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Generic calibration procedures and results for nacelle-based profiling lidars

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Abstract

In power performance testing, it has been demonstrated that the effects of wind speed and direction variations over the rotor disk can no longer be neglected for large wind turbines [1]. A new generation of commercial nacelle-based lidars is now available, offering wind profiling capabilities. The use of profiling nacelle lidars to assess power performance could remove the need to erect expensive meteorology masts, especially offshore.

Developing standard procedures for power curves using lidars requires to assess lidars measurement uncertainty that is provided by a calibration. Based on the calibration results from two lidars, the Avent 5-beam Demonstrator and the Zephir Dual Mode (ZDM), we present a **generic methodology to calibrate profiling nacelle lidars**.

Objectives

The objectives of this work are to:

1) Develop generic calibration procedures, i.e. applicable to any type of nacelle-based lidar irrespective of their type (pulsed or continuous-wave) and design.
2) Apply the calibration procedures to both the 5-beam Demonstrator and the ZDM lidars. (see pictures below).
3) Provide calibrated lidars, since both are to be installed on nacelles of wind turbines during measurements campaigns (see www.unitte.dk), which goal is to develop procedures to assess power performance that could be applied in any type of terrain (flat or complex, onshore or offshore).

Pictures of the 5-beam Demonstrator (left) and the Zephir Dual Mode (right), during their calibration at DTU Wind Energy test site, Høvsøre, DK

The fundamental reason for developing calibration procedures is to **assign uncertainties to lidars wind measurements**. Commercial applications of lidars, e.g. power performance testing or resource assessment, demand the estimation of measurement uncertainties.

Metrology standards [2] define a calibration as a 3-step process:

- **Establishing a relation** between the measurand and reference quantity value;
- **Uncertainties measurand** = uncertainties on reference + calibration process ;
- Apply the calibration relation to preserve **traceability** in the measurement chain.

Calibration procedure principles

A lidar probes the wind by emitting light through a laser beam. Aerosols contained in the atmosphere scatter part of the laser light back to the lidar. Three levels of measurands exist in a lidar:

•The "rawest" one is the time domain of electrical current induced by the backscattered light on which spectral analysis is performed.

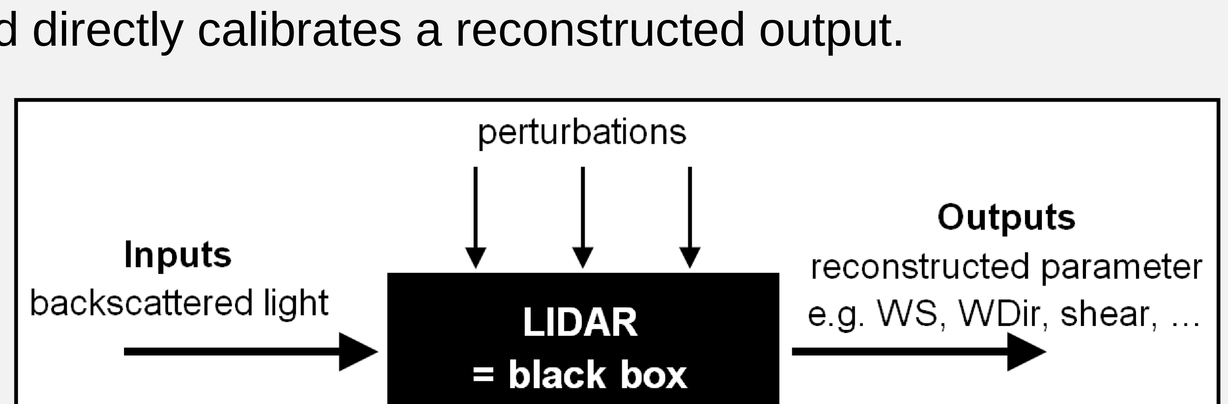
•The Doppler spectra generated then yield the Doppler frequency. The line-of-sight (LOS) velocity – or Radial Wind Speed (RWS) – is directly proportional to the Doppler frequency.

•Finally, algorithms combine RWS measurements to derive reconstructed wind parameters, e.g. wind speed and direction, shears, veers, etc.

Two different calibration concepts can be identified, called black box and white box. The black box method directly calibrates a reconstructed output.

In the black box calibration principle:

- ***Advantages:** fast and easy to implement; no information required about the post processing and reconstruction algorithm*
- ***Limitations:** each reconstructed output should be calibrated (multiple calibrated reference instruments needed); e.g. how would vertical shear be measured by a reference?*

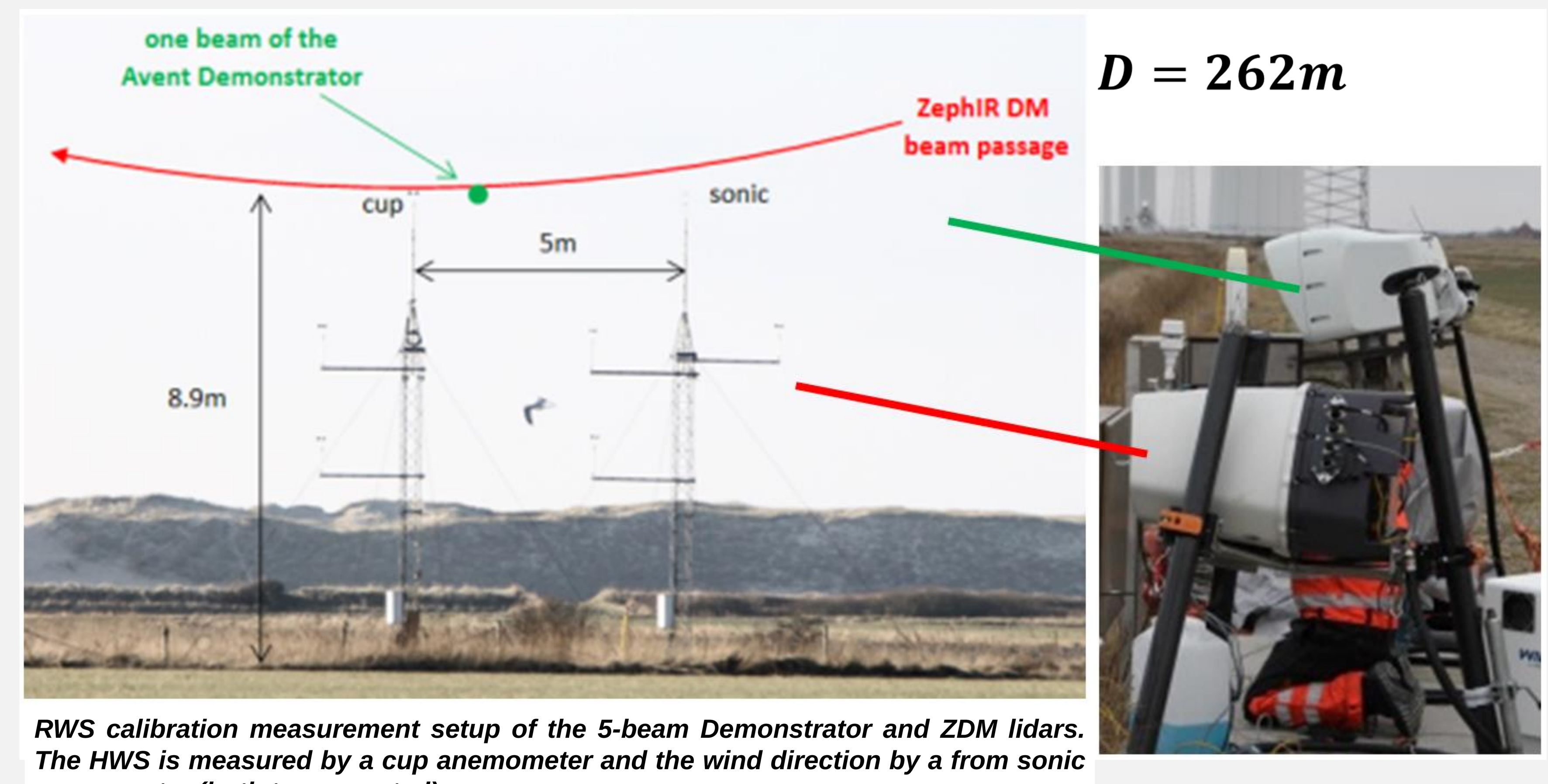


The white box calibration is a generic method that can be applied to all profiling nacelle lidars, in which the algorithms' input quantities are calibrated, i.e. the RWS, the beam localisation quantities (inclinometers), and the geometry of the scanning pattern. **The uncertainty estimation of any reconstructed parameter is theoretically permitted by the white box approach**. Thus, we have chosen this method.

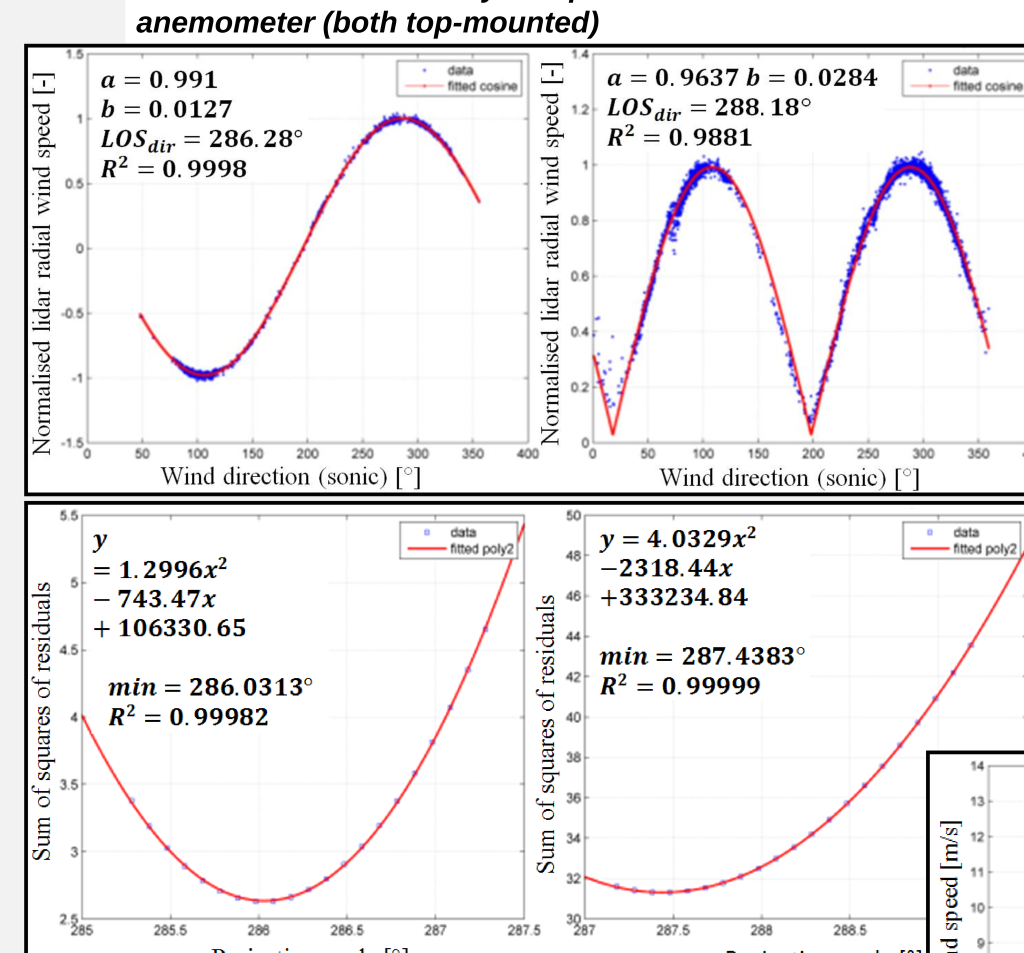
White box calibration steps, setup and results

The data required for the RWS calibration are time-averaged of: calibrated measurements of horizontal wind speed (HWS) and direction (θ); lidar RWS and beam inclination $\varphi_{physical}$. These data enable a reference equivalent RWS to be obtained by projecting the HWS onto the LOS direction (LOS_{dir}):

$$Ref_{eq\,RWS} = HWS \cdot cos\left(\varphi_{physical}\right) \cdot cos(\theta - LOS_{dir})$$



RWS calibration measurement setup of the 5-beam Demonstrator and ZDM lidars. The HWS is measured by a cup anemometer and the wind direction by a from sonic anemometer (both top-mounted)

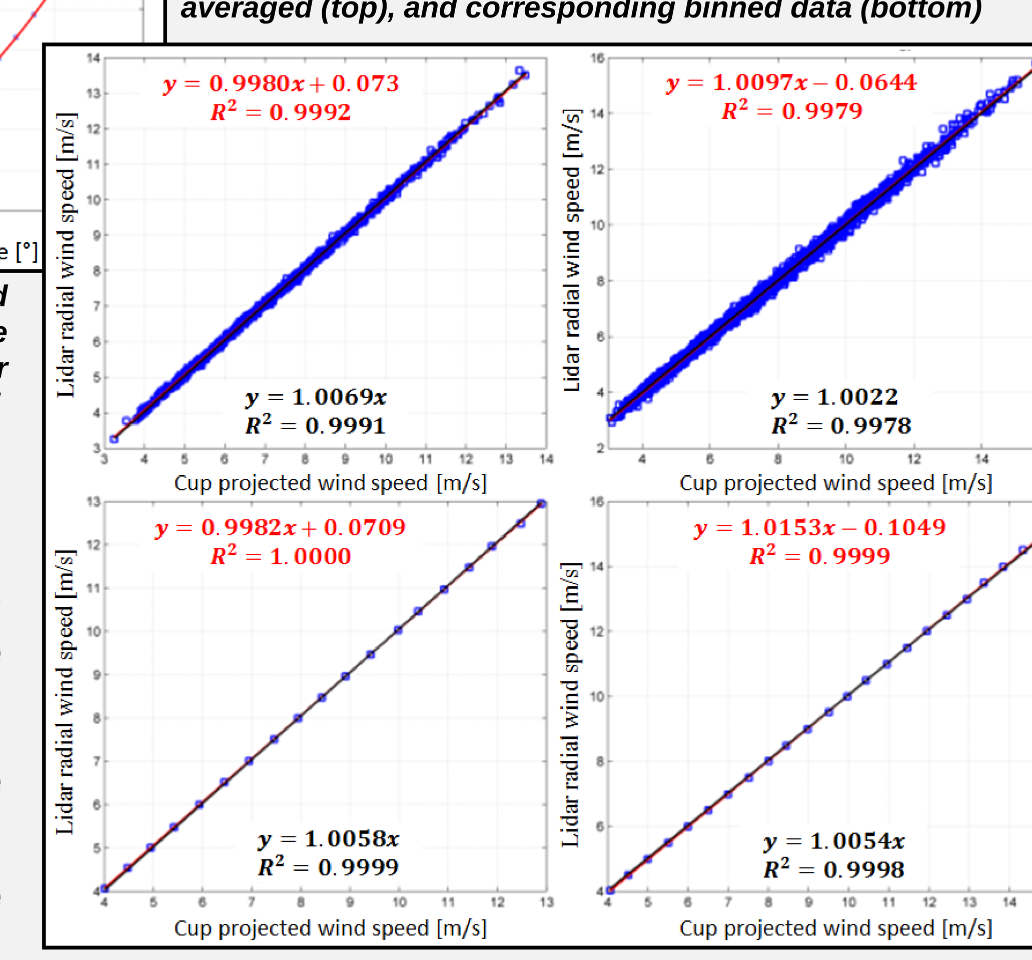


LOS direction evaluation: 5-beam Demonstrator (left) and ZDM (right) lidars. Top: cosine and rectified cosine response to wind direction respectively. Bottom: finer evaluation by use of a "Residual Sum of Squares process"

The **LOS direction is estimated** by:

1. Fitting the lidar response to the wind direction.
2. Linear regressions between the RWS and $Ref_{eq\,RWS}$ using different projection angles are performed, and the RSS are reported. The accurate LOS direction corresponds to the minimum of the fitted parabola.

Calibration relation results: 5-beam Demonstrator (left) and ZDM (right) lidars. Linear regressions on "raw" 10-min averaged (top), and corresponding binned data (bottom)



The calibration results (binned data) show consistent gains in the forced regression with an error of less than 0.9% for both the ZDM and the five LOS of the 5-beam Demonstrator.

R^2 coefficients are all > 0.9999 and the gains vary between 1.0056 and 1.0090 (5-beam Demonstrator). For ZDM, the gain is 1.0054.

Conclusions

Calibrations results have proven to be satisfactory in both cases with a high level of agreement between the lidars' RWS and the reference measurements, confirming the feasibility of the white box calibration. The methodology is generic and could therefore form the scientific basis of standardised nacelle lidars calibration procedures. The generic procedures, including the derivation of uncertainties, will be detailed in a journal paper.

References

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3. Wagner R. et al.: "Power curve measurement with a nacelle mounted lidar", [2014], Wind Energy, Vol: 17, issue: 9, pages 1441–1453.
4. Courtney M.: "Calibrating nacelle lidars", [2013], DTU Wind Energy E-0020.

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