Wind Turbine Inflow and Wake Measurements Using Scanning Lidar: “WindScanners”

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2018 Sandia Blade Workshop
August 28-29, 2018
Lubbock, Texas
Our “WindScanner Vision” 2007:

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

Picture: Test site Høvsøre, Denmark:
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

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 Continuous wave (CW)
6” Telescope SR WindScanner ver. 2.0
Focal range 20 - 300 m
Long range Wind Scanners synchronously operating to measure wind speeds
VISION I:
Full scale off and on shore measurements on WT arrays & wakes
e.g. as here at Horns reef
Vision II: RI Windscanner
Secure wind resource estimation in particular in complex terrain
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)
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

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

\[ C_p = 4a(1 - a)^2 \]
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

Turbine Stopped

U Component

Wind Speed (m/s)

x (m)

Freestream

Hub

25% Span

50% Span

75% Span

100% Span

125% Span

DTU Wind Energy, Technical University of Denmark
Hub-height 3 min. average, $U = 11.42$ m/s

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

$W = 0.11$ 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

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

Negative speed when flow is coming from North East direction
Positive speed when flow is coming from South West direction

Positive speed when flow is coming from South West direction
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

Zephr 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.
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

$V_r [\text{m/s}]$
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
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

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

DTU Wind Energy: Mikael Sjobom, Nikolaos Angelou, Torben Mikkelsen
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
Short-range WindScanner Measurements on the wake of the Vestas multi-rotor turbine
Experimental Setup – Side view

"close"-wake scanning planes

"far"-wake scanning plane

Scanning planes characteristics

Distance between lines \( (\varnothing) \) 0.1

Height [m] 10 – 87

Duration (minutes) 10
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.