ENERGY

3D Nacelle Mounted Lidar in Complex Terrain

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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 located at 240m and 265° from turbine
Terrain

![Terrain Map]

- Ref Met
- Test Turbine

Legend:
- 650 m
- 600 m
- 550 m
- 500 m
- 450 m
- 400 m
- 350 m

Distance:
- 0.0 km
- 0.5 km
- 1.0 km
- 1.5 km
- 2.0 km
- 2.5 km

20 RD
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
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

\[ V_{\text{Hub Height}} = V_{\text{ref 1,2}} \left( \frac{H_{\text{Hub Height}}}{H_{\text{ref 1,2}}} \right)^\frac{V_{\text{ref 1}}}{\ln \frac{V_{\text{ref 1}}}{V_{\text{ref 2}}}} \]
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

![Diagram showing the process]

1. Choose future turbine installation
2. Install **Mast A** and **Mast B**
3. Measure hub height wind speeds
4. Calculate $R = \frac{V_A}{V_B}$
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

\[ R = \frac{V_{0.5D}}{V_{2.5D}} \]

1. Nacelle lidar installation
2. Turbine idling or RPM <1
3. Derive upper and lower wind speeds at 0.5D and 2.5D
4. Interpolate height wind speeds at 0.5D and 2.5D
5. Calculate \( R = \frac{V_{0.5D}}{V_{2.5D}} \)
6. Transpose future \( V_{2.5D} \) by multiplying by \( R \)
Wind Speed Correlations

<table>
<thead>
<tr>
<th>Bin Center</th>
<th>Slope</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>270°</td>
<td>0.996</td>
<td>0.986</td>
</tr>
<tr>
<td>280°</td>
<td>0.996</td>
<td>0.988</td>
</tr>
</tbody>
</table>

Important Filters:
- Minimum 3.5m/s for lidar and met mast
- No Maximum wind speed
- Wind shear $0.0 < \alpha < 0.5$
- Availability $\geq 0.40$

The compared wind speeds here are the raw measurements before any site calibration factors have been applied.
Site Calibration – Turbine OFF

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

<table>
<thead>
<tr>
<th>Bin Center</th>
<th>IEC - 2009</th>
<th>Lidar- $V_{0.5D}/V_{2.5D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>270°</td>
<td>0.980</td>
<td>0.970</td>
</tr>
<tr>
<td>280°</td>
<td>0.983</td>
<td>0.964</td>
</tr>
</tbody>
</table>

- Turbine RPM must be off or idling
- $265^\circ \leq \text{yaw} \leq 285^\circ$
- Wind direction $265^\circ \leq \text{WD} \leq 285^\circ$
- Min wind 4 m/s
- Max wind 16 m/s
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

- Turbine RPM must be <1

- $265° \leq \text{yaw} \leq 285°$

- Turbine not intentionally shut down
- 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!
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

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

- 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!*
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

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

- Site specific!
**Blockage Effect**

- 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

- Turbine RPM > 8
- Min wind speed 3.5m/s
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 without all the support from my advisors at:
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Thank you for your attention!

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