TotalControl

Advanced integrated supervisory and wind turbine control for optimal operation of large Wind Power Plants

Wind field measurements using LiDAR
Deliverable no. 3.6

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Document information

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Definitions/Abbreviations

Abbreviation	Definition
CFD	Computational fluid dynamics
DTU	Technical University of Denmark
LDT	Levenmouth Demonstration Turbine
LOS	Line-of-sight
LRWS	Long-range WindScanner
OREC	Offshore Renewable Energy Catapult

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EXECUTIVE SUMMARY

Field testing is essential for validation of wind turbine controller enhancements such as those proposed in Task 3.1 of the TotalControl project. This is to ensure that the expected performance improvements are achieved under real operating conditions given practical limitations and differences from design assumptions of the wind turbine. With the opportunity to use the Samsung 7MW LDT prototype as a test-bed, this project provides a unique opportunity to test a wide range of controller enhancements on one of the largest modern commercial turbines in operation, which is representative of the newest generation of turbines designed for the offshore market.

DTU and ORE Catapult have installed two advanced lidar systems on the nacelle of the Levenmouth Demonstration Turbine (LDT) - one to measure the inflow wind field and one to measure the wake, using DTU's unique 3D scanning lidars to provide exceptional coverage of both the upstream and downstream flow field around the wind turbine. These measurements will be used both for real-time control of the turbine and for analysis to compare flow model predictions with real-world observations.

This report begins by outlining the project motivation, followed by describing the lidar systems and their data formats. Details specific to the measurement campaign at Levenmouth are presented including device pre-calibration and the onsite installation procedure. Initial checks of data quality against a nearby met-mast are presented which confirm that the systems are operating as expected. A description of the enhanced turbine controller and its interface is followed with a test plan outlining the goals and requirements of the field campaign. Finally, various issues faced in the pursuit of executing the tests are reflected upon.

1. INTRODUCTION

The wind turbine industry has seen significant growth year on year and it is expected to see further growth in the future. The rapid growth in installed capacity and significant reductions in the levelized cost of energy (LCoE) have been driven by the upscaling to the turbine technology leading to ever increasing turbine sizes. Larger individual turbines can extract more power form the wind however turbine components are subjected to larger loads.

The role of the turbine controller is pronounced in large wind turbines because deviation from optimum condition does not only lead to large losses of potential clean energy from the wind turbine but also increases the risk of damaging turbine components. A key parameter used by wind turbine controllers for power optimisation and load reduction is the average wind speed in the turbine rotor.

Measurement of wind speeds at wind farms have traditionally been carried out by meteorological (MET) masts situated at the wind farm. Individual turbine hub height speeds have also been conventionally are measured by nacelle mounted anemometers. Recently, the use of Light Detection and Ranging (lidars) for wind speed measurement in the wind industry is becoming more common due to the many benefits they offer over traditional measurement techniques. Recently, lidars have started being mounted on turbine nacelles to measure wind fields ahead of the wind turbines for various applications, including wind turbine control.

This report documents the installation, measurements and validation of two lidars installed on the 7MW Levenmouth turbine as part of TotalControl Task 3.2.2. Two lidars, a DTU spinner lidar and DTU long-range WindScanner system (LRWS) have been installed on the Levenmouth Demonstration Turbine (LDT) and these are described in detail section 2. The process for managing the data collected from these turbines have been documented in section 3. The calibration procedure for the LIDARs are detailed in section 4.

The measurements from the installed lidars have been validated using measurements from a met-mast located on the turbine site. The results of the site validation of the forward-facing spinner lidars are presented in section 8 while the work relating to the design of the lidar-turbine interface and validation tests plans are presented in sections 6 and 7 respectively.

1.1. Purpose of measurements

The spinner lidar and long-range WindScanner system (LRWS) will deliver measurements for subsequent tasks within work package 3 of the Total Control project.

The forward-facing spinner lidar measures the wind flow at multiple distances ahead of the turbine's rotor and provides measurements that are more representative of the wind flow field than the nearby met-mast. This detailed inflow characterisation will be valuable for the field testing of the adaptations of the 7MW Levenmouth turbine controller described in TotalContol Deliverables 3.2, 3.4 and 3.5, as well as providing the controller input signal which is needed in the case of the LiDAR-assisted Control (LAC) in D3.5 which relies on the preview of wind speeds ahead of the turbine. Lidar measurements will therefore play a role in the validation of these controller adaptations in deliverables 3.7 and 3.8. Also, the turbine wake will be monitored by the rear-facing lidar to validate the effect of power and yaw set-point changes required for wind farm control.

As part of Total Control task 3.2, deliverable 3.9 aims to develop a predictive model of wind velocity in the rotor plane by utilising upwind measurements. These measurements will be acquired via the strategically placed spinner lidar. The lidar measurements are key inputs that will feed boundary conditions of the Computational Fluid Dynamic (CFD) models that will estimate the flow in the rotor plane. The CFD models will also deliver down stream flow characteristics which can be validated with wake measurements from the LRWS.

1.2. Lidar measurement systems

Two lidar systems with differing measurement processes and objectives are included in the Levenmouth test campaign. This is necessary in order to provide data requirements for real-time control and for collecting observations used in comparison against flow model results. In this particular setup, turbine inflow conditions are measured using the forward-facing spinner lidar, while wake conditions are measured using the rear-facing long-range WindScanner (LRWS). Both systems were designed and developed by DTU together with commercial partners and are presented in greater detail within Section 2.

2. Description of lidars

2.1. Spinner lidar

The DTU spinner lidar was designed specifically for nacelle-mounted turbine installations. It has been used both in forward (inflow) and rear-facing (wake) configurations in past projects (Herges et. al, 2017). The laser technology is based on continuous-wave (CW) principles where light is continuously directed and focused at discrete points in 3D space. CW lidars are well suited for short-range measurements (i.e. up to ~150m) and provide fast sampling rates (here: 500 Hz point sampling leading to one full scan per second). This indicates its suitability for providing the forward-looking information, where interference from the turbine's blades can be mitigated and a reconstructed wind measurement is available to the turbine controller once per second.

The scanner-head of the Spinner lidar consists of two optical prisms with a deflection angle of 15°. The two prisms rotate in a constant speed, with a fixed ratio between them (13/7). When the measurement distance away from the instrument is fixed, then the rotating prisms steer the laser beam in a scanning pattern similar to a rose curve with a *k*=13/7. A combination of all available points along the scan are used together to reconstruct a single wind vector (u,v,w) which is transmitted to the wind turbine controller interface. The reconstruction algorithm is presented in: Peña et. al, 2019.

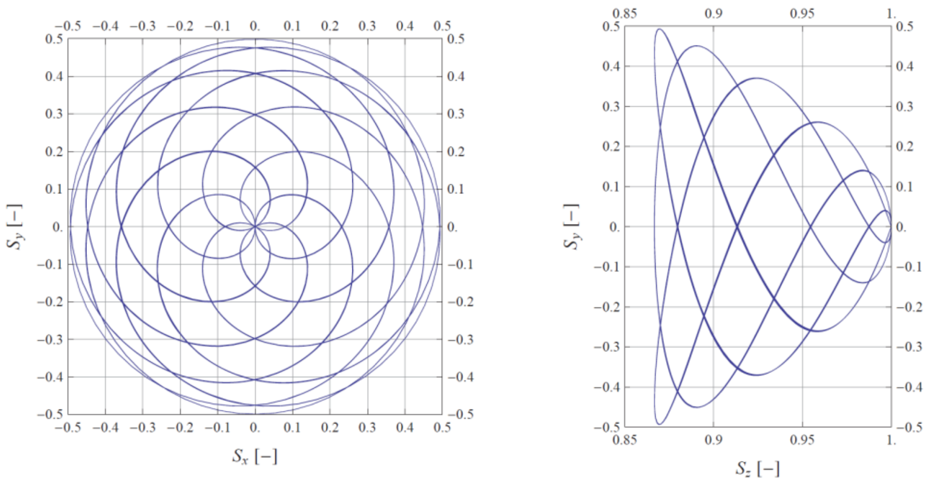

Figure 1 Spinner lidar fixed scan pattern

2.2. Spinner lidar data formats

The spinner lidar can output two files per minute if the appropriate storage option is enabled: one .spin-file and one .spec-file. The .spec files contain raw Fourier-transformed spectral data while the .spin files contain the processed line-of-sight measurement and various operational information of the lidar system.

Table 1 The format of .spin-files. Total size: 46 bytes.

Name	Type	Description
Index	uint16	Sample number in the scan pattern.
Utc	int64	UTC time.
Vlos	float32	Line of sight velocity estimate. NaN if no wind speed could be determined.
Quality	float32	Quality of the estimate. 0<q<1, 1 being the best.
Power	float32	Total power in the spectrum.
Azimuth	float32	The azimuth of the lidar. 0 corresponds to the side where the motor is pointing upwards.
Sx	float32	The x-component of the unit vector ˆs.
Sy	float32	The y-component of the unit vector ˆs.
Focus	float32	The focus distance in meters.
Inclination	float32	Inclination of the lidar
ScalingFactor	float32	max(spectrum)/65535. Multiply spectrum with this value to obtain the original spectrum
temperature	float32	Temperature in the control box

For every scan a special record is added to store the calculated wind vector. This is recognised by the index number being set to 10000. The format of this special record is:

Table 2 The format of .spin-files (wind vector). Total size: 46 bytes.

Name	Type	Description
Index	uint16	10000 (code for wind vector)
u	float32	u-component
v	float32	v-component
w	float32	w-component
Neff	Int32	Number of good points in estimate
NA	Char*32	Bytes to make the record 46 bytes long

Table 3 The format of .spec-files. Total size: 512 bytes.

Name	Type	Description
FftData	*uint16[256]*	*The normalized spectrum*

The system stores files locally but has limited capacity (500 GB).

2.3. Spinner lidar streaming data

This spinner lidar has an added feature to determine the wind vector from the measured scan pattern in real-time. The system will stream the calculated vector as UDP packets. The format of the message is specified below, this can be changed if required. The UDP-packet is sent every time a full scan has completed.

Table 4 The format of the UDP-packet. Total size: 12 bytes. byte order: little-endian

Name	Type	Description
u	float32	u component of the estimated wind vector
v	float32	v component of the estimated wind vector
n	Int32	Number of good measurements in the wind vector estimate

2.4. Long-range WindScanner (LRWS)

The long-range WindScanner system (LRWS) is a pulsed Doppler wind lidar with steerable scan head (Vasiljevic et. al, 2016). The lidar hardware was developed together with Leosphere and is available commercially as the WindCube 200S. The DTU-developed WindScanner software allows for a range of additional capabilities over the commercially available system; such as extended monitoring abilities, coordinated multi-lidar scanning and the execution of complex trajectories following arbitrary geometries.

Being a pulsed long-range lidar, the LRWS' measurement range extends to a maximum of ~5 km (using the longest pulse length) while simultaneously measuring at multiple distances (range gates) along the beam path. This makes it a suitable choice for measuring wind turbine wakes as it can observe both the near and far wake flow. By installing the LRWS atop the turbine nacelle, a flat (horizontal) plane can be scanned at zero elevation angle behind the turbine. This cross section clearly captures the flow patterns of the wind turbine wake, as is demonstrated in Figure 2. This is a visualization of a single wake scan from real data in the field campaign at Levenmouth.

The scan pattern can be changed on the fly throughout the measurement campaign, and shorter deviations from the main strategy may be requested for various reasons (e.g. further investigation of certain observed phenomena, measurement performance checks, and verification of beam positioning). However the dominant strategy is to run continuous plan position indicator (PPI) scans as seen in Figure 2. In this scenario, an azimuth sweep of 60 degrees (+/- 30 degrees centred in plane with the rotor) scanning at 2 degrees/second and consisting of 60 lines-of-sight (LOS) is performed at zero degrees elevation. A 200 ns (middle) pulse length with 128 point FFT processing is used, with an accumulation time of 500 ms per LOS. Range gates (measurement distances) begin at 100 m and increase in 20 m increments to the maximum range of 2000 m. In this configuration, one complete scan is executed in 30 seconds, plus 2-3 seconds which are needed for repositioning the scan head in preparation for the subsequent scan.

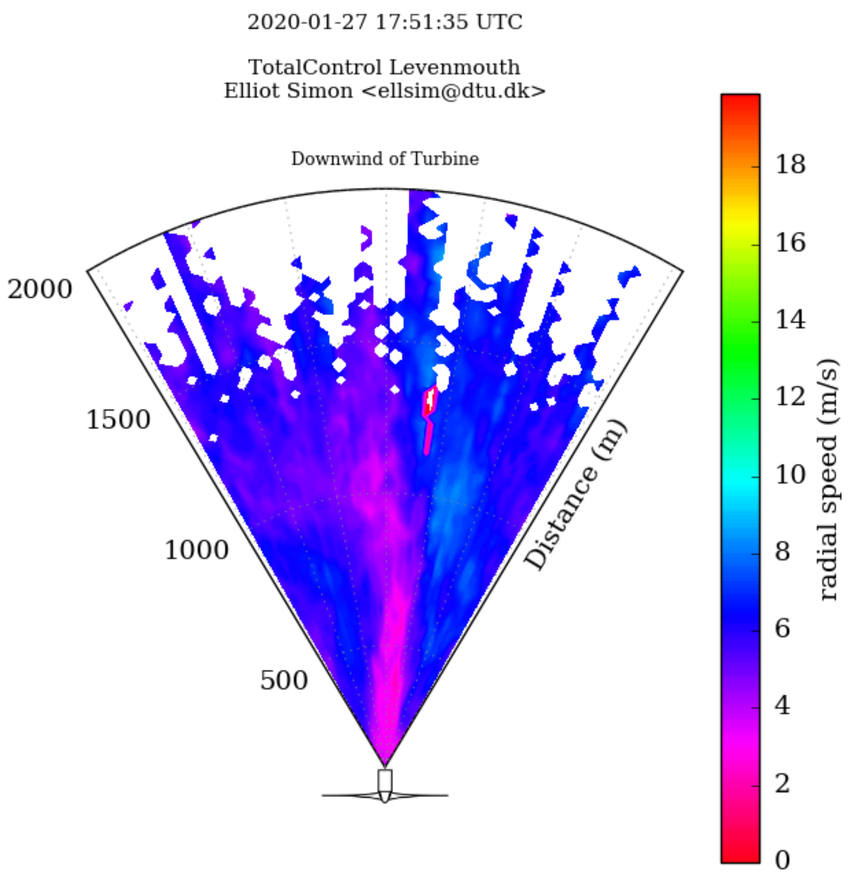

Figure 2 Wind turbine wake measured with rear-facing LRWS (single scan) during normal operation on the LDT. The object visible is hard target contamination by the nearby met-mast.

2.5. LRWS data formats

There are three levels of LRWS data products which will be delivered as part of the final campaign dataset.

- Level 1: Raw data:

  The native data storage format of the LRWS consists of sets of three text files generated every 10-minutes, which are stored on the lidar's internal hard drive (wind, scanner and system files). These files are stored within scenario directories which are created when the LRWS is commanded to begin measuring (either due to an error or previous stop command). The data files are stored separately due to the differing sampling rates between the acquisition loops. Each text file is in semicolon separated format with period decimal notation. Timestamps are recorded in LabVIEW epoch (seconds since January 1, 1904) with UTC time zone. There are no labelled headers present, and the raw data may need to have corrections applied. Therefore we suggest users to work with the downstream data products explained below.

- Level 2: Labelled data:

  The (raw) text-file based lidar measurements are subsequently converted into labelled NetCDF v4 format using the e-WindLidar lidar data converter (Lidaco, 2020). This follows the Unidata Common Data Model with specifics adapted for remote sensing data. Full documentation of this data format is reported in: Vasiljevic et. al, 2018. This dataset contains labelled coordinates and dimensions, and metadata attributes explaining the measurement setup and positions. It can be read with standard computing software such as Python (xarray package) and Matlab.

- Level 3: Processed data:

  Processed data products are built using Level 2 data and are the result of data analysis procedures applied to cleaned and quality controlled measurement data. The strategy for performing analysis on the completed wake scan dataset is not yet finalized. This is foreseen to include averaging of time periods to determine static wake deflection and dissipation, and possibly to extend to tracking wake dynamics for comparison with more complex flow models. Level 3 data products do not follow a set standard format but will be accompanied by descriptions and access instructions via readme files and/or further publications.

3. DATA MANAGEMENT PLAN

3.1. Data flow

A data flow chart of both lidars installed on the LDT is shown in the figure below.

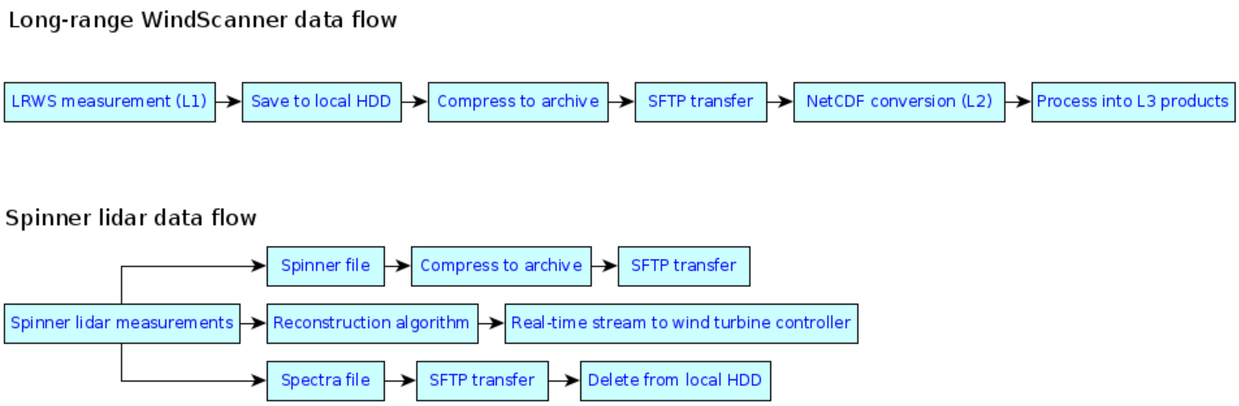

Figure 3 Measurement data flow chart from both lidar systems installed on the LDT

3.2. Storage

All data and documentation from the field campaign is stored on a file server managed by DTU. The file server is accessible externally through secure file transfer protocol (SFTP). Project partners will have access to the dataset with read-only credentials. Please contact Elliot Simon for access instructions. The structure of the dataset aims to be self-explanatory and is complemented with readme files where appropriate.

3.3. Backup

All files on the aforementioned storage location are incrementally backed up to a separate file server on DTU's internal network. This process is done automatically as a scheduled task. Wind measurements from both lidars are archived (i.e. not deleted) on the local HDD until the end of the field campaign as a secondary backup measure against potential data loss.

4. LIDAR PRE-TEST (CALIBRATION)

4.1. Spinner

Before the spinner lidar was installed on the turbine, DTU performed an alignment of the scan pattern and the inclinometer, as well as a preliminary test of the lidar at Risø.

For the calibration the spinner lidar was placed 8 meters from a wall and the pattern was recorded using an infrared camera as seen in the pictures below.

Figure 4 Scan pattern from the spinner lidar recorded on the wall

Three points in the pattern and the exact position of the lidar were measured with a Leica MS60 MultiStation. From this the azimuth, tilt and roll of the instrument were calibrated and it was verified that the path of the prism was as expected within a reasonable tolerance.

Next, the spinner lidar was placed on top of a shed roof next to a met-mast at Risø hereby copying a former experiment with a similar spinner lidar described in Peña et al. 2019. The lidar was tilted 30° in order to point towards the sonic anemometers and cups in the met-mast and the focus distance was set so that the spinner lidar measures near the cup anemometers in the met-mast.

The 10-minute averaged radial velocities of the lidar was compared to the radial velocity of the cups and sonics in the mast as described in: Peña et al. 2019. Only periods with wind directions along the line-of-sight between the lidar and the met mast (+-30°) were used in the comparison. The results for this comparison can be seen in Figure 5 which shows good agreement between the cup anemometer and the spinner lidar.

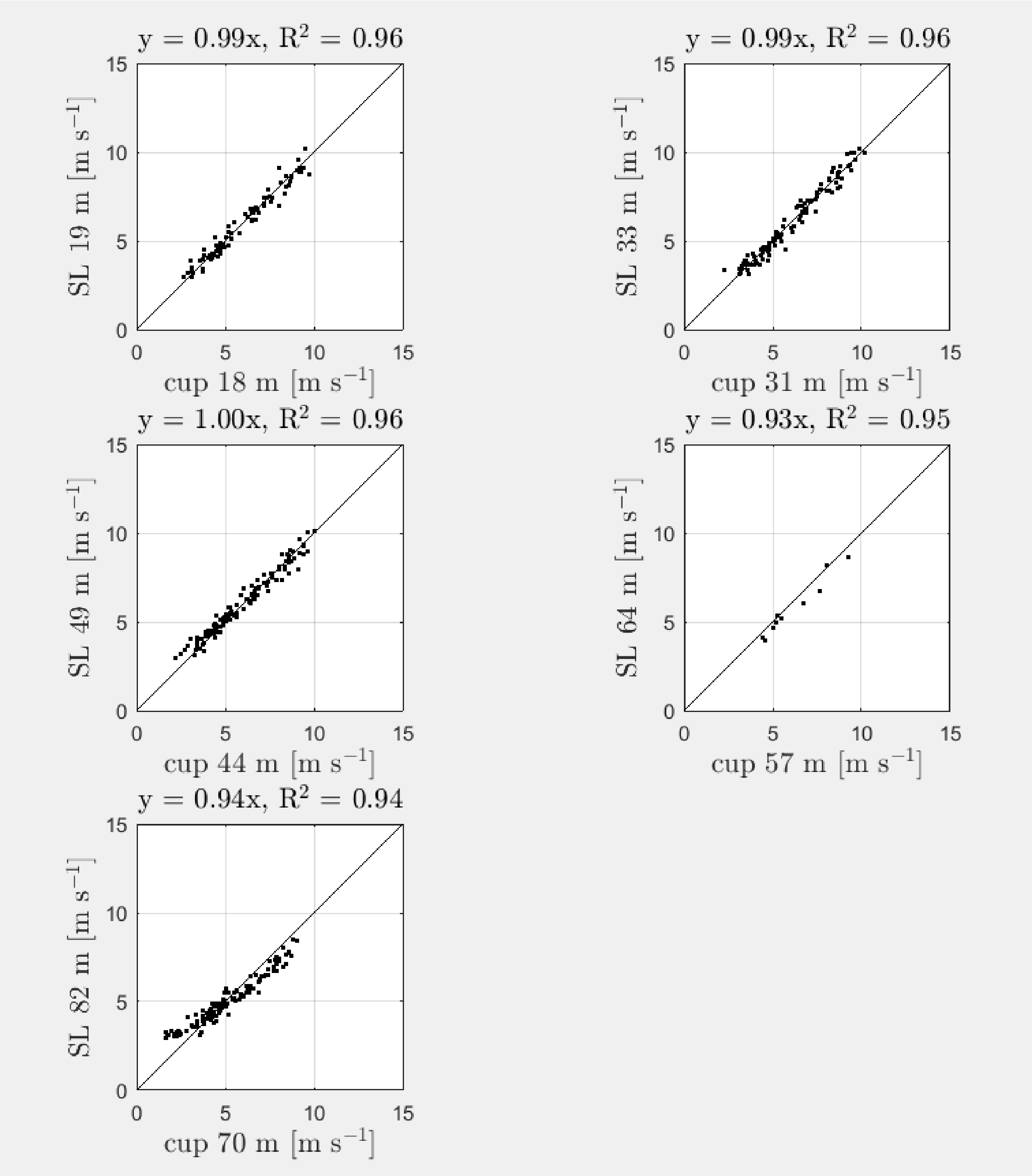

Figure 5 Comparisons of 10-min averages of radial velocities between the cup anemometers in the mast and the spinner lidar using points on the center line in the pattern closest to the cups

To test the implementation of the algorithm to estimate the wind vector from the spinner lidar pattern, we plotted the u component and the horizontal velocity calculated from the estimated wind vector together with the wind speed measurement in two heights nearest to the point where the centreline of the spinner hits the met mast (Figure 6). The wind direction measured by the spinner lidar and a wind vane in the met-mast shows the angle to the line connecting the spinner and the mast. When this angle is close to zero- as it should be when the lidar is placed on top of a turbine, the u component will be equal to the horizontal wind speed. The estimated wind vector works best for winds coming from the front and does not work for winds from the side as can be seen below when the wind direction is close to -90 °. The wind vector estimation is expected to be more accurate when the spinner lidar is not tilted.

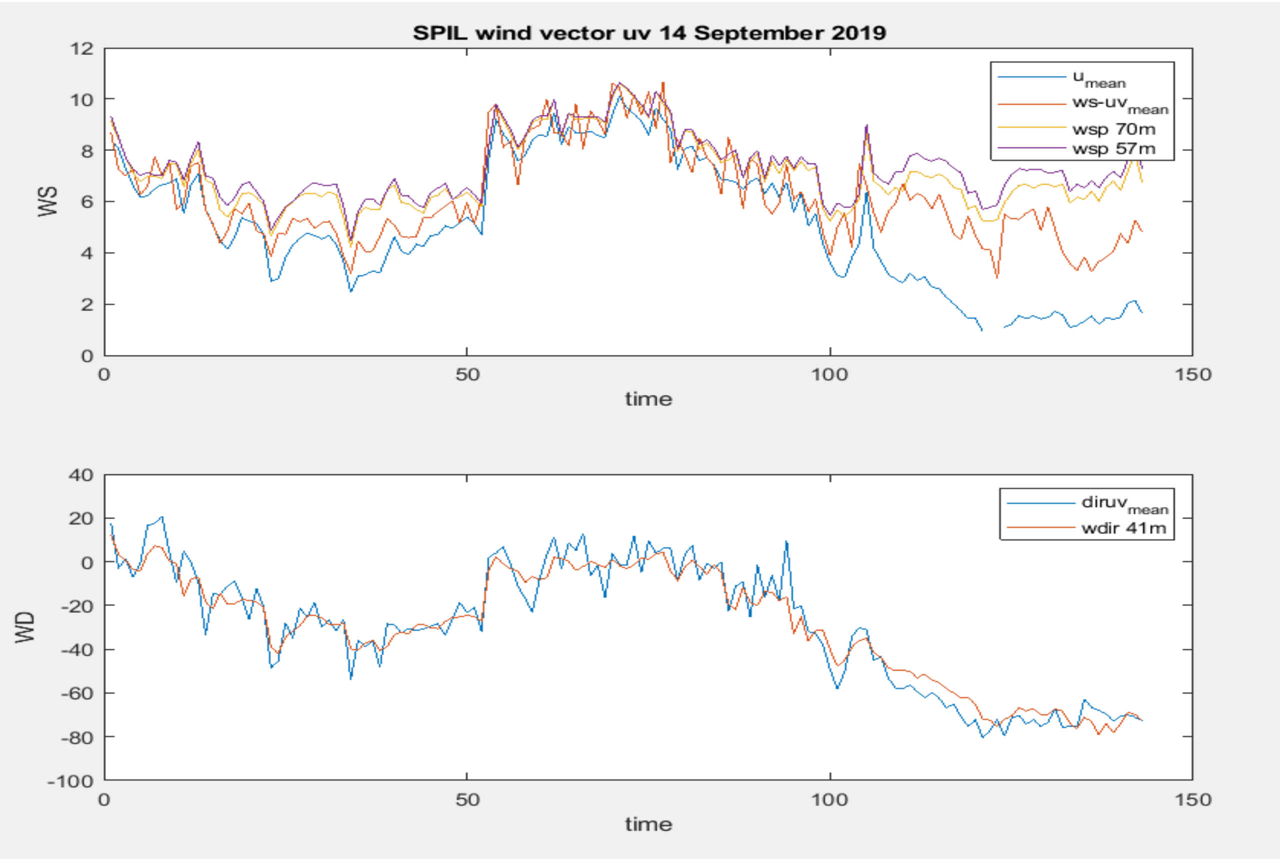

Figure 6 10-minute averaged values of the estimated spinner lidar wind measurement and the wind speeds measured at the met-mast for one day

4.2. LRWS

When installing the long-range WindScanner on the turbine it is important that the system is correctly levelled to ensure that the beam is pointing in the desired direction. Even a small pitch or roll error of the scanner can result in large displacement of the beam far away from the scanner.

In the procedure for levelling the system, the beam position is determined by scanning the beam through an area with a hard target (Vasiljevic, 2014). By looking at the Carrier to Noise ratio (CNR)-signal, which is much higher for hard targets than for the atmosphere, the position of the hard target in the scanner coordinate system can be determined. Figure 7 shows a CNR-mapping of a hard target, in this case a stick.

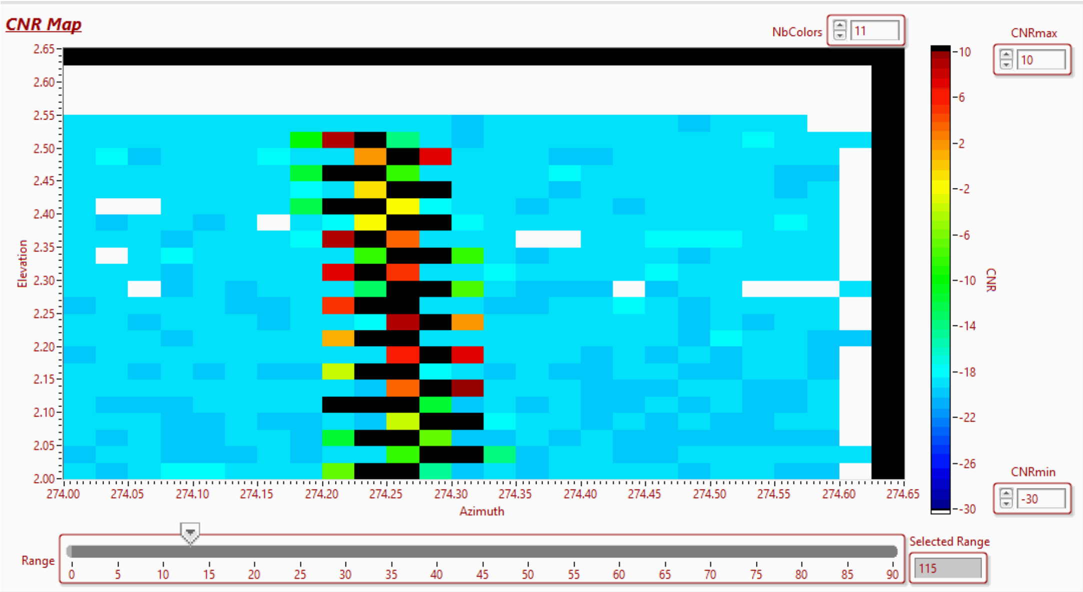

Figure 7 Example of CNR-map of a stick in the range of 115 m. The blue colour corresponds to low CNR from the air around the stick. The black and red colour corresponds to high CNR-signal from the hard target (stick).

The CNR-map gives the actual azimuth and elevation angles of the beam in the scanner coordinate system when the beam was pointing to the top of the stick. Using a differential GPS, the X,Y,Z (north, east and height) positions of the scanner-head and the top of the stick are recorded in a UTM coordinate system. From the UTM positions, the expected pointing direction (azimuth and elevation) from the scanner-head to the top of the stick (if the system was levelled) is calculated. By comparing with the actual azimuth and elevation position of the beam when the beam was pointing to the top of the stick, the misalignment is determined.

The pitch and roll are changed by adjusting the legs of the scanner. This is done iteratively and when the actual and expected elevation and azimuth angles match, the system is levelled. The procedure is carried out using multiple stick/hard targets in different position to align the different degrees of freedom (i.e. pitch and roll).

At the site where the scanner is installed there are no hard targets available to perform the mapping since the scanner is on top of a turbine nacelle. For that reason, the above procedure was carried out at the Risø test site in Denmark before sending it to the site in Scotland. After levelling the system, the inclination values of a two axis inclinometer installed on the optical rack inside the scanner was recorded. These values were later used to level the system at the site once the lidar was installed atop the turbine. The inclinometer values for the levelled system are given in Table 5.

Table 5 Calibrated inclinometer values for the LRWS

Axis	Inclination (degrees)
X	0.24
Y	-0.19

5. LIDAR INSTALLATION

In order to safely install the lidars on the turbine, optimum locations were agreed between DTU and OREC. Frames and attachment systems were designed to support the lidars during their life on the turbine (assumed 1 year).

Both lidars were delivered to the Levenmouth site for installation in the below locations:
1. Front-facing lidar on the nacelle roof
2. Rear-facing lidar on the rear gantry

Figure 8 Lidar installation locations - front-facing lidar on nacelle roof (1) and rear-facing lidar on rear gantry (2)

Both lidars were installed, calibrated and tested for data output on the 24th of January 2020 and can be monitored via remote access (both to the internal lidar PCs and the two monitoring cameras installed to view the systems remotely).

5.1. Spinner lidar

The spinner lidar is installed on the front of the nacelle roof. This frame was designed to the following design requirements:

- Maximise height to reduce obstruction of view from the hub, but still maintain access for servicing.

- Be as central as possible to ensure symmetrical disruption of view from the blades
- Withstand site wind conditions for design life of 1 year and 50-year storm
- Avoid damage to the nacelle roof
- Have back up attachment systems inside the nacelle via cable tether to ensure the lidar is retained in case of catastrophic damage to the frame
- Reduce the risk of lightning strikes

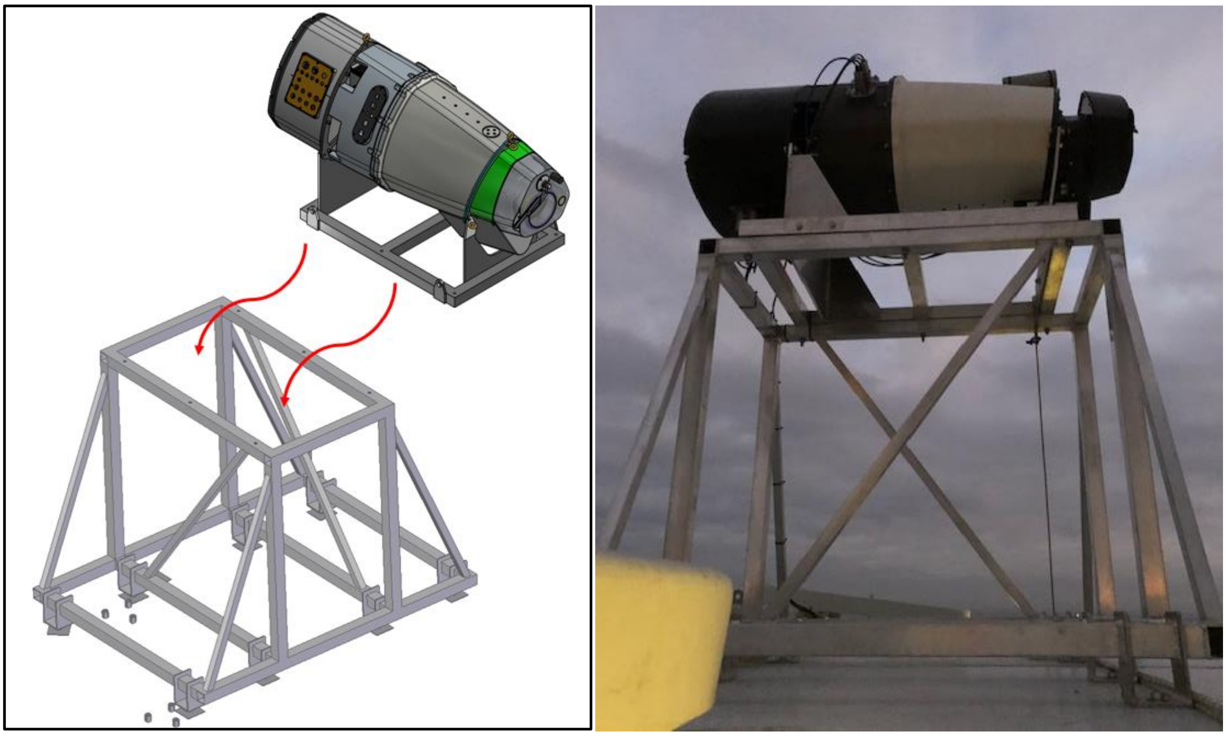

Figure 9 Spinner lidar as installed on the forward nacelle roof of the LDT

5.2. LRWS

The LRWS is installed within the rear gantry of the nacelle roof. This frame was designed to the following design requirements:

- Maximise the platform height to reduce obstruction of view from gantry railings, but still maintain access for servicing via gantry access. This means that rope access is not required for access
- Place the scan-head as central as possible to achieve symmetry in the wake scans
- Withstand site wind conditions for a design life of 1 year and 50-year storm
- Avoid damage to the nacelle roof
- Reduce the risk of lightning strikes

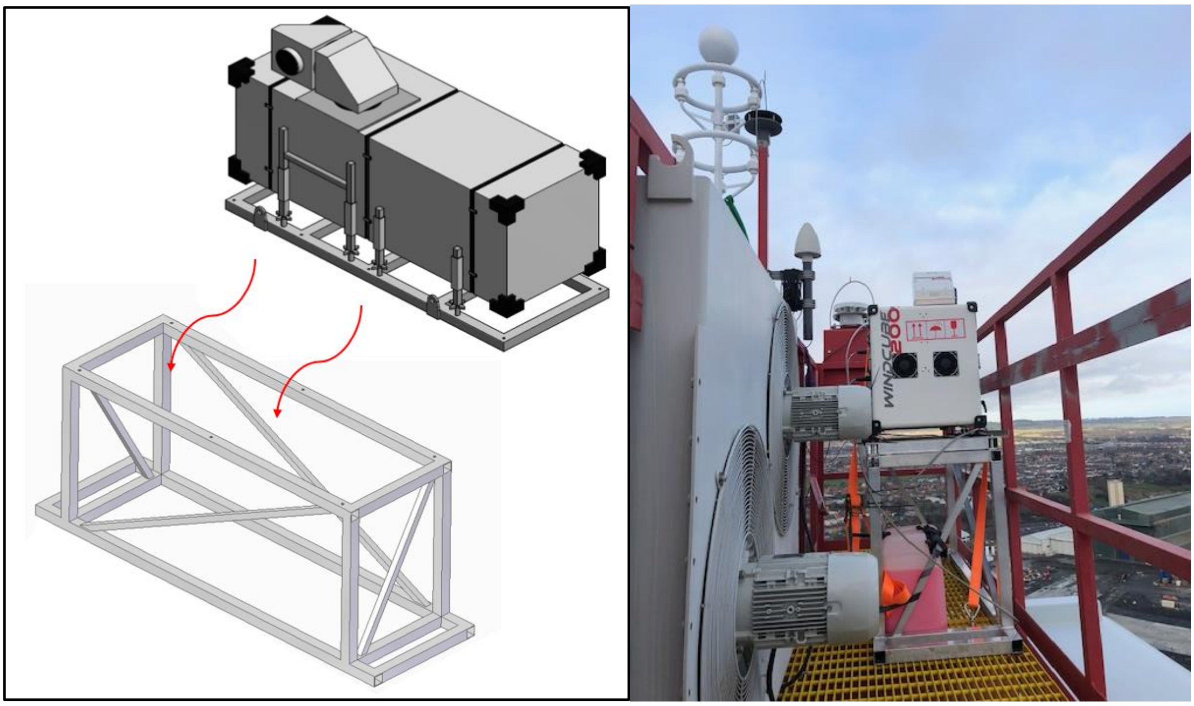

Figure 10 Long-range WindScanner as installed on the rear-gantry of the LDT

6. WIND TURBINE CONTROLLER INTERFACE

6.1. Data format

The modified turbine controller software will receive the following input signals:

Signal name	description	Data type	SVI address
Wind speed u component	Lidar estimate of rotor-averaged horizontal wind speed 120m in front of the rotor	Float32	WTC/CI/CI_LidarWindSpeedU
Wind speed v component		Float32	WTC/CI/CI_LidarWindSpeedV
Lidar data valid	A signal to communicate to the turbine controller that the values from the lidar are correct.	boolean or int	WTC/CI/CI_LidarDataValid
Lidar Watchdog	This signal should change state regularly, say at 10Hz. If it ceases changing state the TC will stop using lidar values	boolean or int	WTC/CI/CI_LidarWatchdog

6.2. Driver

OREC is creating interface software in a new PLC (not the turbine control PLC). This will communicate with the lidar via UDP and write values to the turbine controller PLC via a Bachmann SVI. DNV GL will add new controller inputs for the OREC interface software to write to.

6.3. Implementation

A new PLC will be set up to manage and check the inputs to the controller from the spinner lidar in order to protect the controller from potential signal errors. A site visit is required to do this, but this is not possible at this time due to Covid-19 restrictions. It will be completed for the tests planning in D3.7 and D3.8.

7. TEST PLAN

The turbine control test plan will be performed according to the following table:

Table 6 TotalControl test plan on LDT

	Below rated wind speed	Above rated wind speed	Forward-facing LiDAR required	Rear-facing LiDAR required
Yaw misalignment	Yes	-	Yes	Yes
Power reduction	-	Yes	Preferably	Preferably
Power reduction (delta)	Yes	(Yes, less important)	Preferably	Yes
LiDAR-assisted control (LAC)	-	Yes	Yes	If available
Individual pitch control (IPC)	-	Yes	If available	If available
Active power control (APC)	Yes	Maybe downwards only?	If available	If available
Model predictive control (MPC)	Yes (the transition is important)		If available	If available

8. SITE VALIDATION RESULTS

8.1. Blade filtering

The spinner lidar is placed behind the rotor on top of the wind turbine nacelle. In order to get a good wind speed estimate from the 400 line-of-sight velocities in the scan pattern, it is necessary to filter the measurements where the laser hits a blade which obstructs the line-of-sight. The spinner lidar program does this by filtering the measurements with low velocities (depending on the rotational speed of the turbine) and high power values- as passing hard targets usually give a higher signal than aerosols (Angelou and Sjöholm, 2015). The line-of-sight (LOS) velocities measured by the spinner lidar are plotted in the following figure as a function of power (or signal strength).

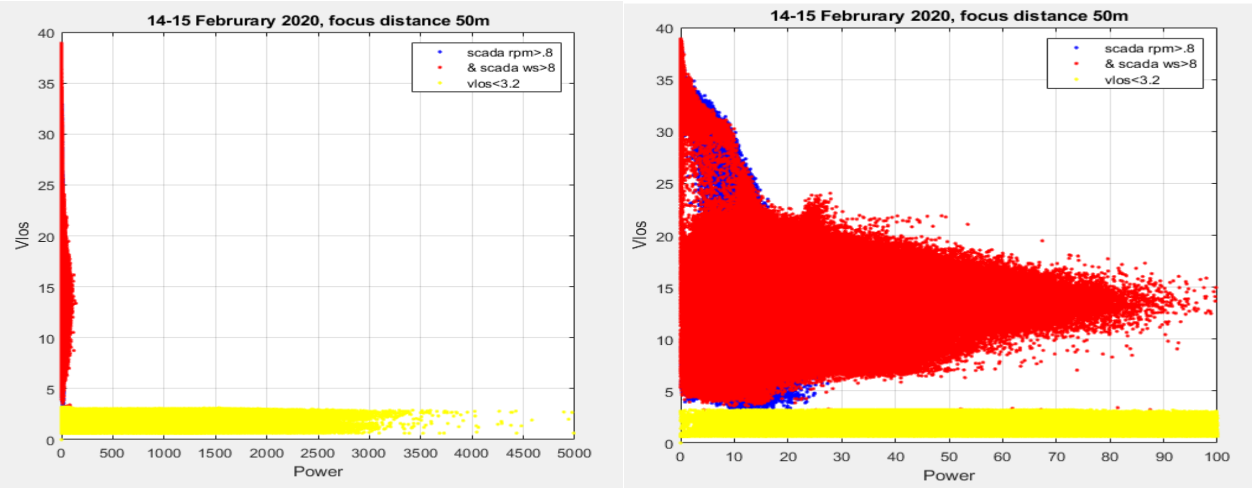

Figure 11 Spinner lidar LOS speed vs signal strength (P) from February 14-15th 2020

The wind estimation algorithm removes measurements with velocities below 3.2 m/s and measurements with a power value above 100. In addition, estimates based on too few good LOS measurements are skipped. Finally, measurements with too large a value of w (vertical wind component) will not be considered valid.

8.2. Comparison of spinner measurements against met-mast data

As a final confirmation that the spinner lidar is operating as expected, we will compare time series data measured using the nearby met-mast' top cup anemometer (110m) against data measured by the spinner lidar. These are not directly comparable as the mast and the turbine are approximately 395m apart and the lidar measurements are only valid while the turbine is running (otherwise we do not know if the lidar is pointing into the wind). Further, the lidar measurements will be influenced by the induction zone. The comparison is only to demonstrate a reasonable validation of the setup.

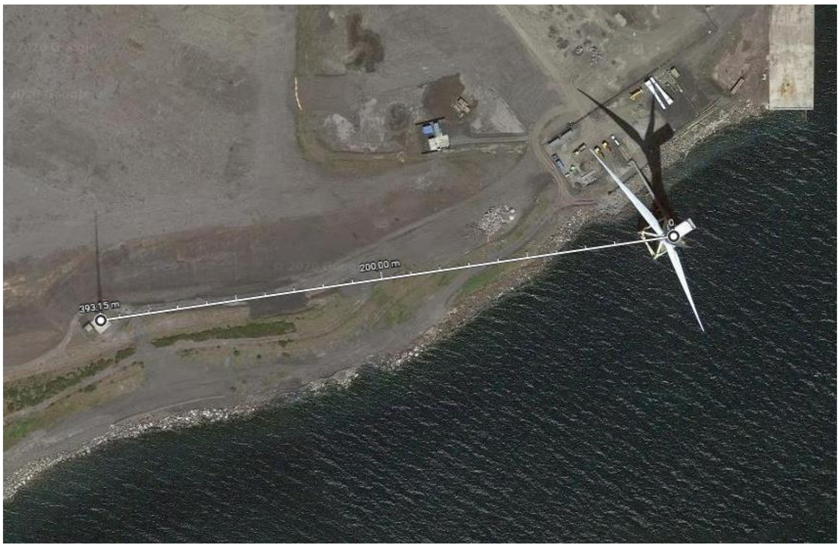

Figure 12 Aerial photo from Google Earth of the LDT and met-mast. The direction between the mast and turbine is 81°

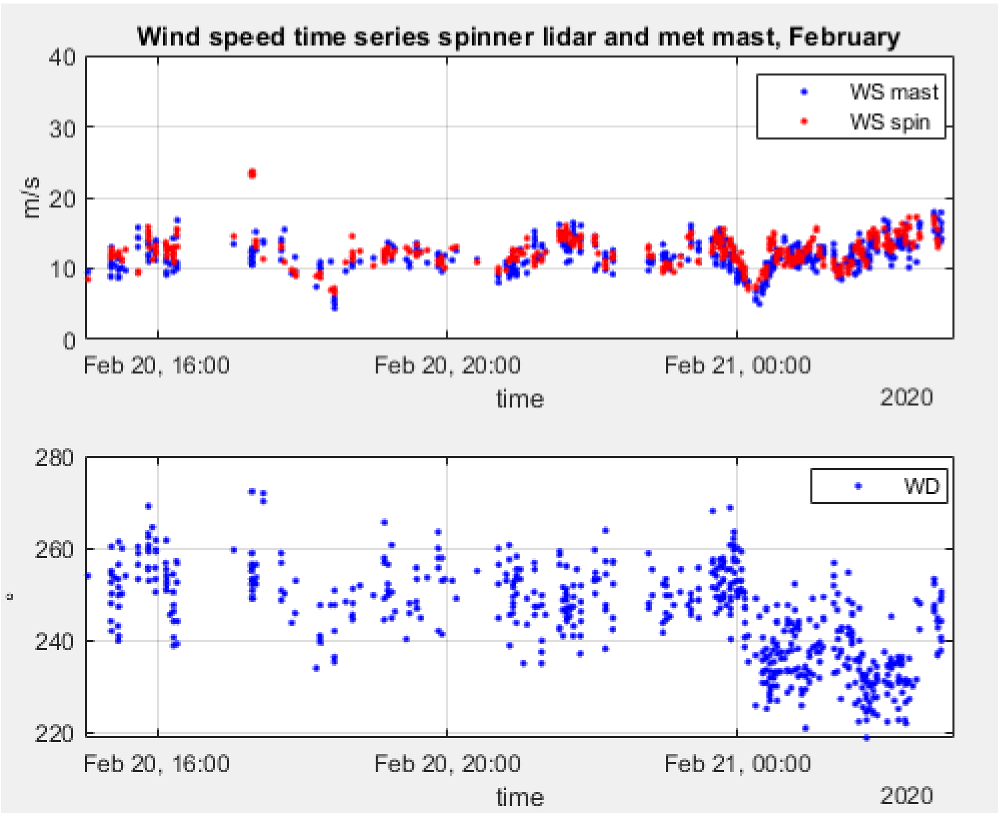

Figure 13 Time series measured by both the spinner lidar (focus distance 150m) and the met-mast cup anemometer

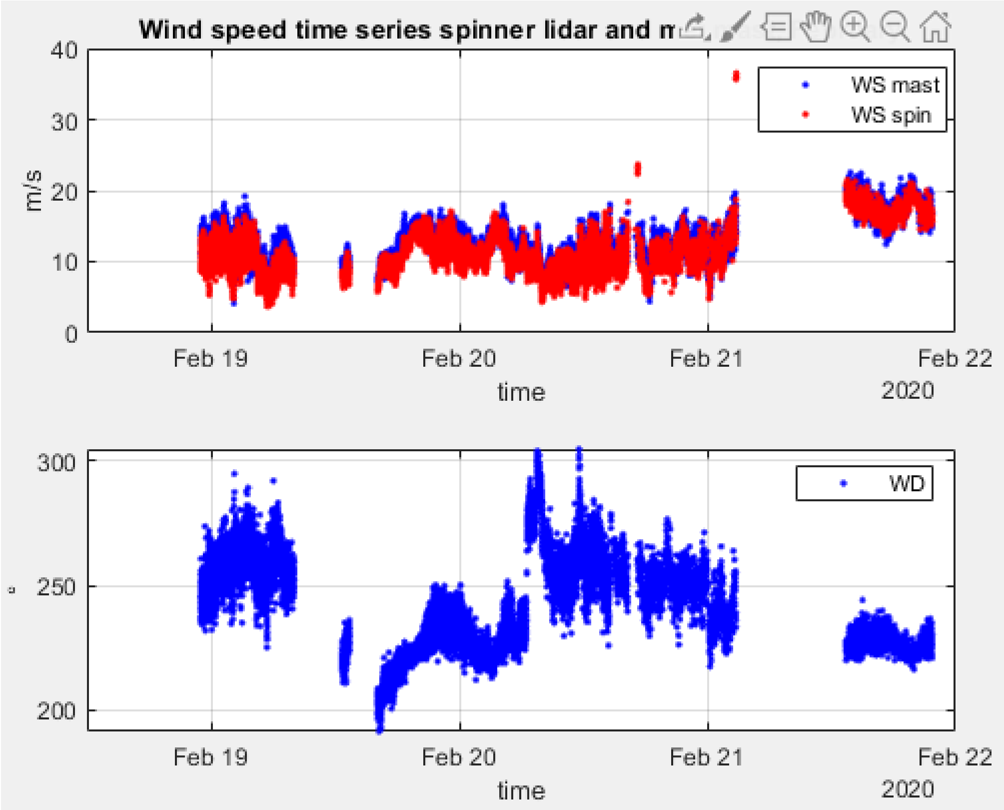

Figure 14 Time series measured by both the spinner lidar (focus distance 50m) and the met-mast cup anemometer

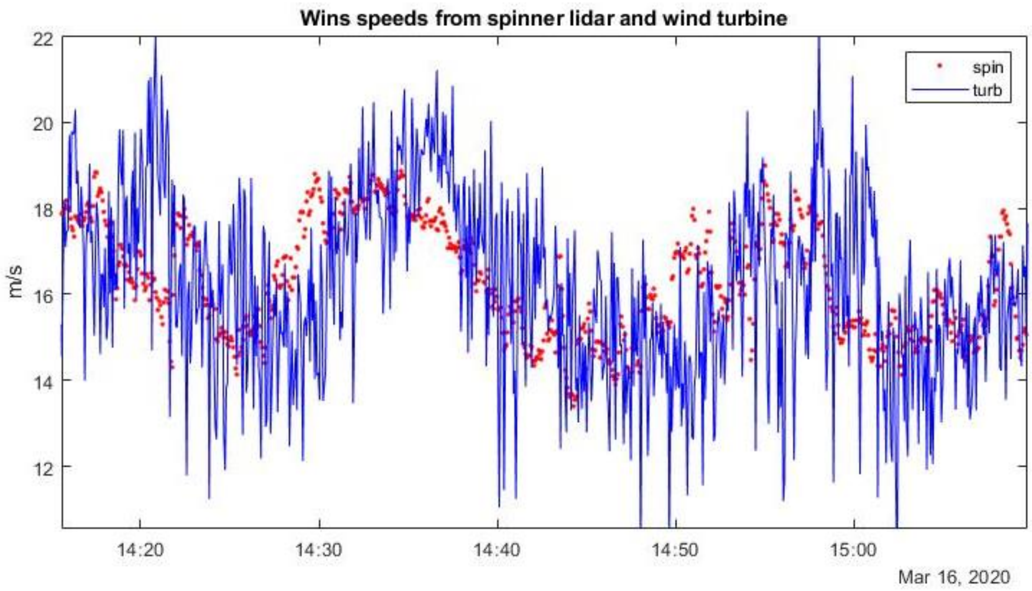

Figure 15 Time series of wind speeds from the spinner lidar compared to wind speeds reported by the turbine

As can be seen from the plots, the spinner lidar measures a slightly lower wind speed than the met mast and not surprisingly more so closer (50m) to the turbine.

It is difficult to make a relevant comparison of the 10-minute averaged wind speed values of the spinner lidar and the measurements obtained at the met-mast. The data were obtained in February and during this time the spinner was set to many different focus distances; most of them very close to the rotor. The comparison would perhaps be more relevant with measurements from late March or April where the focus distance was set at 150m or 120m. Unfortunately, we do not have access to these data yet.

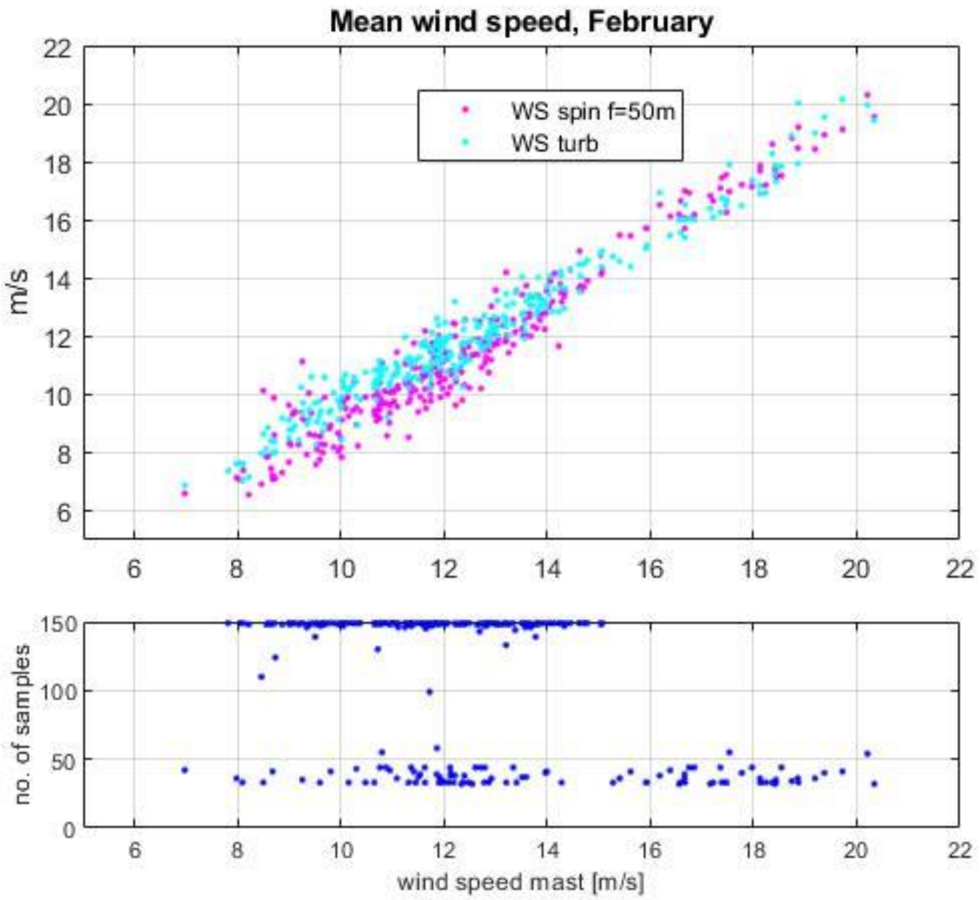

Figure 16 Comparison of 10-minute averaged wind speed values from the spinner lidar and met-mast (110m cup anemometer)

Figure 16 shows 10-minute averaged wind speeds from the spinner lidar and the turbine plotted against wind speeds of the met-mast at 110m and the number of sample values available in the 10-minute period from the spinner lidar. During the test period, in order to reduce motor wear, the spinner is running at 500 RPM giving a scan pattern every 4 seconds. Therefore the maximum sample rate in a 10-minute period is 150 LOS/second. This motor speed is meant to be increased to 2016 RPM during the test periods giving a wind vector value every second. To retain the same number of LOS measurements in the scan the sample frequency of the spinner must be increased accordingly.

9. CHALLENGES

A number of unforeseen issues have arisen during the planning and execution of the field campaign. They are outlined here:

- Lidar hardware repairs

  During an initial pre-test of equipment at Risø, the LRWS lidar system scheduled for use in the Levenmouth field campaign (nicknamed Whittle) was found to be operating with severely reduced performance. Various troubleshooting steps were taken to attempt correcting the issue (i.e. centring and adjusting focus on optical lenses, modifying software settings). A measurement of the emission power of the laser resulted in a large disparity to the design specifications. After extracting the system's optical rack and testing individual components, the EDFA (laser amplifier) was discovered to be faulty. This component is highly specialized and only manufactured by one company (Lumibird, formerly Keopsys) in France. Delays were then further compounded by Vaisala's recent acquisition of Leosphere which complicated the procedure for obtaining spare parts directly from component suppliers. This delay led into France's summer holidays where the supplier was not available for conducting business. After the new EDFA was received at DTU, a complex procedure requiring specialized facilities (i.e. a laser optical bench) and qualified personnel was required to correctly install and recalibrate the optical system. This was then followed by field testing to ensure correct operation. These repairs were a significant undertaking which greatly delayed the project and were not anticipated. Suggested ways of mitigating this risk in future projects is to keep an inventory of spare parts at institutions such as DTU which have the ability to perform repairs, and/or to schedule in longer maintenance and testing periods between field campaigns using the lidar equipment.

- Brexit

  Due to the timeframe of the project schedule, there were concerns from legal representatives at DTU (who owns the measurement systems) that trade issues could occur when repatriating the lidar systems back to Denmark at the end of the measurement period. Since Scotland would be a member of the EU single-market upon import but likely not upon export. Attempts were made to obtain a carnet but this was met with confusion from authorities in both countries as there was no procedure or guidance in place for this situation. In the end, a cargo manifest was prepared to document the items transported and their condition. We do not yet know the outcome of this challenge. Suggestions are to avoid operating in countries with political risk, and for governments to plan for and communicate changes in trade policy.

- Weather

  Weather restrictions played a minor role in delays to the installation for the Lidars due to wind speed restriction at the site, however careful planning and forecast checking meant only 2 days delay. There have been some issues with the operation of the LRWS as some rainwater made its way inside the (supposedly watertight) power supply housing, however this has now been remedied and there have been no further issues. The completion of the tests to follow will be dependent on the ability to fill the wind speed bins for each test which may slightly prolong the tests.

- Approval of test plan

  The Levenmouth turbine Asset Owners (OREC) maintain a very tight approvals process for any works on the turbine which could potentially cause damage to the asset. The project delivery team within OREC have taken a staged approach to the approval process for the TotalControl project. Approval has so far been granted for the installation of the lidars for the duration of the program and for the first of the tests – the yaw misalignment test.

- Other works on turbine

  Other maintenance works on the turbine including issues with the nacelle crane, repair to the nacelle roof doors, and repairs to the blade strain gauges have had various impacts on the project delivery schedule, however these issues are now resolved. The operation of the turbine throughout the program will also influence the delivery of the test program if there are any issues causing downtime.

- Covid-19

  Travel restrictions due to the global coronavirus pandemic have caused numerous delays towards executing the tests. Firstly, mandatory lockdowns in Denmark and Scotland have prevented a planned service trip to repair minor hardware issues with the lidars. The technicians which are normally working onsite are currently in home quarantine which complicates service requests and monitoring of the equipment. The planned PLC installation is not considered essential work and therefore all tests requiring the new turbine controller and onsite monitoring of the turbine are on hold until the lockdown is lifted.

10. CONCLUSIONS

A full-scale field campaign is underway which will demonstrate advanced wind turbine control concepts on the 7MW Levenmouth Demonstration Turbine in Scotland. Two state of the art scanning lidars have been lifted and installed on the turbine nacelle which will observe both the incoming 3D flow field and downstream (wake) conditions. These measurements will be used both for real-time predictive control of the wind turbine, as well as for creating a high-quality reference dataset to compare against numerical model predictions. Analysis of the initial data from the spinner lidar has been compared against measurements from a nearby met-mast which shows overall good agreement and suggests that the system is operating as expected. Data from the long-range WindScanner also clearly depicts the observable wake under normal operating conditions. Although unforeseen issues have resulted in delays to the project, we are confident that the project is progressing positively and that the forthcoming test and measurement campaign will produce a high quality and well documented dataset with a great scientific potential towards improving our understanding of wind turbine control.

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