Lidar wind measurements in bridge engineering

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[e]University of Bergen

http://nn.wikipedia.org/wiki/Uburen#mediaviewer/File:Lysefjordbroen_sett_fra_Sokkanuten.jpg

Overview

- Background and motivation
- Wind lidar measurement principles
- Wind characteristics relevant to design of long-span bridges
- Pilot measurement campaing at Lysefjord bridge with
  - Single pulsed lidar
  - Short range WindScanners
- Brief overview over Fino1 and Bjørnafjord measurements
- Summary

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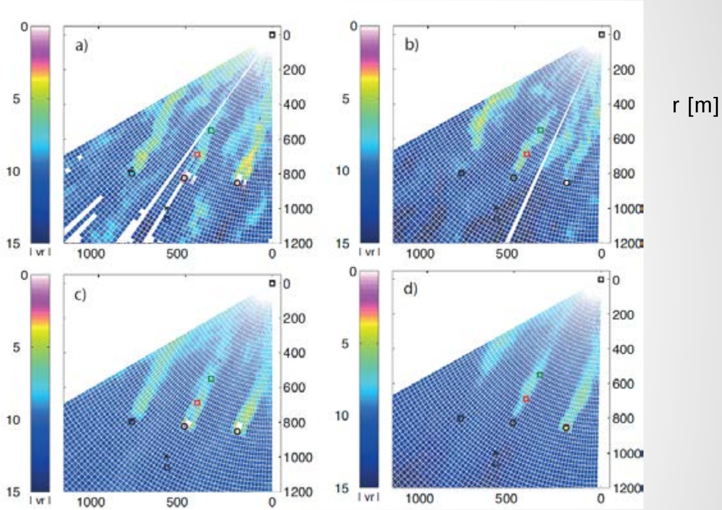
Background and motivation

- Accelerated development of wind velocity measurement devices based on the remote optical sensing over the past decade.
- Versatile use of lidars in wind energy (wind characteristics in complex terrain, wake studies, wind forecasting, power curve assessment, feed-forward control strategies etc.)

- => Possibility to complement wind measurements traditionally performed by the sonic anemometers from the met-masts on land, in the vicinity of the bridge site.

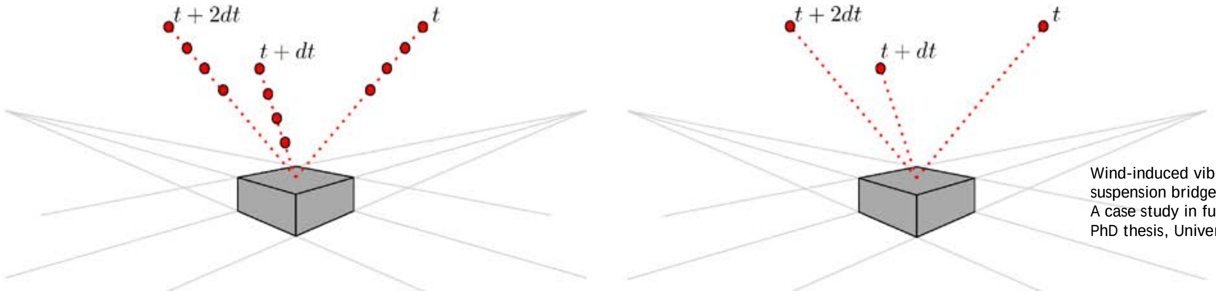


Contour plots of PPI scans at 4.7◦ (left) and 7.1◦ (right) elevation angle of a) & b) instantaneous, c) & d) 10 minutes mean wind speeds on November 1st, 2013. Circles, squares and the cross indication the locations of turbines, Windcubes and the met mast, respectively.

[1] Characterisation of single wind turbine wakes with static and scanning WINTWEX-W LiDAR data, Valerie-M. Kumer, Joachim Reuder, Benny Svardal, Camilla Sætre, Peter Eecen
Energy Procedia, *Volume 80*, *2015*, *Pages 245-254*

LIght Detection And Ranging
Measurement principles

- Laser beam emission and detection of the backscattered light.
- Wind velocity along a laser beam (Line Of Sight) estimated from the frequency shift of the backscattered light relative to the emitted light. λ=1.565 µm commonly used for wind measurements.
- Two types of emitted light signals:



Pulsed lidar with simultaneous along-beam measurements, shown at three consecutive time steps (dt~1s)

Continuous wave lidar monitoring volume(s) at a single focus distance.
Example: 50 measurement volumes distributed between 0˚ and 360˚ azimuth angle at a fixed height, dt=20 ms, i.e. 1 s for the entire scan at a given distance.

Wind-induced vibrations of a suspension bridge
A case study in full-scale, E. Cheynet, PhD thesis, University of Stavanger

- Fixed / restricted measurement orientation or
- Flexible orientation with scanning lidars or lidar systems

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Volume averaging effects

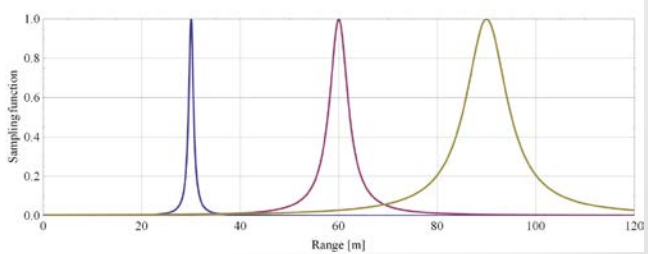
- Measurement over a finite volume stretched along the light beam, centered at the focus range of the light beam.

Pulsed lidar

Lidar (Leosphere)	Typical measurement range	Range gates
WINCUBE 100S	3km (100m resolution, 1s accumulation time)	25, 50, 75, 100 m
WINDCUBE 200S	6km (100m resolution, 1s accumulation time)	25, 50, 75, 100 m
WINDCUBE 400S	10km (200m resolution, 1s accumulation time)	75, 100, 150, 200m

- Fixed resolution
- Possible range gate overlap

CW lidar



Sampling functions for the ZephIR 150 CW lidar

Full width at half maximum (FWHM) 12.6 m at r=100 m and 3.15 at r=50 m.

From: Short-range WindScanner.dk, Technical Specification Document Sjöholm M. and Mikkelsen T.

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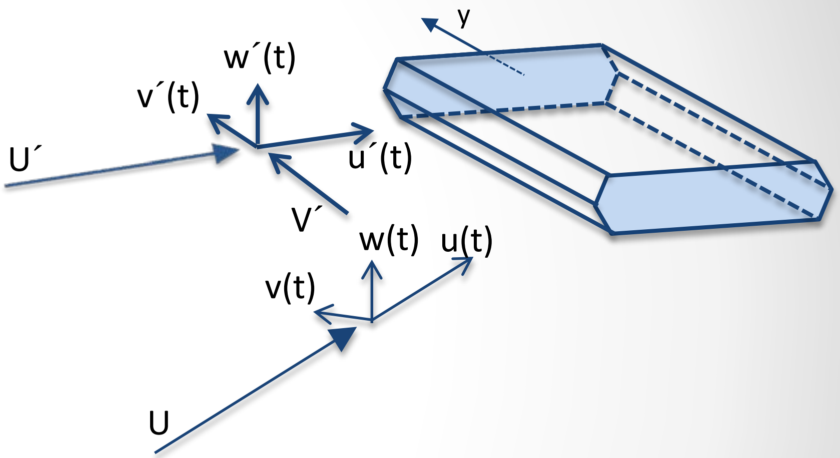
Wind characteristics relevant to design of long-span bridge

- Design mean wind speed (10 min, p=0.02)
- Turbulence intensity, I_u, I_w
- Turbulence spectra $S_u(f)$, $S_w(f)$
- Spatial structure of turbulence:

  Cross-spectra $S_{uu}(\Delta y, f)$, $S_{ww}(\Delta y, f)$, Co-coherence
- Other aspects:

  Flow uniformity in complex terrain

  Non-stationarity...



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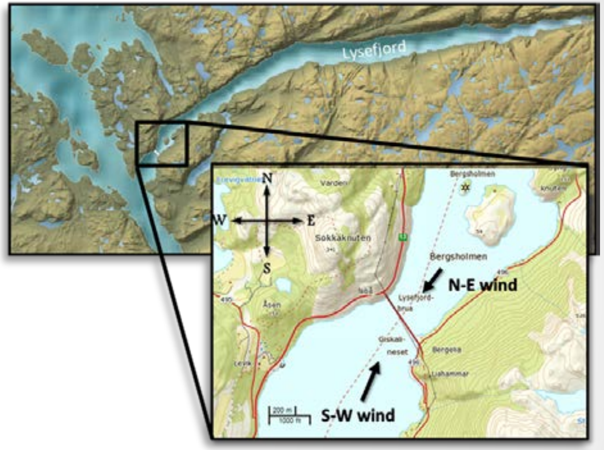
Pilot project on wind characterisation by lidars at Lysefjord bridge

Main bridge characteristics:

- 640 meter span
- Main span 446 m
- Towers 105 m tall
- 12 main cables
- Opened in 1997

- Design wind speed:
  Mean value: 36 m/s
  3-seconds gust 49 m/s

	Period[s]
HS-1	7,71
HS-2	1,80
HS-3	1,20
HA-1	2,26
HA-2	1,67
HA-3	1,00
VS-1	3,49
VS-2	2,50
VS-3	1,15
VA-1	4,69
VA-2	1,70
VA-3	0,83
TS-1	0,87
TS-2	0,31
TS-3	0,18
TA-1	0,47
TA-2	0,23
TA-3	0,15



- Demonstrate relevance of lidars for assessment of wind conditions for long-span bridges.
- Explore new lidar-based measurement setups and the data interpretation.

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Overview of monitoring activities

1. Long-term wind and response measurements

   (Nov 2013/May2014/May215 -): 5+3 sonic anemometers and 4+6 accelerometers +GNSS station for position/displacement monitoring

   Supported by the Norwegian Public Road Administration, University of Stavanger and NORCOWE (Norwegian Center for Offshore Wind Energy).

2. Wind characterization by lidars

   Part 2A (March – June 2014): one long-range pulsed Doppler lidar

   Part 2B (1 week in May 2014): two synchronized short-range WindScanners

   Supported by the Norwegian Public Road Administration,
   NORCOWE (University of Bergen /CMR), Leosphere A/S, UiS and the Danish Technical University.

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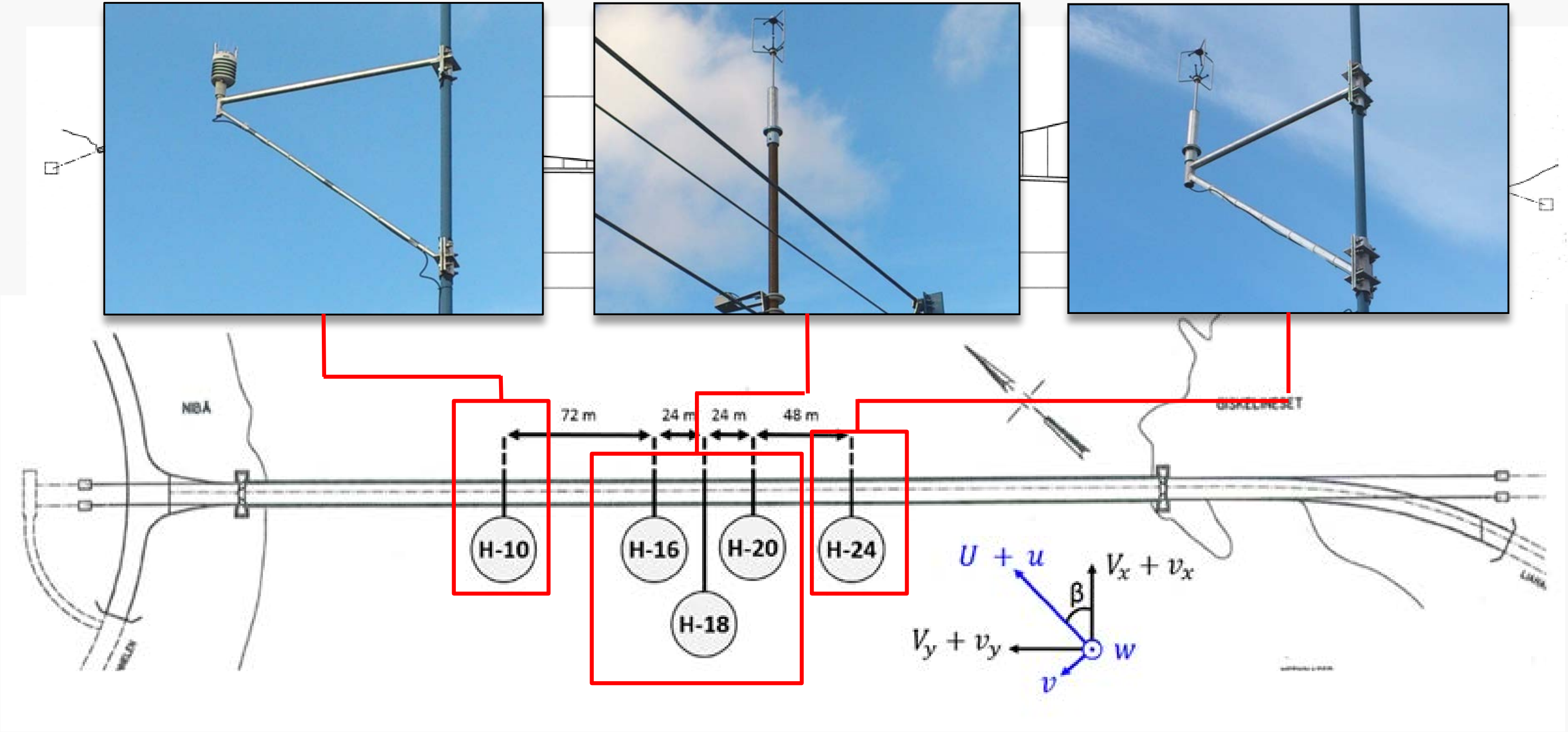
Long term set-up: Sonic anemometers Wind MatsterPro 1561-PK-020 and one Vaisala Weather Station WXT520 (H-10)



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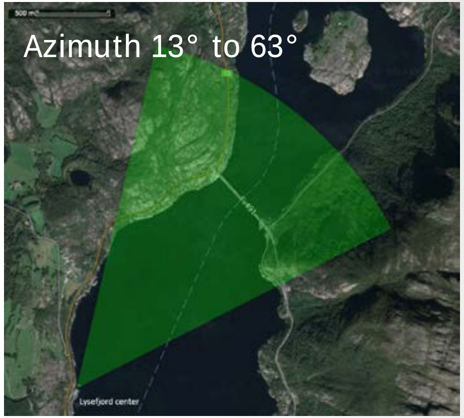
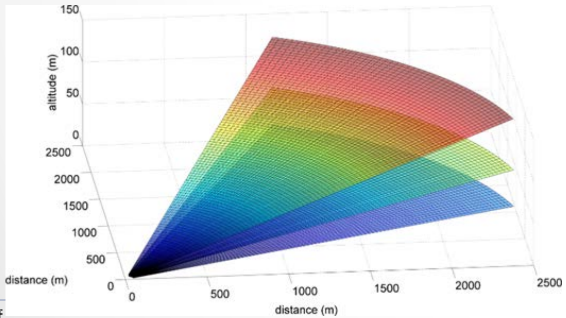
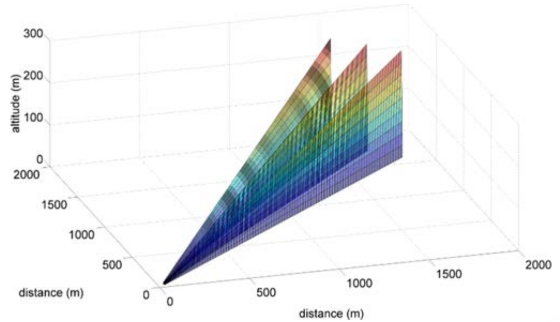
Wind flow characterization by a long-range pulsed Doppler lidar (March 2014 – June 2014)

- Collaboration between UiS and NORCOWE (UiB, CMR and Leosphere)
- WindCube100S, scanning modes:
  - Doppler Beam Swinging mode (DBS)
  - Plan Position Indicator mode (PPI)
  - Range Height Indicator mode (RHI)
  - Sequential Fixed Line of Sight mode (LOS)
- 25 m range gates





PPI, elev. 0.8°, 1.8° and 3.2°



RHI Azimuth 37 °,38 ° and 39 °

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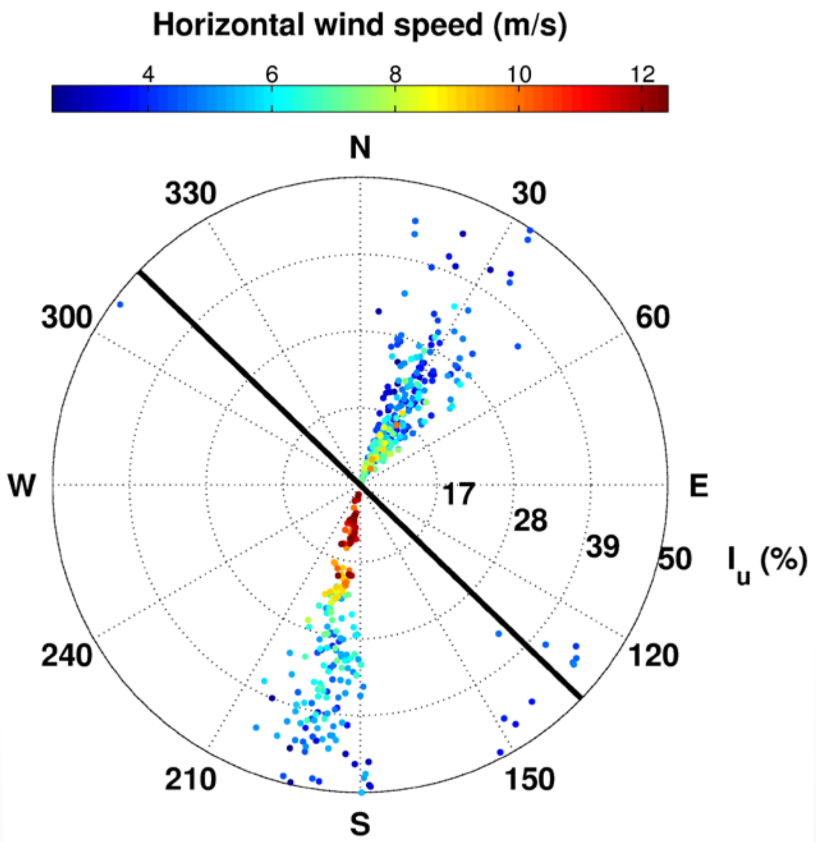
Example: Mean wind speed and turbulence intensity I_u recorded by sonics on 22.5.2014



Comparison of the WindCube100S and the sonic anemometer data

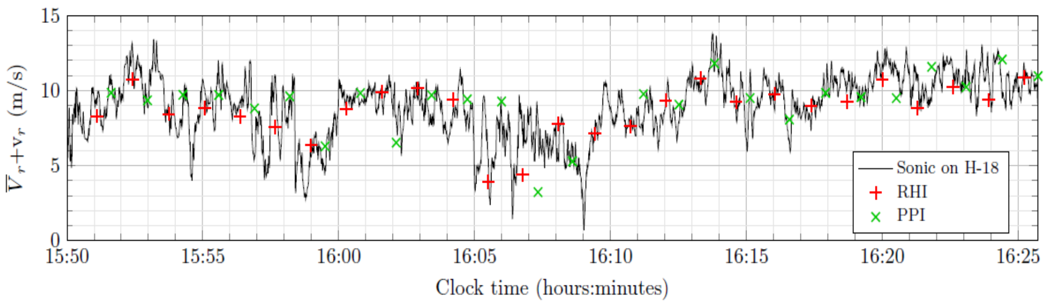


Figure 6 Along-beam wind velocity from the PPI scan, the RHI scan and the anemometer on H-18 on 2014-05-22 (S-SW wind).

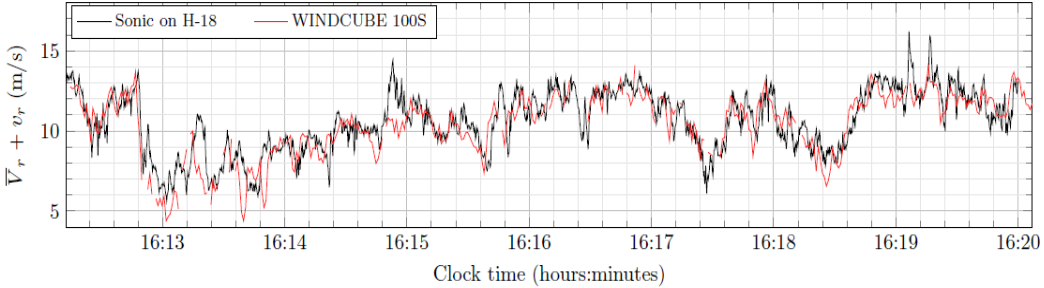


Figure 7 Along-beam wind velocity from the LOS scan and the anemometer on H-18 on 2014-05-22 (S-SW wind).

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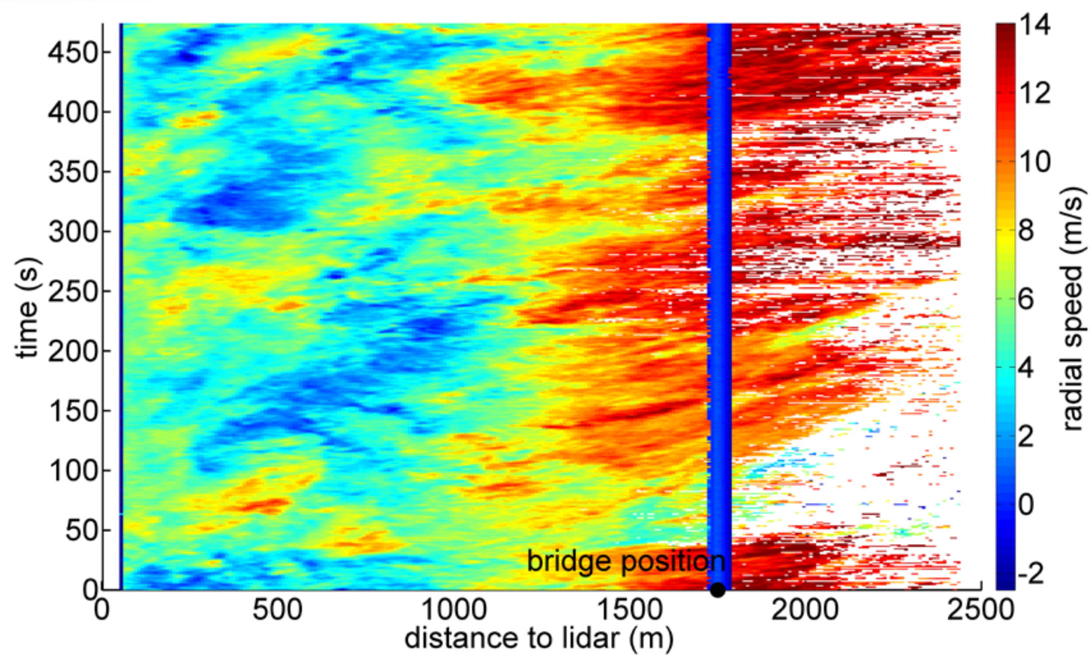
[3] Assessing the potential of a commercial pulsed lidar for wind characterization at a bridge site,
Etienne Cheynet, Jasna Bogunovic Jakobsen, Jonas Snbjörnsson, Joachim Reuder, Valerie Kumer, Benny Svardal,
to appear in Journal of Wind Engineering and Industrial Aerodynamics.

Non-scanning, fixed line-of-sight, measurements:

Example of a LOS data by WindCube100S,



Radial wind velocity recorded by a LOS scan elev=1.8°
azim=39°; 22.05.2014 starting at 16:12:06

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Comparison of the wind statistics based on the WindCube100S and the sonic anemometer data

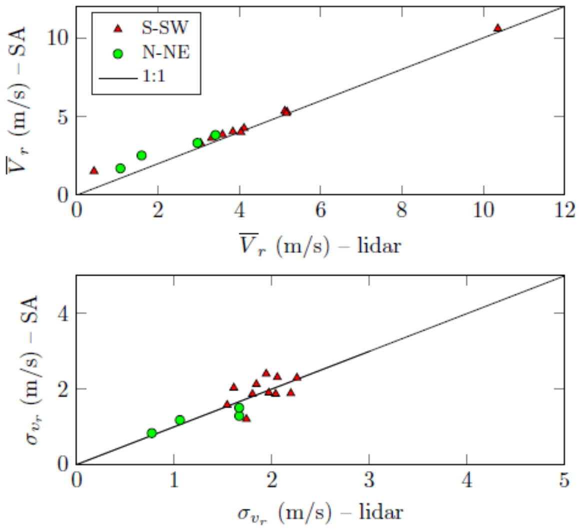

Figure 8 Mean value and standard deviation of the line-of-sight wind component measured by the lidar and the sonic anemometer (SA) on H-18. The data set used is recorded on 2014-05-22 between 10:56 and 16:20 with the LOS scanning mode (15 samples of 8 min to 10 min duration).

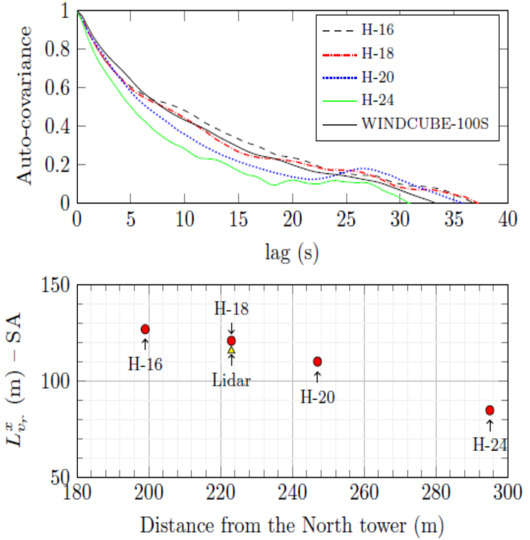

Figure 9 Top: Auto-covariance function for the LOS scan and the corresponding anemometer records, with $\overline{V}_r = 10.4\,\mathrm{m\,s^{-1}}$. Bottom: along-beam integral length scales from the sonic anemometers on H-16 to H-24. The data set used is recorded on 2014-05-22 between 16:12 and 16:20 (Fig. 7).

From [3]

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Power spectral density

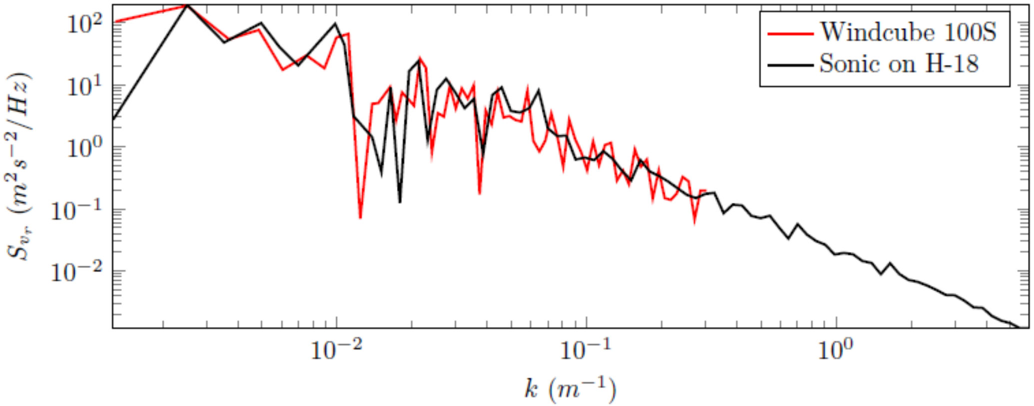

Fig. 8 Power spectral density of the recorded time series between 16:12:06 and 16:20:00.

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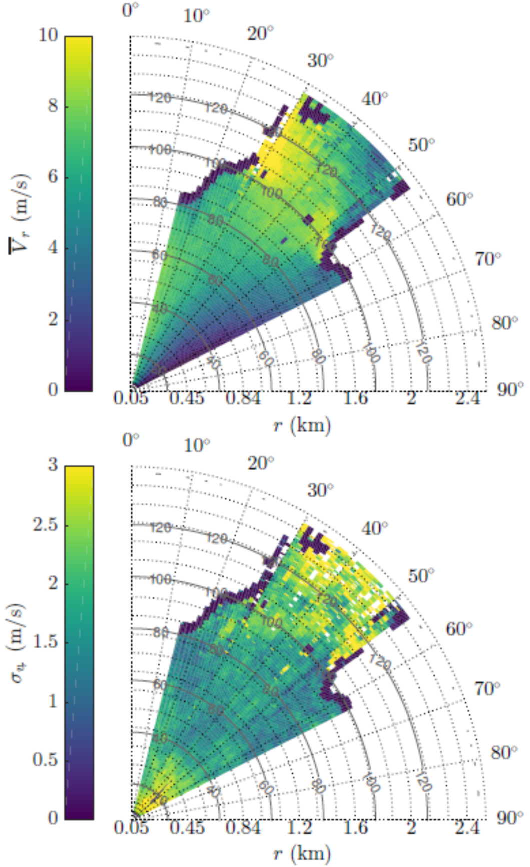

Figure 13 Mean (top) and standard deviation (bottom) of the along-beam wind velocity derived from PPI scans recorded on 2014-05-22 between 16:50:22 and 17:25:44 with an elevation of 3.2°. The wind was blowing from S-SW with $\overline{V}_x = 8.0\,\mathrm{m\,s^{-1}}$ at the bridge site. The radial grey contour indicates the altitude (in meters) above the sea level.

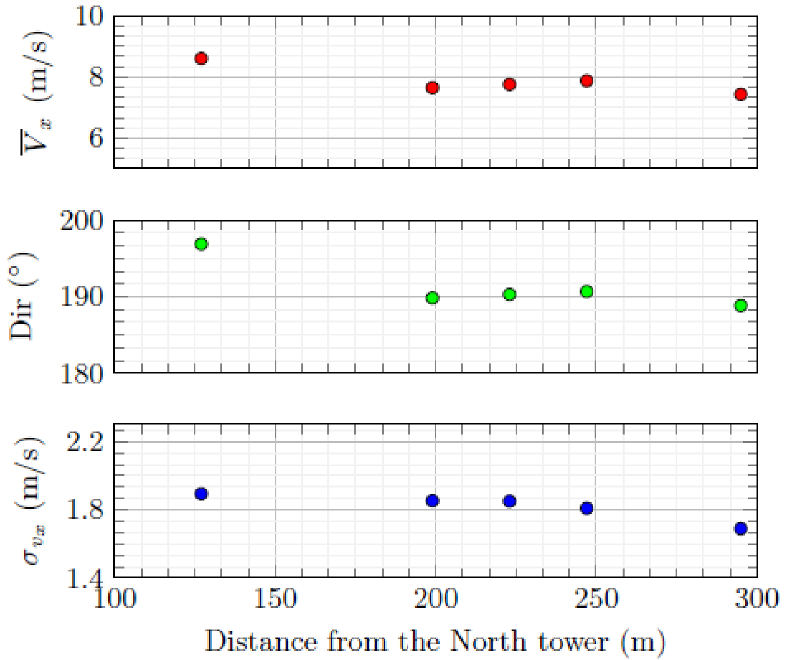

Figure 15 Mean wind velocity (top), mean wind direction (middle) and RMS of the wind velocity (bottom) along the bridge, based on anemometer records between 16:50:22 and 17:25:44 on 2014-05-22.

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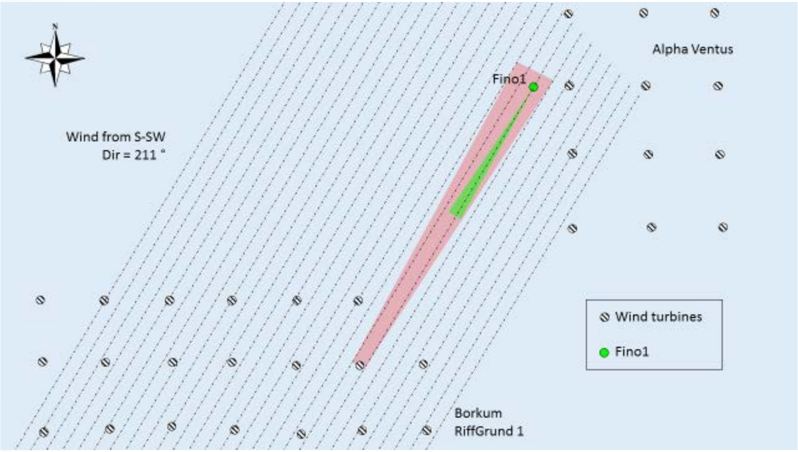
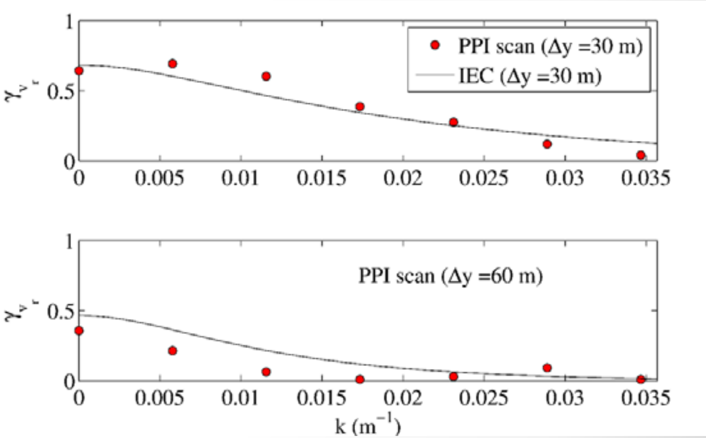
Fino 1 coherence measurements by a single long range lidar



Lateral root coherence



Fs=0.13 Hz

Challenge: alignment with the mean wind direction

[4] Wind coherence measurement by a single pulsed Doppler wind lidar,
Etienne Cheynet, Jasna Bogunovic Jakobsen, Benny Svardal, Joachim Reuder, Valerie Kumer,
Energy Procedia, Volume 94, September 2016, Pages 462–477

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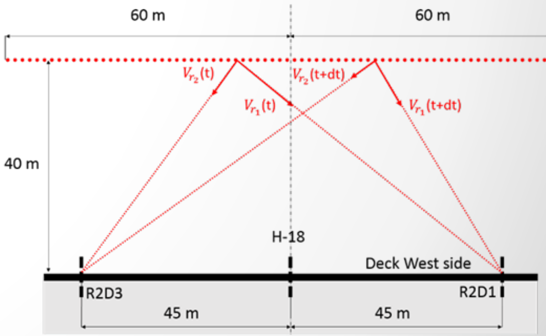
Multi-lidar measurements, May 2014
Short range WindScanners deployment

- Two short-range WindScanners developed by the Technical University of Denmark, building on ZephIR150, deployed on the bridge walkway on the West side.
- Synchronized to map the airflow in different planes (horizontal and “vertical”) SW from the bridge, and operated remotely.
- High-frequency, separate LOS data also recorded.
- The Doppler spectra averaged such that LOS wind velocities were provided at about 390 Hz and the scan pattern frequency was 1 Hz.
- Scanning sequences devoted to capturing the spatial characteristics of the inflow, as well as various forms of the bridge signature in the airflow.



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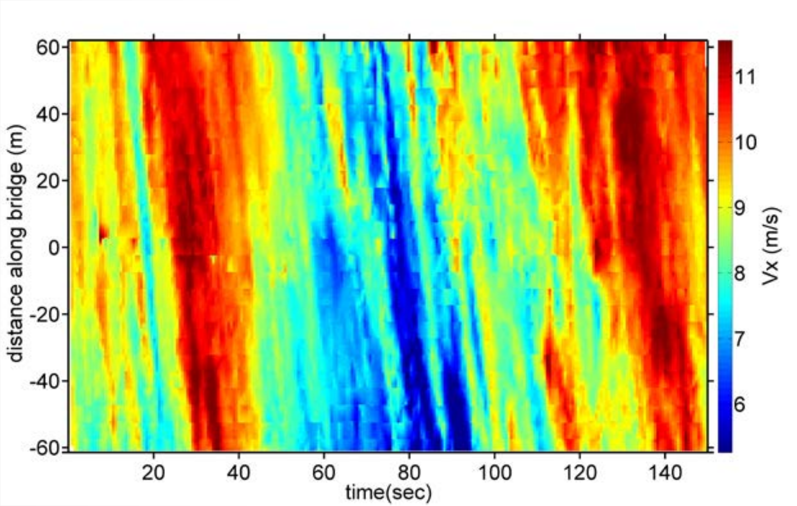
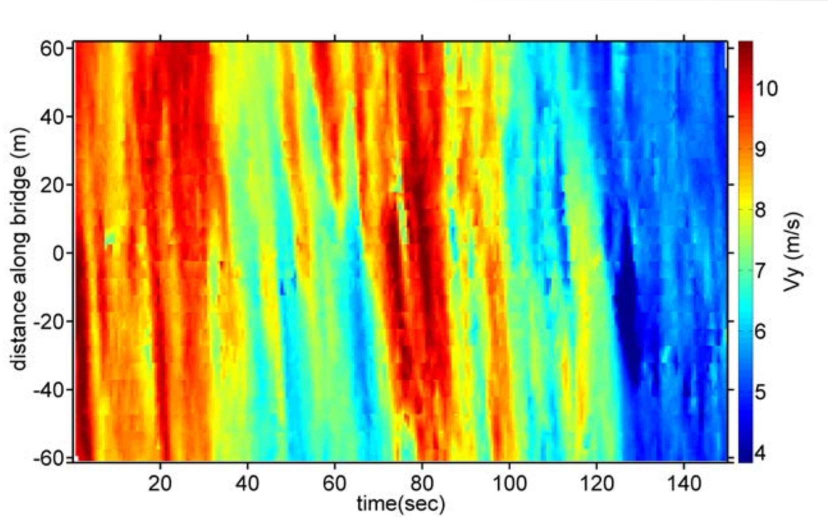
Horisontal wind velocity scan 40 m in front (SW) of the bridge by Short-range WindScanners





22.5.2014, 17:20, Horizontal wind component perpendicular to (left) and along (right) the bridge

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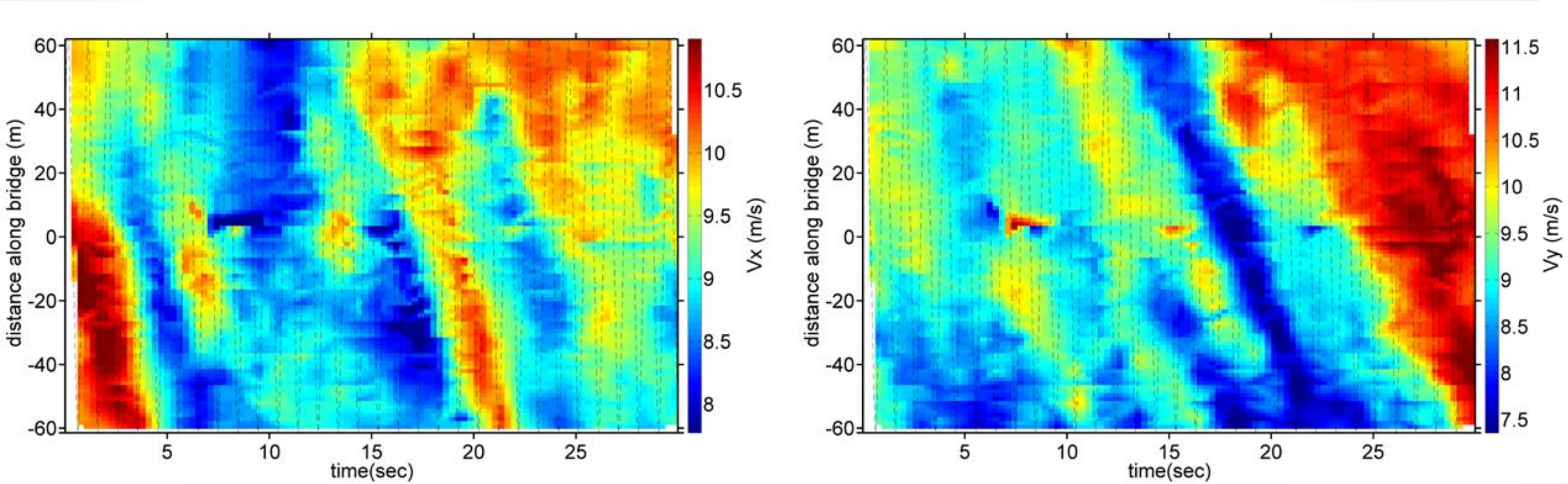
Horisontal wind velocity scan 40 m in front (SW) of the bridge by Short-range WindScanners



22.05.2014, 17:20, Horizontal wind component perpendicular to (left) and along (right) the bridge. Scan pattern overlaid the measurements.
=>Wind from South

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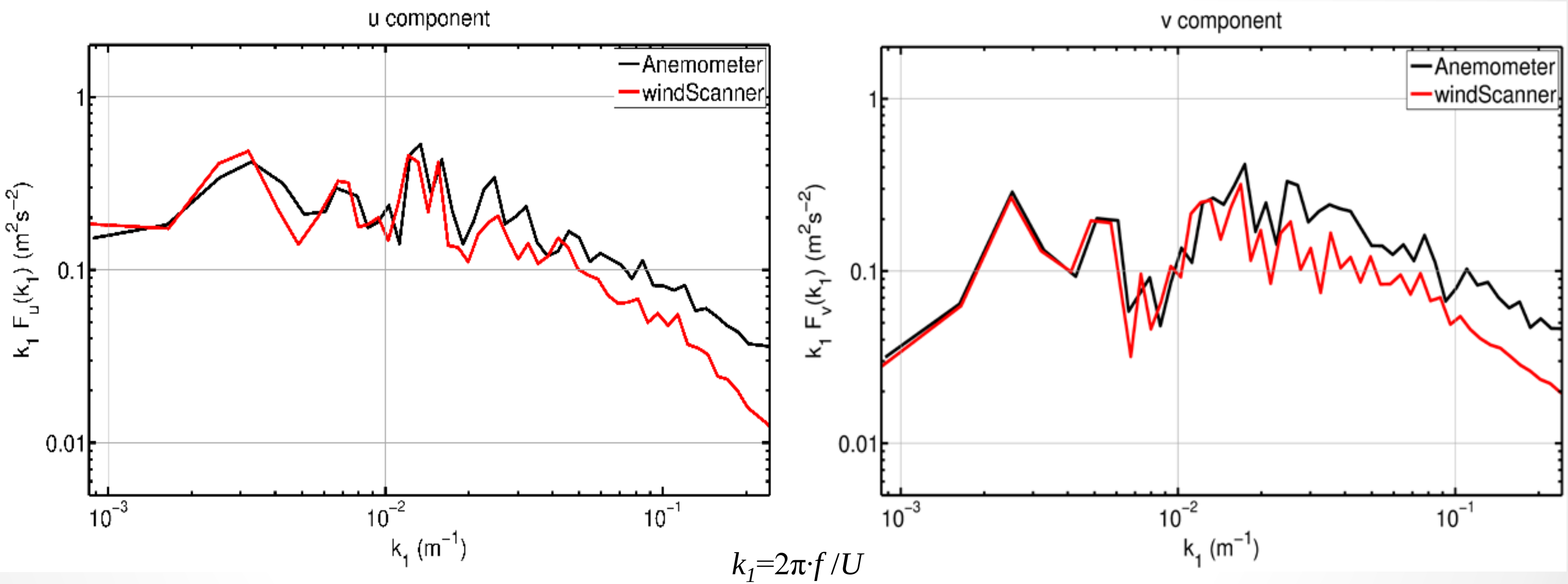
Spectra based on short-range WindScanners and sonic anemometers



$k_1 = 2\pi \cdot f / U$

Power spectral density of the longitudinal (left) and lateral turbulence (right), based on 20 minutes data starting at 17:20, 22.5.2014.

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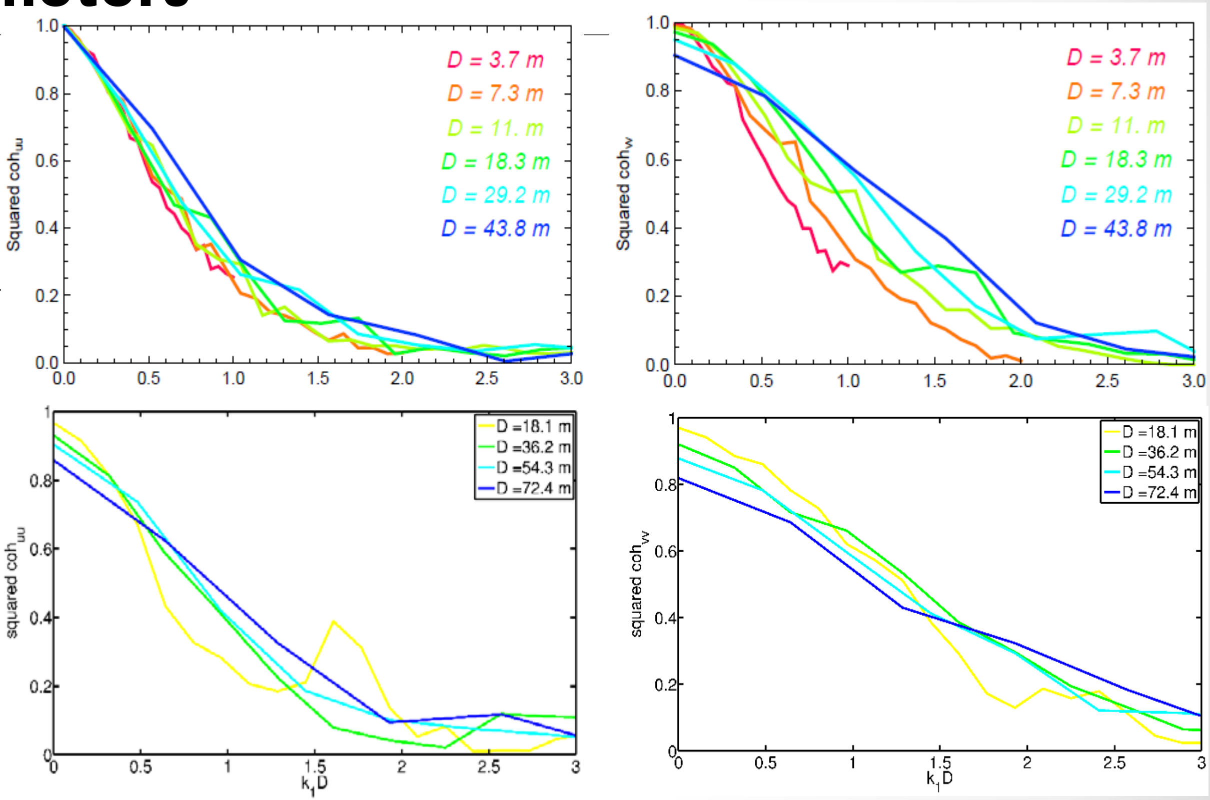
Coherence based on short range WindScanners and sonic anemometers

$$\left|Coh_u(D,k_1)^2\right| = \frac{\left|F_{uAuB}(k_1)\right|^2}{F_{uA}(k_1)F_{uB}(k_1)}$$



Squared coherence of the along-wind turbulence (left) and the lateral turbulence (right).
D is the across-wind projection of the distance Δy between the observation “points”.

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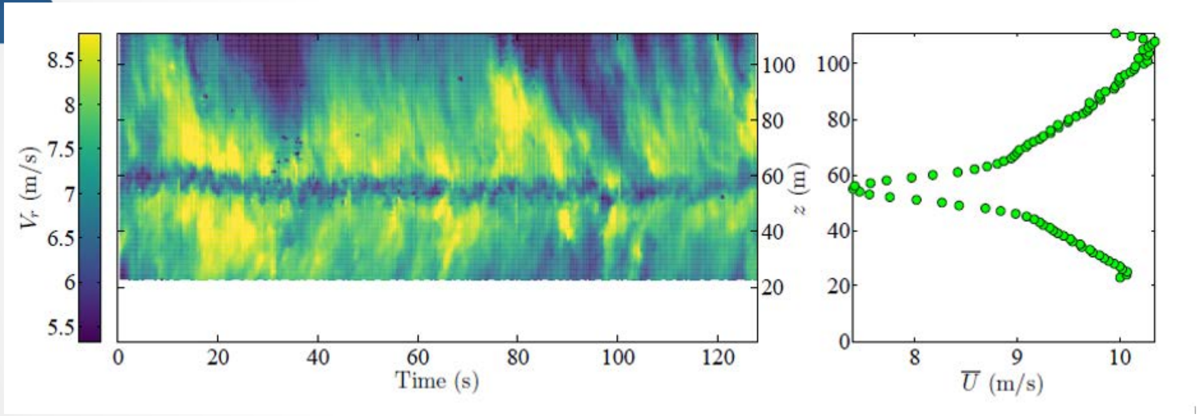
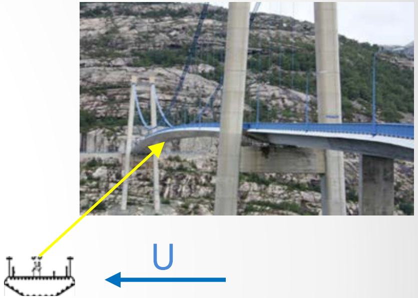
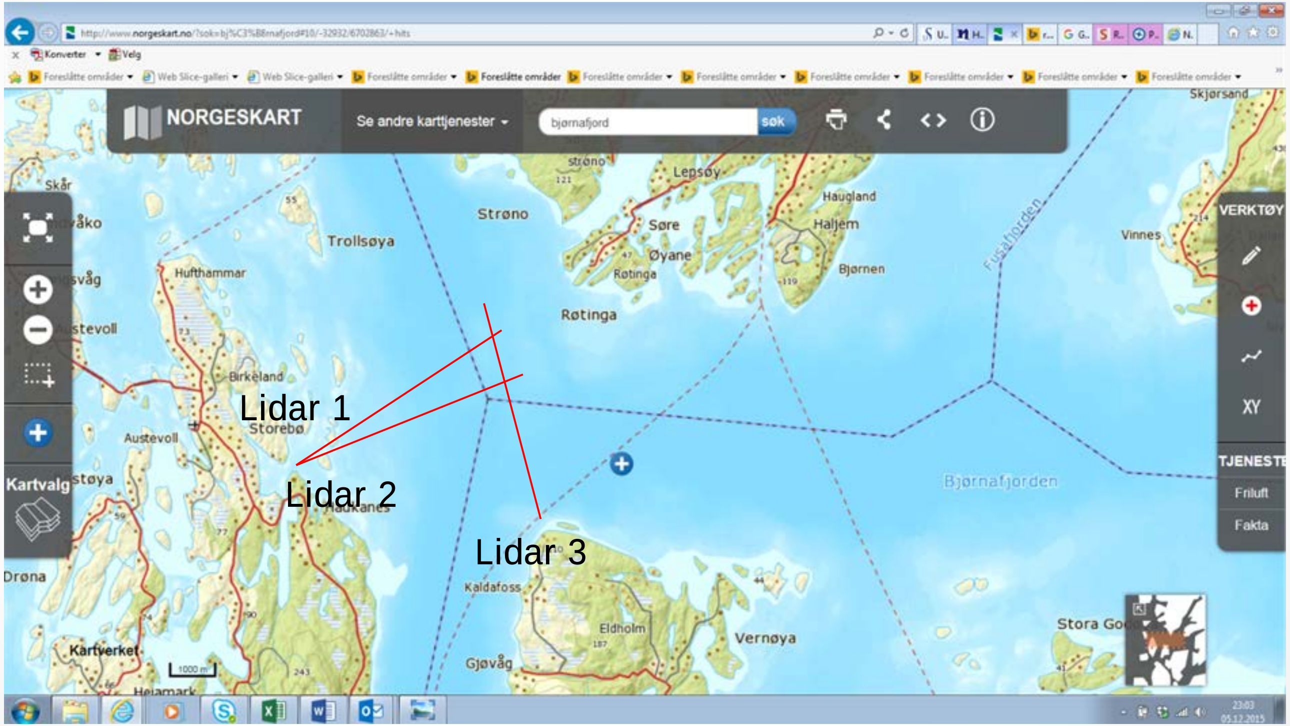
Wake measurements by short range WindScanners





Cheynet et al., BBAA VIII, June 2016

Bjørnafjorden measurement campaign May-June 2016
DTU WindScanner system with 3 WindCube 200S



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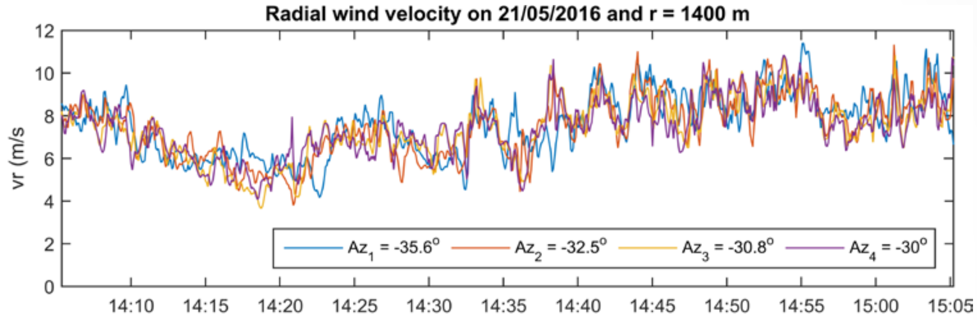
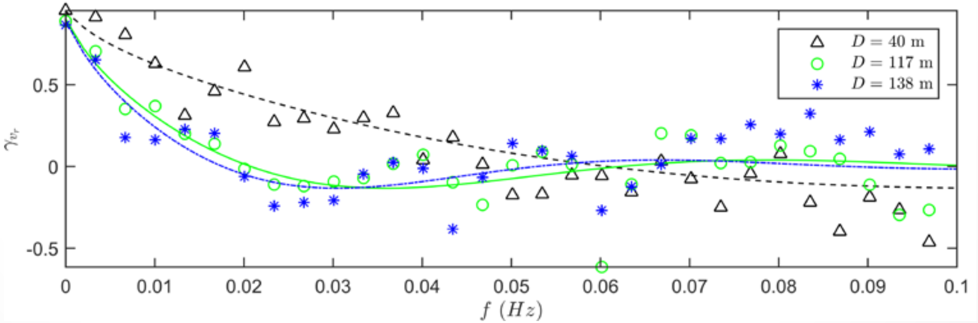
Preliminary results from the Bjørnafjord data





Summary

- Wind measurement techniques based on optical remote sensing offer valuable supplement to wind monitoring by cup and sonic anemometers for long-span structures, in particular for surveying large, low-frequency wind gusts, and prior to bridge construction.
- Synchronized multi-lidar arrangement fundamental to capture the spatial character of turbulence.
- Second order statistics based on lidar data relates well to the results based on «point» measurements
- Further work needed to develop measurement configurations for several km wide fjord spans, considering the trade off between the domain size, spatial and temporal resolution.

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