भारतीय मानक

IS/IEC 61400-50-3 : 2022

Indian Standard

पवन ऊर्जा उत्पादन प्रणाली

भाग 50-3 पवन मापन के लिए नैकेले-माउंटेड लिडार का उपयोग

Wind Energy Generation Systems

Part 50-3 Use of Nacelle-Mounted Lidars for Wind Measurements

ICS 27.180

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NATIONAL FOREWORD

This India Standard (Part 50/Sec 3) which is identical to IEC 61400-50-3 : 2022 'Wind energy generation systems — Part 50-3: Use of nacelle-mounted lidars for wind measurements' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Wind Turbines Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to International Standards for which Indian Standards also exists. The corresponding Indian Standards, which are to be substituted, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 61400-12-1 Wind energy generation systems — Part 12-1: Power performance measurements of electricity producing wind turbines	IS/IEC 61400-12-1 : 2017 Wind energy generation systems: Part 12 Electricity producing wind turbines, Section 1 Power performance measurements	Identical

The Committee has reviewed the provisions of the following International Standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard:

International Standard	*Title*
IEC 61400-12-2	Wind energy generation systems — Part 12-2: Power performance of electricity producing wind turbines based on nacelle anemometry

Only English language text has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the International Standard.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

CONTENTS

Indian Standard

WIND ENERGY GENERATION SYSTEMS

PART 50-3 USE OF NACELLE-MOUNTED LIDARS FOR WIND MEASUREMENTS

1 Scope

The purpose of this part of IEC 61400 is to describe procedures and methods that ensure that wind measurements using nacelle-mounted wind lidars are carried out and reported consistently and according to best practice. This document does not prescribe the purpose or use case of the wind measurements. However, as this document forms part of the IEC 61400 series of standards, it is anticipated that the wind measurements will be used in relation to some form of wind energy test or resource assessment.

The scope of this document is limited to forward-looking nacelle-mounted wind lidars (i.e. the measurement volume is located upstream of the turbine rotor).

This document aims to be applicable to any type and make of nacelle-mounted wind lidar. The method and requirements provided in this document are independent of the model and type of instrument, and also of the measurement principle and should allow application to new types of nacelle-mounted lidar.

This document aims to describe wind measurements using nacelle-mounted wind lidar with sufficient quality for the use case of power performance testing (according to IEC 61400-12-1:2017). Readers of this document should consider that other use cases may have other specific requirements.

This document only provides guidance for measurements in flat terrain and offshore as defined in IEC 61400-12-1:2017, Annex B. Application to complex terrain has been excluded from the scope due to limited experience at the time of writing this document.

Corrections for induction zone or blockage effects are not included in the scope of this document. However, such correction or uncertainty estimation due to blockage effects may be applied if required by the use case, under the responsibility of the user.

The purpose of this document is to provide guidance for wind measurements. HSE requirements (e.g. laser operation) are out of the scope of this document although they are important.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 61400-12-1:2017, *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*

ISO/IEC 61400-12-2:2013, *Wind energy generation systems – Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61400-12-1:2017 and the following apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
carrier-to-noise ratio
CNR
measure of signal quality for a pulsed lidar defined as the ratio between the heterodyne current power and the total noise power in the detection bandwidth

Note 1 to entry: By default, CNR is CNR wide band (CNR_{wb}). We can also define CNR narrow band (CNR_{nb}) as the ratio between the heterodyne current power and the noise power in the Doppler peak bandwidth. This does not depend on spectral signal processing. CNR is different from Signal-to-Noise Ratio (SNR). SNR is the ratio between the Doppler peak power and the noise power standard deviation.

Note 2 to entry: $SNR = CNR_{\mathrm{nb}}\sqrt{n}$, with n: number of averaged pulses.

3.2
continuous wave lidar
CW lidar
a lidar transmitting a laser signal of constant amplitude and frequency and receiving backscattered light at the same time

3.3
correlated uncertainties
a pair of uncertainty components in which an unknown error on one of the components is correlated to some degree to the error on the other component

Note 1 to entry: The value of the correlation coefficient can vary between -1 and 1.

[SOURCE: JCGM 100:2008; 5.2]

3.4
data availability
ratio between the number of measurement points accepted on the basis of a predefined data quality and the maximum number of measurement points that can be acquired during a given measurement period

3.5
final values
values provided by the nacelle lidar system for use in wind energy assessment applications such as WTG power performance testing

Note 1 to entry: Therefore, the accuracy of the final value is the key consideration when using nacelle lidar in wind energy applications. Examples of final values include (but are not limited to) horizontal wind speed and wind direction.

3.6
free wind speed
wind speed that would be present at the turbine location if the turbine was not there

3.7
homodyne detection
measurement technique in which the received signal is mixed with a signal of the same frequency as that of the transmitted signal

Note 1 to entry: The mixing product at the difference frequency contains information on the magnitude of the Doppler shift induced in the received signal, but not whether that Doppler shift is positive or negative.

3.8
heterodyne detection
measurement technique in which the received signal is mixed with a signal of a different frequency to that of the transmitted signal

Note 1 to entry: The mixing product at the difference frequency contains information on both the magnitude and the sign of the Doppler shift induced in the received signal.

3.9
intermediate values
inputs to the wind field reconstruction (WFR) model or algorithm, which delivers final values as output

Note 1 to entry: Examples of intermediate values include (but are not limited to) line of sight (LOS) speeds.

3.10
line of sight
LOS
direction originating at the laser source and oriented along the axis of the transmitted laser beam, corresponding to the beam propagation path

3.11
line of sight speed
LOS speed
magnitude of the component of the wind velocity in the LOS

3.12
LOS speed turbulence intensity
ratio of the LOS speed standard deviation to the mean LOS speed, determined from the set of measurement data samples of LOS speed, and taken over a specified period of time

Note 1 to entry: See Clause 6 for the characteristics of turbulence measured with lidar.

3.13
measurement
process of experimentally obtaining one or more quantity values that can reasonably be attributed to a measurand

[SOURCE: JCGM_200_2012; 2.1]

3.14
measurement accuracy
closeness of agreement between a measured quantity value and a true quantity value of a measurand

[SOURCE: JCGM_200_2012; 2.13]

3.15
measurement bias
estimate of a systematic measurement error

[SOURCE: JCGM_200_2012; 2.18]

3.16
measurement period
interval of time between the first and last measurements

[SOURCE: ISO 28902-1:2012, 3.10]

3.17
measurement uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

[SOURCE: JCGM_200_2012; 2.26]

3.18
nacelle-mounted lidar
NML
wind lidar mounted on the nacelle of a WTG generator

EXAMPLE A lidar placed in the spinner of a WTG is not considered nacelle-mounted in the case where it follows the spinner's rotation about the rotor axis.

Note 1 to entry: A wind lidar can only be considered as nacelle-mounted if the lidar is fixed in the frame of reference of the nacelle (but not the rotor frame of reference).

3.19
probe length
measure of the radial extent of the lidar probe volume, which can be defined in terms of the distance between the two points at which the radial sensitivity of the lidar is half of its maximum value: the full-width at half-maximum (FWHM) sensitivity

- For pulsed coherent lidars: The probe length is the distance between the FWHM levels of the Velocity Range Weighting Function (VRWF).
- For pulsed incoherent lidars (direct detection lidars): The probe length is the distance between the FWHM levels of the laser pulse. (assuming no range averaging).
- For CW coherent Lidars: The probe length is the distance between the FWHM levels of the Lorentzian weighting function.

Note 1 to entry: The Velocity Range Weighting Function describes the relative efficiency of collecting velocity information as a function of distance around the nominal range. An ideal weighting function would be a Dirac function at 0 (the wind speed is measured at one point). The integral of the weighting function (from minus to plus infinity) is equal to 1. The VRWF is the normalized convolution of the range gate profile with the pulse amplitude profile.

3.20
probe volume
volume located along the laser beam propagation path in which particles scattering light back to the lidar system contribute significantly to the received signal

3.21
pulsed lidar
lidar transmitting a laser signal during a short time period (the pulse) at regular intervals and receiving backscattered light between the pulses

3.22
remote sensing
technique for wind measurement where the instrument is distant from the locations where the wind vector is sensed

3.23
roll angle
angle of rotation of the lidar about the roll axis, with respect to the design orientation of the lidar defined as horizontal

Note 1 to entry: The roll axis passes through the origin of the lidar coordinate system in a direction representative of the average measurement direction of the lidar. The exact definition of the roll axis shall be documented by the lidar manufacturer. For a scanning lidar it is suggested that the roll axis is defined as the unit vector with the same direction as the average of the unit vectors describing the beam's trajectory. For a fixed beam lidar it is suggested that the roll axis is defined as the unit vector with the same direction as the average of the unit vectors describing the lidar's fixed beams.

3.24
scalar average
scalar number found by dividing the sum of scalar data by the number of items in the data set

3.25
scanning lidar
lidar in which the direction of a single transmitted beam is scanned

Note 1 to entry: In this document, two types of scanning lidars are considered:

1) Fixed-pattern-scanning lidar: the beam is scanned following a fixed, predefined trajectory (this trajectory is typically planar or conical)
2) Programmable-scanning lidars: the beam is scanned in a programmable manner.

In contrast, a fixed-beam-geometry lidar is a lidar in which the laser beam is transmitted in a number of different, but fixed, directions that are addressed sequentially or simultaneously.

3.26
specific measurement campaign
SMC
an implementation of a use case

3.27
tilt angle
angle of rotation of the lidar about the tilt axis, with respect to the design orientation of the lidar defined as horizontal

Note 1 to entry: The tilt axis passes through the origin of the lidar coordinate system, is perpendicular to the roll axis, and is horizontal when the lidar is in the design orientation defined as horizontal.

3.28
turbulence intensity
ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

[SOURCE: IEC 61400-1:2019, 3.58]

3.29
use case
combination of the following three elements:

- Data requirements: objectives arising from the application and independent of instrument capabilities.
- Measurement method: lidar technique selected to fulfil the data requirements. The scope of this guidance is restricted to methods using nacelle-mounted lidar and evaluation of their accuracy under the operational conditions described.
- Operational conditions: circumstances that may influence measurement accuracy.

[SOURCE: CLIFTON, A. et al., 2018]

3.30
vector average
vector found by dividing the sum of vectors by the number of items in the dataset

3.31
wind direction
direction of the horizontal component of the wind velocity

3.32
wind field reconstruction
WFR
process of combining intermediate values, such as the LOS speeds associated with multiple LOSs, to retrieve the final values relevant to the use case

3.33
wind lidar
remote sensing device that transmits energy from a laser source into the atmosphere and analyses the signal reflected from particles being carried by the wind to measure the characteristics of the wind

Note 1 to entry: The word "lidar” is used for wind lidar throughout this document.

Note 2 to entry: Most wind lidars working principles rely on the Doppler effect, where the frequency of the light backscattered by particles moving with the wind is Doppler shifted.

3.34
wind measurement equipment
WME
meteorological mast or remote sensing device

[SOURCE: IEC 61400-12-1:2017,3.29]

3.35
wind shear
change of horizontal wind speed with height

Note 1 to entry: In this document, the focus is on the change of wind speed with height across the turbine rotor span.

3.36
wind shear exponent
exponent of the power law model of the variation of horizontal wind speed with height above the ground

Note 1 to entry: The power law formula is

$$v_{z2} = v_{z1}\left(\frac{z_2}{z_1}\right)^{\alpha} \quad (1)$$

where

v_{zi} is the horizontal wind speed at height z_i;

α is the wind shear exponent.

3.37
wind speed
magnitude of the local wind velocity

Note 1 to entry: The horizontal wind speed is the magnitude of the projection of the wind velocity onto the horizontal plane.

3.38
wind veer
change of wind direction with height across the WTG rotor

[SOURCE: IEC 61400-12-1:2017, 3.32]

3.39
wind velocity
vector pointing in the direction of motion of an infinitesimal volume of air surrounding the point of consideration, the magnitude of the vector being equal to the speed of motion of this air "parcel" (i.e. the local wind speed)

Note 1 to entry: The vector at any point is thus the time derivative of the position vector of the air "parcel" moving through the point.

[SOURCE: IEC 61400-1:2019, 3.73, modified – "minute amount" has been changed to "infinitesimal".]

3.40
yaw misalignment
angle resulting from the horizontal deviation of the WTG rotor axis from the wind direction

[SOURCE: IEC 61400-1:2019, 3.77, modified – "angle resulting from the" has been added]

4 Symbols and abbreviated terms

NOTE Symbols are specific to this document (not to be confused with other standards).

Abbreviation	Description
CNR	carrier-to-noise ratio
CW	continuous wave
DLL	dynamic-link library
EV	environmental variable
FWHM	full-width half-maximum
HSE	health safety environment
LOS	line of sight
NML	Nacelle-mounted lidar
RSS	residual sum of squares
SCADA	supervisory control and data acquisition
SMC	specific measurement campaign
SNR	signal-to-noise ratio
VRWF	velocity range weighting function
WFR	wind field reconstruction
WME	wind measurement equipment
WTG	wind turbine generator

Variable	Description	Unit
C_j	uncertainty component of a LOS speed, which is correlated between left and right beam (Annex A)	m/s

Variable	Description	Unit
d	horizontal distance between the terrain point and the calibration mast (7.5.2.2)	m
D	rotor diameter of tested WTG	m
D_{n}	rotor diameter of the neighbouring turbine	m
$Dir_{\mathrm{OffsetCorr}}$	correction angle between true north and nacelle orientation angle $Dir_{Yaw,TR}$ (D.2.4)	deg
$Dir_{\mathrm{TrueNorth}}$	nacelle orientation relative to true north (D.2.4)	deg
$Dir_{\mathrm{1,Nac,TR}}$	10-min average turbine-reported relative wind direction of first sensor (D.2.4)	deg
$Dir_{\mathrm{2,Nac,TR}}$	10-min average turbine-reported relative wind direction of second sensor (D.2.4)	deg
$Dir_{\mathrm{Yaw,TR}}$	10-min average turbine-reported nacelle orientation (D.2.4)	deg
H	hub height	m
h	height threshold for an obstacle to be considered significant	m
H_0	height by which beam 0 is elevated after a tilt and roll displacement specific to Annex B	m
H_1	height by which beam 1 is elevated after a tilt and roll displacement specific to Annex B	m
H_{OH}	vertical distance between lidar optical head and rotor axis	m
H_{ref}	height above ground of the reference wind speed instrument used in the lidar calibration	m
i	if used as an index: reference to the wind speed bin number	-
k	coverage factor according to E.2.2 of IEC 61400-12-1:2017	-
L_0	distance between beam origin and detection point for beam 0 specific to Annex B	m
L_1	distance between beam origin and detection point for beam 1 specific to Annex B	m
L_{e}	distance to a neighbouring obstacle (10.4.2)	m
l_{h}	Height of an obstacle	m
L_{n}	distance to a neighbouring turbine (10.4.2)	m
l_{w}	width of an obstacle	m
L_{probe}	lidar probe length	m
L_{ref}	horizontal distance between lidar and reference (in calibration)	m
L_{u}	horizontal distance between the rotor plane and the upstream measurement position	m
N	number of data in a bin	-
R	total distance between the lidar and the reference instrument in lidar calibration set up (7.5.4)	m
r	distance between an obstacle and the calibration mast	m
$r_{i,j}$	correlation between uncertainty components (Annex A)	-
R_{b}	measurement range along the LOS (10.4.2)	m
R_{conf}	lidar measurement range (configured) (7.5.4)	m

Variable	Description	Unit
s	mean terrain slope (7.5.2.2)	%
u_{cal}	calibration uncertainty of the reference wind speed sensor used to measure V_{hor}	m/s
u_{daq}	data acquisition system uncertainty	m/s
u_{HWS}	uncertainty of the reconstructed horizontal wind speed	m/s
U_i	variable for an uncertainty component (A.2)	
u_{inc}	uncertainty due to the inclined beam and measurement range	m/s
$U_{L,i}$	uncertainty components of the left LOS, which are uncorrelated, specific to (A.2)	m/s
u_{lgt}	uncertainty related to the mounting of lightning finial, if there is one	m/s
u_{mast}	uncertainty due to mounting of the reference sensor used to measure V_{hor}	m/s
u_{ope}	classification uncertainty of the reference wind speed sensor used to measure V_{hor}	m/s
$u_{\mathrm{ope,lidar}}$	operational uncertainty of the lidar (9.3)	m/s
u_{pos}	uncertainty due to the beam positioning	m/s
$U_{R,i}$	uncertainty components of the right LOS, which are uncorrelated, specific to (A.2)	
u_{range}	measurement range uncertainty	m
u_{residual}	uncertainty from residuals of calibration function (9.2.1)	m/s
u_{sens}	uncertainty of the reference sensor in the calibration setup (7.6.2.2)	m/s
u_{probe}	uncertainty due to the horizontal wind flow variation within the lidar probe volume	m/s
$u_{\mathrm{vert\_pos}}$	uncertainty due to the height difference between the reference sensor and the LOS	m/s
$u_{\mathrm{V,hor}}$	horizontal wind speed uncertainty	m/s
$u_{\mathrm{V,LOS}}$	uncertainty of the LOS speed estimate	m/s
$u_{V_{\mathrm{m}}}$	uncertainty of the measured wind speed (A.4)	m/s
u_{rfr}	reference wind speed uncertainty	m/s
$u_{\langle v\rangle,\mathrm{WFR}}$	propagated uncertainty of the LOS speed uncertainties through the WFR algorithm	m/s
$u_{\mathrm{WFR,par}}$	uncertainty due to parameter in WFR algorithm (9.2.2)	m/s
$u_{\langle\Delta v\rangle,\mathrm{measHeight}}$	uncertainty due to varying measurement height (9.4)	m/s
$u_{z_{\mathrm{m}}}$	uncertainty of measurement height (A.4)	m
u_{α}	uncertainty of the shear exponent (A.4)	-
u_{θ}	uncertainty of the wind direction	deg
$u_{\theta,\mathrm{LOS}}$	uncertainty of LOS estimate	deg

Variable	Description	Unit
$u_{\theta,r}$	relative wind direction uncertainty	deg
u_{φ}	beam elevation angle uncertainty	deg
$\bar{V}$	horizontal wind speed from lidar measurement and WFR algorithm	m/s
V_{2LOS}	reconstructed horizontal wind speed with the 2 LOS reconstruction method (Annex A)	m/s
V_{H}	horizontal wind speed extrapolated to the desired measurement height (Annex A)	m/s
V_{hor}	horizontal wind speed measured by the wind speed reference instrument during calibration (Annex A)	m/s
V_{L}	LOS speed of the left LOS as seen from behind the lidar (A.1)	m/s
V_{LOS}	LOS speed	m/s
$V_{LOS,norm}$	normalised lidar LOS speed (used for the determination of θ_{LOS} during calibration)	-
V_{m}	horizontal wind speed at the height the beams were pointing at during the measurement (A.4)	m/s
$V_{NAC,TR}$	10-min averaged turbine-reported wind speed (D.2.4)	m/s
V_{R}	LOS speed of the right LOS as seen from behind the lidar (A.1)	m/s
V_{ref}	reference wind speed, in the LOS direction, used in the calibration	m/s
V_{x}	longitudinal wind speed component (A.1)	m/s
V_{y}	transversal wind speed component (A.1)	m/s
W	vertical wind speed measured by a reference instrument during calibration	m/s
X_{OH}	horizontal distance between lidar optical head and rotor plane	m
z	the terrain height relative to the reference plane (7.5.2.2)	m
z_{H}	desired measurement height (A.4)	m
z_{m}	height at which the lidar acquires measurements (A.4)	m
α	shear exponent	-
β	angle between two beams in the plane containing the two beams (7.2.1.2)	deg
β_{max}	largest horizontal angle between any two beam positions within the trajectory/geometry (10.4.2)	deg
γ	opening angle between two beams that are symmetrical with respect to the horizontal plane – specific to example in Annex B	deg
γ_{V}	projection of γ onto the vertical plane – specific to example in Annex B	deg
$\Delta Dir_{i,Nac}$	difference in angle between two wind direction measurements from nacelle-based sensors averaged over wind speed bin i	deg
ΔV	difference between LOS speed and reference speed (7.6.4)	m/s
ΔV_{hor}	wind speed correction due to measurement height variability (Annex A)	deg
δ	the angle between the lidar optical axis and the LOS being calibrated (7.5.4)	deg

Variable	Description	Unit
δ_{v}	relative error on the LOS speed due to inflow angle (7.5.5)	
δ_{cal}	correction resulting from inclinometer calibration (C.2)	deg
δ_{H}	vertical angle between horizontal plane and direction from lidar optical head to hub height at 2.5D (C.2)	deg
δ_{Nac}	difference in tilt angle of the nacelle between its orientation while the WTG is in normal operation and while it is at stand-still (C.2)	deg
δ_{ope}	nacelle tilt angle when WTG is in normal operation (C.2)	deg
$\delta_{\text{StandStill}}$	nacelle tilt angle when WTG is at-stand still (C.2)	deg
δ_{tot}	lidar optical head pre-tilt angle	deg
θ	wind direction measured by the wind direction reference instrument during lidar calibration (Clause 7)	deg
θ_0	approximation of the direction θ_{LOS}	deg
θ_{2LOS}	horizontal wind direction obtained from the 2-LOS WFR algorithm	deg
$\theta_{\text{induction}}$	wind direction sector to be excluded from the measurement to account for the influence of flow distortion on lidar probe volumes in the induction zone of a neighbouring turbine or other obstacle	deg
θ_{LOS}	LOS direction	deg
θ_{proj}	projection angle (Clause 7)	deg
θ_{r}	relative wind direction ($\theta_r = \theta - \theta_{LOS}$)	deg
θ_{wake}	wind direction sector to be excluded from the measurement to account for the influence of the wake of a neighbouring turbine or other obstacle	deg
ρ	roll angle	deg
σ_{dev}	standard deviation of the difference between the LOS speed and the reference wind speed (7.6.4)	m/s
τ	tilt angle	deg
φ	elevation angle of the lidar beam during lidar calibration (Clause 7)	deg
ψ	the angle between wind velocity vector and the horizontal plane (inflow angle), see 7.5	deg

5 Overview

5.1 General

This document is applicable to nacelle mounted lidars(NML) that use the following measurement principle: the fundamental measurand of the lidar is the line of sight (LOS) speed. The required measurands, for example, the horizontal wind speed and direction, are derived from multiple measurements of LOS speed, together with parameters (such as lidar tilt and roll angles, the angle between each LOS and the lidar optical axis) that define the LOS direction and the measurement range.

The algorithm used to derive the required measurands is referred to as wind field reconstruction (WFR). The inputs to the WFR algorithm are referred to as intermediate values (e.g. LOS speeds, lidar tilt and roll angles, etc.). The outputs of the WFR algorithm are referred to as the final values (e.g. horizontal wind speed).

5.2 Measurement methodology overview

The overall methodology includes two phases of the specific measurement campaign (SMC), lidar calibration and measurement campaign execution.

Phase 1: Calibration and sensitivity to the environmental variables

The calibration method described in Clause 7 of this document follows the "white box calibration" approach to calibrate and provide uncertainties on the intermediate values. The calibration provides calibration factors and measurement uncertainties specific to each unit and therefore has to be performed separately for each lidar unit.

Environmental conditions during the SMC will vary from those during calibration of the lidar unit. The resulting contribution to measurement uncertainty is assessed by analysing how sensitive the accuracy of each intermediate value is to these variations. These sensitivities are assumed to be characteristic of the type of lidar and applicable to any unit of that type. The treatment of these sensitivities is described in 8.2.

At the time of writing of this document there is not enough experience with NML to be able to assess how varying environmental conditions affect WFR. In the present edition of this document we therefore take the pragmatic approach of assigning a value of zero to this component of the measurement uncertainty, providing there is an evidence-base to demonstrate a sufficient level of measurement accuracy for a particular type of lidar. The requirements of such an evidence-base are described in 8.3.

The calibration and the sensitivity analysis of the intermediate values provide the main uncertainty components that have to be propagated through to uncertainties in the final values (e.g. horizontal wind speed) for the SMC.

The calibration of the nacelle lidar unit and the sensitivity analysis of the type of nacelle lidar shall be performed before the start of the SMC.

Note that the procedure described in this document differs from the approach described in IEC 61400-12-1:2017 for ground-based remote sensors, which describes the calibration and/or verification of final values (e.g. the horizontal wind speed) only. The evaluation of the contribution to measurement uncertainty due to the effects of varying environmental conditions on wind speed measurement accuracy is referred to in IEC 61400-12-1:2017 as "classification", but that terminology is not used in the present edition of this document as no "class" is assigned to the lidar type.

Phase 2: Execution of specific measurement campaign

Data requirements of the use case implemented by the SMC are provided in the relevant standard (e.g. IEC 61400-12-1:2017 for power performance testing). The execution of a typical measurement campaign using an NML follows 4 steps:

1) preparation – including site assessment, measurement sector and preparation of lidar mounting on the nacelle;
2) measurements;
3) complete measurement uncertainty assessment;
4) reporting.

5.3 Document overview

The main clauses of this document are not mutually dependent. Therefore, it is possible to refer to only certain parts of the main clauses rather than all clauses to adapt this document to a particular use case. However, the main clauses are presented in a logical sequence that could be applied in practice.

Clause 6 describes the requirements a lidar shall fulfil so that the various methods described in this document are applicable.

Clause 7 describes procedures and requirements for the calibration of NMLs.

Clause 8 describes the assessment of the sensitivities of intermediate values to changing environmental conditions. It also describes the requirements of an evidence-base able to support the assumption of zero contribution to measurement uncertainty due to environmental effects on WFR.

Clause 9 describes how the uncertainties on the intermediate values (resulting from calibration according to Clause 7 and sensitivity analysis according to Clause 8) are propagated to the final values (e.g. horizontal wind speed and direction) through the WFR algorithm. An example for a 2-LOSs lidar is provided in Annex A.

Clause 10 describes the NML specific aspects to be considered in the preparation phase of the SMC.

Clause 11 describes the measurement procedure, including filtering and database requirements, and sensor output and ancillary system requirements needed for monitoring measurements during the SMC.

Clause 12 provides the minimum requirements for reporting that are specific to NMLs (the overall requirements for reporting are provided by the use case).

6 Lidar requirements

6.1 Functional requirements

For compatibility with this document, the nacelle-mounted lidar shall meet at least the following functional requirements:

1) The lidar shall report at least one of the following:
    a) reconstructed horizontal wind speeds, wind directions relative to the lidar optical axis and an estimate of the turbulence intensity;
    b) intermediate values from which horizontal wind speeds, directions and an estimate of the turbulence intensity can be reconstructed;
2) LOS speeds shall be available to support the calibration procedure.
3) The lidar shall be equipped with one or more inclinometers to measure the angles required for the WFR algorithm with a sampling rate greater than or equal to the horizontal wind speed reconstruction rate.
4) Measurements of tilt and roll angles (and any other parameters required for WFR) shall be reported in the data stream.
5) The lidar shall be able to measure at one or more known distances (ranges) in front of the rotor. The measurement distance shall fulfil the requirements of the use case. (For example, for power performance measurements compliant with IEC 61400-12-1:2017, this distance should be between 2 and 4 times the rotor diameter of the WTG being tested, with distance measured from the rotor plane.).

6) Lidar measurement data shall have an accurate timestamp (± 2 s) with respect to a known reference. Such time references can be provided by GPS or by the host turbine's time reference.
7) It shall be possible to align the measurement equipment to within 1-degree standard uncertainty in the yaw degree of freedom.
8) The lidar shall report a data quality control code.
9) The above parameters shall be available at least as 10-min statistics.

6.2 Documentary requirements

6.2.1 Technical documentation

To provide the technical information required to support the calibration, sensitivity of uncertainties, and the operation of the lidar, the following shall be documented:

1) the means of measuring the LOS speed (e.g. continuous or pulsed coherent Doppler lidar);
2) the lidar probe length – L_{probe} as defined in 3.19;
3) the number of beams – The number of beams is defined by the number of possible optical paths in a system. An optical path is defined by the succession of optical components crossed by the light from the source to the atmosphere.

   For example, a device with beam originating from a single laser source switched or split to different paths (e.g. different telescopes) of parallel design is considered a multi-beam device. A device with a beam originating from a single laser source and oriented in various directions using a moving prism or mirror is considered a single-beam device;
4) whether the lidar operates with a fixed-beam geometry, a fixed scanning pattern or a programmable scanning pattern;
5) a description of the beam geometry or scanning pattern including relevant angles and angle tolerances;
6) the internal coordinate system, including the sign convention;
7) the rate of scanning, meaning the time between completed executions of the entire scanning pattern;
8) for scanning lidars, estimate of the dynamic position uncertainty (see 7.2.2);
9) whether the instrument measures at single or multiple ranges, and in the latter case, the temporal sequence of the different ranges (e.g. one range per 10-min interval, sequential switching between ranges within a 10-min interval or acquisition of data from multiple ranges during each measurement within a 10-min interval);
10) the means by which the instruments discriminate between various ranges (e.g. focusing or range-gating);
11) a general description of the method of calculating the horizontal wind speed, relative wind direction and estimate of the turbulence intensity from the measured LOS speeds (the WFR method);
12) information on how the estimate of the turbulence intensity relates to a point measurement of turbulence intensity (e.g. as measured by a cup anemometer);
13) the rate at which reconstructed horizontal wind speeds and wind directions are available in the data stream or in the recorded data;
14) how the quality control code should be interpreted;
15) a technical description of the inclinometer(s) used in the instrument and their measurement principle (e.g. if it is an accelerometer or gyroscopic sensor). This documentation should at least cover measurement range, resolution, accuracy and sampling rate;
16) the current firmware version of the unit;
17) the list of known environmental and operational limitations of the unit (e.g. inclination, temperatures, etc.).

6.2.2 Installation and operation documentation

To support the installation and operation of the lidar on a WTG, the documentation shall also describe:

1) the dimensions and weight of the main lidar components and their mounting arrangements;
2) the power requirements and consumption of the lidar;
3) the full process used to mount the lidar on the WTG nacelle including a list of permanent modifications that may need to be made to the WTG;
4) the system and/or process used to align the lidar optical axis with a projection of the rotor axis onto the horizontal plane;
5) the details of any cabling required;
6) data connection requirements;
7) clock synchronisation requirements;
8) requirements of other resources or consumables, such as screen washer fluid;
9) any procedures to ensure eye safety or certification demonstrating that no such procedures are necessary.

7 Calibration and uncertainty of nacelle lidar intermediate values

7.1 Calibration method overview

The methodology entails calibrating the inputs to the lidar's WFR algorithm. The process is divided into five steps: the first three concern the calibration of the beam position quantities (beam trajectory, inclinometers, and measurement range), and the last two consist in calibrating the LOS speed, V_{LOS}, and assessing its uncertainty, $u_{V_{\mathrm{LOS}}}$. The procedures to calibrate the quantities describing the beam position are specific to the lidar technology and the particular geometry/trajectory of the lidar beam. The calibration and assessment of the uncertainty of V_{LOS} are more generic, but the details (particularly the determination of beam position) may well still depend on the exact nature of the lidar technology.

The determination of beam position requires accurately positioning and detecting the lidar beam(s), which is achieved by either:

- visualizing the laser beam with e.g. an infrared sensitive card or infrared camera, or;
- performing a hard target test. A hard target test consists of blocking the beam with a reflective surface, and then measuring the target's position. When the beam is blocked, the level of the signal measured by the lidar is extremely high compared to when the beam is not blocked. For homodyne lidars a moving target is necessary since zero speed is undetectable.

The calibration of the nacelle lidar shall be performed for every lidar unit before the start of the SMC. The duration of the period for which the calibration is considered valid and the number of SMCs allowed within that period shall be determined by the guidance associated with the use case and by the advice of the manufacturer. Any change in e.g. optical components or firmware that affects the measurements requires a new calibration.

7.2 Verification of beam trajectory/geometry

7.2.1 Static position uncertainty

7.2.1.1 Method

The angles defining the beam geometry (for fixed-beam-geometry lidars) or the beam trajectory (for scanning lidars) shall be measured as follows:

- for fixed-beam-geometry lidars: angles between various LOSs;
- for fixed-pattern- and programmable-scanning lidars: values of the angles characterizing the scanning trajectory (e.g. cone angle for fixed-pattern conically scanning lidar; azimuth and elevation angles for programmable-scanning-lidar).

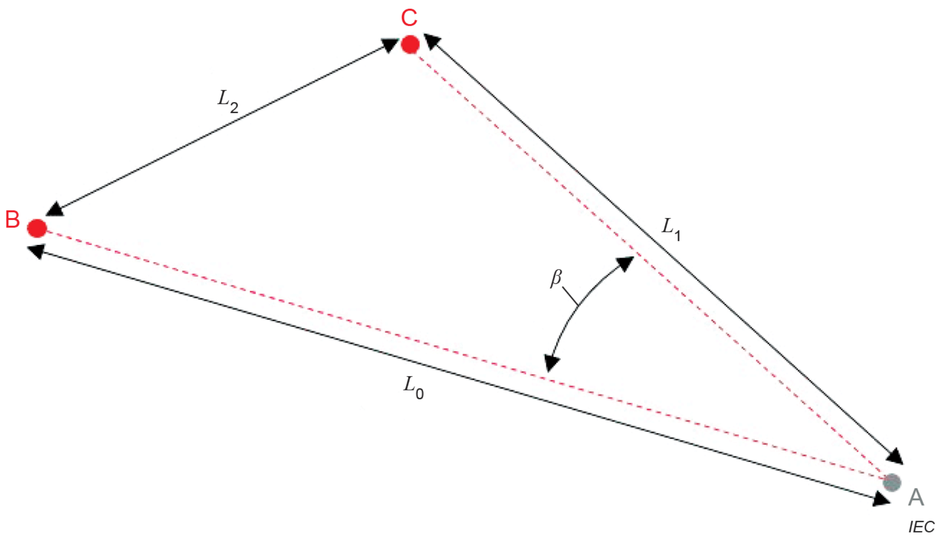
The uncertainty of the measured angles shall be stated. The test results (measured angles and their uncertainties) shall be compatible with the values and tolerances stated in the manufacturer specifications (technical documentation provided according to 6.2.1 (item 4)).

7.2.1.2 Example

An example of beam geometry verification is given in Figure 1 for a two-beam (fixed-beam-geometry) nacelle lidar. In this case, the verification of beam geometry consists of verifying the angle β between the two LOSs (see Figure 1). The distances L_0, L_1, L_2 are measured (e.g. using a theodolite). The angle β between the two beams in Figure 1 is given by:

$$\beta = \text{acos}\left(\frac{L_0^{\ 2} + L_1^{\ 2} - L_2^{\ 2}}{2 L_0 L_1}\right) \tag{2}$$

The uncertainty of the measured angle is derived from the uncertainty of measurements of L_0, L_1 and L_2.



NOTE Point A represents the beam origin and L_0 and L_1 are the distances to the detected beam positions B and C.

Figure 1 – Example of opening angle β between two beams

7.2.2 Dynamic position uncertainty

For a scanning lidar, when it is measuring whilst the beams are in motion (or moving rapidly and then stopping), there will be an additional position uncertainty due to the inability of the motion control system to provide the exact position. This uncertainty is termed dynamic position uncertainty. In addition to the static measurement of the opening angles and uncertainties of these measurements, the dynamic position uncertainty for the trajectory shall be quantified or provided.

7.3 Inclinometer calibration

The purpose of the inclinometer calibration is to establish the relationship between the lidar inclinometer indications of tilt angle ($\tau_{\text{indicated}}$) and roll angle ($\rho_{\text{indicated}}$), and reference measurements (τ_{measured}, ρ_{measured}).

The procedure consists of:

1) reading the indicated inclinometer position values, $\tau_{\text{indicated}}$, $\rho_{\text{indicated}}$;
2) measuring the distance and height difference of the beams' position relative to the beams' origin (e.g. using a theodolite);
3) deriving the tilt and roll angles, τ_{measured}, ρ_{measured} , and comparing them to the inclinometer values.

This procedure should be repeated for combinations of at least five different values of $\tau_{\text{indicated}}$ and at least five different values of $\rho_{\text{indicated}}$. The calibration range should cover as much as possible of the range of tilt and roll angles values expected during the SMC. The calibration range shall be reported.

The uncertainty of the measured tilt and roll angles shall be stated.

Annex B presents a suggested methodology for field measurements of tilt and roll angles for the example of a 2-beam lidar.

7.4 Verification of the measurement range

The measurement range shall be verified using one of the following methods:

- Visual observation of the backscatter levels at different ranges, from a target of known position.
- Performing a statistical analysis of the LOS speed calibration data: the lidar is configured to several ranges around the distance at which a reference instrument is located. The correlations between the reference wind speed and the LOS speeds measured at the different ranges are analysed. The highest correlation is expected at the range closest to the reference instrument.
- A focus calibration method (for a homodyne lidar with a fixed or variable focus), for example, by measuring the beam diameter as a function of distance along the LOS or by measuring the strength of the lidar return signal scattered from a moving target at a fixed calibration range as the lidar focus is adjusted.

It is recommended that the verified range is close to the measurement range used in the LOS speed calibration (see also 7.5.4 regarding calibration range recommendations).

The verification of the measurement range shall be performed for every beam. The uncertainties shall be reported.

7.5 LOS speed calibration

7.5.1 Method overview

The purpose of this calibration is to establish the relationship between the lidar-measured wind speed in one LOS, V_{LOS}, and a reference speed along the LOS, V_{ref}, obtained from traceably calibrated reference instruments. The reference speed is measured at the focus point for a CW lidar, or at the centre of the probe length for a pulsed lidar.

For this purpose, the lidar is installed at a test site according to requirements described in 7.5.2, in a setup according to 7.5.3 and the lidar measurement range is configured as described in 7.5.4. The LOS speed calibration procedure is described in 7.5.5 to 7.5.7.

V_{ref} is the projection of the wind velocity onto the LOS, and in its most general form is expressed as

$$V_{\mathrm{ref}} = V_{\mathrm{hor}} \cdot \cos\varphi \cdot \cos\left(\theta - \theta_{\mathrm{los}}\right) + W \cdot \sin\varphi \quad (3)$$

where

V_{hor} is the horizontal wind speed, measured by the wind speed reference instrument;

φ is the elevation angle of the lidar beam from horizontal plane (see Figure 4);

θ is the wind direction, measured by the wind direction reference instrument;

θ_{los} is the LOS direction;

W is the vertical wind speed, measured by a reference instrument.

Since in flat terrain the vertical component of the wind velocity is normally much smaller than the horizontal component ($W \ll V_{\mathrm{hor}}$), with a small elevation angle and small inflow angles (e.g. between −2° and +2°), the impact of the contribution of the vertical component can be neglected, and formula (3) can be written as:

$$V_{\mathrm{ref}} = V_{\mathrm{hor}} \cdot \cos\varphi \cdot \cos\theta_{\mathrm{r}} \quad (4)$$

where $\theta_{\mathrm{r}} = \theta - \theta_{\mathrm{los}}$ is the wind direction relative to the LOS, i.e. the difference between the wind direction and the LOS. V_{ref} as expressed in formula (4) is the reference wind speed used in the following subclauses. Note: The definition of V_{ref} in equation (4) requires vector averaging of the measurements of V_{hor} and θ.

The LOS speed calibration shall be performed for every beam.

7.5.2 Calibration site requirements

7.5.2.1 Definitions

The lidar is set to measure at a range immediately adjacent to the mast-mounted reference sensor (see 7.5.3). The horizontal distance between the lidar and the reference is L_{ref}. The height of the reference sensor over the terrain is H_{ref}. The lidar probe length is L_{probe} with the middle of this length adjacent to the measurement sensor (note that the lidar also senses wind before and beyond the probe length, see 3.19). The reference plane is a horizontal plane passing through the base of the reference mast. Terrain height $z(r)$ is measured from this plane (where r is the horizontal distance from the met mast in the beam direction). Figure 2 provides a schematic representation of this calibration setup.

Two specific areas have particular requirements given below, as shown in Figure 3. The sensing area is a disk parallel to the reference plane, centred at the reference sensor, with diameter $2L_{\text{probe}}$. The inflow area is a sector defined by the wind direction sector used in the calibration with radius $L_{\text{ref}} + 15L_{\text{probe}}$ and apex at the nacelle lidar.

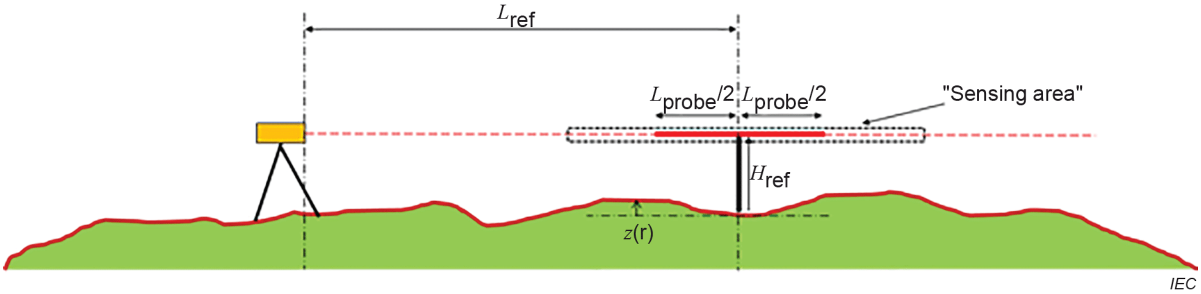


Figure 2 – Side elevation sketch of calibration setup

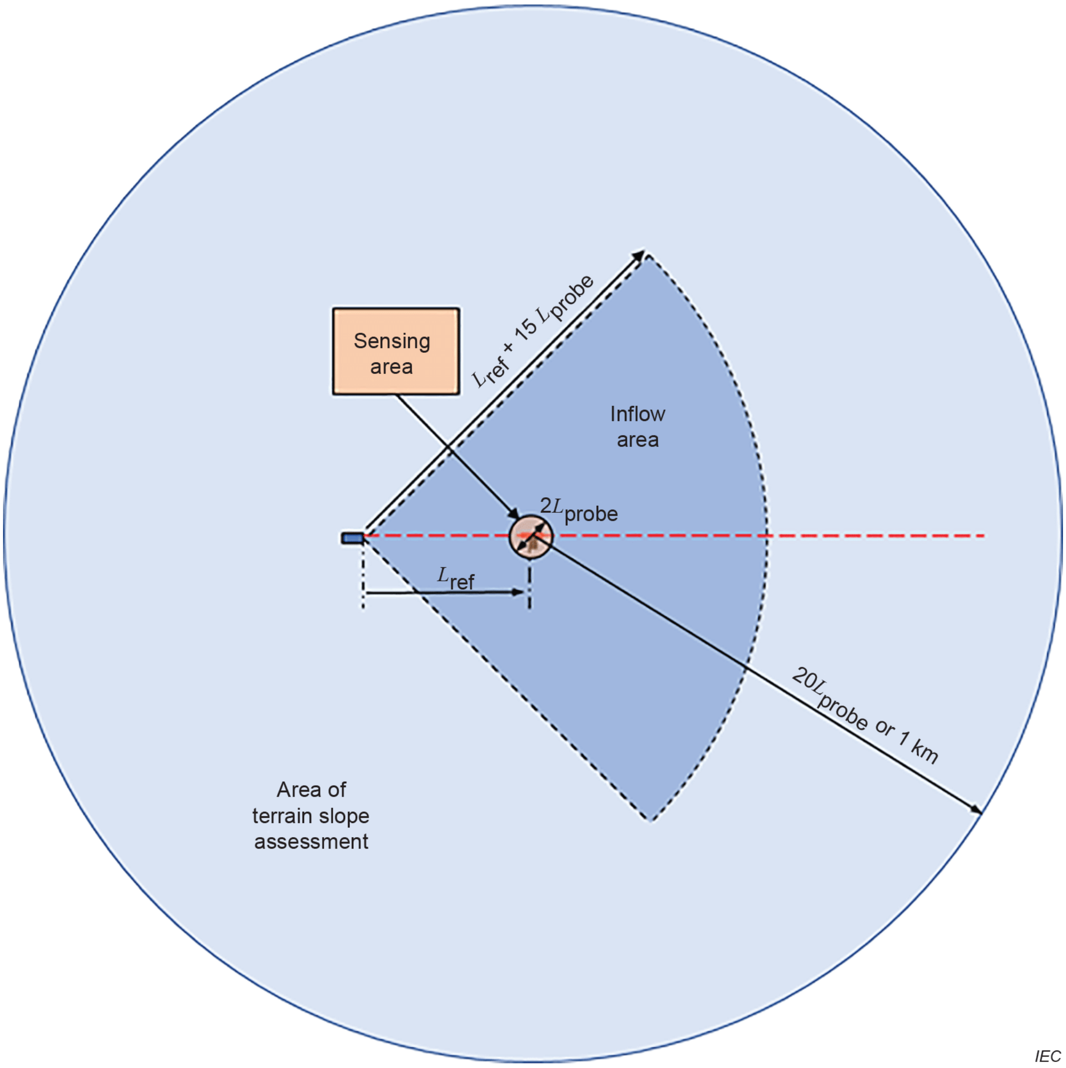


Figure 3 – Plan view sketch of sensing and inflow areas

7.5.2.2 Terrain requirements

The calibration site shall be flat and fulfil the following requirements:

- Terrain slope: inside a circle centred on the middle of the probe length and with radius 1 km or $20L_{probe}$ (the maximum value of these two), a plane is fitted to a digital terrain model with a resolution of 30 m or finer. The plane slope shall not exceed 1 %.
- Mean terrain slope: for each point inside the inflow area, but outside the sensing area, a slope, s, is calculated as: $s = z / d$, where z is the terrain height relative to the reference plane, and d is the horizontal distance between the terrain point and the calibration mast. It is recommended to use a digital terrain model with a resolution of 30 m or finer. The absolute value of the mean of the terrain slope, s, shall not exceed 1 %.
- Height variation:
  - within the sensing area, the terrain height, z, must not vary by more than $\pm H_{ref} / 20$, i.e.

$$\left| \max z - \min z \right| \leq H_{ref} / 20 .$$

  - within the inflow area but outside the sensing area, height variations may not exceed these limits:

$$\left|\max z\right| \le H_{\text{ref}} / 10$$

$$\left|\min z\right| \le H_{\text{ref}} / 10$$

where the terrain height at the calibration mast position is $z = 0$.

7.5.2.3 Roughness changes

There should be no major roughness change (land use or land type change) within the inflow area.

7.5.2.4 Obstacles

No obstacles (including trees and bushes) are permitted that can cause significant wakes or partial wakes in the sensing area. The significance of the obstacle is determined by its height, as follows:

- Inside the sensing area, an obstacle is considered significant if the obstacle's height is greater than $H_{\text{ref}} / 10$.
- Inside the inflow area and outside the sensing area, an obstacle is considered significant if the obstacle height is greater than h, where $h(r)$ is a linear function of the distance r to the calibration mast, defined as

$$h(r) = \frac{H_{\text{ref}}}{10}\left(\left(r - L_{\text{probe}}\right)\frac{1}{6L_{\text{probe}}} + 1\right) \quad (5)$$

so that:

$h\left(r = L_{\text{probe}}\right) = H_{\text{ref}} / 10$,

$h\left(r = 15\ L_{\text{probe}}\right) = H_{\text{ref}} / 3$.

Significant obstacles are permitted if the distance to any measurement point (reference sensor or part of lidar probe volume) is larger than 20 rotor equivalent diameters D_{e}, with

$$D_{\text{e}} = 2 * \frac{l_{\text{h}} * l_{\text{w}}}{l_{\text{h}} + l_{\text{w}}} \quad (6)$$

where l_{h} and l_{w} are the height and width of the obstacle, respectively.

For example, a second met mast with a side length of 0,2 m and a height of 30 m has an equivalent diameter of 0,4 m and must hence keep a distance of at least 8 m from the other mast.

7.5.3 Setup requirements

The lidar shall be installed on the ground or on a stiff elevated platform. The design of the support and platform shall prevent deflection of the lidar exceeding ±0,1° or a maximum height variation between the LOS and reference instrument of ±1 % of the reference height (the minimum value of these two).

The beam to be calibrated shall be accurately pointed towards the reference instruments, which are mast-mounted. The reference instruments used for measuring V_{hor} and θ 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 instruments shall include:

- one cup or 3D sonic anemometer for V_{hor} measurements;
- one 3D sonic or vane for θ measurements (for determining the relative wind direction θ_r);
- a secondary wind speed and direction measurement for quality control of the primary instrument;
- a measurement of inflow angle or vertical wind speed (for filtering).

Optionally, the reference instruments should also include (recommendation):

- a horizontal wind speed measurement at a different height, for shear measurements (same type as the primary V_{hor} sensor);
- a temperature sensor, to filter out data below a given temperature threshold, to discard data affected by ice accumulation or bearing friction drift on the reference sensors. Alternative sensors or methods to detect failure or degradation of the reference instruments due to icing are not excluded, but shall be described in the lidar calibration report;
- pressure and humidity sensors may be required to determine sensitivity of calibration to environmental variables, and/or to check that the V_{hor} sensor is within class limits.

The sensors shall be installed in one of the following ways:

- on the same mast, either on:
  - a single top-mounted arrangement (IEC 61400-12-1: 2017, G.2),
  - a side-by-side top-mounted arrangement (IEC 61400-12-1: 2017, G.3), or
  - a side-mounting arrangement following IEC 61400-12-1: 2017, G.4 and the following stricter requirements:
    i) Since the anemometer will be influenced by the presence of the mast, the mounting boom, and possibly the guy wires, a second anemometer at the same height shall be used to derive a mast blockage correction, following Annex S of IEC 61400-12-1:2017.
    ii) The minimum distance of the anemometer to the centre of the met mast shall ensure that the mast influence on the anemometer wind speed readings shall remain less than 1 % for the whole measurement sector.
    iii) The height difference between the wind direction and the wind speed sensors shall not be greater than 2 m.
- on two separate masts, each of them a single top-mounted arrangement (IEC 61400-12-1:2017, G.2), where the reference wind speed and wind direction sensors are at the same height. The horizontal distance between the two masts shall not be greater than 10 m.

Finally, the calibration layout shall ensure that the presence of the mast will not significantly affect the flow through the lidar probe volume being calibrated (e.g. the wake of the cup anemometer, mast or boom should not influence wind conditions in the probe volume), for the range of wind directions in the measurement sector used during the calibration campaign.

The beam elevation angle from the horizontal plane φ should be as small as possible, and it shall not be greater than 10°.

The beam should be located close to the reference speed anemometer. The beam height shall be within 1 % of the reference anemometer height, and within a horizontal distance of 2 to 5 m from the reference speed anemometer. The beam position and its uncertainty shall be reported.

7.5.4 Calibration range

The measurement setup of a lidar calibration should be as close as possible to the measurement setup in its later application.

The measurement range, R_{conf}, is defined as the distance between the lidar and the plane orthogonal to the optical axis (e.g. the axis of symmetry of the lidar trajectory, if it exists), such that

$$R_{conf} = R \cdot \cos\delta \quad (7)$$

where

R is the distance along the LOS (not the horizontal distance) from the laser beam origin to the reference instrument. $R = L_{ref}\cos\varphi$, where L_{ref} is the horizontal distance between the laser beam origin and the reference instrument and φ is the elevation angle of the laser beam (for the calibrated LOS);

δ is the angle between the optical axis and the LOS being calibrated.

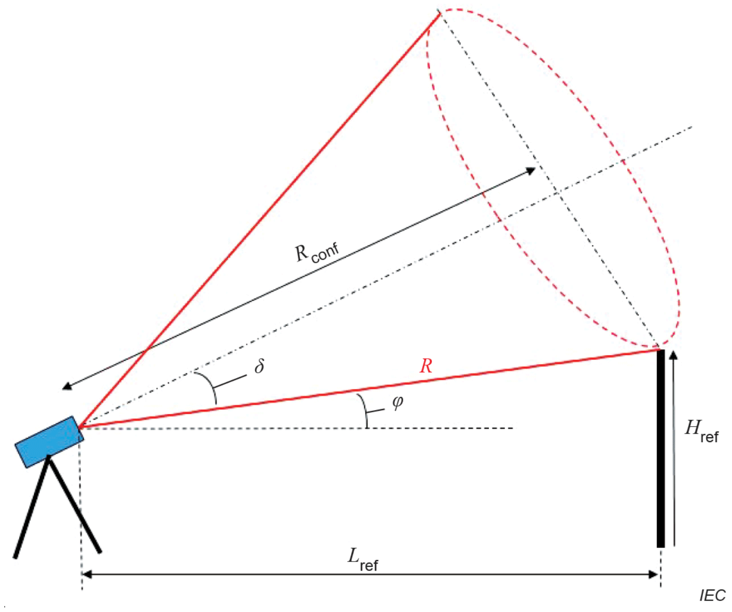


Figure 4 – Sketch of a calibration setup

7.5.5 Calibration data requirements and filtering

The definition of V_{ref} (formula (4)) is based on 10-min vector average measurements of V_{hor}, θ and $\varphi V_{hor}\sin\theta V_{hor}\cos\theta$. The dataset for the analysis shall be filtered according to the following criteria:

- V_{hor} shall be within the range for which the anemometer was calibrated (typically, between 4 m/s and 16 m/s);
- θ shall be within a contiguous sector around the LOS ($\theta_{LOS} \pm 40°$ or smaller is recommended). The sector limits shall be decided on the basis of the site characteristics (see 7.5.2), direction sensor geometry, and directions free of flow perturbations from obstacles at the site. A narrow sector corresponds well to normal operational conditions of NMLs, since the wind direction relative to the turbine yaw position is usually small. However, a narrow sector will usually increase the time required to perform the calibration.

- There shall be sufficient quality and quantity of data within the averaging period. Filters based on e.g. V_{LOS} availability and/or CNR above threshold should be applied. The specific metric and threshold depend on the lidar type and the aerosol distribution at the site.
- For LOS selection in scanning lidars the lidar LOS shall be within a given azimuth and/or elevation sector;
- Periods during which failure or degradation of the measurement equipment occurred (e.g. due to icing) shall be discarded.
- It can be shown that the relative error of the LOS speed due to the inflow angle ϵ_{V} is given by

$$\epsilon_{\mathrm{V}} = \tan\psi \tan\varphi \qquad (8)$$

  where ψ is the wind inflow angle and φ is the beam elevation angle. The inflow angle shall be filtered such that the magnitude of ϵ_{V} will not exceed 0,002. Filtering according to the inflow angle is also recommended regardless of the lidar beam elevation angle if the accuracy of the horizontal wind speed measurement (V_{hor}) decreases with increasing inflow angle.

The lidar measurements and the reference instrument(s) shall be synchronised in time. A synchronisation tolerance of ±1 %, i.e. ±6 s for 10-min averaging intervals, is acceptable according to IEC 61400-12-1:2017.

Data shall be collected until the requirements defined in 7.5.7 are satisfied.

7.5.6 Determination of LOS

7.5.6.1 General

The LOS shall be evaluated. This may be done in two steps. First, the lidar response to the wind direction is fitted to a function in order to retrieve an approximate LOS. Next, a process based on residual sum of squares (RSS) is applied, yielding the final value of the LOS. The advantage of this method is that the θ_{LOS} values are obtained in the frame of reference of the reference wind direction sensor.

7.5.6.2 Fitting the lidar response to wind direction

The first approximation of the LOS is evaluated by fitting the normalised lidar LOS speed ($V_{\mathrm{LOS,norm}}$) to a function of the wind direction (θ). In this analysis, all wind direction sectors are valid except for site related specifications (e.g. tower shadow, obstacles, wakes from neighbouring turbines, etc.). The normalised LOS speed is:

$$V_{\mathrm{LOS,norm}} = \frac{V_{\mathrm{LOS}}}{V_{\mathrm{hor}} cos\varphi} \qquad (9)$$

The fitting function f_{fit} is:

- a cosine for a heterodyne lidar: $f_{\mathrm{fit,1}} = A_1 \bullet \cos(\theta - \theta_0) + B_1$;
- a rectified cosine for a homodyne lidar: $f_{\mathrm{fit,2}} = A_2 \bullet \left|\cos(\theta - \theta_0)\right| + B_2$.

The fitting process yields best estimates of $A_{1,2}$ $B_{1,2}$ and θ_0. Ideally $A_{1,2} = 1$ and $B_{1,2} = 0$. θ_0 is the estimate of θ_{LOS}. Figure 5 shows an example of normalized wind speed vs direction and the results of a cosine fit.

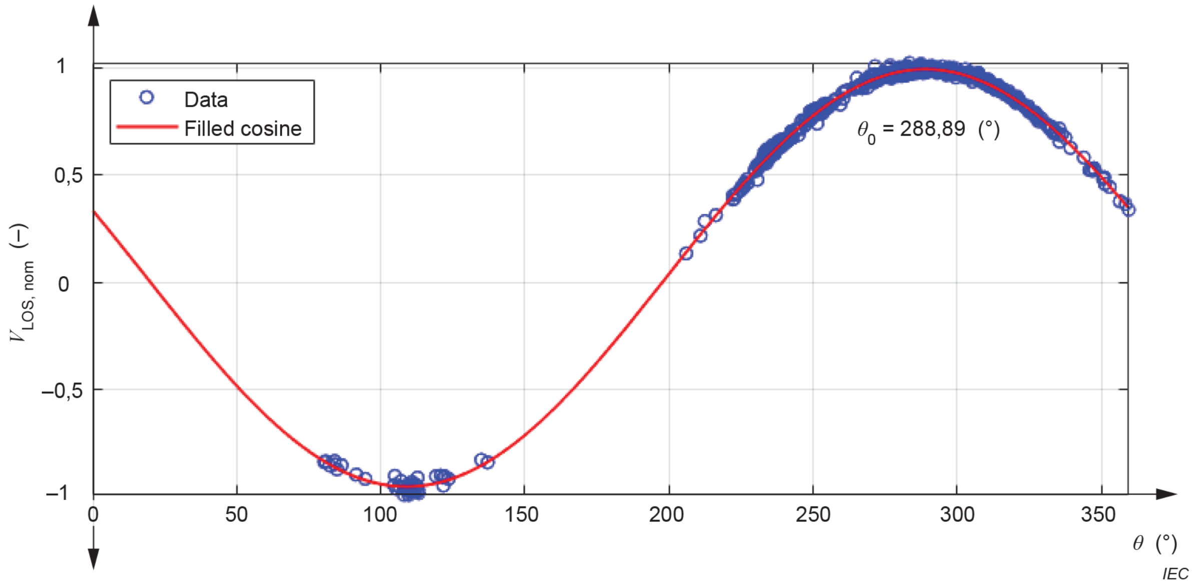


Figure 5 – Example of lidar response to the wind direction and cosine fit

7.5.6.3 Refining the estimated LOS using residuals

A statistical process is used to refine the estimation of θ_{LOS}:

1) For 20 values of $\theta_{proj}\left(\theta_{proj,i}; i = 1,\ldots,20\right)$ centred around θ_0 with an increment of 0,1°:

   a) Evaluate $V_{ref,i}$ for all 10-min data, as:

$$V_{ref,i} = V_{hor} \bullet \cos\varphi \bullet \cos\left(\theta - \theta_{proj,i}\right); \quad (10)$$

   b) Perform a linear regression between V_{LOS} and $V_{ref,i}$

$$V_{LOS\_fit,i} = a\ V_{ref,i} + b; \quad (11)$$

   c) Evaluate $RSS_i = \sum_{k}^{N}\left(V_{LOS} - V_{LOS\_fit,i}\right)^2$.

2) Plot RSS_i vs $\theta_{proj,i}$ ($i = 1, \ldots, 20$).

3) Fit to a second-order polynomial (see example in Figure 6).

4) θ_{LOS} is the projection angle that provides the minimum RSS. This is the value to be used in the procedure described in the rest of Clause 7, in particular for the evaluation of V_{ref} according to formula (4): $V_{ref} = V_{hor} \bullet \cos\varphi \bullet \cos\left(\theta - \theta_{LOS}\right)$.

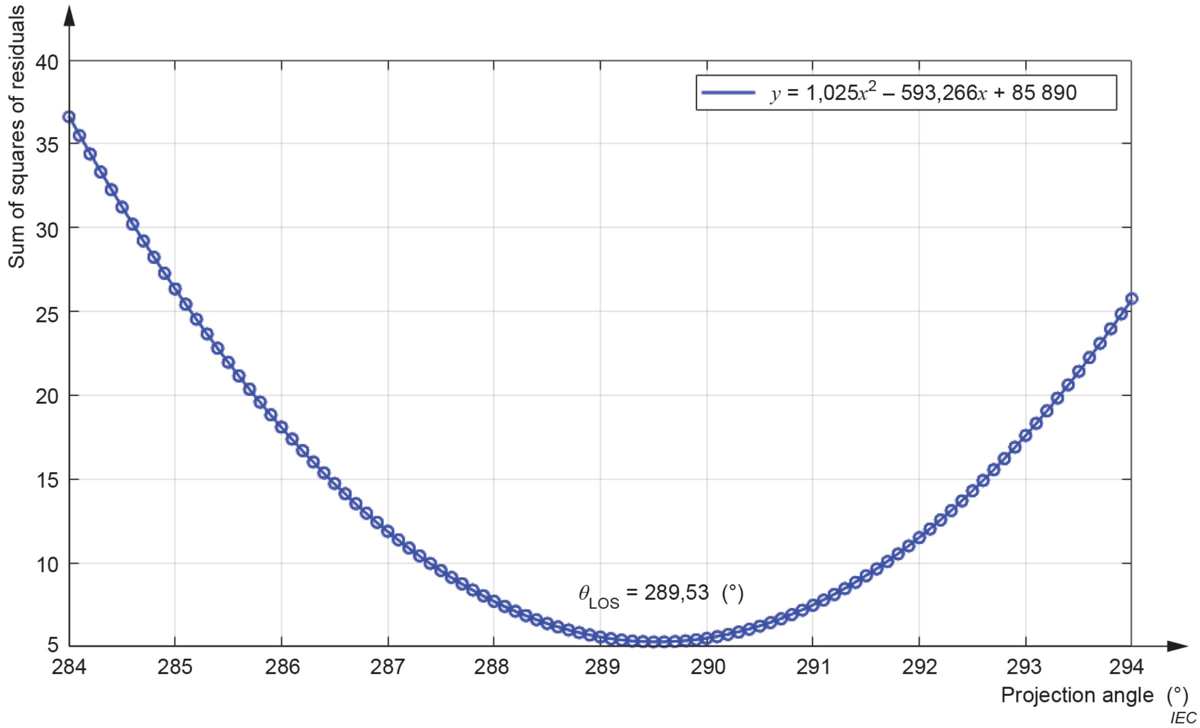


Figure 6 – Example of LOS evaluation using the RSS process: RSS vs θ_{proj}

7.5.7 Binning of data and database requirements

It is recommended to first make a scatter plot of V_{LOS} vs V_{ref} for the entire filtered 10-min dataset, in order to identify outliers visually, and investigate these as necessary. The valid data are then 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:

- 300 valid data points have been obtained from the calibration of each beam;
- all bins from 4 m/s to 12 m/s are complete. Note that the usual wind speed range of calibrations in wind tunnels is 4 to 16m/s. However, in nacelle lidar calibrations, it can be time consuming to obtain wind speeds greater than 12m/s in the specific LOS. Sometimes even completion up to 12 m/s might be difficult to achieve (e.g. low wind season). When that is the case, the calibration range may have to be reduced to 4 to 10 m/s. This must be reported as a deviation from this procedure. Furthermore, an extra uncertainty term shall be applied to the reconstructed wind speed.

7.6 Uncertainty of the LOS speed measurement

7.6.1 General

As the LOS speed is calibrated against V_{ref} , the uncertainty of V_{LOS} results from the combination of the uncertainty of V_{ref} , the statistical uncertainty of the deviation between V_{LOS} and V_{ref} and the uncertainty due to neglecting the vertical component of the wind in formula (4).

7.6.2 Uncertainty of V_{ref}

7.6.2.1 General

As expressed in formula (12), reference wind speed is a function of V_{hor} , φ , θ and θ_{LOS} (where $\theta_{\mathrm{r}} = \theta - \theta_{\mathrm{LOS}}$ is the wind direction relative to the LOS). In the most general case the uncertainties of these quantities can reasonably be assumed to be uncorrelated, and the combined uncertainty of V_{ref} can be expressed as:

$$u_{V_{\mathrm{ref}}} = \sqrt{\left(\frac{\partial V_{\mathrm{ref}}}{\partial V_{\mathrm{hor}}}\right)^2 u_{V_{hor}}^2 + \left(\frac{\partial V_{\mathrm{ref}}}{\partial \varphi}\right)^2 u_{\varphi}^2 + \left(\frac{\partial V_{\mathrm{ref}}}{\partial \theta_r}\right)^2 u_{\theta_r}^2} \tag{12}$$

The sensitivity coefficients are:

$$\frac{\partial V_{\mathrm{ref}}}{\partial V_{\mathrm{hor}}} = \cos\varphi \, \cos\theta_r \tag{13}$$

$$\frac{\partial V_{\mathrm{ref}}}{\partial \varphi} = -V_{\mathrm{hor}} \sin\varphi \, \cos\theta_r \tag{14}$$

$$\frac{\partial V_{\mathrm{ref}}}{\partial \theta_r} = -V_{\mathrm{hor}} \sin\theta_r \, \cos\varphi \tag{15}$$

The uncertainties and sensitivity factors may be calculated from bin-averaged values[1]. For angular quantities, the recommendation is to average the values of the angles, e.g. $\cos\left(\mathrm{avg}(\theta_r)\right)$.

All uncertainties are expressed as standard uncertainties with a unity coverage factor (k=1). In the case where the application requires expanded uncertainty, reference is made to E.2.2 of IEC 61400-12-1:2017.

7.6.2.2 Horizontal wind speed uncertainty

The uncertainty of V_{hor} is the combination of the reference wind speed sensor uncertainty and the uncertainty due to the fact that the reference sensor is not measuring exactly in the same volume as the LOS being calibrated:

$$u_{V_{\mathrm{hor}}} = \sqrt{u_{\mathrm{sens}}^2 + u_{\mathrm{pos}}^2} \tag{16}$$

The uncertainties of the reference sensor used to measure the horizontal wind speed shall be calculated according to IEC 61400-12-1:2017:

[1] In theory, it is more accurate to calculate uncertainties and sensitivity factors for all 10-min values and then average. The recommendation above is used for practical purposes to allow reproducibility of the uncertainty calibration results without requiring the data base.

$$u_{\text{sens}} = \sqrt{u_{\text{cal}}^2 + u_{\text{ope}}^2 + u_{\text{mast}}^2 + u_{\text{lgt}}^2 + u_{\text{daq}}^2} \tag{17}$$

where the uncertainty sources related to the reference wind speed sensor are as follows:

u_{cal} is the calibration uncertainty of the reference sensor used to measure V_{hor} – u_{cal} is generic and includes not only the pre-calibration uncertainty, but also the uncertainty related to the in-situ monitoring and/or the post-calibration of the sensor;

u_{ope} is the operational uncertainty of the reference sensor used to measure V_{hor} (also called classification);

u_{mast} is the uncertainty due to mounting of the reference sensor used to measure V_{hor};

u_{lgt} is the uncertainty related to the mounting of lightning finial, if there is one;

u_{daq} is the data acquisition uncertainty of the reference sensor used to measure V_{hor}.

The uncertainties due to the relative position and different measurement volume of the reference sensor compared to the calibrated LOS probe volume are expressed as:

$$u_{pos} = \sqrt{u_{\text{probe}}^2 + u_{\text{inc}}^2 + u_{\text{vert\_pos}}^2} \tag{18}$$

where

u_{probe} is the uncertainty due to the variation of the wind speed within the lidar probe volume. It results from the horizontal variation of the wind speed along the probe volume, which is mainly caused by terrain effects, and, in addition in the case of an inclined LOS, from non-linear wind shear in the height range covered by the probe length. It is recommended to estimate this uncertainty in dependence of the calibration height and the probe length. This uncertainty generally increases with decreasing calibration height and increasing probe length. In the case of an inclined LOS, the estimation of this uncertainty should also depend on the wind shear measured at the reference met mast. This uncertainty generally increases with increasing elevation angle of the LOS. As an alternative, u_{probe} can be estimated from calibrations performed at various measurement ranges around the range matching the reference met mast. A typical value for u_{probe} is 0,1 % for a horizontal LOS and 0.2 % for a tilted LOS.

u_{inc} is the uncertainty due to the inclined LOS and the measurement range.

The most significant error related to the LOS inclination (apart from alignment errors that are considered in $u_{\text{vert\_pos}}$) is caused by a measurement range error. Even if the LOS passes exactly past the reference sensor, the height at which a measurement is made will be wrong if there is a range error. Therefore, for an inclined LOS, a range error leads to a height error. Using a simple power law model the uncertainty due to inclination will be

$$u_{\text{inc}} = \alpha \frac{\sin\varphi \; u_{\text{range}}}{H_{\text{ref}}} V_{\text{hor}} \tag{19}$$

where α is the shear exponent, φ is the inclination angle, u_{range} is the range uncertainty and H_{ref} is the measurement reference height. u_{range} can be estimated from the measurement range verification (see 7.4).

Another uncertainty related to the range uncertainty is associated with the horizontal displacement of the centre of the probe volume relative to the position of the reference measurement. Terrain effects can cause differences in wind speed at both positions and can contribute to the uncertainty of the reference measurement. This uncertainty can be significant in the case of large range uncertainties compared to the calibration height and should be estimated similarly to the uncertainty of the probe length (u_{probe}).

$u_{\text{vert\_pos}}$ is the uncertainty due to the height difference between the reference sensor and the LOS (alignment error – Note that this uncertainty is also valid for a horizontal beam).

For example, 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:

$$u_{\text{vert\_pos}} = \alpha \frac{u_{\text{H}}}{H_{\text{ref}}} V_{\text{hor}} \tag{20}$$

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

There are three uncertainty sources in the vertical positioning:

- Height error resulting from non-ideal orientation of the lidar during installation. The uncertainty is significant especially in case of small calibration heights H_{ref}
- A possible systematic drift of the tilt angle of the lidar, e.g. due to systematic wind load or systematic drift in time. This uncertainty shall be evaluated on the basis of the change of the tilt inclinometer measurements of the lidar with wind speed and time. This uncertainty can easily dominate, especially for lidars mounted on platforms or with low calibration heights.
- vibrations of the lidar. This uncertainty is usually insignificant and may be ignored.

The sub components resulting from the first two sources shall be evaluated individually and shall be combined on the assumption that they are independent of each other.

7.6.2.3 Relative wind direction uncertainty

The uncertainty of the relative wind direction is

$$u_{\theta_r} = \sqrt{u_{\theta}^2 + u_{\theta_{\text{los}}}^2} \tag{21}$$

where

u_{θ} is the uncertainty of the wind direction sensor in the measurement sector. This uncertainty is calculated according to IEC 61400-12-1:2017, E.12 excluding north mark, boom orientation and magnetic declination uncertainties, since the LOS is calculated in the frame of reference of the sensor. This is therefore typically only the uncertainty resulting from residuals of the wind direction sensor calibration.

A second uncertainty source is the possible systematic drift of the tilt angle of the lidar during the calibration, e.g. due to systematic wind load or systematic drift in time. This uncertainty shall be evaluated based on monitoring the tilt angle of the lidar during the calibration. It shall be considered to be independent from the uncertainty of the inclination angle resulting from the installation of the lidar, i.e. both uncertainties shall be added in quadrature.

$u_{\theta_{\text{LOS}}}$ is the uncertainty of the determination of the LOS, related to the statistical evaluation of θ_{LOS}. For the method described in 7.5.6, this uncertainty is estimated to be 0,1°.

7.6.2.4 Beam elevation angle uncertainty

u_{φ} characterises the uncertainty of the angle used in the vertical projection of the horizontal wind speed onto the LOS. Its value is obtained from either:

- the inclinometer's calibration – for a test setup where the lidar is installed on a platform and the tilt inclinometer readings, in combination with the lidar height, are used to obtain the beam elevation value used in the projection or;
- the uncertainty of the direct measurement of φ – for a test setup where the lidar is installed on the ground or a very stable platform, and φ is obtained with a direct measurement (e.g. theodolite).

7.6.3 Flow inclination uncertainty

The vertical component of the wind vector is neglected in the evaluation of V_{ref} (according to formula (4)).The neglected term is treated as an uncertainty of V_{ref} due to flow inclination:

$$u_{\psi_i} = \text{W} \sin\varphi_i \bullet\!= V_{\text{hor}} \tan\psi_i \sin\varphi_i \tag{22}$$

where:

- u_{ψ_i} is the uncertainty of V_{LOS} due to flow inclination
- W is the vertical wind speed
- φ is the beam elevation angle
- V_{hor} is the horizontal wind speed
- ψ_i is the inflow angle, estimated as $\tan^{-1}(W / V_{\text{hor}})$. For the estimation of u_{ψ_i} the bin average of the inflow angle ψ_i can be used.

7.6.4 Uncertainty of the LOS speed measurement

The uncertainty of the V_{LOS} measurement is expressed for each wind speed bin as:

$$u_{V_{\text{LOS}}} = \sqrt{u_{V_{\text{ref}}}^2 + \left(V_{\text{hor}} \sin\varphi \cos\theta_{\text{r}}\right)^2 {u_{\psi_i}}^2 + \frac{\sigma_{\text{dev}}^2}{N}} \tag{23}$$

where

$u_{V_{\text{ref}}}$ is the uncertainty of the reference wind speed used in the calibration in formula (12);

σ_{dev} is the standard deviation of the difference $\Delta V = (V_{LOS} - V_{ref})$ in the bin (ΔV shall be calculated for each 10-min interval, and then its standard deviation (within the LOS speed bin) is computed);

N is the number of data in the bin;

u_{ψ_i} is the flow angle uncertainty (see 7.6.3).

All LOS calibration uncertainty components are summarised in Table 1, including their uncertainty type.

Table 1 – Summary of calibration uncertainty components

No.	Component	Type	Description
Reference anemometer			
1	Calibration uncertainty, u_{cal}	B	Calibration uncertainty of the reference anemometer sensor according to IEC 61400-12-1:2017
2	Operational characteristics, u_{ope}	B	Anemometer class according to IEC 61400-12-1:2017
3	Mounting, u_{mast}	B	Mounting uncertainty of the anemometer
4	Lighting finial, u_{lgh}	B	Uncertainty of the reference anemometer due to lightning finial
4	Data acquisition, u_{daq}	B	Data acquisition system uncertainty
Lidar probe length			
5	Site effects, u_{probe}	B	Horizontal wind flow variation within the lidar probe volume
Height error			**Measurement errors due to wind shear**
6	Installation, u_{vert_pos}	B	Height difference between reference anemometer and LOS due to installation of optical head
7	Measurement range, u_{inc}	B	Height difference between reference anemometer and LOS due to measurement range error
Relative wind direction, u_{θ_r}			
8	Reference wind direction sensor, u_{θ}	B	Deviation from linearity and other instrument uncertainties
	Determination of line of sight, $u_{\theta_{los}}$	B	Uncertainty following the procedure of 7.5.6
Projection error			**Errors in the angle used in projection**
9	Installation, u_{φ}	B	the inclinometers' calibration uncertainty or the uncertainty of the direct measurement of φ (e.g. theodolite)
10	Flow inclination, u_{ψ}	B	Uncertainty due to neglecting the contribution of $W \sin\varphi$
Calibration measurements			
11	Statistical uncertainty	A	$\sigma_{dev} / \sqrt{N}$

7.7 Calibration results

The average of the difference between V_{LOS} and V_{ref} in the bin, $\Delta V = V_{LOS} - V_{ref}$, shall be calculated for each bin. The calibration results shall be reported using the format in Table 2.

The nacelle lidar LOS speeds may be corrected based on the results of the calibration. The correction is mandatory if the bin-averaged deviation (ΔV) is greater than the uncertainty $u_{V_{\text{LOS}}}$ for any wind speed bin. The correction shall be based on a linear regression between the bin-averaged reference speed and the bin-averaged lidar LOS speed. If $|\Delta V| < u_{V_{\text{LOS}}}$, the correction of the LOS speeds is optional.

Table 2 – Calibration table example

i , bin number	V_{ref} (m/s)	V_{LOS} (m/s)	N	ΔV (m/s)	$\sigma_{\Delta V}$ (m/s)	$u_{V\text{ref}}$ (m/s)	$u_{V_{\text{LOS}}}$ (m/s)
7	4,04	4,13	13	0,10	…	0,05	…
8	4,51	4,57	20	0,06	…	0,06	…
9	4,98	5,05	31	0,07	…	0,06	…
10	5,45	5,51	12	0,06	…	0,07	…
11	5,98	6,08	22	0,10	…	0,07	…
…	…	…	…	…	…	…	…
23	12,01	12,05	30	0,04	…	0,12	…
24	12,47	12,58	6	0,11	…	0,12	…
25	12,95	13,01	14	0,06	…	0,12	…
26	13,53	13,63	20	0,11	…	0,13	…
27	13,95	14,01	12	0,05	…	0,13	…
28	14,49	14,56	7	0,08	…	0,13	…
29	15,01	15,05	5	0,04	…	0,14	…

When several LOS speeds have been calibrated, a table containing the uncertainties for all the calibrated lines of sight shall be part of the results. This table shall report in different columns the uncertainties that are correlated and uncorrelated, respectively, between different lines of sight. An example of the mandatory contents for the calibration of N lines of sight is given in Table 3. A detailed example for two lines of sight is presented in Annex A.

Table 3 – Calibration table example
(n=1…N; N is the total number of lines of sight calibrated)

i , bin number	$u_{\text{corr},1}$	$u_{\text{uncorr},1}$	…	$u_{\text{corr},n}$	$u_{\text{uncorr},n}$	….	$u_{\text{corr},N}$	$u_{\text{uncorr},N}$

$u^2_{\text{corr},n}$ is the quadratic sum of the uncertainty terms that are correlated between the beams for the n^{th} LOS.

$u^2_{\text{uncorr},n}$ is the quadratic sum of the terms that are uncorrelated between the beams for the n^{th} LOS.

7.8 Calibration reporting requirements

7.8.1 Report content

The calibration report shall provide the information listed in 7.8.2 to 7.8.6.

7.8.2 General lidar information

- lidar unit: model, year of manufacture, serial number, firmware identification, beam configuration, scan geometry;
- range gate(s);

7.8.3 Verification of beam geometry/trajectory (according to 7.2)

- definition of the angle(s), e.g. cone angle, half/full opening angle between two coplanar LOSs, etc.;
- description of the measurement setup;
- description of the method to measure the angle(s);
- description of the measurement equipment;
- table of results: measured angles, reported uncertainties and compatibility to the manufacturer specifications;

7.8.4 Inclinometer calibration (according to 7.3)

- description of the measurement setup;
- description of the method;
- description of the measurement equipment;
- table of results: indications of tilt angle ($\tau_{\text{indicated}}$) and roll angle ($\rho_{\text{indicated}}$), measured angles (τ_{measured}, ρ_{measured}) and reported uncertainties;
- plots of indicated tilt and roll angles vs measured tilt and roll angles;

7.8.5 Verification of the sensing range (according to 7.4)

- description of the measurement setup;
- description of the method;
- description of the measurement equipment;
- results of the range verification;

7.8.6 LOS speed calibration (for each LOS)

- site description (7.5.2), including panoramic pictures of the site;
- description of the measurement setup (7.5.3);
- description of the reference equipment, including: types and serial numbers of sensors, calibrations, sketch of met-mast arrangement;
- location of the lidar and lidar probe volume with respect to reference equipment;
- method of alignment of the LOS;
- description of the lidar settings, including measurement ranges (7.5.4), time base relative to UTC and method of synchronization with reference instruments;
- measured beam position, and uncertainty;
- data collection start and end times;
- description of filters applied to the measurement database (7.5.5);
- description of the method to determine the LOS, and the LOS obtained (7.5.6);
- calibration function for each LOS speed, with V_{ref} as the dependent variable (y), and V_{LOS} as the independent variable (x). The calibration function is an ordinary least square fit. The R^2 shall be reported as well;
- scatter and bin plots of V_{LOS} vs V_{ref} , and plots of (V_{LOS} vs V_{ref}) vs relevant variables (e.g. V_{ref} or TI);

- one figure including both plots of ΔV and $\pm u_{V_{\mathrm{ref}}}$ as a function of V_{ref} ;
- time series plot of lidar tilt and roll angles for each LOS calibration;
- table(s) with calibration results and uncertainties (7.7);
- table(s) with uncertainties for all the calibrated lines of sight, reporting in different columns uncertainties that are correlated and uncorrelated, respectively, between different lines of sight.

8 Uncertainty due to changes in environmental conditions

8.1 General

Calibration of a lidar (as in Clause 7) establishes the measurement uncertainty of wind speed measurements made by the device under a particular set of environmental conditions. Environmental conditions during the SMC will be different from those encountered during calibration, introducing further measurement uncertainty.

This additional measurement uncertainty is assessed by analysing the influence of environmental variables (EVs) on measurement accuracy. The process consists of two stages:

1) assessing the contribution to the uncertainty of measurement of the intermediate values due to changes in EVs (see 8.2);
2) establishing the range of operational conditions under which the EVs can be taken to have no influence on the WFR model (see 8.3).

This influence of EVs on measurement accuracy is expected to be characteristic of a specific model of lidar (hardware and software) and its configuration under defined operational conditions. The two-step process described above shall be applied to each lidar model.

8.2 Intermediate value uncertainty due to changes in environmental conditions

8.2.1 Documentation

The contribution to the uncertainty of measurement of each intermediate value due to changes in environmental conditions shall be assessed for each significant EV. The lidar manufacturer shall provide details of this assessment in a manner amenable to independent review.

8.2.2 Method

8.2.2.1 General

The method of assessment of each such uncertainty contribution will depend on the EV and the intermediate value. The assessment may be made experimentally, through laboratory testing, by simulation, or using theoretical analysis.

Each EV shall be assessed over a range covering at least the values expected or measured during the tests forming the evidence-base (see 8.3) that supports the adequacy of the WFR model. Where the uncertainty due to changes in an EV is assessed experimentally, such assessment may require more than one test to cover the required range of values.

8.2.2.2 Uncertainty assessment through sensitivity analysis

The contribution to the uncertainty of measurement of an intermediate value due to changes in environmental conditions may be assessed through a sensitivity analysis. The sensitivity of the accuracy of an intermediate value to an EV is defined as the rate of change of the error in the intermediate value to changes in that EV.

The associated contribution to uncertainty of the intermediate value is estimated by multiplying the sensitivity by a suitable range. If the EV is measured during both the calibration and the SMC then the absolute difference between the mean values of the EV may be used as that range. If the EV is not measured then the range used should be an estimate of the maximum range (such as that given in Table L.3 of IEC 61400-12-1:2017) divided by $\sqrt{6}$ (which is the product of the divisors in L.2.7 and L.4.4 of IEC 61400-12-1:2017).

8.2.2.3 Sensitivity test for LOS speed

The sensitivities of LOS speed to changes in EVs may be assessed through a sensitivity test similar to those described in L.2 of IEC 61400-12-1:2017 (although the definition of sensitivity in that document is slightly different to the one given above). In such a test, the LOS speed is compared to a reference wind speed measurement for a range of values of each EV. The following experimental conditions shall be fulfilled in such a test:

- The site and set up shall follow the requirements from 7.5.2 and 7.5.3. A minimum of 1 080 data points covering the LOS speed range from 4 m/s to 12 m/s with at least 5 data points in each bin (0,5 m/s width) is required;
- Where possible, the reference parameters shall be measured using reference sensors (not the lidar being tested). If the lidar reports a measurement of backscatter intensity, this may be used to assess aerosol density.

8.2.3 List of environmental variables to be considered

A minimal list of EVs to be considered is as follows:

- air temperature, pressure, relative humidity and density;
- cloud base height;
- aerosol density (as measured by backscatter intensity for example);
- turbulence intensity;
- linear wind speed variation within the lidar probe volume;
- non-linear (e.g. power law) variation of wind speed within the lidar probe volume;
- data availability within the 10-min period.

Note that not all of these EVs will affect every intermediate value (for example, the calibration accuracy of a tilt sensor is not expected to be sensitive to aerosol density). The list of EVs is not exhaustive and is extendable on the basis of a suitable technical rationale.

8.2.4 Significance of uncertainty contribution

If the contribution to the uncertainty of measurement of the intermediate value due to an EV is smaller than half the calibration uncertainty (k=1) as per Clause 7, that contribution may be considered negligible.

8.3 Evidence-base supporting the adequacy of the WFR

Independently from the sensitivity of the intermediate values, the WFR model may be sensitive to some EVs. As there is no simple or established way of evaluating such sensitivities, this document provides a criterion of non-sensitivity of the WFR model to EVs. This criterion is based on an evidence-base consisting of comparisons between wind speed measurements made by a nacelle lidar (final values, not intermediate values) and those made by an acceptable calibrated reference.

The evidence-base shall consist of a minimum of five tests in which satisfactory accuracy of the final values has been demonstrated. For at least two of these tests, the lidar under test shall be mounted on a normally-operating WTG. For the remainder of the tests, the lidar may be mounted on the ground or on a fixed platform.

A successful test consists of:

- at least 600 10-min averaged data points;
- at least 150 10-min data points above 8 m/s;
- at least 150 10-min data points below 8 m/s;
- for a test of a lidar mounted on the nacelle of a WTG:

  bin-wise mean deviations from the reference measurements shall fall within the uncertainty (coverage factor of k=1) of the reference measurement for all bins with a minimum of 6 pairs of 10-min data points;
- for a test of a lidar mounted on the ground or on a fixed platform:

  a single-parameter regression between the measurements shall exhibit a regression slope within 2 % of unity and a coefficient of determination (R^2) of at least 0,97.

Acceptable reference instruments for use in establishing the evidence-base include:

- cup anemometer with a class better than 1,7A or 1,7C installed and operated in compliance with IEC 61400-12-1:2017 (Clause 7), or
- ground based lidar calibrated and classified in accordance with IEC 61400-12-1:2017 Annex L, or
- a separate reference NML compliant with this document.

The following requirements apply to nacelle-mounted tests in the evidence-base:

- NML operation shall be limited to sectors for which measurements are not affected by operating WTGs or obstacles, as defined in 10.4.1 of this document;
- The terrain, for a given sector, shall comply with the requirements of Table B.1 from IEC 61400-12-1:2017 for both the WTG and WME positions (as further described in 10.4.2).

Each of the following requirements shall be fulfilled at least by one of the tests in the evidence-base:

- The lidar under test was mounted on a WTG with a rotor diameter within 30 % of the rotor diameter of the WTG in the new measurement campaign.
- The measurement range used in the test is within 0,5 rotor diameters (of the WTG used in the new measurement campaign) of the measurement range to be used in the new measurement campaign.
- The measurement height in the test is within 30 % of the hub height of the turbine in the new measurement campaign.

8.4 Requirements for reporting

The evidence-base supporting the assumption of zero contribution to measurement uncertainty due to environmental effects on WFR for a specific lidar in an SMC shall be cited. The sensitivities of the intermediate variables shall be documented.

The lidar manufacturer shall produce a sensitivity analysis report that contains as a minimum:

- lidar manufacturer name, model type and version number;
- date of report;
- report version history;
- author, reviewer and authoriser names;
- a description of the lidar;
- sensitivities for the EVs listed above;

- description of the method used to arrive at the values of the sensitivities;
- ranges of the variables within which the sensitivities are held to be valid;
- value of any additional sensitivities and their method of determination;
- summary of the evidence-base.

Should any measurement discrepancies be observed that indicate an incomplete evaluation of uncertainty, these shall be reported to the authors of the evidence-base and the sensitivity analysis report which shall be amended to:

- refine the description of the operational conditions to exclude those in which the discrepancy occurs, recompile the evidence-base, and if the evidence-base remains satisfactory, further restrict measurements to those supported by the new evidence-base;
- if the effect is limited to intermediate variables, accommodate the conditions in which the discrepancy occurs in the sensitivity analysis procedure by the inclusion of additional EVs.

9 Uncertainty of reconstructed wind parameters

9.1 Horizontal wind speed uncertainty

The uncertainty of the horizontal wind speed shall be estimated.

The calibration (according to Clause 7) and possible sensitivities to EVs (according to 8.2) provide the uncertainty of the intermediate values: LOS speed measurements along the various LOSs and the quantities characterising the lidar beam trajectory (inclination angles, angle between lidar optical axis and each LOS, cone angle, etc.).

The uncertainty of the horizontal wind speed at the desired measurement height is found by combining four terms (represented in Figure 7):

1) the uncertainty of the WFR algorithm output – the uncertainties of the intermediate values are combined through the WFR algorithm (see 9.2).
2) the uncertainty due to the WFR algorithm suitability, assumed to be 0 m/s if the conditions described in 8.3 are verified (see 9.3).
3) the uncertainty due to variation of the measurement height, either due to tilt and roll of the nacelle or terrain height variation or both (see 9.4).
4) the possible extra uncertainty due to lidar measurement inconsistacny (see 9.5).

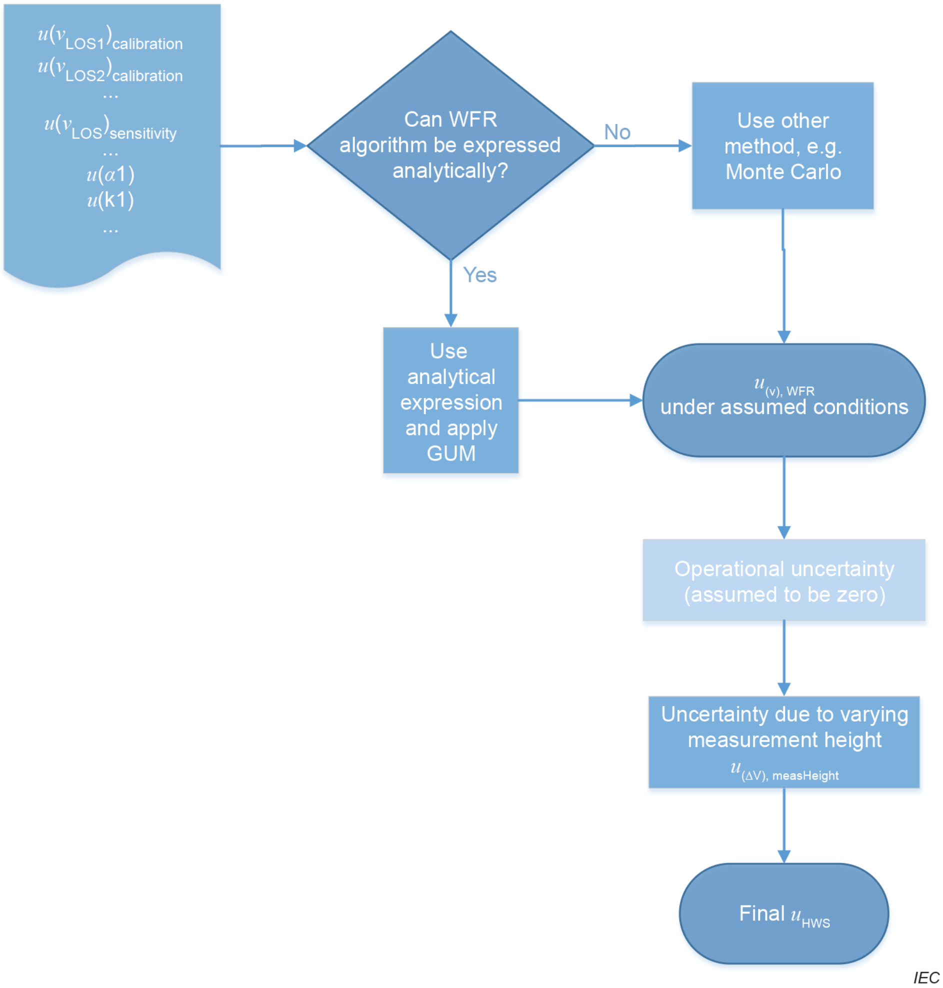


Figure 7 – High level process for horizontal wind speed uncertainty propagation

9.2 Uncertainty propagation through WFR algorithm

9.2.1 Propagation of intermediate value uncertainties $u_{\langle V \rangle,WFR}$

The uncertainty of intermediate values (derived according to Clause 7 and 8.2) is propagated to the horizontal wind speed through the reconstruction algorithm used during the SMC.

a) If the GUM (see JCGM 100:2008) is applicable (e.g. differentiable algorithm), the explicit equations or approximations should be used to propagate uncertainties of the intermediate values to the final variable uncertainties following the GUM methodology (see Annex A).

b) If the GUM is not applicable or the equations are not provided by the author of the algorithm, other uncertainty propagation methods shall be used (e.g. Monte Carlo method). In such a case, the author/owner of the algorithm shall provide:

- either the algorithm itself (e.g. in a readable script format) or an executable (DLL);
- the list of input quantities to the algorithm;
- the list of output quantities.

It is necessary to have an estimate of the uncertainty of all input quantities. If an input quantity can be calibrated (e.g. lidar tilt and roll angles), it shall be calibrated. If an input quantity cannot be calibrated, an uncertainty estimate should be provided (e.g. range uncertainty).

The calibration residuals shall be considered as an additional uncertainty component u_{residual} at the application of the lidar. The calibration residuals are defined as the bin-averaged deviation (ΔV_i) as per 7.7. If the LOS speeds are corrected based on the calibration results, the residuals shall be estimated as the differences between $V_{\mathrm{LOS},i}$ corrected by the calibration function, and $V_{\mathrm{ref},i}$ ("i" denotes the calibration bin index).

9.2.2 Uncertainties of other WFR parameters $u_{\mathbf{WFR,par}}$

If the reconstruction algorithm includes parameters other than the input quantities, the author of the algorithm shall indicate them and provide an estimate of the effect of their uncertainty for the final values. An examples of such parameters would be a parameter applied in the algorithm; Or, if a fit is used to optimise the reconstruction of the horizontal wind speed, uncertainty resulting from the fitting procedure should also be treated as a parameter.

9.3 Uncertainty associated with the WFR algorithm $u_{\mathbf{ope,lidar}}$

The horizontal wind speed measurement uncertainty arising due to the variations in the performance of the WFR algorithm under varying EVs needs to be considered. The purpose of 8.3 is to provide criteria for considering the model's assumptions to be acceptable such that no further uncertainty needs to be added. If the conditions described in 8.3 are verified, this uncertainty term is null.

9.4 Uncertainty due to varying measurement height $u_{\langle\Delta V\rangle,\mathbf{measHeight}}$

Every beam or LOS of a nacelle lidar probes the wind at varying heights above the ground due to one or both of the following mechanisms:

- The turbine nacelle tilting and rolling under the varying thrust and torque applied on the rotor by the wind, which makes the lidar beams tilt up or down or roll around the turbine rotor axis;
- The lidar following the yawing motion of the turbine nacelle such that, if the terrain is not perfectly flat or the turbine tower is slightly tilted, the height of the lidar beam above ground level changes.

It is recommended to correct for the measurement height variation (see 11.8) either as part of the WFR algorithm or during post processing. In any case, the uncertainty of the measurement height shall be accounted for.

- If the WFR algorithm provides the output of the final variables at the height required by the SMC, uncertainty estimation is undertaken as part of the propagation from intermediate to final values (9.2).
- If the WFR does not account for the actual measurement height, but the measurement height is corrected for in post-processing (see 11.8), the residual uncertainty from this correction shall be estimated and documented. See Annex A.4 for an example.
- If the measurement height is not corrected for, either in the WFR or in post-processing, the uncertainty shall be estimated as the maximum range of possible correction (e.g. assuming an exponential shear with a conservative shear exponent) to the reconstructed horizontal speed divided by the square root of three.

9.5 Uncertainty due to lidar measurement inconsistency

According to 11.9, if a deviation is observed during the measurement period, an additional uncertainty term shall be applied. The corresponding uncertainty assessment shall be described in the report.

9.6 Combining uncertainties

The above four (9.2.1, 9.2.2, 9.4, 9.5[2]) types of uncertainties can be considered as fully uncorrelated and shall be added in quadrature.

An example of the uncertainty estimation of the horizontal wind speed for a WFR using two LOSs is given in Annex A.

10 Preparation for specific measurement campaign

10.1 Overview of procedure

The requirements of the SMC (e.g. IEC 61400-12-1:2017 for power performance measurement) and their implications for NML measurements ought to be prepared before the start of the measurement campaign. This clause and Figure 8 describe the minimal requirements to be considered in this preparation.

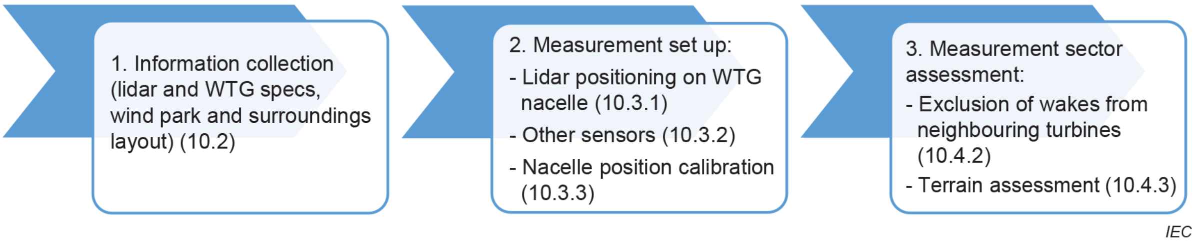


Figure 8 – Procedure flow chart

10.2 Pre-campaign check list

It is recommended to prepare a pre-campaign check list before starting the measurement campaign. This check list should address all the information required in Clause 12 (reporting format) to the extent it can be determined prior to the campaign.

Minimum, but not limited to, information contained in the check-list should be:

- documentary requirements (according to 6.2);
- lidar calibration certificate (according to Clause 7);
- lidar sensitivity analysis report (according to Clause 8);
- relevant information for installation of the lidar on the WTG (see 10.3.1);
- software change log with respect to the sensitivity analysis report;
- description and location of the additional sensors to be used during the measurement campaign if needed (see 10.3.2);
- measurement sector evaluation (exclusion of wake and obstacles, terrain assessment) according to 10.4;
- description of the measurement methodology (following the requirements for the SMC). In particular, special attention should be given to the time synchronization of the lidar data and turbine data (see 11.4).

2 If the consistency check is applied to the intermediate variables the related uncertainty should be propagated through the WFR algorithm according to 9.2.1.

10.3 Measurement set up

10.3.1 Lidar installation

The lidar shall be installed according to the lidar manufacturer's guidelines. Positioning and fixation of the various lidar parts (e.g. optical head and processing unit) on or in the nacelle should follow the WTG manufacturer recommendations.

It is recommended to consider at least the following points prior to the installation day:

- The location of the lidar with regard to the instrumentation on the turbine should be chosen so that the influences between these are minimized. It is recommended to make sure that the lidar optical head does not disturb the nacelle anemometer and wind vane. A minimum distance shall be respected. This should be defined with the WTG owner and manufacturer. A check of a change in turbine yaw misalignment can be achieved during the measurement campaign (see 11.2 and Annex D).
- The lidar measurement volume is determined by the lidar optical head position on the nacelle, the beam trajectory or beams geometry, and the tilt and roll angles of the lidar optical head. The following inputs are needed (see Annex C):
  - the horizontal distance from the lidar optical head to the rotor centre (reference for horizontal distances);
  - the height of the lidar optical head from the rotor centre;
  - the turbine nacelle tilt and roll angles (due to tower bending) as a function of the wind speed during WTG operation and at stand still.

  The information on the dimensions of the nacelle and the turbine tower bending can be provided by the WTG manufacturer or estimated through measurements in an initial phase.
- The lidar optical axis should be aligned with the horizontal projection of the rotor axis. In practice, this requires defining a reference line on the nacelle.

See Annex C for further recommendations and examples.

10.3.2 Other sensors

For some SMCs (e.g. power performance measurements and loads assessment), it is required to measure the air density.

In that case, an air pressure and temperature sensor shall be part of the measurement setup. A relative humidity sensor is recommended as per IEC 61400-12-1:2017.

The location of the instrumentation shall be selected in a way that ensures that the following individual conditions are met.

Air temperature and relative humidity (if measured) sensor(s) shall have a minimum impact from dissipated or radiated heat from the energy conversion process. To check this, a reference sensor may be placed in a second position.

The air pressure sensor shall be located in a position that ensures that the sensor is in contact with the atmosphere.

The sensors' mounting shall comply with the requirements from IEC 61400-12-2:2013, 7.4.

10.3.3 Nacelle position calibration

The nacelle position (yaw angle) shall be calibrated and the calibration shall be monitored for changes throughout the measurement campaign. The calibration shall take place according to the WTG operations manual or according to the instructions and procedure of the tester. The operational status and yaw calibration documentation of the WTG shall be reported as described in 12.4.

10.4 Measurement sector

10.4.1 General

A suitable measurement sector shall be defined taking the location of obstacles and the terrain topography into consideration.

10.4.2 Assessment of influence from surrounding WTGs and obstacles

The WTG where the lidar is mounted on and the lidar beam(s), at the measurement range, shall not be influenced by neighbouring WTGs or obstacles. The criteria for determining a significant obstacle (given its height and distance from the turbine where the lidar is mounted on) are identical to IEC 61400-12-1:2017, Annex A. The sector defined as in IEC 61400-12-1:2017, Annex A shall be restricted so that the lidar beam(s) (at any position within the trajectory/geometry) are never affected by the wake of a neighbouring turbine or obstacle (see Figure 9).

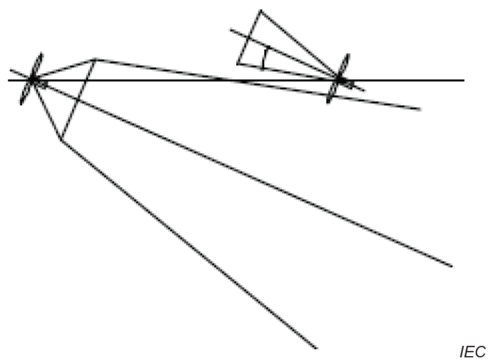


Figure 9 – Plan view sketch of NML beams upstream of WTG being assessed and neighbouring turbine wake

Obstacles shall be evaluated according to IEC 61400-12-1:2017, A.3 (Table A.1) replacing L for R_b with:

$$R_b = R_{conf} / \cos(\beta_{max} / 2) \quad (24)$$

where R_{conf} is the measurement range and β_{max} is the largest horizontal angle between any two beam positions within the beam(s) trajectory/geometry (full opening angle in this context).

The sectors to be excluded due to the wake of each neighbouring WTG or other obstacle shall be centred on their direction to the WTG where the lidar is mounted on. The width of the sector is given by the maximum between β_{max} and θ_{wake}, defined by formulae (25), (26) or (27) as appropriate (see Figure 10):

- If $L_n - R_b > 2D_n$ or $L_e - R_b > 2D_e$ (as appropriate), then:

$$\theta_{wake} = 1{,}3\tan^{-1}\left(2{,}5\frac{D_n}{L_n - R_b} + 0{,}15\right) + 10° \quad (25)$$

or

$$\theta_{wake} = 1{,}3\tan^{-1}\left(2{,}5\frac{D_e}{L_e - R_b} + 0{,}15\right) + 10° \quad (26)$$

- If $L_n - R_b \le 2D_n$ or $L_e - R_b \le 2D_e$, then:

$$\theta_{wake} = 1{,}3\tan^{-1}\left(1{,}4\right) + 10° = 80{,}8° \quad (27)$$

where

D_n is the rotor diameter of the neighbouring turbine;

D_e is the rotor diameter of a significant obstacle;

L_n is the distance to the centre of the tower of the neighbouring turbine;

L_e is the distance to the centre of the obstacle.

The equivalent rotor diameter D_e shall be evaluated according to formula (A.1) of IEC 61400-12-1:2017 A.4. A stopped WTG should be treated as a cylinder with a width equal to the tower base diameter and a height equal to the upper tip height.

Figure 10 illustrates formulae (25) to (27).

The sector exclusion given by this formula covers for the influences of the wake of the neighbouring turbine or obstacle on the WTG where the lidar is mounted on and the lidar probe volumes. As the nacelle-mounted lidar is forward-looking, the lidar probe volumes are constantly upstream and never in the wake of WTG it is mounted on.

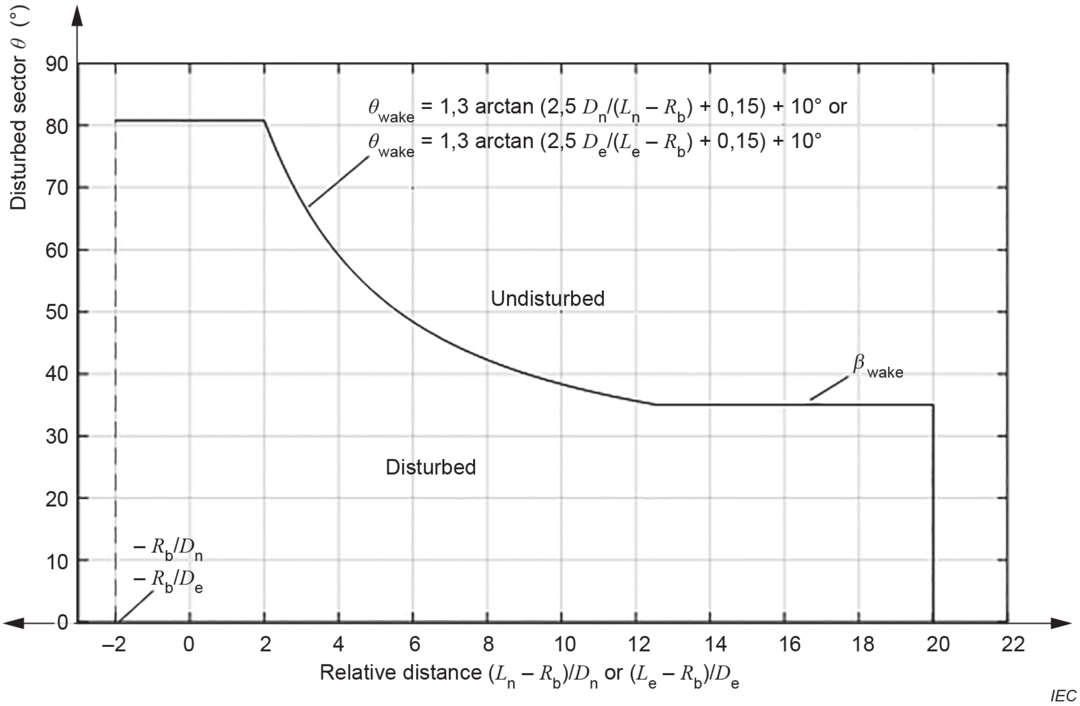


Figure 10 – Sectors to exclude due to wakes of neighbouring and operating WTGs and significant obstacles

In addition:

- Any neighbouring and operating WTG shall be more than twice its rotor diameter away from the turbine where the lidar is mounted on ($L_n > 2D_n$), and any significant obstacle shall be more than two equivalent diameters away from the turbine where the lidar is mounted on ($L_e > 2D_e$);
- The minimum distance from the lidar measurement volumes and each neighbouring turbine or obstacle shall be two rotor diameters or two equivalent diameters as appropriate. This shall be assessed on the centre[3] of the probe volumes as follows:

  In situations where $-2D_n < L_n - R_b < 2D_n$ or $-2D_e < L_e - R_b < 2D_e$, the sector to be excluded shall be taken as the largest of θ_{wake} and $\theta_{induction}$, the latter being calculated according to formula (28)or (29).

$$\theta_{induction} = \beta_{max} + 2\cos^{-1}\left(\frac{R_b^2 + L_n^2 - (2D_n)^2}{2R_b L_n}\right), \text{ or:} \tag{28}$$

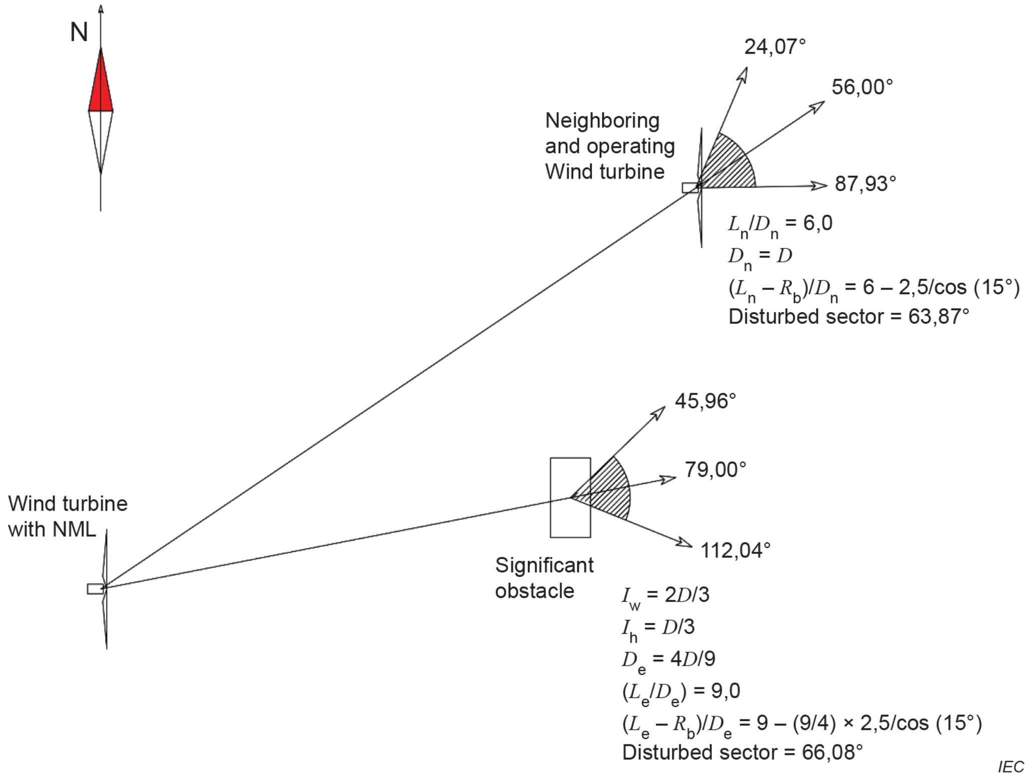
$$\theta_{induction} = \beta_{max} + 2\cos^{-1}\left(\frac{R_b^2 + L_e^2 - (2D_e)^2}{2R_b \times L_e}\right) \tag{29}$$

Formulae (25) to (29) assume that the turbine on which the lidar is mounted does not experience a yaw error or that this error has been corrected before the measurement campaign starts.

[3] Note that lidars measure in probe volumes. Here a practical approximation is taken by only considering the centre of the probe volume. According to 11.3, the resulting measurement sector is to be confirmed with a consistency analysis of the data measured during the SMC and reduced if necessary.

A consistency check of the turbine yaw misalignment can be achieved during the consistency check of the measurement sector (11.3) by comparing the directions at which the lidar beams are disturbed with the directions of neighbouring obstacles and turbines.

An example of measurement sector calculation with one neighbouring turbine and one other obstacle is shown in Figure 11.



NOTE In this example, the total sector to be excluded is 24,07° to 112,04°.

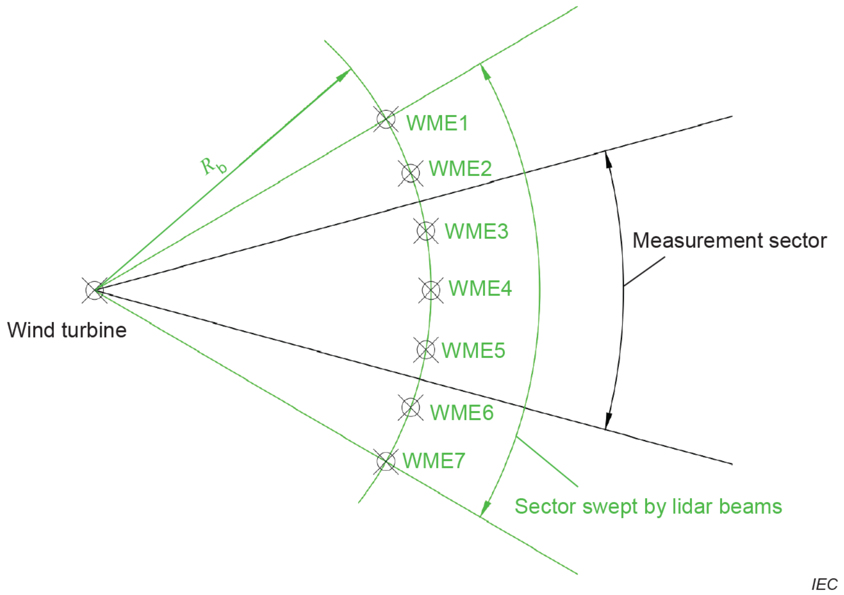
Figure 11 – Example of sectors to exclude due to wakes of a neighbouring turbine and a significant obstacle

10.4.3 Terrain assessment

An assessment of the terrain elevation shall be conducted as per Annex B of IEC 61400-12-1:2017, with the following considerations and amendments:

- The position of the centre of probe volumes for the two LOSs with the largest horizontal separation shall be considered instead of the WME. Here each probe volume is assumed to be a unidimensional segment (i.e. probe volumes' dimensions perpendicularly to the LOSs are assumed negligible).
- For a NML, "the distance between the WTG under test and the measurement equipment" is approximated as R_b, as defined in formula (24).
- Table B.1 of IEC 61400-12-1:2017 shall be applied for the evaluation of the surroundings of the WTG where the lidar is mounted on and for the evaluation of the surroundings of the probe volumes.
- The probe volumes are constantly moving with the nacelle yawing motion. Therefore, the evaluation of the surrounding of the probe volumes shall be assessed for various possible positions within the measurement sector as follows:
  – the full directional sector which is swept by lidar beams when measuring in the measurement sector is to be discretized by 10° including its extremities;

– for every 10° sample of the possible beam directions, Table B.1 of IEC 61400-12-1:2017 shall be applied with the lidar measurement range R_b, as illustrated in Figure 12.



NOTE Table B.1 from IEC 61400-12-1:2017 to be assessed centred on points WME1 to WME7.

Figure 12 – Example of full directional sector discretization

- If, for a given measurement sector, the terrain does not fully comply with the requirements of Table B.1 from IEC 61400-12-1:2017 for either the WTG or WME positions, then, the terrain is defined as "complex terrain", at least for this measurement sector, and this document is not applicable. However, reducing the measurement sector to reach a situation where all criteria of Table B.1 from IEC 61400-12-1:2017 are met, is allowed.
- The elevation profile of the terrain at the distance R_b within the sector swept by the lidar beams while measuring wind from the measurement sector (arc from points WME1 to WME7 in the example of Figure 12), shall be documented. If the variation of elevation along this arc exceeds the limits given by the use case or causes any violation of the assumptions of the WFR, either the measurement sector shall be reduced or a correction shall be applied according to 11.8.

11 Measurement procedure

11.1 General

The objective of the measurement procedure is to define a clear set of criteria to ensure that measurement data collected by a nacelle-mounted lidar is accurate, repeatable and reproducible.

11.2 WTG operation

The mode of operation of the WTG throughout the measurement campaign shall be determined by the requirements of the SMC, and the machine configuration shall not be changed.

The yaw system shall be operational and the nacelle position calibrated according to 10.3.3.

Normal maintenance of the WTG shall be carried out throughout the measurement period, but such work shall be noted in the test log. Any maintenance which may affect the wind speed measurements by the nacelle lidar or the turbine's response shall be avoided.

It is required to check that the installation of the nacelle lidar does not affect the operating performance of the WTG (e.g. introduce a yaw error). Annex D describes methods for investigating the potential impacts and how they should be documented. The methods can also be used as sanity check of the yaw signal from the WTG.

It is recommended to periodically check the condition of the nacelle cover where the lidar is installed, and the tilt angle, to detect possible degradation of the roof cover (since it is likely that the design of the roof cover did not consider the load of a lidar device).

11.3 Consistency check of valid measurement sector

It is required to check that none of the lidar beams/LOSs are disturbed by the wake of a neighbouring turbine or obstacle for the measurement sector defined according to 10.4. This can be detected

- either by a sudden change of lidar-estimated relative wind direction (see Figure 13);
- or a sudden change in the difference between the LOS turbulence intensity (defined as the ratio of the 10-min standard deviation and 10-min mean of the LOS speed) of the different lines of sight with yaw direction (see Figure 14).

If one of the beams is detected to be disturbed by a wake, the available measurement sector shall be reduced by removing the additionally observed disturbed sector, plus an extra 5 degrees on either end of this disturbed sector.

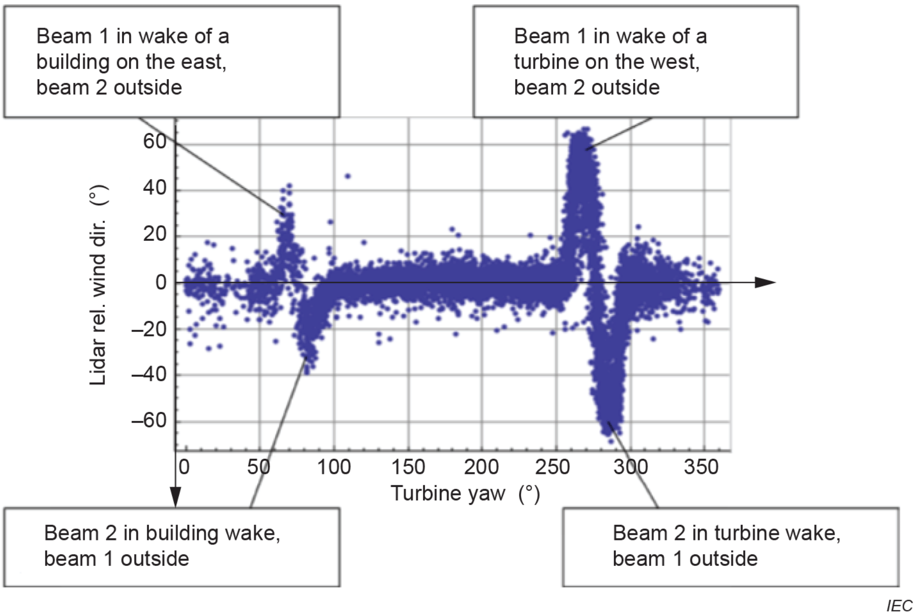
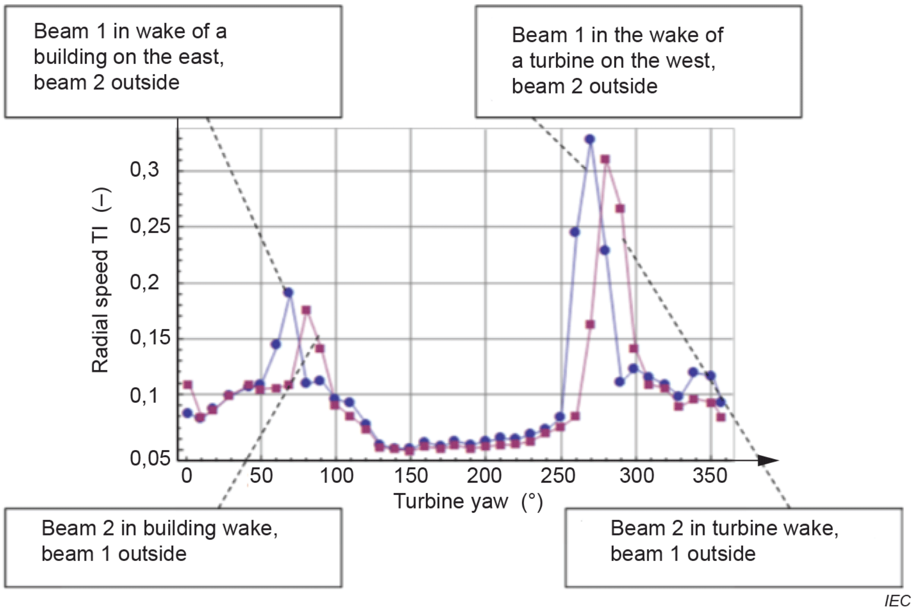


Figure 13 – Lidar relative wind direction vs turbine yaw for a two-beam nacelle lidar [Wagner R, 2013]



NOTE Each dot/square corresponds to a bin average value for an example bin width of 10 degrees, however a 5-degree bin width may also be applied. Blue dots: beam 1; Purple squares: beam 2 [Wagner R, 2013].

Figure 14 – Example of LOS turbulence intensity vs turbine yaw, for a two-beam nacelle lidar

11.4 Data collection

Data shall be collected continuously at the sampling rate following the lidar manufacturer's instructions. Blade-passing will have an impact on the sampling rate of the valid measurements. The validity of a sample should follow the lidar manufacturer instructions. It should be documented how many samples of valid measurement are collected for each record. As rotor speed will influence the number of valid samples per record, it is required to plot the number of samples per record as a function of wind speed or rotor speed. Furthermore, documentation of how the valid measurement points are distributed in time across each 10-min statistical value is recommended.

The nacelle lidar data acquisition system shall store:

- either sampled data
- or 10-min statistics (mean, standard deviation, maximum and minimum) of the valid data and data recovery or valid data indicator.

It will typically be required to integrate data from separate data acquisitions systems (e.g. the turbine signal for wind direction or yaw position is usually required and may be unavailable for direct measurement). In these cases, the nacelle lidar data acquisition system clock shall be synchronised to the rest of the data acquisition systems within 1 %, or 6 s provided 10-min periods data are collected. This synchronisation shall be checked and maintained throughout the measurement campaign.

The data may be comprised of the intermediate values (i.e. LOS speeds) and/or the final values (i.e. horizontal wind speeds). Further data may be required based on the needs of the SMC. Selected data sets shall be based on 10-min periods.

11.5 Data rejection

The data rejection criteria shall follow the requirements of the SMC. The general principle is that data sets should be excluded from the database under the following circumstances:

- WTG is not in the desired mode of operation for the SMC;
- failure or degradation of the measurement equipment;
- wind direction outside the measurement sector(s) as defined in 10.4;
- lidar data availability is below a threshold (e.g. due to blade passing or atmospheric conditions) for sufficient characterization of the 10-min period.

In the last bullet point above, availability may be limited at least by measurement distance, lidar type, and the position of the lidar on the nacelle. Currently, no clear guideline for a fixed availability value is available. Instead, it is to be defined by the user to ensure sufficient data availability specific to the configuration and application.

All rejection criteria shall be clearly reported. If possible, a sensitivity analysis should be performed for each filter to determine if there is any influence or bias in the measurement results. For instance, if a nacelle lidar provides a signal availability value for each record, the threshold used for filtering signal availability should be adjusted to determine if any bias is introduced to the wind speed using a specific threshold.

11.6 Database

The database requirements shall follow the requirements for the SMC (e.g. IEC 61400-12-1:2017 for power performance measurements).

11.7 Application of WFR algorithm

The reconstruction algorithm should be applied to the 10-min average of the LOS speeds[4].

It is recommended that as much information concerning the nacelle yaw position is recorded as possible. This information can include the 10-min mean yaw position, the standard deviation of the yaw position and the yaw motor activity[5].

[4] On certain nacelle lidar configurations (e.g. the simple two-beam configuration), attempting to calculate a mean speed from the instantaneously reconstructed wind speeds (a scalar mean) will result in an error since any speed difference between the scanning positions will always result in an apparent lidar over-speeding. At the beam scanning rate of the lidar (of the order of 1/s), in any turbulent flow there will always be significant speed differences between the beam scanning positions (separated by a distance of the order of 100 m). As the turbulence intensity increases, the size of the error due to this effect can become quite significant (orders of %). Instead it is recommended to reconstruct the horizontal wind speed based on 10-min mean values of the LOS speeds. When averaging over this much longer time period, it is much more reasonable to assume that the average wind speeds sensed are identical and no inherent over-speeding will be incurred.

[5] For a nacelle lidar recording a vector average, a constant yaw misalignment within the averaging period does not affect the averaged wind speed. In the same way, the mean yaw misalignment (difference between turbine yaw and wind direction) does not affect the vector averaged wind speed. However, assuming a constant magnitude wind speed, fluctuations of the wind direction around the mean value result in theory in an underestimation of the vector average. The magnitude of the error depends on the amplitude of the fluctuations and their duration. The worst-case scenario is a step change in turbine misalignment half-way through the averaging period (e.g. change in wind direction but delay in turbine yawing). Simple calculations have shown that for a 10-degree step change in yaw position occurring half-way through the 10-min averaging period, the reported vector average will be 0,4 % lower than the correct value. It is therefore recommended that as much information as possible concerning the nacelle yaw position is recorded.

11.8 Measurement height variations

It is required to consider variations in the elevation of the nacelle lidar beams above ground or sea level during the measurements. Irrespective of terrain, the lidar moves with the nacelle reacting to the thrust of the rotor which can cause a variation in measurement height. Correcting for changes in elevation can be part of the WFR process or can be applied in post-processing. It shall be documented how the terrain variations and nacelle movements were quantified and accounted for.

- If there is a constant height difference between the turbine position and measurement location over the entire measurement sector, the height difference should be considered in the setup of the tilt of the nacelle lidar according to 10.4.
- If the difference in terrain elevation across the measurement sector exceeds the limits given by the use case, the error in wind speed should be corrected for, either directly in the WFR algorithm or on the 10-min average reconstructed wind speed. The correction method shall be documented and an additional uncertainty term should be applied according to 9.4. If the requirements of the use case are met in a part of the measurement sector, the measurement sector can be adjusted to fulfil the measurement height requirements. See also 10.4.
- Similarly to terrain variations, changes in measurement height due to lidar tilt exceeding limits of the use case should be corrected for, either directly in the WFR or on the reconstructed wind speed. The correction method shall be documented and an additional uncertainty term should be applied according to 9.4.

In any case, the lidar tilt angle shall be monitored during the entire measurement campaign and reported at least as average values per direction bin of 10° and horizontal wind speed bin of 0,5 m/s.

11.9 Lidar measurement monitoring

The consistency of the lidar wind speed measurement throughout the whole measurement period shall be assessed and validated. If a deviation is observed during the measurement period, an additional uncertainty term shall be applied. The monitoring methodology and corresponding uncertainty assessment shall be described in the report. As an alternative to monitoring, a post-calibration of the lidar can be carried out and compared to the pre-calibration following the accuracy requirements of the SMC.

12 Reporting format – relevant tables and figures specific to nacelle-mounted lidars

12.1 General

The reporting shall fulfil the requirements of the SMC (e.g. for power performance testing, the reporting shall fulfil the requirements from IEC 61400-12-1:2017, Clause 10) and the nacelle-mounted lidar specific information listed in 12.2 to 12.7. Any deviations from the procedure described in this document shall be reported.

12.2 Specific measurement campaign site description

a) WTG coordinates (including reference system and datum; e.g. UTM, WGS 84);

b) coordinates of sector limiting turbines and obstacles;

c) selected measurement sector according to 10.4 and verification that the expectations of being free from influence of other turbines or obstacles are met according to 11.3;

d) offshore: Average tide and wave height, definition of normal sea level at the site;

e) onshore:
   - results of terrain assessment according to 10.4.3;
   - terrain data base and resolution;
   - terrain height along the arc with radius equal to the lidar measurement range R_b where the lidar is measuring (see 10.4.3);

12.3 Nacelle lidar information

a) type of the nacelle lidar, serial number, operating software version;
b) nacelle lidar number of beams and geometrical description of the scanning patterns (including relevant angles);
c) all details of the set-up of the nacelle-mounted lidar, including position on the nacelle, configuration of operating software, measurement range(s), tilt and roll angles and their monitoring;
d) reference to calibration report according to 7.8;
e) reference to results from sensitivity analysis of intermediate values (8.2) and reference to evidence-base supporting adoption of a negligible uncertainty contribution from the WFR according to 8.4;
f) relation between the lidar reported turbulence intensity and the TI measured by a cup anemometer;
g) results of the assessment of the consistency of the lidar wind speed measurement and a description of the employed methodology (see 11.9).

12.4 WTG information

Unless specified otherwise in the SMC reporting requirements the following information about the WTG shall be reported.

a) make, model, year of production;
b) hub height and the height reference used to determine hub height;
c) rotor diameter;
d) turbine control (i.e. pitch or stall controlled) and the rotor speed as a function of horizontal wind speed;
e) dynamic tilt angle under thrust loading over wind speed;
f) definition of the yaw signal (range, number of revolutions, algebraic sign, North offset in degrees and method how this has been verified);
g) yaw signal calibration report (see 10.3.3);
h) definition of the time stamp reference;
i) definition of provided status signals;
j) check that the installation of the nacelle lidar does not affect the operating performance of the WTG (e.g. introduce a yaw error) according to 11.2;

12.5 Database

a) measurement period;
b) system availability in the measurement period;
c) log of changes
   - changes to the lidar;
   - changes to the turbine;
   - services / regular maintenance conducted and observations.
d) documentation of synchronisation between separate data acquisitions systems (e.g. the turbine signal or SCADA and nacelle-mounted lidar) including synchronisation method and monitoring throughout campaign (see 11.4);

e) description of data analysis including:
   - information about lidar samples validity (see 11.4):
     i) criteria used to determine sample validity;
     ii) plot of the number of valid samples per record as a function of wind speed; plot as a function of rotor speed is also recommended;
     iii) it is recommended to document how the valid samples are distributed in time across each 10-min statistical value;
   - all data rejection criteria shall be clearly reported (see 11.5). The total number of data sets removed shall be reported. Optionally, number of datasets removed by each filter individually and cumulatively by applying the filters may be reported as well;

f) a general description of the method of calculating the horizontal wind speed and relative wind direction from the measured LOS speeds (WFR method);

g) environmental conditions (variables identified as non-negligible according to 8.2) after filtering;

h) a description of the monitoring method to assess the consistency of the lidar measurements (11.9) and if observed inconsistencies lead to an additional uncertainty, the uncertainty calculation associated with this method.

12.6 Plots

a) scatter plot of lidar tilt angle as a function of horizontal wind speed (including mean, standard deviation, minimum and maximum);

b) scatter plot of lidar roll angle as a function of horizontal wind speed (including mean, standard deviation, minimum and maximum);

c) if relevant, scatter plot of deviation of the WFR height to desired measurement height as a function of horizontal wind speed (including mean, standard deviation, minimum and maximum).

12.7 Uncertainties

A detailed uncertainty assessment of the lidar final variables (according to Clause 9) shall be reported. See the example in Annex A.

Annex A
(informative)

Example calculation of uncertainty of reconstructed parameters for WFR with two lines of sight

A.1 Introduction to example case

In this annex, an uncertainty analysis is presented for a lidar employing a WFR method based on wind speed measurements from two LOSs. This WFR is the typical application of a fixed-beam-geometry lidar but is also used in other types of scanning lidars. However, in the latter case, the dynamic positioning uncertainty has to be considered as well, which is omitted here.

In this example, it is assumed that the lidar has been calibrated according to Clause 7 prior to the deployment and the two LOSs have been calibrated one after the other using the same reference instruments (cup anemometer for the horizontal wind speed and wind vane for the wind direction).

In the following angular brackets denote an average over 10-min time series and a bar denotes a variable that represents a 10-min average but is not calculated as an average from high frequency data. The formulae of the 2-LOS WFR method to calculate the horizontal wind speed are

$$\overline{V_x} = \frac{V_L + V_R}{2\cos(\beta/2)\cos(\tau)}, \tag{A.1}$$

$$\overline{V_y} = \frac{V_L - V_R}{2\sin(\beta/2)\cos(\rho)}. \tag{A.2}$$

The horizontal wind speed $\bar{V}_{2LOS}$ is calculated as the quadratic mean of the longitudinal and transversal wind speed components

$$\bar{V}_{2LOS} = \sqrt{\overline{V_x}^2 + \overline{V_y}^2}. \tag{A.3}$$

The relative wind direction Θ_{2LOS} is calculated as the two-argument inverse tangent of the longitudinal and transversal wind speed components

$$\bar{\Theta}_{2LOS} = \text{atan2}\left(\overline{V_y};\overline{V_x}\right). \tag{A.4}$$

The variables denote the following quantities:

- V_x is the longitudinal wind speed component;
- V_y is the transversal wind speed component;
- V_l is the LOS speed for the left LOS, seen from behind the lidar;
- V_R is the LOS speed for the right LOS;
- β is the angle between the two LOSs;
- τ is the tilt angle;
- ρ is the roll angle.

A.2 Uncertainty propagation through WFR algorithm

In this case, the WFR algorithm is analytical and explicit, therefore the GUM methodology can be applied. The general formula for combining uncertainties according to the GUM is:

$$U_c^2 = \sum_{i=1}^{K}\left(\frac{\partial f}{\partial x_i}\right)^2 U_i^2 + 2\sum_{i=1}^{K-2}\sum_{j=i+1}^{K} r_{i,j}\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right)U_i U_j \quad \text{(A.5)}$$

where $f(x_y, x_2, \dots x_N)$ is the function combining the dependent variables, x_i, and the U_i are their uncertainties. This form allows for a non-zero correlation between uncertainty components, denoted by $r_{i,j}$. These terms are important in this case because many of the uncertainty components on the left LOS are correlated to their corresponding terms on the right LOS.

In this example, the horizontal wind speed is approximated to the longitudinal component of the wind vector and the transversal component is neglected, which is equivalent to a zero yaw-error. Thus f is given by:

$$f\left(V_L, V_R, \beta, \tau\right) = \overline{V_x} = \frac{V_L + V_R}{2\cos(\beta/2)\cos(\tau)} \quad \text{(A.6)}$$

The uncertainties of the half opening angle $\beta/2$ and tilt angle can be neglected because they are several orders of magnitude lower than the uncertainty of the LOS speed uncertainties. The formula does not include any parameter that could have its own uncertainty ($u_{WFR, par} = 0$).

Therefore, the combined uncertainty depends only on the terms included in the uncertainty of the speed measurement along both LOSs. The different uncertainty terms are considered either fully correlated ($r_{i,j}$ = 1) or uncorrelated ($r_{i,j}$ = 0). Furthermore, the correlated uncertainty terms are considered to have the same value for both LOSs whereas the uncorrelated terms may have different values for each LOS. An explanation for each uncertainty term is given in Table A.1.

Based on these considerations, the uncertainty of each LOS can be decomposed as uncorrelated and fully correlated uncertainty terms

$$u_L^2 = \sum_{i=1}^{M} U_{L,i}^2 + \sum_{j=1}^{N} C_j^2 \quad \text{(A.7)}$$

and

$$u_R^2 = \sum_{i=1}^{M} U_{R,i}^2 + \sum_{j=1}^{N} C_j^2 \quad \text{(A.8)}$$

where the uncertainty components $U_{L,i}$ and $U_{R,i}$ are uncorrelated and unequal between LOSs and the uncertainty components C_j are correlated and assumed equal between the LOSs. The indices 'L' and 'R' indicate the left and right LOS. Note that none of the components are correlated within one beam.

The combined uncertainty of the reconstructed wind speed $u_{V,\mathrm{WFR}}$ is

$$u_{V,\mathrm{WFR}}^2 = \left(\frac{1}{2\cos\left(\beta/2\right)\cos\tau} \right)^2 \left(\sum_{i=1}^{M} (U_{\mathrm{L},i}^2 + U_{\mathrm{R},i}^2) + 4\sum_{j=1}^{N} C_j^2 \right) \quad \text{(A.9)}$$

From this formula, it can be appreciated the importance of identifying the correlated uncertainty terms since they contribute with double weight as compared to the uncorrelated terms. As a consequence, it is important to make separate summations of the correlated and uncorrelated terms in the uncertainty budgets of the calibration and of the sensitivity of intermediate values to EVs so that they can be correctly combined. It is also important that the summations are made with the correct sensitivity coefficients already applied so that all uncertainty components are scaled to LOS speed.

Table A.1 – Uncertainty components and their correlations between different LOSs for this example

Symbol in formula (A.9)	Uncertainty component	Correlation of uncertainty between LOSs	Explanation
C_1	Calibration uncertainty, u_{cal}	1	Uncertainties of the reference cup anemometer – assumed to be fully correlated because the same cup anemometer has been used for the calibration of both LOS speeds.
C_2	Operational characteristics, u_{ope}	1	
C_3	Mounting, u_{mast}	1	
C_4	Data acquisition, u_{daq}	1	
C_5	Site effects, u_{terr}	1	Uncertainty due to reference site effects – assumed to be fully correlated because both LOSs have been calibrated at the same location.
$U_{L,1}$; $U_{R,1}$	Height error, $u_{\mathrm{vert\_pos}}$	0	Uncertainty due to the beam height relative to the reference instruments height – assumed to be decorrelated because they are specific to each LOS calibration.
C_6	Measurement range, u_{inc}	1	Uncertainty due to the reference measurement range – assumed to be fully correlated because the range configuration has been kept unchanged during the calibration of both LOSs.
C_7	Reference wind direction sensor, u_{θ}	1	Uncertainty due to the reference vane – assumed to be fully correlated because the same vane has been used for the calibration of both LOS speed.
$U_{L,2}$; $U_{R,2}$	Determination of line of sight, $u_{\theta_{\mathrm{los}}}$	0	Uncertainty of the LOS is specific to each LOS calibration – especially here since we assume they have been calibrated one after the other and the lidar optical head had to be moved between the calibration of the two LOSs.
$U_{L,3}$; $U_{R,3}$	Projection error, u_{φ}	0	Uncertainty of the beam elevation angle is specific to each LOS calibration – especially here since we assume they have been calibrated one after the other and the lidar optical head had to be moved between the calibration of the two LOSs.
$U_{L,4}$; $U_{R,4}$	Residuals from application of calibration, u_{residual}	0	The calibration function is determined individually for each beam calibration.

Symbol in formula (A.9)	Uncertainty component	Correlation of uncertainty between LOSs	Explanation
Note that this table would be different if a different calibration setup had been used (e.g. if both LOSs had been calibrated simultaneously using two different sets of reference instruments).			

Note that the uncertainties resulting from the calibration are given as a function of the LOS speed and they need to be converted to a function of the horizontal wind speed.

A.3 Operational uncertainty of the lidar and WFR algorithm

The lidar type in this example is assumed to fulfil all criteria from 8.3 to justify neglecting the contribution to measurement uncertainty due to environmental effects on the WFR ($u_{ope,lidar} = 0$).

A.4 Uncertainty contributions from variation of measurement height

According to 11.8, it is required to consider variations in the elevation of the nacelle lidar beams above ground or sea level during the measurements and estimate the related uncertainty. In this example, the WFR algorithm (formulae (A.1) to (A.4)) does not account for the measurement height variation (i.e. both LOSs are assumed to measure at the same height independently of the turbine nacelle tilt or yaw variations). Therefore the uncertainty has to be estimated in post processing.

Assuming there is no height difference between the LOSs at any time, every 10-min value of the reconstructed horizontal wind speed V_m can be scaled to the desired measurement height (e.g. hub height) assuming an exponential shear profile $V_H = V_m \left(\frac{z_H}{z_m} \right)^{\alpha}$ giving a potential correction of

$$\Delta V_{hor} = V_H - V_m = V_m \left[\left(\frac{z_H}{z_m} \right)^{\alpha} - 1 \right] \quad \text{(A.10)}$$

where z_H is the desired measurement height and z_m the actual measurement height. The shear exponent α should be taken from measurements if available, otherwise a constant may be assumed which is reasonable for the terrain, e.g. $\alpha = 0{,}1$ for offshore applications.

- If the horizontal wind speed is not corrected for height, the uncertainty should be calculated from the maximum range of possible correction, i.e. using a conservative estimate of the shear exponent in formula (A.10):

$$u_{\Delta V,\text{measHeight}} = \frac{\Delta V_{hor}}{\sqrt{3}} \quad \text{(A.11)}$$

- If the horizontal wind speed is corrected for height, the residual uncertainty of the correction can be obtained following GUM from differentiating ΔV in (A.10) with respect to shear, measurement height, and measured wind speed.

$$u_{\Delta V,\text{measHeight}}^2 = \left[V_\text{H} ln\left(\frac{z_\text{H}}{z_\text{m}}\right)u_\alpha\right]^2 + \left[V_\text{H}\frac{(-\alpha)}{z_\text{m}}u_{z_\text{m}}\right]^2 + \left[\left(\left(\frac{z_\text{H}}{z_\text{m}}\right)^\alpha - 1\right)u_{V_\text{m}}\right]^2 \tag{A.12}$$

where u_α is the uncertainty of shear, u_{z_m} is the uncertainty of actual measurement height, and u_{V_m} is the uncertainty of the measured wind speed ($u_{V_\text{m}} = u_{V,\text{WFR}}$). For example, in a typical application one might have $z_\text{H} = 100\text{m}$, $z_\text{m} = 98\text{m}$, $\alpha = 0{,}1$, and $V_\text{m} = 10\text{m/s}$, which gives a residual uncertainty due to varying measurement height after the measurements have been corrected of $u_{V,\text{measHeight}}^2 = \left(0{,}2\frac{\text{m}}{\text{s}}u_\alpha\right)^2 + \left(0{,}01\frac{1}{\text{s}}u_{z_\text{m}}\right)^2 + \left(0{,}002u_{V_\text{m}}\right)^2$.

The uncertainty of the measurement height u_{z_m} can be traced back to the uncertainty of tilt angle measurement u_τ

$$u_{z_\text{m}} = u_\tau R_\text{conf} / (\cos\tau)^2 \tag{A.13}$$

where R_conf is the measurement range.

The uncertainty due to roll of the lidar optical head is several orders of magnitude smaller than the uncertainty due to tilt. Therefore, this uncertainty term may be neglected.

A.5 Wind speed consistency check

In this example, it is assumed that the consistency check of the lidar wind speed measurement according to 11.9 has not shown any deviation during the measurement period and no uncertainty need to be added.

A.6 Combined uncertainty

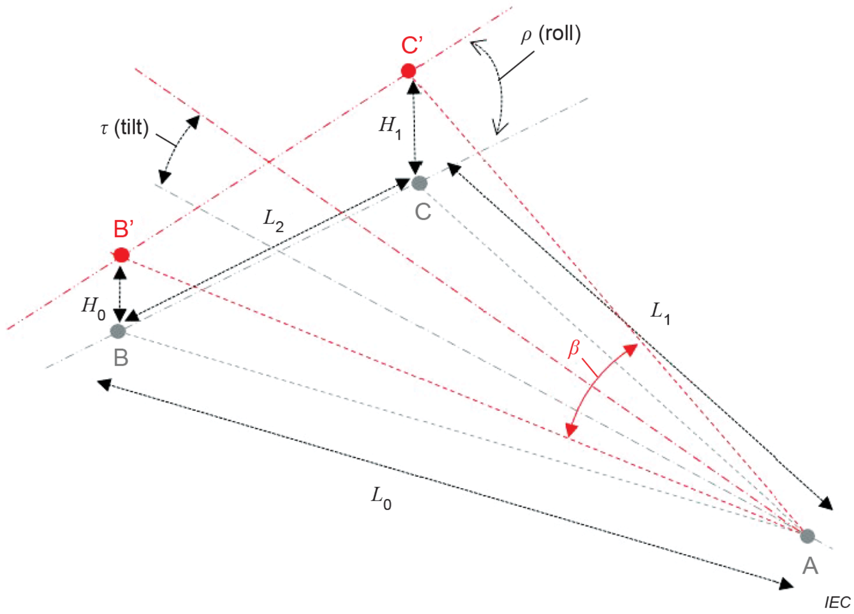
Putting all components together, the uncertainty of reconstructed horizontal wind speed, in this example, is:

$$u_\text{HWS}^2 = u_{V,\text{WFR}}^2 + u_{\Delta V,\text{measHeight}}^2 \tag{A.14}$$

Annex B
(informative)

Suggested method for the measurement of tilt and roll angles

The following procedure provides simultaneously the inclinometers calibration and the opening angle value between two beams[6]. Figure B.1 shows the geometry of two lidar beams exactly levelled in the horizontal plane (grey, points ABC), and after a tilt displacement τ and a roll displacement ρ (red, points A'B'C'). Point A is the origin of the beams (at the lidar telescope), point B is the detected position of beam 0 at distance L_0 and point C is the detected position of beam 1 at distance L_1. The horizontal distance between the two detected beam positions B and C is L_2. The (full) opening angle of the lidar beams is β. Due to the tilting (angle τ) and the rolling (angle ρ), the beam 0 and beam 1 positions are lifted by heights H_0 and H_1 respectively.



Key:

A: beam origin

B and C: detected position of beam 0 and beam 1

Figure B.1 – Pair of tilted and rolled lidar beams (red) shown in relation to the reference position (grey)

Since the tilt and roll displacements are expected to be relatively small (for practical reasons), CC' and BB' are approximated to be perpendicular to the ABC plane. Then, the tilt displacement and the roll displacement are given by:

6 For some lidar types, the angles between LOSs can be determined with the same test and measurement setup used for the inclinometer calibration; in other cases, a separate test is required.

$$\tau = \operatorname{atan}\left(\frac{\frac{H_0}{L_0}+\frac{H_1}{L_1}}{2\cos\left(\frac{\beta}{2}\right)}\right) \qquad \text{(B.1)}$$

$$\rho = \operatorname{atan}\left(\frac{\frac{H_1}{L_1}-\frac{H_0}{L_0}}{2\sin\left(\frac{\beta}{2}\right)}\right) \qquad \text{(B.2)}$$

For a lidar geometry consisting of only two horizontal beams, the measured tilt and roll angles are:

$$\tau_{\text{measured}} = \tau \qquad \text{(B.3)}$$

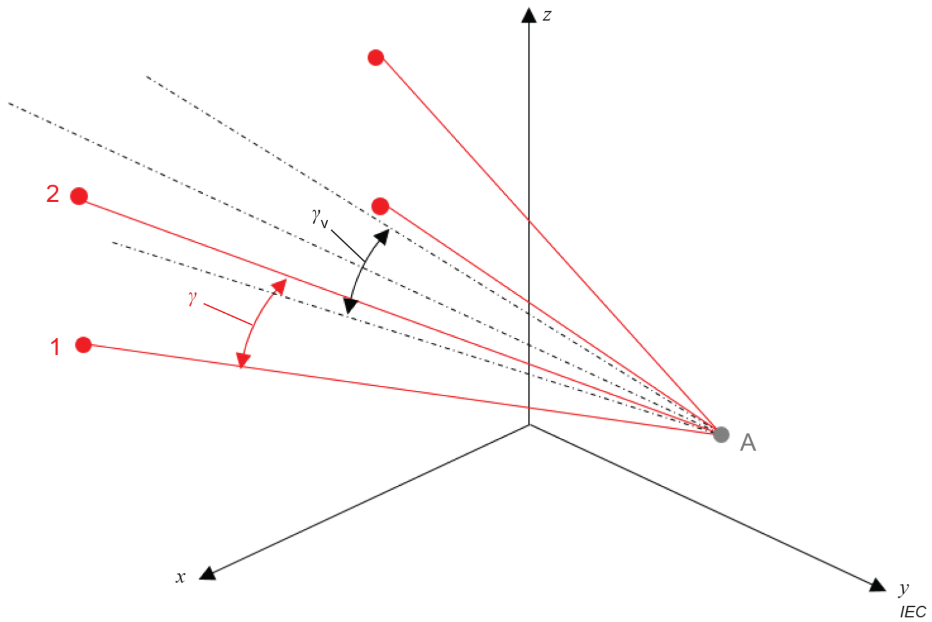
$$\rho_{\text{measured}} = \rho \qquad \text{(B.4)}$$

For a lidar geometry consisting of two lower beams and two upper beams, with a vertical and a horizontal plane of symmetry, the measured tilt and roll angles are:

$$\tau_{\text{measured}} = \tau + \gamma_V / 2 \qquad \text{(B.5)}$$

$$\rho_{\text{measured}} = \rho \qquad \text{(B.6)}$$

Where γ_V is the projection of γ (opening angle between two beams symmetric with respect to the horizontal plane) on the vertical plane of symmetry of the lidar, as depicted in Figure B.2.



NOTE γ_V is the projection in the plane YZ of the opening angle (γ) between LOS 1 and 2.

Figure B.2 – Opening angle between two beams symmetric with respect to the horizontal plane(γ) and its projection onto the vertical plane of symmetry of the lidar (γ_V)

The procedure can also be adapted to fixed-geometry scanning lidars by detecting the beam at two different azimuthal positions of the scanning pattern.

Annex C
(informative)

Recommendation for installation of lidars on the nacelle

C.1 Positioning of lidar optical head on the nacelle

It is recommended to consider the following steps prior to the installation day to determine where to install the lidar optical head and processing unit, in case that the lidar has a separate processing unit, outside and inside the nacelle.

The location of the lidar with regard to the instrumentation on the turbine should be chosen so that the influences between these are minimized. A non-exhaustive list of recommendations for avoiding such interferences is provided below:

- To avoid interferences on the lidar it is recommended to install the lidar as follows:
  - as centred as possible to avoid differences in availability of beams on the left and the right sides of the trajectory/geometry;
  - making sure that all LOSs that are used for the WFR are free of obstacles (with the exception of the blade passing which cannot be avoided), see Figure C.1 and Figure C.2.

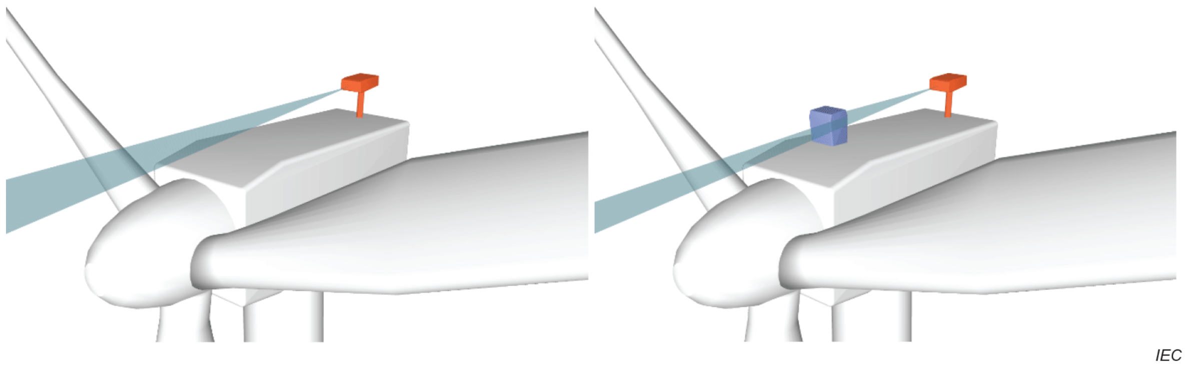


Figure C.1 – Example of a good (left) and bad (right) position for a 2-beam lidar

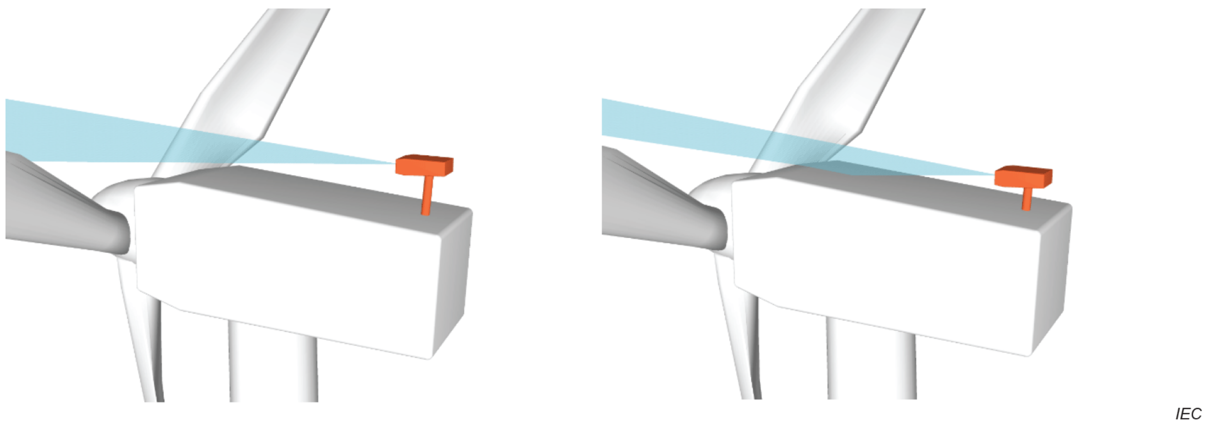


Figure C.2 – Example of a good (left) and bad (right) position for a 4-beam lidar

- Prior to the lidar installation, it is recommended that work instructions be produced by either the OEM or an independent consultant. In case the work instructions are produced by an independent consultant, they shall be approved by the OEM or the turbine owner. The work instructions will ensure:

– the safety of the personnel performing the installation of the lidar and of the personnel performing turbine maintenance;
– the turbine structural integrity;
– the turbine performance integrity (e.g. the lidar Optical Head shall not disturb the turbine.

C.2 Lidar optical head pre-tilt for fixed beam lidars

For most use cases, the lidar optical axis should aim at hub height at 2.5 D upstream of the rotor, which usually requires to tilt the optical head slightly downwards (as illustrated in Figure C.3) to compensate for:

1) The height of the optical head above hub height (H_{OH}):

$$\delta_{\mathrm{H}} = \tan^{-1}\frac{H_{\mathrm{OH}}}{L_{\mathrm{u}} + X_{\mathrm{OH}}}$$

where

X_{OH} is the horizontal distance between lidar optical head and rotor plane;

L_u is the horizontal distance between the rotor plane and the upstream measurement position;

H_{OH} is the vertical distance between lidar optical head and rotor axis.

2) The difference in tilt angle of the nacelle between turbine operation and turbine stand still (this should be obtained from either numerical simulations or measurements): $\delta_{\mathrm{Nac}} = \delta_{\mathrm{ope}} - \delta_{\mathrm{StandStill}}$;

3) The correction found in the inclinometer calibration: δ_{Cal}.

The total pre-tilt angle is given by:

$$\delta_{\mathrm{tot}} = \delta_{\mathrm{H}} + \delta_{\mathrm{Nac}} + \delta_{\mathrm{Cal}}$$

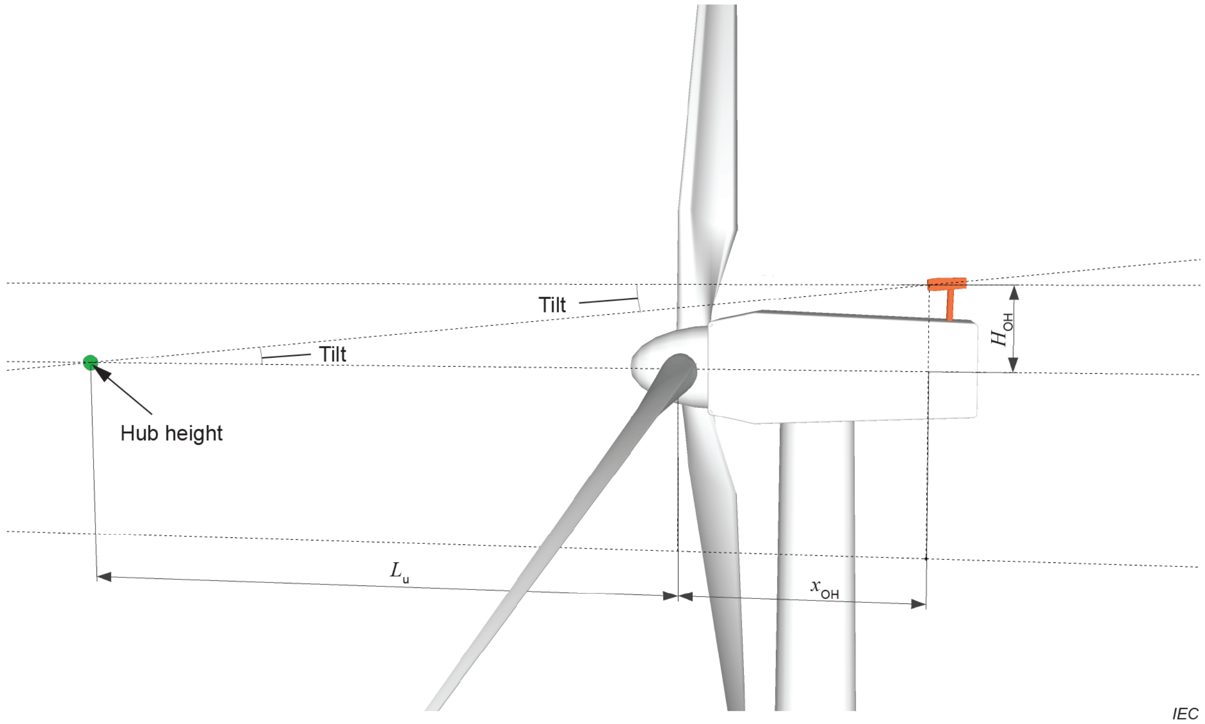


Figure C.3 – Sketch of lidar optical head pre-tilted downwards to measure at hub height (example for a two beam lidar)

Such pre-tilting is mainly relevant for 2-beam nacelle lidar that can only measure at one height and are not equipped with real time turbine nacelle motion compensation. For nacelle lidars able to measure the wind speed at 2 or more heights (e.g. fixed-beam-geometry lidar with more than 2 beams or conically scanning lidars) the actual pre-tilt of the Lidar shall be reported in order to calculate the correction of the vertical wind shear effect and the wind conditions at the desired measurement height.

C.3 Attachment points for the lidar

At least the following recommendations shall be considered when defining the attachment points:

- Before installing a lidar the reaction forces and momenta acting on the roof covers of the nacelle should be calculated. It should be checked that the corresponding safety reserve factor is met according to industry best-practice.
- The attachment points of the lidar should be placed in a location of the structure where their material properties are not deteriorated/affected by such location itself.
- The lidar should not be installed where the safety anchor points are located, due to servicing access requirements.

Annex D
(informative)

Assessing the Influence of nacelle-mounted lidar on turbine behaviour

D.1 General

The presence of a lidar on the turbine nacelle may influence the sensors that measure wind speed and wind direction, usually placed on the back side of the nacelle. These signals are commonly used in turbine control, e.g. for yawing to the predominant wind direction, thus there could be a case that the lidar influences the nacelle sensors measurements to a degree that the turbine performance is affected. The significance of impact from the lidar installation depends on the use case.

The amount of influence depends on the location and dimensions of both the nacelle instruments and the lidar. Following the placement and installation instructions of Clause 10 should result in no (or negligible) influence; however it is recommended to do a consistency check to verify this using one of the methods described below, depending on the specific case. If a significant change has been detected after the lidar installation, a new position for the lidar should be found or, in case this is not an option, the differences between the two phases should be considered as an additional uncertainty of the wind speed measurement. Discrepancies should be reported in the measurement report.

D.2 Recommended consistency checks methods

D.2.1 General

This document describes three different approaches which may be selected based on available information and setting:

- Documentation-based approach: This approach is recommended in case the WTG manufacturer has sufficient experience with a certain WTG model in combination with a specific sensor type. In such a case a work instruction document would be published determining position and mounting specifics of the lidar.
- Data-based approach in a side-by-side placement of WTGs in a wind farm: This approach uses the relative performance of a WTG before and after the lidar installation to detect its influence on the nacelle instrumentation. Two WTGs of identical type are exposed to the same wind conditions and thus the relative performance, regardless of variations in inflow conditions, should show only small variations. This method is expected to be the default approach, unless enough experience is gained to apply the documentation-based approach.
- Data-based approach using the relative power curve of the assessed WTG before and after the lidar installation: this approach is suggested for situations in which documentation and nearby turbines are not available, for example in prototype testing. It requires considering variations in inflow conditions and to collect data from the wind speed and wind direction sensors. This may require installing additional instrumentation on the nacelle. This scenario is therefore expected to be used only if the former two approaches cannot be applied.

D.2.2 Documentation-based approach

For specific cases (e.g. WTG nacelle size, anemometer placement, lidar location), relevant documentation such as photos and drawings can be used as evidence that there is no disturbance of the nacelle instruments and thus no influence on the WTG performance.

D.2.3 Data-based approach using neighbouring WTG

D.2.3.1 General

The general idea of this approach is to compare various WTG parameters (or proxies) between the WTG where the lidar is mounted on and a reference WTG without lidar, before and after lidar installation.

The following 10-min SCADA signals are needed from both reference WTG and the WTG with lidar, for both the periods before and after lidar installation:

- active power (kW): average & minimum;
- WTG availability signal;
- ambient temperature (°C): average;
- nacelle position (°): average – the nacelle position signal should be calibrated and corrected (if needed) to be provided as a value relative to the true North;
- nacelle wind speed (m/s): average;
- nacelle wind direction (°): average.

D.2.3.2 Reference WTG selection

The reference WTG shall have an undisturbed sector, similar to the one of the WTG with lidar. It shall also run on the same operational settings, both before and after the lidar installation, and these settings must remain unchanged for both reference WTG and the WTG with lidar. Only grid un-curtailed operation of both test and reference WTGs will be included in the analysis.

D.2.3.3 Check of influence on WTG power output

The relationship between the reference WTG and the WTG with lidar shall be assessed (e.g. as a linear regression; see Figure D.1) twice:

i) one time before the lidar installation (i.e. in the absence of lidar)

ii) and another time after the lidar installation.

Valid points for the concurrent datasets of both reference WTG and WTG with lidar should fulfil the following criteria:

- average wind direction within common undisturbed sector;
- average power within 3 % to 97 % of nominal power;
- WTG availability 100 % within the 10-min period;
- minimum power > 0 kW;
- average ambient temperature >2 °C.

Figure D.1 shows an example of comparison of concurrent active power data between two neighbouring turbines, where no change in the relationship before and after is apparent. There is limited experience in applying this methodology and thus no specific criteria are suggested in this document version.

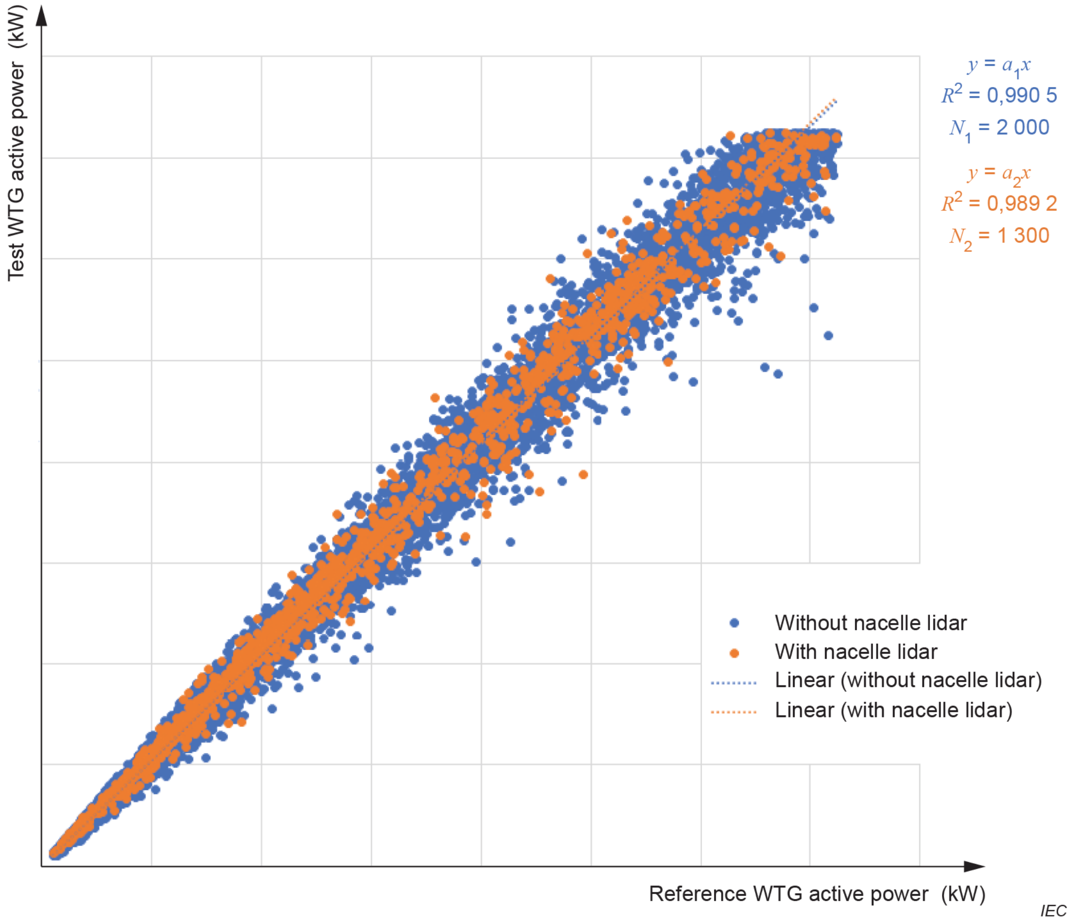


Figure D.1 – Example of reporting the side-by-side comparison

D.2.3.4 Check of influence on WTG's nacelle position

To investigate whether the lidar installation has influenced the WTG yaw behaviour, the electrical power ratio of the two WTGs should be plotted as a function of the nacelle position signal of the same turbine, for the two time periods: before and after the installation. An example of such a relation is given in Figure D.2. For both time periods, the binning range shall be kept the same and the amount of points in the sector of interest, as well as the point distribution, should be comparable.

In the case where the lidar installation has influenced the turbine yaw behaviour, the position of the ratio peak will change relative to the peak position before the lidar installation. Thus, if the peak remains at the same position after the lidar installation, it can be concluded that the turbine behaviour has not changed and that the lidar does not interfere with the sensors used for the turbine orientation. A variation of the peak position of the order of 1° to 2° degrees in either direction is within the experimental uncertainty of the method and therefore not considered as a change.

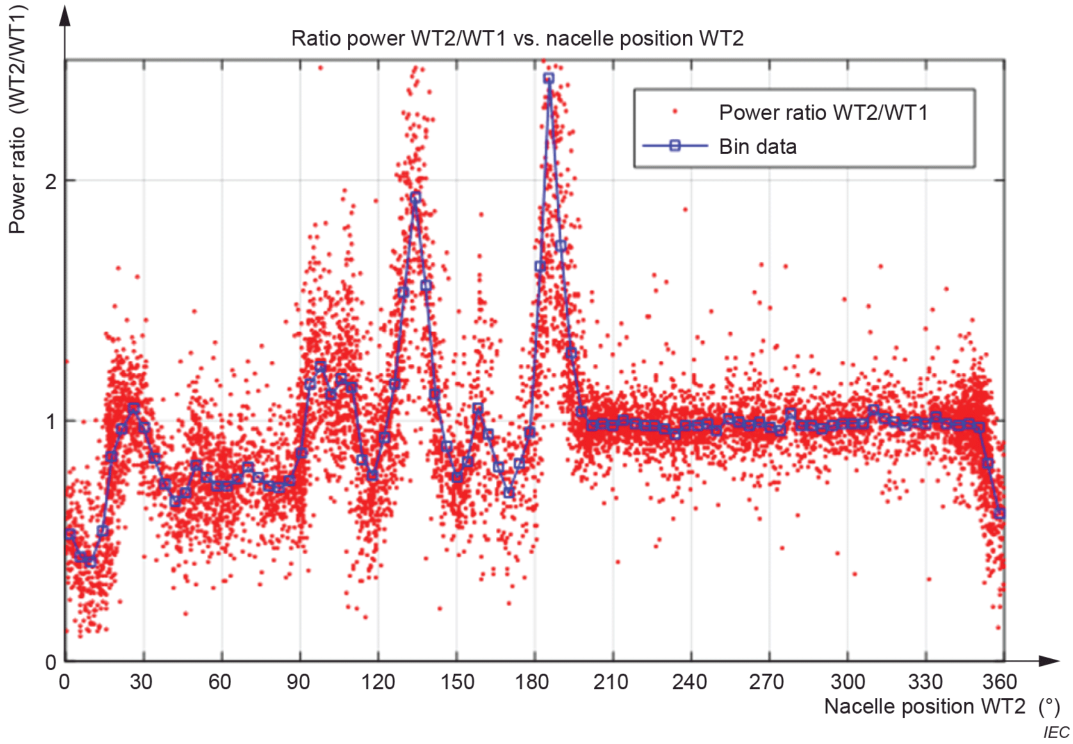


Figure D.2 – Example of the power ratio between two neighbouring turbines

D.2.3.5 Check of influence on WTG's wind speed and direction sensors

An alternative approach to establish whether the lidar installation has influenced the readings of either of the turbine's wind speed/direction sensors, is to examine the relation of the two anemometer / wind direction signals for a specific wind speed range as a function of the nacelle position in the free sector, before and after the installation of the lidar. The relation between the involved sensors will remain similar before and after the lidar installation if no influence exists from the installed lidar on either sensor.

D.2.4 Data-based approach using only the WTG being assessed

D.2.4.1 General

This approach aims at detecting a significant change in the difference between the relative wind direction measured by the two nacelle wind direction sensors, before and after the nacelle lidar installation. The approach is described in Figure D.3.

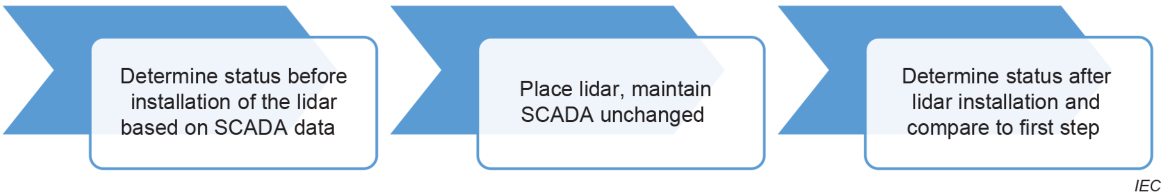


Figure D.3 – General process outline

This approach is based on the assumption that the single source of adverse influence on the turbine control originates from a change in the relative wind direction reported by the wind direction sensors on the nacelle.

D.2.4.2 Required signals

This approach requires the following turbine-reported signals – indicated by the index TR (without further correction applied):

- nacelle anemometer wind speed , $V_{\text{Nac,TR}}\left[m/s\right]$;
- primary nacelle wind direction, $\text{Dir}_{\text{1,Nac,TR}}\left[°\right]$;
- secondary nacelle wind direction, $\text{Dir}_{\text{2,Nac,TR}}\left[°\right]$;
- nacelle position, $\text{Dir}_{\text{Yaw,TR}}\left[°\right]$.

The two $\text{Dir}_{\text{k, Nac,TR}}$ signals are understood to be the wind direction signals relative to the orientation of the nacelle. A typical magnitude during operation is on the order of ± 5 degrees. Many WTG designs provide by default a single signal derived from the two sensors for $Dir_{\text{k,Nac,TR}}$. Since this approach aims at detecting a systematic flow direction change, this approach requires the individual signal of each of the two nacelle wind direction sensors.

The signal processing must remain the same before and after the lidar installation.

Since the nacelle position signal is used to select the 10-min samples within the measurement sector, the nacelle position signal should be calibrated and corrected to be provided as a value relative to the true North, for every 10-min sample:

$$Dir_{\text{TrueNorth}} = \left(Dir_{\text{Yaw,TR}} + Dir_{\text{OffsetCorr}}\right) \bmod 360° \tag{D.1}$$

where $Dir_{\text{OffsetCorr}}$ is an offset angle to correct $Dir_{\text{Yaw,TR}}$ relative to true North.

It is recommended to calibrate the nacelle position signal one month prior to the installation of the NML. Since the yaw encoder can be subject to drift, it is recommended to re-check the validity of the calibration just before or/and just after the installation of the NML.

D.2.4.3 Baseline

A baseline dataset needs to be collected prior to the lidar installation. The selected dataset should fulfil the following criteria:

- $Dir_{\text{TrueNorth}}$ within the measurement sector (In case of doubt regarding the accuracy of the North alignment, reduction of the sector is advisable.);
- minimum wind speed range: 6 m/s to 10 m/s;
- minimum number of samples: 12 samples (i.e. 2 hours) per 0.5m/s bin.

The baseline is obtained by applying the following steps to the selected data:

1) for every 10-min sample within the selected dataset, evaluate the difference between the two nacelle wind direction sensors:

$$\Delta Dir_{\text{Nac}} = Dir_{\text{1,Nac,TR}} - Dir_{\text{2,Nac,TR}}$$

2) bin the data in wind speed bins of 0.5m/s;

3) for each bin, evaluate:

- the bin-averaged value of the nacelle wind speed, $v_{i,\mathrm{Nac,TR,\ before}}$,
- the bin-averaged value of the difference between the two nacelle wind direction sensors, $\Delta Dir_{i,\mathrm{Nac,\ before}}$,
- the bin standard deviation of the difference between the two nacelle wind direction sensors, $\sigma_{i,\Delta Dir,\mathrm{before}}$;

4) plot $\Delta Dir_{i,\mathrm{Nac,before}}$ vs $v_{i,\mathrm{Nac,TR,before}}$, with $\sigma_{i,\Delta Dir,\mathrm{before}}$ as error bars (see example in Figure D.4).

The $\Delta Dir_{i,\mathrm{Nac,before}}$ function should ideally be a constant value close to 0 degrees.

D.2.4.4 Lidar influence assessment

Once the lidar has been installed, data acquisition from the SCADA system is continued unchanged (i.e. the lidar data is not used as a data stream fed to the turbine control). A new dataset should be selected following the same criteria as the baseline. $\Delta Dir_{i,\mathrm{Nac,after}}$, $\sigma_{\mathrm{i,\Delta Dir,after}}$ and $v_{i,\mathrm{Nac,TR,after}}$, should be evaluated following the same process as the baseline corresponding parameters. The results with bin averages and standard deviations before and after the lidar installation are shown in a single plot (see example in Figure D.4).

It is considered that the lidar has no influence on the nacelle direction sensors if both of following criteria are fulfilled for at least 90% of the wind speed bins:

- The bin-averaged difference, $\Delta Dir_{i,\mathrm{Nac}}$, before and after the lidar installation, does not differ by more than 4 degrees:

$$4^\circ \leq \left| \Delta Dir_{i,\mathrm{Nac,before}} - \Delta Dir_{i,\mathrm{Nac,after}} \right| \qquad \text{(D.2)}$$

- The bin-averaged difference after the lidar installation, $\Delta Dir_{i,\mathrm{Nac,after}}$, is within $\Delta Dir_{i,\mathrm{Nac,before}} \pm \sigma_{i,\ \Delta Dir,\mathrm{before}}$.

In the example plot in Figure D.4, no systematic change has been identified. The specific details are expected to vary with turbine designs.

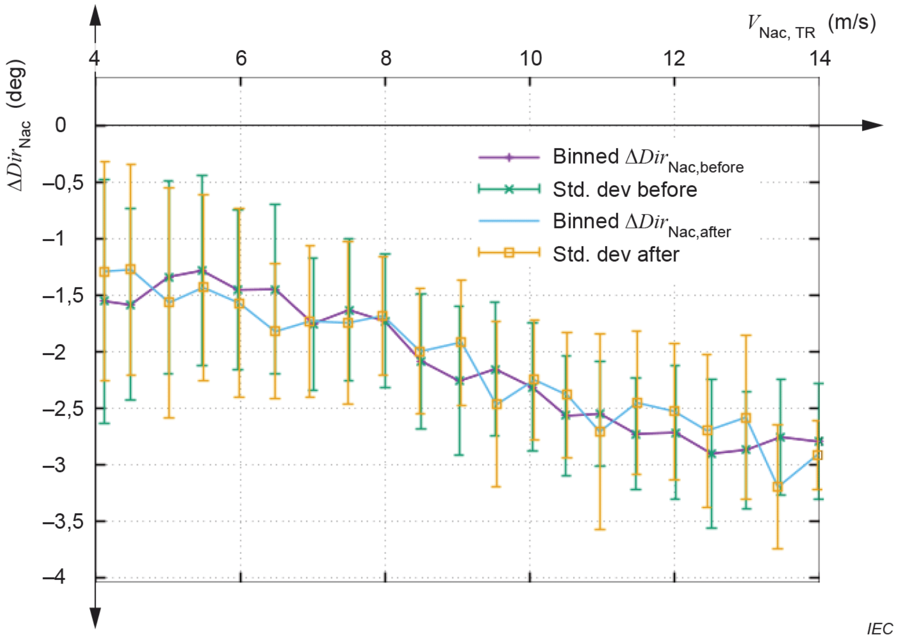


Figure D.4 – Example of binned ΔDir_{Nac} function for a setting where the lidar has not significantly influenced the two nacelle wind direction sensors' reported signals

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This Indian Standard has been developed from Doc No.: ETD 42 (21804).

Amendments Issued Since Publication

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