

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 50-3: Use of nacelle-mounted lidars for wind measurements**

**Systèmes de génération d'énergie éolienne –
Partie 50-3: Utilisation de lidars montés sur nacelle pour le mesurage du vent**



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2022 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Discover our powerful search engine and read freely all the publications previews. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 300 terminological entries in English and French, with equivalent terms in 19 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Recherche de publications IEC -

webstore.iec.ch/advsearchform

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études, ...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

IEC Just Published - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Découvrez notre puissant moteur de recherche et consultez gratuitement tous les aperçus des publications. Avec un abonnement, vous aurez toujours accès à un contenu à jour adapté à vos besoins.

Electropedia - www.electropedia.org

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 300 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 19 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.



IEC 61400-50-3

Edition 1.0 2022-01

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 50-3: Use of nacelle-mounted lidars for wind measurements**

**Systèmes de génération d'énergie éolienne –
Partie 50-3: Utilisation de lidars montés sur nacelle pour le mesurage du vent**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.180

ISBN 978-2-8322-1063-9

**Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**

CONTENTS

FOREWORD.....	6
1 Scope.....	8
2 Normative references	8
3 Terms and definitions	9
4 Symbols and abbreviated terms.....	14
5 Overview	18
5.1 General.....	18
5.2 Measurement methodology overview	19
5.3 Document overview.....	20
6 Lidar requirements.....	20
6.1 Functional requirements.....	20
6.2 Documentary requirements	21
6.2.1 Technical documentation	21
6.2.2 Installation and operation documentation.....	22
7 Calibration and uncertainty of nacelle lidar intermediate values	22
7.1 Calibration method overview	22
7.2 Verification of beam trajectory/geometry	23
7.2.1 Static position uncertainty.....	23
7.2.2 Dynamic position uncertainty	24
7.3 Inclinator calibration	24
7.4 Verification of the measurement range.....	24
7.5 LOS speed calibration.....	25
7.5.1 Method overview	25
7.5.2 Calibration site requirements	26
7.5.3 Setup requirements	28
7.5.4 Calibration range	30
7.5.5 Calibration data requirements and filtering.....	30
7.5.6 Determination of LOS	31
7.5.7 Binning of data and database requirements	33
7.6 Uncertainty of the LOS speed measurement	33
7.6.1 General	33
7.6.2 Uncertainty of V_{ref}	34
7.6.3 Flow inclination uncertainty.....	37
7.6.4 Uncertainty of the LOS speed measurement	37
7.7 Calibration results	38
7.8 Calibration reporting requirements	39
7.8.1 Report content.....	39
7.8.2 General lidar information	40
7.8.3 Verification of beam geometry/trajectory (according to 7.2).....	40
7.8.4 Inclinator calibration (according to 7.3)	40
7.8.5 Verification of the sensing range (according to 7.4)	40
7.8.6 LOS speed calibration (for each LOS).....	40
8 Uncertainty due to changes in environmental conditions.....	41
8.1 General.....	41
8.2 Intermediate value uncertainty due to changes in environmental conditions	41
8.2.1 Documentation	

8.2.2	Method	41
8.2.3	List of environmental variables to be considered	42
8.2.4	Significance of uncertainty contribution	42
8.3	Evidence-base supporting the adequacy of the WFR	42
8.4	Requirements for reporting	43
9	Uncertainty of reconstructed wind parameters	44
9.1	Horizontal wind speed uncertainty	44
9.2	Uncertainty propagation through WFR algorithm	45
9.2.1	Propagation of intermediate value uncertainties $u_{\langle V \rangle, WFR}$	45
9.2.2	Uncertainties of other WFR parameters $u_{WFR, par}$	46
9.3	Uncertainty associated with the WFR algorithm $u_{ope, lidar}$	46
9.4	Uncertainty due to varying measurement height $u_{\langle \Delta V \rangle, measHeight}$	46
9.5	Uncertainty due to lidar measurement inconsistency	46
9.6	Combining uncertainties	47
10	Preparation for specific measurement campaign	47
10.1	Overview of procedure	47
10.2	Pre-campaign check list	47
10.3	Measurement set up	48
10.3.1	Lidar installation	48
10.3.2	Other sensors	48
10.3.3	Nacelle position calibration	49
10.4	Measurement sector	49
10.4.1	General	49
10.4.2	Assessment of influence from surrounding WTGs and obstacles	49
10.4.3	Terrain assessment	52
11	Measurement procedure	53
11.1	General	53
11.2	WTG operation	53
11.3	Consistency check of valid measurement sector	54
11.4	Data collection	55
11.5	Data rejection	56
11.6	Database	56
11.7	Application of WFR algorithm	56
11.8	Measurement height variations	57
11.9	Lidar measurement monitoring	57
12	Reporting format – relevant tables and figures specific to nacelle-mounted lidars	57
12.1	General	57
12.2	Specific measurement campaign site description	57
12.3	Nacelle lidar information	58
12.4	WTG information	58
12.5	Database	58
12.6	Plots	59
12.7	Uncertainties	59
Annex A (informative)	Example calculation of uncertainty of reconstructed parameters for WFR with two lines of sight	60
A.1	Introduction to example case	60
A.2	Uncertainty propagation through WFR algorithm	61
A.3	Operational uncertainty of the lidar and WFR algorithm	63

A.4	Uncertainty contributions from variation of measurement height.....	63
A.5	Wind speed consistency check.....	64
A.6	Combined uncertainty	64
Annex B (informative)	Suggested method for the measurement of tilt and roll angles.....	65
Annex C (informative)	Recommendation for installation of lidars on the nacelle	68
C.1	Positioning of lidar optical head on the nacelle.....	68
C.2	Lidar optical head pre-tilt for fixed beam lidars.....	69
C.3	Attachment points for the lidar	70
Annex D (informative)	Assessing the Influence of nacelle-mounted lidar on turbine behaviour.....	71
D.1	General.....	71
D.2	Recommended consistency checks methods.....	71
D.2.1	General	71
D.2.2	Documentation-based approach	71
D.2.3	Data-based approach using neighbouring WTG	72
D.2.4	Data-based approach using only the WTG being assessed.....	74
Bibliography		78
Figure 1	– Example of opening angle β between two beams	23
Figure 2	– Side elevation sketch of calibration setup.....	26
Figure 3	– Plan view sketch of sensing and inflow areas	27
Figure 4	– Sketch of a calibration setup	30
Figure 5	– Example of lidar response to the wind direction and cosine fit.....	32
Figure 6	– Example of LOS evaluation using the RSS process: RSS vs θ_{proj}	33
Figure 7	– High level process for horizontal wind speed uncertainty propagation	45
Figure 8	– Procedure flow chart	47
Figure 9	– Plan view sketch of NML beams upstream of WTG being assessed and neighbouring turbine wake	49
Figure 10	– Sectors to exclude due to wakes of neighbouring and operating WTGs and significant obstacles	51
Figure 11	– Example of sectors to exclude due to wakes of a neighbouring turbine and a significant obstacle	52
Figure 12	– Example of full directional sector discretization	53
Figure 13	– Lidar relative wind direction vs turbine yaw for a two-beam nacelle lidar [Wagner R, 2013].....	54
Figure 14	– Example of LOS turbulence intensity vs turbine yaw, for a two-beam nacelle lidar	55
Figure B.1	– Pair of tilted and rolled lidar beams (red) shown in relation to the reference position (grey).....	65
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)	67
Figure C.1	– Example of a good (left) and bad (right) position for a 2-beam lidar	68
Figure C.2	– Example of a good (left) and bad (right) position for a 4-beam lidar	68
Figure C.3	– Sketch of lidar optical head pre-tilted downwards to measure at hub height (example for a two beam lidar)	70
Figure D.1	– Example of reporting the side-by-side comparison	73

Figure D.2 – Example of the power ratio between two neighbouring turbines	74
Figure D.3 – General process outline	74
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	77
Table 1 – Summary of calibration uncertainty components	38
Table 2 – Calibration table example	39
Table 3 – Calibration table example (n=1...N; N is the total number of lines of sight calibrated)	39
Table A.1 – Uncertainty components and their correlations between different LOSs for this example	62

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

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

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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

The text of this International Standard is based on the following documents:

Draft	Report on voting
88/845/FDIS	88/853/RVD

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,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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)	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
$\delta_{StandStill}$	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.).

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, $u_{V_{LOS}}$. 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).

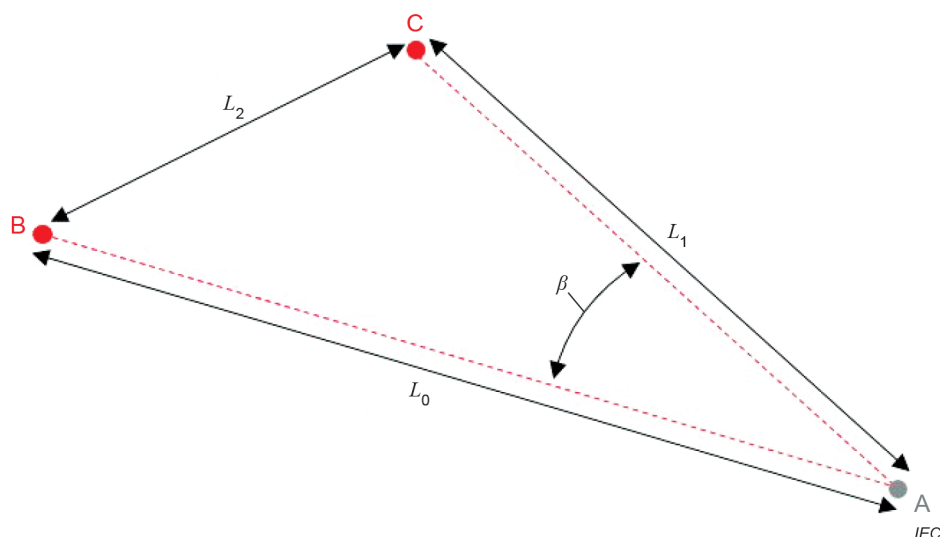
The uncertainty of the measured angles shall be stated. The test results (measured angles and their uncertainties) shall be compatible with the values and tolerances stated in the manufacturer specifications (technical documentation provided according to 6.2.1 (item 4)).

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:

$$\beta = \arccos\left(\frac{L_0^2 + L_1^2 - L_2^2}{2L_0L_1}\right) \quad (2)$$

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

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

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 ($W \ll V_{\text{hor}}$), with a small elevation angle and small inflow angles (e.g. between -2° and $+2^\circ$), the impact of the contribution of the vertical component can be neglected, and formula (3) can be written as:

$$V_{\text{ref}} = V_{\text{hor}} \cdot \cos \varphi \cdot \cos \theta_r \quad (4)$$

where $\theta_r = \theta - \theta_{\text{los}}$ 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.

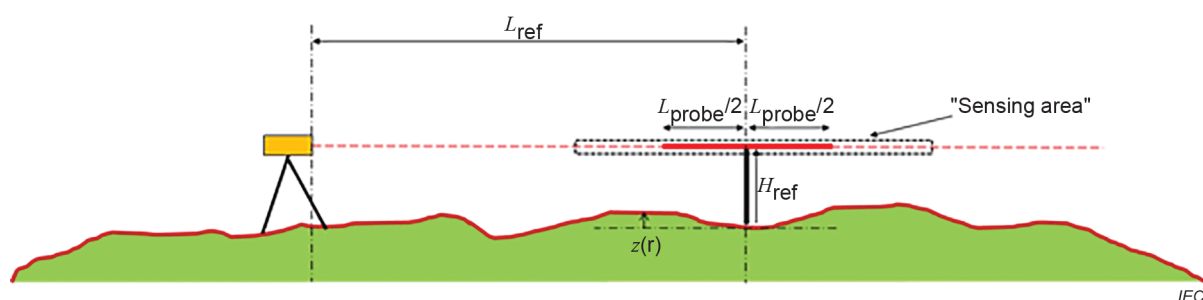
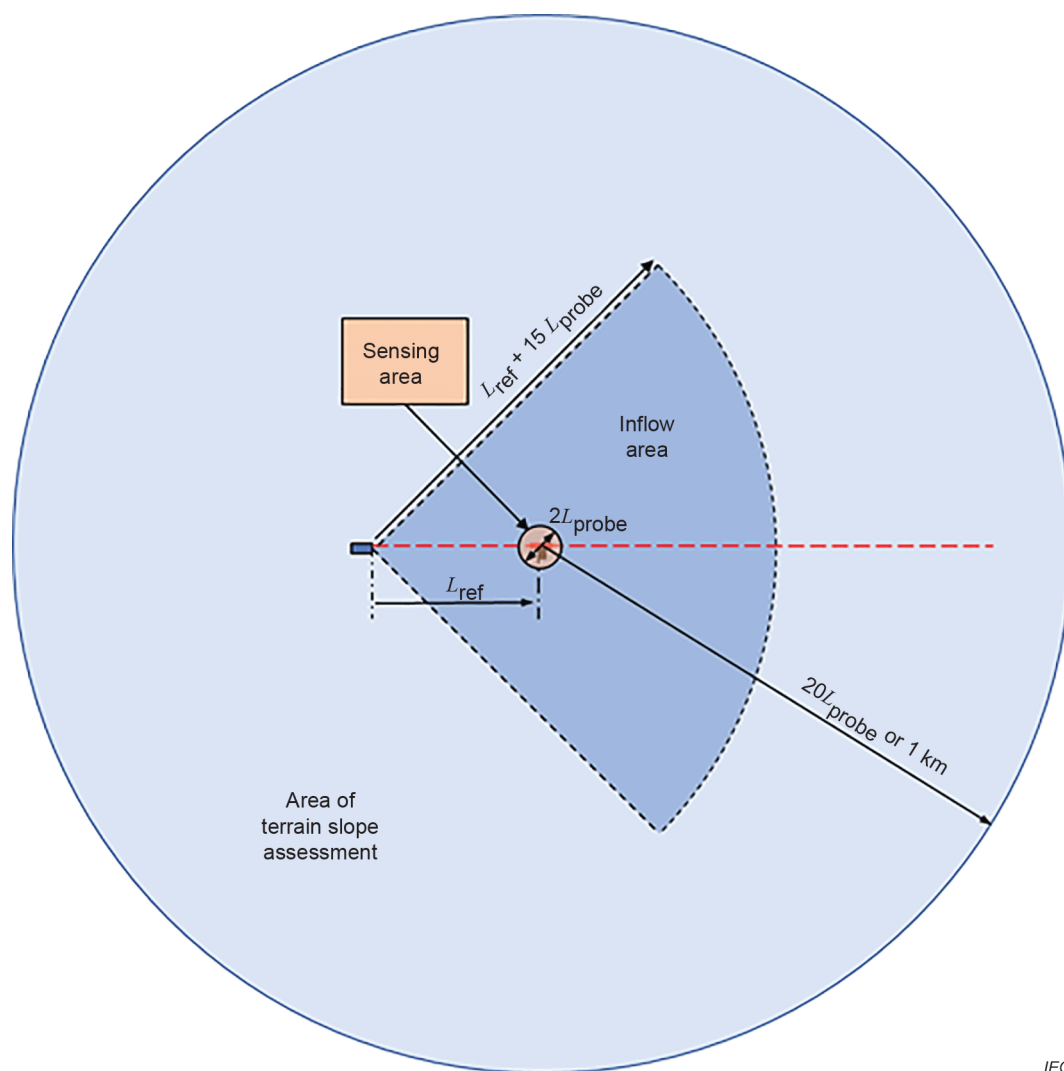


Figure 2 – Side elevation sketch of calibration setup



IEC

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 $20L_{\text{probe}}$ (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 $\pm H_{\text{ref}} / 20$, i.e.

$$\left| \max z - \min z \right| \leq H_{\text{ref}} / 20.$$
 - within the inflow area but outside the sensing area, height variations may not exceed these limits:

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

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

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

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

so that:

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

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

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

$$D_e = 2 * \frac{l_h * l_w}{l_h + l_w} \quad (6)$$

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 $\pm 0,1^\circ$ 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

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

where

R is the distance along the LOS (not the horizontal distance) from the laser beam origin to the reference instrument. $R = L_{\text{ref}} \cos \varphi$, 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.

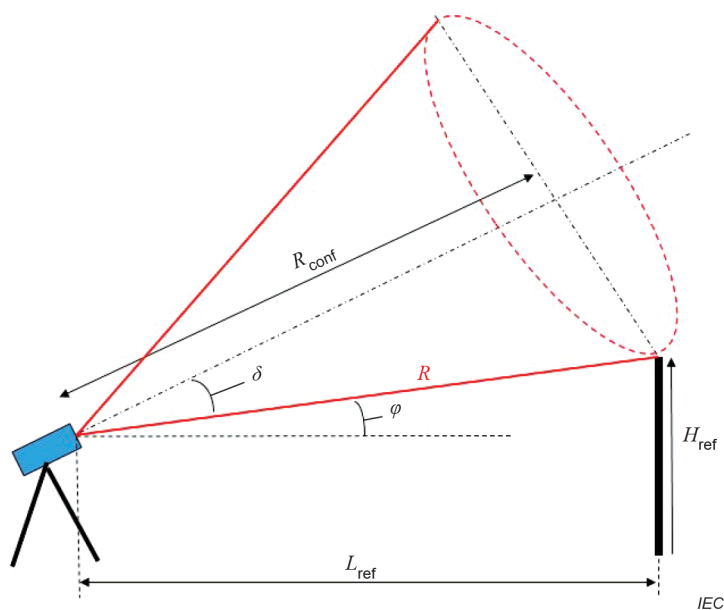


Figure 4 – Sketch of a calibration setup

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 $\varphi V_{\text{hor}} \sin \theta V_{\text{hor}} \cos \theta$. 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 ($\theta_{\text{LOS}} \pm 40^\circ$ 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

$$\epsilon_v = \tan \psi \tan \varphi \quad (8)$$

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 $\pm 1\%$, 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 ($V_{\text{LOS,norm}}$) 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:

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

The fitting function f_{fit} is:

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

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.

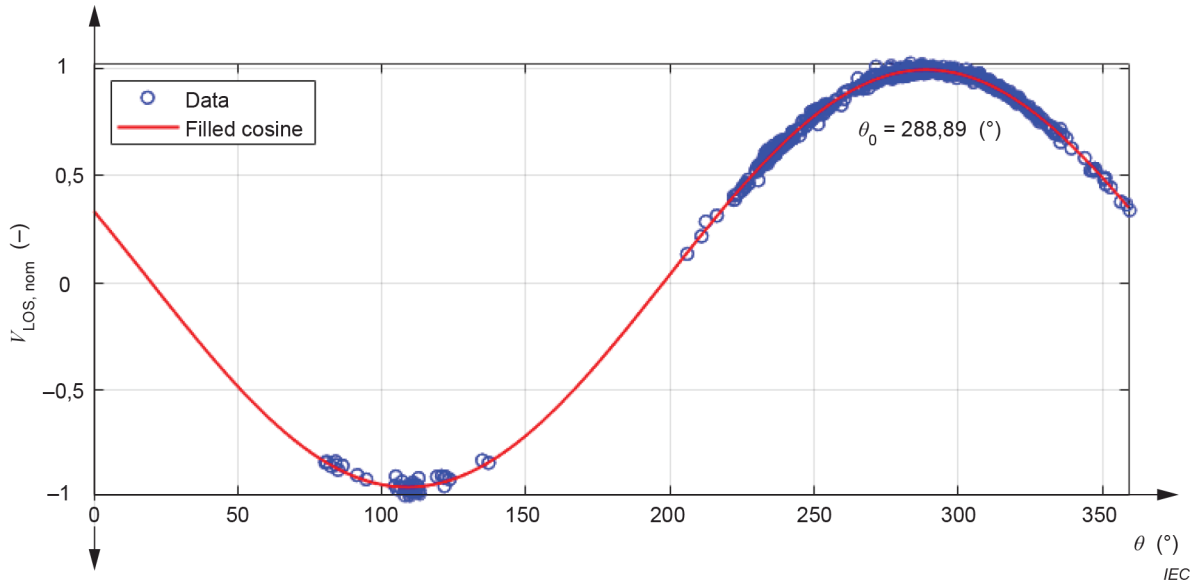


Figure 5 – Example of lidar response to the wind direction and cosine fit

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 $\theta_{proj}(\theta_{proj,i}; i = 1, \dots, 20)$ centred around θ_0 with an increment of $0,1^\circ$:

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

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

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 $RSS_i = \sum_k^N (V_{LOS} - V_{LOS_fit,i})^2$.

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

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): $V_{ref} = V_{hor} \cdot \cos \varphi \cdot \cos(\theta - \theta_{LOS})$.

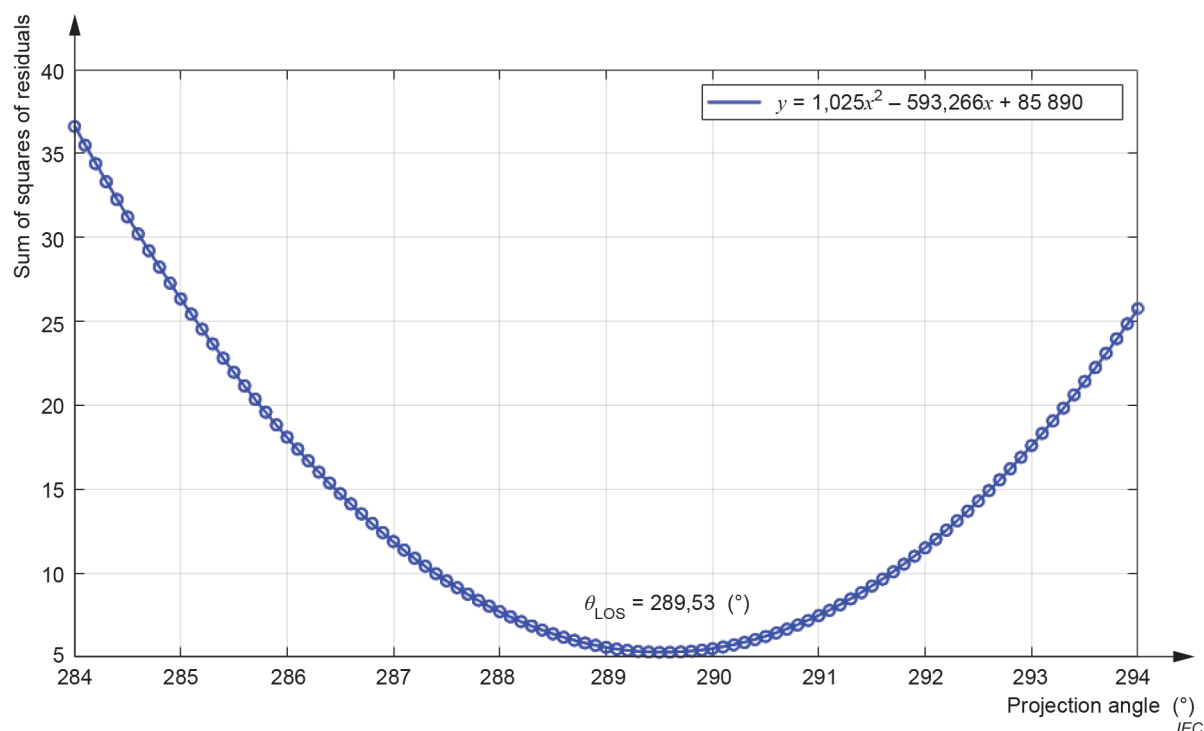


Figure 6 – Example of LOS evaluation using the RSS process: RSS vs θ_{proj}

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 $\theta_r = \theta - \theta_{\text{LOS}}$ 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:

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

The sensitivity coefficients are:

$$\frac{\partial V_{\text{ref}}}{\partial V_{\text{hor}}} = \cos \varphi \cos \theta_r \quad (13)$$

$$\frac{\partial V_{\text{ref}}}{\partial \varphi} = -V_{\text{hor}} \sin \varphi \cos \theta_r \quad (14)$$

$$\frac{\partial V_{\text{ref}}}{\partial \theta_r} = -V_{\text{hor}} \sin \theta_r \cos \varphi \quad (15)$$

The uncertainties and sensitivity factors may be calculated from bin-averaged values¹. For angular quantities, the recommendation is to average the values of the angles, e.g. $\cos(\text{avg}(\theta_r))$.

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:

$$u_{V_{\text{hor}}} = \sqrt{u_{\text{sens}}^2 + u_{\text{pos}}^2} \quad (16)$$

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.

$$u_{\text{sens}} = \sqrt{u_{\text{cal}}^2 + u_{\text{ope}}^2 + u_{\text{mast}}^2 + u_{\text{igt}}^2 + u_{\text{daq}}^2} \quad (17)$$

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_{igt} 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:

$$u_{\text{pos}} = \sqrt{u_{\text{probe}}^2 + u_{\text{inc}}^2 + u_{\text{vert_pos}}^2} \quad (18)$$

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

$$u_{\text{inc}} = \alpha \frac{\sin \varphi \, u_{\text{range}}}{H_{\text{ref}}} V_{\text{hor}} \quad (19)$$

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:

$$u_{\text{vert_pos}} = \alpha \frac{u_H}{H_{\text{ref}}} V_{\text{hor}} \quad (20)$$

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

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

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 $0,1^\circ$.

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:

$$u_{\psi_i} = W \sin \varphi_i \approx V_{\text{hor}} \tan \psi_i \sin \varphi_i \quad (22)$$

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:

$$u_{V_{\text{LOS}}} = \sqrt{u_{V_{\text{ref}}}^2 + (V_{\text{hor}} \sin \varphi \cos \theta_r)^2 u_{\psi_i}^2 + \frac{\sigma_{\text{dev}}^2}{N}} \quad (23)$$

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 $\Delta V = (V_{\text{LOS}} - V_{\text{ref}})$ 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, $u_{\text{vert_pos}}$	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, $u_{\theta_{\text{los}}}$	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	$\sigma_{\text{dev}} / \sqrt{N}$

7.7 Calibration results

The average of the difference between V_{LOS} and V_{ref} in the bin, $\Delta V = V_{\text{LOS}} - V_{\text{ref}}$, 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 $u_{V_{LOS}}$ 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 $|\Delta V| < u_{V_{LOS}}$, 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)	$u_{V_{ref}}$ (m/s)	$u_{V_{LOS}}$ (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	$u_{corr,1}$	$u_{uncorr,1}$	...	$u_{corr,n}$	$u_{uncorr,n}$		$u_{corr,N}$	$u_{uncorr,N}$

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

$u_{uncorr,n}^2$ 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 Inclinator 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 $\pm u_{V_{\text{ref}}}$ 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 inconsistency (see 9.5).

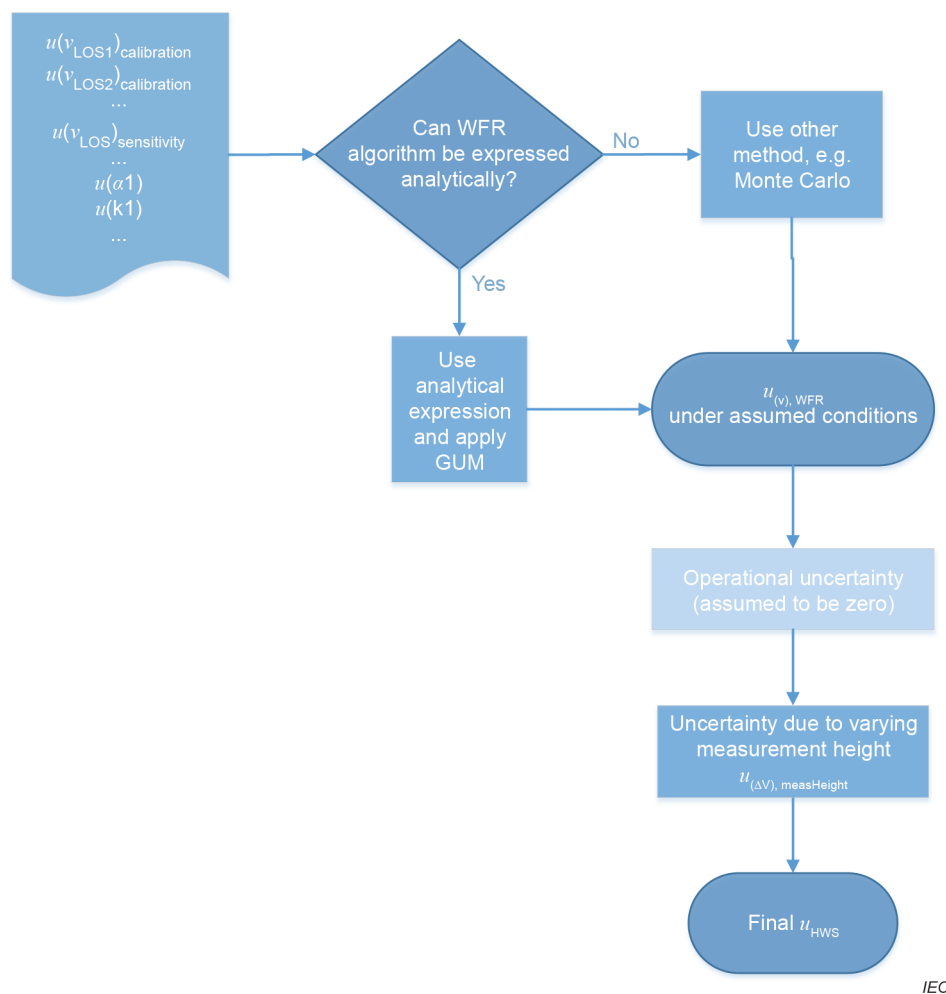


Figure 7 – High level process for horizontal wind speed uncertainty propagation

9.2 Uncertainty propagation through WFR algorithm

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

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.

- 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).
- 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 $V_{LOS,i}$ corrected by the calibration function, and $V_{ref,i}$ ("i" denotes the calibration bin index).

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

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 $u_{ope,lidar}$

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 $u_{(\Delta V),measHeight}$

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

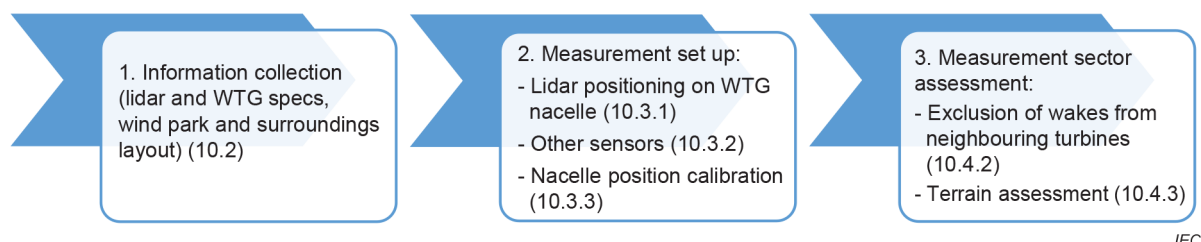
The above four (9.2.1, 9.2.2, 9.4, 9.5²) types of uncertainties can be considered as fully uncorrelated and shall be added in quadrature.

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.



IEC

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.