WIND POWER | WEATHER & CLIMATE | AVIATION WEATHER | AIR QUALITY & INDUSTRIAL RISK

High-Frequency Wind Retrieval Algorithms from Nacelle-Mounted Lidars for Wind Turbine Control Applications

Leosphere

National Renewable Energy Laboratory

Stuttgart Wind Energy

David Schlipf, Paul Mazoyer, Matthieu Boquet,
Steffen Raach, Andrew Scholbrock, Paul Fleming

18th International Symposium for the Advancement of Boundary-Layer Remote Sensing (ISARS'2016)
Varna, Bulgaria
June 6 – 9, 2016
NREL/PR-5000-66701

Motivation

- Enhanced turbine control opens the door for better performances and reduced fatigue increasing dramatically the efficiency of wind turbine.

- Very short-term prediction of wind speed is crucial for optimized controller performances.

- Lidar integrated to turbine offers great potential to capture upwind and to feed turbine controller with the best information to achieve high performance control.

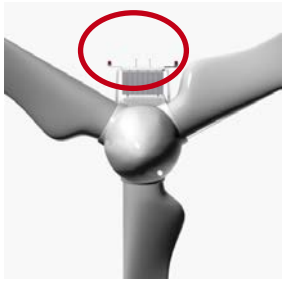
Overview

- Introduction to Wind Turbine Control
- Nacelle-Mounted Lidar
- Measurement Campaign
- High Frequency Reconstruction Parameters
- Results and Summary

Introduction to Wind Turbine Control

Wind Turbine Control

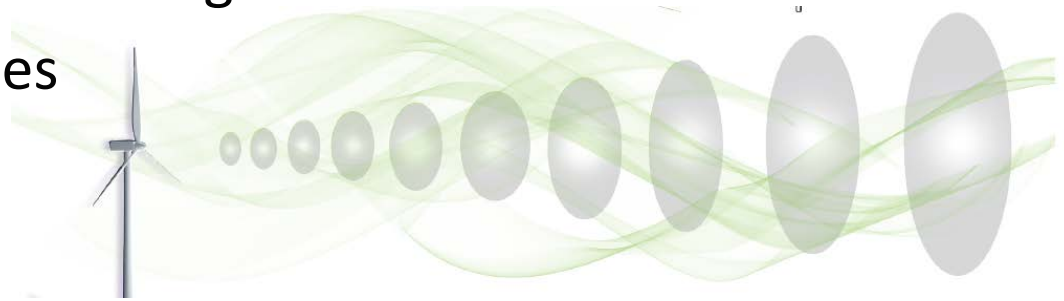
Current Control Strategy



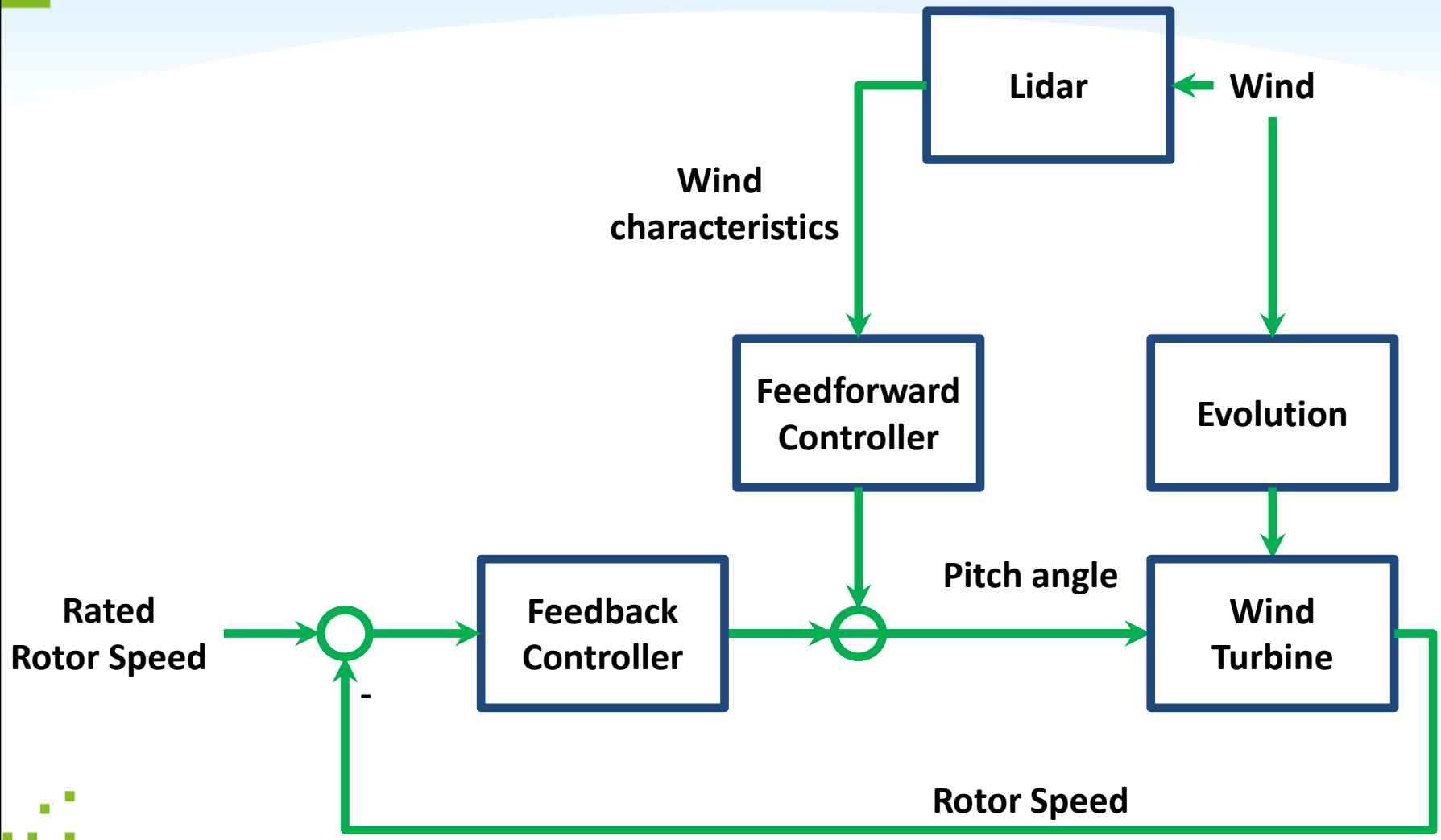
- Wind measurement on nacelle only usable for yaw control
- Turbine reacts after changes in wind already impacted on the structure

Lidar-Assisted Control Strategy

- Wind sensing ahead of each turbine
- Turbine reacts better to wind gusts
- Fewer loads on turbines



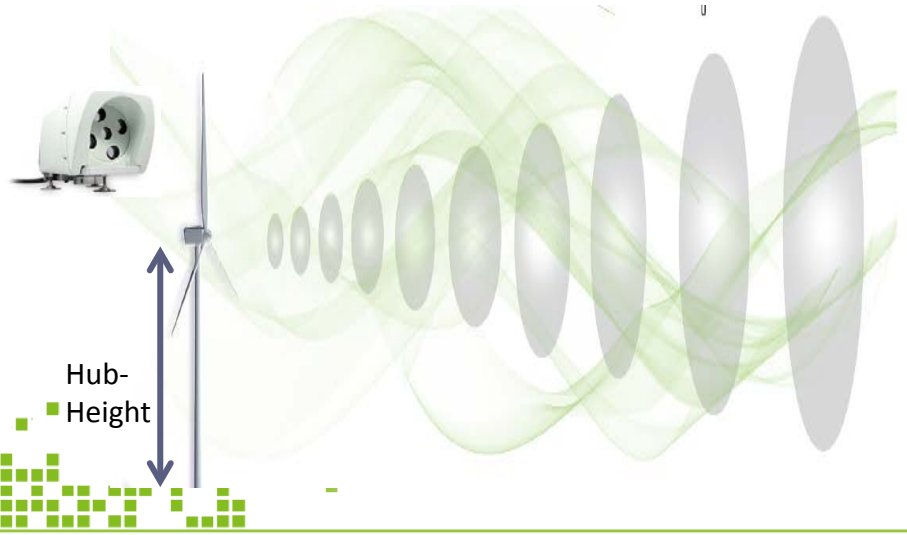
Collective Pitch Feedforward Control

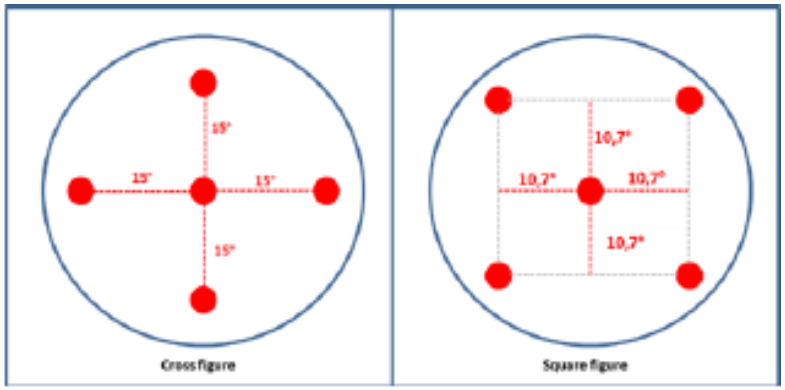


Nacelle-Mounted Lidar

Avent Nacelle-Mounted Lidar

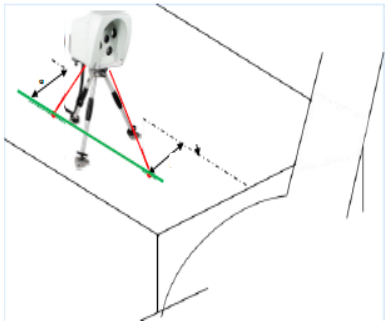
- Pulsed Doppler Lidar
- Customized beams (4 or 5) : Opening angle are either 30° and 21.4°
- 10 simultaneous range-gates : minimum 50, maximum 400
- 4 Hz measurement
- Customization of the Lidar for turbine control to match the turbine manufacturers requirements





Calibration and Installation

- Lidar is calibrated against a reference
  - Comparison to reference Lidar for 10 minutes data to ensure consistency of data before mounting
- Lidar needs to be aligned with the yaw of the turbine



Measurement Campaign

NREL Campaign

TURBINE

- CART2 Research Turbine : 36.7 meters tall
  - National Wind Technology Center (Colorado, USA)
  - Two-bladed
  - Variable-speed variable-pitch
  - 42.7 m rotor
  - 277 kW (nominal 600 kW)
  - 36 rpm (nominal 41.7 rpm)
  - 10 ms^{-1} rated wind speed
  - Heavily instrumented

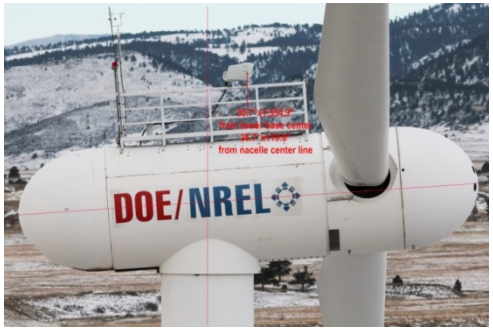
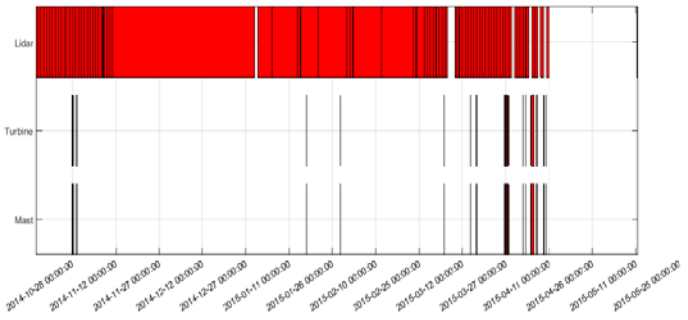


Photo Credit: Lee Jay Fingersh, NREL 33621

MAST

- Met-mast : 58 meters tall
  - Wind sensors at 27 m, 38 m & 58 m
  - Direction sensors at 27 m, 38 m & 58 m
  - Temperature sensors
  - 85 m from the CART2 turbine (293°)
  - 4 Hz data

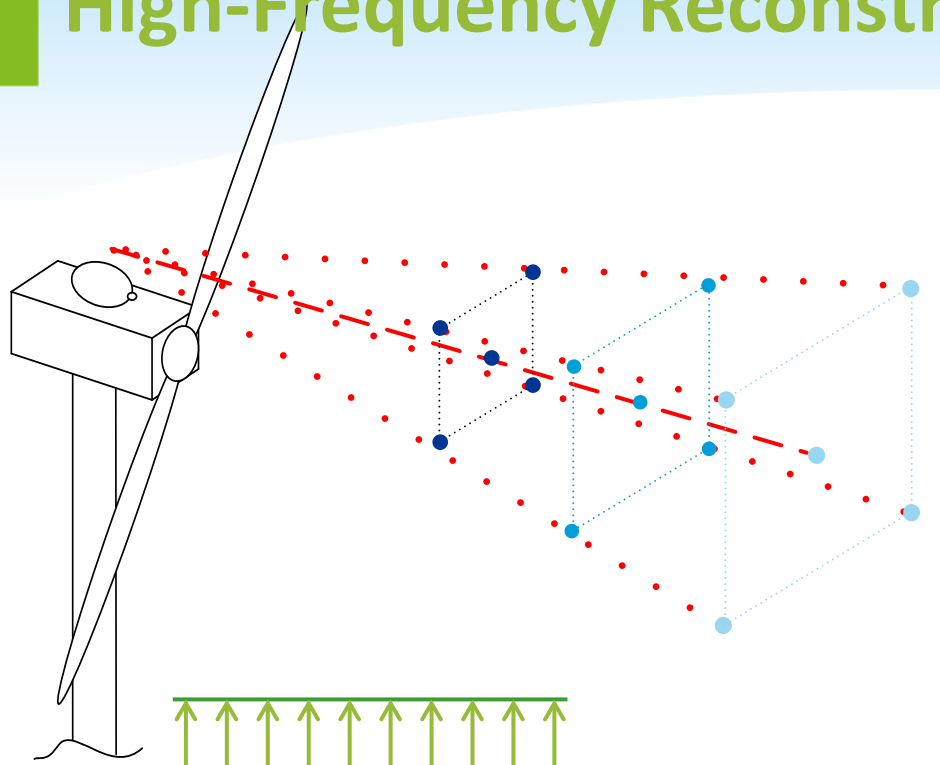


Timeline of the collocated data

Considered data : 2 days

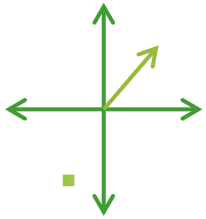
High-Frequency Reconstruction Parameters

High-Frequency Reconstruction



RAWS

Shear



Direction

- wind characteristic relevant to Wind Turbine Control
  - Primary wind characteristic
    - Rotor averaged wind speed
  - Secondary wind characteristic
    - Horizontal wind speed
    - Horizontal wind shear
    - Vertical wind shear
    - Horizontal wind direction
    - Vertical wind veer
    - Turbulence intensity

Different windows for different wind characteristics

Radial wind speed
Radial wind speed status

- *At time t*
- *For each range*
- *No tilt/roll used*

0 sec

Rotor averaged wind speed

Averaging time

T1

Upper beam wind speed
Lower beam wind speed
Horizontal wind speed, vertical shear

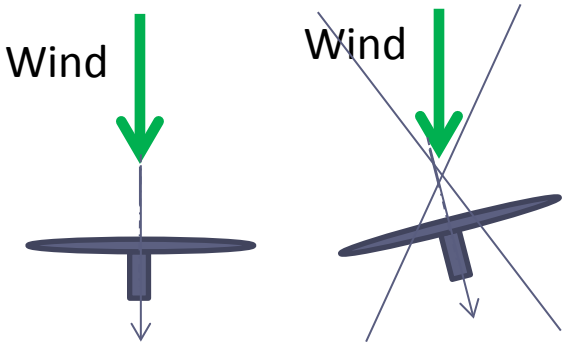
+ horizontal wind shear

T2

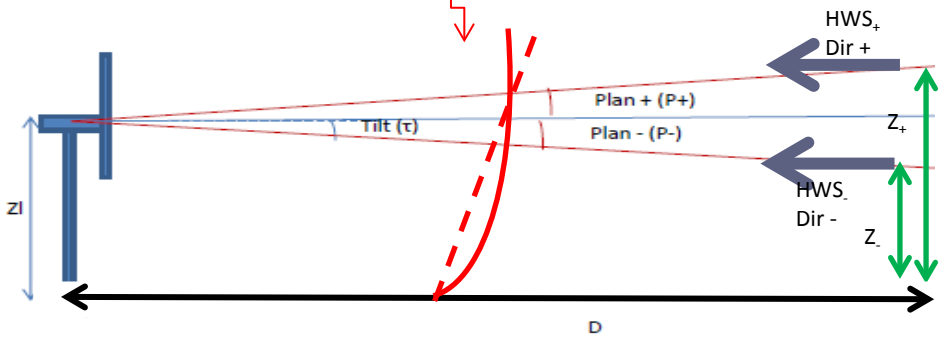
Upper beam wind direction
Lower beam wind direction
Horizontal Wind direction, veer

T3

Turbulence intensity for each beam



Turbine facing wind



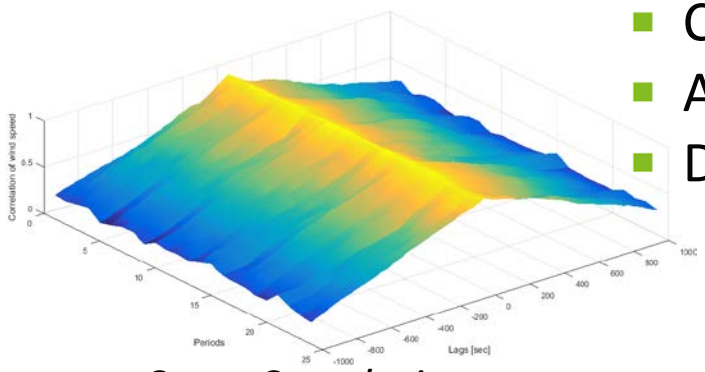
Assumptions on wind profile

Results and Summary

Data Selection and Synchronization

Site layout

Signal	Constraint
Turbine yaw	>285° and <315°
Wind direction from mast	>285° and <315°
Temperature	>0,1°
Wind speed from mast	>3 m/s

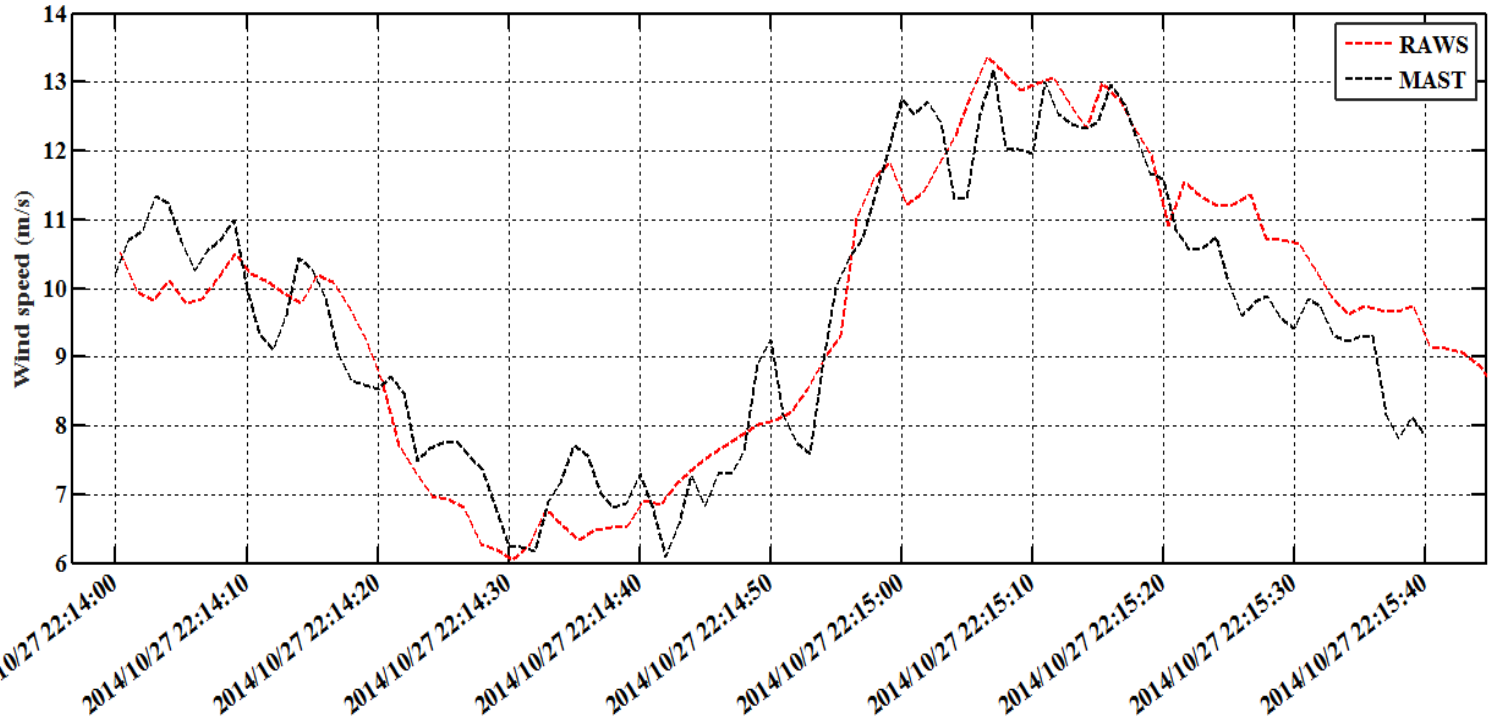


Cross Correlation between mast and Lidar

- Considered distance: closest to met mast
- After all filtering 250 000 -> 9305 samples.
- Data synchronization:
  - No bias
  - Peak of cross correlation within 10-second spread

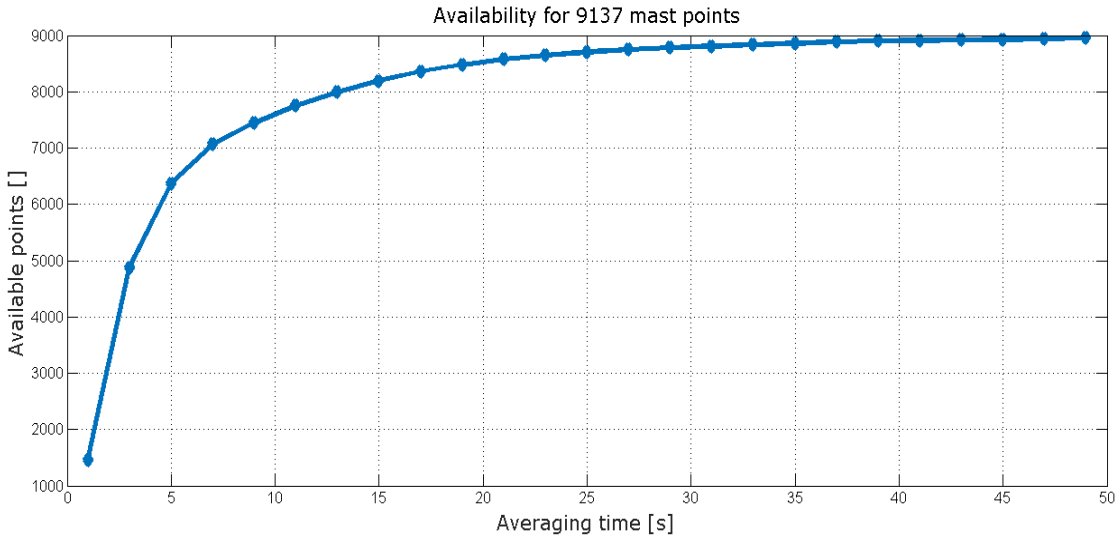
Results Primary Wind Characteristic

- RAWS reconstruction compared to a met-mast



Results Secondary Wind Characteristics

Several averaging times are compared

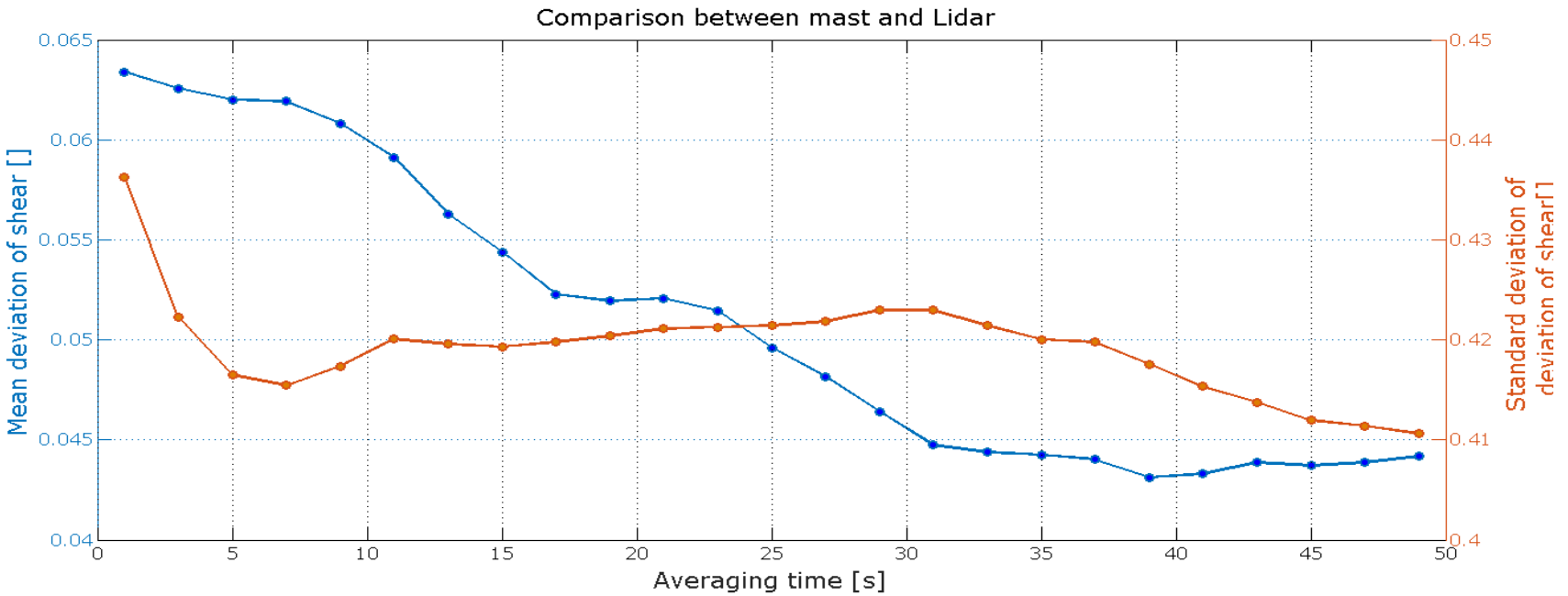


Averaging time [s]	Availability
0	16%
2	54%
4	71%
6	79%
8	83%
10	87%
12	89%
14	92%
16	93%
18	95%
20	96%
22 -> 24	97%
26 -> 32	98%
34 -> 46	99%
48	**100%**

- **Horizontal wind speed requires all five radial wind measurements be available**

Results Secondary Wind Characteristics

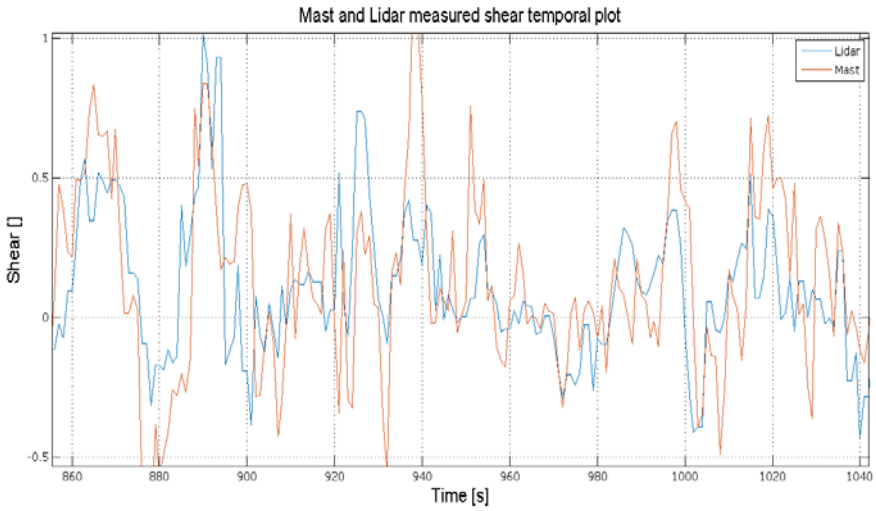
Several averaging times are compared

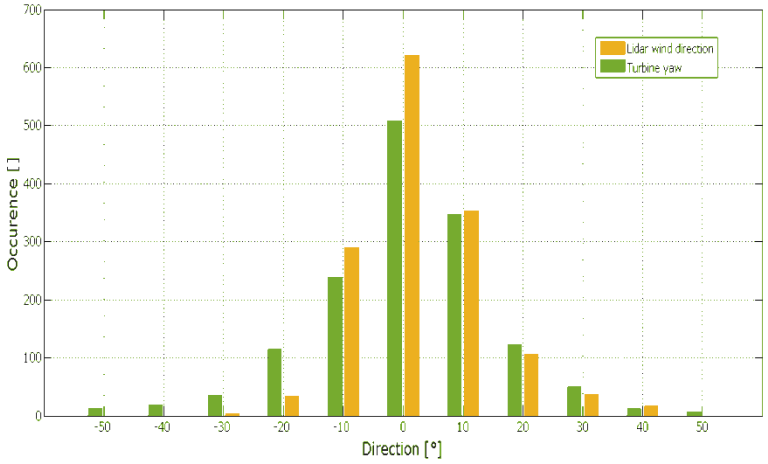


- Mean error gets lower with increasing averaging time :
  -> **Accuracy** increases with averaging time : **expected**
- Slight optimum for std of deviation at 5 seconds then increase with averaging time to 31 seconds then decrease :
  -> **Precision** has an optimum : **to be studied.**

Results Secondary Wind Characteristics

- From several campaigns, an optimum averaging time is identified: 20 seconds

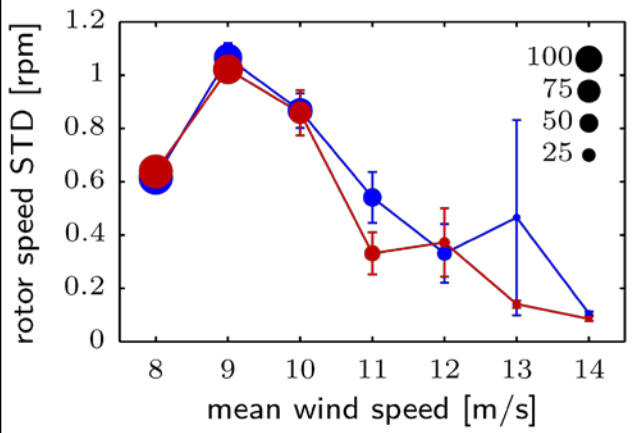


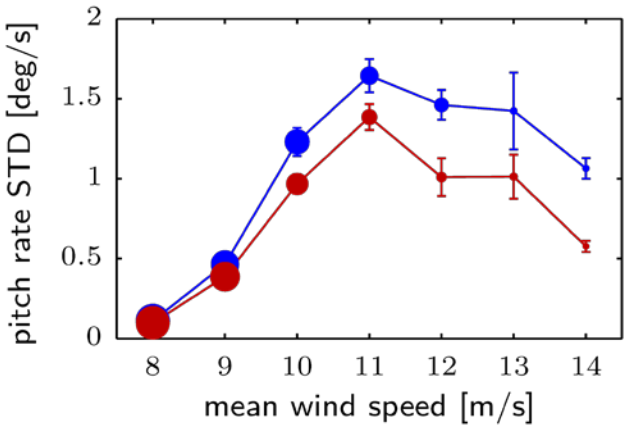


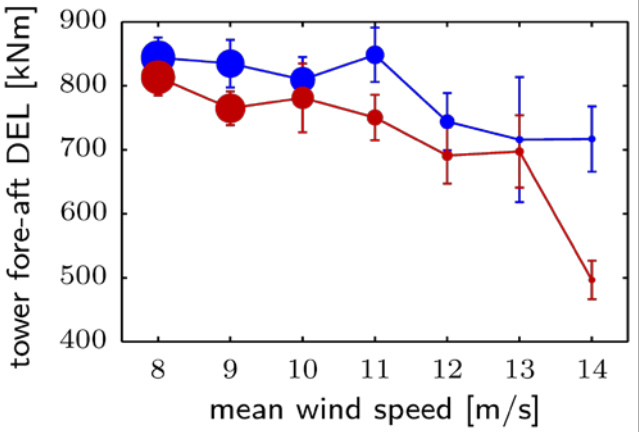
- **Vertical shear reconstructed at 1Hz shows good fit.**
- **For wind direction, accuracy is high but precision low due to synchronization between Lidar, turbine and mast.**

Effect on Wind Turbine Control

- Actual load measurements were undertaken when Lidar is plugged and unplugged using RAWS (from SWE Gateway)
- Decreases in tower loads and pitch activity is observed thanks to lidar FF.





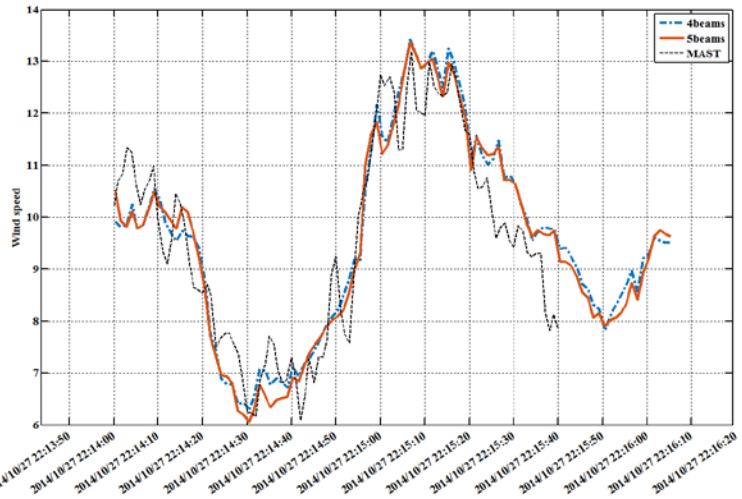


Blue curve is Lidar unplugged
Red curve is Lidar plugged

D. Schlipf, P. Fleming, S. Raach, A. Scholbrock, F. Haizmann, R. Krishnamurthy, M. Boquet, P. W. Cheng, *An Adaptive Data Processing Technique for Lidar-Assisted Control to Bridge the Gap between Lidar Systems and Wind Turbines*, Scientific Track of European Wind Energy Association Annual Event (EWEA), Paris, France, November 2015.

Effect of Number of Beams?

- The RAWS is estimated from the 4-beam and 5-beam (from the same dataset) and compared to the met-mast.



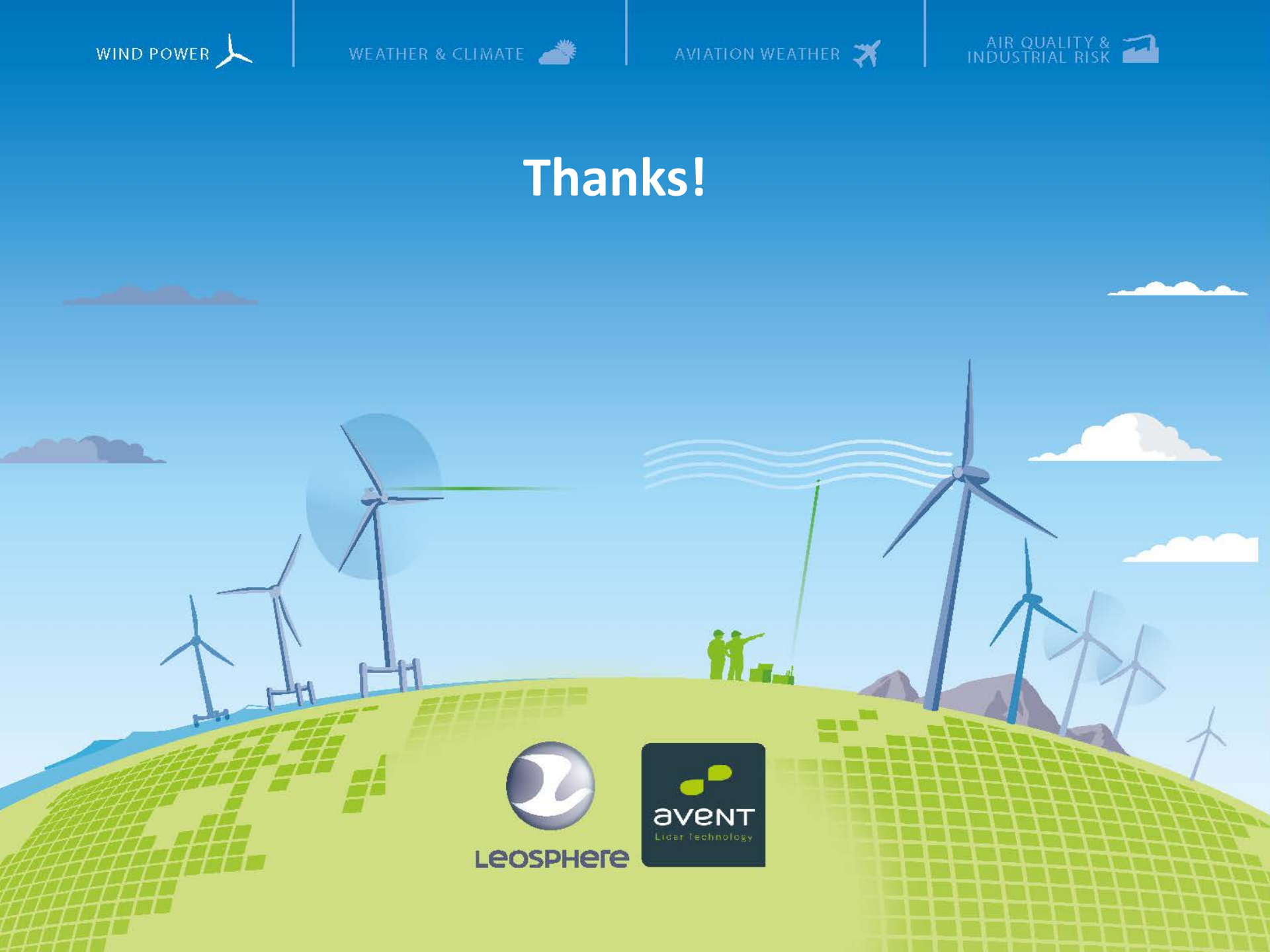
- This shows good correlation with the met-mast, in both conditions and no significant change compared to 4-beam and 5-beam RAWS

Summary

- Results from internal lidar data processing have been compared to met mast data
- Primary wind characteristic are averaged over shorter time and can be used directly for control
- Secondary wind characteristics such as wind shear and wind direction are averaged over 20 s and show good agreement with met mast and turbine

WIND POWER | WEATHER & CLIMATE | AVIATION WEATHER | AIR QUALITY & INDUSTRIAL RISK

Thanks!



External Validation of Rotor Averaged Wind Speed (RAWS)

- The RAWS from the 5-beam measurements was compared to wind speed estimator from turbine and mast data at the NREL site by DNV-GL.