ENERGY

3D Nacelle Mounted Lidar in Complex Terrain

PCWG – Hamburg, Germany

Paul Lawson

25.03.2015

SAFER, SMARTER, GREENER

Agenda

- Introduction and Project Background
- Lidar Specifications
- Wind Speed Derivation
- Met Mast and Lidar Comparisons
- Lidar Uncertainty from Terrain
- Concluding Remarks

Project Motivation

- Demonstrate the capability of 3D nacelle mounted lidar to produce an accurate power curve in complex terrain

Potentials

- Reduce installation time, campaign duration, and overall cost
- More measurement points across the rotor area to better estimate power performance
- Track the wind with the yaw position
- Perform site calibration of sites where it is not feasible or possible
- Multiple measurement distances could provide an alternative to site calibration

Challenges

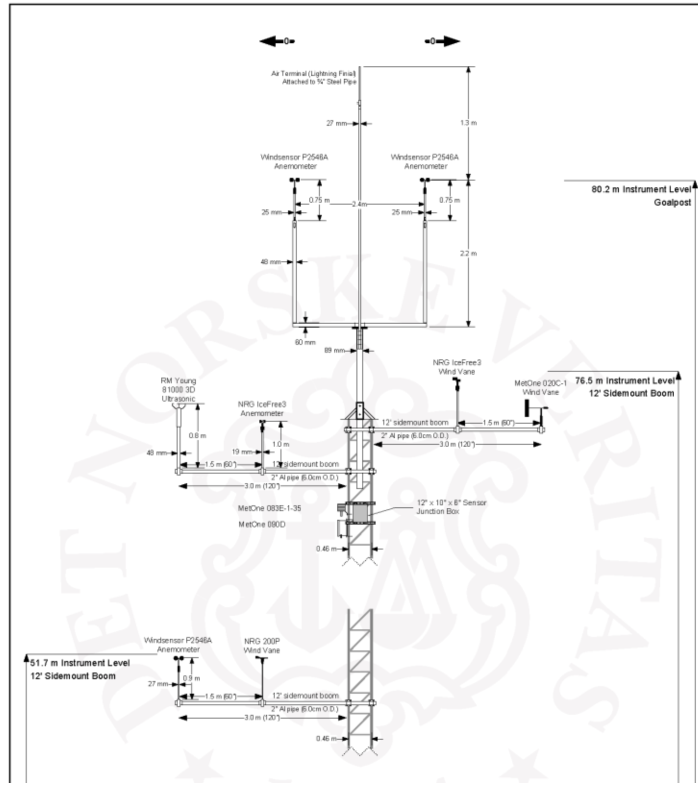
- Must make several assumptions to resolve horizontal wind
- Complex terrain results in variable beam heights above ground
- Measures a volume rather than a fixed point
- An accurate power curve assessment revolves around an accurate site calibration

Project Background

Campaign Details

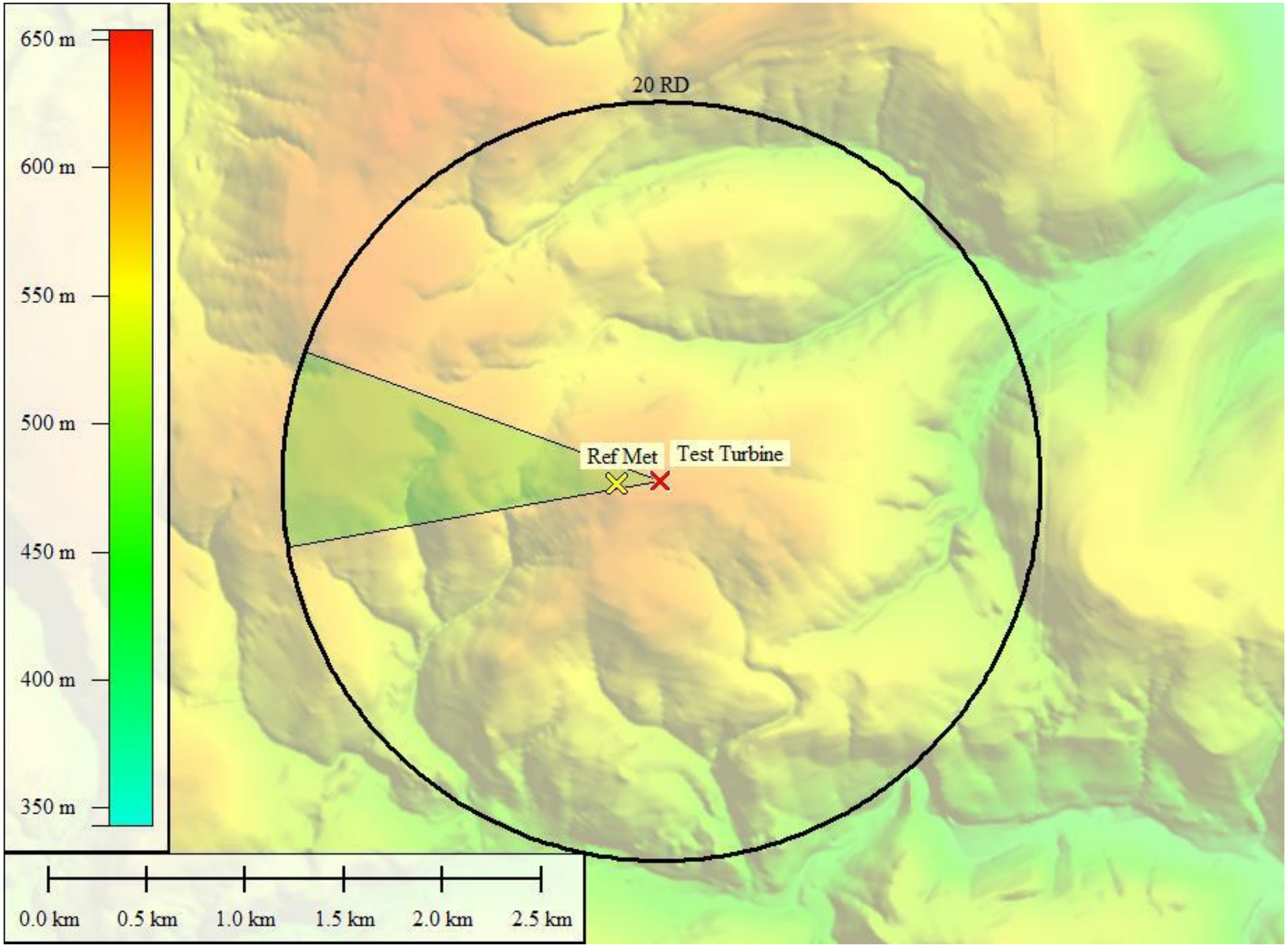
- Previous site calibration – DNVGL 2009 in accordance with IEC standards
- Site complexity characterization – IEC 61400-12-1
- Cold climate, winter in north-eastern United States
- Duration of current campaign: November 5, 2014 – February 14, 2015
- Two valid 10° sectors:
  - 265°-275°
  - 275°-285°

Met Mast Anemometry



- Met mast located at 240m and 265° from turbine

Terrain



650 m
600 m
550 m
500 m
450 m
400 m
350 m
20 RD
Ref Met
Test Turbine
0.0 km
0.5 km
1.0 km
1.5 km
2.0 km
2.5 km

Lidar Specifications

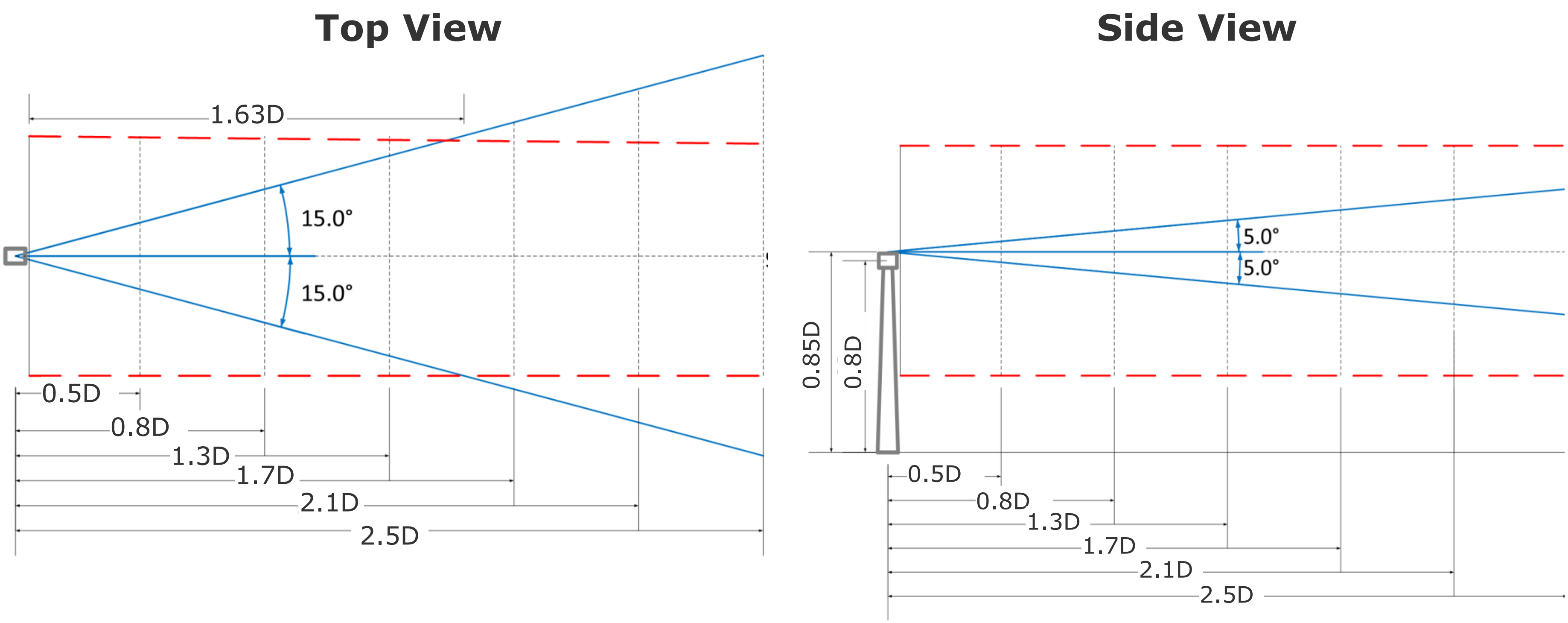
Cooperative Project

- Beta test for prototype lidar based off Wind Iris platform

Lidar Specifications

Manufacturer	Avent
Model	Prototype
Type	Pulsed
Beam configuration	4 beams with rectangular arrangement. Horizontal separation of 30° Vertical separation of 10°
Measurement ranges [m]	0.5D, 0.8D, 1.3D, 1.7D, 2.1D, 2.5D, 2.9D, 3.3D, 3.8D, 4.2D
Outputs	Horizontal wind speed, wind direction, shear and veer exponents, REWS, TI
Measurement Width	±14.5m
Refresh Rate	1 second
Operational Availability	No recorded downtime due to environmental effects

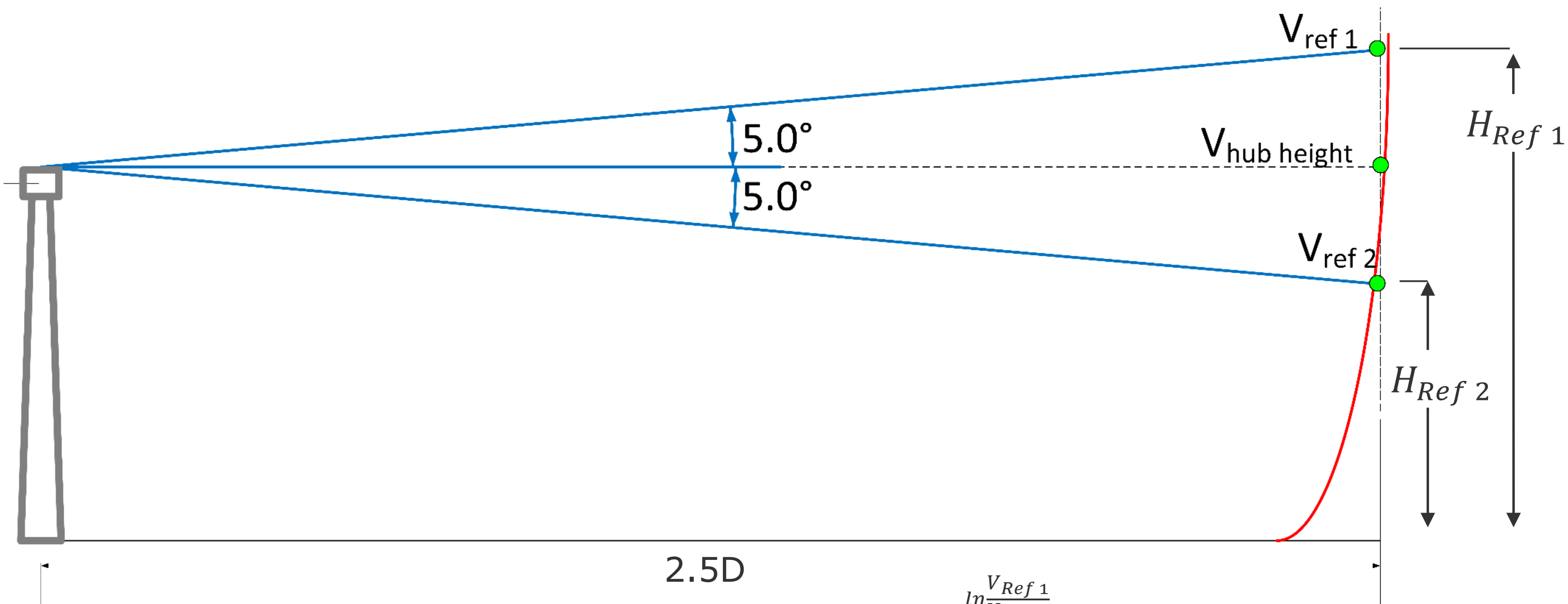
Nacelle Lidar in Complex Terrain: Beam Positioning



- First 6/10 measurement distances shown for the top and side views
  - Met mast located at 2.5D
- The lidar beam exits the projected swept area [---] at 1.63D

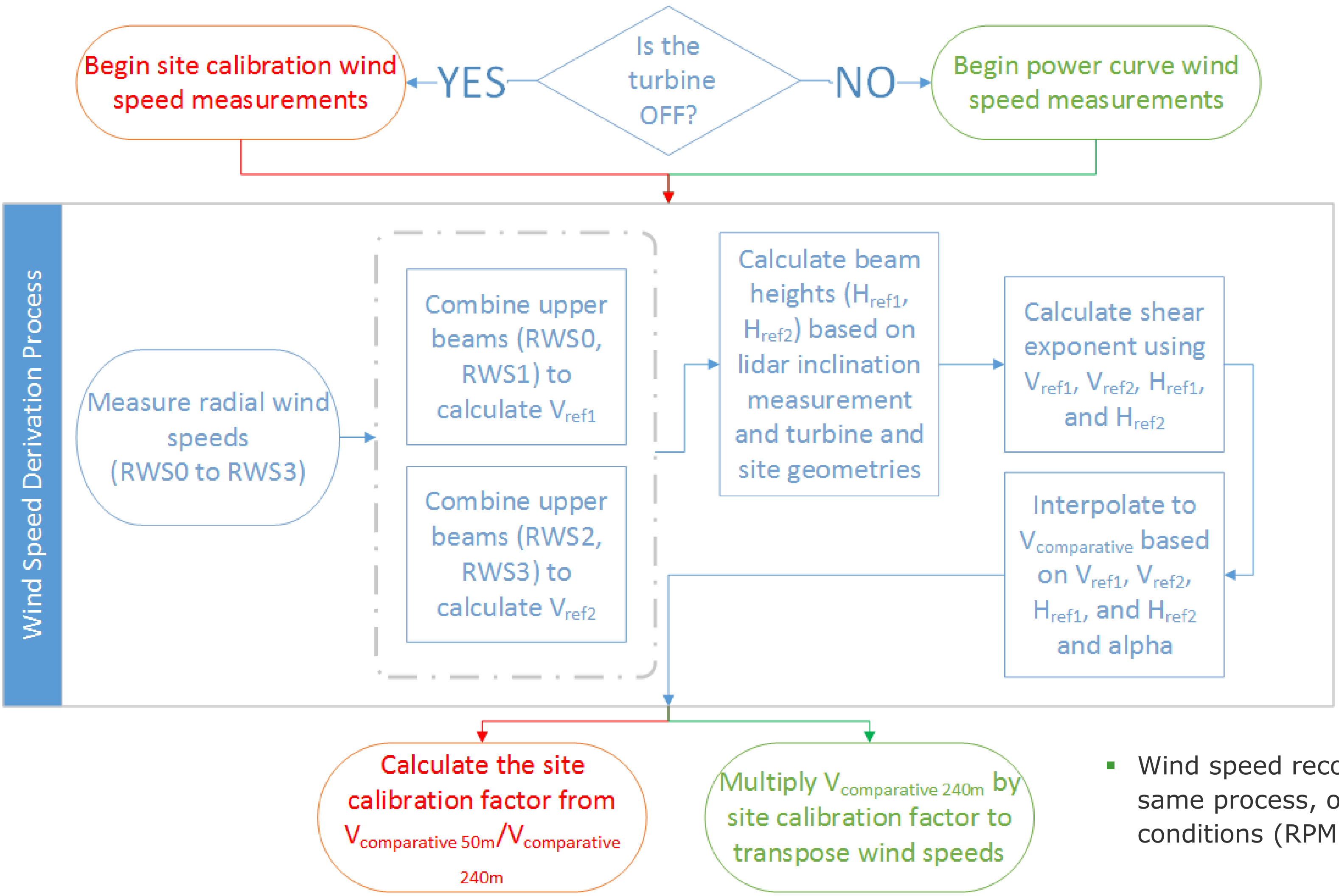
Lidar Hub Height Horizontal Wind Speeds

- Two horizontal wind speeds are derived at different heights (from the upper and lower pairs of beams)
- The power law can be incorporated to reconstruct a wind profile and interpolate for hub height wind speeds



$$V_{Hub\ Height} = V_{Ref\ 1,2}\left(\frac{H_{Hub\ Height}}{H_{Ref\ 1,2}}\right)^{\frac{ln\frac{V_{Ref\ 1}}{V_{Ref\ 2}}}{ln\frac{H_{Ref\ 1}}{H_{Ref\ 2}}}}$$

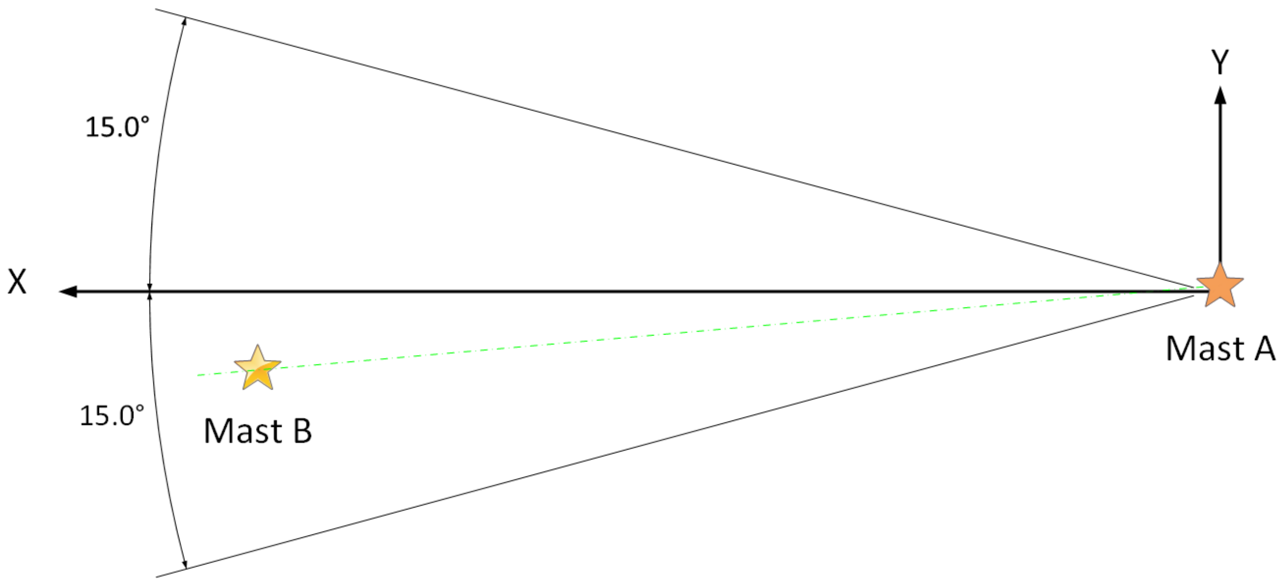
Site Calibration and Wind Speed Interpolation



- Wind speed reconstitution is the same process, only turbine conditions (RPM speed) differ

What is a Met Mast Site Calibration?

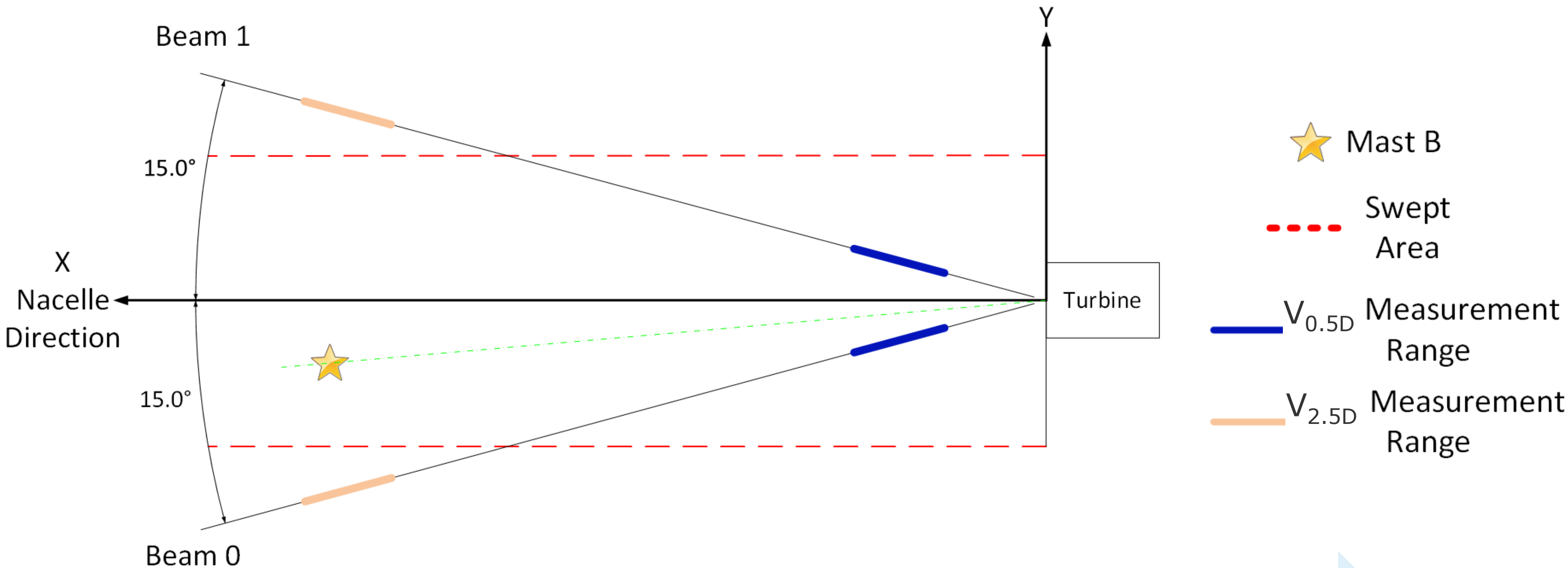
- A ratio of wind speeds used to describe far away wind speeds and transpose them to the turbine position
- Previous site calibration completed in 2009 in accordance with IEC standards



1. Chose future turbine installation
2. Install Mast A and Mast B
3. Measure hub height wind speeds
4. Calculate $R=V_A/V_B$
5. Remove Mast A for turbine installation
6. Transpose future V_B by multiplying by R

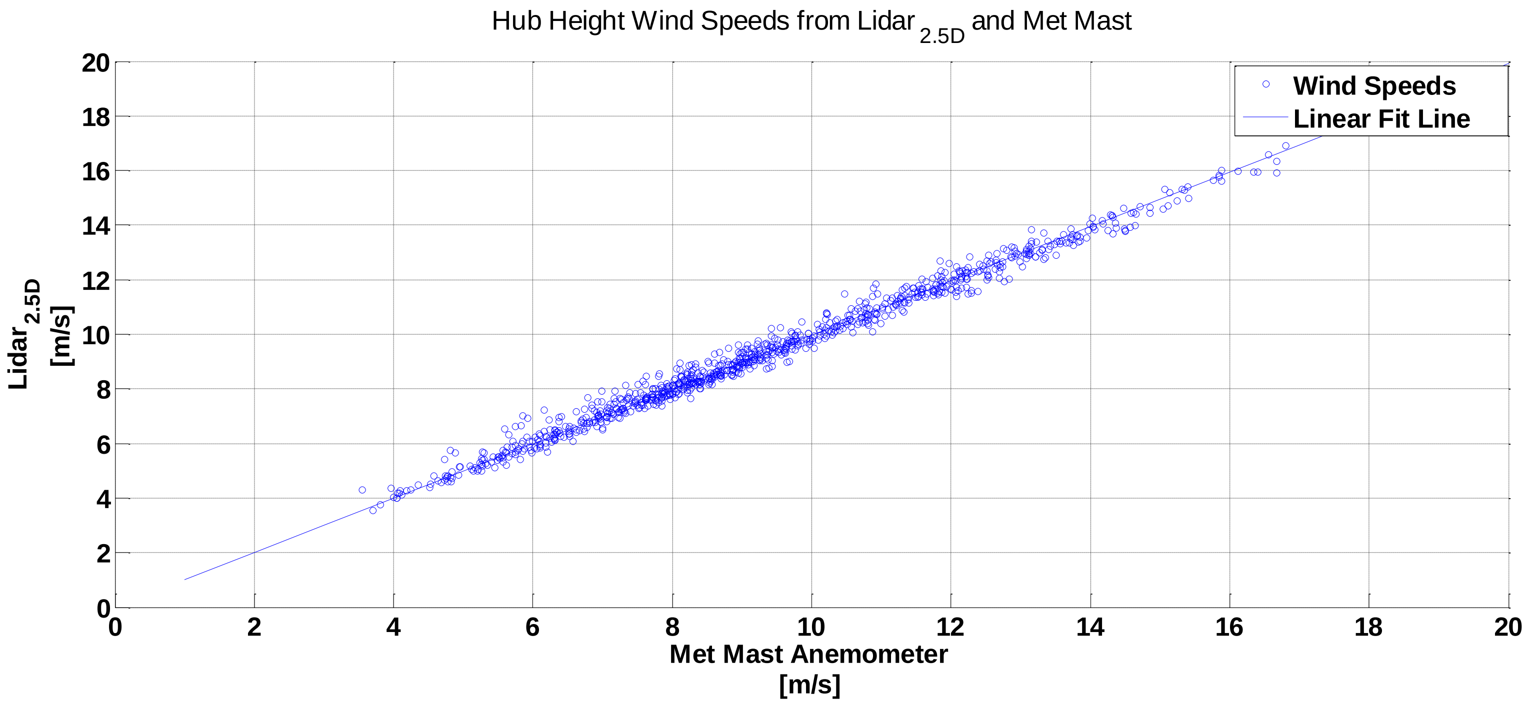
What is a Lidar Site Calibration?

- A ratio of wind speeds used to describe far away wind speeds and transpose them to the turbine position



Nacelle lidar installation → Turbine idling or RPM <1 → Derive upper and lower wind speeds at 0.5D and 2.5D → Interpolate height wind speeds at 0.5D and 2.5D → Calculate $R=V_{0.5D}/V_{2.5D}$ → Transpose future $V_{2.5D}$ by multiplying by R

Wind Speed Correlations



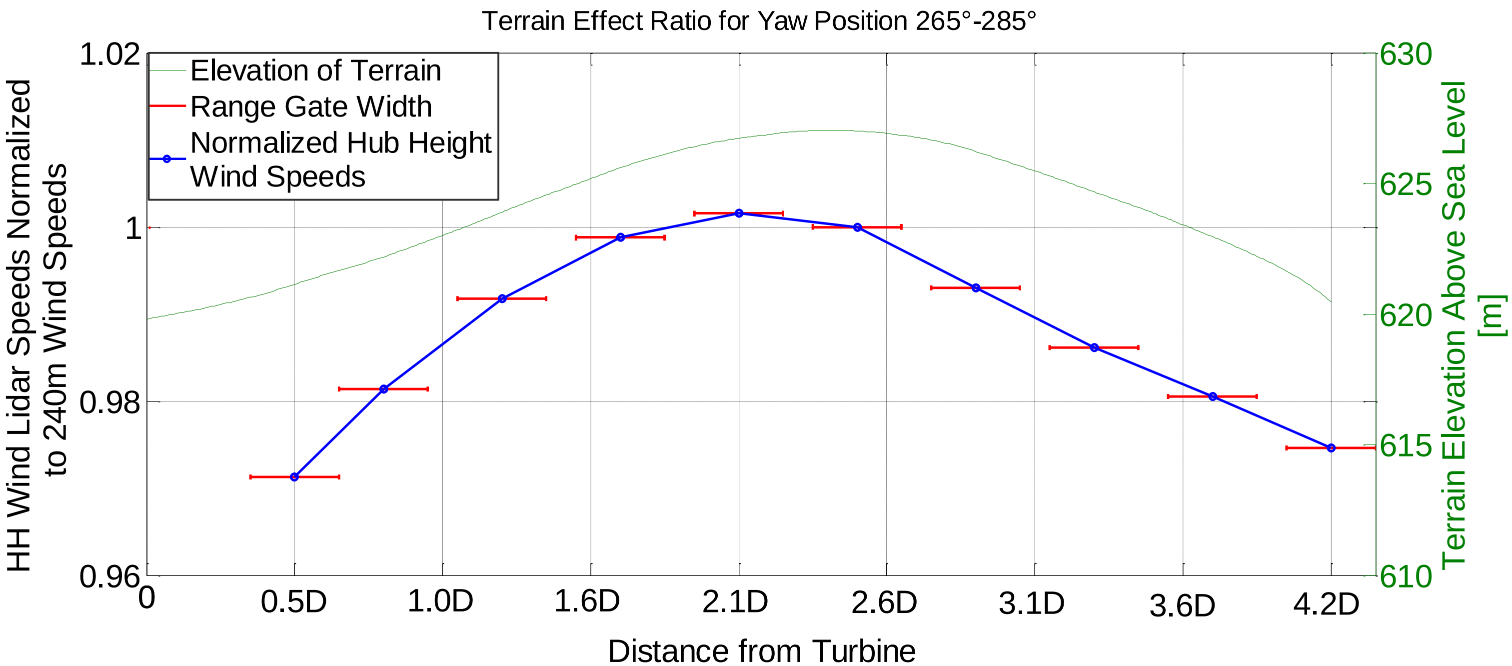
Important Filters

- Minimum 3.5m/s for lidar and met mast
- No Maximum wind speed
- Wind shear $0.0 \leq \alpha \leq 0.5$
- Availability ≥ 0.40

Bin Center	Slope	R^2
270°	0.996	0.986
280°	0.996	0.988

- The compared wind speeds here are the raw measurements before any site calibration factors have been applied

Site Calibration – Turbine OFF

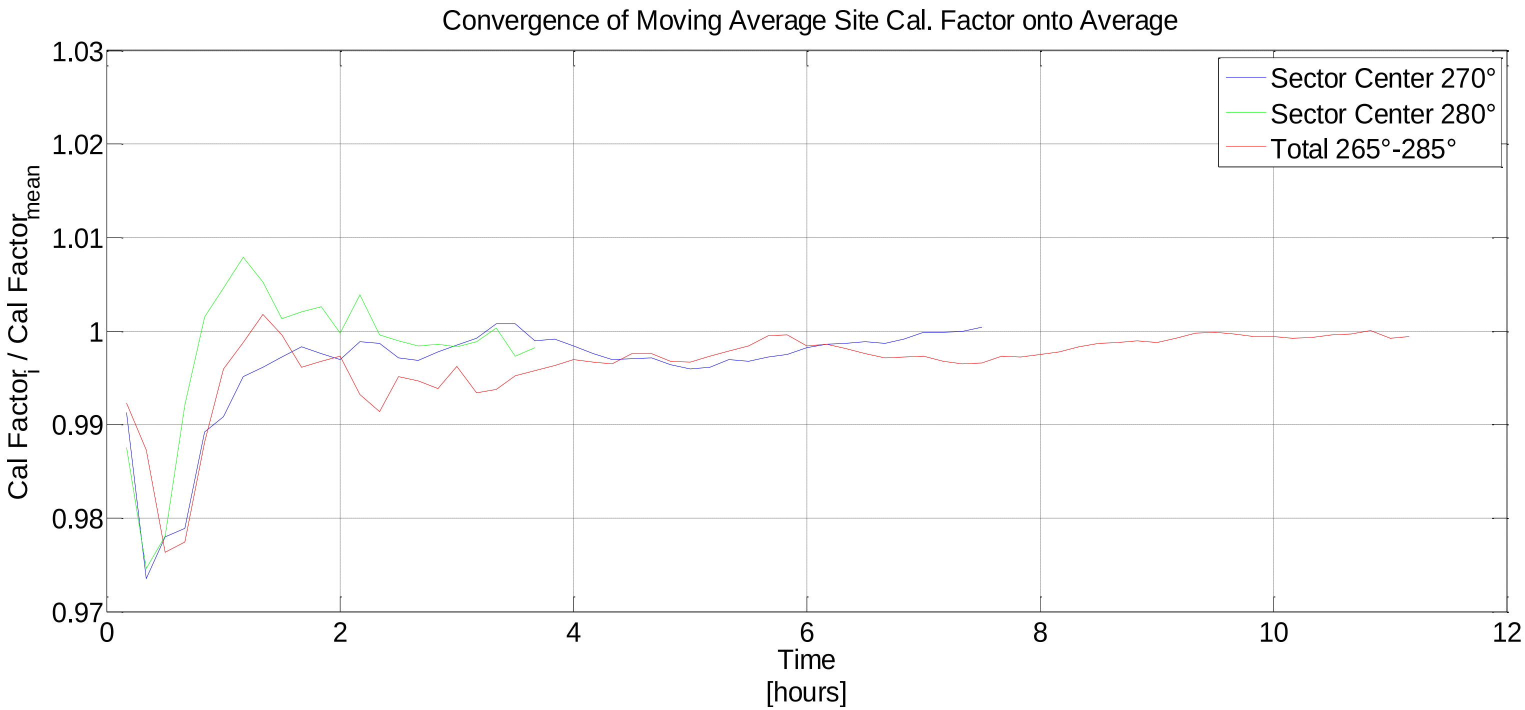


- Turbine RPM must be off or idling
- 265°≤yaw≤285°
- Wind direction 265°≤WD≤285°
- Min wind 4 m/s
- Max wind 16 m/s

- Lidar hub height wind speeds normalized to those measured at 2.5D
- Red lines are the measured range gates ±(≈14.5m)
- Comparison to IEC approved site calibration from 2009 (pre-turbine installation)

Bin Center	IEC - 2009	Lidar- $V_{0.5D}/V_{2.5D}$
270°	0.980	0.970
280°	0.983	0.964

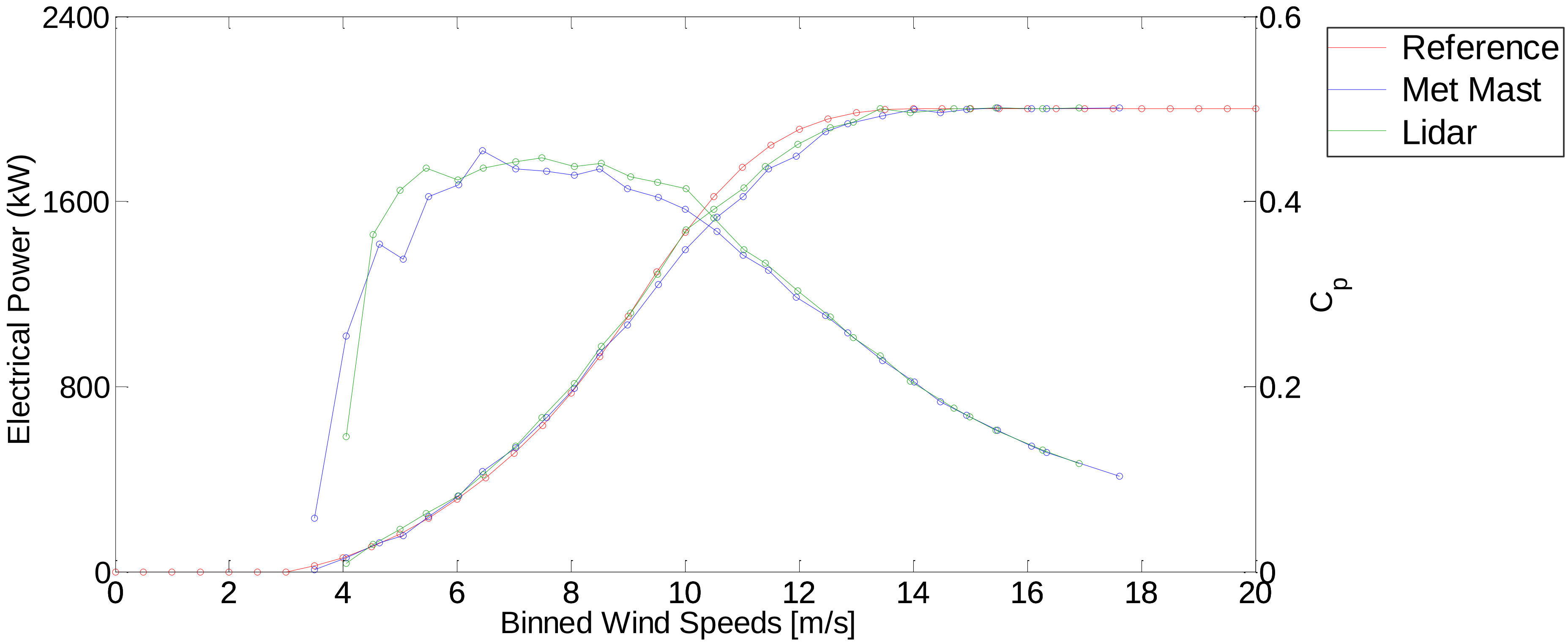
Convergence of the Terrain Correction Factor



- Turbine RPM must be <1
- 265°≤yaw≤285
- Turbine not intentionally shut down

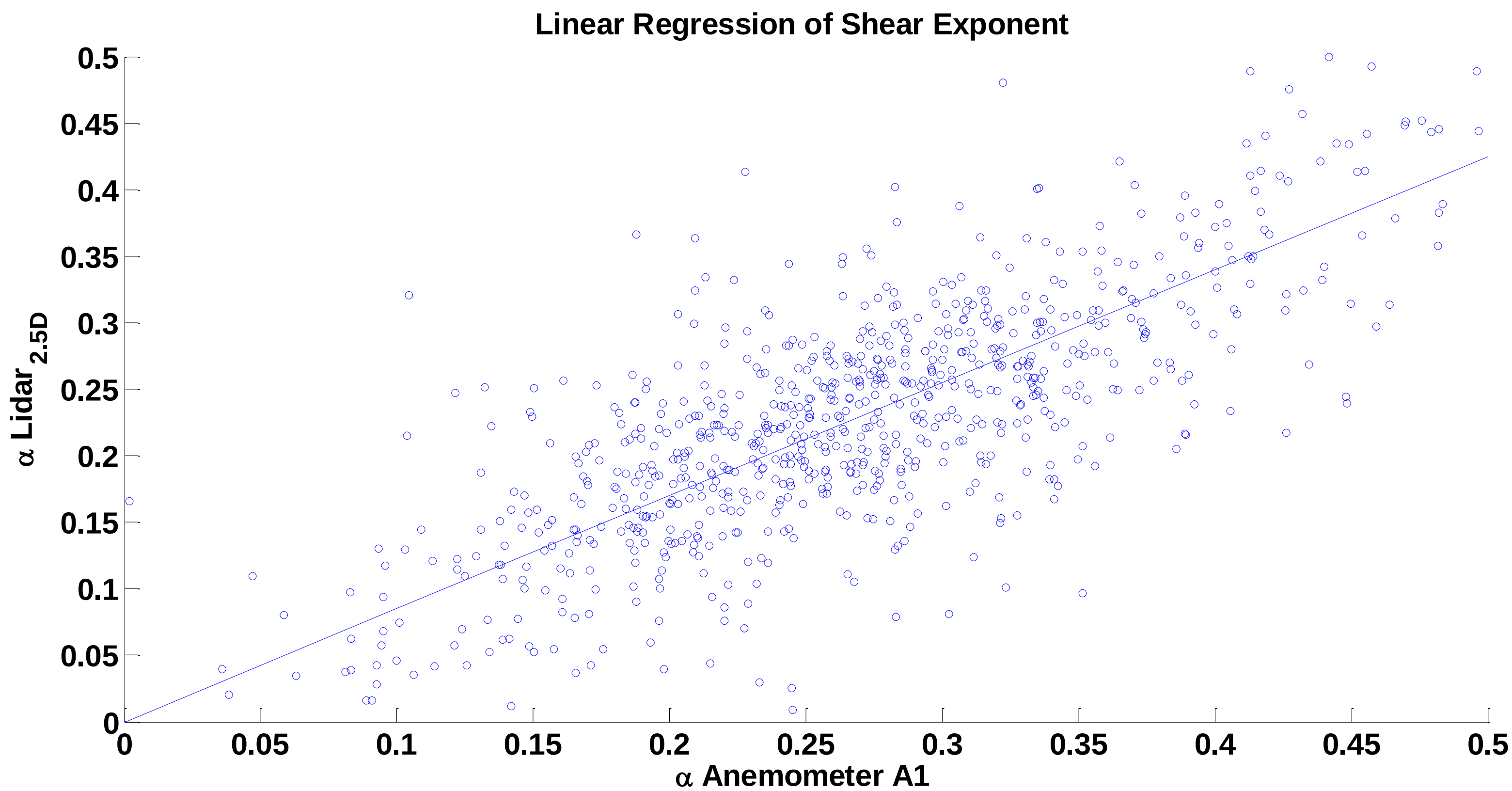
- The moving average of V_{50m}/V_{240m} normalized to the final, overall average outlined
  - Initial stages of convergence (analysis) of site calibration factor in accordance with IEC 61400-12-1, Annex C, Section C.3
- After 7.5 hours (45 samples) the 270° centred sector is trending at 0.9999, 0.9999, 1.000, 1.0004
  - Does not yet meet full requirements of 24hrs of data per 10° sector

Power Curves Comparison



- Respective site calibration factors have been applied
- Lidar power curve is shifted to the left as a result of lower measured wind speeds and lower site calibration factors
- Close proximity of lidar power curves, suitable for real world application!

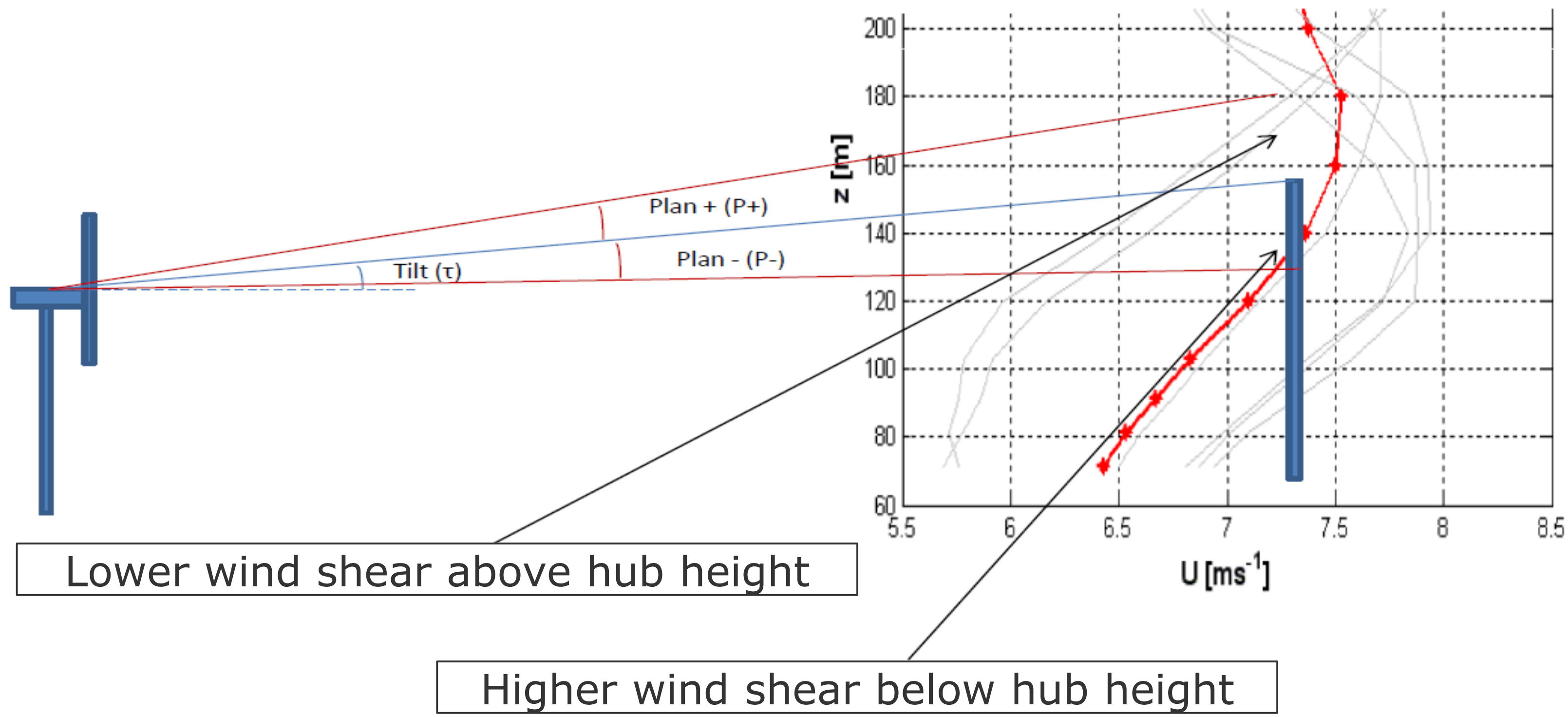
Shear Exponent Comparison



- Slope of 0.849 for a linear line forced through 0
- R^2 value of 0.5497
- 10 minute averages

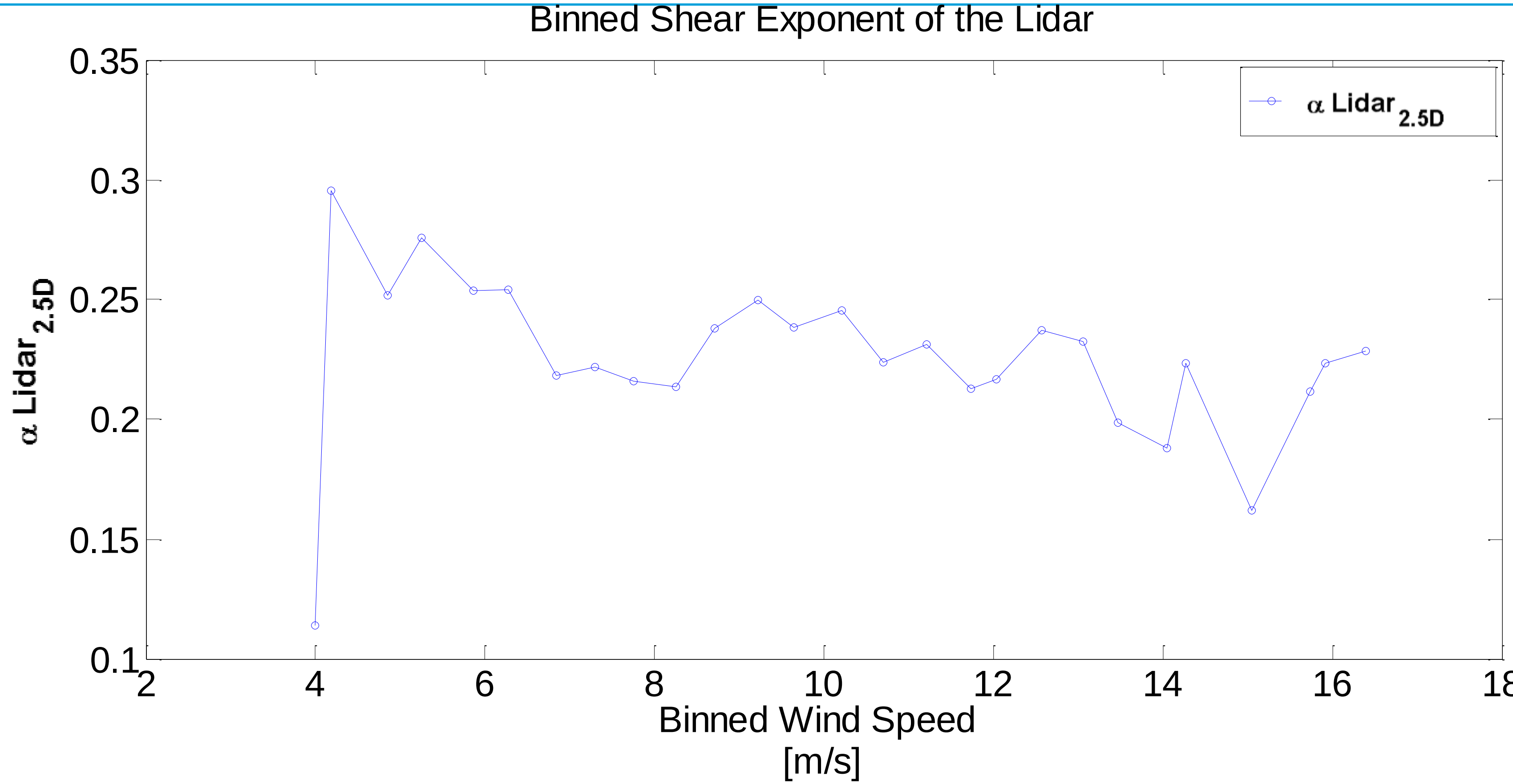
- Modelling of the wind profile using *different reference elevations*
  - Lidar shear was calculated with the upper and lower beam pairs while the met mast used two cup anemometers at 80.2m and 51.7m above ground level
- Lidar measures above and below hub height - better representation of the profile

Start of Explanation for Lidar-Mast Shear Differences



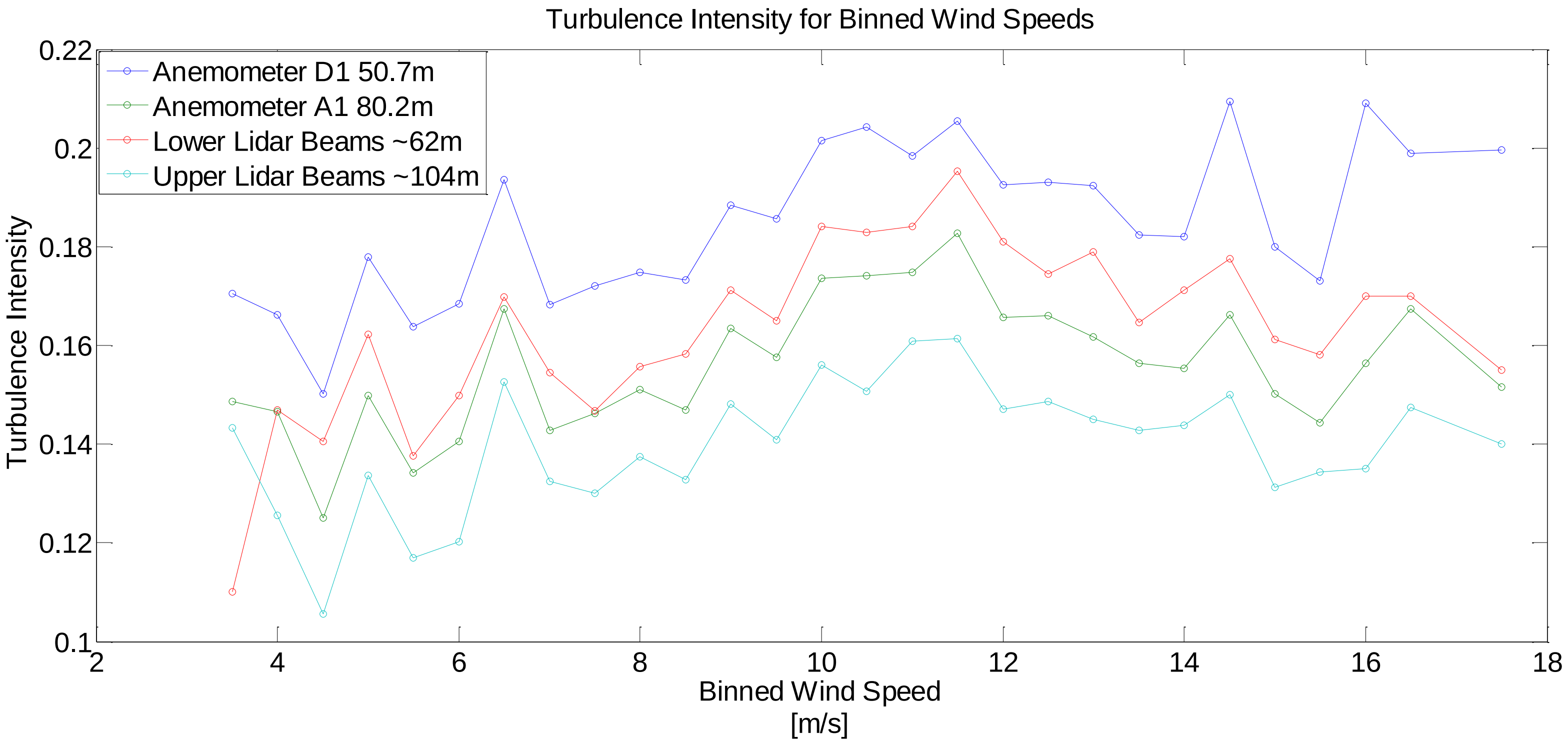
- Lidar measures above and below hub height - better representation of the profile
- The cup anemometer measures wind speeds at and below hub height
- Different measurement points along the wind profile (i.e. mast and lidar) can result in wind shear exponent differences

Shear Exponent Comparison



- Wind shear values binned into 0.5m/s bins
- Very low sample count in the 4m/s bin, not sufficient to be statistically representative (a total of 9 samples)

Turbulence Intensity



- Binned wind speed data (0.5m/s bins)

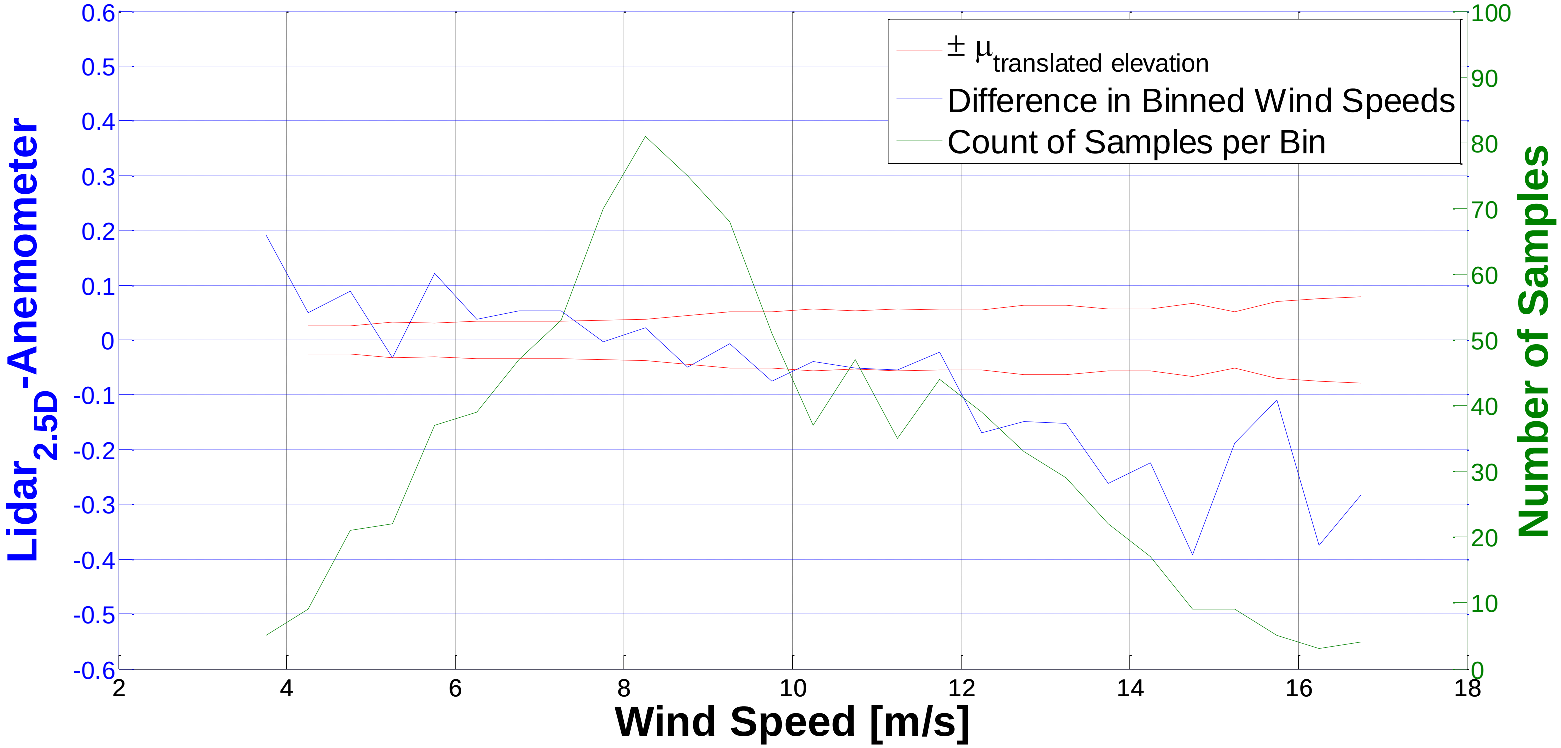
- A good approximation exists and the expected trend of decreasing TI as height increases is true.
  - Following of the extreme peaks and drops is a promising result
- Lidar TI is calculated from the RWS rather than the actual horizontal wind speed

Uncertainty – Lidar Specific Challenges

- Power law is incorporated, how do uncertainties in beam elevation translate to uncertainties in wind speed?
- Four main sources are identified in the elevation uncertainty:
  - Dynamic tilting of the turbine during operation causing the height beams to change (tilt of turbine binned to the 0.5m/s bins)
  - In calculating the average height of the terrain for the left and the right beams
  - Inherent uncertainty of the lidar position due to uncertainty in the lidar's internal inclinometer
  - Elevation uncertainty from the terrain source and roughness

Not the final solutions…but a first step!

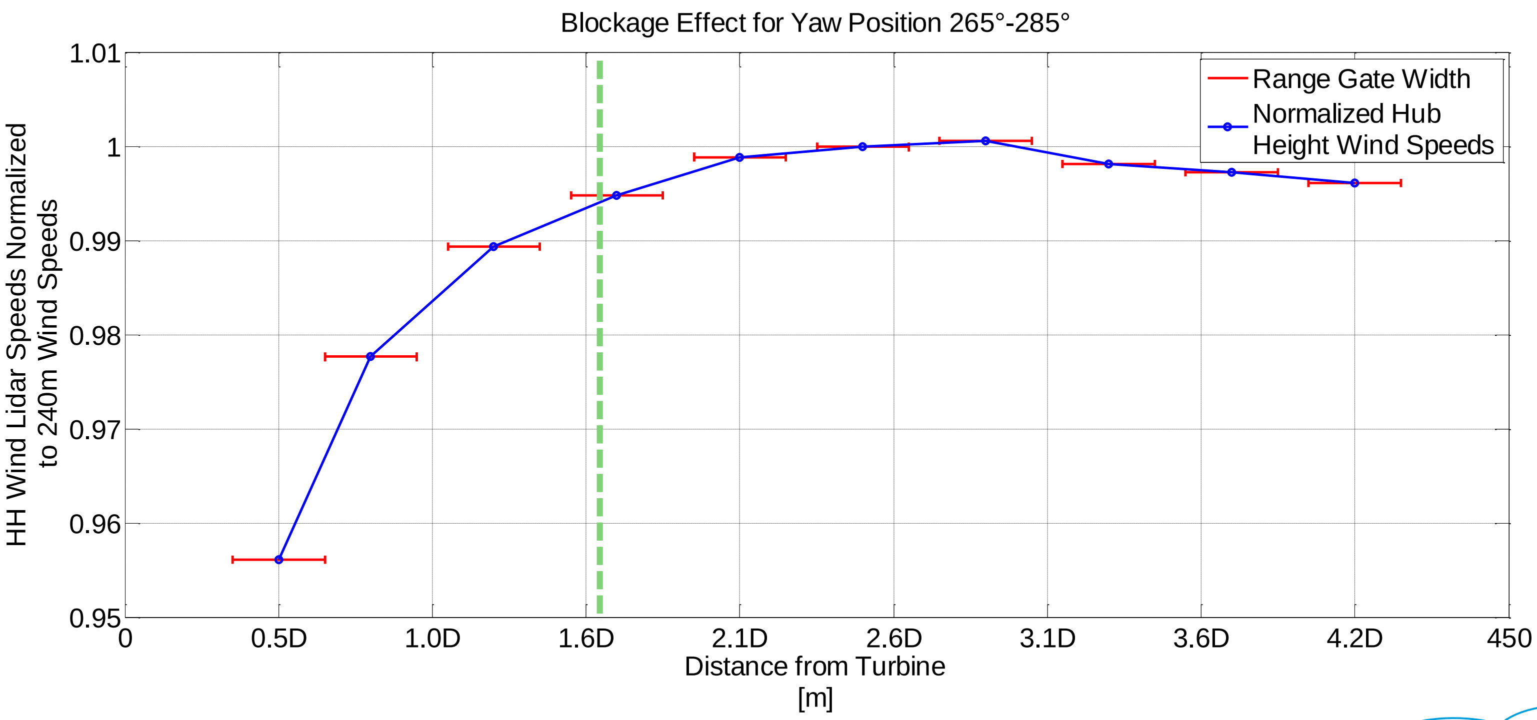
Uncertainty due to Terrain



- Only uncertainty in wind speed due to uncertainty in height of beams is displayed (**red**)
- Site specific!

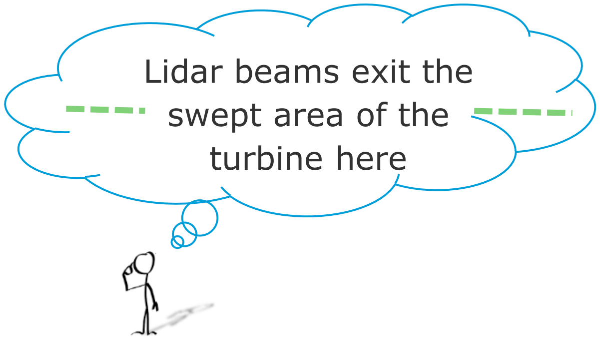
- The four main sources of elevation uncertainty have been translated from measurement elevation above ground (meters) to wind speed (m/s)
  - There exists other lidar uncertainties which are not shown
- These uncertainties would remain within the bounds of cup anemometer uncertainty

Blockage Effect

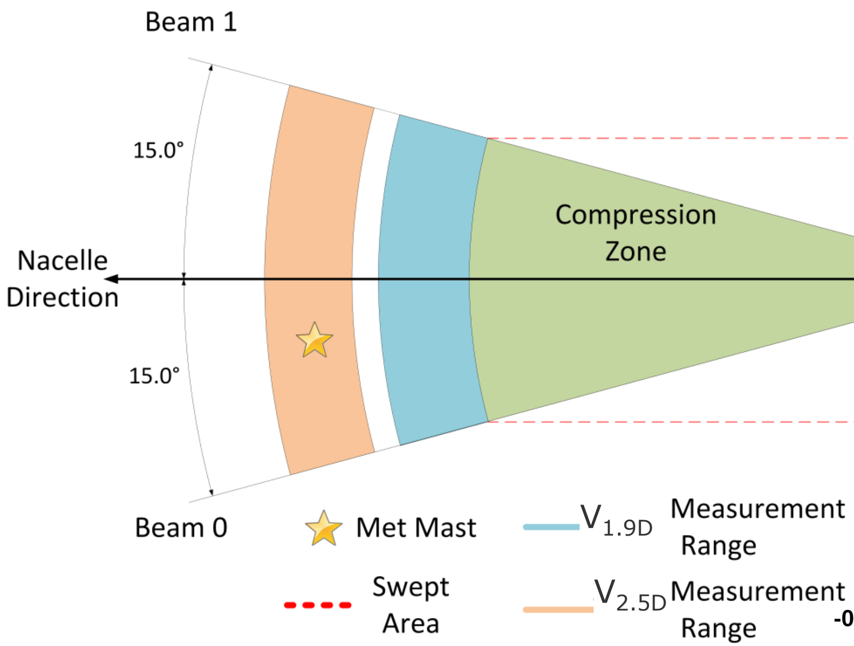


- Turbine RPM > 8
- Min wind speed 3.5m/s

- Lidar hub height wind speeds normalized to those measured at 2.5D
- Site calibration factors have been applied
- Beams exit the swept area at 1.63D, no blockage at 2.1D which is less than 2.5D

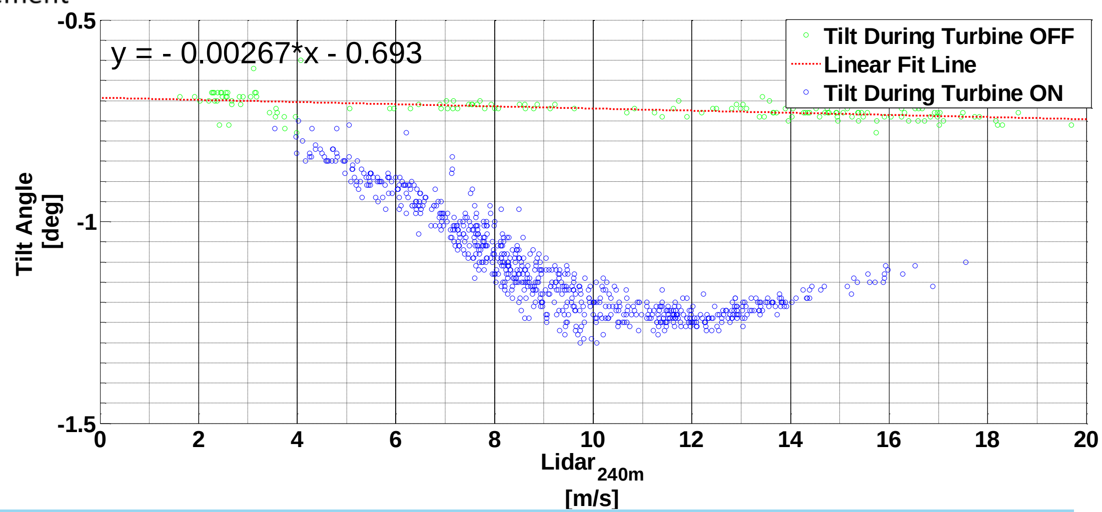


Deviations?



- The compression zone is the lidar measurement range(s) which are encompassed with the swept area
- During terrain effect calculations we pretend this affected area *doesn't exist.*

- There is tilting of the turbine when during (terrain effect) measurements.
  - Passive blockage?



Conclusions

- Positive outcomes
  - Beta test in complex terrain show a high correlation between cup anemometer and lidar measured wind speeds at turbine hub height
  - Successful wind speed retrieval at hub height using power law interpolation method and turbine tilting compensation technique. Encouraging results in shear and TI
  - High convergence on lidar measured site calibration factors with a measurable difference from met mast site calibration factors
  - No lidar downtime due to environmental conditions

- Future Plans
  - Trial at a site with high terrain slopes to attempt vertical wind speed estimations
  - Investigate rotor equivalent wind speed measurements (REWS) and TI renormalization
  - Utilize the lidar measurements as the turbine yaw for additional sector site calibrations

Special Thanks

- A collaborative and international project with promising initial results could not have been done with out all the support from my advisors at:
  - Avent Lidar Technology
  - DNVGL
  - Forwind
  - SunEdison

Thank you for your attention!

Paul Lawson
paul.lawson@dnvgl.com OR paul.Lawson.eng@gmail.com
+49(0)1511 6536623

Luke Simmons
luke.simmons@dnvgl.com

Erik Tüxen
Erik.Tuexen@dnvgl.com

Vineet Parkhe
Vineet.Parkhe@dnvgl.com

Matthieu Boquet
mboquet@leosphere.com

Florian Rebeyrat
frebeyrat@leosphere-avent.com

www.dnvgl.com

SAFER, SMARTER, GREENER