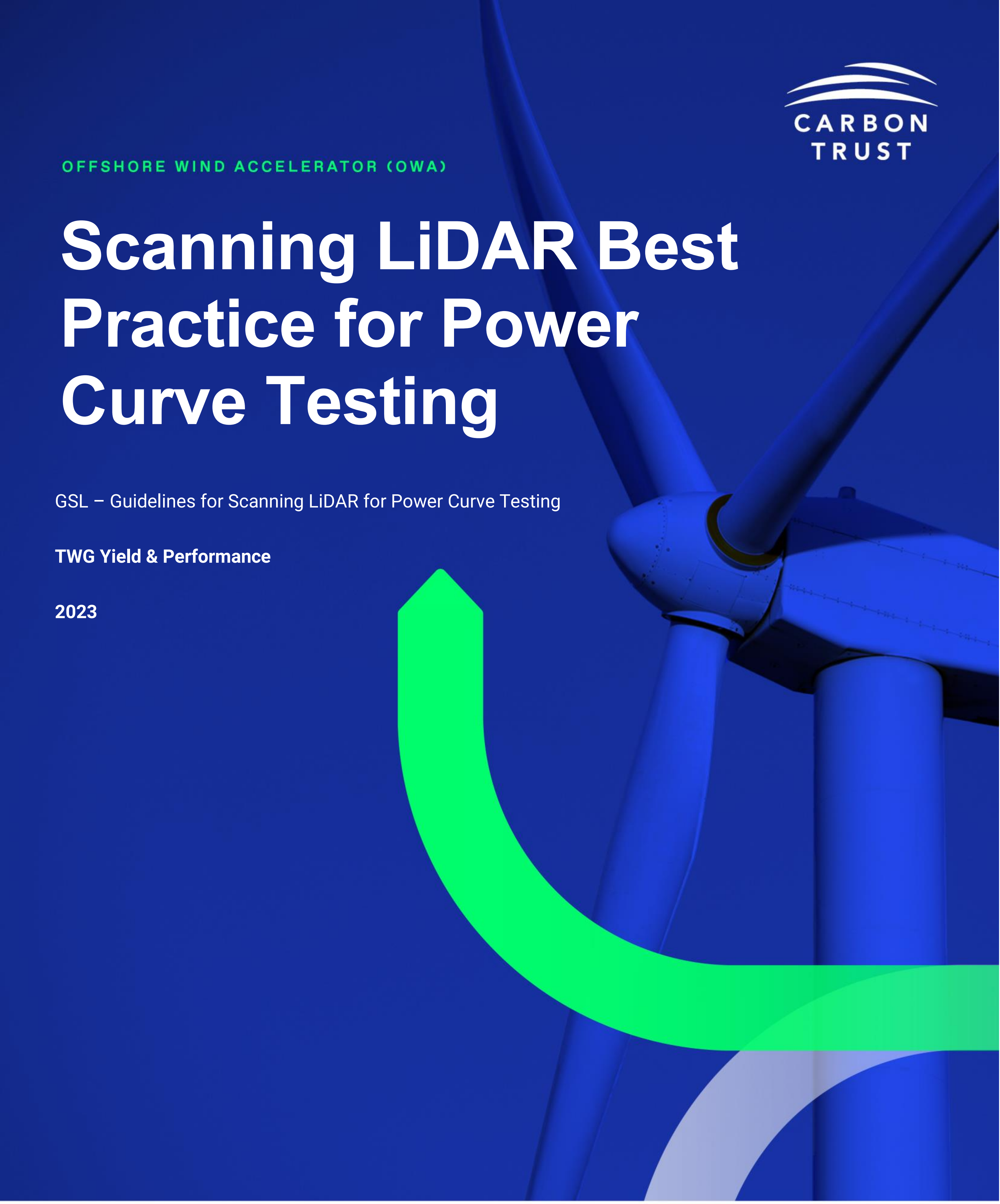

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OFFSHORE WIND ACCELERATOR (OWA)

Scanning LiDAR Best Practice for Power Curve Testing

GSL – Guidelines for Scanning LiDAR for Power Curve Testing

TWG Yield & Performance

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1. Introduction

1.1. Background and scope

Wind turbine power curve verification (PCV) is a crucial measurement task in wind energy since it provides the means for performance monitoring and the basis of energy production guarantees. Offshore, nacelle lidars quickly replaced the traditional (and financially inviable, in this environment) meteorological masts for this purpose. As turbine rotor sizes increases, the need to measure the wind further away from the turbine in PCV (to reduce the blockage effect) increases as well, rapidly approaching the measurement distance range of state-of-the-art nacelle lidars. For this reason long-range scanning lidars, due to their greater measurement range and versatility, can be considered a suitable alternative to nacelle lidars for PCV. One disadvantage, in comparison to nacelle lidars, is that they lack tailor-made standards or guidelines.

Our earlier literature review [1] presented an overview of several scanning lidar applications in wind energy, with special focus on the applicability for PCV of a single (sector-scanning) transition-piece based scanning lidar on a fixed-bottom (i.e. not floating) offshore wind turbine. We reviewed the current power performance measurement standard, IEC 61400-12-1:2017 [2], and highlighted items that need to be modified or completed for the use of transition-piece scanning lidars.

This best practice focuses on wind measurements only. Power measurements and other measurements required for PCV are not described here. For consistency and to the extent possible, this report has a similar structure and uses similar terminology as other measurement standards, in particular the very recently published standard for the use of nacelle lidars IEC 61400-50-3:2022 [3].

1.2. Foreword on IEC 61400-12-1:2017

The IEC 61400-12-1:2017 contains several options regarding the definition of reference wind speed used in the power curve and possible normalizations. In any case, the most essential requirement is to measure the wind speed at hub height (in particular, within ±1% of hub height). Typically, hub height speed is the reference speed most often used to obtain the power curve and corresponding AEP estimates.

Additionally, there is a requirement in the standard to measure wind speed at one additional height between lower blade tip height and lower tip minus one third of the rotor radius. However, this speed is not used to obtain the power curve nor AEP estimates in a hub-height based power curve. It is used to obtain a lower-rotor-half wind shear value, which is used to estimate a power curve (and AEP) uncertainty term related to wind shear.

Optionally, according to the reference standard, more measurement heights may be used during a PCV to obtain wind shear data across the rotor. For example, for a more accurate estimation (i.e. reduction) of the power curve uncertainty components related to shear in a hub-height wind speed-based power curve, or to (optionally) produce a rotor-equivalent wind speed power curve.

The recommendation in this best practice, for typical offshore cases (sites without extreme or highly varying shear), is to prioritize obtaining the most accurate possible hub height wind speed measurement, at the expense of reducing or avoiding, to the extent possible, measurements at other heights (see section 3.2 and 6.2).

2. Lidar requirements

In this section, we list the general requirements for a transition piece (TP) mounted scanning lidar performing power curve verification on an offshore wind turbine.

Physical:

- Footprint suitable for TP deployment whilst honouring governing safety rules.
- Ability to withstand road and vessel transport without degrading pointing calibrations.
- Provision for craning.
- Water and salt resistant (but deployment position should avoid direct wave impact).
- Operate on realistic/available AC power (probably no more than 1.5kW).

Performance (minimum requirements):

- Support PPI and hard target scanning modes
- Measure in beam inclination range of -5° to 30° (sea-surface to upper blade tip at 2.5D, D: turbine rotor diameter)
- Measure in azimuth range ± 90°
- Measure at ranges up to 3D (reach upper blade tip height at 2.5D)
- Measure with maximum effective probe length of D/2
- Measure radial speeds (5 range gates) at 1Hz
- Measure lidar tilt and roll at 1Hz

Accuracy (indicative standard uncertainties):

- LOS wind speed: 1.5%
- Range: 10m
- Azimuth angle: 0.1°
- Elevation angle: 0.1°
- Tilt and Roll: 0.1°

Operational (minimum requirements):

- Lens cleaning ability
- Network monitoring
- Synchronization of lidar clock with reference (e.g. NTP)
- Automatic start-up
- All meta parameters logged to a data file
- One second speeds and beam angles saved to file

- One second inclinometer (tilt and roll) saved to file
- Offline processing (reconstruction) of horizontal wind speed and direction from sector- scanned (PPI) radial wind speeds.

Optional (nice to have!):

- Ability to remotely power cycle lidar equipment
- Ability to automatically push measurement data to external server (e.g. FTP)
- Ability to easily check plausibility of beam position (e.g. flat surface on scanning head for digital spirit level measurements and/or rifle-sight mounting)
- Ability to lock a pre-defined measurement configuration

3. Wind field reconstruction

3.1. Using scanning lidars for standardized measurements

In contrast to both wind lidars and nacelle lidars, scanning lidars are designed to be extremely versatile. Beam geometries are no longer fixed but fully programmable with the help of a high accuracy motion control system. Their programmability gives scanning lidars the ability to tackle many use-cases. Whilst this is a huge strength in terms of versatility, it is paradoxically an inherent weakness in relation to standardized measurements where we require setups to be repeatable and consistent.

Because there is no dedicated use-case, neither is there a dedicated wind field reconstruction. Scanning lidars output files of radial wind speeds, ranges, and beam angles. It is up to the user to convert these into a reconstructed wind field. This is invariably performed as post-processing, i.e. as a separate task at a remote computer using an appropriate computer program. Once again, this is sub-optimal for standardized measurements since it introduces yet another element where conditions and parameters can vary.

When carrying out our PCV scanning lidar calibration (at an onshore test site) and application (the measurements at the turbine), it is vital to keep all conditions and parameters as identical as possible. This applies in particular to the following items (with the most important at the top of the list):

- External processing software
- Scanning trajectory (sector size and scanning speed)
- Pulse configuration (pulse length and pulse repetition frequency)
- Acquisition time (i.e. number of raw pulses averaged to one set of radial speeds)
- Beam focus position (often this is actually fixed)
- Measurement range
- Beam elevation angle

Where any of these conditions or parameters differ between the calibration and the application, it should be explicitly noted in the PCV report.

3.2. Recommendations for scanning parameters

Here we propose some values for the scanning trajectory, the scanning times, and the pulse configuration. These should be regarded as ‘safe’ values based on past experience rather than rigid rules.

3.2.1. Scanning trajectory

Firstly, we recommend measuring only at **one height**, i.e. perform PPI scans at only one elevation angle. This would normally be chosen to be the hub-height at a horizontal distance of 2.5D from the turbine. Whilst this will give little information about the wind shear (some information can be obtained from the speeds at different ranges and therefore different heights), the statistical uncertainty will be minimized by having the maximum number of available scans at the one chosen height.

For sites where extreme or highly varying wind shear is expected, multiple elevation angles can be chosen but **never more than three**. Statistical uncertainty will increase significantly as the number of elevation angles increases.

Use a sector size that fits the undisturbed sector but **do not use less than ±20° or more than ±45°** (i.e. the angular width of the arc-scan shall be between 40-90°). The undisturbed sector can be larger than the scanning lidar measurement sector. Further guidance on selecting the azimuthal range is provided in Section 6.2.

Scan at 1-2°/sec in one direction only to limit the effects of gear backlash. Use a fast traverse to return to the starting point. A “pre-move” point can be added before the starting position (i.e. return past the first point and then come back) to reduce backlash at the beginning of the scan.

Aim for **at least one completed PPI scan per minute** and preferably more.

3.2.2. Beam and pulse configuration

If possible, **ensure that the beam focus is set at around the target measurement range** (between 2.5D and 3D). This will maximize the available backscatter at the most important ranges and will be conducive for high sampling rates. If available, beam focus is adjusted manually from inside the lidar casing. Do this before the calibration (at the calibration site) and do not change it again before or during the application.

Use a **medium pulse length/duration** (e.g. 100m or 300ns). This will be a good compromise between backscatter and spatial resolution. Note that a 100m pulse length will have an effective probe length of around 50m. Within a given range, the backscatter returned from a pulse has an approximately triangular weighting, with the maximum at the centre of the pulse and tapering linearly to each side (reaching zero at the pulse ends). Since our common definition of the probe length is ‘Full Width, Half Maximum’ (FWHM) and the power falls to on half at 0.25 and 0.75 of the pulse, the FWHM is half the physical probe length. Usually, the range gate will be chosen to have this length.

Use an acquisition time of 0.5s (2°/sec scan rate) or 1s (1°/sec scan rate). This corresponds to sampling frequencies of 2Hz and 1Hz respectively and will result in radial speed measurements for each 1° of scanning arc. Acquisition time is the period over which individual Doppler spectra are ensemble averaged. For example, for a pulse repetition frequency of 10kHz, a 1s acquisition time will result in averaging 10,000 spectra.

4. Calibration

4.1. Introduction

Two contrasting concepts are available for lidar calibration, commonly referred to as “black box” and “white box”.

In a black box calibration, the reconstructed wind-speeds derived from the lidar measurements are compared to the reference wind speed- commonly cup anemometer measurements from a met mast. The reconstructed wind speeds are regarded as “black box” since we are not concerned with the actual algorithm – we require no knowledge of this. The wind lidar calibration scheme prescribed in IEC 614000-12-1 ed:2, Annex L is such a black box calibration.

In contrast, nacelle lidars are calibrated using the white box concept. This is described in detail in IEC 61400-50-3. Here we calibrate the uncertain inputs to the wind speed reconstruction algorithms; the LOS speed, the measurement range, and the beam angles. These individual uncertainties are then propagated through the wind field reconstruction algorithm to provide estimates of the horizontal wind speed uncertainties. In this approach, the ‘contents’ of the box, i.e. the details of the reconstruction algorithm, are now important to know and hence the box is now ‘white’. This white box approach is necessary since in a black box calibration of a nacelle lidar (on-shore and at low heights), it would be impossible to achieve the necessary horizontal flow-field homogeneity that is a key assumption in the flow field reconstruction model.

Scanning lidars performing sector scanning should ideally be calibrated using the white box concept since it is also unlikely that we can experience the same horizontal flow-field homogeneity onshore as we will find at most offshore sites. However, we are obliged, for the time being, to resort to a simpler black box calibration since we do not yet have the tools to propagate the component uncertainties through the somewhat complicated wind field reconstruction algorithm. This is clearly an area where more research is required to develop both analytical and Monte-Carlo methods that can together impart a sufficient degree of confidence.

A power performance verification according to IEC61400-12-1 requires a calibration of the reference wind speed measurement used to obtain the power curve. In this case, it is the horizontal wind speed (HWS or V_{hor}) derived from scanning lidar measurements. In the context of that standard, a lidar calibration is the process of obtaining: a) a transfer function between lidar wind speed measurements and a reference measurement (from a cup anemometer), and b) associated uncertainties. The validity and accuracy of the wind speed calibration, as well as those of the wind speed measurements during the power curve campaign, are determined by the reference wind speed uncertainty and by the scanning lidar’s pointing accuracy (which determines

its ability to measure wind speeds at the correct location). Reference wind speed uncertainty is determined with reference to 61400-12-1 ed.2 and will not be further elaborated on here. To minimize the lidar pointing uncertainty, the beam positioning quantities shall be checked during the calibration process. This part is specific to scanning lidars and will be described below.

The process presented in this section is divided in two parts:

- the calibration of quantities relevant to the beam position (pitch and roll inclinometers, scanning head homing position, and measurement range),

- the calibration of the horizontal wind speed, V_{hor}, and its uncertainty assessment, u_{Vhor}.

The calibration shall be performed before the start of the power curve campaign, and it is recommended to perform a post-calibration after the PCV (especially if it can be used as pre- calibration for the next measurement campaign). The calibration validity duration should not exceed two years. Changes in lidar components or firmware that affect the wind measurements, as well as changes to the wind reconstruction software (if the previous version is not available), require a new calibration. Mechanical damage or shock require a new calibration as well.

Additionally, other values that should be checked in the course of routine maintenance include: the soft-focus position, the backlash in scan head gears, the beam centering and alignment of mirrors, and the following error threshold in the motion controller. A description of these tests is outside the scope of this best practice.

4.2. Calibration of beam position quantities

Beam position errors can be caused by angle errors or a range error. Angle errors may be due to levelling errors (inclinometer errors) or errors in the scanning head angle (motor offsets and gear backlash). Inclinometer errors will translate to measurement height errors. An incorrect horizontal levelling of the system introduces a sinusoidal beam elevation angle error that varies as a function of azimuth. The consequence is the laser beam will be higher than intended at one extreme and lower (to the same degree) at the other extreme. In contrast, a fixed elevation offset error will produce a consistent height deviation across all azimuth angles.

4.2.1. Pitch and roll inclinometers

An inclinometer calibration establishes the relationship between the lidar inclinometer indications of pitch angle ($\tau_{indicated}$) and roll angle ($\rho_{indicated}$), and reference measurements ($\tau_{measured}$, $\rho_{measured}$). The reference pitch and roll measurements require an accurate detection of the lidar

beam that may be achieved by either:

- visualizing the laser beam with e.g. an infrared sensitive card or infrared camera, or;
- using a hard target, i.e. blocking the laser beam with a reflective surface or object. When the beam is blocked, the level of the backscattered signal measured by the lidar is considerably greater than when the beam is not blocked.

The following procedure is performed onshore. The outcome achieves a levelled lidar system and calibrated inclinometer values which can be referenced during offshore installation to position the lidar in a similarly levelled position.

- Deploy the lidar system on a flat and solid surface.
- Roughly align the lidar casing to North using a compass
- Roughly level the lidar casing using the coarse feet adjustments and bubble levels
- Use a digital level placed on the scan head while in home position to improve the levelling along both axes using the fine feet adjustments. Note the starting values of the inclinometer

- Place at minimum 3 survey marking sticks in the ground (2 aligned N-S & 1 aligned E, or 2 E-W & 1 N, etc.) roughly 100 meters or further from the lidar. It is also possible to use other objects if there is a small distinguishable feature (e.g. met-mast boom or instruments)
- Use a high-accuracy GPS (e.g. field controller or total station theodolite) to measure the positions of the scan head and survey targets
- Calculate azimuth and elevation angle geometry between the reference (lidar scan head) and targets
- Use the lidar CNR Mapper software to find the exact location of the top of the sticks and note these positions. This method uses the backscatter signal intensity to image hard targets in order to locate their precise position
- Compare the calculated and measured stick positions to identify the tilt of the system and decompose this into pitch and roll errors
- Begin to correct the levelling error by finely adjusting the feet along each axis being levelled
- Correct the pitch and roll errors and re-map targets iteratively until the elevation error is very small and consistent across all stick positions
- Ensure all feet are making contact with the ground and are under load
- Note down the calibrated inclinometer readings. Optionally an offset can be entered to set the calibrated position to zero degrees on all axes

Following the above procedure the lidar will be correctly levelled when the inclinometer readings match the calibrated values.

4.2.2. Scanning head homing position

Home is the reference position of the scan head and corresponds to zero degrees in azimuth and elevation. Normally the home azimuth is aligned to North such that the given azimuth corresponds to the actual geospatial bearing. Therefore, this alignment must be performed after the lidar has been installed in its measuring position (i.e. it cannot be pre-aligned before installation). At minimum, one hard target (object such as a wind turbine with a known position) is mapped and then compared with the calculated bearing to determine the azimuth offset, which is then applied in the lidar configuration software. The object(s) used for hard targeting should ideally have as small of an apparent size as possible (i.e. small physical size and far range) in order to achieve the lowest uncertainty in azimuth alignment. For example, targeting a unique small object like a railing or pole on a neighbouring TP will give a better result than using the very wide turbine tower.

4.2.3. Measurement range check

The measurement range shall be checked, as part of the calibration process. It is recommended that the tested range is similar to the measurement range used in the wind speed calibration and the power curve campaign. For this reason, it may be convenient to do this test during the lidar installation for horizontal wind speed calibration (section 4.3) using the calibration mast as a target, or it can be done in a different setup. This check may consist of a visual observation of the laser light backscatter levels at different measurement ranges, from a target of known position.

The uncertainty or resolution in the measurement range check shall be stated in the calibration report.

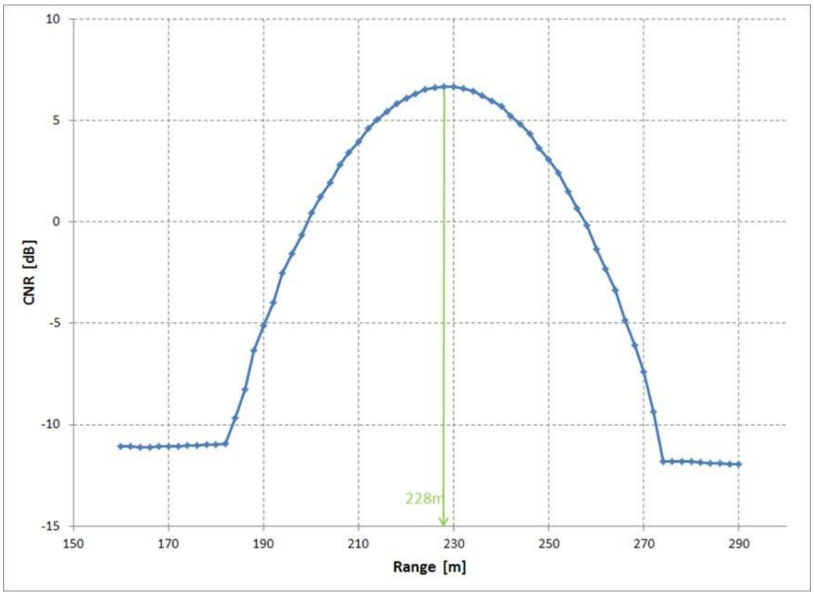

Figure 1 Results from a range calibration test. The peak of the curve gives the nominal range.

An example of range calibration using a meteorological mast as a target is shown in Figure 1. The lidar beam was trained at the mast at a known height with the lidar configured for a number of closely packed and overlapping ranges around the target range (calculated from the lidar and mast positions and the beam elevation angle). The range best centred on the mast gives the highest signal strength since the centre of the probe has the highest collection efficiency (returns the most light).

It is important to know at what height the lidar beam is hitting the target, since the length between the lidar and the impact point will increase with height. One solution is to perform this check with a close to horizontal beam. In this case, small errors in the elevation angle will have a minimal effect on the actual range. A second approach is to identify a point higher up on the target – in the case of a mast, typically a side boom found through a careful vertical scanning.

4.3. Horizontal wind speed calibration

4.3.1. Method overview

Before the PCV campaign, the lidar horizontal wind speed measurements shall be calibrated at least at one height (close to the intended hub height) and possibly at other heights of interest, close to the measurement heights at which the lidar will measure during the power curve verification.

In a wind speed calibration the lidar is installed on the ground in front of a meteorological mast that contains reference instruments, among them a cup anemometer at the intended calibration height, which provides the reference speed against which the lidar is calibrated. The lidar is set up to perform an arc-scan centred around this reference cup anemometer.

This section presents recommendations regarding the test site and the experimental setup, and details of the calibration procedure.

4.3.2. Calibration site requirements

The method to retrieve the horizontal wind speed (and wind direction) by a lidar performing a sector scan relies on two assumptions: 1) that the vertical wind speed does not significantly contribute to the measured LOS speed, and 2) that the wind is homogenous in the scanned region. The first requirement is typically fulfilled in offshore and onshore flat terrain sites. Regarding the second one, almost any calibration onshore will suffer from a lower flow homogeneity than a corresponding measurement offshore (in wake-free conditions). For this reason, an onshore calibration will inevitably give us a somewhat higher calibration uncertainty than would be the case if we were able to perform the calibration in truly representative offshore conditions. The calibration site should be chosen carefully, to limit this effect. The calibration site shall have these minimum requirements:

- Flat terrain.
- Homogeneous terrain cover in the scanning sector and the wind direction sector used in the calibration.
- IEC compliant mast with sensors at the required height (the PCV hub-height ±15%). In the calibration, the lidar measurement height should match the reference instrument height exactly.
- A suitable location for deploying the lidar at the appropriate distance from the mast, preferably with reasonable access and available power and network sources.

We recommend that the calibration site requirements described in IEC 61400-50-3 section 7.5.2 are fulfilled, as much as possible.

4.3.3. Setup requirements

The lidar shall be installed on the ground (not on uncompacted soil; ideally concrete or paved areas) or on a stiff and stable surface.

The lidar beam shall be accurately pointed towards the instrument used to measure the reference horizontal wind speed (V_{ref}). The reference instrument is mast-mounted, and it should be, preferably, a cup anemometer. This reference instrument shall be calibrated and comply with the requirements in IEC 61400-12-1:2017 (Clause 7) with regards to calibration, mounting, and operational characteristics. The reference mast instruments shall include in each calibration height, as a minimum:

- one cup anemometer for V_{ref} measurements;
- one 3D sonic or vane for wind direction measurements (used for filtering);
- a secondary wind speed and direction measurement for quality control of the primary instruments;
- a measurement of inflow angle or vertical wind speed (for filtering).

Additionally, air temperature should be measured to allow for filtering of potentially ice affected cup anemometer wind speed data. A precipitation measurement can also be useful for checking for deteriorated lidar performance in rain. Shear should be measured at the calibration mast, to estimate the uncertainty terms in section 4.3.7.

The meteorological mast and sensor mounting shall be compliant with IEC 61400-12-1: 2017, Annex G, where the “single top-mounted anemometer” arrangement (G.2.) is the preferred option since it gives the lowest uncertainty due to flow distortion due to mounting, but other options (e.g. side-boom-mounted anemometer) are possible at the expense of an increased cup mounting uncertainty and potentially interference from guy wires on the lidar measurements.

The beam elevation angle from the horizontal plane should match the offshore set up, and it should not be greater than 20°.

The central LOS should be aimed at the same height as the cup anemometer, at a recommended horizontal distance of 5m.

4.3.4. Lidar installation and configuration

The lidar measurement set up should be as close as possible to the power curve campaign. For the calibration to be truly valid, the intended power curve measurement strategy (scanning trajectories, sector angles, timing and lidar pulse length and acquisition time) should be strictly adhered to in the calibration. In practice, for practical reasons, a given tolerance should be

expected between the calibration setup and the PCV setup. This might be:

- Scanning sector size within ±10 degrees, respecting still the global recommended limits
- Scanning speed the same
- Acquisition time the same
- Elevation angle within ±5 degrees

A deliberate decision could be taken not to calibrate at all the intended measurement levels in the PCV. This could be because not all measurement heights are available at the calibration site but that the un-calibrated wind measurements are still considered to be valuable for the offshore campaign.

A lidar user should be conscious of how the levelling will be conducted in the offshore PCV and should try to reproduce it as much as possible during calibration. For example, in the offshore turbine it might be practical to have the long side of a rectangular lidar case aligned to the railing (i.e. perpendicular to the measurement sector centreline) to free as much walkway space as possible in the transition piece. This alignment, ideally, should be duplicated in the calibration. In this case, the roll inclinometer (instead of pitch) is most critical to obtain the correct beam height.

Once the lidar is deployed and levelled in its calibration position, it is recommended to perform the range check described in section 4.2.3. This has the advantage that the actual elevation angle for the calibration is known, and it justifies using a lower sensing height uncertainty in the calibration uncertainty budget (Section 4.3.7). However, usually this is not possible in the PCV offshore; since there is not a meteorological mast to use as a target (alternative targets might be used offshore such as other turbines and TPs, a drone, the water surface, a ship etc.).

At the end of the calibration and before dismantling the lidar, double-check the elevation angle and measurement range using the same test described in Section 4.2.3.

If a reference flat surface is available on the scan head (recommended as a requirement for future scanners) it would be advised to check the angle of this flat surface with the lidar positioned at its target elevation angle. This will create the basis of a simple plausibility check when the lidar is installed offshore.

The lidar measurements and the reference instruments shall be synchronised in time. Any time synchronisation differences between the two data acquisition systems shall be within ±6 seconds (for 10-minute averaging intervals), as this is acceptable according to IEC 61400-12-1:2017. Time synchronization shall be set up before the calibration start and monitored during the calibration.

4.3.5. Data processing and filtering

Typically, the raw data (containing the line-of-sight speeds) from the lidar is downloaded by the user and the horizontal wind speed (and direction) reconstruction is performed by a software provided by the manufacturer or a third party. It is recommended to make an initial comparison to the reference (mast) data as a plausibility check within a few days after the calibration start. This is to ensure that the lidar is configured correctly and that lidar and reference data acquisition system times are correctly synchronised.

The calibration dataset consists of 10-minute averaged data from lidar and reference, to be consistent with IEC 61400-12-1:2017.

Since the sector-scanning lidar raw data (line-of-sight speeds) are fit to a cosine function to reconstruct 10-minute mean wind speeds and wind directions, the reconstruction algorithm shall provide:

- a metric of the ‘quality of fit’: how well the LOS speeds fit to the theoretical cosine function.
- a metric of the number of reconstructed data valid in a 10-minute interval.

These metrics should be included in the filtering process. Some examples could be the goodness of fit and the sum of squared error (SSE) between the LOS speeds and the curve fit or the mean error.

The reconstructed lidar 10-minute horizontal wind speeds and the corresponding reference data shall be filtered according to the following criteria:

- V_{ref} shall be within the range for which the anemometer was calibrated (typically, between 4 m/s and 16 m/s);
- The wind directions shall be within the designated valid measurement sector (the range of directions for which the terrain is deemed homogeneous and not further outside the lidar scanning sector than will be applicable offshore).
- There shall be sufficient quality and quantity of data within the averaging period. Filters

based on internal lidar parameters (e.g. lidar CNR above threshold) and the lidar reconstruction quality metrics should be applied. The specific metrics and thresholds depend on the lidar type and the conditions (e.g. turbulence, aerosol distribution) at the site. The suitability of the selected filters may be checked using the calibration dataset, for example by plotting the wind speed deviations ($V_{lidar} - V_{ref}$) as a function of the metrics or variables used in the filtering (e.g. number of data in the averaging period, signal strength value, goodness of fit, etc.).

- Periods during which failure or degradation of the reference measurement equipment occurred (e.g. due to icing) shall be discarded.
- Obvious outliers shall be investigated and may be removed. For this purpose, it is recommended to make a scatter plot of speeds (V_{lidar} vs V_{ref}) and directions (D_{lidar} vs D_{ref}) for the pre-filtered 10-minute dataset, in order to identify outliers.

Data shall be collected until the requirements defined in 4.3.6 are satisfied.

4.3.6. Data binning and results

The data binning and completion criteria are based on the most recently published standard involving lidar calibration, IEC 61400-50-3:2022. The valid data are binned based on V_{ref} with a bin width of 0.5 m/s, and bins centred in multiples of 0.5 m/s.

A bin is considered complete if it contains a minimum of five data points. The database is considered complete when:

- There are at least 600 ten-minute valid data points after filtering;
- All bins from 4 m/s to 16 m/s are complete.

The average difference between V_{lidar} and V_{ref} in the bin, $\Delta V = \overline{V_{lidar} - V_{ref}}$, shall be calculated for each bin. The calibration results shall be reported using the format in Table 1, where:

i	is the bin number
V_{ref}	is the reference wind speed average in the bin
V_{lidar}	is the lidar wind speed average in the bin
N	is the number of data in the bin
ΔV	is the average of the differences between liar and reference speed in bin
$\sigma_{\Delta V}$	is the standard deviation differences between liar and reference speed in bin
u_{ref}	is the uncertainty of the reference
u_{lidar}	is the lidar calibration uncertainty

The calculation of uncertainties u_{ref} and u_{lidar} is presented in section 4.3.7.

i, bin number	**V_{ref} (m/s)**	**V_{lidar} (m/s)**	**N**	**ΔV (m/s)**	**$\sigma_{\Delta V}$ (m/s)**	**$u_{V_{ref}}$ (m/s)**	**$u_{V_{lidar}}$ (m/s)**
8	…	…	…	…	…	…	…
9	…	…	…	…	…	…	…
10	…	…	…	…	…	…	…
11	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…
29	…	…	…	…	…	…	…
30	…	…	…	…	…	…	…
31	…	…	…	…	…	…	…
32	…	…	…	…	…	…	…

Table 1 Calibration table example

4.3.7. Uncertainty

Following the same approach as IEC 61400-50-3:2022, the calibration uncertainty of the V_{lidar} measurement can be expressed in each wind speed bin as:

$$u_{V_{lidar}} = \sqrt{u_{V_{ref}}^2 + \frac{\sigma_{dev}^2}{N}} \qquad (1)$$

The uncertainty of V_{ref}, $u_{V_{ref}}$, is the combination of the reference wind speed sensor uncertainty and the uncertainty due to this sensor not measuring exactly in the same volume as the arc- scanning lidar:

$$u_{V_{ref}} = \sqrt{u_{sens}^2 + u_{pos}^2} \qquad (2)$$

The reference sensor speed uncertainty shall be calculated according to IEC 61400-12-1:2017:

$$u_{sens} = \sqrt{u_{cal}^2 + u_{ope}^2 + u_{mast}^2 + u_{lgt}^2 + u_{daq}^2} \qquad (3)$$

where:

u_{cal}	is the calibration uncertainty of the sensor used to measure V_{ref}
u_{ope}	is the reference sensor operational uncertainty (also called classification uncertainty)
u_{mast}	is the reference sensor mounting uncertainty
u_{lgt}	is the uncertainty related to the mounting of lightning finial, if there is one close to the reference sensor;
u_{daq}	is the reference sensor data acquisition uncertainty.

The uncertainty due to the relative position and different measurement volume of the reference sensor compared to the scanning-lidar sensing volume is:

$$u_{pos} = \sqrt{u_{probe}^2 + u_{inc}^2 + u_{vert\_pos}^2} \tag{4}$$

where:

u_{probe} is the uncertainty due to the variation of the wind speed within the lidar sensed volume (consisting of the LOS probe volume moving in an arc trajectory). It results from:

i. the wind inhomogeneity along the arc, or horizontal variation of the wind speed in the sensed volume, mainly due to terrain effects,
ii. non-linear wind shear in the height range spanned by the probe volume.

This uncertainty may be estimated based on the calibration height, the lidar probe length and arc scan width, and the wind shear measured at the reference met mast. A value u_{probe} = 0.05% or greater should be used.

u_{inc} is the uncertainty due to the inclined arc-scan plane and the measurement range uncertainty.

For a non-horizontal arc-scan plane, a range error leads to a measurement height error. Using a simple power law model the uncertainty due to a non-horizontal arc- scan plane and a range error will be

$$u_{inc} = \alpha \frac{\sin \varphi u_{range}}{H_{ref}} V_{hor} \tag{5}$$

where α is the shear exponent, φ is the inclination angle, u_{range} is the range uncertainty and H_{ref} is the height of the reference instrument. u_{range} can be estimated from the measurement range check (see 4.3.2).

u_{vert_pos} is the uncertainty due to the height difference between the reference sensor and the centre of the arc scan. This uncertainty arises from uncertainties in the effective elevation angle, including both the accuracy of the levelling and the accuracy of the scanner head (its ability to turn accurately by the commanded amount).

Modelling the vertical shear profile using a power law and shear exponent α, with a reference instrument height H_{ref}, an uncertainty u_H in the beam position would correspond to a wind speed uncertainty of:

$$u_{vert\_pos} = \alpha \frac{u_H}{H_{ref}} V_{hor} \tag{6}$$

where

$$u_H = u_\varphi \cdot R \cos \varphi \tag{7}$$

R is the measuring range, φ is the elevation angle and u_φ is the uncertainty in elevation angle.

α can be either the average shear measured during the calibration (if shear measurements are available) or a typical value for the site.

In Annex A we will develop simple expressions for u_{vert_pos} and u_{inc} using estimates of range uncertainty uR and elevation angle uncertainty u_φ pertaining to our calibration (or operational) setup.

4.4. LOS speed check

An obvious and valuable check is to compare the LOS speed with a projected value from an adjacent cup anemometer. This can either be as a separate ‘staring’ (beam stationary) test or (as described below) by picking radial speed values as the scanning beam passes the reference mast. The reference wind speed, projected according to wind direction and lidar beam inclination, should be close (±1.5%) to the radial speed recorded by the lidar. If it is not, then something is almost certainly wrong, and this should be investigated before the calibration continues.

Using the data collected according to Section 4.3 and selecting the LOS closest to the reference sensor, a calibration of that LOS speed may be performed, following the guidelines in IEC 61400- 50-3:2022, with necessary adaptations specific to the existing horizontal wind speed calibration setup.

5. Combined uncertainty of the scanning lidar in the application

During operation (the offshore PCV campaign), the lidar speed uncertainty is the combination of the calibration uncertainty and the position uncertainty during the application (note that this is in addition to the position uncertainty from the calibration). The positional errors during PCV probably will be significantly larger than during calibration since usually we do not have a target to verify the beam position, and the transition piece will tilt somewhat. The wind speed uncertainty (analogous to the one during calibration) arising from these positional errors will be denoted $u_{pos_{op}}$. Additionally, an uncertainty term $u_{\Delta Zhub}$ is added to account for the deviation from the IEC 61400-12-1 requirement to measure at hub height, since the lidar actual measurement height varies as the lidar tilt varies (together with the transition piece) as a function of wind load.

Therefore, the lidar wind speed uncertainty in operation $u_{lidar_{op}}$ will be:

$$u_{lidar_{op}} = \sqrt{u_{cal}^2 + u_{pos_{op}}^2 + u_{\Delta Zhub}^2} \tag{8}$$

With:

$$u_{\Delta Zhub} = \frac{z - H_{hub}}{H_{hub}} \alpha \tag{9}$$

Where z is the actual measurement height (derived from inclinometer data) and α is a shear exponent representative of the local shear conditions (close to hub height) for the given dataset. A representative α value for the site may be assumed. Alternatively, in this context, α could be estimated from wind speed measurements from range gates corresponding to heights above and below hub height (within a horizontal distance from the rotor between 2D and 4D). We consider this only a “local” shear estimate since usually, due to the relatively low beam elevation angle, it is derived from heights close to hub height. Typically these would be far from the close to lower blade tip (and close to upper blade tip) suggested in IEC 61400-12-1 for shear characterization during the PCV.

Where u_{cal} is the horizontal wind speed calibration uncertainty, and we assume that the inclusion of an uncertainty due to inhomogeneity or terrain effects on the sensed volume is not necessary offshore.

Traditionally, an operational uncertainty is also added. This represents the unknown errors arising from differences in the calibration and application conditions. For a scanning lidar calibrated onshore and operating offshore it is improbable that there will be significant extra errors since the offshore conditions (horizontal homogeneity) are more conducing to high quality lidar measurements than the conditions onshore (degraded homogeneity). We therefore propose that no extra operational uncertainty is added in this case.

6. Measurement campaign preparation

6.1. Pre-campaign preparations

A suitable position on the transition piece of the wind turbine shall be identified which satisfies the following, to the extent possible:

- Has a clear line-of-sight view into the predominant wind direction(s) with minimal obstructions
- Allows access to the ports and maintenance hatches of the lidar
- Does not impede personnel movement around the working area
- Has a stable and flat floor surface
- Provides the ability to safely route cabling to the inner-tower connections
- Has anchor points (D-rings, floor grates, etc.) for securing the lidar against movement

The recommended equipment to be prepared before installation includes:

- Scanning lidar system
- Computer (controller/data logger) with sufficient hard disk capacity
- Lidar power supply and power cables with appropriate plug termination
- Network power switching relay for remote power cycling of equipment
- Washer pump and fluid reservoir filled with antifreeze-cleaner
- Ethernet cables and networking equipment (e.g. network switches and modems)
- External GPS receiver if using GPS radio as clock source
- Network surveillance camera for monitoring and troubleshooting
- Ratchet straps for securing lidar after installation
- Survey equipment (e.g. GNSS/D-GPS receiver) used to obtain accurate position measurement of the lidar
- Digital level used to coarsely level the lidar
- Sea surface (i.e. infrared) and air temperature sensors to provide atmospheric stability classification. Digital sensors can interface with data logger PC.

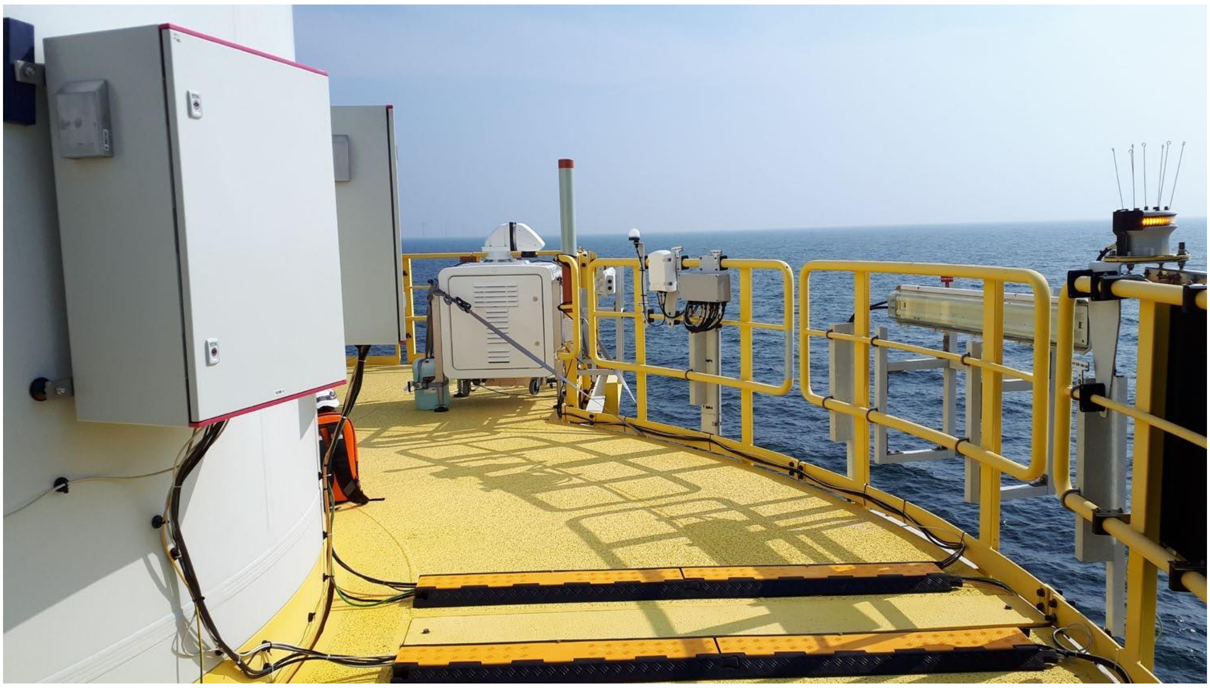

Figure 2 Example of transition piece installed scanning lidar.

After the scanning lidar and auxiliary equipment is moved into place on the transition piece platform and connected to power and network, the lidar shall be settled into its final position. For this step, the platform should be as stable (non-moving) as possible. Ensure the wind turbine has been shut down for several hours and ideally perform this during calm wind and wave conditions. Begin by ensuring that the lidar is raised up high enough to clear any railings or other objects which may obstruct the view from, or potentially strike the scan head. Next, place the digital level atop the scan head and coarsely level the system to achieve close to zero-degree tilt along both its axes. Attach the ratchet straps and tighten to secure the lidar in place. Next, refer to the calibrated inclinometer readings obtained from Section 4.2.1 which indicate the target pitch and roll values from the lidar's internal inclinometer when the system is perfectly levelled. While observing the inclinometer readouts from the lidar software, finely adjust the levelling to reach the target values. Monitor the readings over a period of 10-minutes to ensure that the system remains levelled and that the motion of the transition piece does not impact the average levelled position.

Once the equipment installation is complete, measure the absolute position of the lidar scan head and any hard targets visible from the lidar's position (e.g. other wind turbines, substations, met masts, etc.). At this point, the elevation angle plus/minus the previously determined elevation angle offset (Section 4.2.2) will correspond to the actual elevation angle (assuming the platform is levelled/not moving), however the azimuth angle will not necessarily be oriented where zero degrees points to North. Begin by clearing any azimuth offset present in the lidar configuration software. Move the lidar beam roughly towards the hard target object and use the CNR mapper function to scan towards the object along a wide area. If no CNR mapper function is provided by the lidar software, it is usually possible to manually create a composite program of multiple PPI scans to emulate the same functionality. Begin by scanning a wide area with large steps in azimuth and elevation and a long span in range. Monitor the lidar's CNR measurements until a peak is observed. The corresponding distance at the peak represents the range to the target, and range gates can then be configured to surround this value. Note the beam angles and range where the hard target was identified and repeat the CNR mapper measurements using smaller angular steps to achieve finer resolutions until the object that was surveyed can be clearly identified. Calculate the absolute (North-aligned) bearing between the measured positions of the lidar and hard target and compare to the angles found empirically using the CNR mapper approach. The elevation angle (plus/minus offset) should correspond exactly, while the difference between the azimuth angles represents the azimuth offset which shall be applied in the lidar's software settings. To confirm correct implementation, repeat the CNR mapping procedure using the North-aligned bearing and ensure the object is visible in the expected position. Save this scan pattern to allow it to be repeated throughout the campaign. Only one hard-target alignment is required, however repeating this procedure using multiple objects increases confidence in the result.

6.2. Measurement setup

The offshore measurement setup shall follow a similar configuration used in the onshore calibration and is based on the specifications presented in Section 3.2.1.

The lidar shall be programmed to scan in a PPI (plan position indicator) configuration, where the lidar scan head's elevation angle is held constant while its azimuth sweeps at a fixed speed across the appropriate measurement sector. The azimuth range should be centred upwind of the turbine towards the site's predominant wind direction. The total width of the sector scan should be between 40 degrees (minimum) and 90 degrees (maximum). A proposed default value is 60 degrees. It is crucial that the lidar has a free and clear line of sight across the entire sector scanned region. Holding the other parameters constant- larger azimuth ranges extend the span of the wind measurement sector and improve the model fit of the wind field reconstruction. However, this comes at the cost of a lower sampling rate and the dimensional expansion of the assumption of horizontal homogeneity in the measured wind field. The ultimate blend of parameters should be chosen to reflect site-specific conditions.

Based on the available evidence relevant for power curve measurements, there is no clear advantage to performing successive PPI scans at multiple heights (i.e. elevation angles). Benefits to this approach include gathering measurements of wind shear and wind veer across the turbine rotor. However, drawbacks are also introduced, mainly originating from the decreased sampling rate and associated expansion in statistical uncertainty. There are possibilities to incorporate a blend of scan trajectories (e.g. multi- height PPIs, RHIs, DBS/VAD scans) with varying ratios of execution time per 10-minute period. However, there are no results available from which to provide best practice recommendations at this time. Other indirect methods which could provide similar inputs to filters or models without the use of the scanning lidar are conceivable. This could include sea-air differential temperature, a dedicated vertical profiling lidar etc. Lastly, if the PPI scan has a sufficiently high elevation angle with range gates spaced at the appropriate distances, the rotor span in the vertical direction can be measured across a horizontal span (however, the points will not all be positioned at the same 2.5D distance from the turbine and more assumptions or modelling will need to be introduced).

The elevation angle used shall correspond to the rise in altitude between the lidar scan head position and the wind turbine's hub height at 2.5 rotor diameters in horizontal distance. i.e.

$$\varphi = \tan^{-1}\left(\frac{H_{hub} - H_{lidar}}{2.5D}\right)$$

The resulting target elevation angle shall then by corrected by any elevation homing offset discovered in the onshore calibration (Section 4.2.2). Any potential azimuth homing offset can be disregarded as this is already incorporated in the hard-target azimuth alignment procedure.

Range gates should be selected close to the target distance (i.e. hub height at 2.5D) along the beam path (i.e. Euclidean distance and not horizontal distance). It is recommended to densely pack range gates with close spacing near the target position (e.g. across the rotor area), while also supplementing with sparse separations outside this area. The exact range gate spacing is dictated by the measurement span (i.e. beginning to end distance), elevation angle, range resolution (i.e. pulse duration), and processing capabilities of the lidar. A recommended starting point is to use between 2 to 5 meter dense spacing covering the rotor span ± 15% in height, and 10 to 25 meter sparse spacing outside this area. If the lidar's processor load is excessive while measuring, the number of range gates should be reduced.

The scan speed shall be sufficiently low enough to obtain adequate angular resolution and number of samples to perform the horizontal wind reconstruction. A scan speed of between 1-2 degrees per second is recommended. The line-of-sight acquisition time is recommended at 500ms. For further distances, increasing this value (up to 1000ms) can improve the measurement range at the expense of a reduced sampling rate. The pulse length or "range resolution" is highly specific to the lidar system. As a general recommendation, 200-400ns pulse lengths are appropriate for the distances relevant to this application.

In addition to the core looping PPI scans used to obtain horizontal wind speeds, it is advised to use the lidar's programmable scheduler to also execute the following on a regular basis:

- Wash and wipe the lens to remove dust, salt deposits, bird droppings. This should run once per day.
- Repeat the hard target scan configured in Section 6.1. This should run once per week.
- A PPI scan pointed down at the sea surface can give further traceability for the levelling status and consistency in the ranging calibration. This should run at minimum, once per week repeating for a block of time (e.g. 30-minutes). The sea surface PPI azimuthal range should be as wide as possible, excluding any region blocking visibility towards the sea by the turbine tower or other obstructions. The elevation angle of the sea surface scan shall be determined by the distance to the water surface and the minimum range gate position given by the shortest pulse duration setting of the lidar. This elevation angle in a typical setup is likely to be between -2 and -5 degrees (zero degrees representing the horizon). Range gate spacing shall be made as dense as possible, between 1 and 2 meters. A full description of the method and results from an offshore study are presented in [4].

6.3. Wind direction measurement sector

The scanning lidar should be placed in a first-row wind turbine to allow for as wide as possible a wind direction measurement sector. Additionally, it is preferable that the central line-of-sight in the arc scan is as close as possible to the prevailing wind direction, both to attempt to speed up completion of the power curve (achieving the required amount of data in the required wind speed range) and to maximize wind speed measurement accuracy (which would decrease as the difference between wind direction and LOS direction increases and approaches 90 degrees).

The wind direction sectors in which the test turbine and the lidar (in particular, its measurement probe volumes and lines-of sight) are in the wake from neighbouring wind turbines or (in the case of the lidar) in the wake of the turbine under test, shall be determined. In an offshore PCV, typically there are not any other relevant obstacles in the area besides the wind turbines in the wind farm.

The sector assessment is performed in two steps: firstly by assessing the waked sectors from the test turbine perspective, and subsequently assessing from the scanning lidar's perspective.

6.3.1. Test wind turbine

The sector to exclude due to wakes from a neighbouring and operating wind turbine or an obstacle is taken from [2]:

$$\theta = 1.3\tan^{-1}\left(\frac{2.5D_n}{L_n} + 0.15\right) + 10° \tag{10}$$

where D_n is the rotor diameter of the operating and neighbouring wind turbine and L_n is the distance to the wind turbine from the tested wind turbine. Note that IEC 61400-12-1:2017 assumes $\theta = 0$ for $L_n/D_n > 20$ (wakes from turbines at a distance greater than 20 rotor diameters are considered negligible) and does not take into account nearby wind farm wakes.

6.3.2. Scanning lidar

To select a valid measurement sector for the scanning lidar, the following steps should be followed:

- The sector should be contained in the wind turbine wake-free sector (as per 6.3.1).
- Exclude wind directions for which the scanning lidar measurement volume is in the wake from the turbine on which it is installed. As a rule of thumb, this could be the azimuth of the central LOS (in the arc) +180° ± 45°.
- Generally, to attempt to increase the correlation between the scanning lidar measurements and the wind seen by the wind turbine, the wind direction should be restricted to match the arc scan width, or the arc scan width ±30° but without exceeding the turbine wake-free sector.

6.4. Post-campaign considerations

It is advisable to take into account the following post-campaign considerations during the campaign preparation and planning phase.

Before removal of the equipment from the offshore transition piece, and while the turbine is shut down, it is necessary to repeat the hard targeting CNR mapping outlined in Section 6.1 to provide confidence that the scanner alignment, offsets, and ranging calibrations have not changed during the campaign.

A post-campaign calibration can be performed onshore following the end of the offshore campaign. The setup and method shall follow the procedures described in Section 4. These activities provide further confidence in the quality of the measurement campaign and assurance in the data gathered. In the event that a discrepancy is discovered, the measurement data can be post-corrected. For example, the discovery of a ranging error could warrant the selection of measurements from a different range gate than initially designated. Likewise, a line-of-sight speed deviation from the pre-campaign calibrations could at best provide a means for correction, and at least an indication of the expanded uncertainty impact from the deviation.

7. Measurement procedure

7.1. Scanning lidar operation/monitoring

The scanning lidar and auxiliary equipment can be operated and monitored remotely provided there is a network connection to the offshore equipment with sufficient bandwidth. The connection should be properly secured e.g. by segmenting the devices into a virtual LAN where traffic is firewall restricted to the required ports and designated whitelisted IP address of the control PC. The operator then connects via encrypted VPN tunnel to the control PC using remote desktop to control the lidar's graphical interface and/or execute command line scripts which interact via the lidar's API.

It is essential to carry out routine (daily) monitoring of the lidar and auxiliary equipment to ensure a successful measurement campaign. This shall include the following tasks:

- Ensure equipment is powered on and measuring
- Confirm correct measurement trajectory is programmed
- Check measurement range (CNR curve and radial speed values)
- Monitor humidity level inside the lidar casing. Desiccant must be changed to prevent range loss when humidity rises above a value prescribed by the manufacturer
- Monitor data disk usage
- Ensure time synchronization is working properly
- Monitor pitch and roll values are within expected ranges

Automating these monitoring checks (i.e. via scheduled API calls or other scripts which alert the operator) in addition to regular human quality control will ensure the best operation and lowest response time to potential errors requiring intervention. It is also recommended to operate the data pipeline and analysis chain while the measurements are being collected in order to pre-empt any potential issues which may be discovered at too late a point to correct.

7.2. Wind Field Reconstruction

Typically, the raw data (containing the line-of-sight speeds) from the lidar is downloaded by the user and the horizontal wind speed (and direction) reconstruction is performed by a software provided by the manufacturer or a third party. It is recommended to make an initial comparison of wind speed and wind direction against the turbine data (nacelle wind speed and wind direction) as a plausibility check within the first days after the installation. This is to ensure that the lidar is configured correctly and that lidar and turbine data acquisition system times are synchronized.

The dataset consists of 10-minute averaged data from lidar and reference, to be consistent with IEC 61400-12-1:2017.

7.3. Data corrections

The scanning lidar’s inclinometer should be corrected based on the inclinometer calibration results such that zero degrees pitch and roll represent a levelled plane. The lidar horizontal speed may be corrected too based on the speed calibration results. Both corrections are strongly recommended if the deviations measured in the calibrations are greater than the uncertainty of the calibration reference measurements (reference angles, in the case of the inclinometer calibrations; reference speed, in the case of the wind speed calibrations).

7.4. Consistency/plausibility checks

7.4.1. Measurement sector check

The consistency of the theoretical measurement sector obtained in section 6.3 should be verified. The purpose is to verify that none of the lidar LOSs are in the wake of a neighbouring turbine. For this, our recommendation is to plot either of the following:

- Lidar-derived wind direction against turbine yaw. A sudden change in the lidar wind direction, or a loss of linearity between the lidar direction measurements and the yaw position data is likely an indication that the part of the lidar arc scan may be in a wake.
- Lidar-derived turbulence intensity against turbine yaw position. An increase in the lidar- derived turbulence may be an indication that a part of the lidar arc scan may be in a wake. This turbulence intensity may be, preferably (and if available in the lidar dataset), the LOS turbulence (standard deviation of the LOS speed divided by the LOS speed) for the different LOS azimuth positions. Alternatively, the turbulence intensity derived from the reconstructed horizontal wind speed may be used, although this might not always be conclusive.

If any of these plots indicates that the lidar measurement volume is affected by wakes, the measurement sector shall be reduced accordingly.

An example is shown in Figure 3. The magnitude of the error in the scanning lidar derived wind direction increases as one end of the arc scan enters the wake, it decreases when it is in full wake, and the inverse happens as the arc scan starts to leave the wake. In this example, the arc scan central line-of-sight was at 275°, so that central LOS is expected to be in full wake of the turbine at direction 95°, as it appears in the plot.

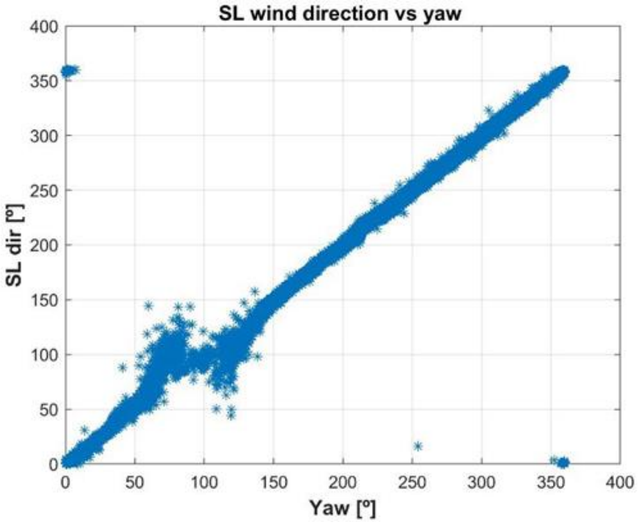

Figure 3 Example of scanning lidar wind direction vs turbine yaw position. The lidar measurement volume is in wake between yaw positions 50° and 130°.

7.4.2. Wind direction check

The turbine yaw position data can provide a useful plausibility check of the scanning lidar wind direction measurements. For this, it is necessary that the yaw position signal offset is correct. Ideally, the yaw position offset should be verified during lidar installation and decommissioning (for example, by yawing the turbine to align it with another turbine in the wind farm), and carefully monitored over time to detect if any offset change appears.

In case that there is not available documentation of any yaw position offset checks during lidar installation or decommissioning, the PCV dataset should be analysed to determine if a yaw position correction is required. One viable way to do it would be to plot (against yaw position) the power ratio between the test turbine and another turbine in the row that is wake-free for a certain sector where the test turbine is not (or vice-versa).

The lidar-derived wind direction should be compared to the wind turbine yaw position signal (corrected for any possible offsets), with two purposes: a) detect any relevant offset in the lidar wind direction measurements; b) a plausibility check to detect clearly erroneous lidar data, for example due to errors in the WFR reconstruction (which would show as a wind direction error). An example is given in Figure 4. Wind direction, turbine filters and basic lidar quality control filters should be applied to obtain meaningful information from this plot and quality check.

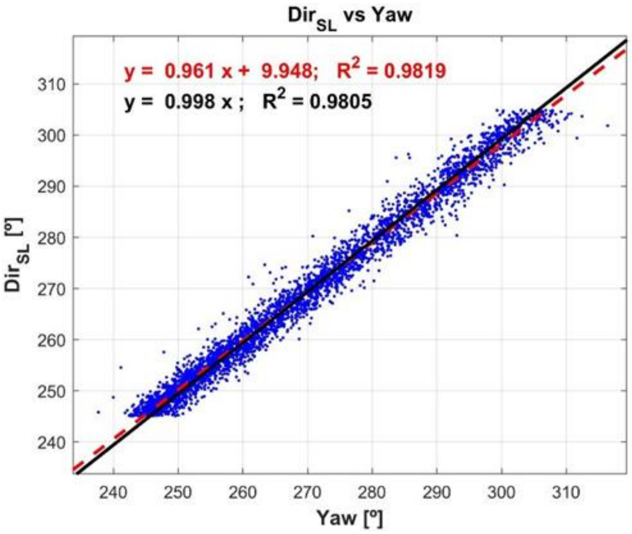

Figure 4 Example of scanning lidar wind direction vs turbine yaw position.

7.5. Data filtering and analysis

Since the sector-scanning lidar raw data (line-of-sight speeds) are fit to a cosine function to reconstruct 10-minute mean wind speeds and wind directions, the reconstruction algorithm shall provide:

- a metric of the 'quality of fit': how well the LOS speeds fit to the theoretical cosine function.
- a metric of the number of reconstructed data valid in a 10-minute interval.

These metrics should be included in the filtering process, which should include (but is not limited to):

- Wind directions within valid wind direction measurement sector (see section 6.3)
- There shall be sufficient quality and quantity of lidar data within each 10-minute period. Filters based on internal lidar parameters and/or the lidar WFR quality metrics should be applied. The specific metrics and threshold depend on the lidar type and the conditions at the site. As a minimum, the same quality filters used during the calibration shall be applied.

The reconstructed lidar 10-minute horizontal wind speeds and the corresponding turbine data shall be further filtered and processed as described in IEC 61400-12-1:2017. Data shall be collected until the requirements defined in IEC 61400-12-1:2017 are satisfied.

7.6. Measurement height

The scanning lidar's pitch and roll inclinometer data shall be recorded (at as high a sampling rate as possible) and monitored during the PCV and should be reported (e.g. as plots) as a function of wind speed and wind direction.

Variations in the elevation of the lidar beams above sea level during the measurements shall be recorded and documented. The lidar moves together with the wind turbine transition piece proportionally to wind loads, which causes a measurement height variation, and deviation from hub height. This height difference should be estimated using the inclinometer data. The motion of the TP and TP-mounted lidar are also affected by wave dynamics.

IEC 61400-12-1:2017 requires that the wind speed be measured within 1% of hub height. The average height difference relative to hub height, in each wind speed bin in the power curve, shall be used to calculate the measurement height uncertainty according to section 5.

7.7. Air density measurements

IEC 61400-12-1:2017 requires air pressure and temperature measurements, and it recommends relative humidity measurements. In the absence of a meteorological met mast, the air density sensors must be turbine mounted. The sensors' mounting shall comply with the requirements from IEC 61400-12-2:2013, 7.4, and the guidance in the recent IEC 61400-50-3 should be followed:

- Air temperature and relative humidity (if measured) sensor(s) shall have a minimum impact from dissipated or radiated heat from the wind turbine energy conversion process.
- The air pressure sensor shall be located in a position where the sensor is in contact with the atmosphere.

8. Reporting requirements

The PCV report shall fulfil the requirements in IEC 61400-12-1:2017, clause 10. Additionally, the following items specific to the use of scanning lidar shall be included in the report.

Coordinates and measurement sector:

- coordinates of test turbine and relevant neighbouring turbines and obstacles.
- selected wind direction measurement sector according to section 6.3, and measurement sector consistency check according to 7.4.1.

Scanning lidar:

- lidar type, serial number, operating software version, WFR tool version.
- geometrical description of the arc scan, including: elevation angle, scan speed, scan time, and azimuth angle span.
- Lidar azimuth offset with respect to North.
- all details of the lidar set-up, including:
  - position on the transition piece, height of optical head relative to TP surface, height of transition piece relative to hub height,
  - configuration of the lidar operating software, WFR tool version and settings,
  - measurement ranges, pulse length (or range resolution)
  - pitch and roll angles
- reference to calibration report (according to section 4);
- Hard target scan results; e.g. mapping images at beginning and end

WTG information

- Brief description of foundation type (monopole or jacket); its stiffness would affect the lidar tilt.

Database:

- Start and end of the PCV.
- Lidar availability in the measurement period;
- Measurement log, with: changes to the lidar; changes to the turbine; services / regular maintenance.
- Documentation of time zone and synchronisation between lidar and other data acquisition systems (e.g. SCADA or turbine data logger), and if any time shifts occurred.
- description of data analysis and filters.
- a description of the WFR method used to obtain the horizontal wind speed and wind direction form scanning lidar data.

- results of the assessment of the consistency/plausibility of the lidar measurements (section 7.4).

Plots

- Lidar pitch and roll vs wind speed and wind direction
- Lidar measurement height (based on inclinometer data) vs wind speed

References

[1] P. Gómez and M. Courtney, “WP1 - Literature review: Scanning lidar for wind turbine power performance testing,” Carbon Trust OWA, 2021.

[2] International Electrotechnical Commission, International Standard IEC 61400: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. 2017.

[3] International Electrotechnical Commission, “IEC 61400 Wind turbines – Part 50-3: Use of nacelle mounted lidars for wind measurements,” 2022.

[4] A. Rott, J. Schneemann, F. Theuer, J. Trujillo, and M. Kühn, “Alignment of scanning lidars in offshore wind farms”, Wind Energy Science, 2022. https://doi.org/10.5194/wes-7-283-2022

APPENDICES

Appendix 1: Deriving the positional uncertainty

Wind speed errors are assumed only to result from measuring at an incorrect height.

The basis for a simple model is to assume a power law wind speed profile with an exponent α

$$V(h) = V_0 \left(\frac{h}{H_0}\right)^{\alpha} \tag{11}$$

For a height error of Δh, the wind speed error ΔV is given by

$$\Delta V = \Delta h \cdot \frac{\partial V}{\partial h} = \Delta h \cdot V_0 \alpha \frac{1}{h} \left(\frac{h}{H_0}\right)^{\alpha - 1} \tag{12}$$

For small perturbations around H_0, we can set $h = H_0$ and the wind speed error simplifies to

$$\Delta V = V_0 \frac{\Delta h}{H_0} \alpha \tag{13}$$

Or

$$\frac{\Delta V}{V_0} = \alpha \frac{\Delta h}{H_0} \tag{14}$$

We can now use (14) to provide a numerical estimate for standard uncertainties due to both height and range. Height uncertainties arise from uncertainties in the effective elevation angle, including both the accuracy of the levelling and the accuracy of the scanner head (its ability accurately to turn by the commanded amount). The measuring height h is simply

$$h = R \sin \varphi \tag{15}$$

where R is the measuring range and φ is the elevation angle. For an uncertainty in elevation angle u_φ, the corresponding height uncertainty $u_{h\varphi}$ is given by

$$u_{h\varphi} = u_\varphi \cdot \frac{\partial h}{\partial \varphi} = u_\varphi \cdot R \cos \varphi \tag{16}$$

Inserting (16) into (14) gives us an expression for the wind speed uncertainty u_{vert_pos} resulting from the elevation angle uncertainty u_φ

$$u_{vert\_pos} = u_\varphi \alpha \frac{R \cos \varphi}{H_0} V_0 \tag{17}$$

Similarly, a range uncertainty u_R will give rise to a corresponding height uncertainty $u_{hR} = u_R \sin \varphi$ and the resulting wind speed uncertainty due to the range uncertainty u_{inc} will be

$$u_{inc} = \alpha \frac{u_R \sin \varphi}{H_0} U_0 \tag{18}$$

Finally, our required wind speed positional uncertainty u_{pos} is

$$u_{pos}^2 = u_{vert\_pos}^2 + u_{inc}^2 \tag{19}$$

$$u_{pos} = \frac{\alpha V_0}{H_0} \sqrt{\left(u_\varphi R \cos\varphi\right)^2 + (u_R \sin\varphi)^2} \qquad (20)$$

We can further simplify and generalise this expression by substituting $R = 2.5D$, $H_0 = D/2$, $\cos\psi = 1$ and $\sin\varphi = 0.2$ (from $(D/2)/2.5D$), giving

$$\frac{u_{pos}}{V_0} = 2\alpha \sqrt{\frac{25}{4} u_\varphi^2 + \frac{1}{25}\left(\frac{u_R}{D}\right)^2} \qquad (20)$$

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