Outcome of the UniTTe project

The UniTTe project provided major advancements for wind turbine performance assessment using the breaking through measurement technology of nacelle mounted lidars. Through collaboration with the relevant industry (including turbine manufacturers, wind farm developer and lidar manufacturer) and through full scale experimental campaigns, the project has demonstrated:

1. power performance verification can be achieved using a nacelle mounted lidar with the same accuracy and reliability as a standard practice with meteorological towers in flat terrain (and offshore)

2. a new method to conduct power performance verification tests in complex terrain using nacelle mounted lidars;

3. using nacelle lidar wind measurement, turbine load assessment can be achieved with the same or greater accuracy than with traditional met mast measurements.

Lidars view from the nacelle of turbine 04, Nørrekær Enge, DK (MC2, WP3)

Nacelle lidar measurement accuracy

Profiling nacelle lidars have been demonstrated to be reliable replacement for meteorological towers for power performance verification in flat terrain. This is of particular relevance for offshore wind turbines where it is usually too costly to erect a met. mast for performance testing.

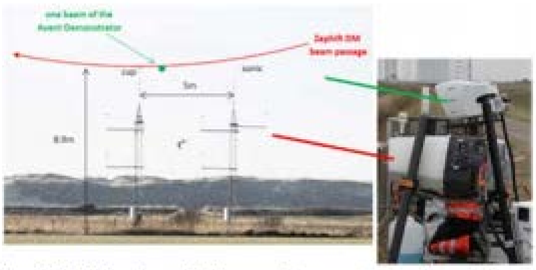


Fig. 3 ZDM (red) and 5-beam Demonstrator (green) beam positions, DTU Wind Energy test site, Høvsøre (DK) [1]

The wind speed measurement uncertainty is a key element in power performance verification. The uncertainty scheme previously developed by DTU for 2 beam nacelle lidars has been thoroughly revised and adapted to profiling lidars. The outcome is a generic methodology for field calibration of nacelle lidars and a very comprehensive uncertainty scheme. The calibration methodology consists in calibrating the LOS speed - of each beam for a multi beam lidar or one narrow scan sector for a scanning lidar - against a calibrated cup anemometer and provides a LOS speed measurement uncertainty. The measurement uncertainty of the nacelle lidars used in the project was within 1 to 2% of the uncertainty of a cup anemometer. The main uncertainty source has actually been identified to be the uncertainty of the reference cup anemometer used in the calibration process.

This approach has been introduced as th "white box" calibration approach and has been broadly re-used by the lidar community, in particular in the IEA Task 32. To our knowledge at least 5 institutions in EU have adopted the procedure for nacelle lidar calibration developed in UniTTe and offer it as a commercial service.

The generality of the approach and the thorough uncertainty budget developed in UniTTe have significantly contributed to start up the writing of a new IEC standard regarding the use nacelle lidars in wind turbine testing (The PT writing the IEC 61400-50-3 was kicked-off in September 2017 and the new standard is expected to be published in 2020).

Main Related Publications:

[1] Calibration report for Avent 5-beam Demonstrator lidar A. Borraccino , M. Courtney.DTU Wind Energy E-0087. March 2016

[2] Calibration report for ZephIR Dual-Mode lidar (unit 351) A. Borraccino , M. Courtney. DTU Wind Energy E-0088. March 2016

[3] "Generic methodology for field calibration of nacelle-based wind lidars", *Remote Sensing of Wind Energy*, (2016), ISSN 2072-4292, 10.3390/rs8110907 *A.Borraccino, M. Courtney, R. Wagner*

Power performance verification

Power performance verification basically relates the power produced by the turbine to the wind speed at the turbine location. It is fair to assume that the wind speed measured upstream of the turbine is the same as the wind speed at the turbine location, as long as the measurements are taken far enough from the rotor so that they are not within the induction zone, where the wind speed is slowed down by the turbine rotor. In complex terrain, the wind flow is disturbed by the topography, and this assumption fails. The common practice is to perform a site calibration, i.e. to assess the effect of the topography by first installing a meteorological tower at the turbine location before the turbine is erected and correlating the wind speed at this position to the wind speed at the reference mast position.

In UniTTe we have investigated a shift paradigm, that is to use nacelle lidar measurements close to the turbine rotor (about one rotor diameter upstream), within the induction zone. The proximity to the rotor considerably reduces or eliminates effect of the topography on the measurements and the need for site calibration. This approach however requires correcting the measurements for the induction effect.

Wind field reconstruction

In the UniTTe project we demonstrated an innovative method to estimate wind field characteristics using nacelle lidar measurements taken within the induction zone. Model-fitting wind field reconstruction techniques were applied to nacelle lidar measurements taken at multiple distances close to the rotor, where a wind model was combined with a simple induction model. The method allows robust determination of free-stream wind characteristics.

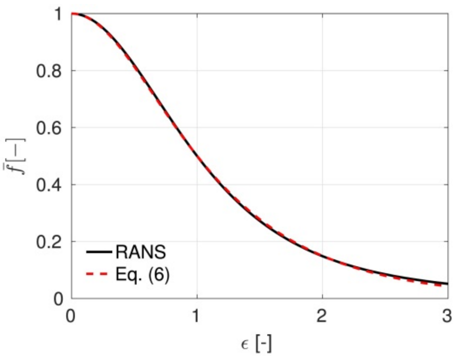
First a simple induction model has been derived. This model has then been used in the model-fitting wind field reconstruction method from nacelle lidar measurements. The method was validated with nacelle lidar measurements taken in flat terrain. Finally the same method was tested on measurements taken with different nacelle lidars at two different complex sites.

Induction model

The generic features of the induction zone of a wind turbine operating in simple inflow conditions were analysed. The induction zone upstream of 6 different wind turbine rotors have been studied using RANS simulations, and the following general features have been found:

• The induction zone forming upstream of rotors operating at the same thrust coefficient is rather insensitive to the load distribution for distances beyond 1 rotor radius (R) upstream. However, the deepest velocity deficit is generated by the rotor having the highest local CT.

• For distances beyond 1 rotor radius upstream of the rotors, the induced velocity is self-similar and independent of the rotor geometry.



Comparison of the self-similar f(ϵ) profile computed from Reynolds-averaged Navier-Stokes (RANS) and analytical model proposed in the paper.[4]

On the basis of these findings, a scaled induction field was defined, thus providing a simple analytical model of the stream-wise velocity upstream of a wind turbine which is applicable for any rotor in the region more than 1 R upstream of the rotor plane. In the valid region, the standard deviation between the model and the average of the RANS simulations is less than 0.7% of the free-stream velocity while the corresponding maximum difference to any of the RANS simulations never exceeds 1.7%. The latter difference should be seen in proportion to a spread between the individual RANS simulations, which maximizes at about 1.3%. Therefore, it was concluded that the proposed model is sufficiently accurate and this model was used in the model fitting wind field reconstruction method applied to the nacelle lidar data.

Application and validation of the model-fitting WFR method in flat terrain

A full scale demonstration campaign was conducted in the Nørrekær Enge Wind Farm (flat terrain). Two different nacelle lidars, an Avent 5 Beam demonstrator and a ZephIR 300, were installed on the nacelle of one wind turbine. Data were collected for 7 months. Mean wind speed measured by the two lidars were within 1.5% of the mast mounted cup anemometer, complying to the requirement of the IEC standard for power performance testing.

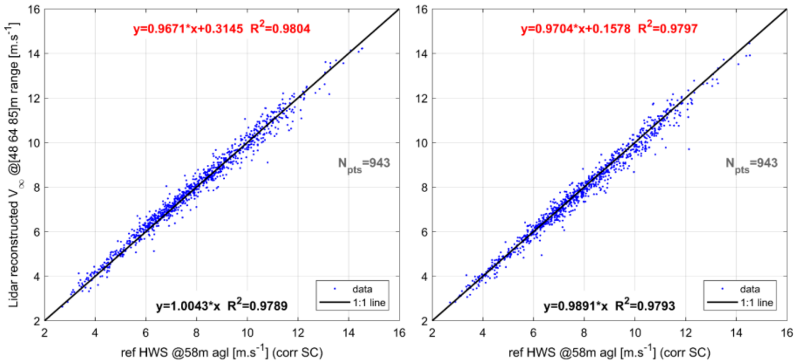
The model fitting WFR method fits 10 min averaged lidar measurements to an assumed wind model by minimising the error between lidar-measured and wind model-estimated line-of-sight velocities. The method was first tested with experimental data from the NKE measurement campaign. The reconstructed wind speed was within 0.5% of the wind speed measured with a mast-top-mounted cup anemometer at 2.5 rotor diameters upstream of the turbine. This technique overcomes measurement range limitations of the currently available nacelle lidar technology.

Application in Complex terrain

Secondly, two nacelle lidars (of the same types as those deployed in NKE) were mounted on a wind turbine in a moderately complex site, Hill of Towie, Scotland (RES' wind farm). The wind speed obtained with the nacelle lidars were compared to the wind speed measured by a ground based ZP300 lidar located 2.7D upstream of the turbine. Both nacelle lidars gave similar results.

- Nacelle lidar wind speed estimated from measurements at 2.7D upstream. In that case the induction effect has been ignored but the nacelle lidar measurments were corrected for the terrain height. The nacelle lidar is not systematically measuring at hub height above ground level due to the terrain slope. The wind speed estimate was within 2% from the ZP300 measurements, corresponding to an error in AEP in the order of 4%.

- Nacelle lidar wind speed estimated form measurements between 0.5D and 1D upstream. In that case the wind-induction model was used to retrieve the free wind speed. In that case, the reference wind speed was the ZP300 wind speed measurements corrected using the site calibration. The free stream wind speed estimate is within 1% from the ZP300 corresponding to an AEP error of approximately 2%.



Comparison of the nacelle lidar free wind speed estimates using the wind-induction model with the ground-based ZP300 profiling lidar measurements. The actual height of the LOS relative to the terrain is accounted for (the terrain correction is used in the reconstruction). Left: 4BWI. Right: ZDM. [6]

Finally, the WFR method was applied to data from another complex site, Ogorje, in Croatia (AkuoEnergy's wind farm). An Avent 4 beam Wind Iris nacelle lidar has been deployed on a Vestas V112 turbine at the Ogorje wind farm in Croatia between June and August 2017. On that site an IEC 61400-12-1 compliant met mast has been used as reference wind speed measurements. Those measurements were analysed in the same way as the Hill of Towie campaign.

With the wind model, the wind speed estimate is 1.7% lower than the cup anemometer wind speed, corresponding to an overestimate of 2.2 in AEP. With the wind-induction model, the wind speed estimate is 2.5% lower than the cup anemometer wind speed corresponding to an overestimate 3.6% in AEP. In the latter case, the reference wind speed is the cup anemometer measurements corrected using the site calibration.

The difference between the two approaches though does not seem to be due to the model and approach themselves, but rather indicate the difficulty to assess a new method by comparison to a reference with relatively high uncertainty due to the site calibration. Comparison without site calibration correction showed better agreement between the lidar wind-induction approach and the cup anemometer measurement (1.4% underestimation).

In those two studies, measurements from nacelle lidars close to the turbine rotor were used to estimate the free stream wind speed. The resulting measured power curves were at least as accurate as the ones obtained using the ground-based profiler measurements corrected with the site calibration. Thus, it was demonstrated that it is possible to measure a turbine's power curve at a (moderately) complex site without the need for a site calibration.

The UniTTe wind turbine power performance verification method using nacelle lidar method is planned to be applied and tested by at least 4 companies in EU.

The work performed in the UniTTe project enabled us to start the development of a new IEC standard (IEC 61400-50-3: Nacelle lidar for wind measurements). The results obtained in the project have also been presented in several meetings of the IEA Task 32; they were especially the focus of the IEA Task 32 Workshop #6 dedicated to power performance verification using nacelle lidars. It also showed the path to a *new way to use nacelle lidar measurements: not just to measure the free field upstream but to make most of the information that can be collected about the wind flow within the induction zone. The IEA task 32 is planning a workshop focusing on the wind field reconstruction methods for nacelle lidar measurements within the turbine rotor induction zone before the end of 2018.*

Main Related Publications:

[4] *"A simple model of the wind turbine induction zone derived from numerical simulations", Wind Energy (2017); 1-10. DOI: 10.1002/we.2137 N. Troldborg, A.R. Meyer Forsting*

[5] "Wind Field Reconstruction from Nacelle-Mounted Lidars Short Range Measurements", *Wind Energy Science, 2, 269–283, doi:10.5194/wes-2-269-2017, 2017 A.Borraccino[1], D. Schlipf[2], F. Haizmann[2], R. Wagner[1]*

[1] DTU Wind Energy, [2] Suttgart Wind Energy, University of Stuttgart

[6] Power performance verification in complex terrain using nacelle lidars: the Hill of Towie campaign. A. Borraccino, R. Wagner, A. Vignaroli, A. R.M. Forsting DTU Wind Energy E-0158 December 2017

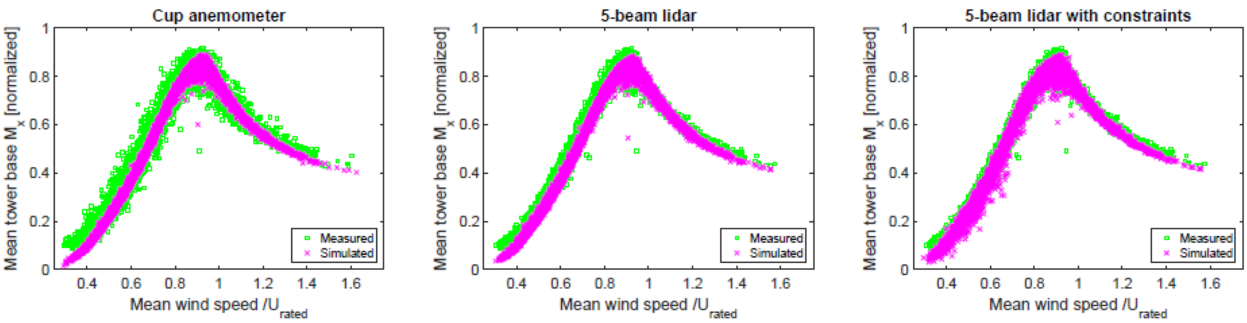
[7] Power performance verification in complex terrain using nacelle lidars: the Ogorje campaign. R. Wagner, A. Borraccino, A. R.M. Forsting DTU Wind Energy E-0157 under review

Loads assessment in flat terrain/offshore

In the UniTTe project, a procedure for carrying out wind turbine load validation based on measurements from nacelle-mounted scanning lidars was defined and demonstrated using the full scale NKE measurement campaign. This campaign included 2 different nacelle lidars, strain gauges on the tower and blades of the turbine and a meteorological mast at 2.5 rotor diameters upstream of the turbine.

The nacelle lidar measurements were processed to be used as inputs to aerolastic load simulations, and the results were compared to simulations where the wind inputs have been determined using the met mast data in compliance with the IEC61400-13 standard. For all simulation cases considered, the use of nacelle-mounted lidar measurements results in load estimation uncertainties lower or equal to those that based on measurements from cup anemometers on the mast. These results demonstrate the usefulness of nacelle-mounted lidars as tools for carrying out load validation without the need of meteorological masts.

The best agreement between the wind field reconstruction from lidar measurements and the met mast measurements was obtained when using lidar data from multiple measurement ranges simultaneously, which also required taking rotor induction into account.



Comparison between measurements of the mean values of the tower-base fore-aft bending moments for a wide wind direction sector and simulations of the same quantity using three approaches for defining wind conditions. Left: cup anemometer at 80 m; Center: 5-beam lidar; Right: 5-beam lidar including high-frequency measurements as constraints [9]

Due to the measurement and scanning characteristics of the nacelle lidars, it is important (and challenging) for lidar-based load validation to estimate turbulence measures as accurate as possible. We have shown that, if available, the Doppler LOS spectrum can be used to directly account for the longitudinal velocity component variance. If not available, similar results for the variance can be obtained by numerically computing the amount of variance filtering that takes place due to lidar volume averaging.

Furthermore, introducing constrained turbulence fields led to an improvement in the correlation between measured and simulated fatigue loads, and to a reduction of the bias and uncertainty of fatigue load estimations. The effect of using constrained simulations on the extreme load predictions was minimal. It is thus expected that the use of constrained simulations is most beneficial for simulating transient events such as gusts and front passages where wind statistics (means and second moments) are not well defined due to non-stationarity. Both near-range and far-range measurements served well as inputs for constrained simulations, but the overall highest reduction of uncertainty was achieved when the turbulence was constrained with nacelle lidar measurements from several ranges.

The UniTTe loads assessment method using nacelle lidar measurements is expected to be applied and tested in 2018 by 3 companies.

Main Related Publications:

[8] "Turbulence characterization from a forward-looking nacelle lidar", *Wind Energy Science*, 2, 133–152, doi:10.5194/wes-2-133-2017, 2017
Authors: A.Peña, J. Mann, N. Dimitrov

[9] "Load simulations using lidar-based wind statistics and high-frequency time series", *under review.*
N. Dimitrov, A. Borraccino, A.Peña, A. Natarajan, J. Mann