 2

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2: Verification of Methodology
The element of the measurement campaign in which the device is operated to acquire data for the wind power investigation is conducted according to the methodology adopted during performance verification.

2.1: Methodology is adequately documented to ensure repeatability of the measurements. The statement of the methodology details any dependence of device performance on the prevailing conditions. For example, the impact of flow inhomogeneity in the volume penetrated by the remote sensing measurements and the influence of other parameters such as temperature is described.

Boulder Protocol: article 3

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3: Verification of Conditions

The conditions prevailing during the element of the measurement campaign in which the device is operated to acquire data for the wind power investigation are considered sufficiently similar to those prevailing during the performance verification period that a divergence in the performance of the device from the performance observed during performance verification would not be expected.

3.1: The influence of the deviation of conditions during the measurement campaign from the conditions during the verification period is understood sufficiently to enable remote sensing measurement uncertainties and biases arising as a result to be reported and adequately supported with reference to current understanding of device response.

3.2: If conditions deviate and the influence of this deviation is not adequately understood, remote sensing is inapplicable. For example, flow inhomogeneity, variable flow inclination, and non-uniformity in the volume defined by the remote sensing measurements, possibly induced by complex terrain, may render remote sensing inapplicable.

3.3: Filtering and data availability are not correlated with conditions such that a bias is introduced into the results.

Boulder Protocol: article 4

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4: Robust Uncertainty Analysis

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

4.1: "Bankability". It is acknowledged that these considerations may have a bearing on whether an investigation is judged to be "bankable" or not. For clarification, bankability is defined as follows:

- The long term productivity of a project is assessed to be sufficient for servicing debt raised to finance its development or acquisition on the basis of the wind power investigation;
- The uncertainty analysis on which the percentiles chosen to represent the long term productivity available to service debt - such as, for example, the P90 against which the finance is secured - is based on an uncertainty analysis that adequately represents the measurements and methods employed during the assessment of the long term productivity of the project.

Boulder Protocol: article 5

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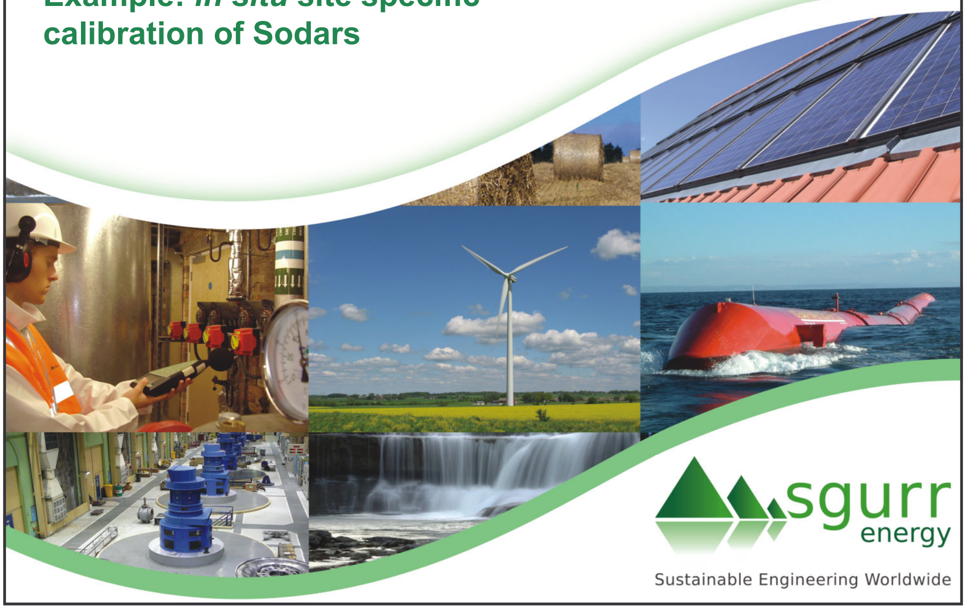
5: Compliance with IEA Guidelines
The specific remote sensing technology, such as Sodar and Lidar, adopted for the purposes of the wind power investigation, is operated in compliance with the most current IEA Guidelines for Best Practice published in relation to the technology, as formulated by the relevant IEA Topical Expert Committees.

5.1: Guidelines for Best Practice with Lidar and Sodar are presented in separate documents.

Example: *in situ* site specific calibration of Sodars



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Why?

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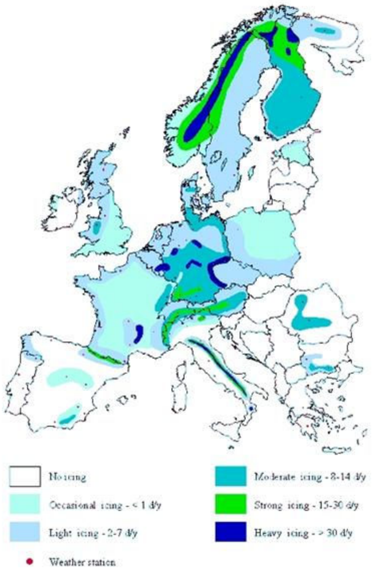

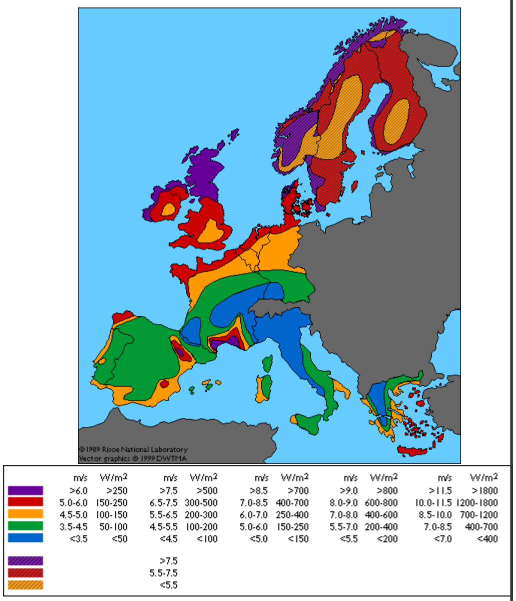

Why?

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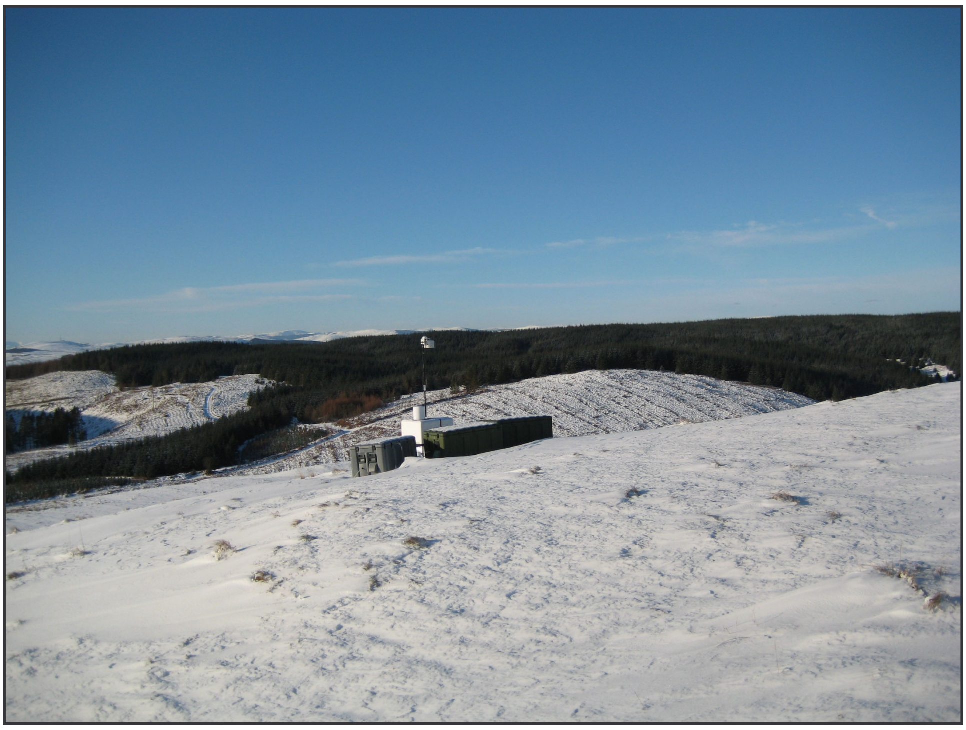
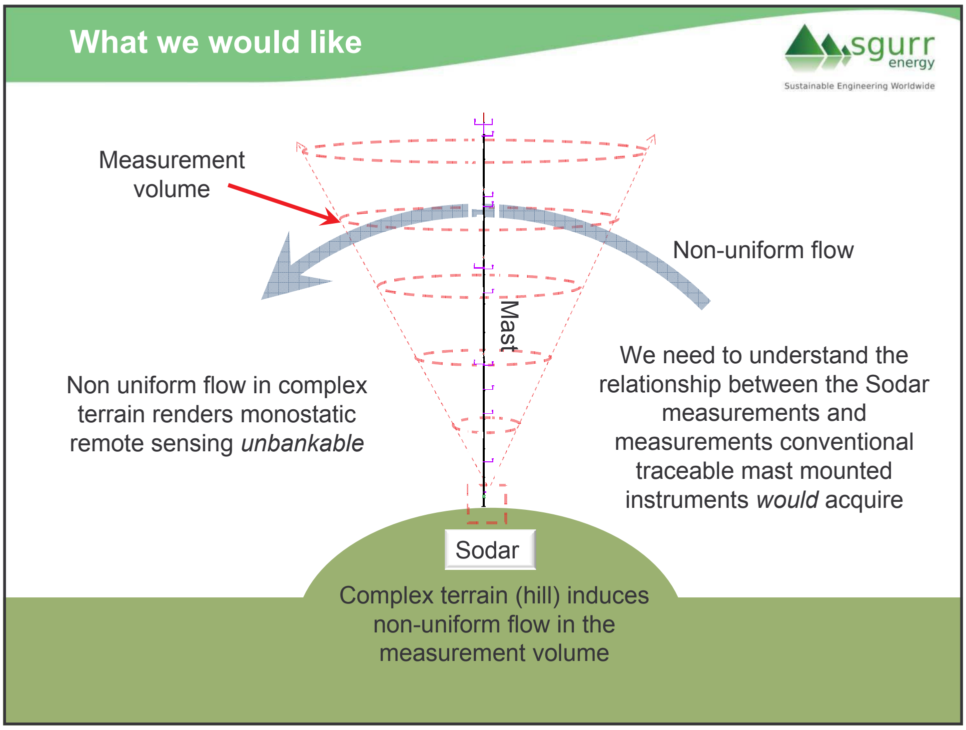
- Good resource are available in cold climate regions;
- Conventional mast mounted instrumentation subject to icing;
- Complex terrain typical of cold climate areas renders monostatic remote sensing results unreliable;
- *In situ* site specific calibrations of monostatic devices could provide sector-wise relationships between what a mast would measure and what the devices record;
- Uncertainty could be assessed in relation to the scatter evident in these relationships.




What we would like
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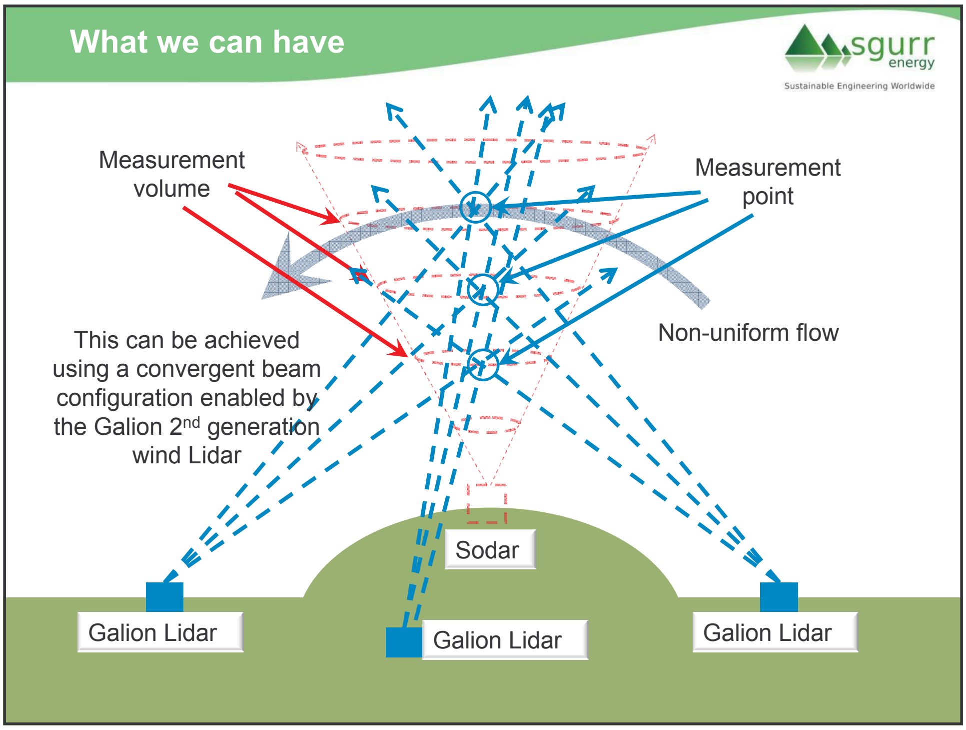
Measurement volume
Non-uniform flow
Mast
Non uniform flow in complex terrain renders monostatic remote sensing *unbankable*
We need to understand the relationship between the Sodar measurements and measurements conventional traceable mast mounted instruments *would* acquire
Sodar
Complex terrain (hill) induces non-uniform flow in the measurement volume


What we can have
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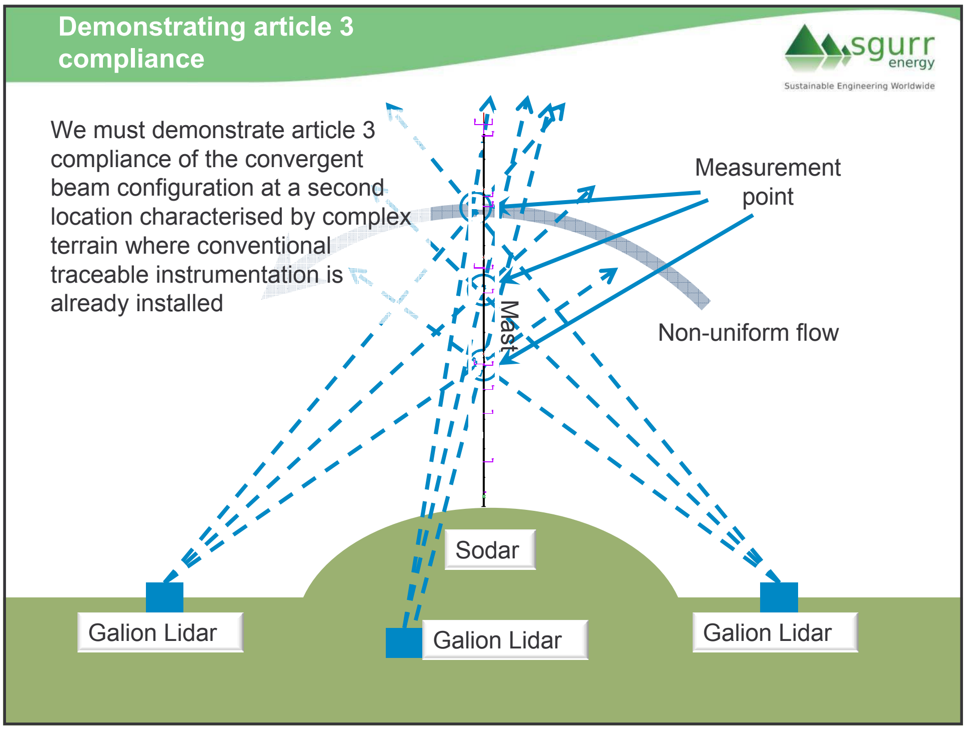
Measurement volume
Measurement point
Non-uniform flow
This can be achieved using a convergent beam configuration enabled by the Galion 2nd generation wind Lidar
Sodar
Galion Lidar
Galion Lidar
Galion Lidar


Demonstrating article 3 compliance
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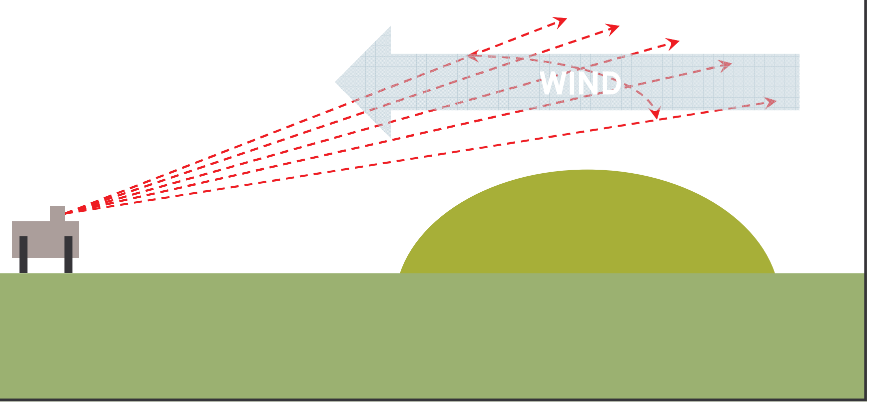
We must demonstrate article 3 compliance of the convergent beam configuration at a second location characterised by complex terrain where conventional traceable instrumentation is already installed
Measurement point
Non-uniform flow
Mast
Sodar
Galion Lidar
Galion Lidar
Galion Lidar

Arc scan

- Arc scan used to measure flow over a ridge;
- Compliance with articles 2 and 3 in this instance is non-trivial and not assumed, since 2nd generation techniques are used in complex terrain.



Arc scan

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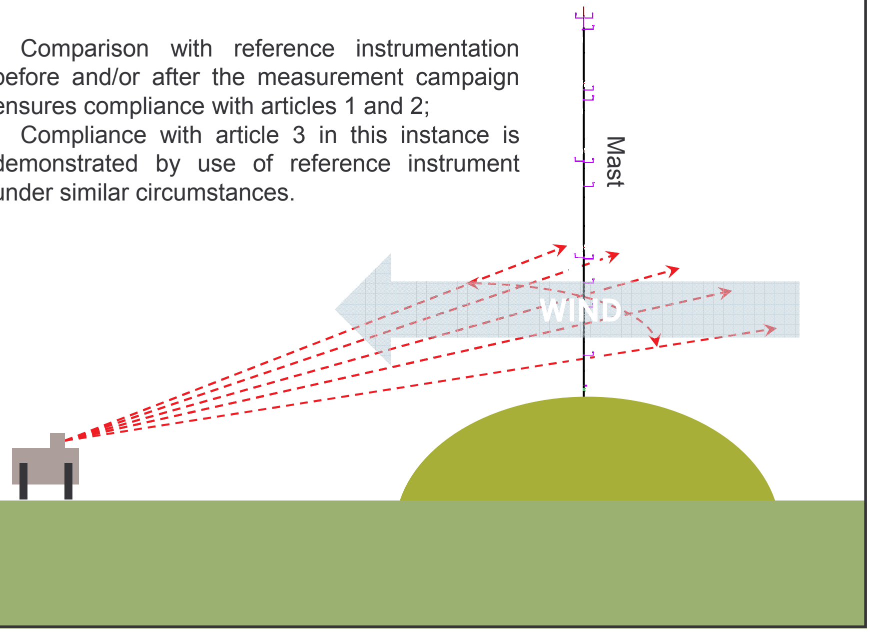
- Comparison with reference instrumentation before and/or after the measurement campaign ensures compliance with articles 1 and 2;
- Compliance with article 3 in this instance is demonstrated by use of reference instrument under similar circumstances.



Conclusions

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Conclusions

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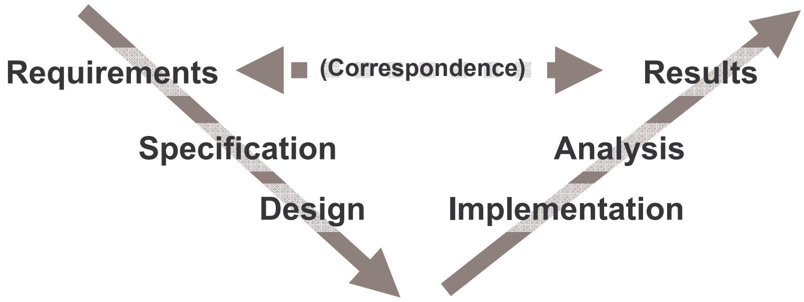
Campaigns were previously designed around what measurements were possible

The capabilities of the Galion mean campaigns are designed around what is required



Any questions?

Email: peter.clive@sgurrenergy.com

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