



BSI Standards Publication

Wind energy generation systems

Part 50-3: Use of nacelle-mounted lidars for wind measurements

National foreword

This British Standard is the UK implementation of EN IEC 61400-50-3:2022. It is identical to IEC 61400-50-3:2022, incorporating corrigendum November 2023.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by IEC corrigendum November 2023 is indicated in the text by AC1 AC1.

The UK participation in its preparation was entrusted to Technical Committee PEL/88, Wind turbines.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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31 December 2023	Implementation of IEC corrigendum November 2023. National foreword corrected.

English Version

Wind energy generation systems - Part 50-3: Use of nacelle-mounted lidars for wind measurements
(IEC 61400-50-3:2022)

Systèmes de génération d'énergie éolienne - Partie 50-3:
Utilisation de lidars montés sur nacelle pour le mesurage du
vent
(IEC 61400-50-3:2022)

Windenergieanlagen - Teil 50-3: Verwendung von auf der
Gondel montierten LiDARs für Windmessungen
(IEC 61400-50-3:2022)

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Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

European foreword

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The following dates are fixed:

- latest date by which the document has to be implemented at national (dop) 2022-11-11 level by publication of an identical national standard or by endorsement
- latest date by which the national standards conflicting with the (dow) 2025-02-11 document have to be withdrawn

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In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61400-1:2019 NOTE Harmonized as EN IEC 61400-1:2019 (not modified)

Annex ZA

(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 61400-12-1	2017	Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines	EN 61400-12-1	2017
IEC 61400-12-2	2013	Wind turbines - Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry	EN 61400-12-2	2013

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 50-3: Use of nacelle-mounted lidars for wind measurements

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International Standard IEC 61400-50-3 has been prepared by IEC technical committee TC 88: Wind energy generation systems.

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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
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- amended.

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The contents of the corrigendum 1 (2023-11) have been included in this copy.

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: $SNR = CNR_{nb}\sqrt{n}$, 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



Documents

Document Sharing Hub

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
$Dir_{OffsetCorr}$	correction angle between true north and nacelle orientation angle $Dir_{Yaw,TR}$ (D.2.4)	deg
$Dir_{TrueNorth}$	nacelle orientation relative to true north (D.2.4)	deg
$Dir_{1,Nac,TR}$	10-min average turbine-reported relative wind direction of first sensor (D.2.4)	deg
$Dir_{2,Nac,TR}$	10-min average turbine-reported relative wind direction of second sensor (D.2.4)	deg
$Dir_{Yaw,TR}$	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_{igt}	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
$u_{\text{ope,lidar}}$	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
$u_{\text{vert_pos}}$	uncertainty due to the height difference between the reference sensor and the LOS	m/s
$u_{V,\text{hor}}$	horizontal wind speed uncertainty	m/s
$u_{V,\text{LOS}}$	uncertainty of the LOS speed estimate	m/s
u_{V_m}	uncertainty of the measured wind speed (A.4)	m/s
u_{rfr}	reference wind speed uncertainty	m/s
$u_{\langle v \rangle, \text{WFR}}$	propagated uncertainty of the LOS speed uncertainties through the WFR algorithm	m/s
$u_{\text{WFR,par}}$	uncertainty due to parameter in WFR algorithm (9.2.2)	m/s
$u_{\langle \Delta v \rangle, \text{measHeight}}$	uncertainty due to varying measurement height (9.4)	m/s
u_{z_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
$u_{\theta, \text{LOS}}$	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)	[AC1] m/s [AC1]
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
$\delta_{StandStill}$	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
$\theta_{Induction}$	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.).