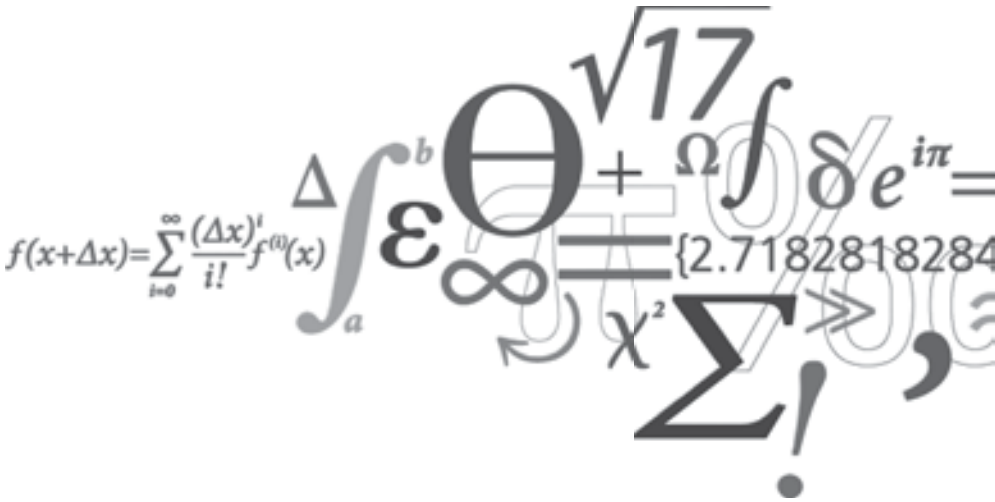
Wind Turbine Inflow and Wake Measurements Using Scanning Lidar: "WindScanners"

Torben Mikkelsen

2018 Sandia Blade Workshop
August 28-29, 2018
Lubbock, Texas



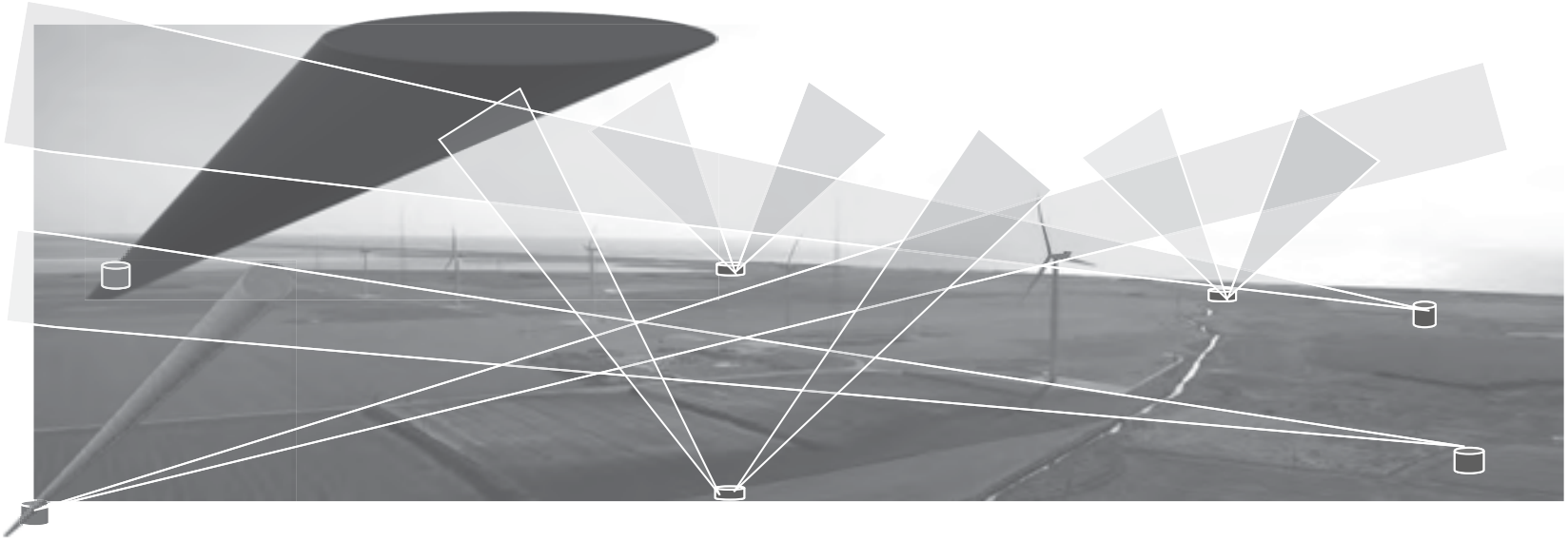
DTU Wind Energy
Department of Wind Energy

The Need for Wind Lidar Measurement Technology …

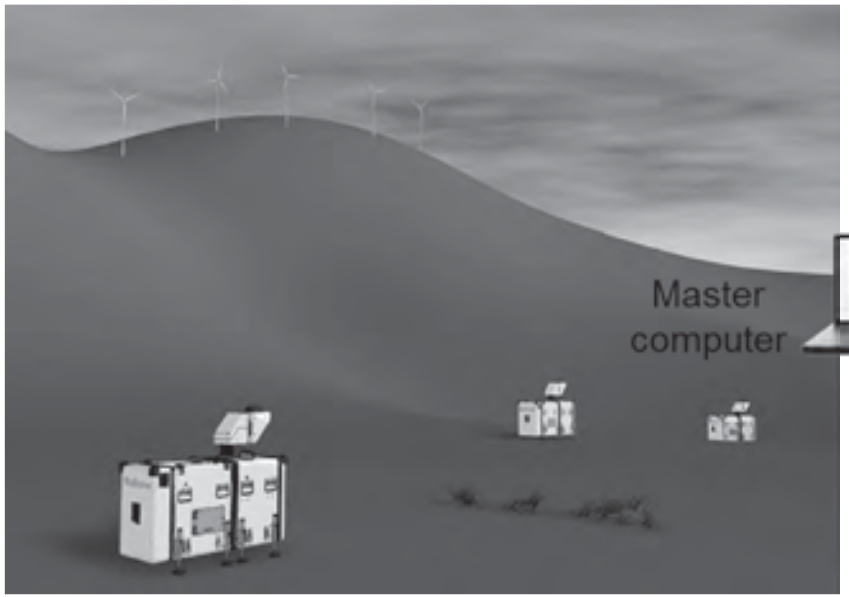
Our "WindScanner Vision" 2007:

Remote sensing based 3D mean and turbulence wind field measurements around future huge WT's

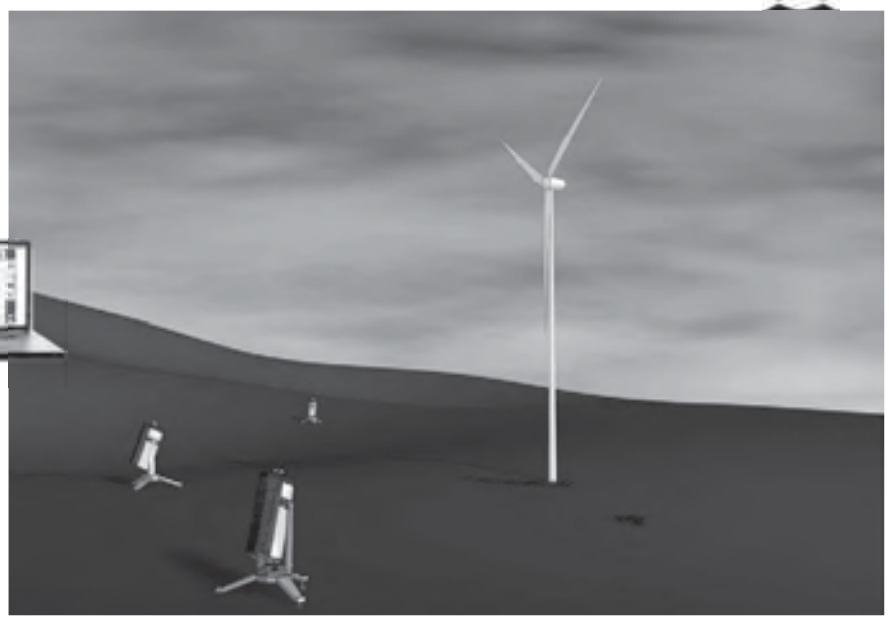
Picture: Test site Høvsøre, Denmark:



WindScanner.eu



Long-range WindScanners map 3D wind fields around entire wind farms



Short-range WindScanners map 3D mean and turbulence fields around single wind turbines

SpinnerLidars for advanced WT control

WindScanner evolution:

From new Wind Lidar Technology towards new Wind Energy Research Infrastructures…:

First CW Wind lidar 2004

MusketeerEX 2007/2008

SpinnerEX 2009

WindScanner. dk2010-2013

En marche…

EU ESFRI Road Map 2010 ff

RI focus

Scientific focus

Technical focus

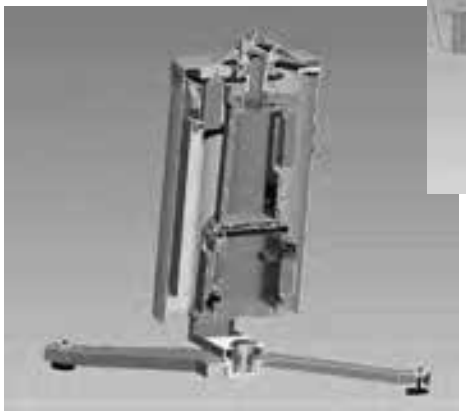
MusketeerEx-II:

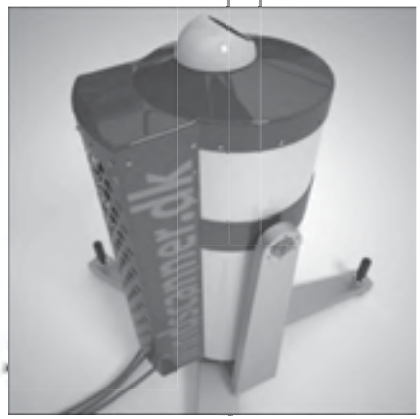
Høvsøre Dec. 2008 Windscanner lidar test

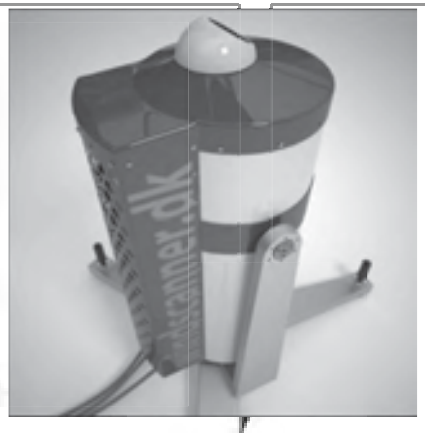
Spatial-resolution improved "Stretch Pod" Unit 107 (left) vs. Windscanner Unit 120 (right)

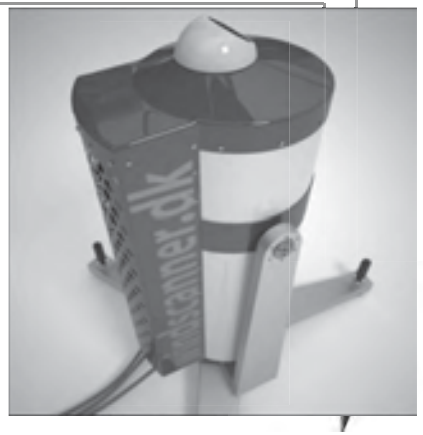
WindScanner.dk: 9-axes time and space control system:

Syncronization and trajectory-coordinated steering of 3 x 3 axes:





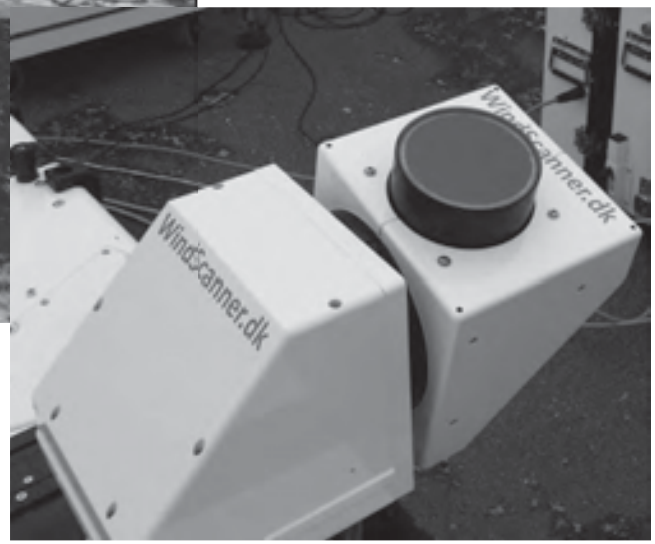




2015 Contineous wave (CW)
6” Telescope SR WindScanner ver. 2.0
Focal range 20 - 300 m

WINDSCANNER OVERVIEW

Long range Wind Scanners synchronously operating to measure wind speeds



(1)

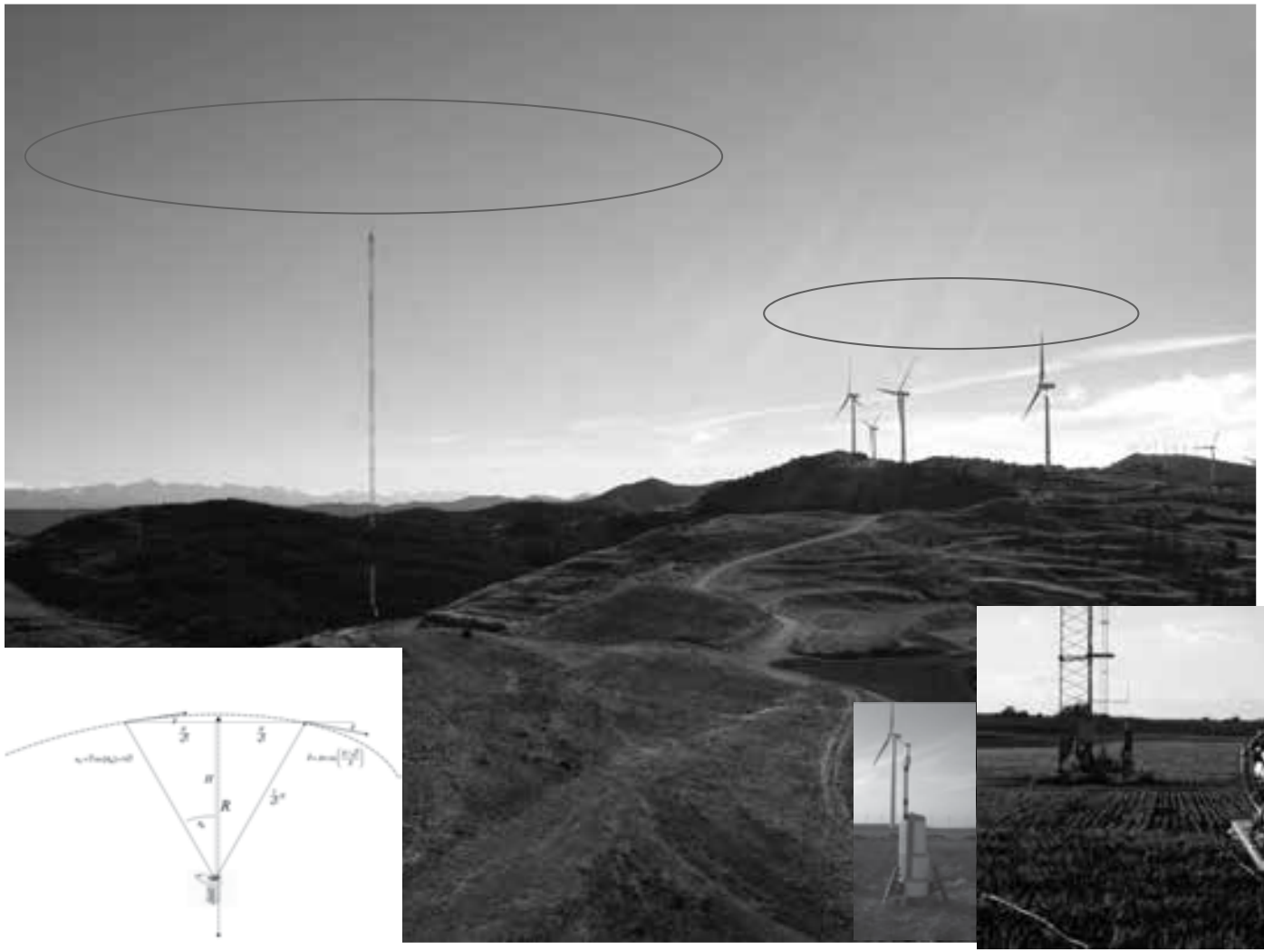
VISION I:

Full scale off and on shore measurements on WT arrays & wakes

e.g. as here at Horns reef

2

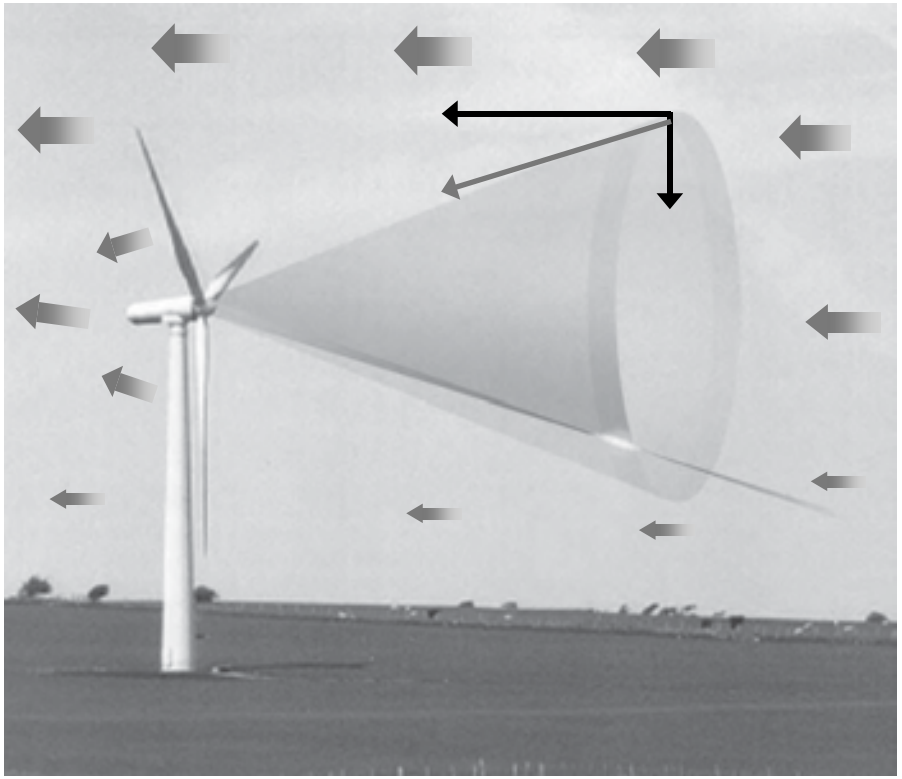
Vision II: RI Windscanner
Secure wind resource estimation in particular in complex terrain

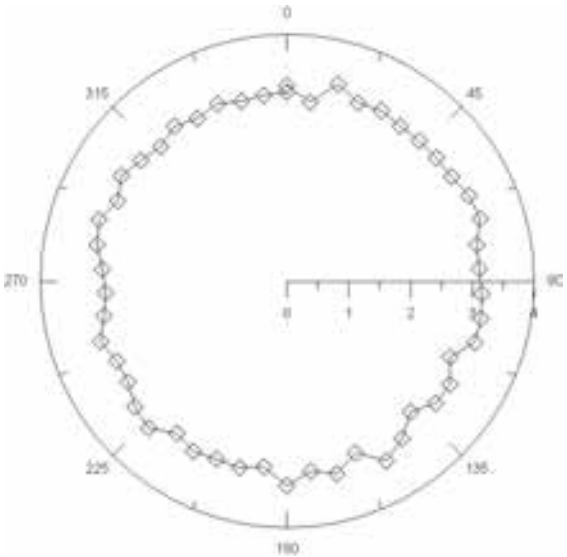


(3)

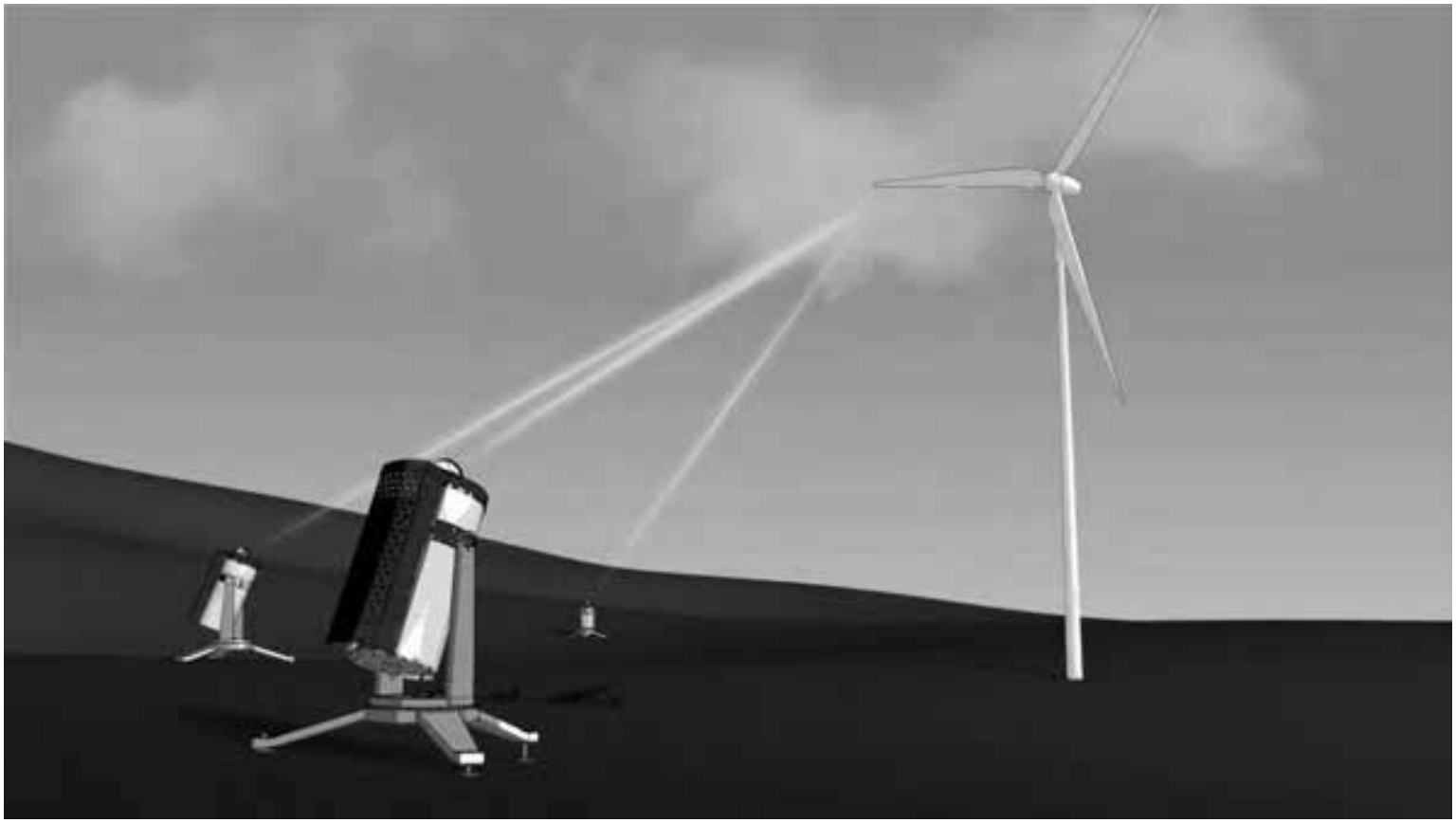
VISION III

Pro-active wind turbine control from upwind measurements by lidars integrated in the nacelle… :

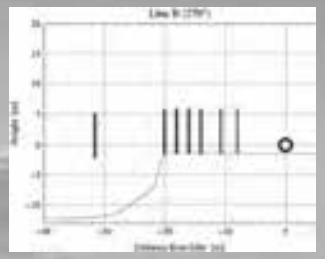


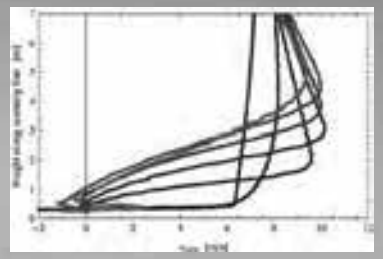


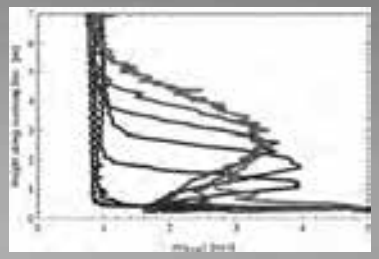
Short-range WindScanners (cw)



Mean wind and turbulence above a steep 12-m high escarpment at the small isolated Bolund peninsula in the Roskilde fjord



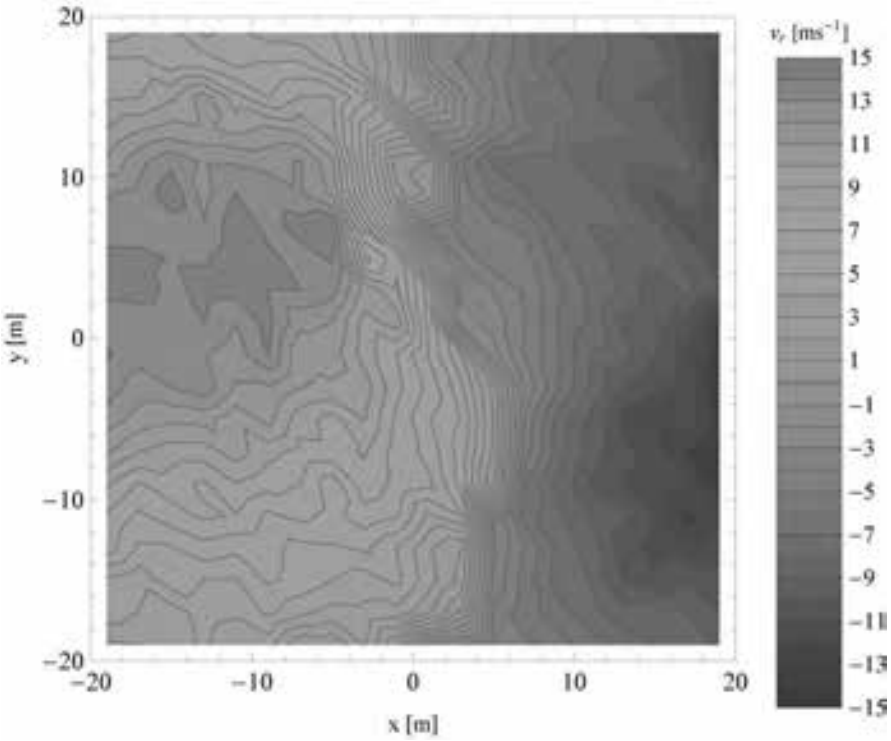




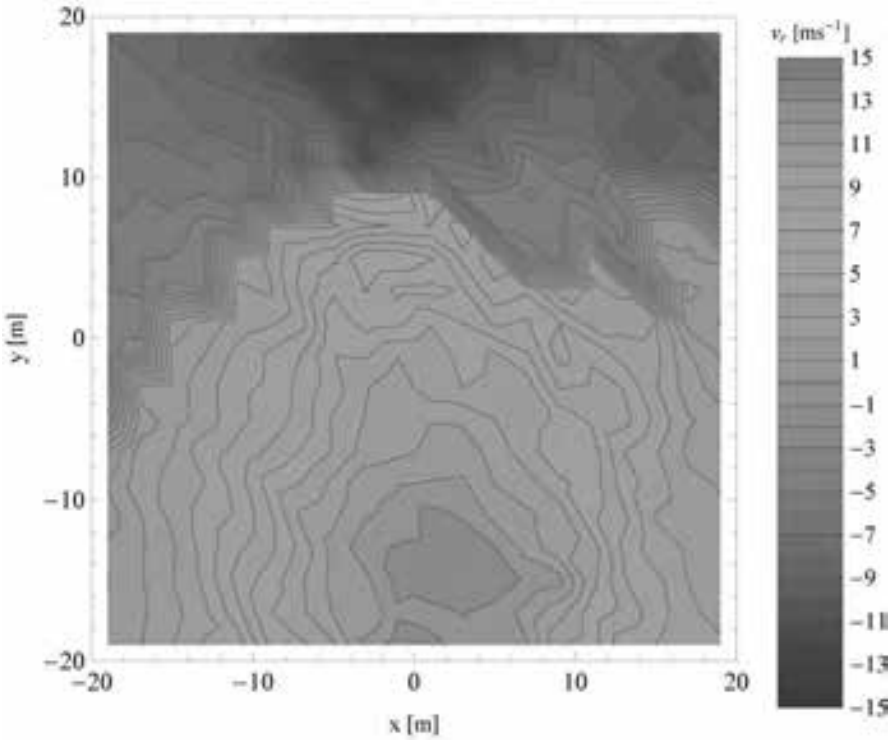
Norwegian offshore rescue helicopter (Sea King 20 ton)

Horizontal scanning Pre-trial :2011-12-06

5 MINUTES AVERAGE:

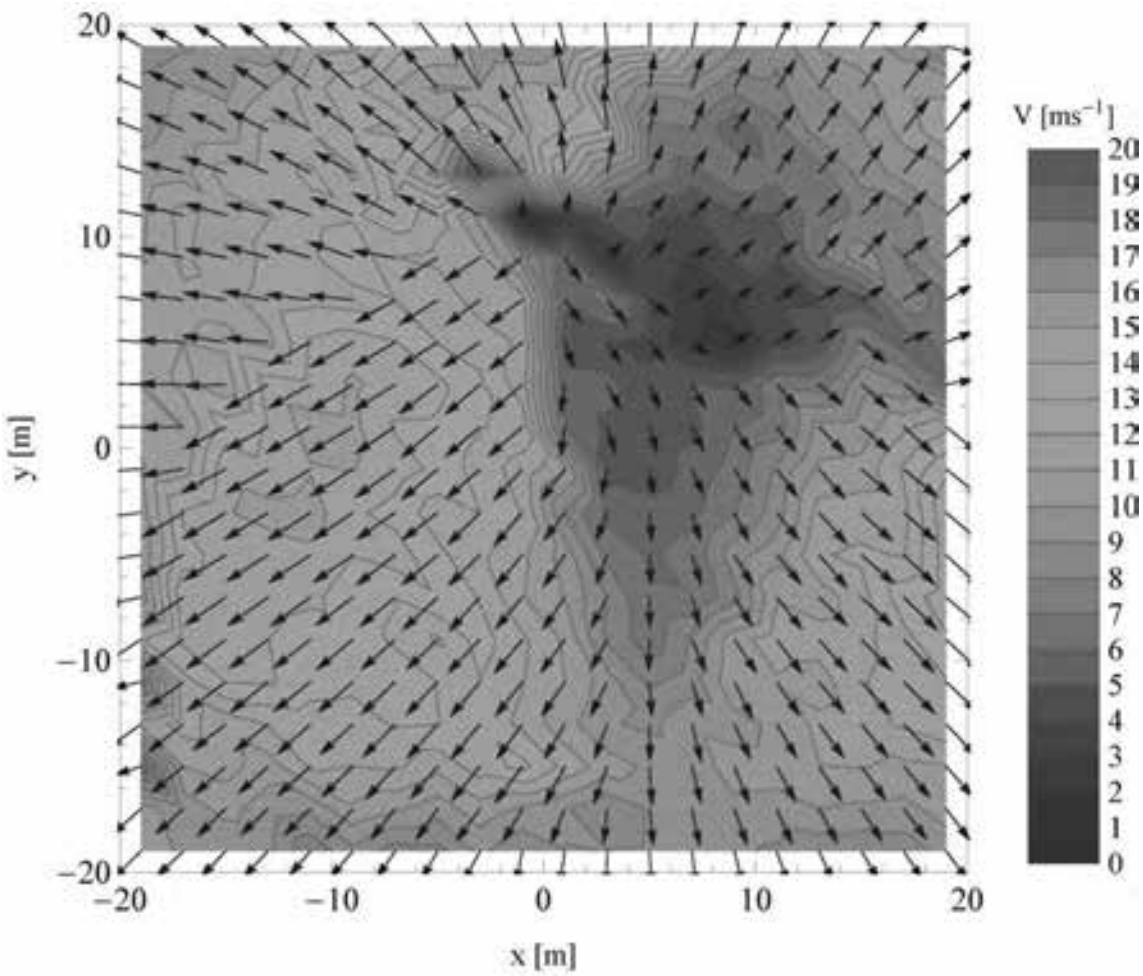


R2D1



R2D2

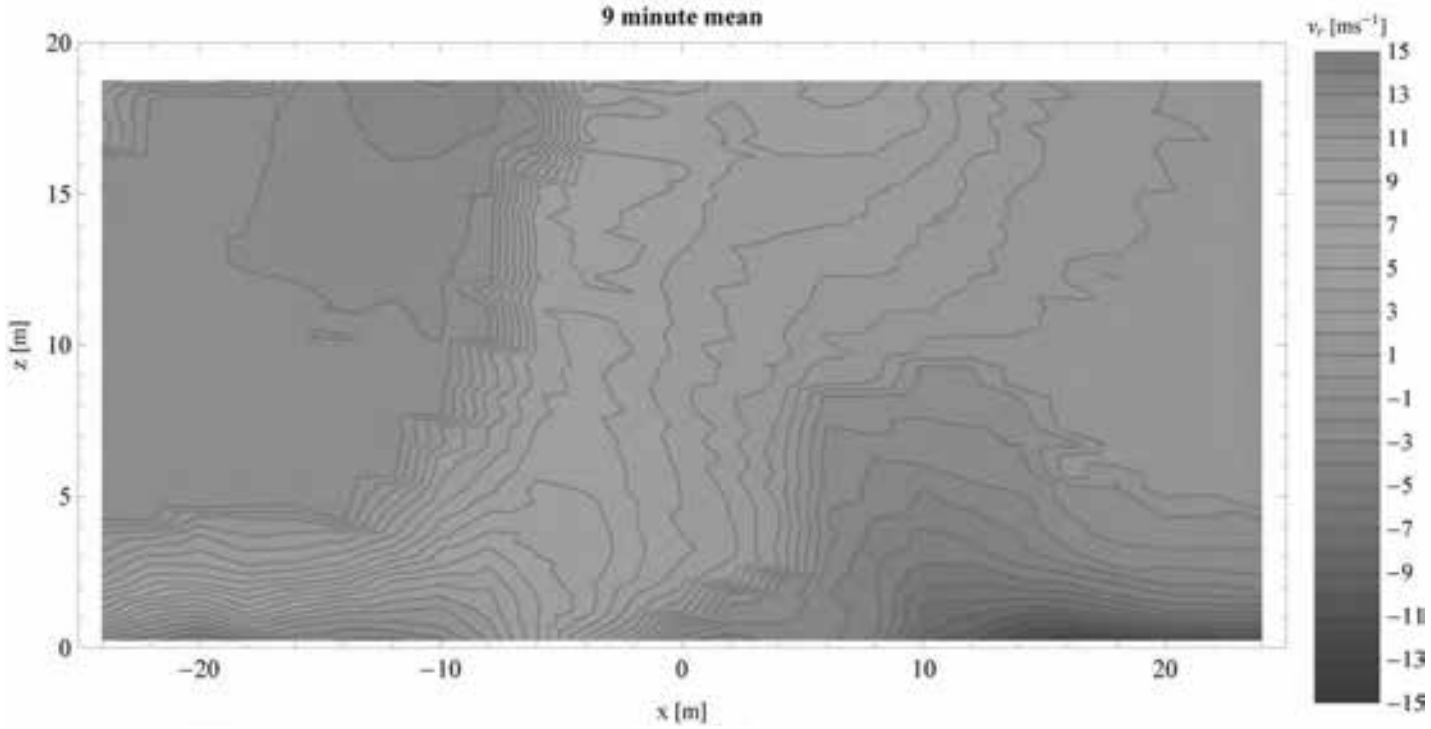
5 MINUTES AVERAGE
Resulting Wind Vector Plot:



Vertical scanning
R2D1 & R2D2: Time 16:50-17:00 2011-12-07

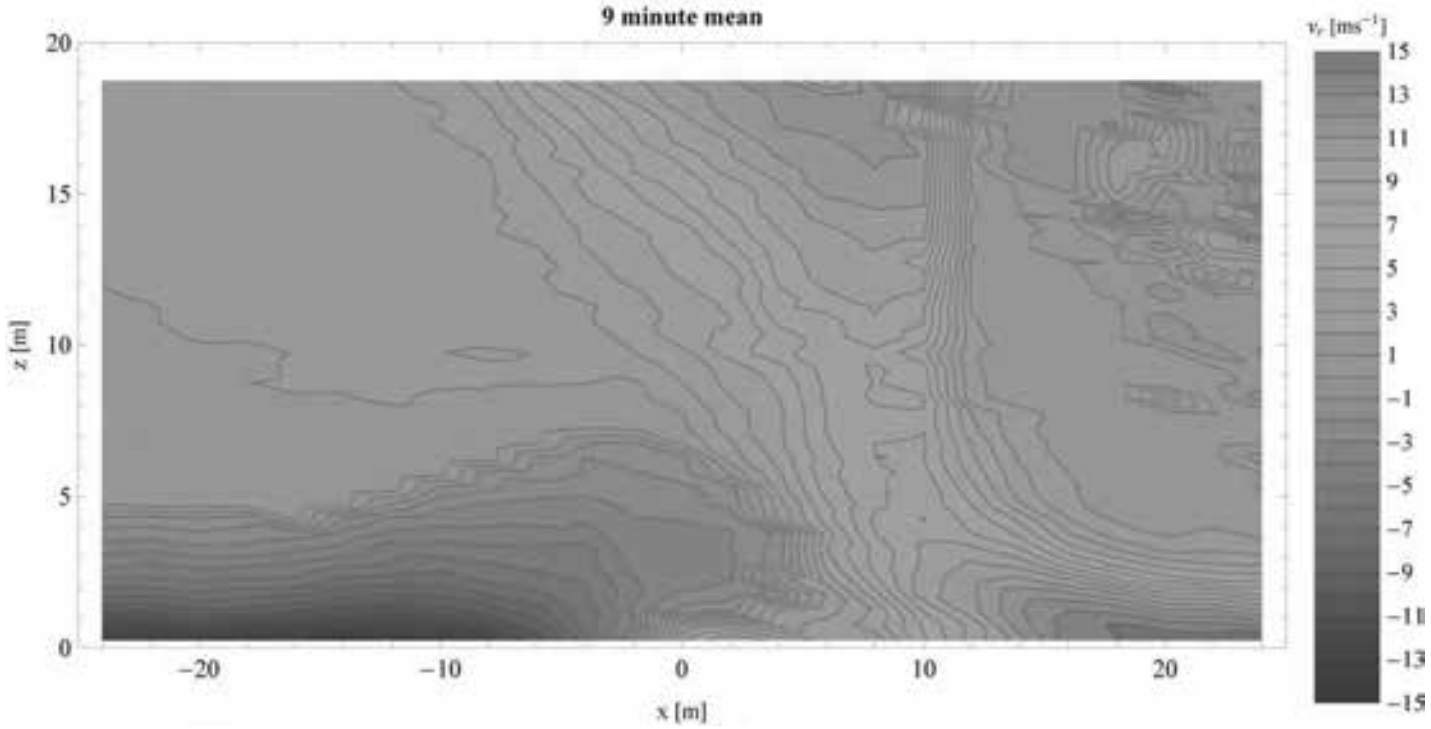
Vertical Scan (9 minute average)

R2D1



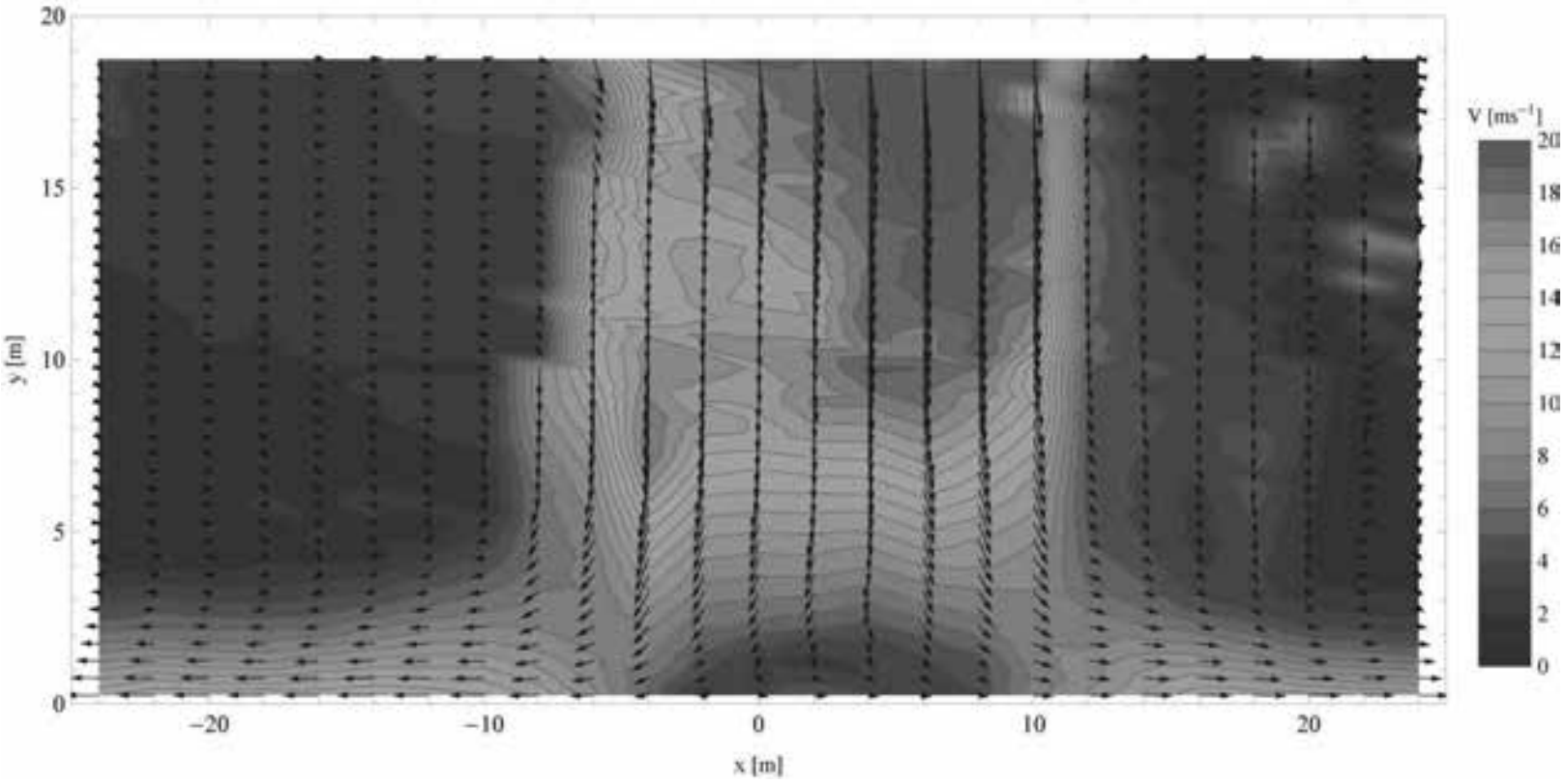
Vertical Scan (9 minute average)

R2D2



Vertical Scan (10 minute average):

R2D1 and R2D2 vertical scans – Combined to final 2D vertical plot:

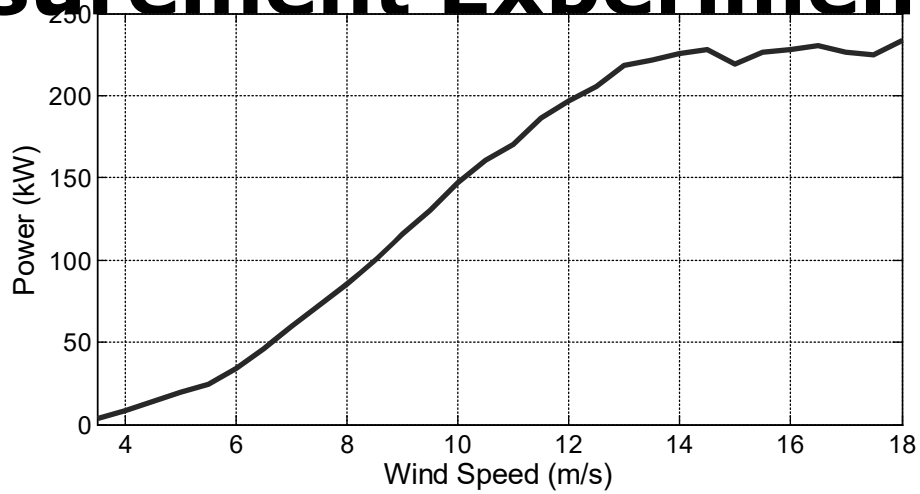


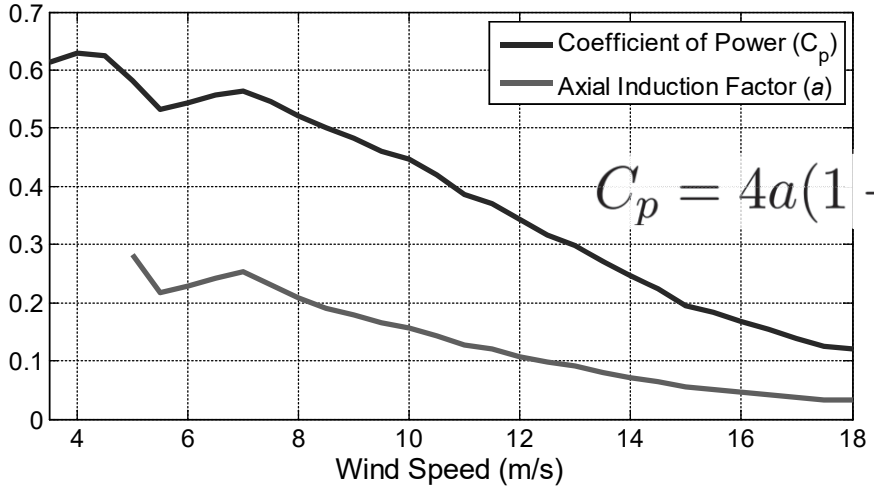
V27 Inflow Measurement Experiment Spring 2014

DTU Wind Energy Short Range WindScanners based on ZephIR continuous-wave lidars with programmable prism and focus motors

- Focus distance: 10 m – 200 m
- Can measure any point within 60° of center direction
- Velocity measurements at 100 Hz

V27 Inflow Measurement Experiment



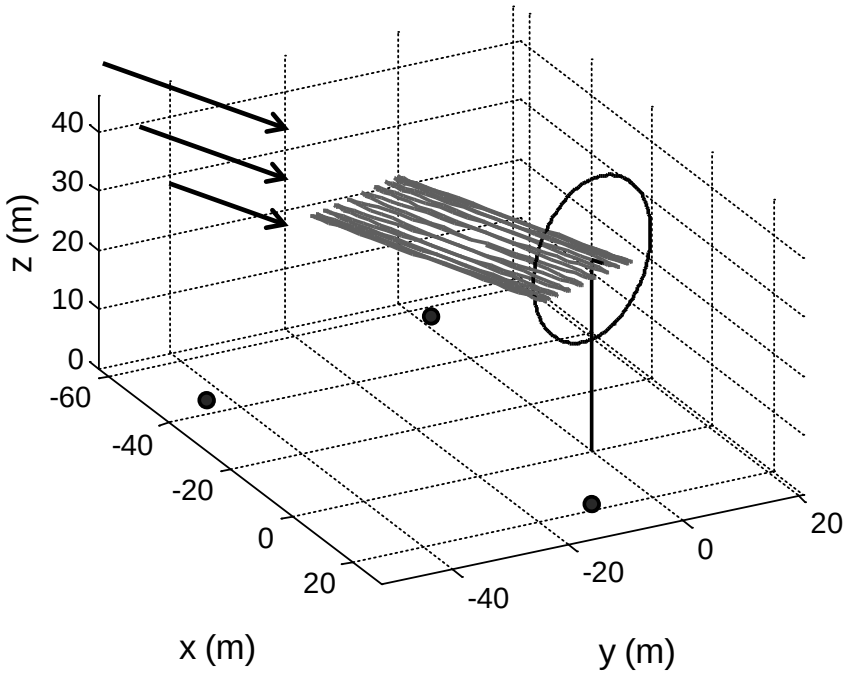


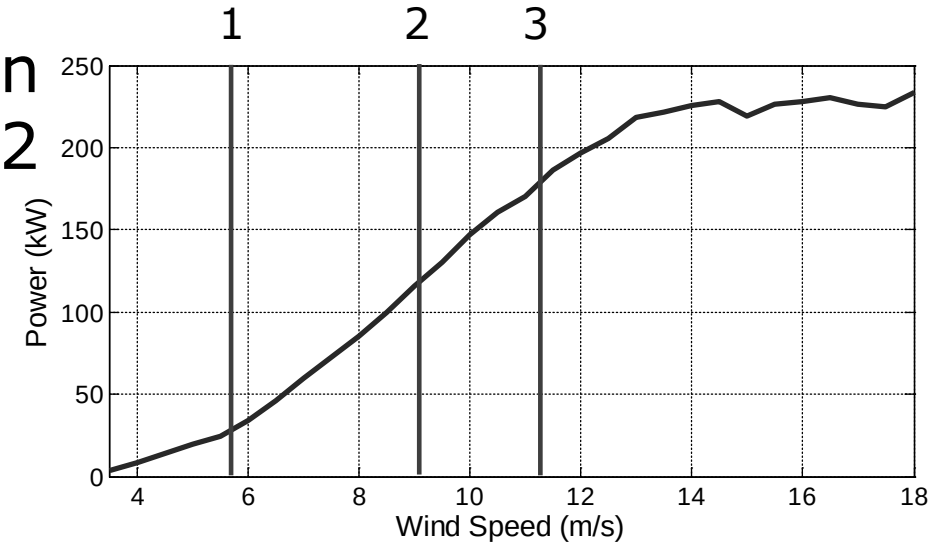
$$C_p = 4a(1-a)^2$$

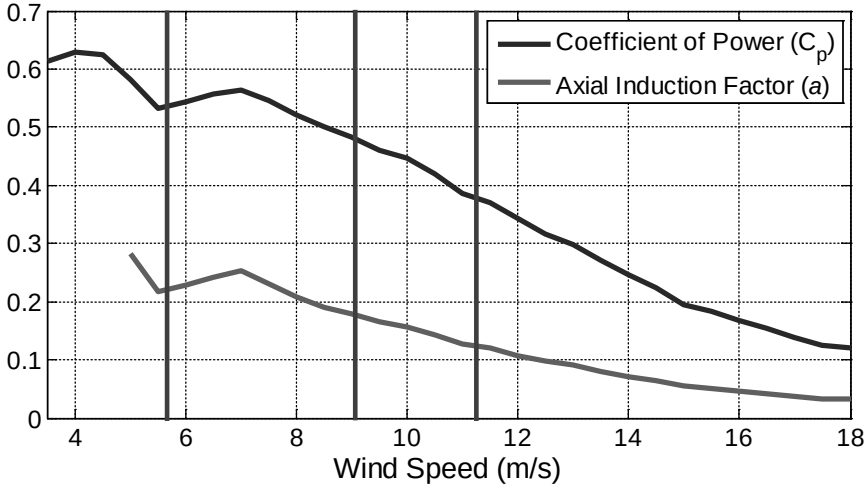
- Vestas V27, 225 kW turbine
- 27 m rotor diameter
- 32.5 m hub height

Data Analyzed

- *xy* plane, 10 sec. scan
- 1.6 *D* upstream to 0.2 *D* downstream
- One side of rotor

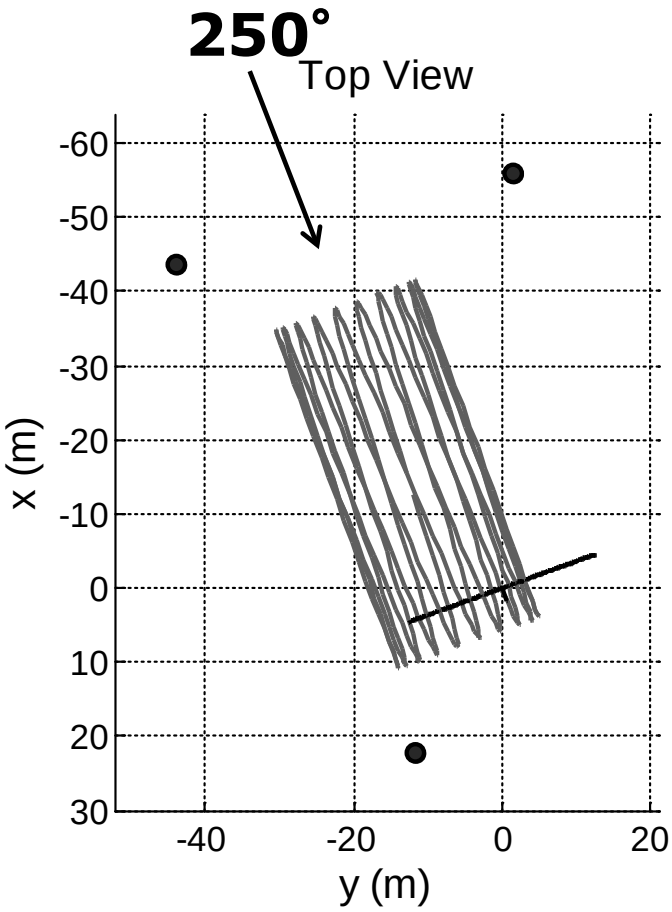




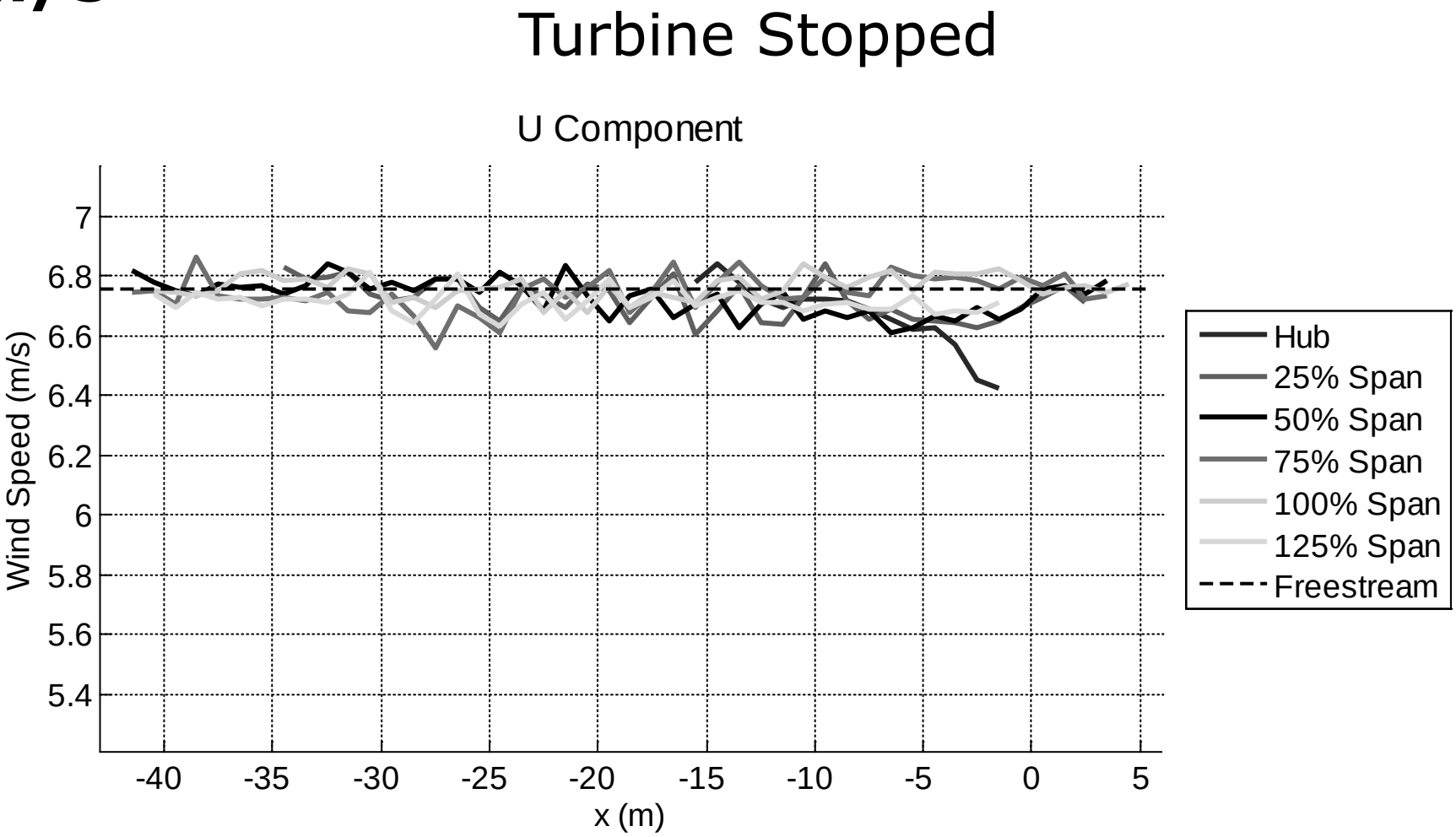


V27 Inflow Measurement Experiment

- Measuring one half of rotor plane at hub height
- Measurements up to 1.6 *D*
- Three lidars allow the measurement of *u,v,w* wind components
- Lidar positions chosen to avoid measuring perpendicular to wind direction
- Lidar positions chosen to minimize focus distance
- Focus distances: 33 – 76 meters
- FWHM of range weighting: 1.5 – 7 meters

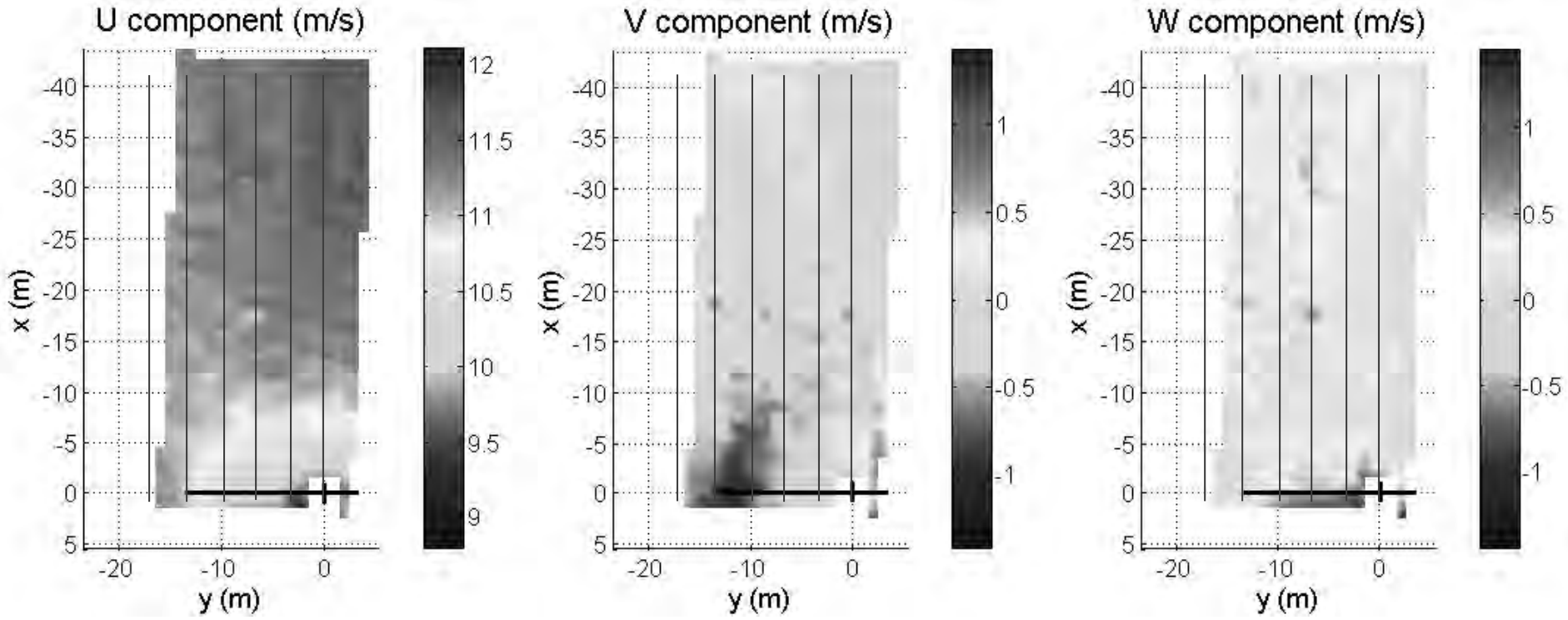


Radial Dependence 3 min. avg., U = 6.76 m/s



Hub-height 3 min. average, U = 11.42 m/s

a estimate from C_p curve = 0.12



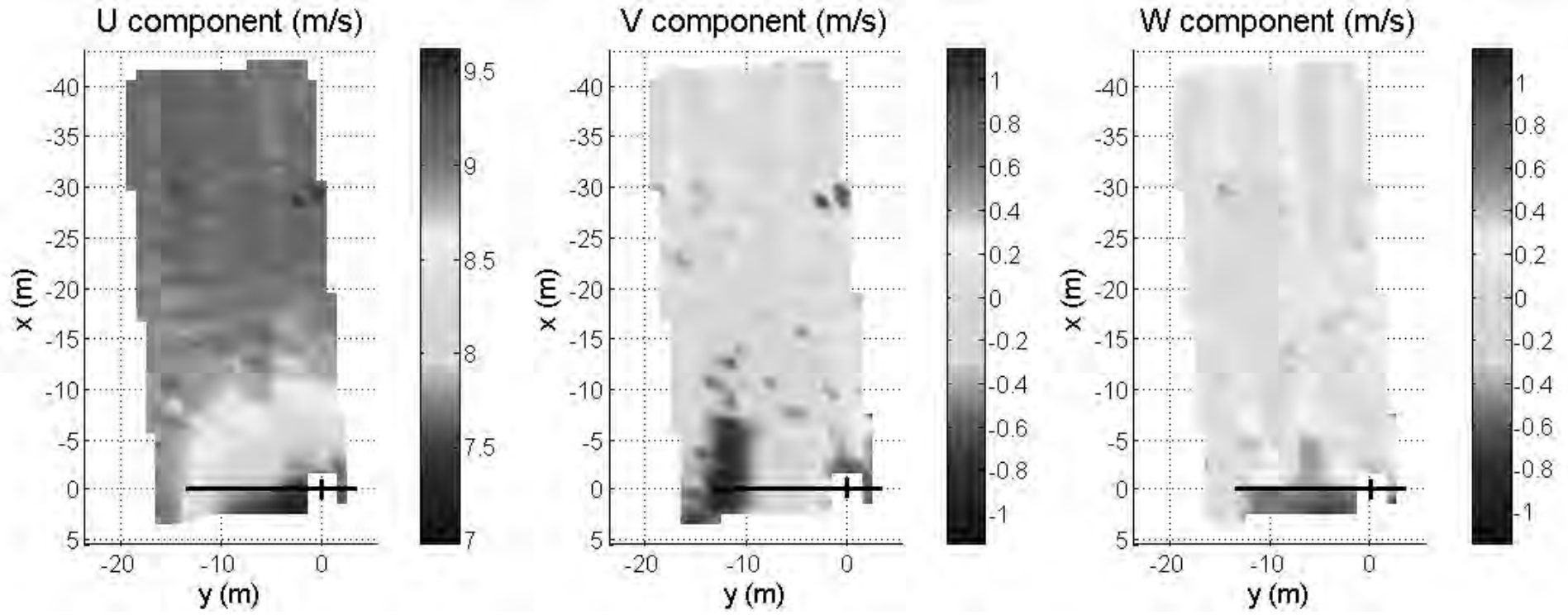
Wind direction = 257.3°

W = 0.28 m/s

Vert. flow angle = 1.4°

Hub-height 4 min. average, U = 9.07 m/s

a estimate from C_p curve = 0.18



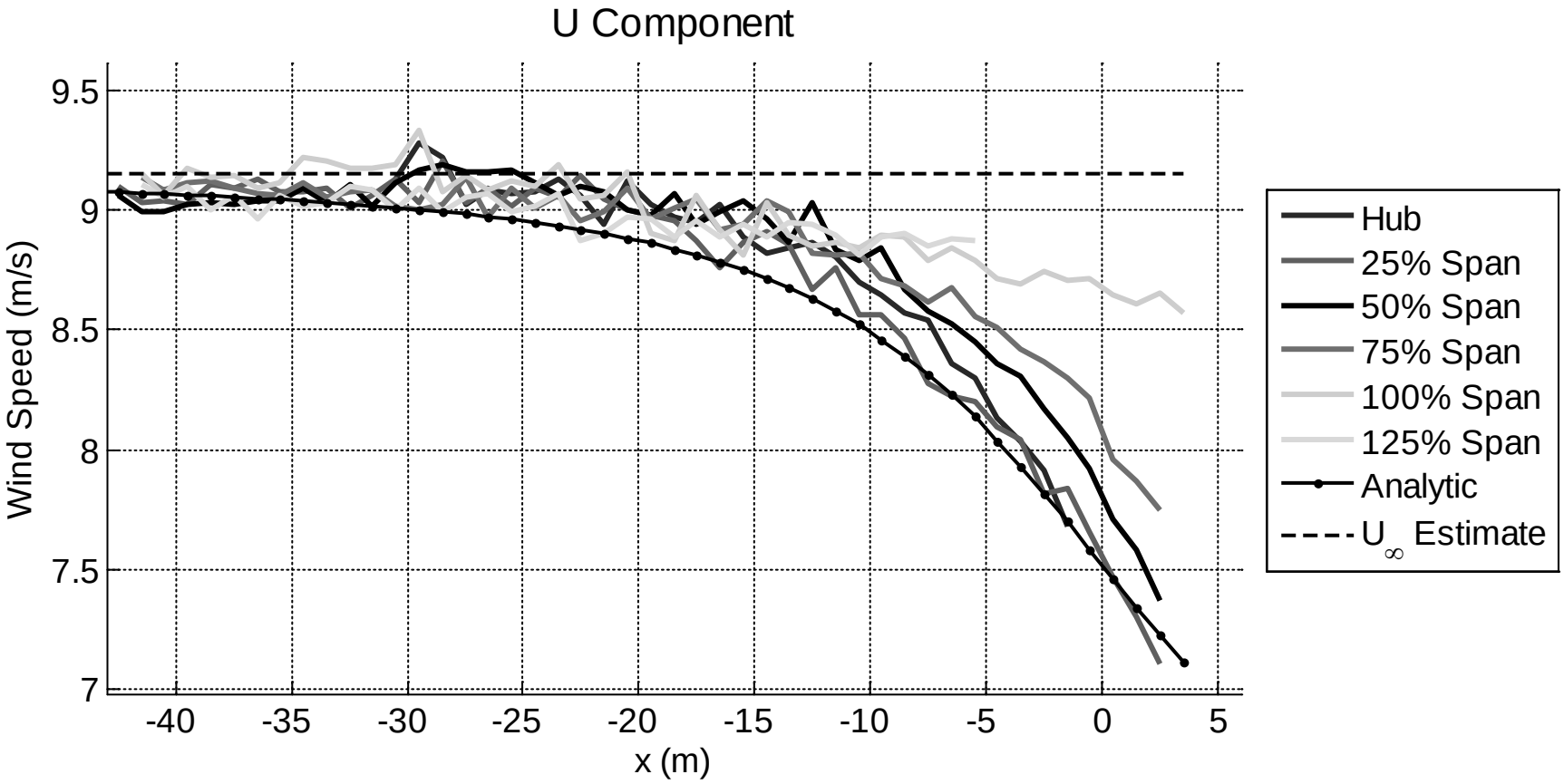
Wind direction = 255.9°

W = 0.11 m/s

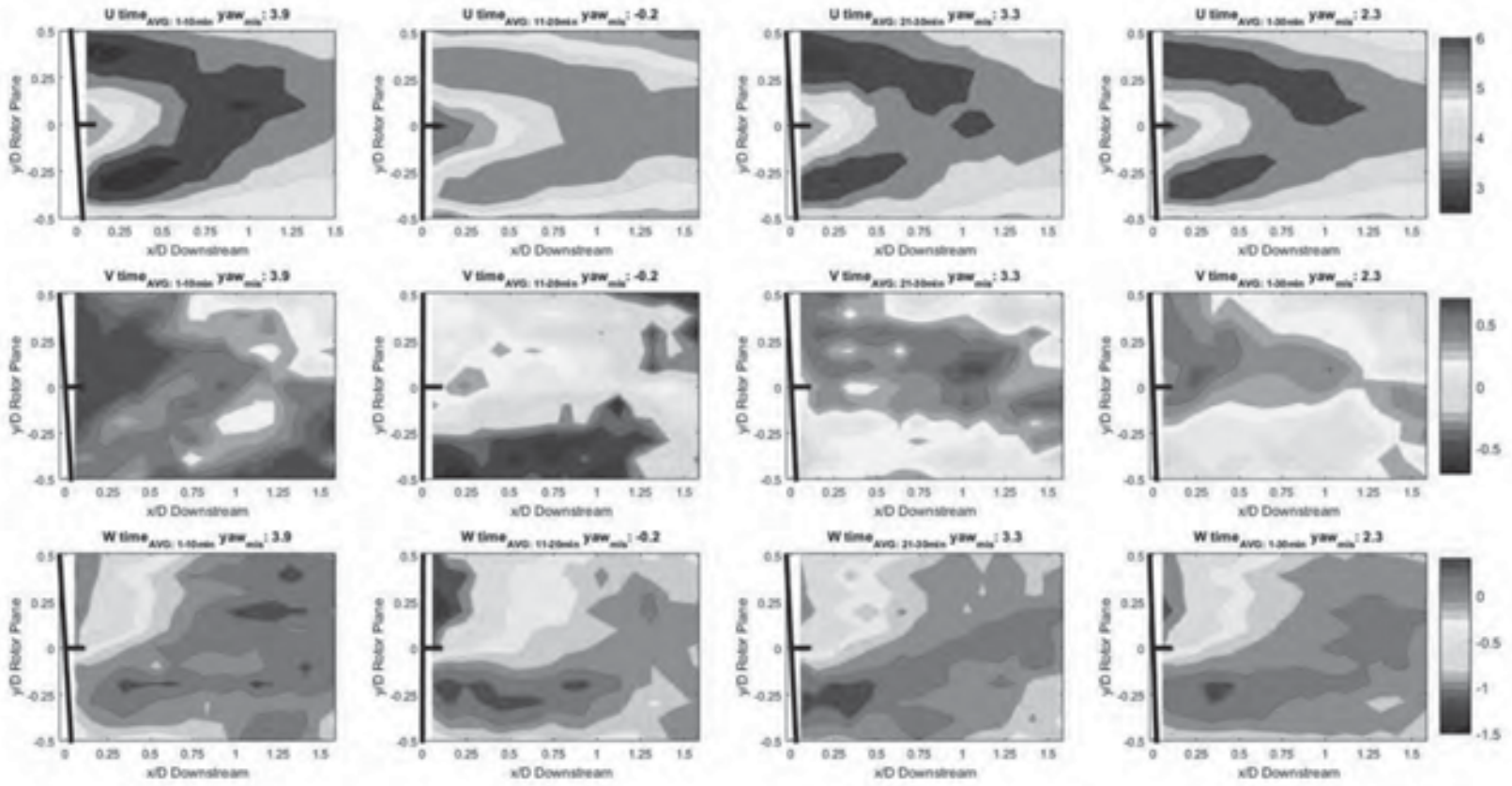
Vert. flow angle = 0.69°

Radial Dependence 4 min. avg., U = 9.07 m/s

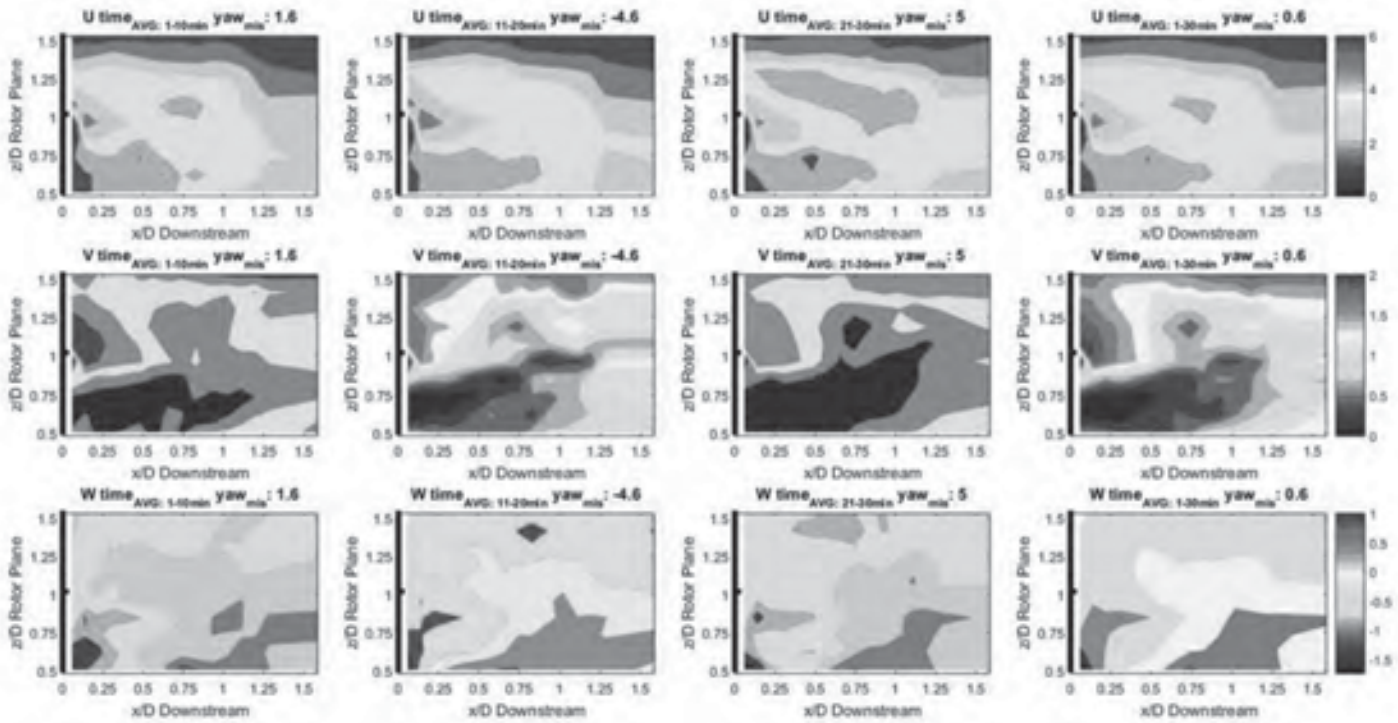
a estimate from C_p curve = 0.18



The u, v and w components of the wind field in a horizontal plane at the hub height.
The top, middle and bottom row show measured u, v and w fields.
Shown are consecutive 10-min mean measurements of (u, v, w) column 1-3 and a 30-min average , column 4.



Lidar scanned wind components in a vertical plane behind the turbine .
The top, middle and bottom panels present *u*, *v* and *w* of the three consecutive 10-min periods (columns 1-3) and of the cumulative 30-min period (column 4).

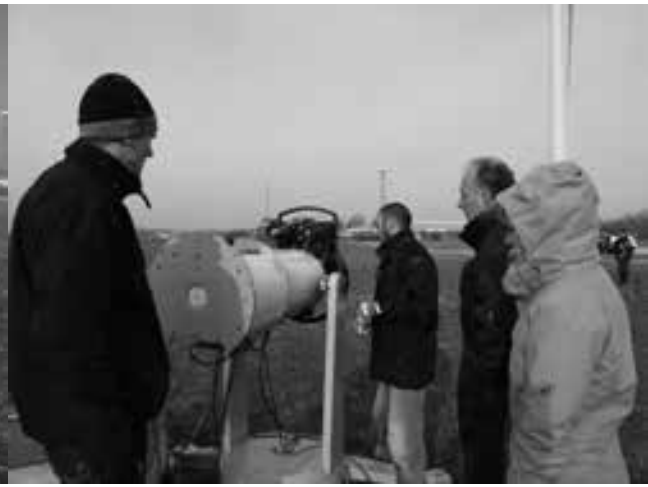


Characterization of wind velocities in the upstream induction zone of a wind turbine using scanning continuous-wave lidars

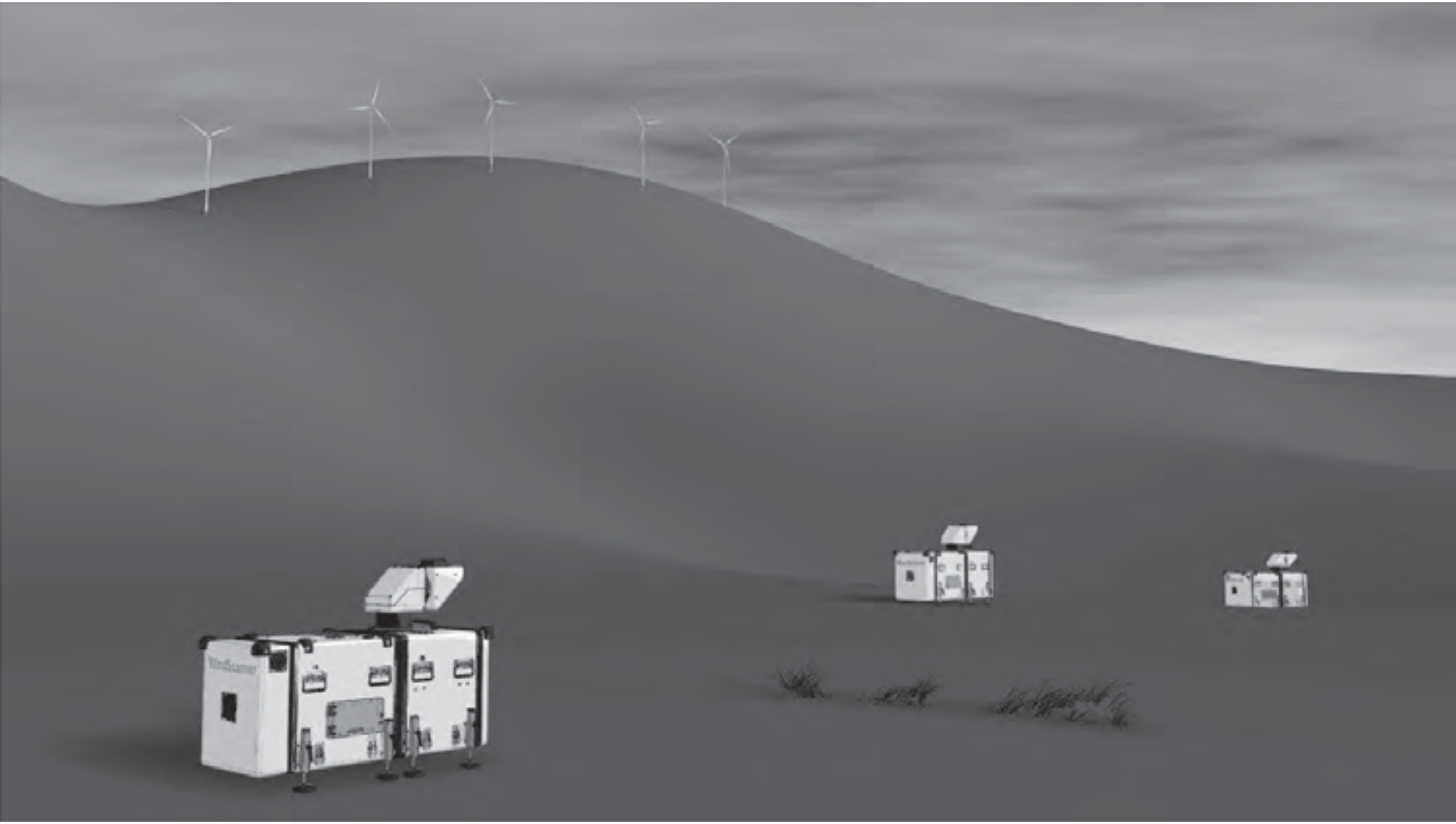
Journal of Renewable and Sustainable Energy **8**, 013301 (2016)

Eric Simley, Nikolas Angelou, Torben Mikkelsen, Mikael Sjöholm, Jakob Mann, Lucy Y. Pao

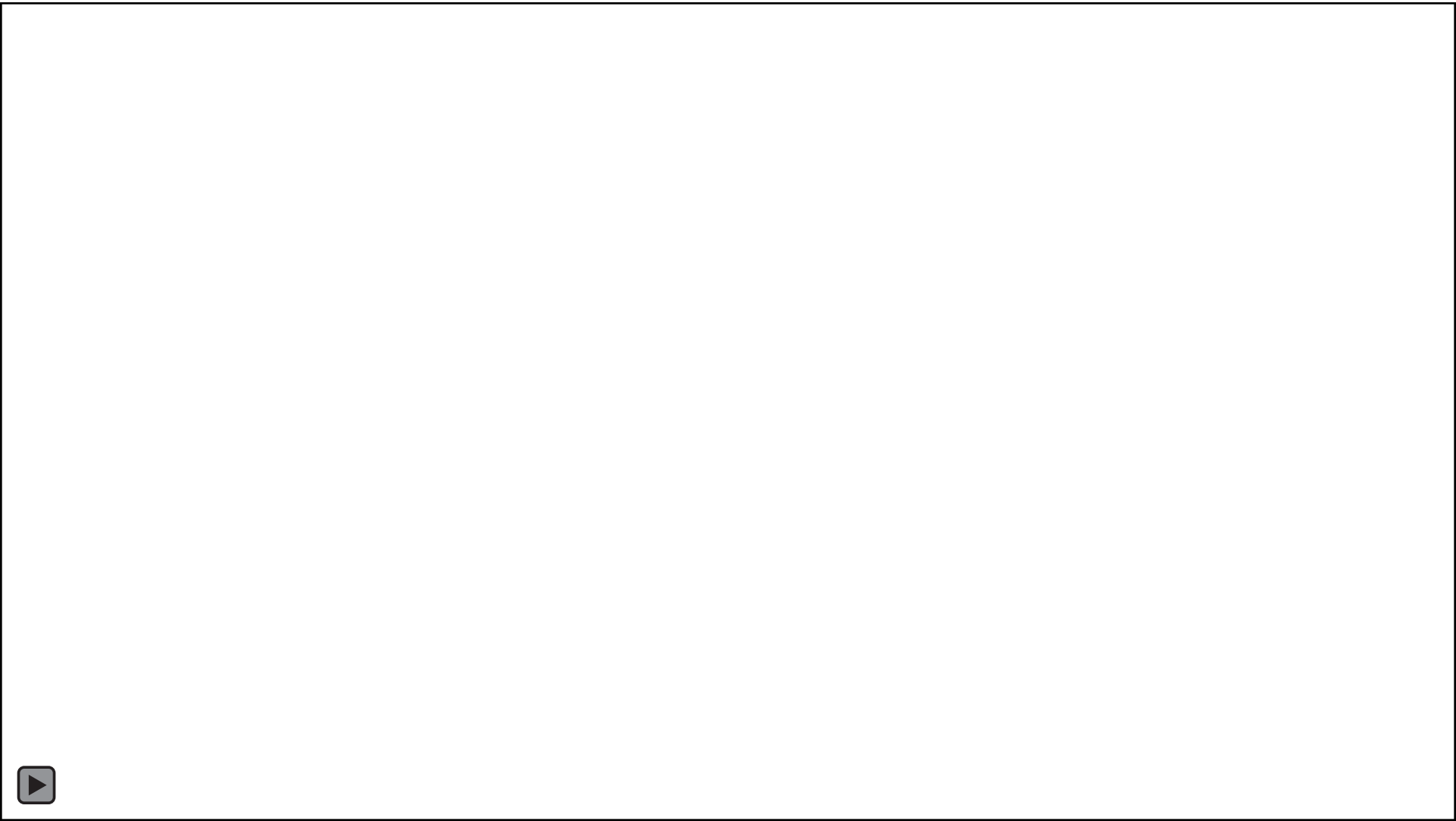




Long-range:

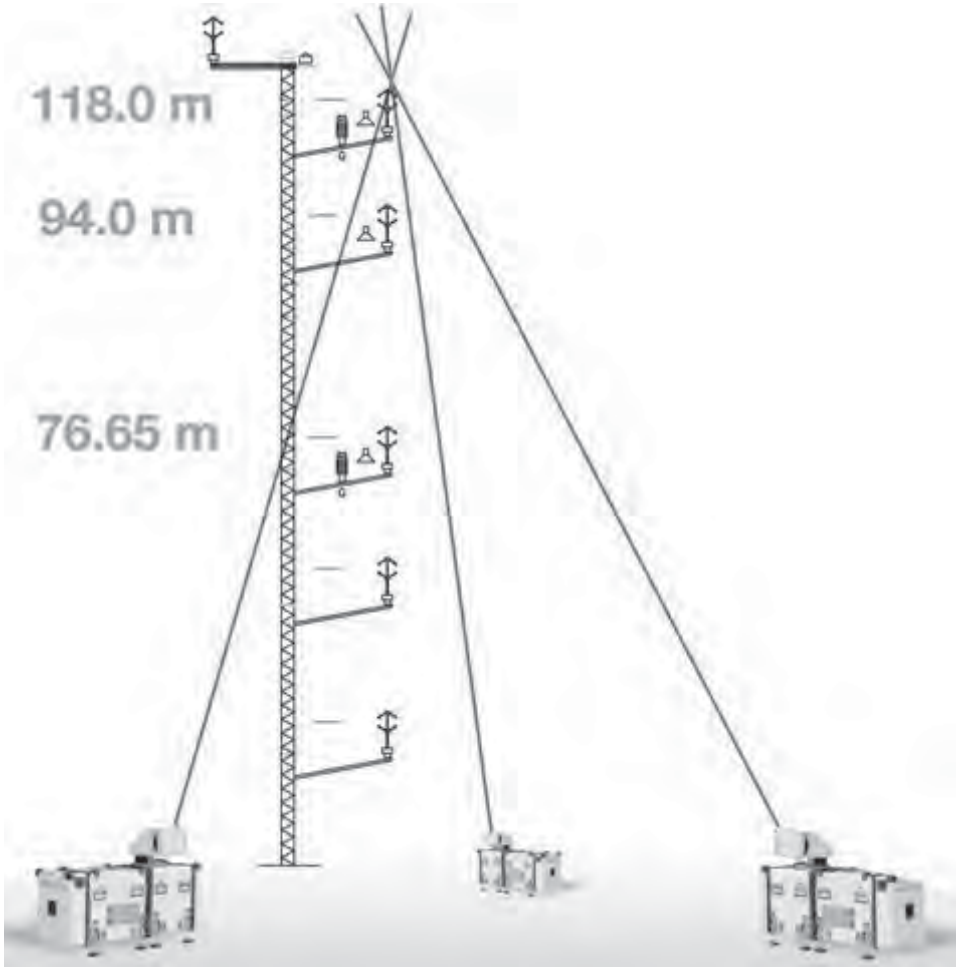


Long-range WindScanner systems

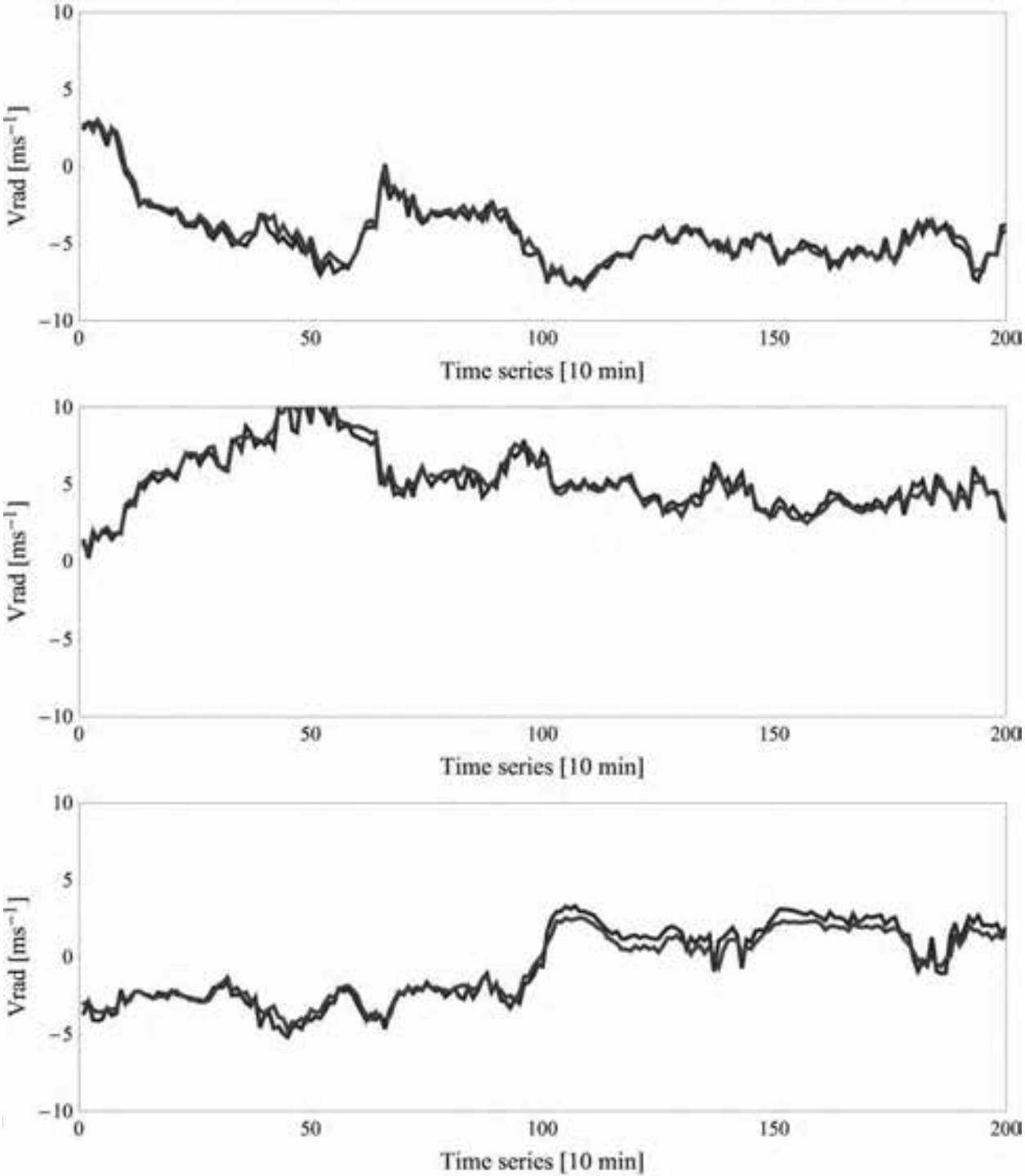


Measurement scenario 1 - LOS

- Intersecting 3 beams at 118m
- Sampling rate 1 Hz
- Pulse length: 200 and 400 ns
- Around 20 hours of collected data



Time series of radial wind speed measurements
R2D1: top,
R2D2: middle
R2D3: bottom
vs
corresponding 3D sonic measurements projected along the line-of-sight of the lidars.



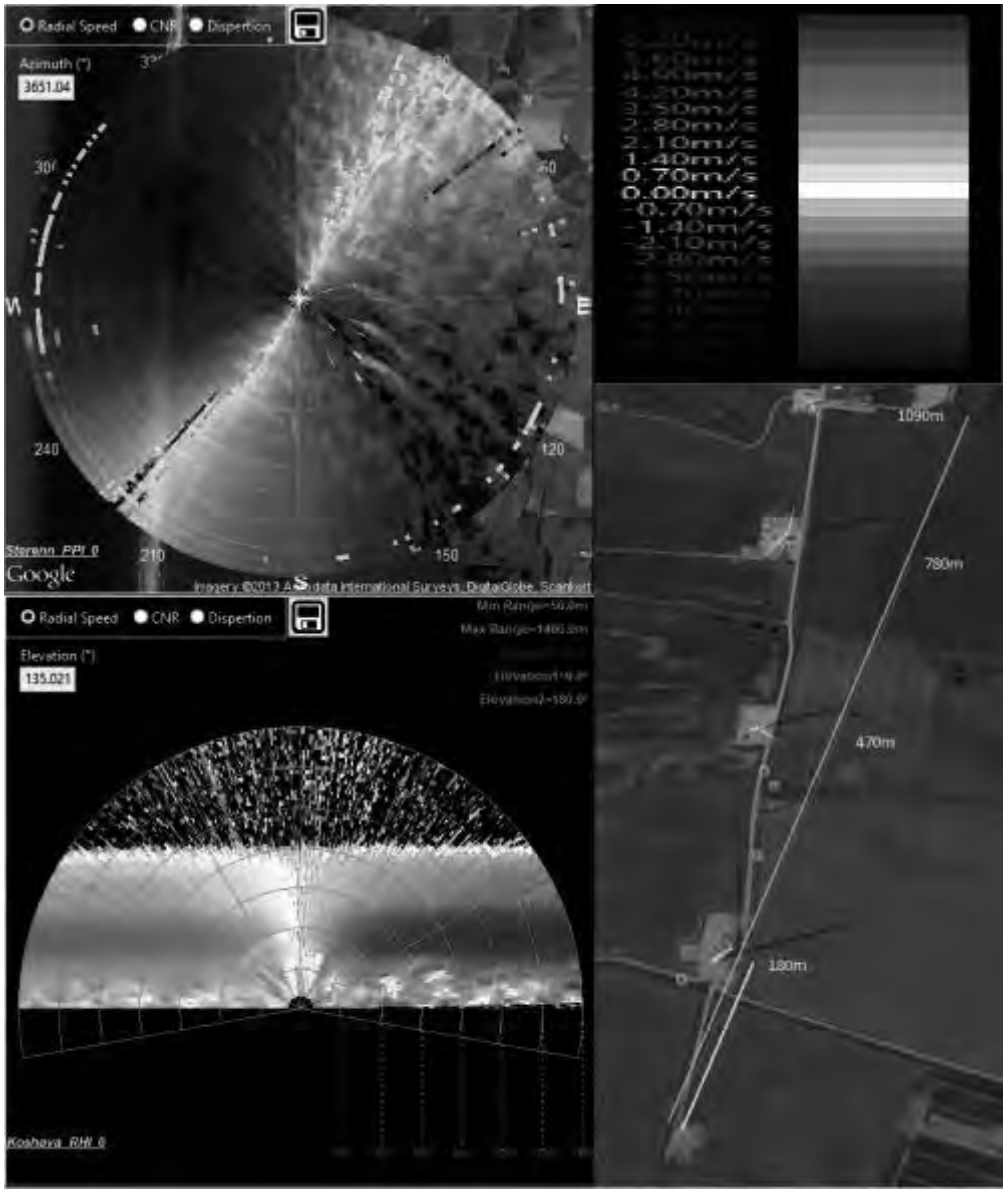
Sonic on Sterenn LOS

sonic

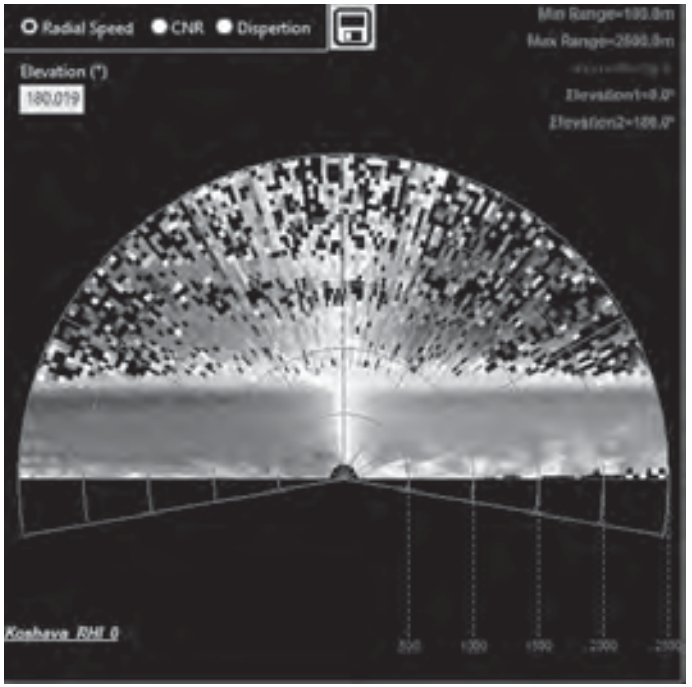
windscanner

Long pulses, 10 min mean, 6 hours of data

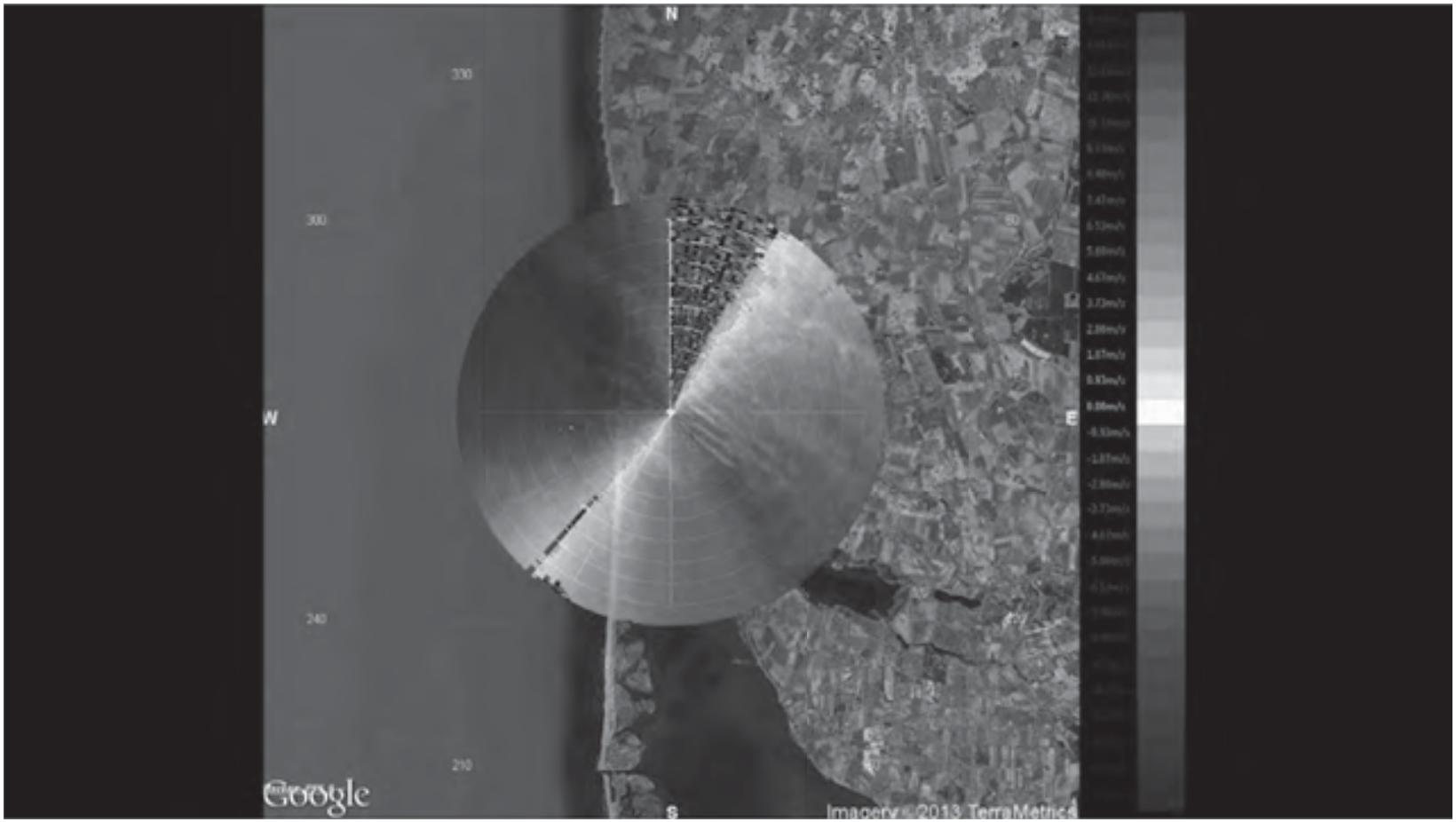
Wakes and….



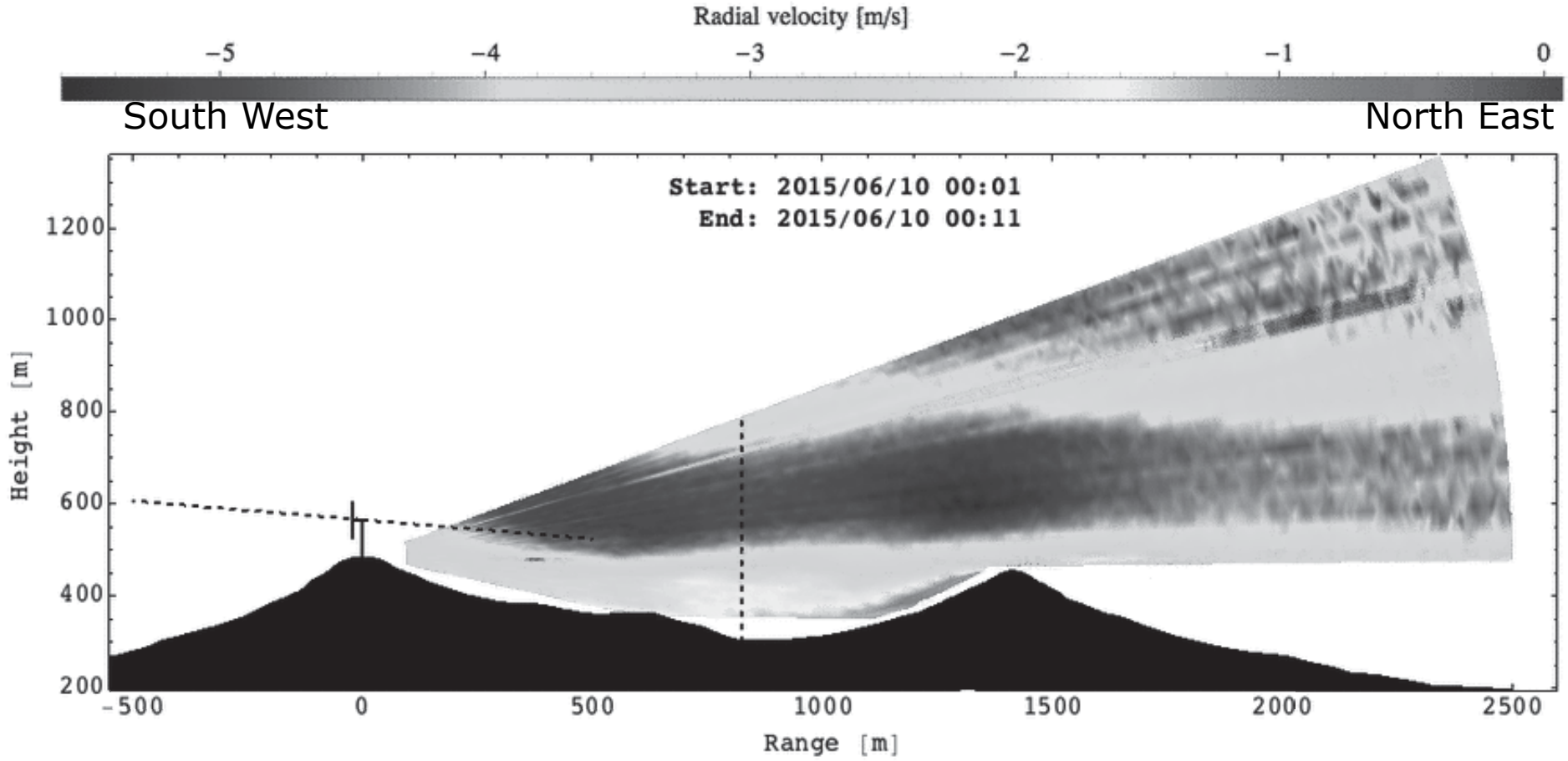
…Jets



Long-range (Leosphere WLS400S) Lidar PPI scanning at Høvsøre. Range 5-6 km.



2 X LONG-RANGE WINDSCANNERS IN COMPLEX TERRAIN - 24H RHI SCANS

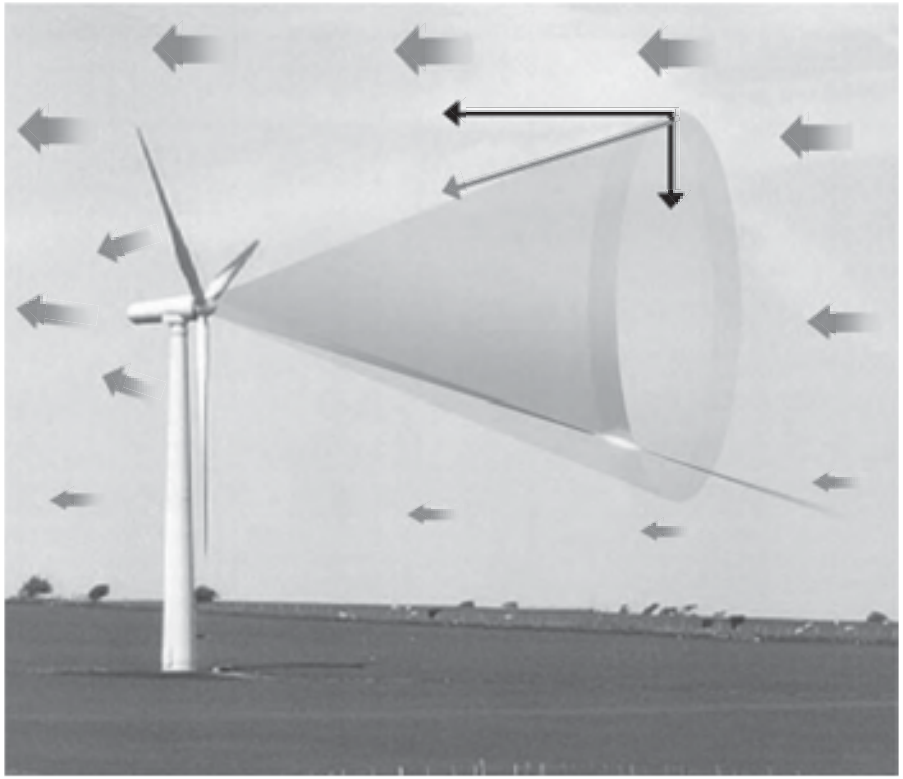


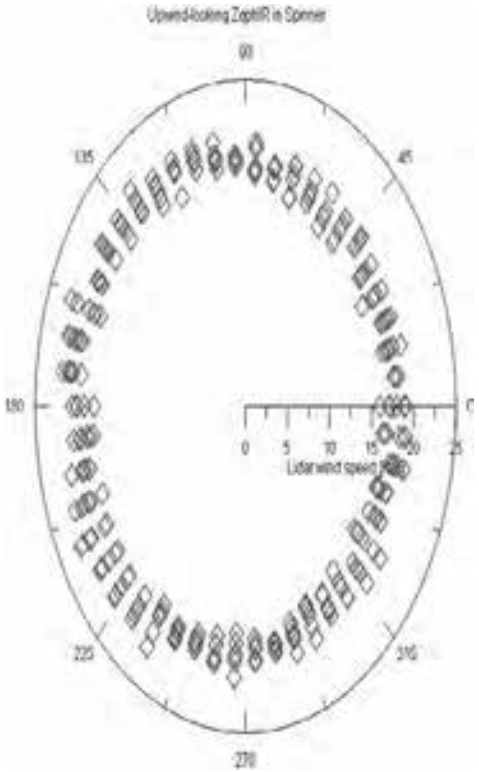
Positive speed when flow is coming from South West direction

Spinner Integrated Lidar

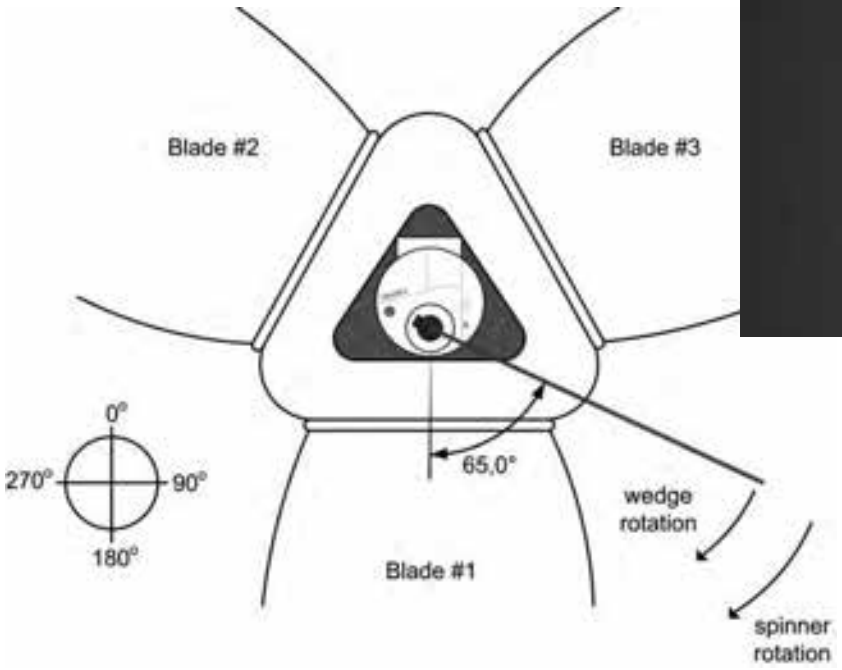
I: Experimental Setup:

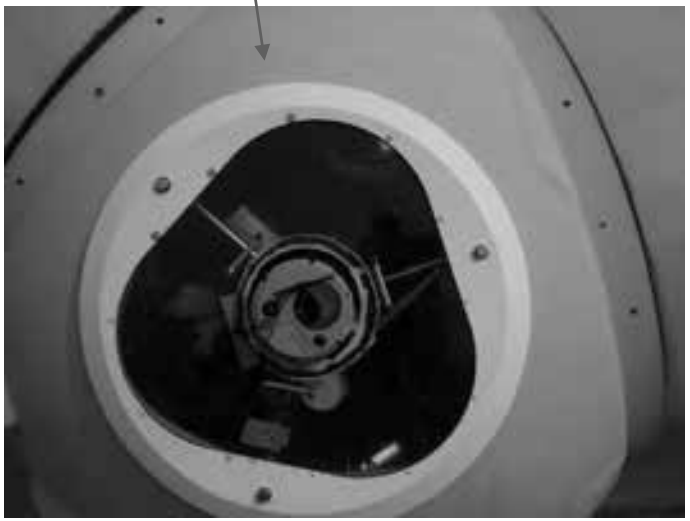
Pro-active wind turbine control from upwind measurements by lidars integrated in the rotating Spinner… :

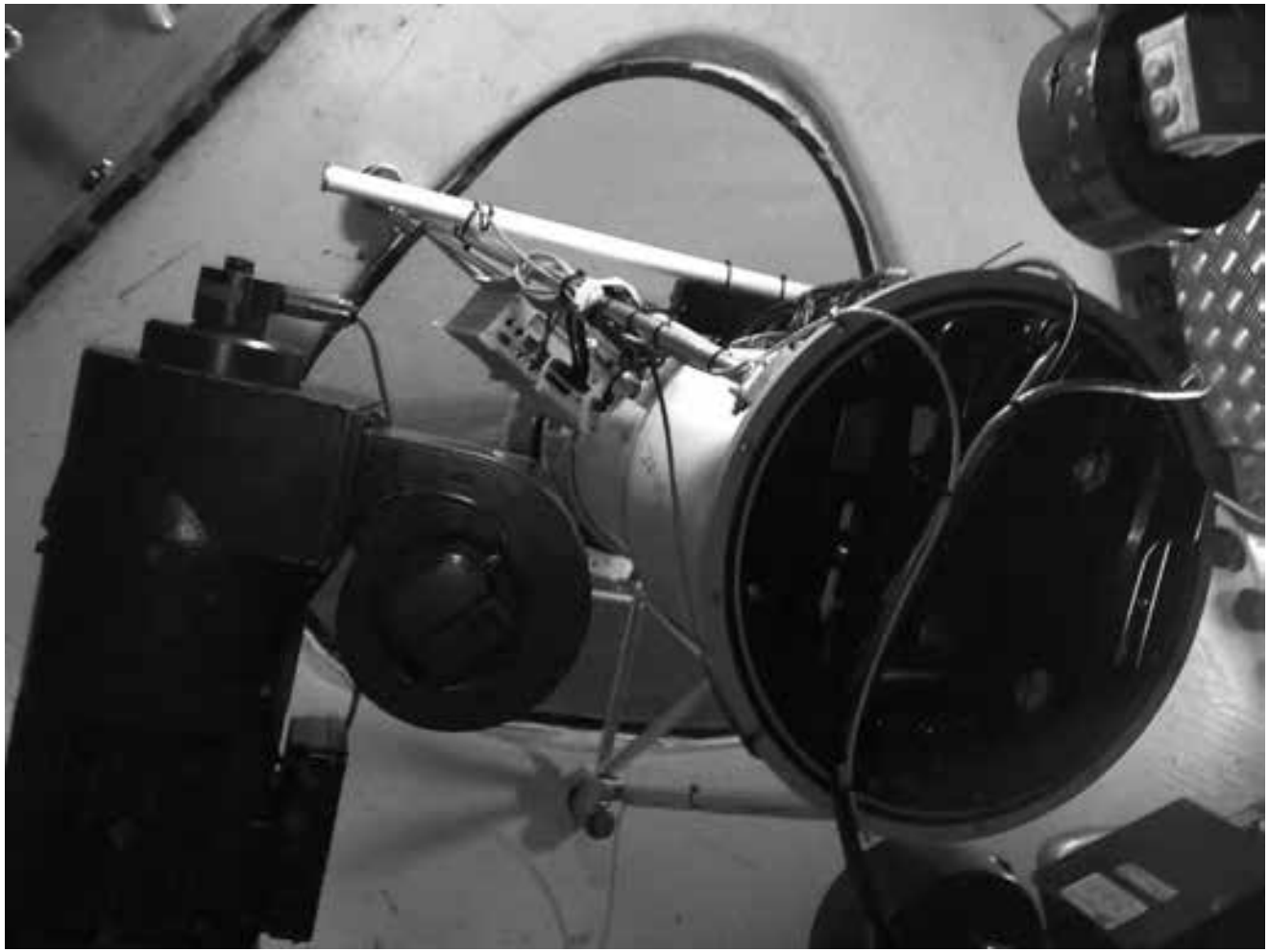




ZephIR VAD SpinnerLidar (2010)

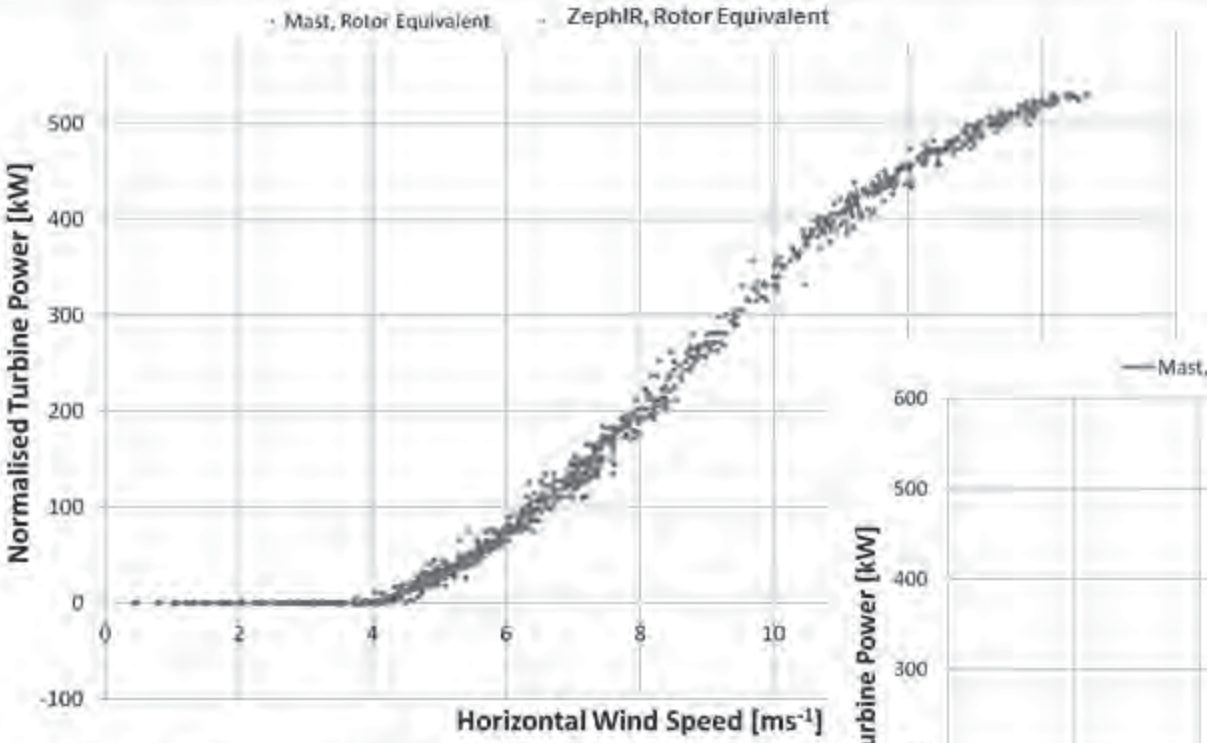




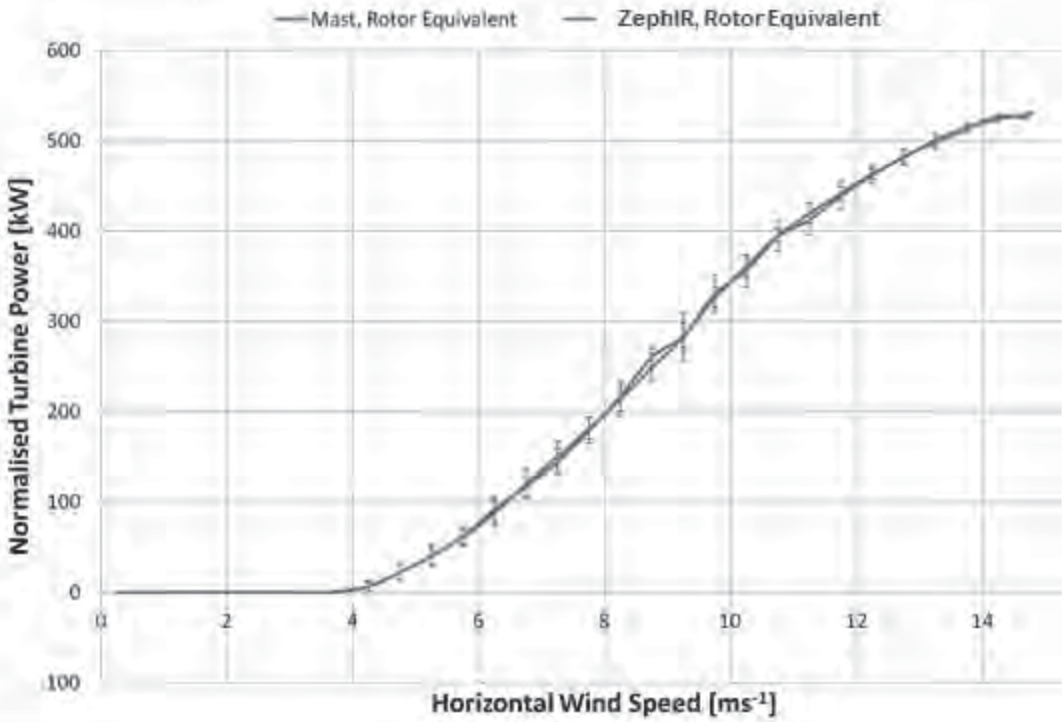


Power Curve measurements with
ZephIR Dual Mode Control Lidar @ DTU Risø Campus NKT550 2013:

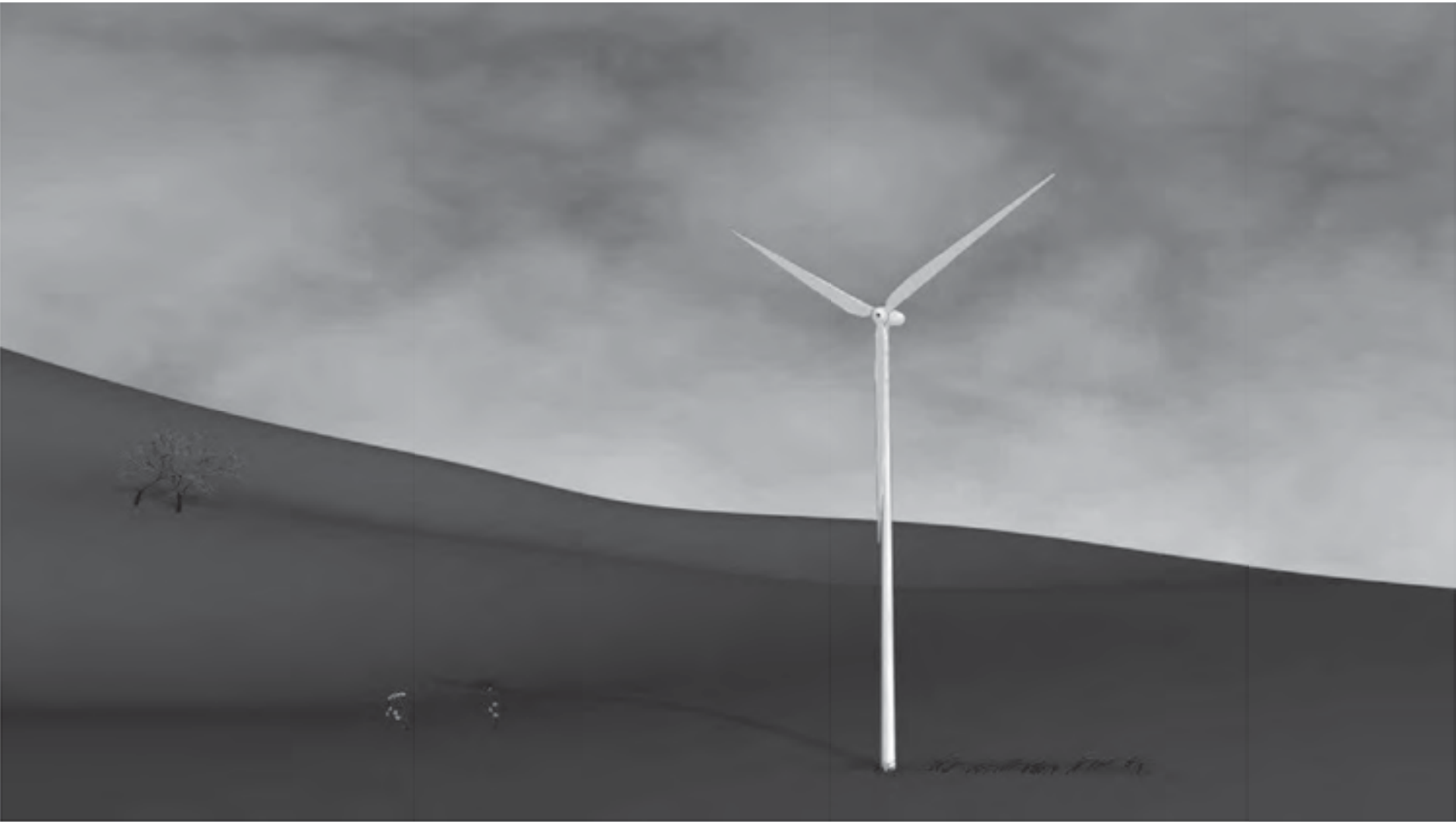
Power curves based on rotor equivalent quantities



ZephIR RE measurement heights of 27, 36, 45 and 54 m at 90 m measurement range. The rotor equivalent mast speeds were calculated using the cups at 27, 36, 45 and 54 m and the sonic anemometers at 16.5, 34.5 and 53,5 m.



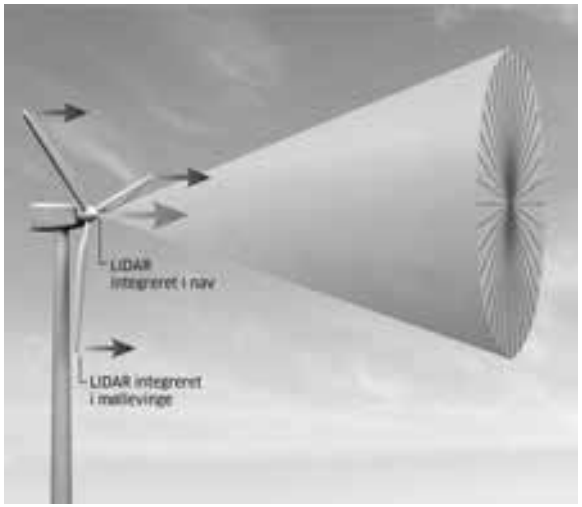
ZephIR Lidar



Innovation products for Wind Turbine Control:

1) 2D Spinner Lidar's

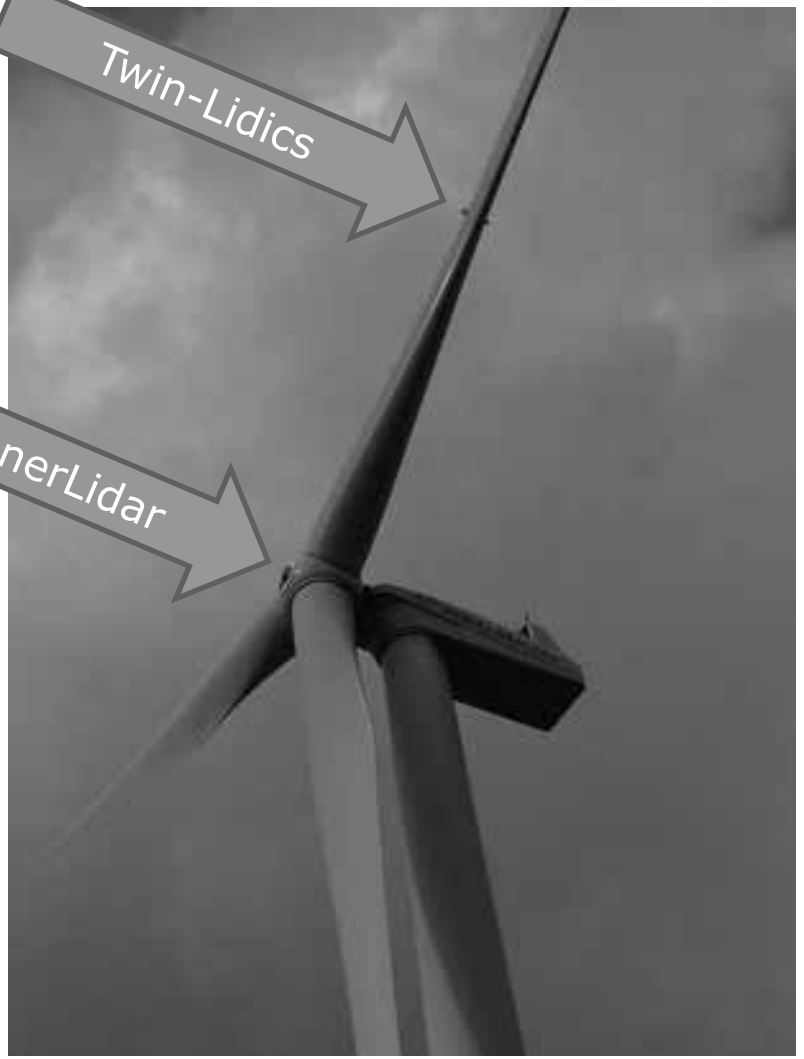
2) Small all-fibre LIDIC's



WindScanner Spin-off Innovation Products:

DTU 2D Spinner Lidar (2012) & small LIDIC's (2012) :

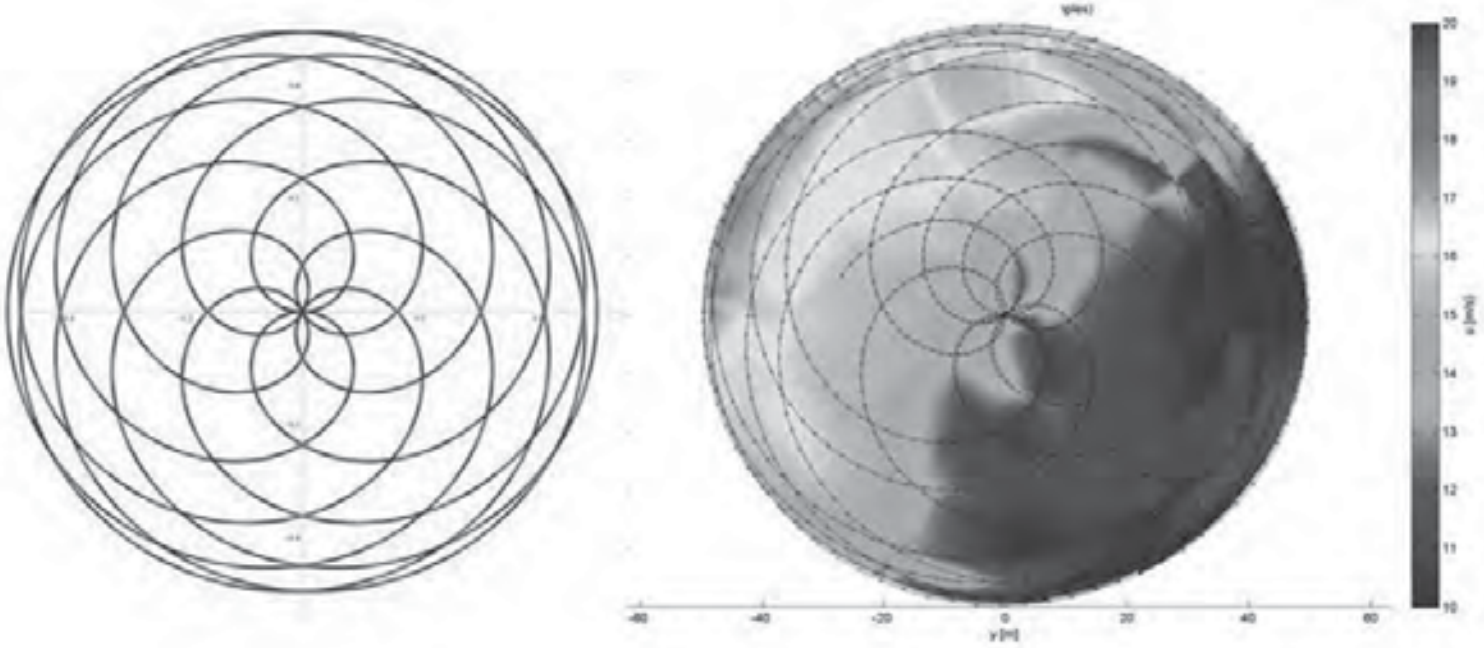
DTU 2D Scanning SpinnerLidar integration at Tjæreborg July 2012:



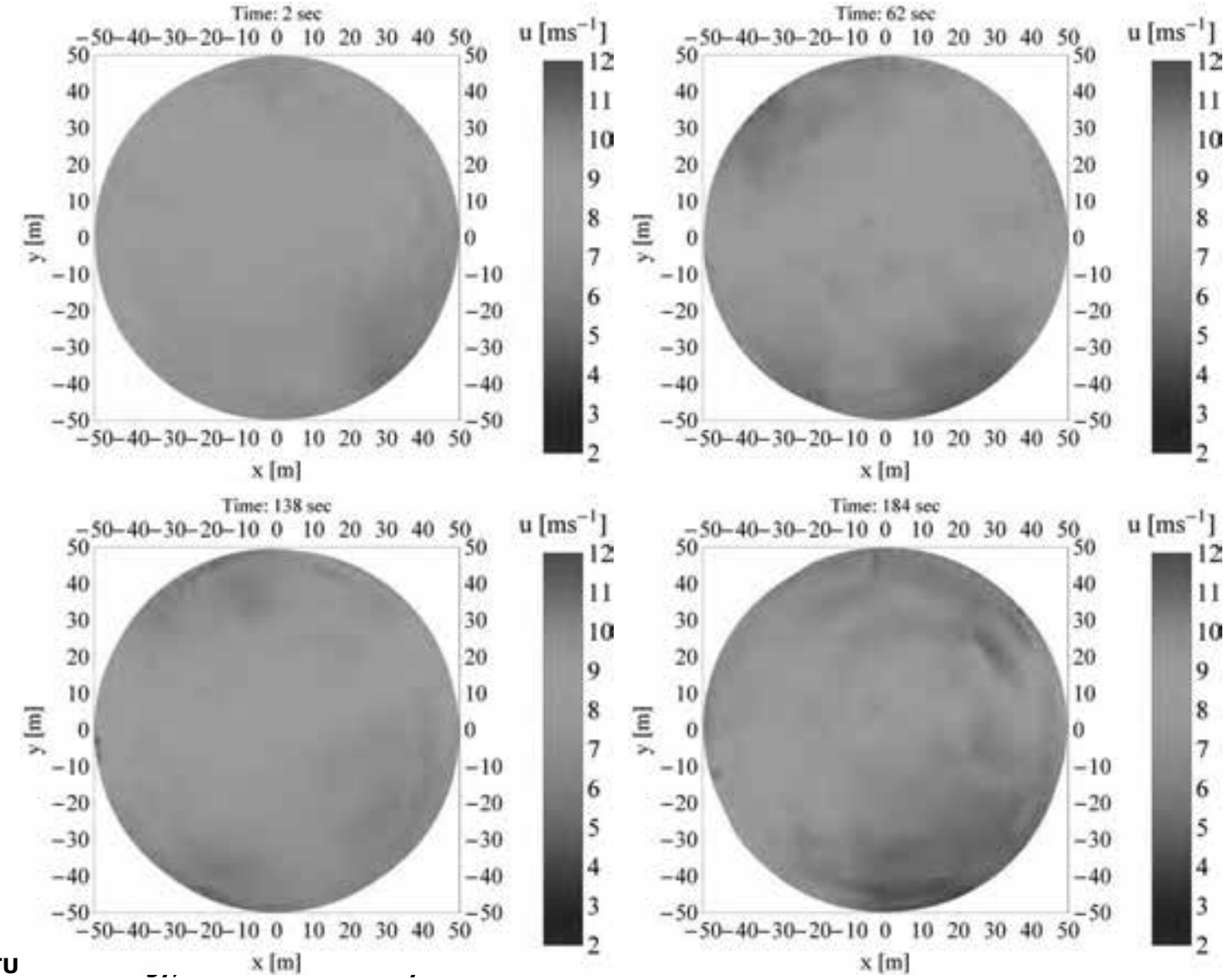
First 2D SpinnerLidar measuring inflow 100 m upwind NM80, 2.3 MW WT (August 2012):

WindScanner (SpinnerLidar) UpWind 2D scanning from the rotating spinner of 2.3 MW NM80.

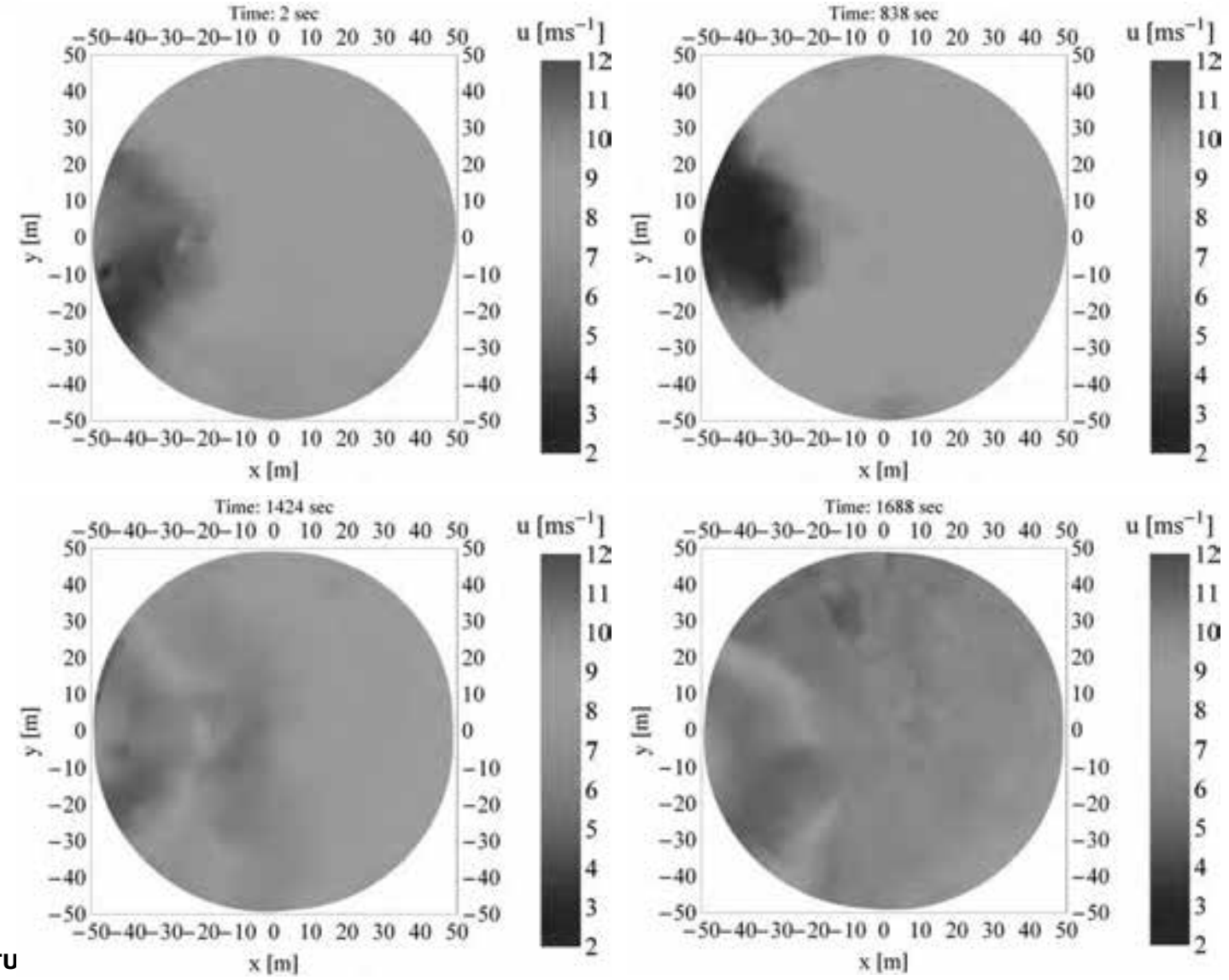
400 wind speed measurement points are retrieved in real time per second :

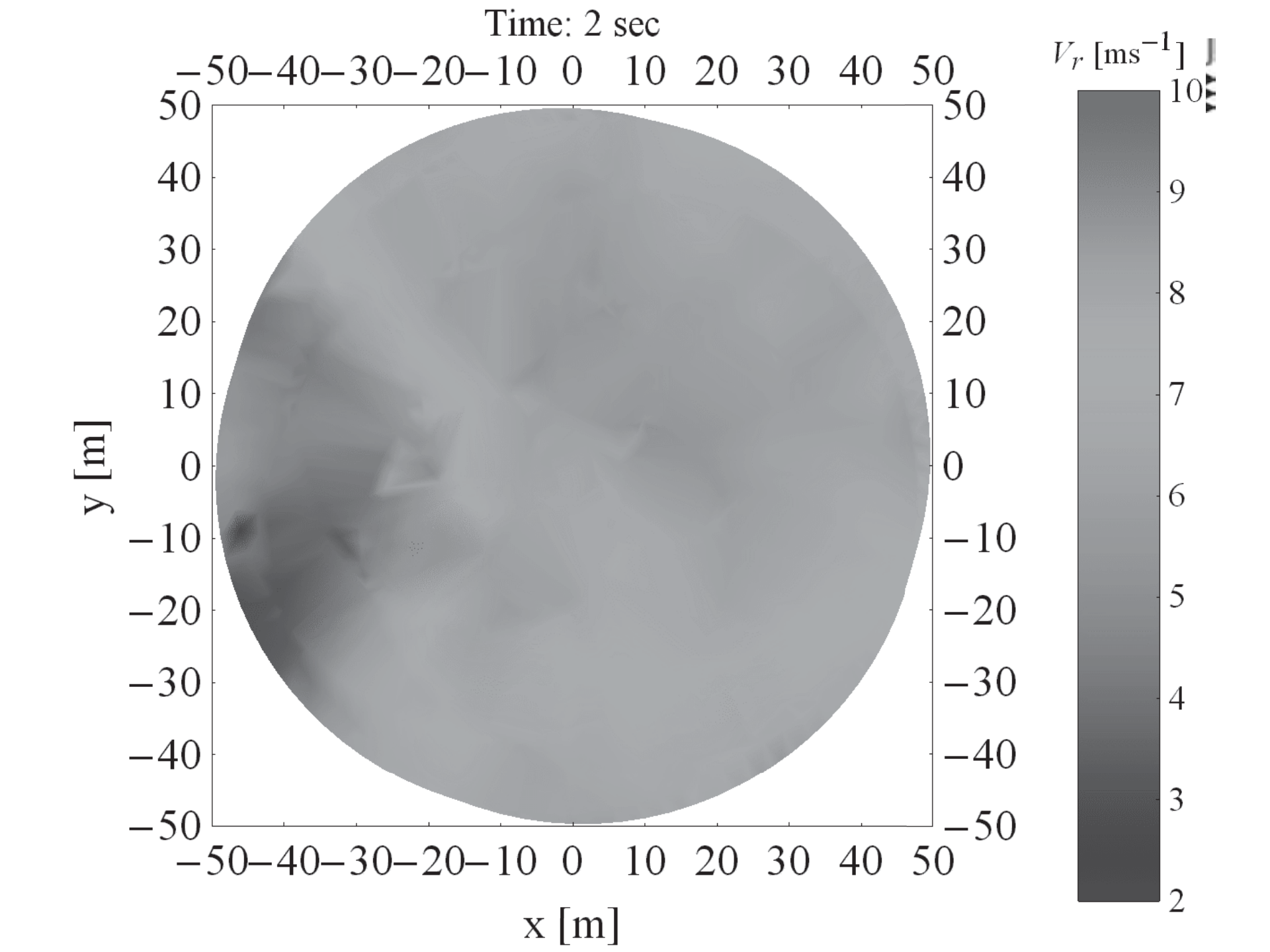


Inflow without wake influence



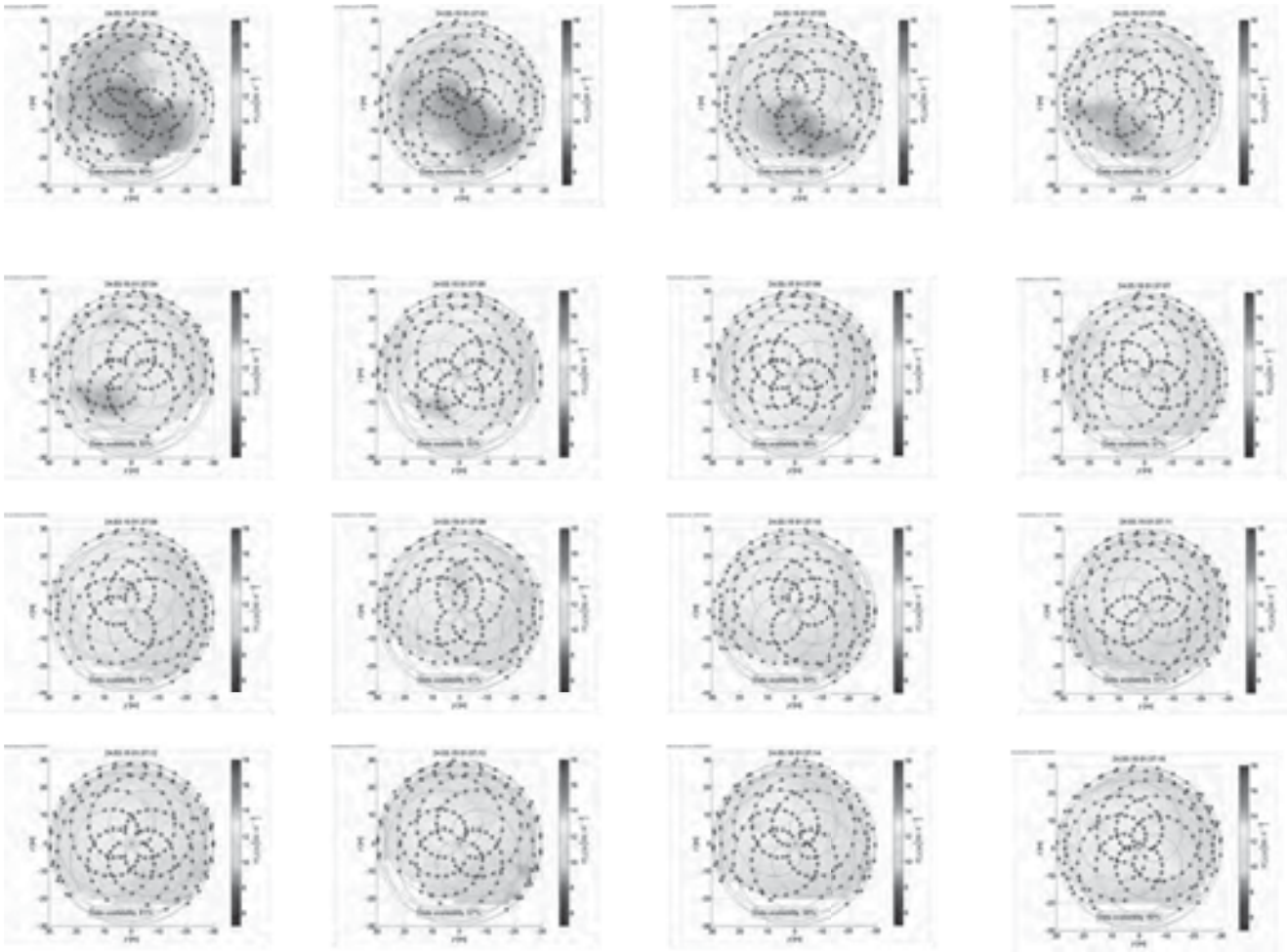
Inflow with wake influence



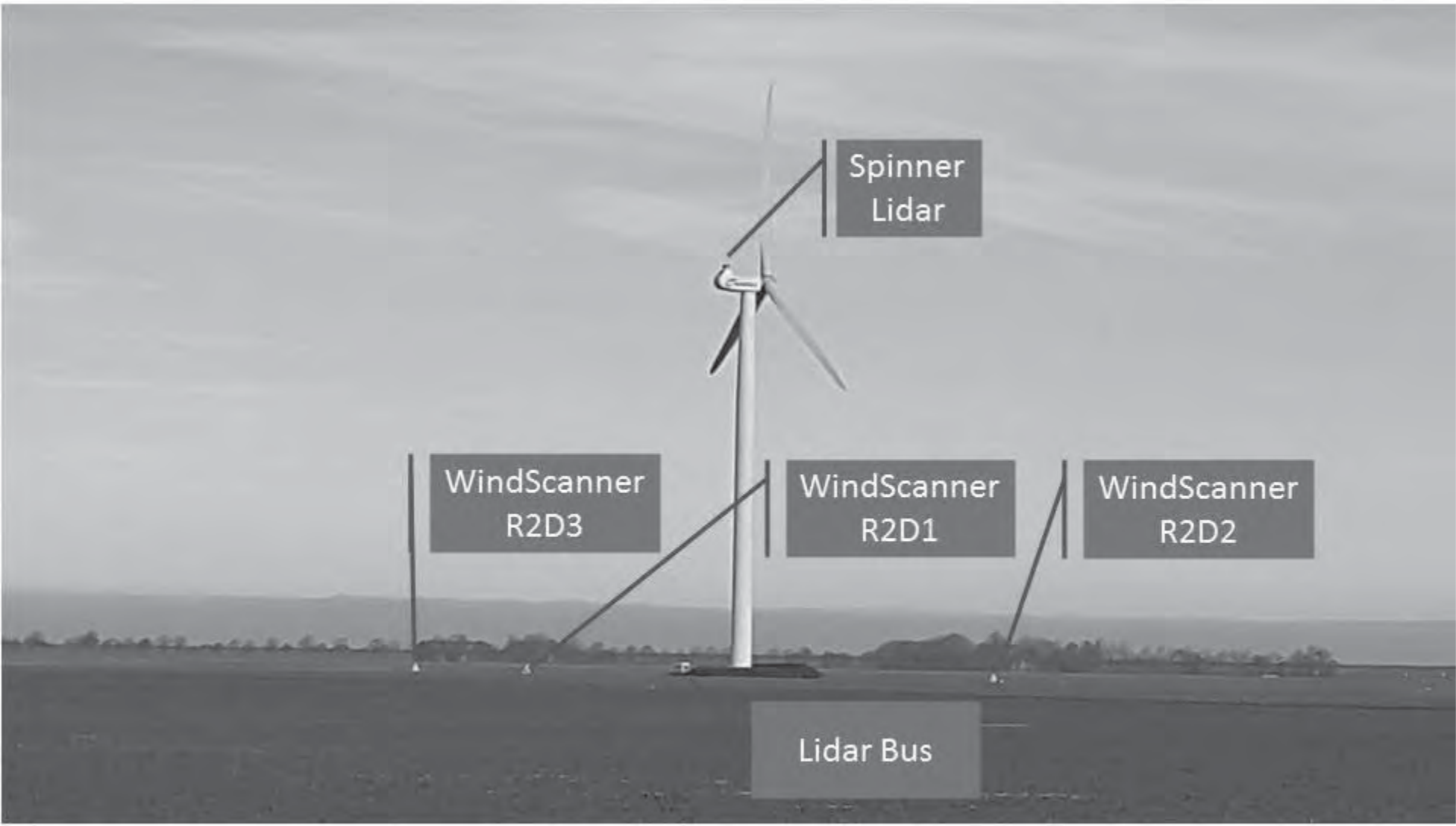

Time: 2 sec
V_r [ms^{-1}]
10
9
8
7
6
5
4
3
2
−50 −40 −30 −20 −10 0 10 20 30 40 50
y [m]
x [m]

2015: DTU SpinnerLidar @ NREL CART3

InnWind.eu DTU SpinnerLidar measured Inflow
CART3 NREL Ø 40 m
V_LOS 2D 1-s frames @ 60 m upwind



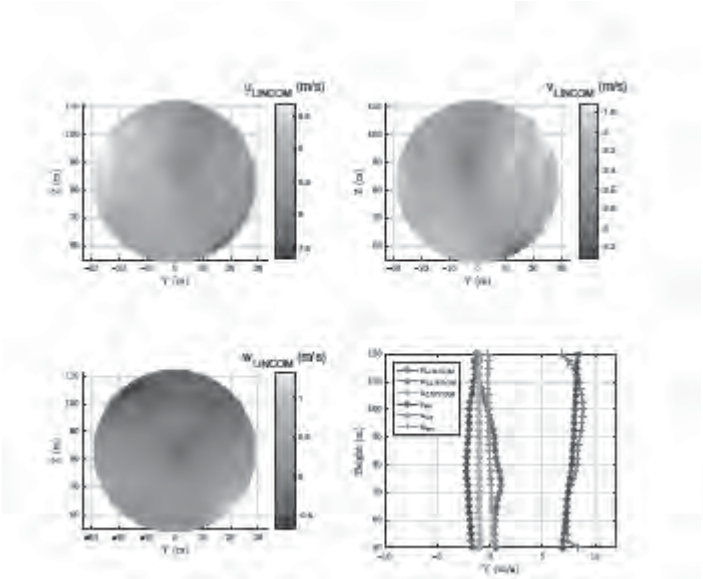
DTU SpinnerLidar on ECN test site 2016-2017

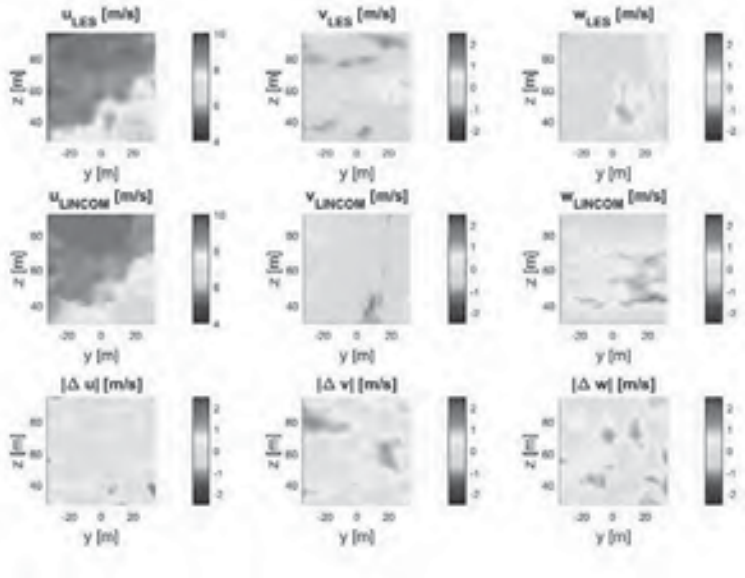

Spinner
Lidar
WindScanner
R2D3
WindScanner
R2D1
WindScanner
R2D2
Lidar Bus

Second IRPWind Analysis paper:

SpinnerLidar w/ Lincom 3D Wind Field reconstruction

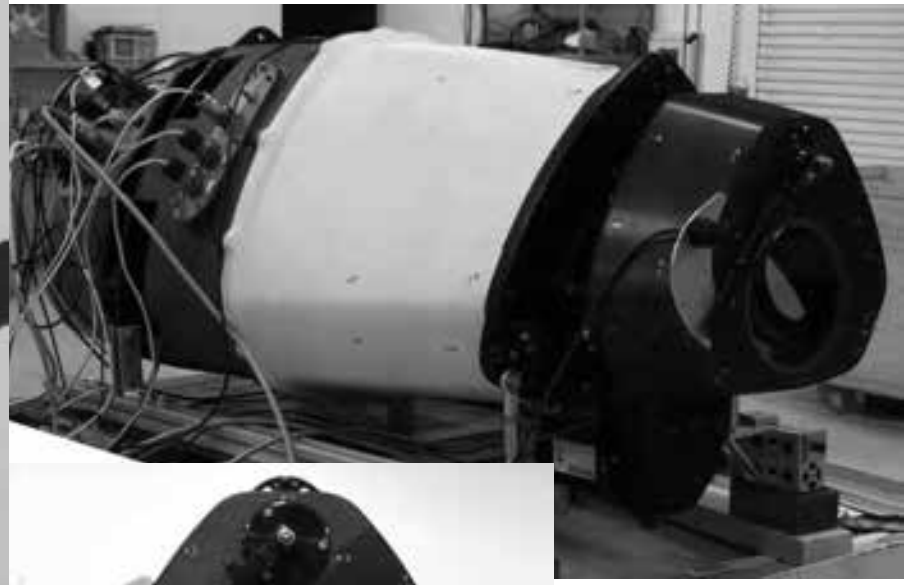
Uni-OL & DTU =>Torque 2018

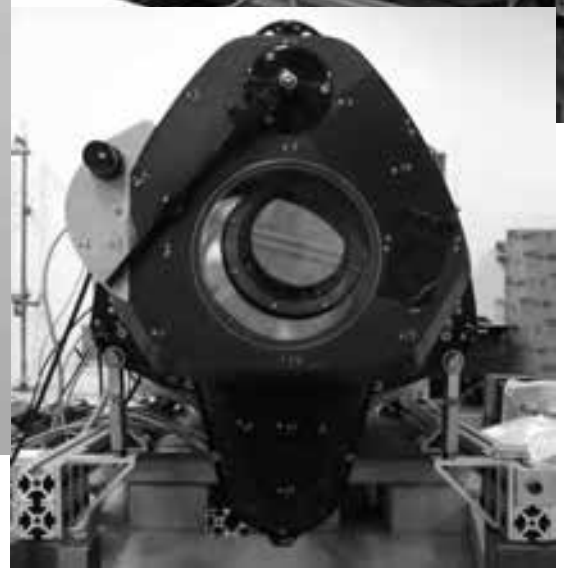




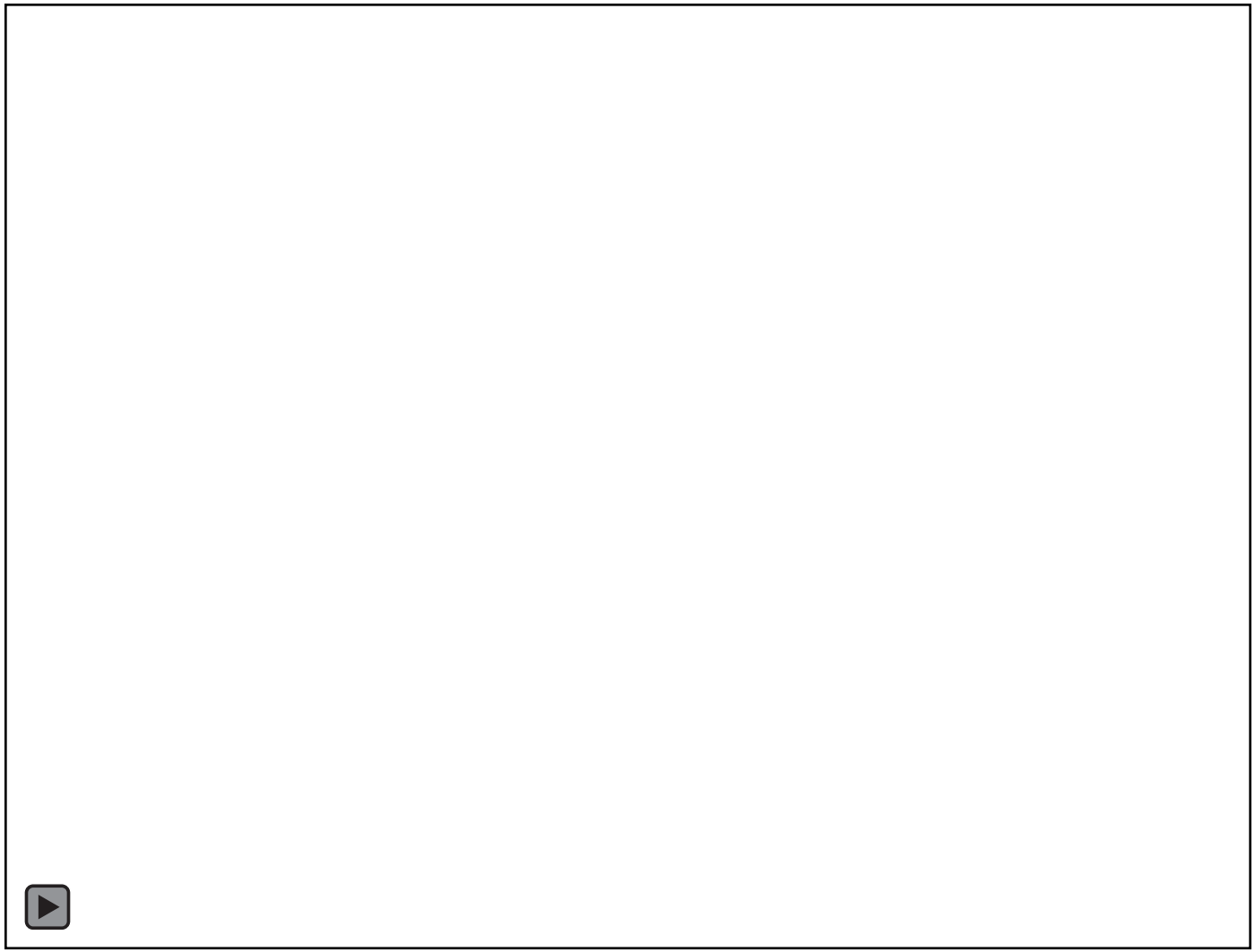
DTU SpinnerLidar @ SWIFT Sandia NL 2017

2D Wake Measurements:

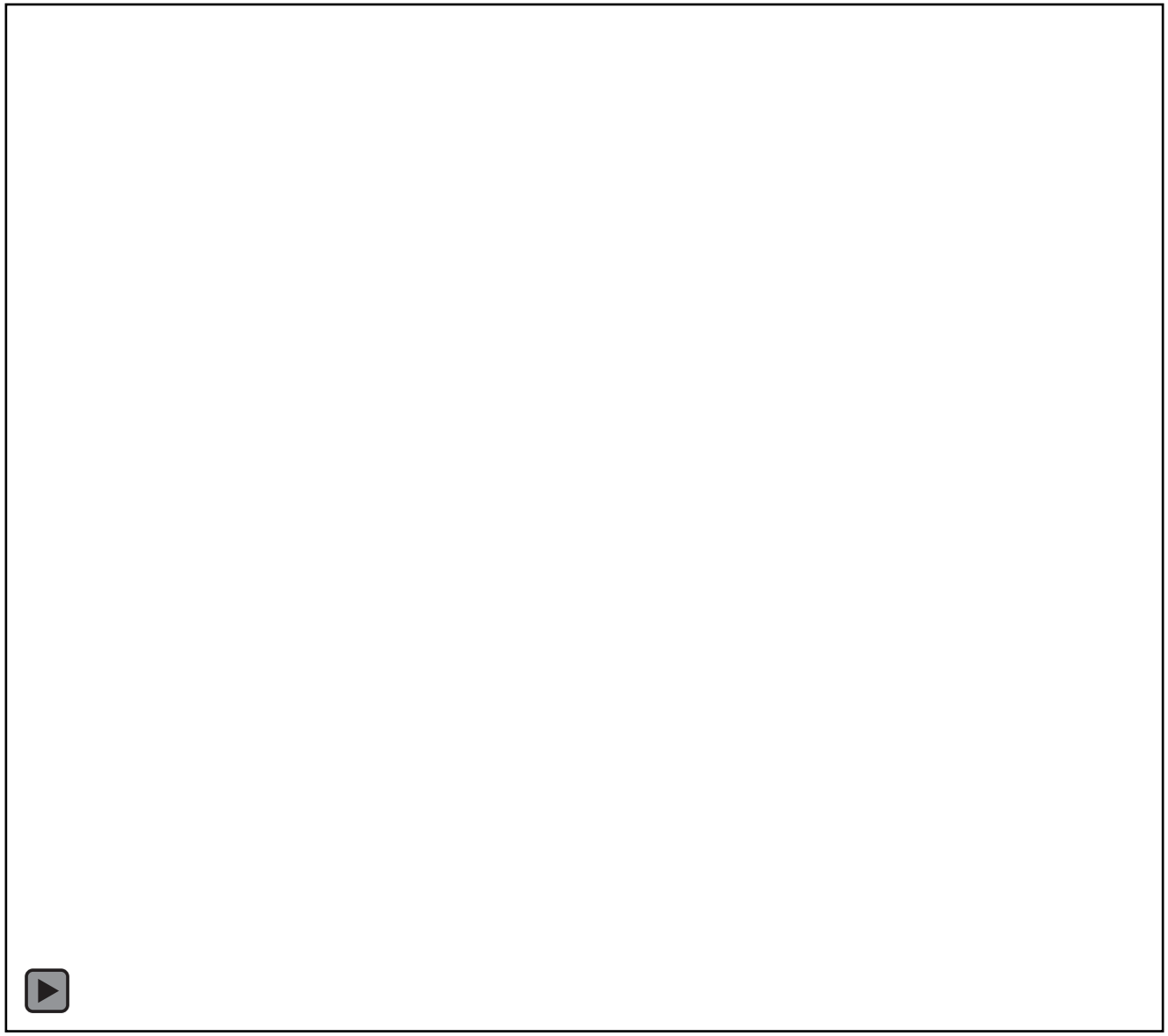




Wake Measurements: DTU SpinnerLidar



LINCOM 3-Component Estimation

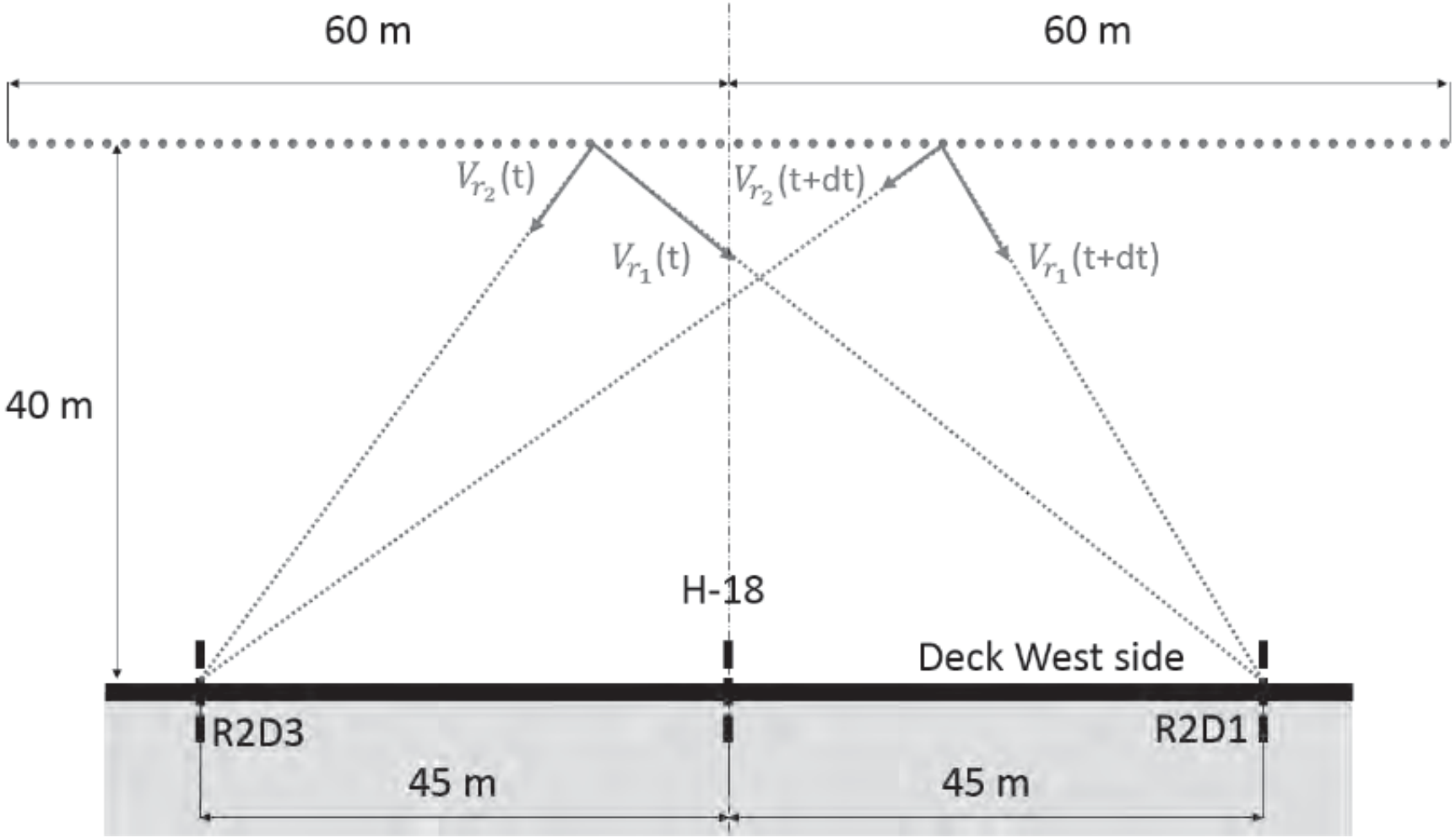


Off shore:

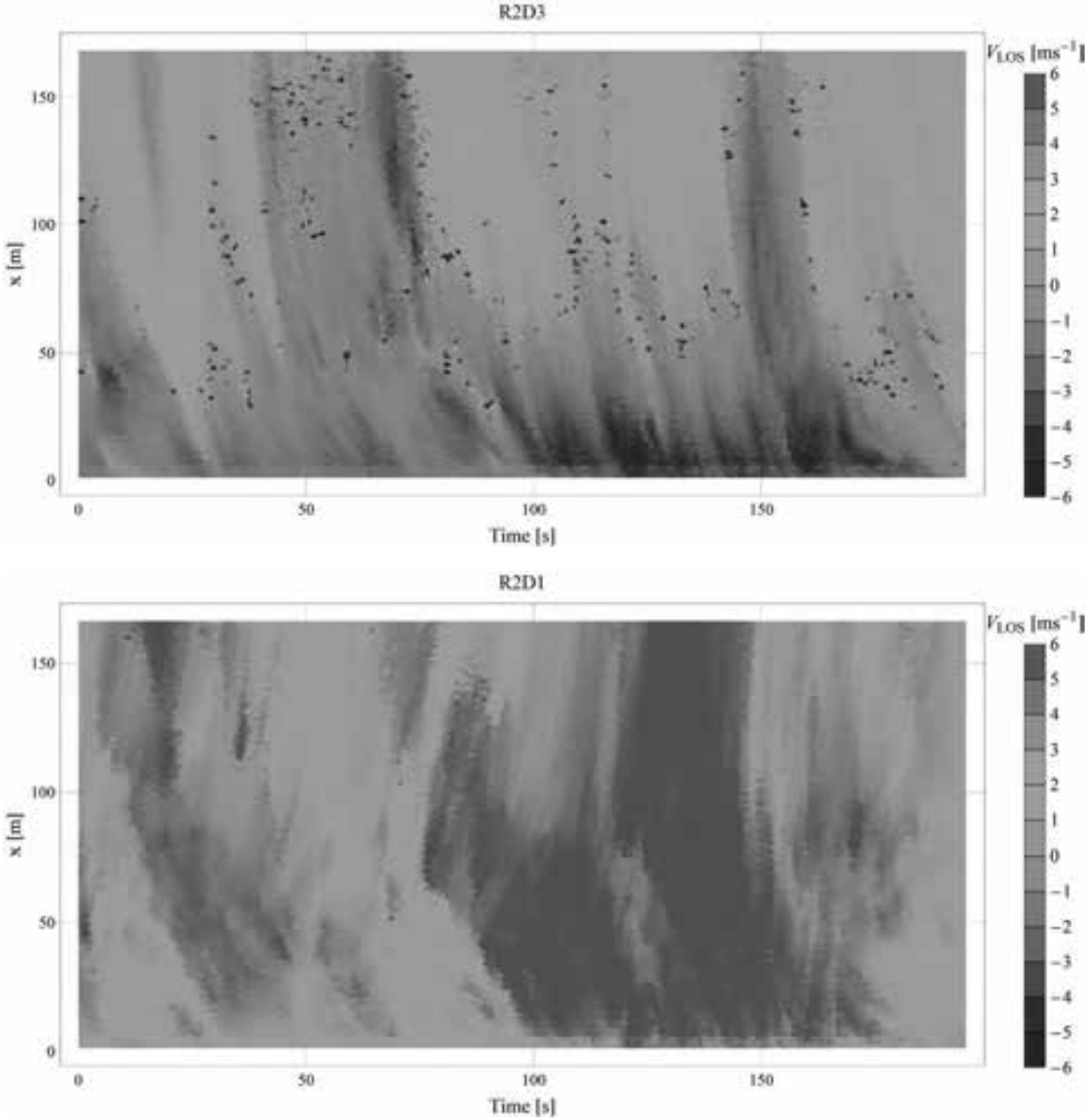

Lysefjordbroa

Top view of setup using two Short-range WindScanners @ Lysefjordbrua, May 2014

[University of Stavanger; Reykjavik University; DTU Wind Energy; Christian Michelsen Research – Norway; Geophysics Institute, University of Bergen]



2D horizontal plane scans 40 m upwind of bridge deck:

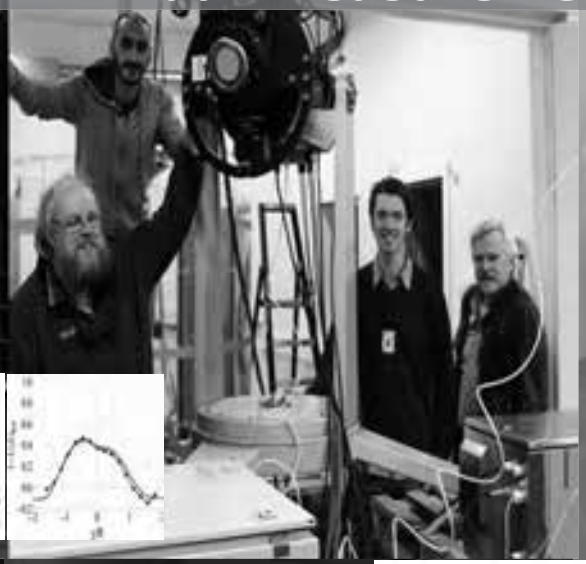


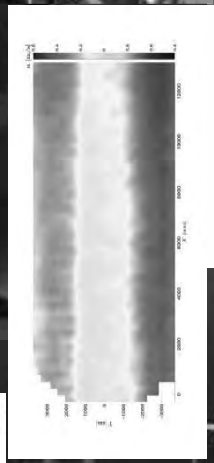
Lidar Measurements in Wind tunnels

Lidar measurements in wind tunnels

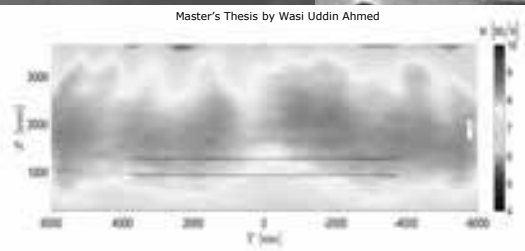
Continuous-wave lidars

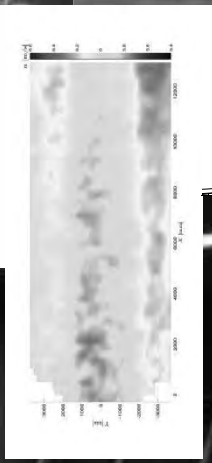
Small volumes at short distances

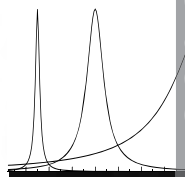


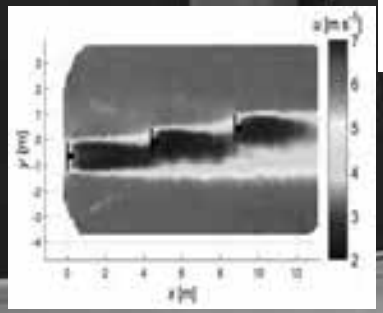


Master's Thesis by Wasi Uddin Ahmed



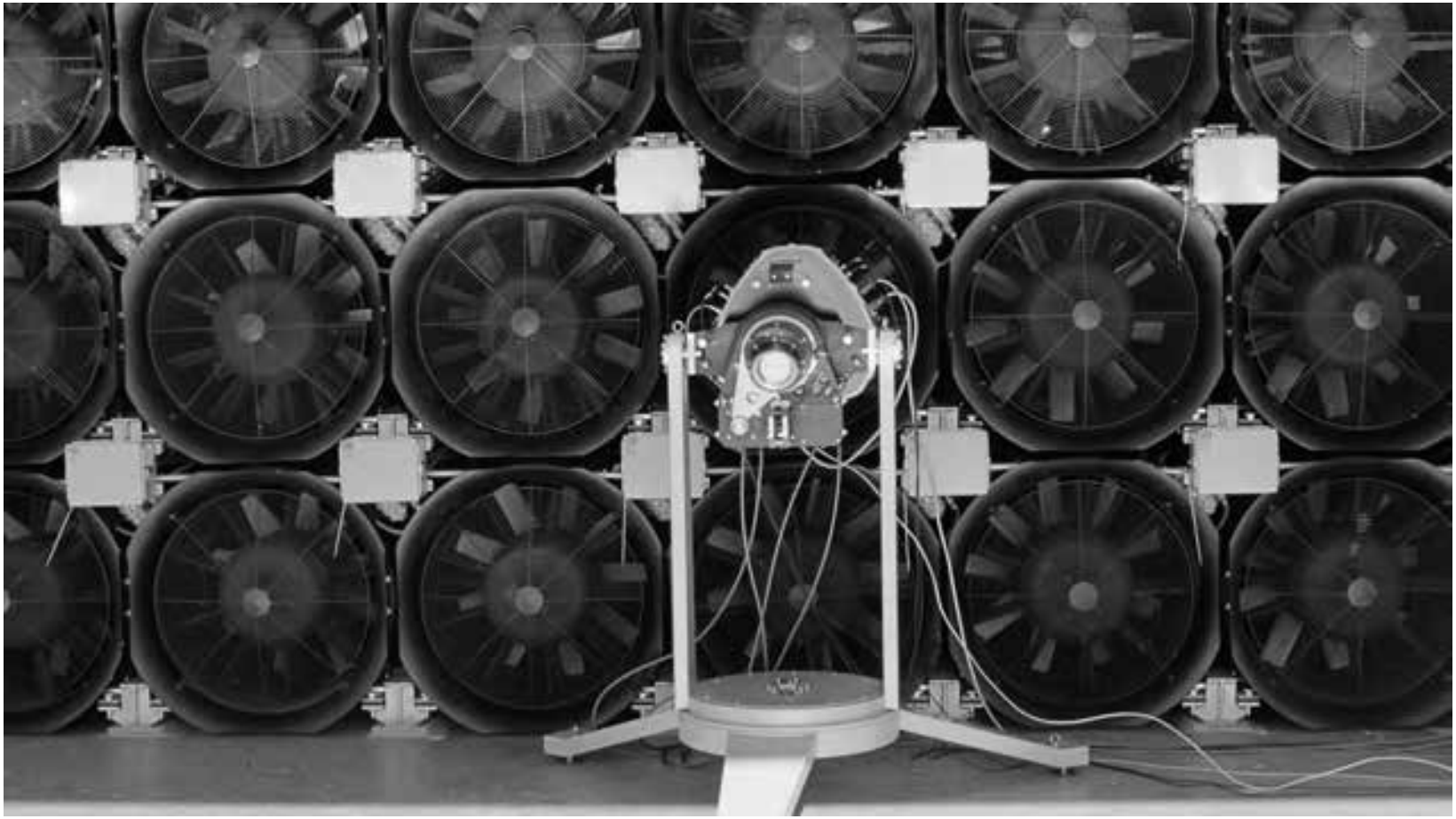




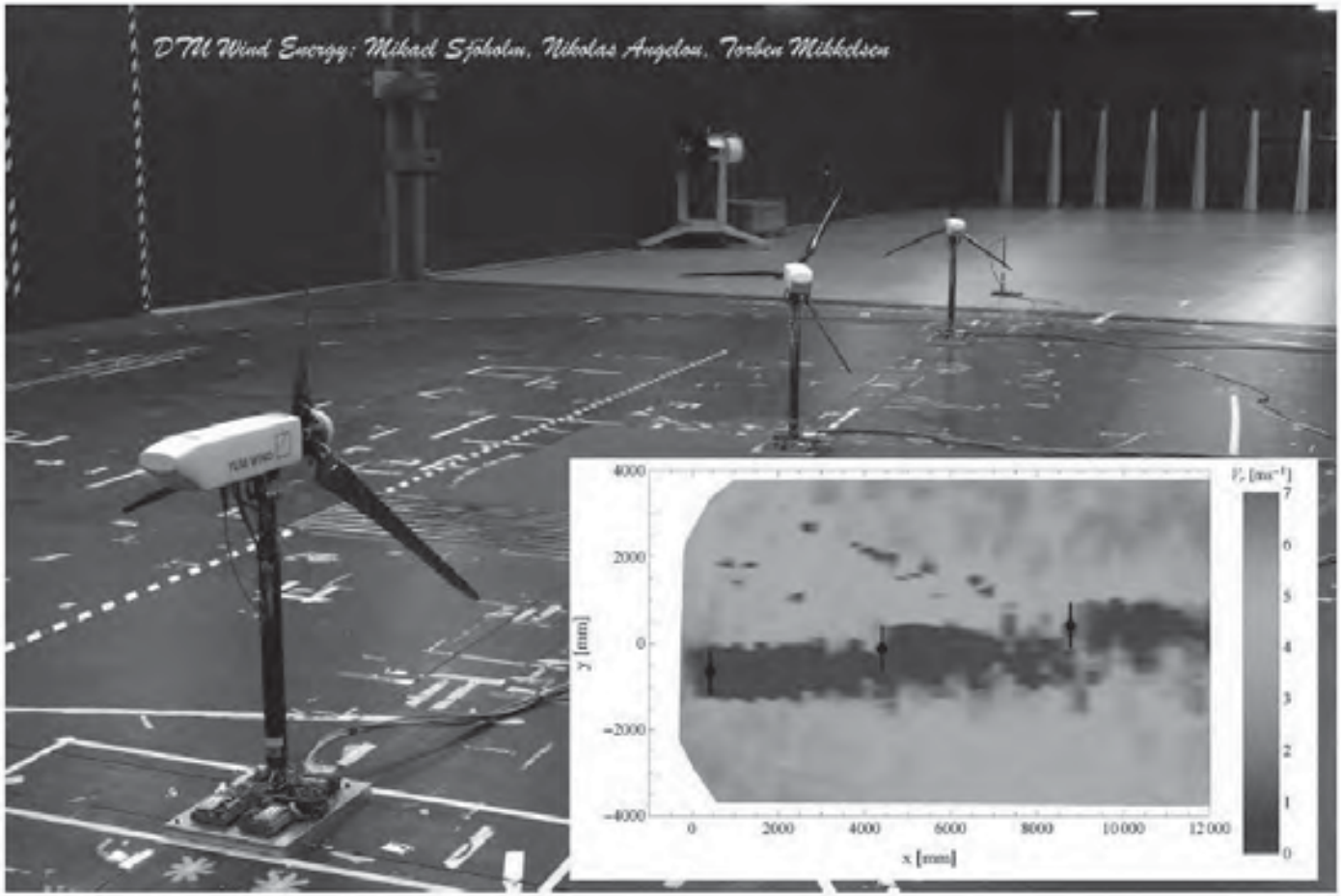


PoliMi, LM Wind Power, NTNU, VTT, Svend Ole Hansen, WindEEE Dome, *Poul la Cour*

WindScanner Wind Sensing Technology @ WindEEE Nov.2014:

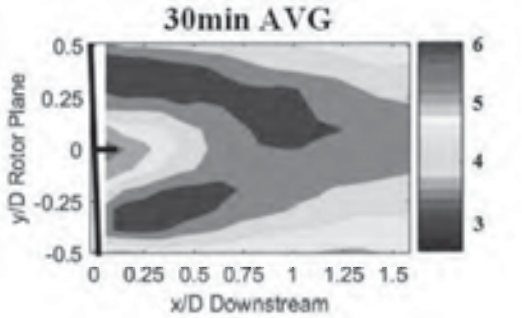


WindScanners and Wind Tunnels

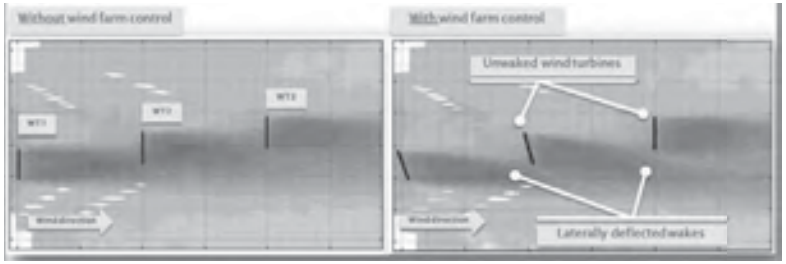


3D Wake Measurements by DTU Wind Energy

Wake Measurements behind a VAWT



Wake behind a HAWT



Measurements of wake steering in the POLIMI Wind tunnel by two WindScanners

Wake behind a Multi-rotor

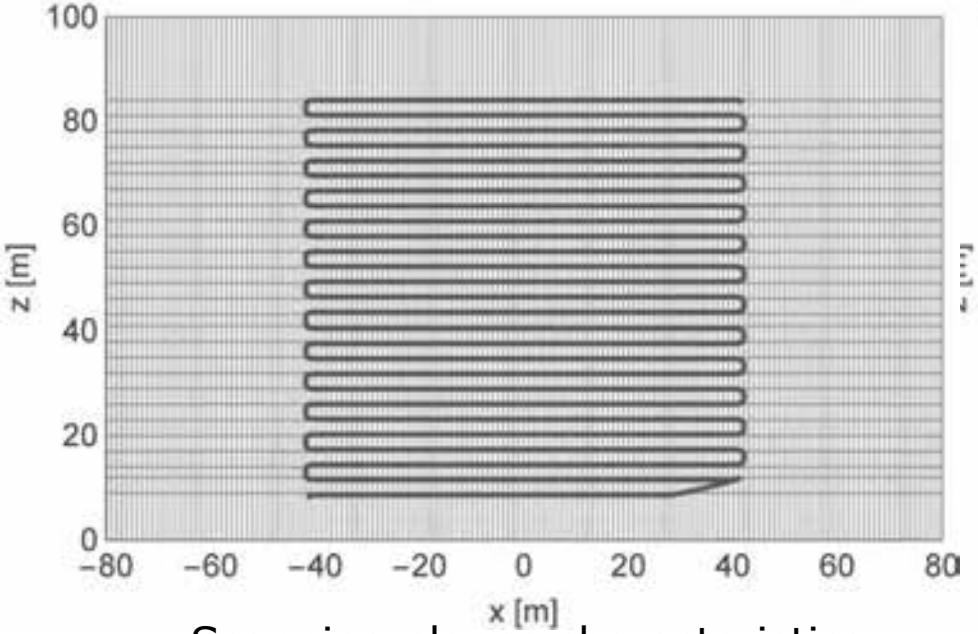
DTU Wind Energy
Department of Wind Energy

Short-range WindScanner Measurements on the wake of the Vestas multi-rotor turbine

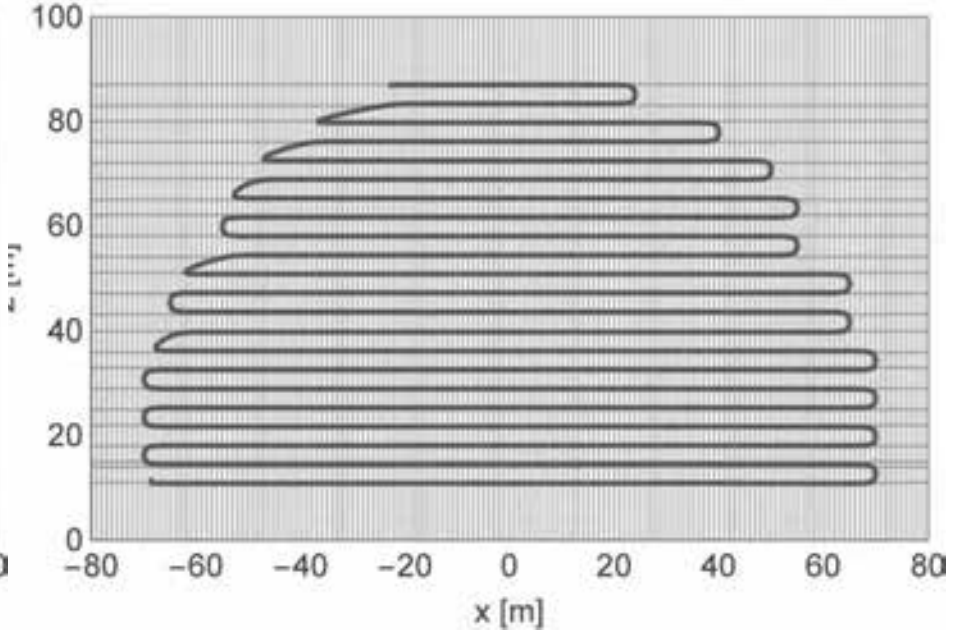
DTU Wind Energy
Department of Wind Energy

Experimental Setup – Side view

"close"-wake scanning planes



"far"-wake scanning plane



Scanning planes characteristics

Distance between lines (Ø)	0.1
Height [m]	10 – 87
Duration (minutes)	10

Technology and Experiments 2015:

WindScanner.eu

DTU

Wind component

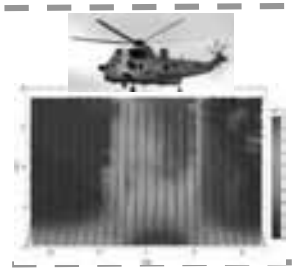
Ground based

Turbine mounted + others

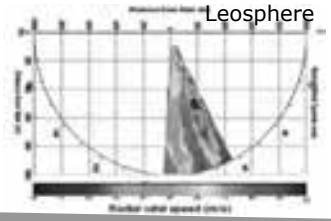
Applications

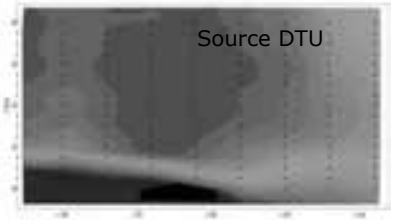
3 D

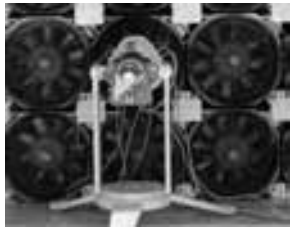
2 D



1 D







Technology

Long-range

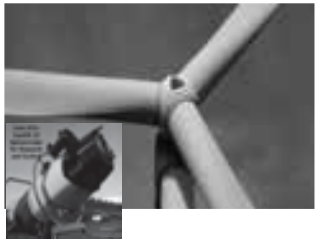
Short-range

WLS 200/400S DTU/IPU ScanHead

DTU/IPU Long-range WindScanner

DTU/IPU Short-range WindScanner

DTU/IPU Short-range WindScanner



DTU/IPU/ZephIR SpinnerLidar

DTU/IPU Lidics

References and Acknowledgements

www.WindScanner.eu

and

www.WindScanner.dk

DTU SpinnerLidar data from the V27 test turbine was collected at the Sandia Scaled Wind Farm Technology (SWiFT) facility as part of the US Department of Energy Wind Energy Technologies Office funded Atmosphere to Electrons (A2e) program.

Collaboration with staff at Sandia and at NREL is highly appreciated.