Nørrekær Enge UniTTe campaign

a ZephIR lidar perspective

Chris Slinger
ZEPHIR LIDAR

UniTTe Open Workshop
November 2016

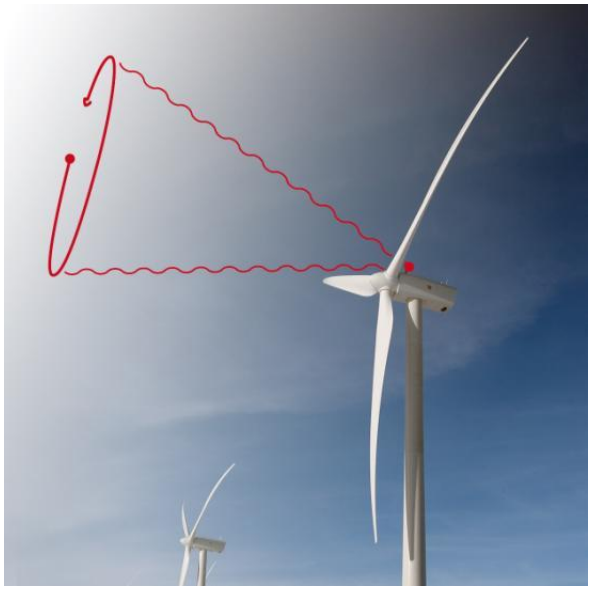
CONTENTS

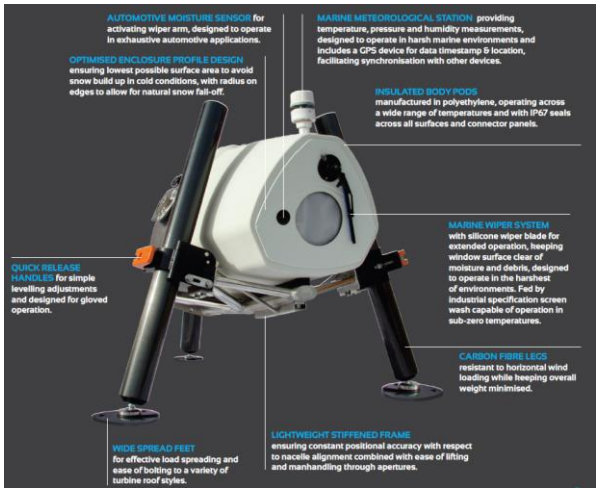
- The ZephIR DM (ZDM) lidar
- UniTTe white box calibration of ZDM used at NKE
- ZDM calibration stability
- The NKE trial and some ZDM results
  - Power curves, induction zone, shear & veer, turbulence, wind yaw misalignment, wake visualisation
- Using blade returns to check for turbine axis ↔ lidar axis alignment
- The ZephIR power curve procedure document
  - for nacelle mounted, circular scan CW lidars

THE ZEPHIR DM – main characteristics

ZEPHIR LTD'S WORKHORSE NACELLE MOUNTED LIDAR

- Circular scan, continuous wave (CW), monostatic homodyne lidar
- Mature product, more 100 turbine deployments
- Optimised for mounting on nacelle roof, but dual mode capability to allow ground use too
- Sealed, integrated single pod
- Visible laser system for accurate alignment with turbine rotor axis
- Inclination and roll sensors ensure knowledge of probe beam position and high availability readout at user specified measurement heights and ranges
- Broad range of measurement capabilities including
  - Hub height and rotor equivalent wind speeds
  - Power law and non-power law vertical wind shear
  - Wind yaw misalignment and veer at multiple, user specified number of heights
  - TI and spectral turbulence
  - Wind flow complexity measurement and visualisation
  - Air pressure, temperature, and humidity using on-board met-station
- State-of-the-art turbine performance, measurement, optimisation and turbine control investigations

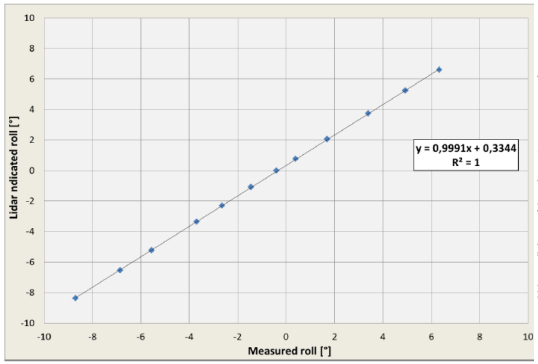


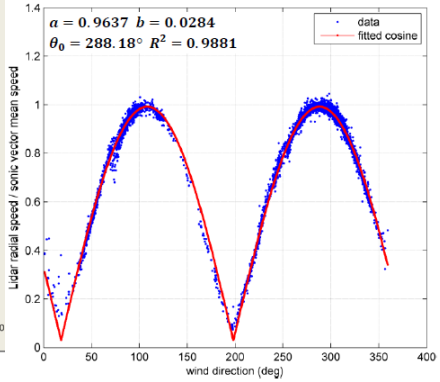


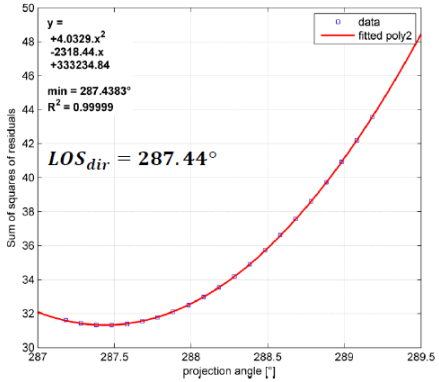
UniTTe white box ZDM calibration

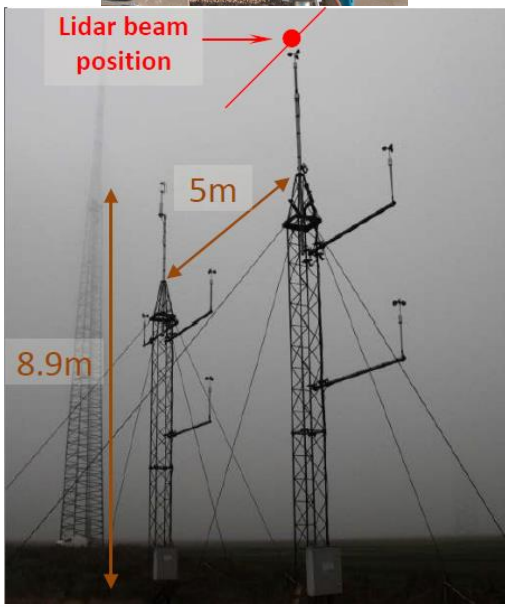
INDEPENDENT CALIBRATION TRACEABLE TO NATIONAL STANDARDS

- Inclinometers calibrated (tilt and roll)
- Scan geometry verification
- LOS velocity calibration
- Confirms accuracy of ZDM technology and ZephIR in-house calibration and validation procedures









"The calibration results proved to be consistent, with a high level of agreement between the measured radial wind speed and reference quantity values"

Summary of calibration results – linear regressions (binned RWS vs. reference)

		"2-deg phase" LOS velocity
LOS direction		287.44°
Number of valid data points		2140
Forced regression on binned data	Gain	1.0050
	R^2	0.9998

Reference: DTU Wind Energy Report E-0088
http://www.unitte.dk/publications-on-unitte/reports

ZephIR Lidar

ZephIR lidar performance stability

- Performance stability is important, especially for long measurement campaigns
- The measurement performance of ZephIR lidars is mechanically defined e.g.
  - Silicon scanning prism defines scan angle
  - DSP quartz clock
  - Mechanical micro cavities define laser wavelength
- ZephIR lidar performance will not drift
- Confirmed by in-house measurements. E.g.
  - Performance measured pre-deployment using 91 m IEC-compliant mast
  - 40 months unattended deployment
  - Performance remeasured

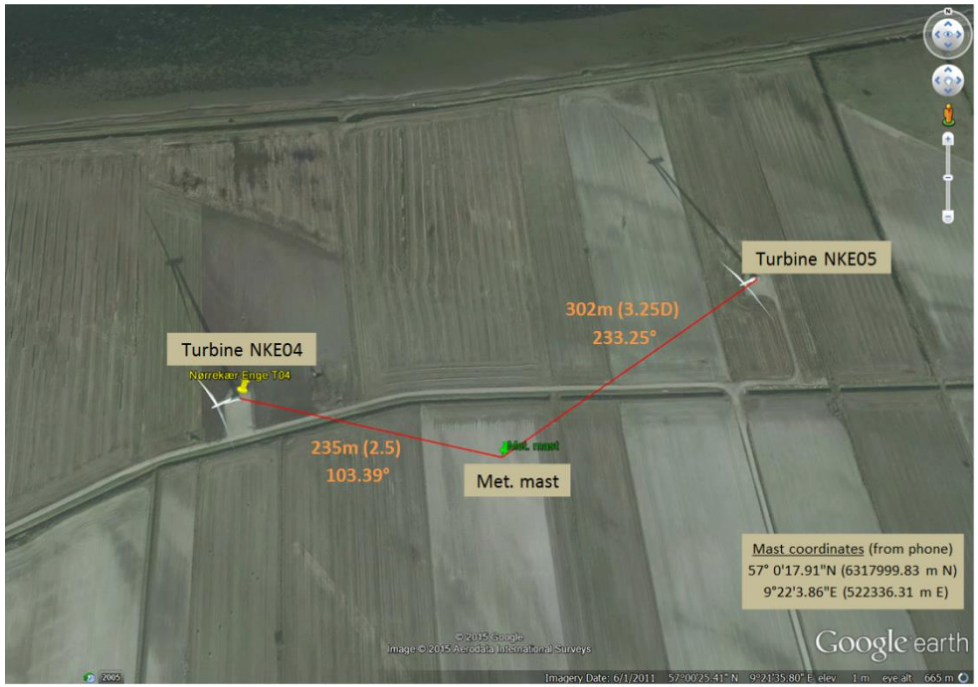
Height[m]	Gradient	R^2
91	1.0108	0.9918
70	1.0122	0.9917
45	1.0084	0.9877
20	1.0027	0.9768

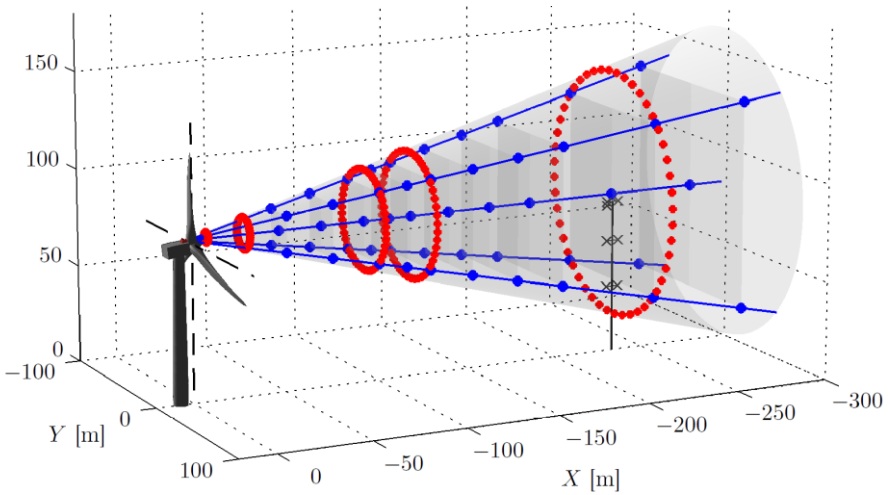
Height	Gradient	R^2
91	1.0124	0.9943
70	1.0112	0.9956
45	1.0114	0.993
20	1.0079	0.9893

Gradient change
+ 0.0016
- 0.001
+ 0.003
+ 0.0052

The Nørrekær Enge UniTTe Campaign

- Onshore, flat terrain
- 13 Siemens 2.3 MW turbines, met mast
- ZephIR DM and Leosphere 5 beam prototype co mounted on heavily instrumented turbine NKE4
- Duration 01jun2015 to 19jan2016



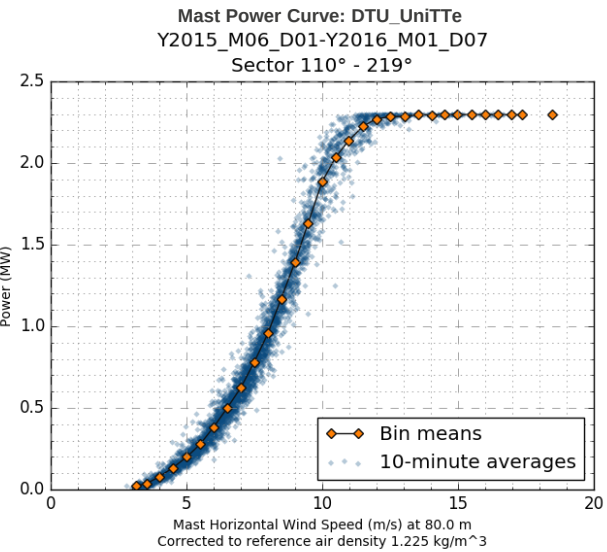


All graphics: Project UniTTe

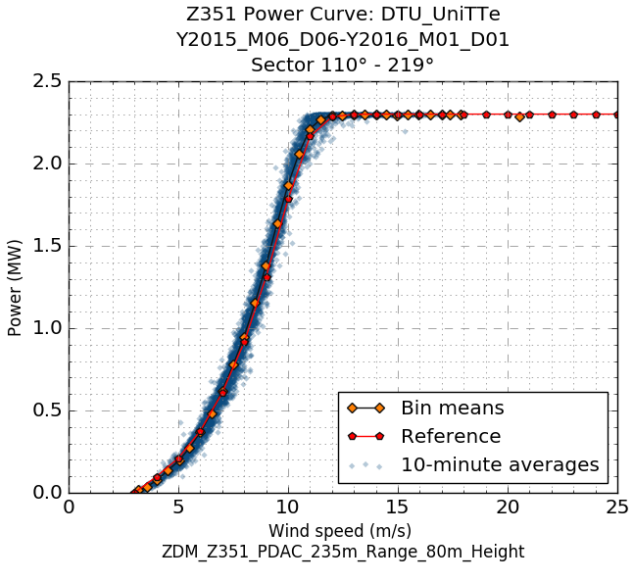
ZephIR DM ranges used shown in red

Analysis of ZephIR data from NKE

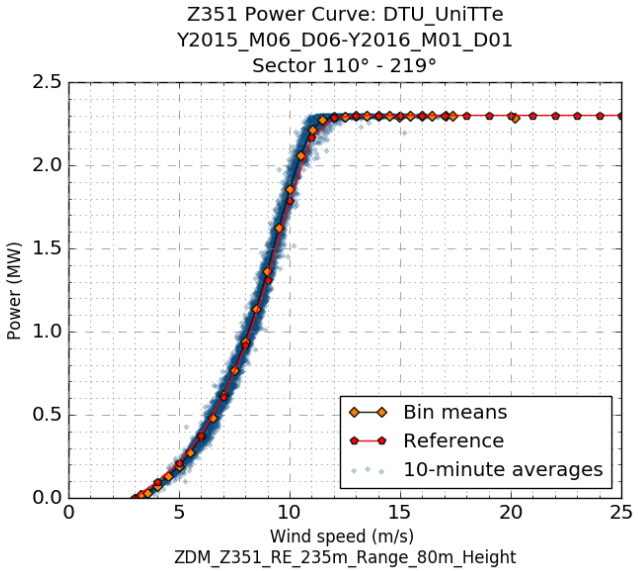
- Work carried out by data analysis team at ZephIR
- Analysis follows that in the newly released ZephIR “Wind turbine power performance measurement” procedure
- Power curves display good consistency and accuracy
  - Clear reduction in scatter of ZDM results compared with met mast
  - REWS power curve displays reduction in scatter compared with hub height power curve
  - Excellent agreement between the ZDM and the mast
- Standard (automatic) ZDM filters applied + sector filtering



Mast data



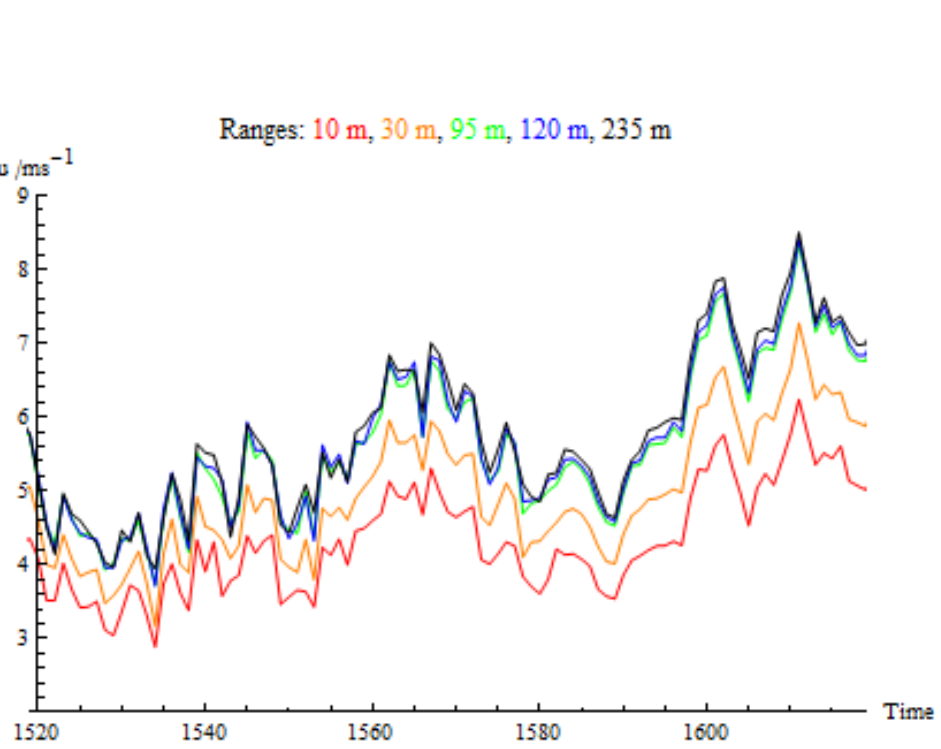
ZDM hub height

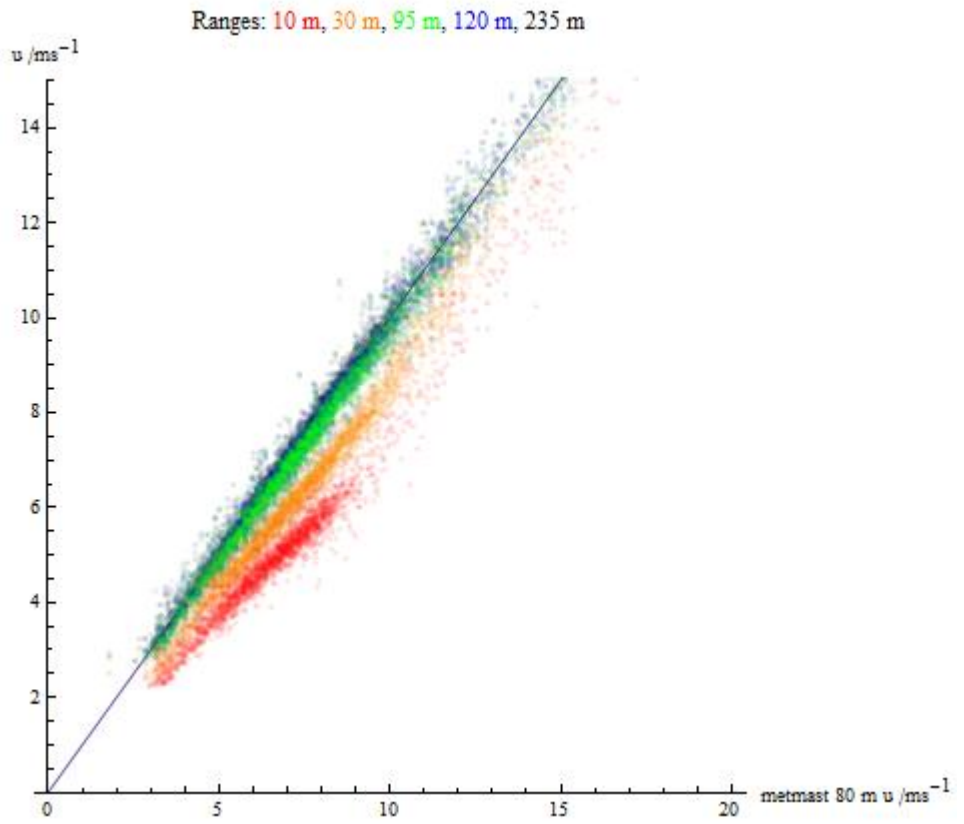


ZDM REWS

Other results from the ZephIR DM at NKE – in The Zone

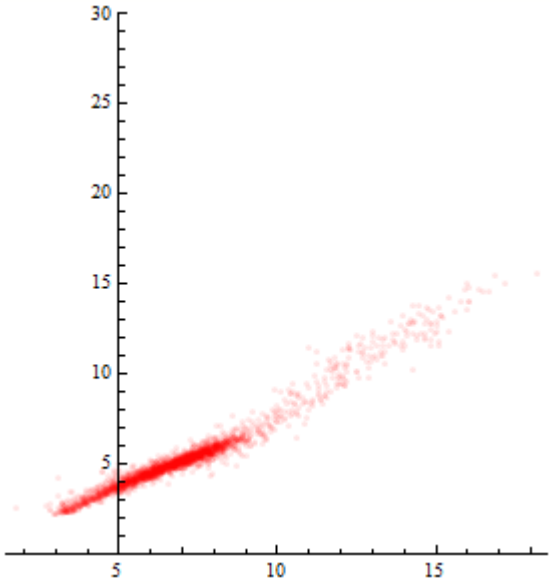
- There is a wealth of data recorded by the ZDM during the campaign
- Measurements inside the induction zone show the usual trends

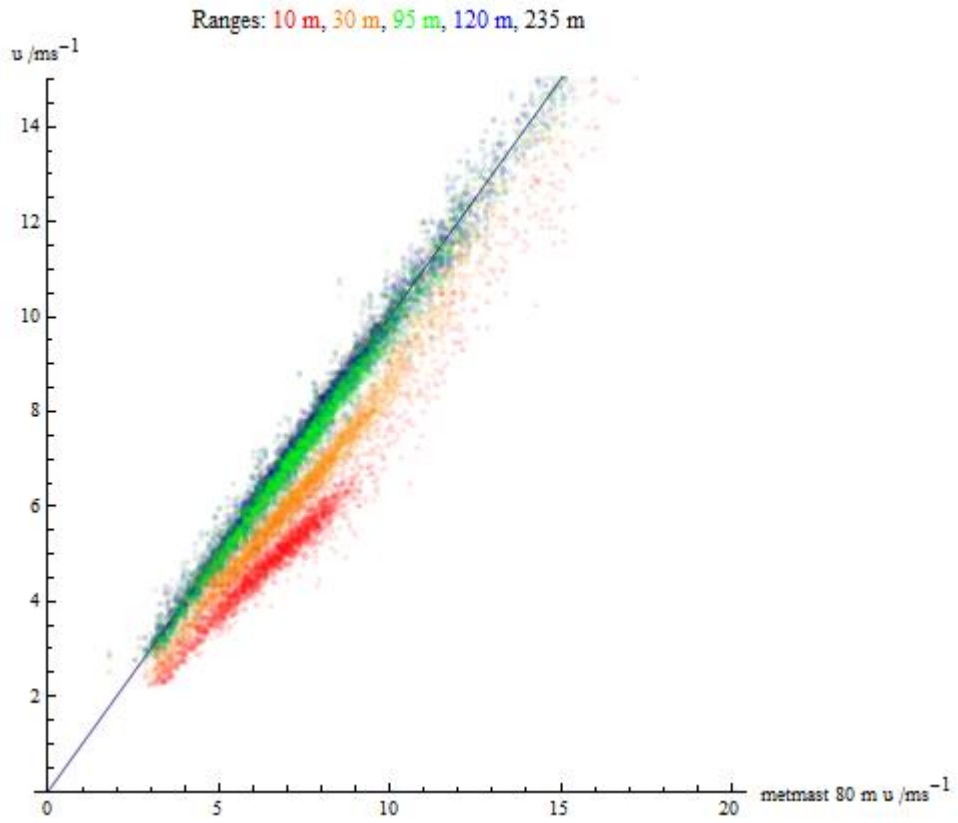




Other results from the ZephIR DM at NKE – in The Zone

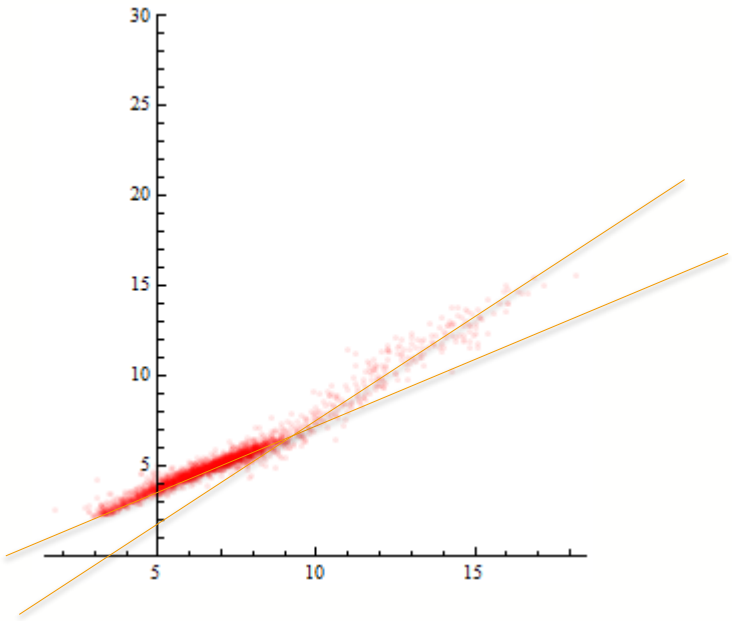
- There is a wealth of data recorded by the ZDM during the campaign
- Measurements inside the induction zone show the usual trends

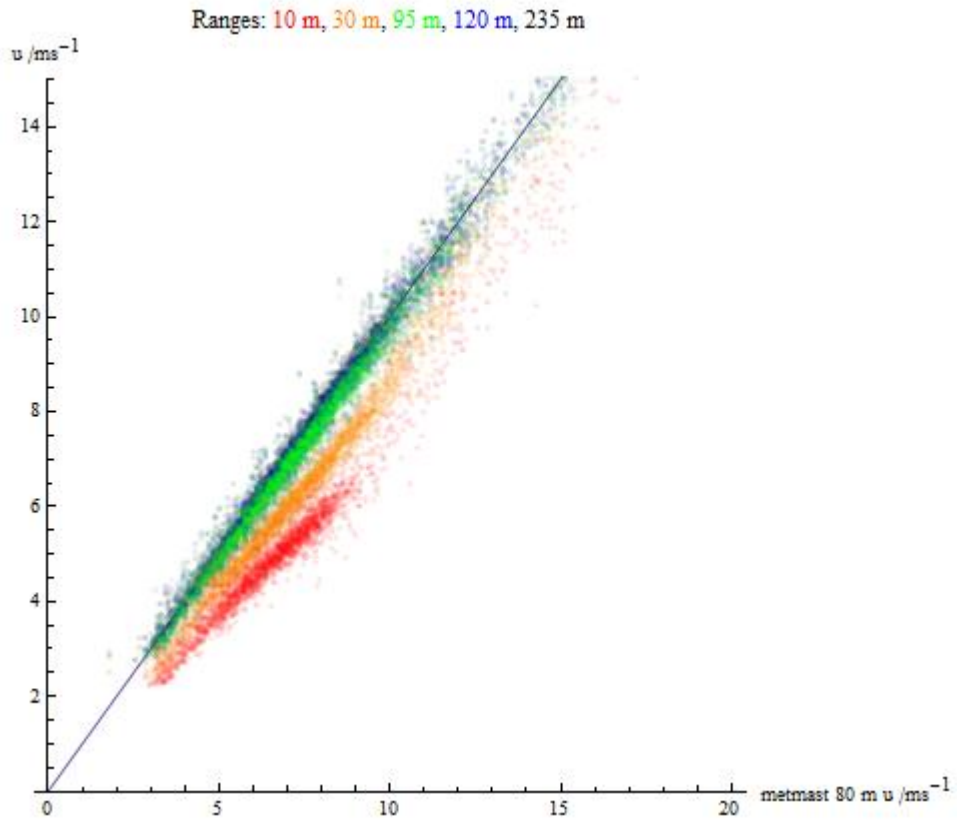




Other results from the ZephIR DM at NKE – in The Zone

- There is a wealth of data recorded by the ZDM during the campaign
- Measurements inside the induction zone show the usual trends

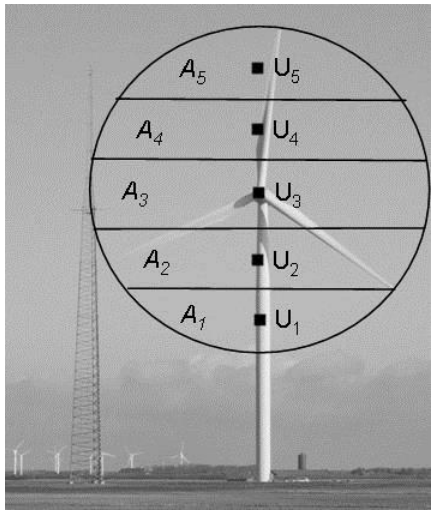


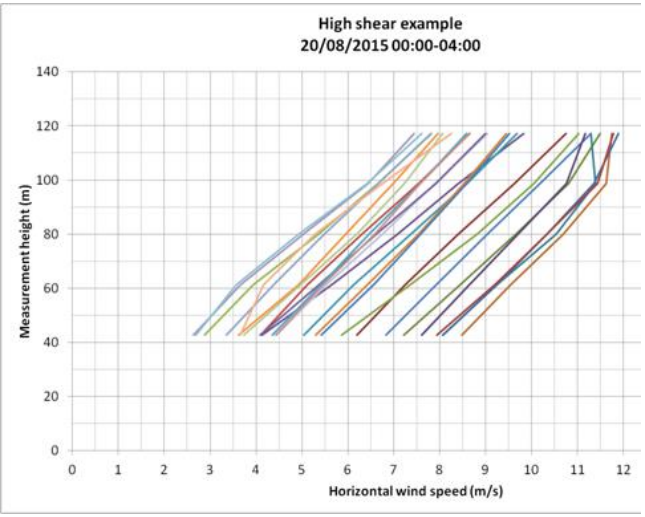


Other results from the ZephIR DM at NKE – shear and veer

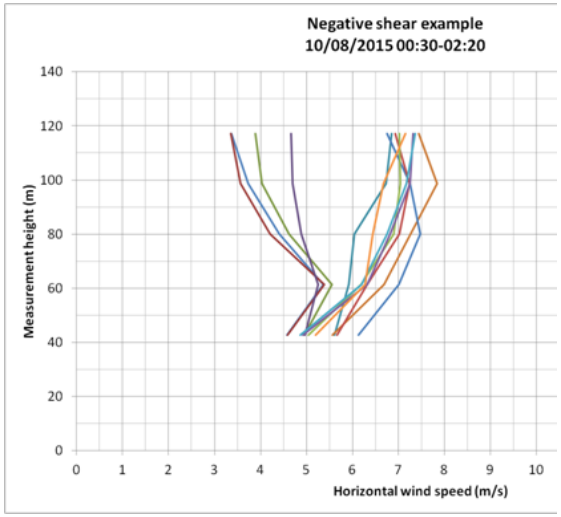
- The ZDM can measure wind speed and direction across the rotor disk
  - allows measurement of non-power law shear profiles
  - allows measurement of veer (variation of wind direction with height)
  - examples of interesting profiles from the NKE campaign below
  - 5 height used in examples below
- The ZDM uses veer for its calculation of REWS, as in Annex Q of IEC 61400-12-1 FDIS

$$v_{REWS} = \left(\sum_{i=1}^{n} (U_i \cos(\phi_i))^3 \frac{A_i}{A} \right)^{\frac{1}{3}}$$

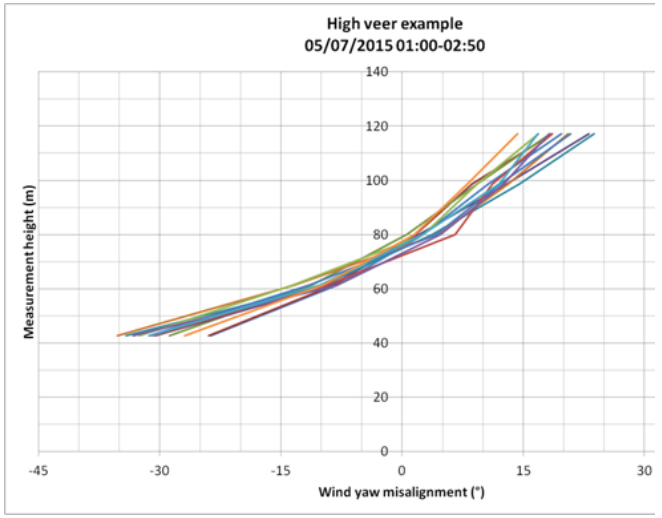




High vertical shear



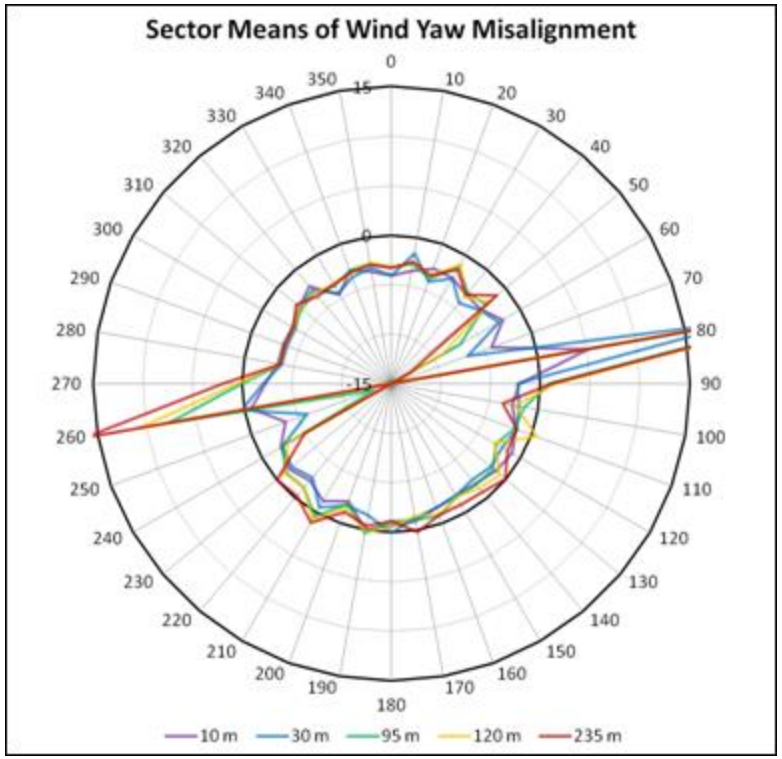
Negative shear

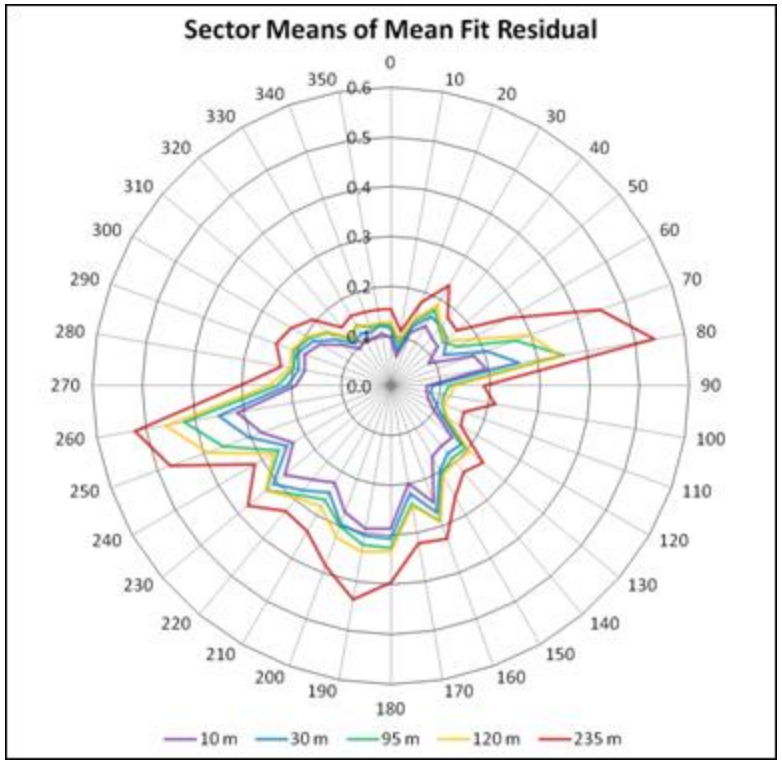


High veer

Other results from the ZephIR DM at NKE – wind yaw misalignment & flow complexity

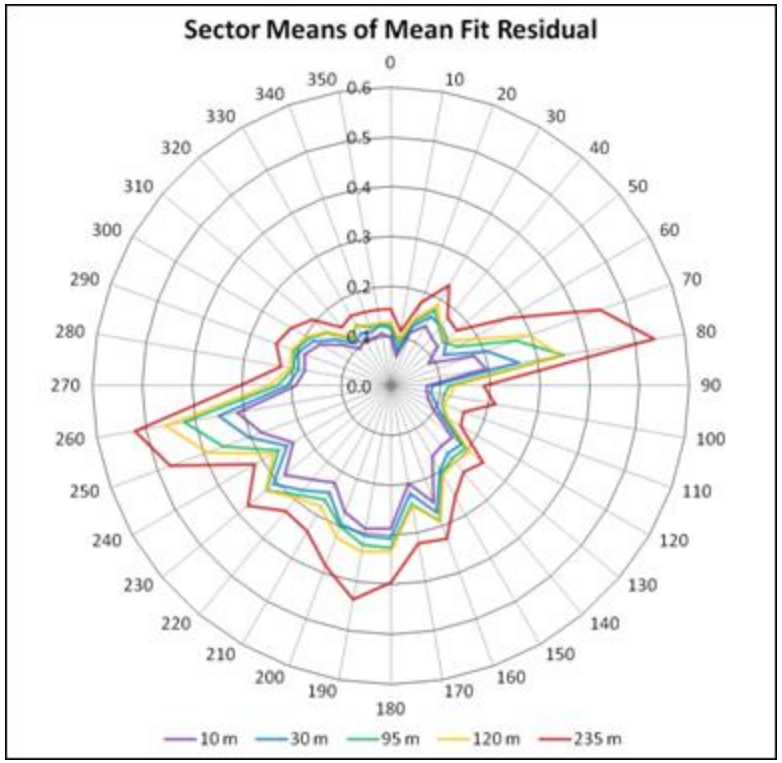
- Mean wind yaw misalignment of -1.9° at 2.5 D (wake free sectors)
- Wind flow complexity measurement detects the presence of neighbouring turbines





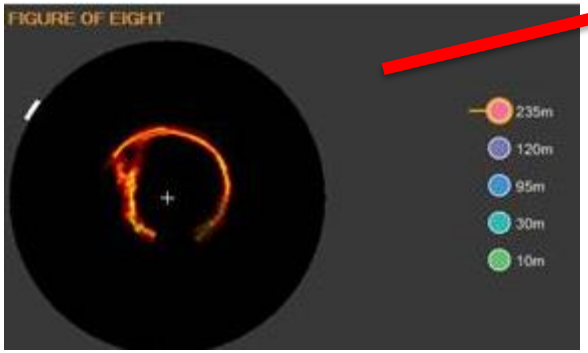
Other results from the ZephIR DM at NKE – wind yaw misalignment & flow complexity

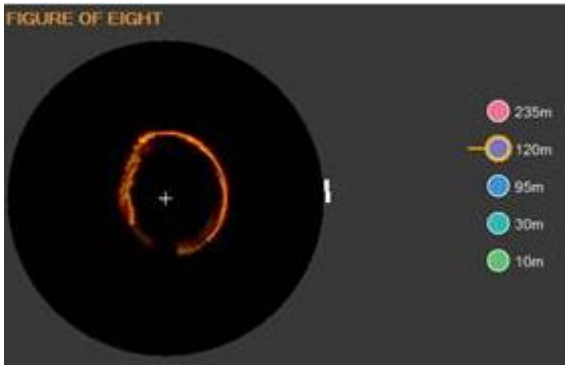
- Mean wind yaw misalignment of -1.9° at 2.5 D (wake free sectors)
- Wind flow complexity measurement detects the presence of neighbouring turbines



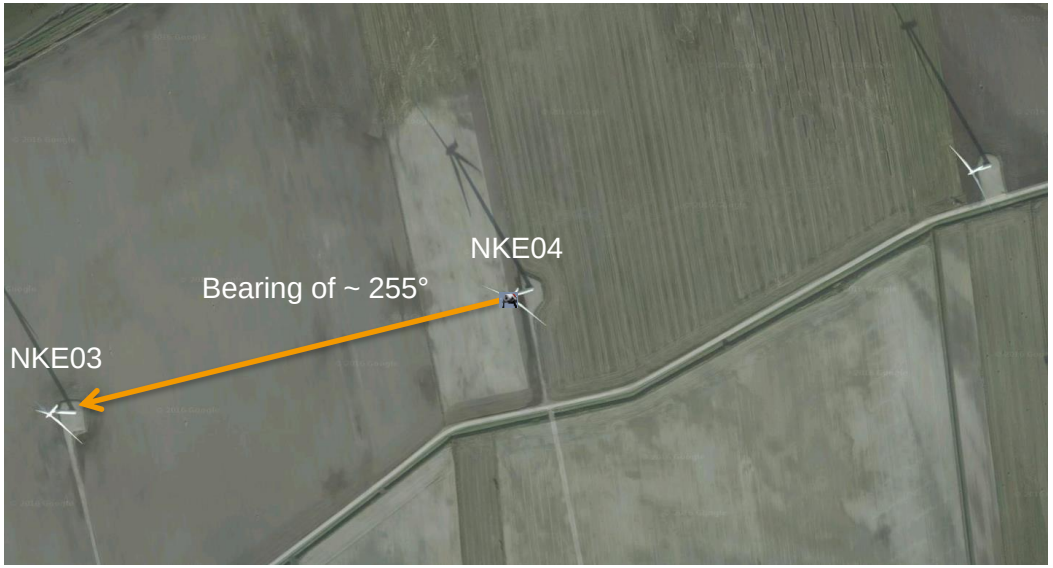
Other results from the ZephIR DM at NKE – wake visualisation

- Examples of ZDM measuring wakes from neighbouring turbine





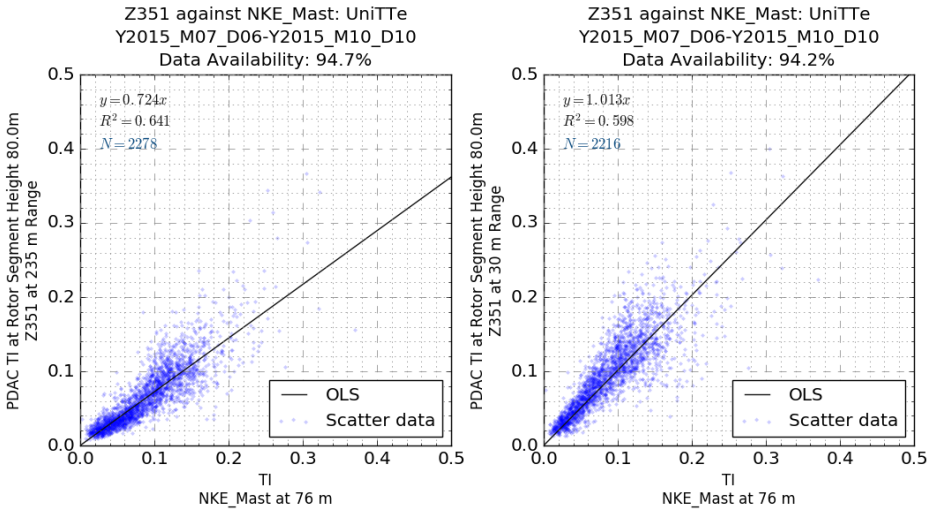
Time and Date (Period Start)	Power (kW)	Yaw (deg)
25/12/2015 17:30	2037.55	251.474

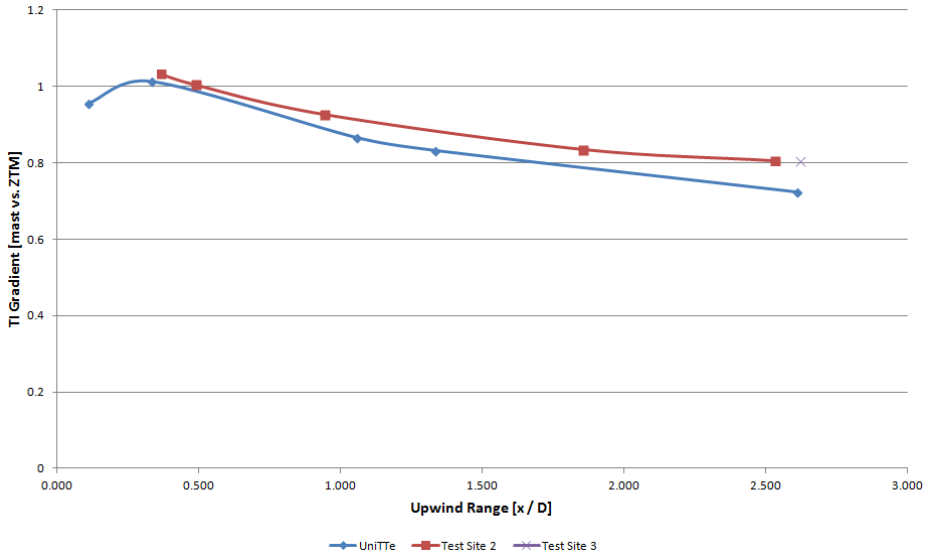


Analysis of ZephIR data from NKE – turbulence data

- TI measurements from all nacelle mounted lidars under-read cups at ranges of 2.5D
- Cups are point measurements; they have inertia
- Lidars use measurements from volumes of space; they have no inertia effects

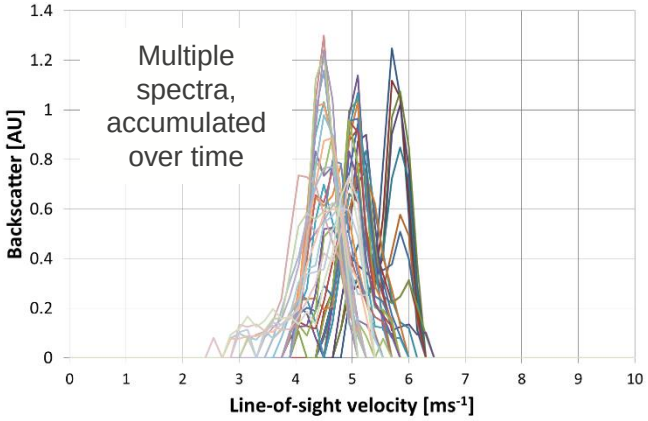
- The ZDM's standard TI outputs under-read the mast cups at 2.5 D, but the discrepancy varies with range



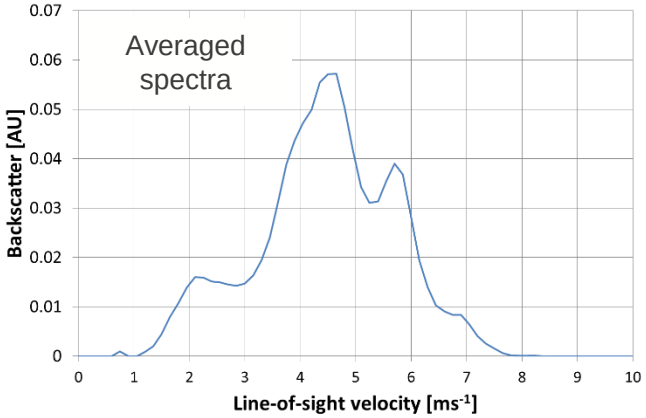


Turbulence analysis by ZephIR DM: spectral turbulence

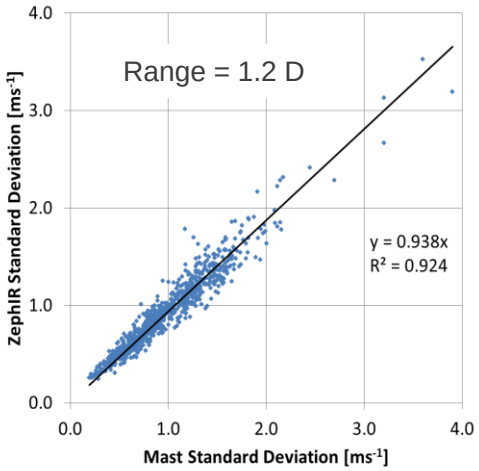
- The ZephIR DM measures and records the full Doppler spectrum at 50 Hz
- These spectra can be used to determine turbulence statistics directly, removing the spatial averaging effects associate with probe beam volumes [Branlard et al]

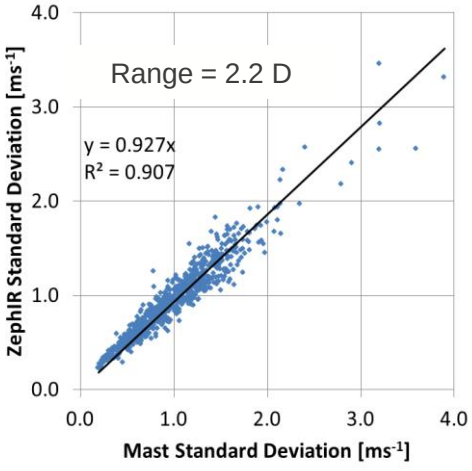


Normalise and average spectra



Preliminary results from ZDM on DTU Nordtank turbine, suggesting range independent statistics



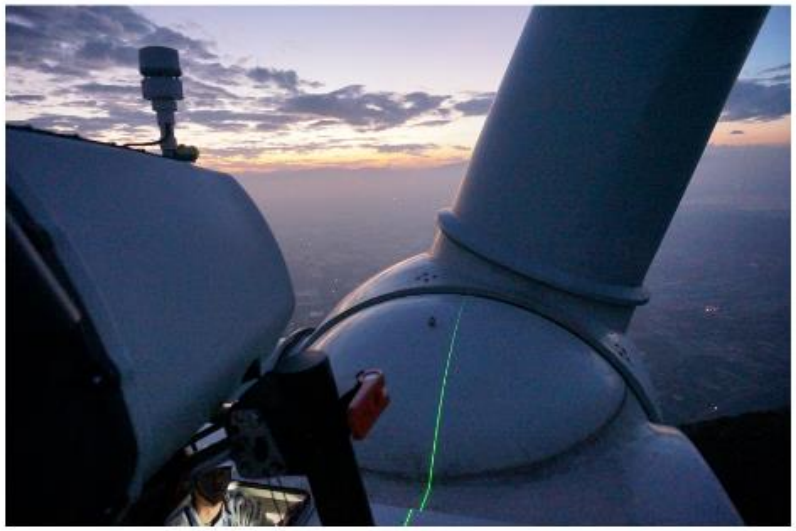


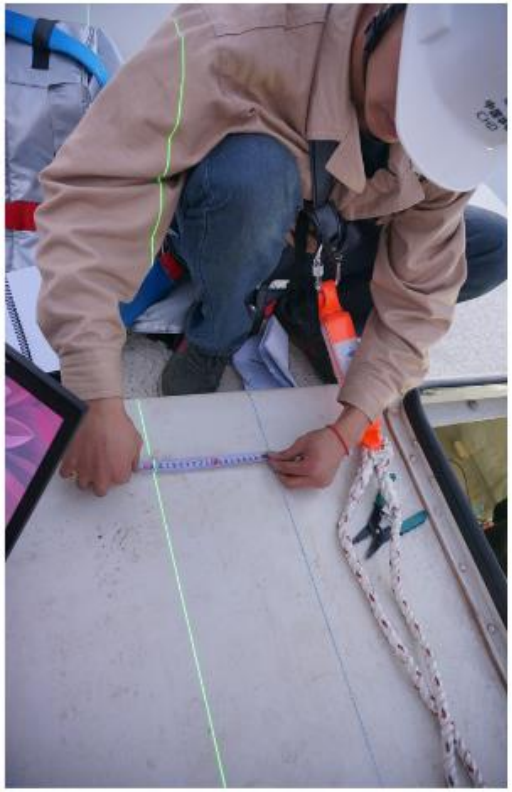
Reference: E. Branlard *et al*, *"Retrieving wind statistics from average spectrum of continuous-wave lidar"*
Atmos. Meas. Tech., **6**, 1673-1683 (2013)

ZephIR Lidar

Other results from the ZephIR DM at NKE – lidar to turbine alignment

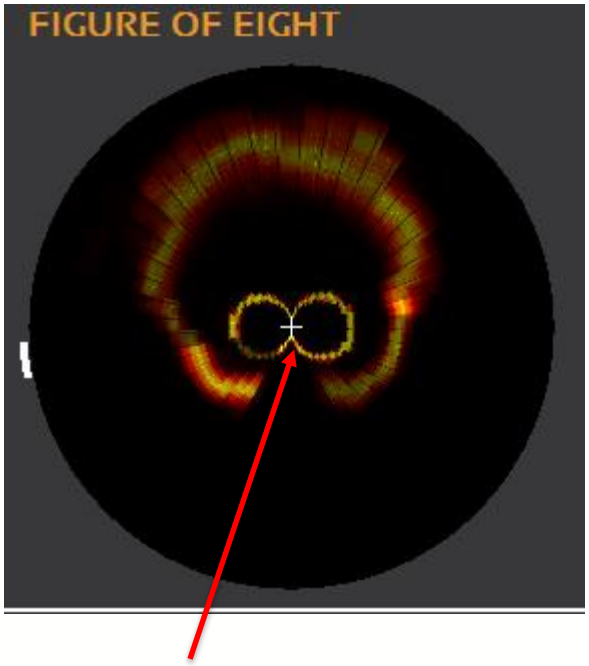
- Good alignment of the lidar with the rotor axis is essential for yaw misalignment analysis
- The ZDM uses a visible alignment laser (VAL) during deployment to help align the ZDM with the rotor axis
- However, sometimes the rotor axis in not known



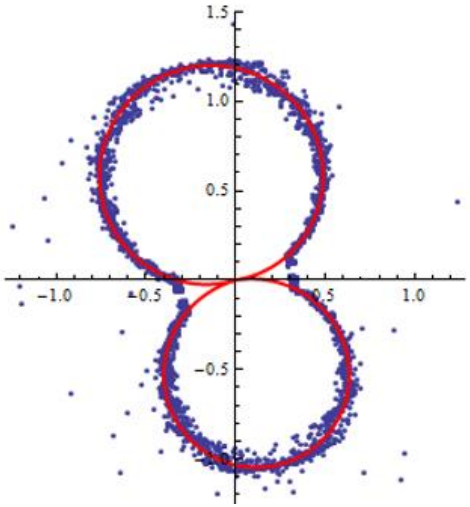


Other results from the ZephIR DM at NKE – lidar to turbine alignment

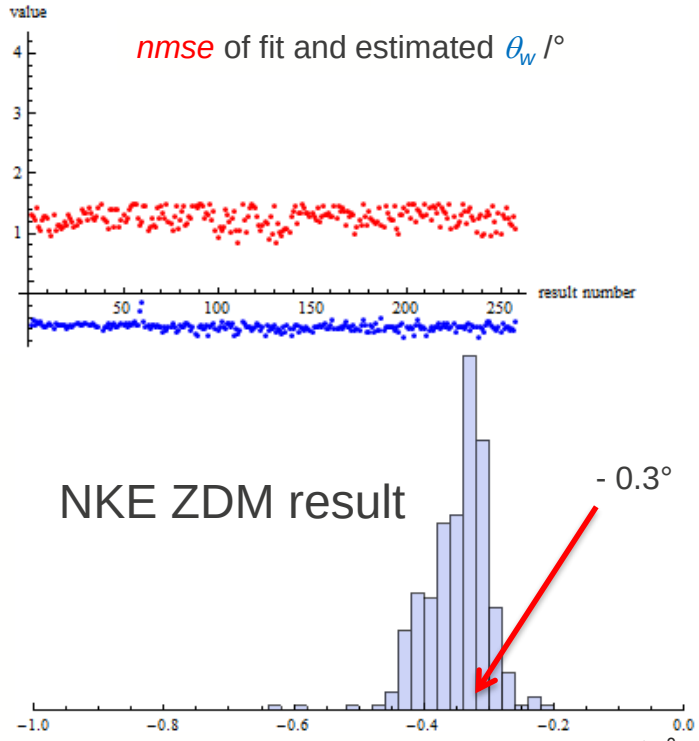
- Good alignment of the lidar with the rotor axis is essential for yaw misalignment analysis
- The ZDM uses a visible alignment laser (VAL) during deployment to help align the ZDM with the rotor axis
- A new technique allows the lidar blade reflections to be used for alignment
  - More accurate than VAL
  - Alignment of lidar with rotor (θw) can be checked remotely at any time during the campaign



Blade return "spectacles"



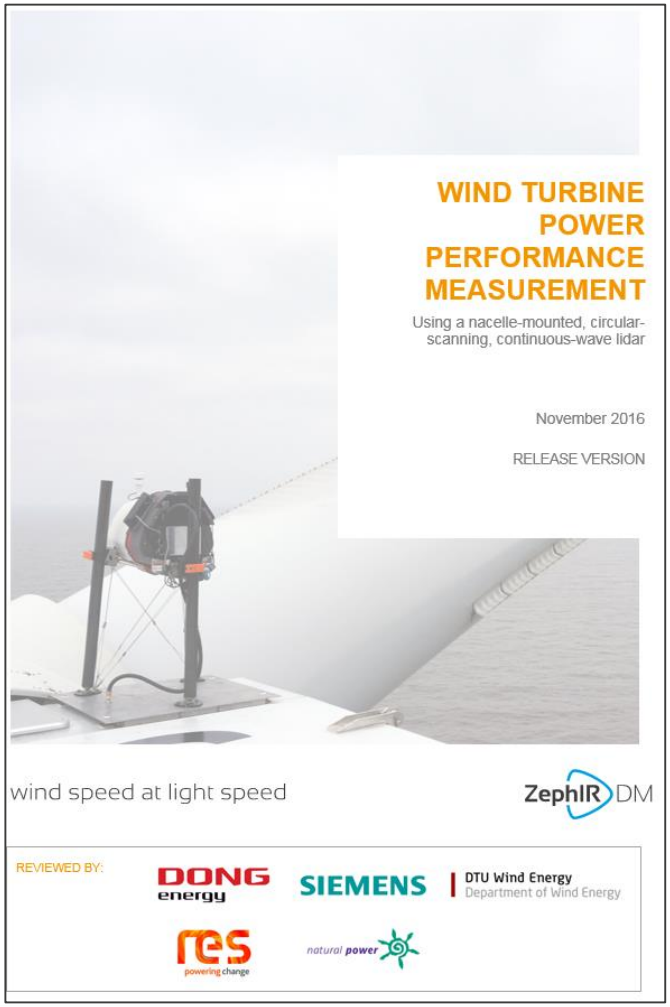
Fit(-)of blade reflections(•)using blade return model



Power curve procedure document

FOR NACELLE MOUNTED CIRCULAR SCANNING CW LIDAR

- Structure is based closely on existing DTU procedure for Avent 2-beam system
- The aim is to make the procedure as generic as possible
- Also, the document contains an appendix with a prescriptive set of instructions that relate specifically to power curve measurement with the ZephIR Dual-Mode lidar
  - This is to ensure customers can follow a well-defined end-to-end process for power curve measurement without ambiguity
  - Standardise settings and filtering
- We are happy for relevant parts of the procedure to form the basis of a generic document for release under the UniTTe project if appropriate



Conclusions

THE ZEPHIR DM PERFORMED TO ITS SPECIFICATION

- Independent calibration/validation confirmed ZephIR factory calibration procedures
- Reliable, on turbine, operation.
  - 95.2% (10 minute) availability at 235 m range
- Correlations and power curves agree well with mast and turbine manufacturer's specifications
- Use of spectral turbulence measures
- Blade returns for accurate measurement/correction of lidar and rotor axis alignment
- The ZDM helped confirm that measurements in the induction zone can wind field reconstruction provide alternative to classic mast instrumentation at 2.5 D
- Looking forwards to the Hill of Towie complex terrain phase of the project !

Fully instrumented turbine 04 in Nørrekær Enge, DK: ZephIR Dual-Mode lidar, 5-beam Avent lidar, spinner anemometer, full loads sensors (MC2, WP3)

CONTACT DETAILS

The Old Barns, Fairoaks Farm
Hollybush, Ledbury, HR8 1EU, UK

Phone: +44 (0)1531 650757
Email: chris.slinger@zephirlidar.com
Web: www.zephirlidar.com