October 2016

Minutes
IEA WIND Task 31+32 Workshop on

Lidar measurements for wake assessment and comparison with wake models

Date: October 4th 2016

Venue: Technical University of Munich, Munich, Germany

Immediately preceding The Science of Making Torque from Wind conference 2016

Workshop leaders:

David Schlipf, SWE University Stuttgart

Task 31: Javier Sanz Rodrigo, CENER, Spain

Task 32: Davide Trabucchi, ForWind – University of Oldenburg, Germany

Minutes by:

Lukas Vollmer, Davide Trabucchi, Javier Sanz Rodrigo, David Schlipf

Agenda Overview

8:30 Welcome and introduction round

9:00 Introduction to the workshop
Javier Sanz Rodrigo (Task 31) and Davide Trabucchi (Task 32)

9:30 Invited presentations:

What has been done so far?

- David Maniaci (Sandia): Lidar measurements at SWIFT
- Sandrine Aubrun (University of Oreleans): SMARTEOLE I
- Nicolai Gayle Nygaard (DONG Energy): Westermost Rough wind farm
- Paul Fleming and Matthew Churchfield (NREL), and Steffen Raach (SWE): The DOE 1.5 campaign at NWTC

10:30 Coffee break

10:45
- Juan-José Trujillo (ForWind – University of Oldenburg): Measuring the wake profile from lidar measurements: The effect of fixed and moving frame of reference
- Kurt Schaldemose Hansen (DTU): Perdigão wind turbine wake measurements
- Rebecca J. Barthelmie (Cornell University): Quantifying wake characteristics from lidar

11:30 Group discussion:
What are the objectives of lidar wake measurements?
12:30 Lunch
13:30 Comparative exercise: wake study based on lidar measurements
14:30 Plenary discussion:
How can we collaborate with existing measurement data?
15:30 Coffee break
15:45 Group discussion:
How can we collaborate in future?
16:45 Workshop wrap-up and formulation of next steps
17:30 End of workshop
Attendees of the conference “The Science of Making Torque from Wind (TORQUE 2016)” will have the possibility to visit the Welcome Cocktail (17:00-20:00).
Additionally, we can organize a dinner, if desired.

Participation List

Name	Country	Institution
Ameya Sathe	Denmark	DONG Energy
Arièle Défossez	France	EDF
Ashim Giyanani	Netherlands	TU Delft
Bart Doekemeijer	Netherlands	TU Delft
Beatriz Cañadillas	Germany	DEWI
Benny Svardal	Norway	Christian Michelsen Research
Carlo Alberto Ratti	UK	ZephIR
Chen Fei	China	Goldwind
Christian Jonsson	UK	Natural Power
David Maniaci	USA	Sandia
David Schlipf	Germany	SWE University Stuttgart
Davide Trabucchi	Germany	University of Oldenburg
Domenico di Domenico	France	IFP Energie Nouvelles
Dongheon Shin	South Korea	Jeju University
Donghun Ryu	South Korea	Korea Testing Laboratory
Ervin Bossanyi	UK	DNV GL
Fabrice Guillemin	France	IFP Energie Nouvelles
Frank Klintø	Denmark	Suzlon
Frederic Blondel	France	IFP Energie Nouvelles
Hugo Herrmann	UK	EDF Energy
Jan Willem Wagenaar	Netherlands	ECN
Jason Jonkman	USA	NREL
Javier Sanz Rodrigo	Spain	CENER
Jinhyuk Son	South Korea	Jeju University
Jonathan W. Naughton	USA	University of Wyoming
Juan José Trujillo	Germany	University of Oldenburg
Juan Pablo Murcia Leon	Denmark	DTU
Jun Li	China	Envision
Kurt Schaldemose Hansen	Denmark	DTU
Kyungnam Ko	South Korea	Jeju University
Laura Corrochano	Spain	Suzlon

Li Jian	China	Goldwind
Li Junxiang	China	Mingyang Wind Power
Liu Yi	China	Mingyang Wind Power
Ludwig Wagner	Germany	GWU-Umwelttechnik
Lukas Vollmer	Germany	University of Oldenburg
Malika Milekovic	France	IFP Energie Nouvelles
Matthew Churchfield	USA	NREL
Mikel Iribas Latour	Spain	CENER
Nick Johnson	USA	DOE
Nicolai Gayle Nygaard	Denmark	DONG Energy
Niels Troldborg	Denmark	DTU
Norman Wildmann	Germany	DLR
Patrick Moriarty	USA	NREL
Paul Fleming	USA	NREL
Paula Doubrawa	USA	Cornell University
Peter Clive	UK	SgurrEnergy
Philipp Gasch	Germany	KIT
Pieter Gebraad	Denmark	Siemens
Rebecca J. Barthelmie	USA	Cornell University
Robert Menke	Denmark	DTU
Sandrine Aubrun	France	University of Orleans
Shi Shaoping	China	Huaneng Clean Energy Research Institute
Sjoerd Boersma	Netherlands	TU Delft
Søren Juhl Andersen	Denmark	DTU
Steffen Raach	Germany	SWE University Stuttgart
Suresh Pillai	India	Suzlon
Tang Hao	China	Goldwind
Thomas Gerz	Germany	DLR
Thomas Herges	USA	Sandia
Tom Berdowski	Netherlands	TU Delft
Torben Mikkelsen	Denmark	DTU
Wiebke Langreder	Denmark	Wind Solutions
Wolfgang Schlez	UK	ProPlanEn
Yan Shu	China	Huaneng Clean Energy Research Institute
Yuko Ueda	Japan	Wind Energy Institute of Tokyo

Minutes

First Morning Session [8:30 – 9:45]

Welcome and introduction round (David Schlipf)

- David welcomes everybody.
- Round of introduction

Introduction to Workshop (Javier Sanz Rodrigo (Task 31) and Davide Trabucchi (Task 32))

- Davide introduces the workshop from the Task 32 perspective and the idea of working closer together with Task 31.
- Javier gives a short presentation of the scope of Task 31.

"What has been done so far?" Four invited speakers

1) David Maniaci (Sandia): Lidar measurements at SWIFT
    - Introduction of the SWIFT site (3 Vestas V27) and the conducted experiments
    - Presentation of Validation & Verification (VV) framework and Phenomenon Importance Ranking Table (PIRT) protocols
    - At SWIFT a spinner lidar is used to measure the wake and a meteorological mast for the atmospheric conditions.
    - The trajectories scanned by the lidar were optimized using lidar simulations of wake measurements within a Large Eddy Simulation wind field. In particular the settings of the lidar trajectories were defined in order to minimize the deviation of the simulated measurements from the reference wind field.
    - For uncertainty reduction of the measurement point positions, the lidar trajectory is calibrated mapping the laser beam with an infrared camera.
    - The lidar measurements showed that the position of the wake is not changing much during stable atmospheric stratification, while a lot of variation was observed during unstable conditions.
    - The data will be available through the A2e project around January 2017.
2) Sandrine Aubrun (Univ. Orleans): SMARTEOLE I
    - Introduction to the SMARTEOLE project consisting of two wind turbines, two ground-based, two nacelle-based lidars and a met mast
    - The plan is to use the measured inflow for turbine control.
3) Nicolai Gayle Nygaard (DONG Energy): Westermost Rough wind farm
    - Presentation of flow measurements with two radars at an offshore wind farm
    - Reconstruction from the LOS velocities will allow for 3D images of the flow
    - The campaign duration is more than a year
    - The radar are not as expensive as an offshore meteorological mast, but much more expensive than lidars.
    - Hard targets were used to align the radar beams.
    - Precipitations have an influence on the measurements.
4) Paul Fleming and Matthew Churchfield (NREL), and Steffen Raach (SWE): The DOE 1.5 campaign at NWT
    - Introduction to wake deflection measurements with a nacelle mounted lidar and an upstream met mast at the NREL facilities in Colorado

- Preparation of the campaign involved the simulation of the scan patterns in LES
- The lidar measurements tend to smooth out turbulent fluctuations in wakes. These effect of was shown through the comparison of a cross section of the wake extracted from LES, a sample of these data at the positions scanned by a lidar simulator, the corresponding simulated lidar measurements.
- Measurement and turbine data will also be made available after the campaign through A2e.
- The need of well-defined procedures for processing the data (interpolation and wind field reconstruction) was pointed out.

Second Morning Session [10:00 – 12:45]

Continuation of previous session, three invited speakers

5) Juan-José Trujillo (ForWind – Oldenburg University): Measuring the wake profile from lidar measurements: The effect of fixed and moving frame of reference
    - Introduction to a campaign at the offshore wind farm alpha ventus with 3 long-range lidar to study wake induced loads at a downwind turbine
    - Averaging in a moving frame of reference filters large scale motions of the wake and might lead to a better representation of the wake influence on downstream turbines.
6) Kurt Schaldemose Hansen (DTU): Perdigão wind turbine wake measurements
    - Introduction to the Perdigão experiment involving an Enercon turbine on a hill ridge, 3 long-range and 3 short-range windscanners and a 20 m meteorological mast
    - The setup allows for measurements of the 3d wind vector.
    - Due to low availability of the short range windscanner, there was no overlapping period for the combined analysis of the short-range and long-range windscanner data.
    - A diurnal cycle of the vertical wake position and the extension of the wake was observed.
    - The data will be available in the NEWA project and a second campaign is following in 2017.
7) Rebecca J. Barthelmie (Cornell University): Quantifying wake characteristics from lidar
    - Challenges and lessons learned from multiple lidar campaigns
    - How to assess uncertainties?
    - Consideration of trade-off between the possibilities of lidars and the purpose of the measurements

Group discussions: What are the objectives of lidar wake measurements?

- David Schlipf summarizes the presentation of the previous session and introduces the following three questions to guide the group discussion:
    1) **Why** do we need lidar wake measurements? For which purpose?
    2) **What** are the objectives of lidar measurements?
    3) **How** should we measure wakes using lidar?

The participants are divided into three groups to discuss the assigned questions. The results are are presented on flip-charts (see

- Attachment 1: Figure 1, Figure 2, Figure 3 and Table 1) in the afternoon session. From the discussion it is concluded that:
    - The scope of lidar measurement of wind turbine wakes is the improvement of wake models. This can be achieved with a better calibration of these models, or some improvements deduced from the better understanding of the wake behavior which can be observed using lidar measurement. The overall benefit is at the end a lower cost of

energy which derived from lower uncertainty in resource assessment, wind turbine and wind farm control and load estimations.

- The objectives of lidar wake measurements can be variegated. It is therefore important to frame the answer to the three questions (why, what and how) into specific use cases, each one addressing different objectives, i.e. the wake shape and position, its recovery rate and expansion, wind farm effect, response to extreme conditions, ...). Besides that, it is very important to measure the inflow conditions of the boundary layer, which will require additional instrumentation.
- As just mentioned, the implementation should be guided by the use cases. Moreover, careful lidar simulations should support the design of an experimental campaign.

Early Afternoon Session [14:00 – 15:30]

Comparative exercise:

Davide Trabucchi: Wake study based on lidar measurements

- Davide presents an exercise to calculate the velocities and their uncertainties measured by a virtual lidar from an LES of a wind turbine wake.
- Comparison of the results by the 4 participants who did the exercise (ForWind- University of Oldenburg, DTU, Zephir & DLR)
- Results mainly differ in the uncertainty estimation.
- Each of the participants explains his approach.
- Discussion about how the uncertainties are defined
- It is decided to create a group that works on exercises to unify the approach to get the wind field from lidar measurements.

How can we collaborate with existing measurement data?

Davide Trabucchi, Lukas Vollmer (ForWind) & Javier Sanz Rodrigo (CENER): Benchmark for wake models based on lidar data

- Presentation of a data set of lidar measurements that were processed for validation with average simulation data
  - Measurements from 2 long range lidar in *alpha ventus* were combined to get a 2D wind field at hub height in a turbine wake (vanDooren et al., 2016).
- Presentation of an approach to create LES data that can be directly compared to the measurements (Vollmer, 2016)
  - To simulate the measured conditions profiles from a meso-scale model are used to get a transient background state in the LES.
- Javier presents how benchmarks for numeric flow models are designed in Task 31.
- Discussion about the suitability of the presented data for a benchmark for wake models
- Plan to prepare a benchmark for wakes simulated with transient LES based on the measurements

Late Afternoon Session [16:00 – 17:30]

How can we collaborate in future?

- The collaboration between the lidar and modeling communities in the near and long term is discussed among groups formed previously
- The results are presented on flip-charts (see Attachment 2: Figure 4 and Table 2). In general the conclusions are:

- The opportunity to work with the data of the experiments presented during the workshop which will be made publicly available should be considered.
- For future campaign it is suggested to design the experiment according to use cases.
- The need of guidelines is identified which could uniform and prescribe how measurement campaign should be designed and how the documentation of the data which could be shared among institutes should be compiled.
- Institutes should cooperate together sharing efforts and experience in a well-defined framework. In this sense workshops could be organized, lessons learned forums could be established, open access software could be shared.
- Existing use cases used to keep experimental campaigns simple and ensure their success. A more specific description of the use cases and their application could facilitate their implementation.
- An overview of the available flow models in terms of application and level of approximation could help to clarify the objectives of measurement campaigns.

Workshop wrap-up and formulation of next steps

From the previous sessions, the following actions can be considered:

1) Select few use cases and define corresponding comparative exercises based on the simulation of lidar measurements in high fidelity wind fields.
2) Define a new benchmark using the *alpha ventus* measurements presented during the workshop. The first attempt will deal with LES and prescribed initial conditions.
3) Extend use cases including recommendations about:
    a. How to document the experimental campaign?
    b. How to process the measurements?
    c. How to format the final data?

Thanks to everybody for organizing as well as participating in the workshop!

Attachment 1

Flip-charts form group discussion 1 on the objectives of lidar wake measurements

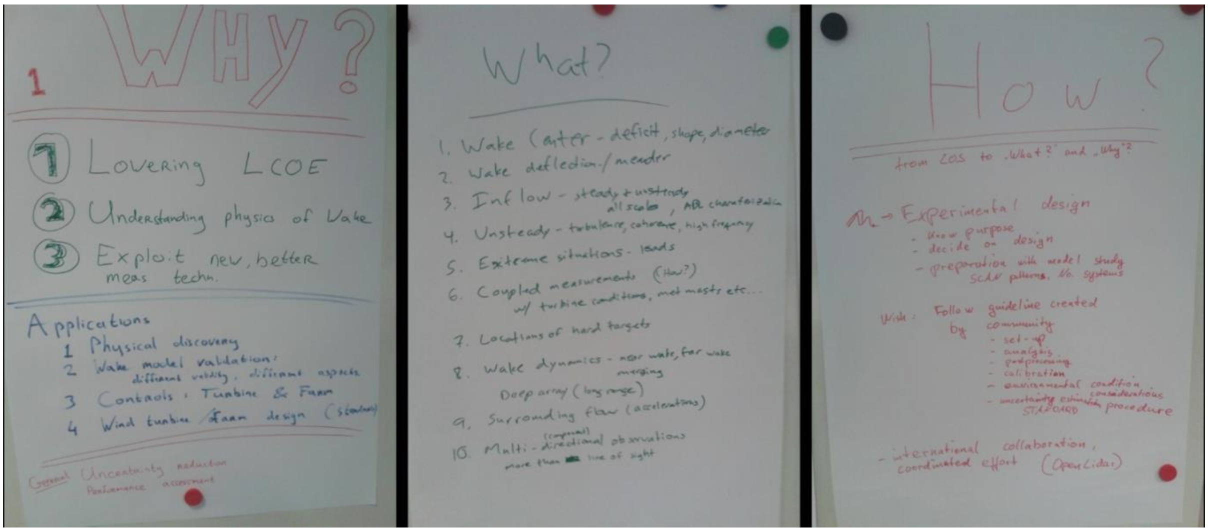


Figure 1: Objectives of lidar wake measurements. Notes of Group 1. (OpenLIDAR)

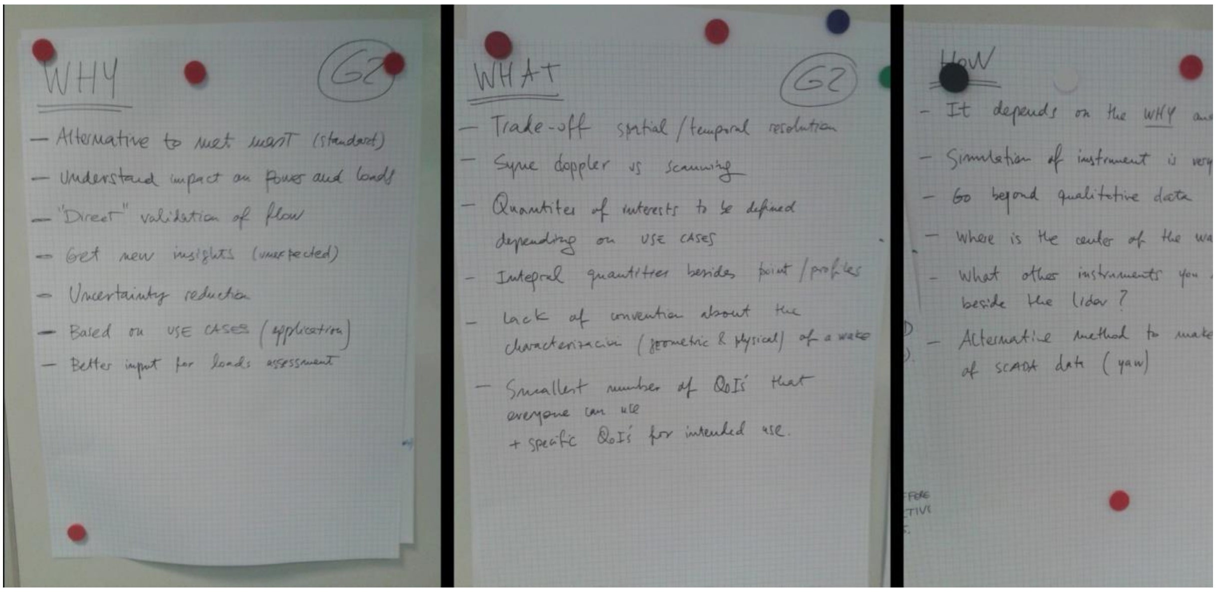


Figure 2: Objectives of lidar wake measurements. Notes of Group 2

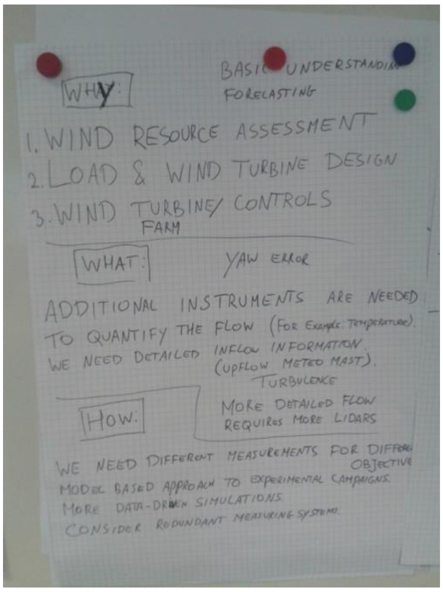


Figure 3: Objectives of lidar wake measurements. Notes of Group 3

Table 1 Results from group discussion on the objective of the lidar measurements

Group	Why?	What?	How?
1	• Low down the cost of energy (wind turbine/farm design, control) • Understand better the physical aspects of wakes (wake model validation) • Exploit new better measurement techniques	• Wake shape (center, shape, diameter) • Inflow (Atmospheric boundary layer, steady and unsteady, all scales) • Extreme situations (load applications) • Wake dynamics (near/far wake, merging wakes) • Deep array effect • Flow around a wind farm (speed-up effect)	• Using additional instrumentation • Concurrent/overlapping multi-directional measurements • Through experimental design (define purpose, prepare with model study of scan patterns, number of systems, other instrumentation) • Follow guidelines created by the community (set-up, calibration, processing, environmental conditions, uncertainty) • International collaborations, i.e. OpenLidar (shared efforts)
2	• Alternative to met. masts • Understand the impact of wakes on power and loads • Direct validation of flow models • Get new insights • Provide a better input for load assessment • Reduce uncertainties • There are specific applications based on use cases	• Trade off (spatial/temporal resolution, synchronized dual Doppler/scanning) • Quantities of interest defined according to use cases • Integral quantities should be investigated besides point and profile measurements • Few quantities of interest which anyone can use and few specific ones for dedicated use • The center of the wake	• How depends on why and what • Simulation of the measurements provide a useful support • Go beyond qualitative data • Use additional instrumentation to lidar • Apply alternative methods to make sense of SCADA data
3	• Basic understanding of wakes to improve models used for wind resource assessment, wind turbine/farm design and control	• Inflow (Atmospheric boundary layer conditions) • Yaw misalignment • Wake center position • Wake recovery rate • Wake diameter	• Different measurement setups are needed for different objectives • Consider redundant measurement systems • Data driven simulations (implement lidar

	• Forecasting power production		measurements directly in the wake models) • Additional instrumentation is needed to characterize the inflow • Model based design of the experimental campaign

(Note that the items listed here do not necessarily represent a consensus of all workshop participants.)

Attachment 2

Flip-charts form group discussion 2 on the future collaboration of the lidar and modeling communities

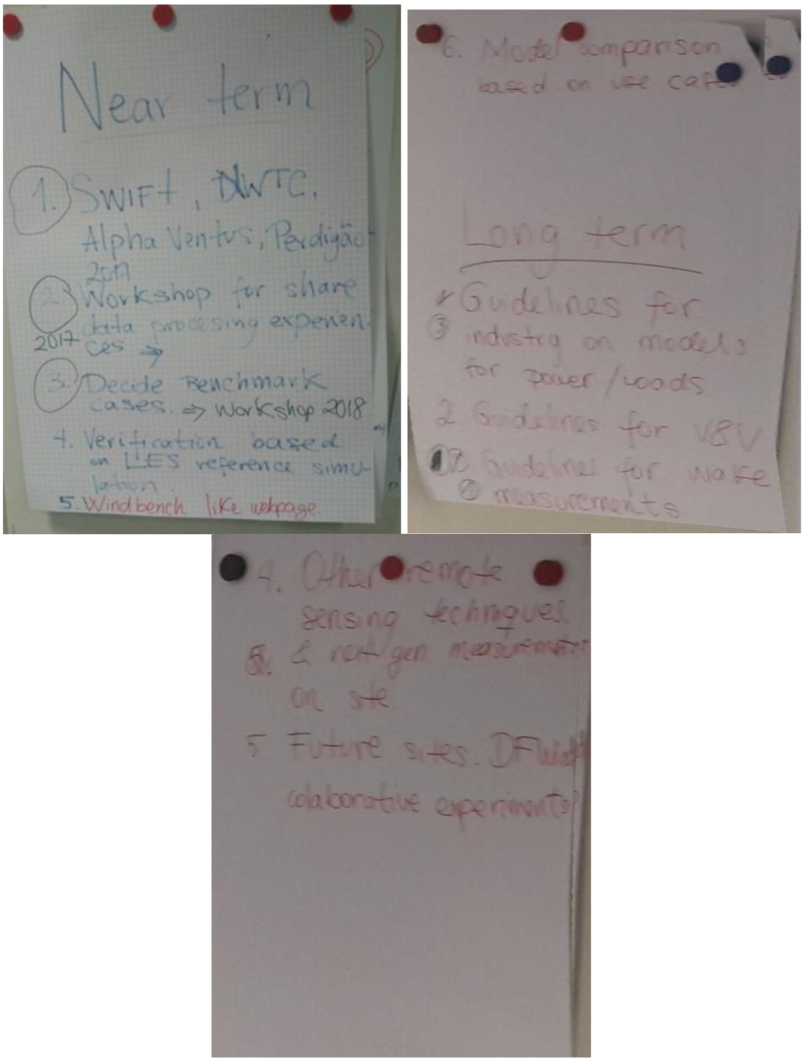
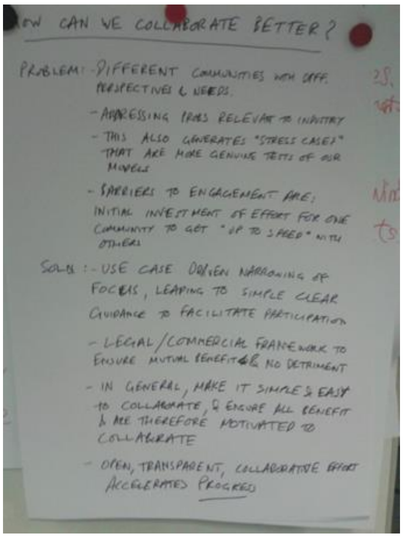


Figure 4: How can we collaborate in the future? From left to right, notes of group 1

Group 1	Group 2	Group 3
Near term **1** Using data available from concluded experiments (SWIFT, NWTC, *alpha ventus* 2014, Perdigão 2017) **2** Workshop to discuss how the experience with the shared data **3** Define benchmark cases **4** Verification based on LES wind fields used as reference **5** Website like windbench **6** Model comparison based on use cases Long term **1** Guidelines for wake measurements **2** Guidelines for Verification and Validation experiments **3** Guidelines for industry on wake models for power/load prediction **4** Other remote sensing technology **5** Collaborative research	Some problems need to be addressed: • Different communities have different perspective and needs • Deal with cases relevant for industry which could be genuine stress cases for the flow models • Barriers to engagement due to gap in background knowledge Possible solutions: • Define and apply use cases (narrowing focus, simple and clear guidance, facilitate participation) • Legal and commercial framework to ensure mutual benefit and no detriment • Keep it simple and easy • Open, transparent and cooperative efforts to accelerate the progress	• Focus on available data and future campaign (SWIFT, NWTC, alpha ventus 2014, Perdigão 2017) • Be very specific on the measurement • Define a guidance for sharing data (measurement protocol, data documentation) • Prepare an overview of the available flow models in terms of application an physical approximation • Open source tools for data analysis (filtering, wind reconstruction) • Establish a lessons learned forum



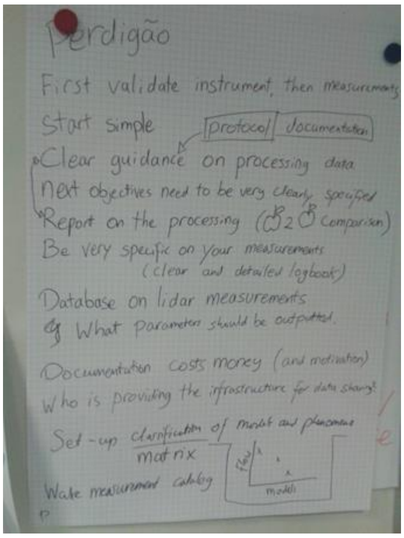


Figure 5: How can we collaborate in the future? From left to right, notes of groups 2 and 3