



BSI Standards Publication

Wind energy generation systems

Part 50-4: Use of floating lidar systems for wind measurements

National foreword

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

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

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TECHNICAL SPECIFICATION

**Wind energy generation systems –
Part 50-4: Use of floating lidar systems for wind measurements**



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WIND ENERGY GENERATION SYSTEMS –

Part 50-4: Use of floating lidar systems for wind measurements

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IEC TS 61400-50-4 has been prepared by of IEC technical committee 88: Wind energy generation systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
88/1042/DTS	88/1094/RVDTS

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 Technical Specification 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/publications.

A list of all parts of the IEC 61400 series, under the general title: *Wind energy generation systems*, can be found on the IEC website.

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- withdrawn, or
- revised.

WIND ENERGY GENERATION SYSTEMS –

Part 50-4: Use of floating lidar systems for wind measurements

1 Scope

The purpose of this part of IEC 61400, which is a Technical Specification, is to describe procedures and methods which ensure that wind measurements using floating wind lidar systems 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 and technical specifications, it is anticipated that the wind measurements will be used in relation to some form of wind energy testing or resource assessment.

The scope of this document is limited to vertically profiling wind lidar devices in or on buoys.

This document aims to be applicable to any type and make of floating wind lidar system. The method and requirements provided in this document are independent of the model and type and of the measurement principle and allow application to new types of floating wind lidar systems as these become available.

This part of IEC 61400 aims to describe wind measurements using floating wind lidar with sufficient quality for the use case of wind resource assessment. Readers of this document can consider other use cases that can have other specific requirements.

Detailed guidance on metocean measurements in general is out of the scope of this document.

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.

IEC 61400-1, *Wind turbines – Part 1: Design requirements*

IEC 61400-3-1:2019, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-12-1:2022, *Wind energy generation systems – Part 12-1 Power performance measurements of electricity producing wind turbines*

IEC 61400-12-5:2022, *Wind energy generation systems – Part 12-5 Power performance – Assessment of obstacles and terrain*

IEC 61400-50-1:2022, *Wind energy generation systems – Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*

IEC 61400-50-2:2022, *Wind energy generation systems – Part 50-2: Wind measurement – Application of ground-mounted remote sensing technology*

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

IEC TS 62600-101, *Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization*

ISO 19901-1, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations*

VIM, International vocabulary of metrology – Basic and general concepts and associated terms (VIM), Technical report, JCGM, 2012 (<https://www.bipm.org/en/publications/guides/vim.html>) [viewed 2024-04-09]

JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, (GUM 1995 with minor corrections) https://www.bipm.org/utis/common/documents/jcgm/JCGM_100_2008_E.pdf [viewed 2024-04-09]

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61400-12-1:2022, IEC 61400-50-0:2022, IEC 61400-50-1:2022, IEC 61400-50-2:2022 and IEC 61400-50-3:2022 and the following apply.

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

3.1.1

ACARA principle

degree to which an uncertainty budget can be considered to be complete and representative of the range of measurement outcomes that can be expected following a thorough and systematic investigation of contributions to the uncertainty budget

Note 1 to entry: ACARA stands for "As Complete As Reasonably Achievable".

3.1.2

acceptance criteria

value or set of values that performance metrics or key performance indicators shall achieve for the data characterised by those metrics to be considered acceptable for the purposes of subsequent analysis

3.1.3

anticipated hub height

hub height of the wind turbines expected to be installed at the site for which a specific measurement campaign (SMC) has been undertaken

3.1.4

as-built report

report documenting the status and configuration of an instrument after it has been manufactured and system integration has been completed, prior to being deployed to a site to acquire measurements

Note 1 to entry: See also factory acceptance test (FAT).

3.1.5**as-deployed report**

report documenting the status and configuration of an instrument after it has been deployed to a site to acquire measurements

Note 1 to entry: See also site acceptance test (SAT).

3.1.6**auxiliary systems**

equipment that supports the wind measurement process and operation of the floating lidar system (FLS) or allows the characterisation of operational conditions

3.1.7**calibration**

process of characterising the performance of an individual unit of a type of instrument with respect to measurement accuracy by comparison with a suitable reference instrument

3.1.8**calibration uncertainty**

contribution to measurement uncertainty that accrues from the accuracy established during calibration

3.1.9**classification**

process of characterising the performance of a type of instrument with respect to the sensitivity of its measurement accuracy to operational conditions, including environmental variables that influence its performance

3.1.10**classification uncertainty**

contribution to measurement uncertainty that accrues from the sensitivities characterised during classification

3.1.11**configuration uncertainty**

contribution to measurement uncertainty that accrues during a specific measurement campaign in relation to the consistency and reproducibility of the configuration of the FLS and measurement setup that applied when the performance of the FLS with respect to accuracy was characterised, such as the calibration of the unit being deployed

3.1.12**coverage factor**

proportion of an averaging interval in which measurements that are averaged to represent conditions during that interval have been acquired

3.1.13**data availability**

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

3.1.14**data completion**

acquisition of data sufficient to fulfil data completion criteria

3.1.15**data completion criteria**

amount of data that needs to be acquired to be considered sufficient for aggregation in a statistical analysis of the conditions being measured

3.1.16**data redundancy**

practice of acquiring more than one measurement of a quantity so that, if one set of measurements proves to be unreliable or is rejected for some reason, information about the quantity is still available

3.1.17**documentation pack**

collection of reports used to document previous activities or instrument status

3.1.18**data pack**

collection of measurements used to characterise previous activities or instrument status

3.1.19**envelope of operational conditions**

range of operational conditions, typically described using ranges of values taken by environmental variables, within which an adequate evidence base exists to support confidence in a particular performance characteristic of a type of instrument

Note 1 to entry: In particular, an EOC may be a range of conditions for which there is evidence that an instrument is not sensitive to those environmental variables for the purposes of classification uncertainty estimation, such that a zero classification uncertainty may be assumed for measurements acquired within that range of conditions using that instrument.

3.1.20**environmental variable**

parameter that characterises some aspect of the environmental conditions prevailing during a measurement campaign, such as temperature, wind shear, turbulence, wave height, etc.

3.1.21**evidence base**

collection of reports documenting tests that demonstrate a performance characteristic of a type of instrument

Note 1 to entry: The evidence base should include a summary of the results documented by these test reports. The results should demonstrate this characteristic and fulfil any minimum requirements for evidence demonstrating this characteristic. In particular, the evidence base may support the application of zero classification uncertainty for a type of instrument operated within a specified envelope of operational conditions.

3.1.22**factory acceptance test**

set of checks undertaken after an instrument has been manufactured, prior to leaving the factory or the manufacturer's facilities, before its first deployment

3.1.23**final uncertainty evaluation**

uncertainty evaluation calculated after the measurement campaign is complete, based on contributions to uncertainty known prior to the campaign, such as the calibration uncertainty, and contributions that are not finalised until after the campaign is complete, such as classification uncertainty based on variations in environmental variables observed during the campaign rather than pre-deployment estimates

Note 1 to entry: See also preliminary classification uncertainty.

3.1.24**final value**

values provided by the floating lidar system for use in wind energy assessment applications and lidar use cases such as wind climate assessment and WTG power performance testing

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

3.1.25**final variable**

variable which can be assigned a final value

3.1.26**fixed reference**

reference instrument that is not subject to motion, which is operated in a ground-based or equivalent manner

3.1.27**floating lidar system**

integrated system consisting of one or more lidar wind measurement devices, installed in or on top of a floating platform, and auxiliary equipment such as a power supply, communication system and secondary sensors

3.1.28**flow distortion**

change in air flow caused by topographical variations, wind turbines, or other obstacles, that results in the wind speed at the measurement location being different from the wind speed at the reference location or other position of interest

3.1.29**FLS type**

distinct make and model of FLS whose instances share performance characteristics which can be assessed by classification, with respect to the sensitivity of accuracy to environmental variables, and more generally by type qualification, with respect to all aspects of performance common to units of that type regarding their suitability for deployment to address a given use case and fulfil its data requirements

3.1.30**FLS unit**

individual instance of an FLS type, whose performance is tested by calibration, with respect to accuracy, and more generally by unit qualification

3.1.31**full calibration test**

test of the performance of a unit with respect to accuracy by comparison with a suitable reference instrument following a procedure with clear data completion criteria

Note 1 to entry: The results of the full calibration test include the determination of the calibration uncertainty associated with the unit. A full test has more stringent data completion criteria than a simplified test. See also simplified calibration test and simplified calibration protocol.

3.1.32**full calibration protocol**

methodology for performing a full calibration test

3.1.33**hardware compensation**

motion compensation achieved by physical adjustments of the configuration and/or orientation of the system by mechanical means

3.1.34**horizontal wind speed and direction**

primitive scalar quantities describing the magnitude and direction of the wind velocity vector projected onto the horizontal plane

3.1.35**instrument qualification**

process by which the performance of a measurement instrument with respect to accuracy, and its response to operational conditions such as environmental variables, are characterised such that its suitability for a given use case can be determined

Note 1 to entry: A type of instrument may be qualified to determine its classification. An individual unit of that type may be qualified to determine its calibration.

3.1.36**instrument qualification cycle**

continual use of additional results obtained using fully qualified instruments in combination with concurrent and collocated reference measurements and measurements of operational conditions such as environmental variables to update and improve instrument qualification in a cyclic manner

3.1.37**intermediate value**

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

Note 1 to entry: Intermediate values are directly measured or observed and are processed in accordance with the WFR model to derive or infer values of the final variables that satisfy the data requirements of the use case being addressed.

Note 2 to entry: Examples of intermediate values include (but are not limited to) line of sight (LOS) speeds, range gate or pulse time of flight, pulse length or duration, pulse profile, beam orientation in terms of azimuth and elevation angle, measurement time.

3.1.38**intermediate variable**

variable which can be assigned an intermediate value

3.1.39**measurement method**

set of operations performed by an instrument and the procedure by which a measurement is derived from the outcome of those operations

3.1.40**measurement principle**

set of physical assumptions on which a measurement method is based

3.1.41**measurement volume**

region of space in which the interactions between wind conditions and lidar emissions take place that form the basis of the measurement of final variables

3.1.42**mechanical anemometry**

wind speed measurement equipment that acquires data through a mechanical interaction between wind conditions and the physical apparatus, whereby the wind exerts a force that causes a component to move, such that wind conditions can be inferred from this motion

3.1.43**meta data**

data that provide information necessary for the interpretation and/or analysis of other data

3.1.44**mooring system**

system connecting the FLS to fixed anchor points via an arrangement of cables or chains in order to keep the FLS in position

3.1.45**motion compensation**

process to adjust measurements that are affected by the motion of the FLS due to waves in order to reduce or eliminate the influence of the motion such that the measurements are independent of sea state to an extent that fulfils the data precision requirements of the use case

3.1.46**motion compensation system**

system that performs motion compensation, either by mechanical actuation of the instrument, software modifications of the data, or some combination of both

3.1.47**motion correction algorithm**

calculation or series of calculations that adjusts or modifies wind measurements to compensate for the motion of the FLS due to waves

3.1.48**motion limits**

maximum permissible values of the excursion of the orientation of a system from a position at rest due to motion, within which measurements remain valid and/or motion compensation methods perform satisfactorily

3.1.49**motion sensor**

instrument for measuring rotational and translational motion of the FLS

3.1.50**null data return**

record indicating that a valid measurement was not acquired

3.1.51**observed operational conditions**

circumstances that were observed to prevail during a measurement campaign, including the values taken by environmental variables, as opposed to those predicted prior to commencing the campaign

3.1.52**offshore fixed platform**

platform that is not floating but is fixed to the seabed

3.1.53**platform motion**

translational or rotational movement of a platform

3.1.54**post-calibration**

calibration of a measurement unit after completion of a specific measurement campaign such that the results of the calibration are characteristic of its performance during the campaign

3.1.55**pre-deployment campaign plan**

set of arrangements and checks put in place prior to deployment of the instrument to site in order to ensure successful execution of the measurement campaign being undertaken

3.1.56

pre-deployment calibration

calibration of a unit undertaken subsequent to previous specific measurement campaigns but prior to the specific measurement campaign for which it is to be deployed, such that the calibration results can be considered indicative of the performance of the instrument during the specific measurement campaign with respect to accuracy

3.1.57

preliminary classification uncertainty

classification uncertainty evaluated on the basis of known instrument sensitivities to environmental variables and pre-deployment estimates of the range of values these environmental variables will take during the measurement campaign

Note 1 to entry: A final classification uncertainty may be evaluated after the measurement campaign is complete on the basis of the observed values of the environmental variables during the campaign.

3.1.58

Q-Q analysis

comparison of similarly ranked quantiles of measured data acquired by two systems making concurrent collocated measurements of the same wind conditions to test the performance of one system relative to the other

3.1.59

reference uncertainty

uncertainty associated with measurements acquired using a reference instrument, that is, the instrument used as a source of data whose accuracy has previously been characterised for comparison during a test when assessing the accuracy of another instrument

3.1.60

reporting

process of generating new documentation for an activity currently underway or being completed, which may form the basis of a new documentation pack or be added to an existing documentation pack

3.1.61

secondary sensor

instrument used to acquire measurements of a quantity whose purpose is to monitor the performance of another, primary instrument that is used as the source of measurements of that quantity for subsequent analysis

3.1.62

sensitivity

extent to which a type of instrument's measurement error depends on the environmental variables that characterise the conditions in which that type of instrument is operating

Note 1 to entry: Sensitivity applies to environmental conditions.

3.1.63

sensitivity analysis

evaluation of the rate at which measurement error varies with an environmental variable

3.1.64

simplified calibration test

calibration test procedure that has less stringent data completion criteria than the corresponding full test protocol, which requires comparison of a unit being tested with a reference system by means of Q-Q analysis rather than regression, in order to enable more rapid completion of the test

Note 1 to entry: Fulfilment of simplified protocol acceptance criteria indicates that the results of the most recent calibration performed in accordance with the full test protocol remain valid.

3.1.65**simplified calibration protocol**

methodology for performing a simplified calibration test

3.1.66**site acceptance test**

process or set of tests conducted prior to deployment of the FLS to the measurement site, undertaken to document that the system has been assembled correctly and conforms to the required functional specifications

Note 1 to entry: The SAT also documents the sensor configuration prior to deployment. Since the SAT typically takes place in port, it is often referred to as a port acceptance test (PAT) or harbour acceptance test (HAT).

3.1.67**specific measurement campaign**

implementation of a use case in which an individual unit is deployed to a site to perform a measurement campaign for a specific project or purpose

3.1.68**system availability**

ratio between the amount of time during which the system was capable of acquiring measurements, irrespective of whether those measurements were subsequently accepted for analysis purposes, and the maximum amount of time during which the system could have been capable of measuring during a given measurement period, including any periods of downtime

3.1.69**trusted reference system**

source of reference data against which measurements of a quantity can be compared to assess their accuracy, which is considered sufficiently reliable and accurate on the basis of fulfilling defined suitability criteria

3.1.70**type qualification**

set of tests undertaken to characterise the performance of a type of instrument with respect to accuracy, availability, and other performance indicators, such that it may be deemed suitable, or qualified, for a given use case

Note 1 to entry: In particular, the procedure that involves testing the accuracy of a type of system, and the sensitivity of that accuracy to operational conditions such as variations in environmental variables that are considered relevant to the qualification process, is termed classification.

3.1.71**uncertainty budget**

known set of contributions to measurement uncertainty, and the total uncertainty evaluated by combining these contributions

Note 1 to entry: The contributions should be identified following a thorough, systematic and hierarchical procedure in accordance with the ACARA principle.

3.1.72**unit qualification**

set of tests undertaken to characterise the performance of an individual instrument with respect to accuracy, availability, and other performance indicators, such that it may be deemed suitable, or qualified, for a given use case

Note 1 to entry: In particular, the test of the accuracy of a unit that forms part of the unit qualification process is termed calibration.

3.1.73

vertically profiling wind lidar

lidar that implements a scan geometry with a fixed elevating angle that varies in azimuth angle such that the measurement volume is above the device and a profile of wind speeds and directions at different heights above the device is acquired

3.1.74

watch circle

area within which the buoy can be found due to the restriction of its movement by its moorings

3.1.75

wave climate

range of surface metocean conditions observed in a given location, described by a wave spectrum and/or by a distribution of wave parameters describing the prevailing sea states

3.1.76

wave sensor

instrument deployed to measure parameters that describe surface metocean conditions

3.1.77

wind field reconstruction

process of combining intermediate values, such as the LOS speeds associated with multiple LOSs, to retrieve the final values relevant to the use case, such as wind speed and direction

3.1.78

wind flow gradient

systematic variations in mean wind speed over an area or horizontal distance, e.g., changes in wind speed with increasing distance from a coastline according to coastal effects on the mean wind flow

3.1.79

yaw measurement

measurement of the orientation of a system around a vertical axis

3.1.80

zero classification

instrument classification that applies within an envelope of operational conditions for which an adequate evidence base exists to support confidence that no sensitivity of performance with respect to accuracy is observed for the type of instrument classified, such that zero classification uncertainty may be adopted within that envelope of operational conditions

3.2 Symbols and abbreviated terms

3.2.1 Symbols

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

δ_i	magnitude of the range between the 10 th and 90 th percentile of the EV in the EOC	
ε_i	amount by which EV i is out of range	
m_i	rate of change of measurement error with EV i	
σ_{devi}	bin-wise standard deviation of difference in wind speed of device under test and reference	ms ⁻¹
Δv_i	bin-wise mean difference (bias) between wind speeds measured by device under test and reference	ms ⁻¹
$\Delta v'_i$	bin-wise wind speed bias which accommodates the uncertainty of the reference	ms ⁻¹



N_i	number of 10-min data points within bin i	-
u_{cal}	calibration (unit qualification) uncertainty	ms^{-1}
$u_{\text{cal}i}$	bin-wise calibration uncertainty contribution	ms^{-1}
u_{cla}	classification uncertainty	ms^{-1}
u_{con}	configuration uncertainty	ms^{-1}
u_{FLS}	uncertainty to be applied to FLS measurements	ms^{-1}
$u_{\text{ref}i}$	bin-wise reference uncertainty contribution	ms^{-1}
$x_{10-90,\text{EOC},i}$	10 th or 90 th percentile value of EV i within the EOC	
$x_{10,\text{EOC},i}$	10 th percentile value of EV i within the EOC	
$x_{90,\text{EOC},i}$	90 th percentile value of EV i within the EOC	
$x_{\text{mean},\text{SMC},i}$	mean value of EV i within the SMC	

3.2.2 Abbreviated terms

ACARA	as complete as reasonably achievable
CFD	computational fluid dynamics
DBS	Doppler beam swinging
DGPS	differential geographical position system
DOF	degree of freedom
EOC	envelope of operational conditions
EV	environmental variable
FAT	factory acceptance test
FLS	floating lidar system
GUM	Guide to Uncertainty of Measurement (JCGM 100:2008)
HSE	health, safety and environment(al)
HAT	harbour acceptance test
AHJ	authority having jurisdiction
IMU	inertial measurement unit
KPI	key performance indicator
LES	large Eddy simulation
LiDAR	light detection and ranging (here: lidar)
LAT	lowest astronomical tide
LOS	line of sight
MSL	mean sea level
NTM	normal turbulence model
NWP	normal wind profile
OEM	original equipment manufacturer
OPDA	overall post-processed data availability
OSA	overall system availability
PEP	project execution plan

QC	quality control
Q-Q analysis	quantile-quantile analysis
RAMS	risk assessment and method statement
RAO	response amplitude operator
ROV	remotely operated vehicle
RSD	remote sensing device
SAT	site acceptance test
SMC	specific measurement campaign
TI	turbulence intensity
UTC	coordinated universal time
VAD	velocity azimuth display
VIM	International Vocabulary of Metrology
WFR	wind field reconstruction

4 Overview

4.1 General

This document is applicable to lidars that are part of a floating lidar system (FLS), a technology which is further described and specified in Clause 5. The lidars are the primary measurement sensor within the FLS, and the fundamental measurand of the lidar is the line-of-sight (LOS) wind speed.

The measurands that are required to fulfil the data requirements of wind resource assessment use cases are primarily horizontal wind speed and direction. These are derived from multiple measurements of LOS wind speed, together with other parameters, including, for example, the angle between each LOS and the lidar optical axis, and lidar tilt, roll, yaw and heave with respect to a reference coordinate system. The algorithm used to derive the required measurands is referred to as wind field reconstruction (WFR). These additional parameters define the LOS direction and the measurement range and are required for WFR to derive wind speed and direction from LOS wind speed measurements. Lidars integrated in FLS are typically vertically profiling lidars, employing the corresponding WFR methods. This technology is covered in detail in IEC 61400-50-2.

The inputs to the WFR algorithm are referred to as intermediate values (e.g., LOS speeds, lidar tilt and roll, and so on). The outputs of the WFR algorithm are referred to as the final values (e.g., horizontal wind speed and direction). WFR for an FLS may include two parts, one defined by the lidar technology (see IEC 61400-50-2) and in some cases a motion correction algorithm to account for the floating environment.

Auxiliary sensors, including those associated with oceanographic observations, biofouling, and other considerations not directly related to the acquisition of the required measurands, are not covered by this document, and the corresponding standards for those sensors should be consulted for guidance on their operation. The relevant guidance regarding health, safety and environmental (HSE) considerations shall be followed.

4.2 Measurement methodology overview

The deployment of a specific FLS unit to a specific location for a specific period of time to measure the required measurands is termed the specific measurement campaign (SMC). This is distinct from other measurements campaigns that are undertaken to evaluate the performance of the unit or type of FLS, e.g., for the purposes of calibration or classification. The SMC is an individual instance of a use case. A use case includes three elements: the implementation of particular measurement method, under operational conditions whose influence on measurement accuracy is adequately understood, to fulfill a particular set of data requirements. An SMC is one such implementation at a specific site where operational conditions are known to satisfy the requirements of a particular project.

The overall methodology of the SMC includes three phases:

- Phase 1: Preparation, including the development of a pre-deployment campaign plan,
- Phase 2: Implementation (or execution), including the deployment of the FLS, and
- Phase 3: Post-deployment assessment, including a final uncertainty evaluation.

This methodology deviates from the method described in IEC 61400-50-3, where only two phases (preparation and execution) are described. The deviation results from the fact that FLS are often deployed at sites that were not previously investigated. It is possible that the ranges of environmental conditions that prevail during the SMC are therefore unknown a priori. As a consequence, a final uncertainty evaluation that includes consideration of the observed operational conditions can often only be performed after the conclusion of the campaign.

An envelope of operational conditions (EOC) for the FLS type, supporting confidence in its performance over a certain range of operational conditions described by the EOC, may be created and may be extended with every measurement campaign where environmental conditions are observed. These observations form an evidence base supporting confidence in FLS performance under similar circumstances. The available evidence base shall be used to define different levels of uncertainty, see Clause 7 and Clause 8.

The evidence base supporting confidence in FLS performance within a range of environmental and operation conditions for a given type of FLS has until now been evaluated with reference to a discrete set of levels of confidence.

This document describes a continuous approach to the comparison of evidence of satisfactory FLS performance to acceptance criteria because the evaluation of the evidence contributes to the calculation of uncertainty. In particular, operation of an FLS within a range of operational conditions for which there is adequate evidence of satisfactory performance, the EOC, incurs no contributions to uncertainty due to the type of FLS being used (classification uncertainty). The contribution to uncertainty outwith this range of operational conditions shall be calculated in accordance with the procedures described in Clause 7 and Clause 8.

It is anticipated that the possibility of increasing the range of operational conditions within which zero classification uncertainty applies will motivate growth of the evidence base for the EOC associated with a given type of FLS through acquisition of suitable observations of environmental conditions and reference measurements during successive measurement campaigns.

4.3 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 specific use case. However, the main clauses are presented in a logical sequence that could be applied in practice.

Clause 5 describes the system requirements an FLS shall fulfil so that the methods described in this document are applicable.

Clause 6 describes procedures and requirements for the calibration of FLS.

Clause 7 describes the assessment of the sensitivities of final (FLS measurement) values to changing environmental conditions.

Clause 8 describes how the total uncertainty of an FLS measurement is made of its contributing components.

Clause 9 describes the measurement procedure for the specific measurement campaign (SMC).

Clause 10 provides the minimum requirements for reporting that are specific to the application of FLS. (The overall requirements for reporting are provided by the use case.)

5 System requirements

5.1 General

Though the main component of the FLS is the lidar wind measuring device, there are several further components which make the wind measurement offshore possible in the first place. Requirements for these are specified in 5.2. The mooring system is also considered a component of the FLS but is detailed separately in 5.3.

The supplier of the FLS should supply all components as an integrated system. Any components exposed to the marine environment should be suitable for use in a marine environment and have certification and/or warranties provided by the sub-component suppliers to confirm the same. Secondary and auxiliary sensors and equipment shall be qualified in accordance with the relevant guidance. The system and its components should have corrosion protection as required in accordance with the relevant standards.

5.2 Floating lidar system (without mooring system)

5.2.1 Functional requirements

The individual components of the floating lidar system shall meet at least the following functional requirements:

- 1) Lidar device: The capability of the type of lidar device being employed on the FLS should meet current industry expectations¹ in onshore and/or offshore fixed platform configurations. The FLS supplier will include in the documentation pack they provide details of the characterisation² of the lidar unit used as part of the FLS.
- 2) Power system: Power supply shall be from multiple sources to ensure continuous power supply (e.g., a combination of wind, solar, fuel cell, or diesel generator).
 - a) All FLS shall include a robust power system that prioritizes safe operation of the FLS.
 - b) Fault notification and system status logging shall be provided. If navigation aids share a power source with other systems, they shall have priority over other systems in low-energy situations.
 - c) The FLS supplier shall include information about the power system in the documentation pack they provide.

¹ "Roadmap for the Commercial Acceptance of Floating LiDAR Technology", Carbon Trust Offshore Wind Accelerator, Version 2.0, 2018, Section 3.3.2

² "Expert Group Report on Recommended Practices 18. Floating Lidar Systems", 1st edition, IEA Wind, 2017. Recommended Practices (RPs) 18, 30, 31 and 32.

- 3) Hardware selection: Components shall be selected to meet a number of technical requirements:
 - a) The FLS design shall ensure that the potential for environmental pollution has been identified and mitigated under normal operational conditions. In particular, this shall address the storage of fuels and/or other fluids relevant to the normal operation of the power system.
 - b) Components exposed to the offshore environment should have an ingress protection rating of IP67 or higher. If this is not possible, alternative means shall be taken to adequately protect components against water ingress as appropriate.
 - c) Equipment housed within an enclosed unit on the FLS can also require ingress protection.
 - d) Component integration designs should also consider the risk of high humidity and deploy mitigation measures to manage this risk.
 - e) The FLS supplier shall include information about hardware components in the documentation pack they provide.
- 4) Data logging and communication: Data processing should be performed on the FLS. If this is not possible, post processing of data shall be managed to maintain transparency and preserve the value of the data.
 - a) The data logging system should have on-board storage capacity sufficient for the planned duration of the deployment, with an extra capacity of at least 3 months of storage for contingency.
 - b) The FLS should provide onboard redundant data capacity where the primary data storage device can be backed up to a secondary storage device (to avoid data loss should the primary data storage device become damaged or corrupted).
 - c) The communications system should enable data transfer to shore in near real time. If power or bandwidth is limited, a subset of diagnostic data that includes FLS status should take precedence over other data.
 - d) The communications system should have more than one channel of communication (e.g., cell phone network protocols, satellite communications, or radio). Switching between channels of communication should be achievable automatically and remotely.
 - e) Communications shall enable continuous monitoring and control of the buoy.
 - f) The communications system should include a wireless communication channel suitable for use from a nearby vessel.
 - g) All data from the FLS and its primary, secondary and auxiliary sensors shall be time synchronized with a common source of time data.
 - h) The FLS supplier shall include information about data logging and communications within the data (documentation) pack they provide.
- 5) Secondary wind speed and direction sensors: In addition to the primary measurements of wind speed and direction, independent measurements from other secondary sensors should record the same quantities for use as an on-board cross-check of lidar operation.
 - a) Sonic anemometers deployed are suitable for the purpose of informing broad plausibility checks of on-board data. It is noted that there is higher inherent uncertainty in the absolute measurements made from anemometry at this level due to flow distortion effects around the platform structure, platform motion and low-level surface effects. These secondary instruments do not fulfil the function of data redundancy. It is possible that the function of data redundancy is only fulfilled by additional lidars.
 - b) An additional onboard lidar may also be suitable as a secondary instrument if it is itself capable of making independent measurements without reference to the primary lidar.

- 6) Yaw measurements: FLS yaw (heading) is essential for the correction of measured wind directions to True North, as the FLS can rotate freely around its mooring.
 - a) The accuracy of the primary yaw measurement system should be at least as good as that from a satellite compass using a differential geographical position system (DGPS) signal. The DGPS based yaw measurement is the recommended approach for yaw measurement.
 - b) A backup yaw measurement system shall also be installed and may also be a DGPS. Alternative yaw data sources, for example a magnetic compass, may be used as a backup. This shall be calibrated within the FLS prior to deployment and monitored during the measurement campaign.
 - c) Yaw correction shall be applied to the FLS lidar, secondary and auxiliary direction sensor data and should be processed on the FLS. If this is not possible, the data may be post processed.
- 7) Motion sensor: Motion sensors mounted on the FLS shall be assessed for accuracy within the FLS. The motion sensors should be capable of capturing the motion of the buoy and lidar described with respect to six degrees of freedom. In the event of the motion of the buoy not being directly related to the motion of the lidar (e.g., hardware compensation), the lidar motion should also be recorded and described with respect to six degrees of freedom. The buoy motion data may be used in combination with the RAO (response amplitude operator) specific to each FLS to help describe the wave climate during operation.
- 8) Wave sensors: In order to assess the performance of the FLS, it is essential that, while the lidar unit is recording wind speed and direction, the sea state shall also be measured and recorded concurrently.
 - a) This may be achieved by sensors mounted on the floating platform (e.g., see point 7), or by other sensors deployed separately in proximity to the FLS.
 - b) If separate sensors are used in proximity to the FLS, they should be located sufficiently near to measure the conditions encountered by the FLS without risking interaction with the FLS or its moorings. If the objective is to measure an associated concurrent wind and metocean dataset then the separate wave sensor should also be located within a similar water depth so as to be considered representative of the FLS deployment location.
 - c) Wave sensors should be designed for marine conditions and should have a history of successful use in metocean applications. Well proven systems that have a stable engineering design are recommended over prototype systems.
 - d) Wave sensors shall be configured to record wave parameters over appropriate averaging periods as defined in relevant guidance, for example, IEC TS 62600-101 or ISO 19901-1.
- 9) Motion compensation system: The data pack provided by the FLS supplier should state if motion compensation is present and, if so, include a description of the motion compensation system and related design features, including:
 - a) Specification of any motion compensation arrangements, which may consist of passive or active mechanical or software approaches separately or in combination.
 - b) The definition of a global and local reference frame.
 - c) The buoy motion that is expected shall be described under:
 - Typical operational conditions, corresponding to the envelope of operational conditions, and
 - Conditions expected during the specific measurement campaign (SMC), where these are outwith the envelope of operational conditions (EOC), if such sea state data are available to the supplier.

- The motion of the buoy should be described as six degrees of freedom (DOF) including translation along and rotation about three axes:
 - i) Vertical axis: heave and yaw,
 - ii) Longitudinal axis: surge and roll,
 - iii) Lateral axis: sway and pitch.
 - For each of the DOFs listed above, the range of motion that is expected shall be described.
- d) The FLS supplier should state motion limits for each of the DOFs within which the motion compensation system has been demonstrated.
- e) For all DOFs for which there is motion compensation, definitions of
- The types of compensation used, and
 - Any limits outside of which compensation is inoperative.
- f) In all cases where motion of the platform or lidar is detected, the DOF to which this applies, and the specification of the sensors used.
- g) If the status of motion compensation changes, the change event shall be flagged and recorded with the time and reason for the change.
- h) Version control of the motion compensation algorithm, including documentation tracking any changes, descriptions of these changes, and dates when these were applied.
- 10) Other auxiliary data sensors: In addition to the lidar and wave sensors, it is recommended to have additional sensors on the FLS to provide additional atmospheric and oceanographic data, to understand the lidar performance, and to provide a more detailed dataset to support future data analysis. Examples of additional data that may be required include:
- a) Air temperature.
 - b) Humidity.
 - c) Air pressure.
 - d) Vertical air temperature profiling – acknowledging that this is currently difficult to achieve.
 - e) Sea surface temperature.
 - f) Wave direction.
 - g) Sea current direction information at different depths or ranges.
 - h) Sea current speed at different depths or ranges.
 - i) Imagery to support management of an FLS test or SMC (e.g., to monitor bird fouling, vessel or sea mammal strikes). For example, this could be achieved using high definition still photos or video streams triggered by an event, depending on network coverage/communication link.
 - j) In order to confirm the location of the FLS is within the watch circle, the location of the FLS shall be measured. For example, this could be achieved by a global positioning system.

The data acquired by the auxiliary sensors listed above will be used to:

- 1) Inform the meteorological and oceanographic conditions on site.
- 2) Help evaluate the uncertainty of the measurement campaign with reference to the FLS evidence base.