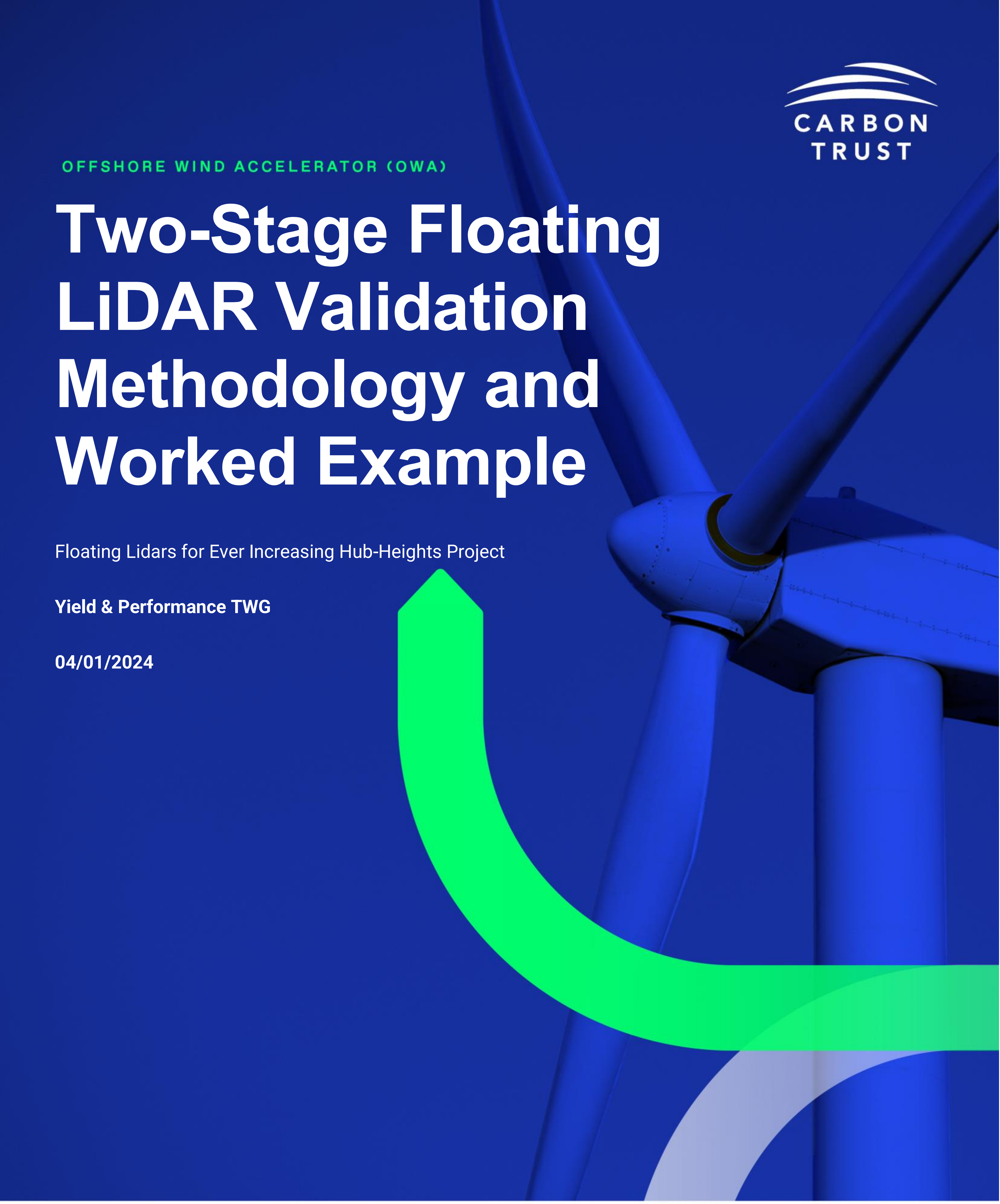

OFFSHORE WIND ACCELERATOR (OWA)

Two-Stage Floating LiDAR Validation Methodology and Worked Example

Floating Lidars for Ever Increasing Hub-Heights Project

Yield & Performance TWG

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Contents

Executive Summary

As offshore wind turbines grow ever larger, there is a requirement to obtain accurate wind resource measurements at ever-higher heights. These data are often obtained using a floating LiDAR system (FLS). Existing industry best practice requires the validation of the FLS unit against a trusted reference measurement system to provide a traceable uncertainty estimate. This trusted system is typically an offshore meteorological mast, which are typically around 100 m high. At higher heights, although best practice allows the use of other reference systems, there is no widely applied and accepted method to achieve a traceable uncertainty estimate for FLS measurements, and there is some evidence of potential biases that could be introduced by buoy motion, LiDAR characteristics, atmospheric gradients and combinations of these effects at higher heights.

The Offshore Wind Accelerator (OWA) project “Floating LiDARs for Ever Increasing Hub Heights” (which will be referred to as “the FLH project” for convenience) sought to quantify these potential biases and identify ways of mitigating the associated risks. Building on a literature and market review [1] and some modelling of LiDAR behaviour, this document describes a two-stage validation methodology for providing traceable uncertainties at high heights, and gives a worked example of the application of that methodology. It is arranged as follows:

- Section 1 summarises key references upon which this document is based.
- Section 2 describes the method, recommended here, for assessing FLS wind speed uncertainty based on a two-stage calibration process (involving an onshore mast and an offshore reference lidar).
- Section 3 sets out a worked example of the method described in Section 2.

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1. Key References

IEC 61400-12-1 [2] was the first place where use of a wind lidar for wind energy industry purposes appeared in a widely used and recognised standard when Annex L was introduced. This bases the uncertainty components for wind lidar use on those familiar from mast anemometry and established a method for uncertainty assessment. Notwithstanding later developments, the overall framework and approach described therein are, to a large extent, those adhered to in the industry today. The standard pertains to fixed lidars (not lidars on floating, moving platforms) and to power performance (not wind resource assessment) but nonetheless is often interpreted for and applied to those scenarios. A new standard (IEC 61400-50-2) has recently been released which separates Annex L from power performance contents and also has wind resource assessment using fixed lidars in scope. Another new standard (IEC 61400-50-4) concerning floating lidars is under development but not yet available. In this document, the existing standard acts as a baseline in how uncertainty contributions are considered, named, estimated and combined.

The Recommended Practice [3] document was produced by the OWA in 2016 and is based wholesale on the recommended practice document developed as an IEA Task (with support from the OWA amongst other organisations). Amongst many other recommended practices for FLS, to a great extent the interpretation of the IEC 61400-12-1 Annex L to an offshore FLS for wind resource assessment is set out here, in a manner aiming to be as consistent as possible in most ways with the standard. Departures from full consistency with the standard of note are: the recommendation that a FLS may be used in the final application without reference to a nearby instrumented mast; the treatment of the FLS as a whole, rather than the onboard lidar, as the instrument under test; and, the possibility to accept a fixed lidar as a suitable trusted reference. In the current document, the Recommended Practice also serves as a baseline for uncertainty estimation, with specific reference to FLS.

The significance of the OWA's LiDAR Uncertainty Standards Review (LUSR) [4] project and document here is that it recommends several departures from the estimation of uncertainty set out or at least implied by the above two reference works. In the present document those recommendations are adhered to. The LUSR document also contains detailed examples and flowcharts which may assist the reader unfamiliar with the combination of uncertainty components in this context.

In addition to these general comments, more detailed comments are made regarding to these key works in Section 2 below, particularly regarding consistency.

As a guide, Table 1 below summarises differences between the Annex L approach and the LUSR approach.

Uncertainty component	**Annex L approach [2], interpreted for FLS**	**LUSR approach [4]**
Combined wind speed uncertainty arising from calibration test	Combination of: • reference sensor uncertainty, • mean deviation, • standard deviation of deviations, • standard deviation of lidar measurements divided by square root of number of data points • uncertainty due to mounting, • uncertainty due to flow variation within the control volume, • uncertainty due to separation distance and flow gradients across the site.	Combination of: • reference sensor uncertainty, • standard deviation of deviations divided by square root of number of data points, • uncertainty due to mounting, • uncertainty due to flow variation within the control volume, • uncertainty due to separation distance and flow gradients across the site. which is valid if the reference uncertainty is not exceeded by the mean deviation.
Uncertainty due to mounting effects	Default magnitude is quoted as 0.1% . May also be assumed to be 0.5% as this value appears in an example.	Normally neglected if specific controls are put in place.
Uncertainty due to separation distance and flow gradients across the site	Estimated as 1% times the separation distance divided by the measurement height.	Estimated as $(D.G_{hor}/\ 1000)$ where D is the separation distance between the lidar and mast in metres, and G_{hor} an estimate of potential horizontal wind speed gradient across the site, in percentage of wind speed per kilometre. Ideally this will be estimated directly for the site, or alternatively a value of 4%/km may be assumed for a flat onshore site, 0.5%/km for coastal sites and 0.05%/km for offshore sites.
Uncertainty due to non-homogeneous flow within the control volume	At one point in the document, guidance is to perform an individual assessment. At another point, applying a value of 2% to 3% is recommended.	Normally neglected unless there is a good reason not to.
Classification uncertainty	A class number approach is one of the three routes available to assessing classification uncertainty.	Do not use a class number approach.

Table 1: Summary of key differences, in uncertainty estimation, between the ‘Annex L’ approach and the ‘LUSR’ approach, the latter being adhered to here.

2. Two-Step Validation Methodology

2.1. Introduction

This section recommends a procedure for estimating wind speed uncertainty when using an FLS offshore, with the FLS having been calibrated with reference to a trusted fixed lidar, which in turn had been calibrated with reference to one or more cup anemometers mounted on a meteorological mast. The expected use case is where the onshore mast is particularly tall (say above 120 m or certainly 100 m), exceeding the heights of offshore reference masts, thus enabling traceable wind speed estimations at the available heights for the FLS. This may be referred to as a two-stage process as a contrast to the case when the FLS is calibrated directly against a mast, and is represented in Figure 1.

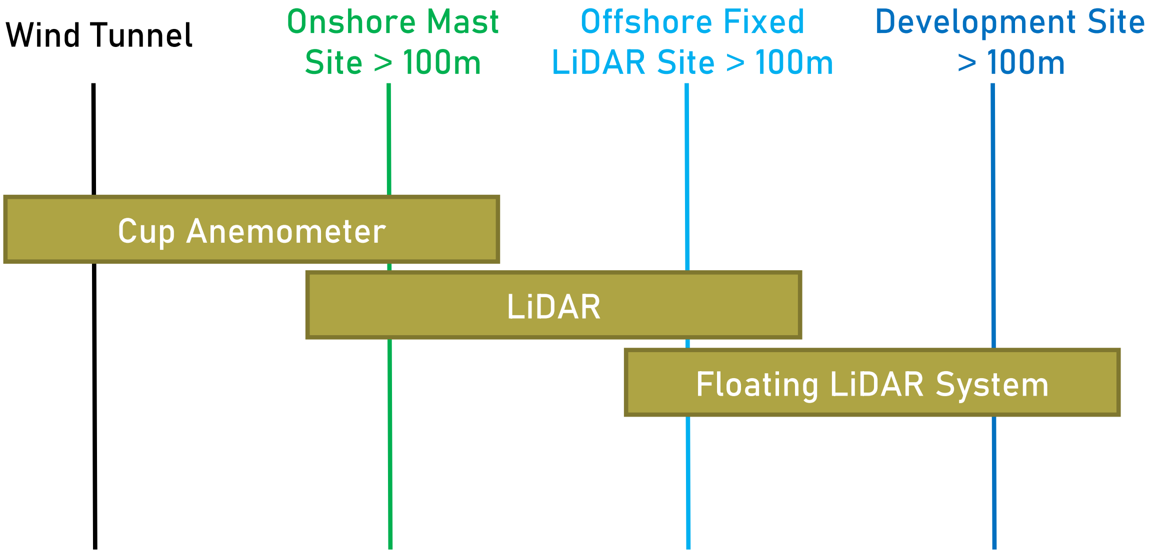

Figure 1: Schematic representation of two-stage calibration process, establishing uncertainty traceability from the FLS deployment on the development site back to the cup anemometers.

2.2. Calibration of Lidar using Reference (Onshore) Meteorological Mast

Summary of approach

Wind speed measurements from a (fixed) vertically profiling lidar and from a trusted reference system – a conventional meteorological mast fitted with cup anemometers – are compared. The calibration uncertainty of the lidar's wind speed measurements is calculated by combining in quadrature, for each wind speed bin, a number of contributing components. These components are: the reference sensor uncertainty; the standard deviation of deviations in the measured data; uncertainty due to mounting effects; and, the uncertainty due to the separation distance between the mast and lidar and possible flow gradients across the site.

Method

The combined wind speed uncertainty is estimated as:

$$u_{VR,cal,i}^2 = u_{VS,i}^2 + \sigma_{VRdev,i}^2 / N_{VR,i} + u_{VR,mnt,i}^2 + u_{VR,sep}^2 \qquad \text{for } |\Delta v_{VR,i}| < u_{VS,i} \qquad \text{E1}$$

Combination in quadrature of uncertainty components as in equation E1 is consistent with section L.4.3. of IEC 61400-12-1, however the make-up of the components therein relies on the LUSR work in several instances.

The reference sensor uncertainty, $u_{VS,i}$, is made up of wind tunnel calibration, cup anemometer classification, mounting, mast correction and data acquisition components according to section L.4.2 of IEC 61400-12-1. The standard deviation of deviations, $\sigma_{VRdev,i}$, is the standard deviation in each bin of the difference between the lidar and anemometer wind speed values, which number $N_{VR,i}$ in total (see section 4.1 of LUSR). The mean deviation between the lidar and anemometer wind speed values is denoted $\Delta v_{VR,i}$. The uncertainty due to mounting effects $u_{VR,mnt,i}$ would normally be assumed negligible if controls were put in place (section 4.5 of LUSR). Uncertainty relating to flow gradients across the site, $u_{VR,sep}$, should be estimated using the following equation (see section 4.3 of LUSR):

$$u_{VR,sep} = \frac{D.G_{hor}}{1000} \qquad \text{E2}$$

where D is the separation distance between the lidar and mast in metres, and G_{hor} is an estimate of potential horizontal wind speed gradient across the site, in percentage of wind speed per kilometre. Ideally this will be estimated directly for the site, or alternatively a value of 4%/km may be assumed for a flat onshore site.

Unlike section L.4.3 of IEC 61400-12-1, and in a consistent manner with section 4.9 of LUSR, there is no significant contribution attributed to inhomogeneous flow within the lidar's measurement control volumes.

2.3. Calibration of FLS using Reference Lidar

Summary of Approach

Wind speed measurements from an FLS and from a trusted reference system – the fixed lidar for which calibration was described in Section 2.2 – are compared. The calibration uncertainty of the FLS wind speed measurements is calculated by combining in quadrature, for each wind speed bin, a number of contributing components. These components are: the reference sensor uncertainty; the standard deviation of deviations in the measured data; uncertainty due to mounting effects; and, the uncertainty due to the separation distance between the fixed lidar and FLS and possible flow gradients across the site.

Method

The combined wind speed uncertainty is estimated as:

$$u_{VF,cal,i}^2 = u_{VR,i}^2 + \sigma_{VFdev,i}^2 / N_{VF,i} + u_{VF,mnt,i}^2 + u_{VF,sep}^2 \qquad \text{for } |\Delta v_{VF,i}| < u_{VR,i} \qquad \text{E3}$$

This is the same as equation E1, save for the subscript VR (denoting wind speed from the remote sensing device or lidar, as used in IEC 61400-12-1) is replaced with the subscript VF, here denoting wind speed from the FLS.

As such, most of these components do not require further explanation if Section 2.2 is referred to. An exception is the reference sensor uncertainty, $u_{VR,i}$, which is made up from the following components combined in quadrature (consistent with L.4.1 in IEC 61400-12-1):

1. Uncertainty resulting from the calibration test – this is $u_{VR,cal,i}$ from equation E 1.
2. Uncertainty resulting from classification. Here we must assume that lidar classification tests have been performed establishing a set (which may be empty) of significant environmental variables, and sensitivity coefficients relating the environmental variables to observed wind speed error, and that the classification test was performed with the same or similar equipment to that used in the lidar calibration of Section 2.2. The values of the significant environmental variables recorded during both the lidar and the FLS calibration

tests are then combined with these coefficients to derive the classification uncertainty. This is described in section 4.2 of LUSR, which refers to and is consistent with section L.2 of IEC 61400-12-1.

3. Uncertainty due to non-homogenous flow within the measurement volume is assumed to be small and therefore neglected (see section 4.9 of LUSR).
4. Uncertainty due to mounting effects is normally assumed to be small and therefore neglected (see section 4.5 of LUSR).

Significance of Mean Deviation Term

A mean deviation term $\Delta v_{VR,i}$ appears in equation E1, and likewise $\Delta v_{VF,i}$ appears in equation E3. The implication is that if the mean deviation exceeds the reference uncertainty, then the uncertainty estimation is invalid and a correction ought to be applied. This is similar in essence to the approach outlined in Annex L, where the mean deviation term is compared with the calibration uncertainty (using the Annex L definition) with the mean deviation component removed, rather than comparing with the reference uncertainty.

In practice this is problematic, and there is reluctance amongst practitioners to apply a correction if (either version of) the condition is not met. The following observations are made on this subject:

1. The condition not being met may be restricted to a small number of bins and may be attributed to those bins not containing sufficient data points, so the argument may be made that the exceedance is effectively allowed.
2. It may be considered valid to increase the coverage factor to *k=2* in the uncertainty magnitude part of the exceedance check, which clearly provides more opportunity for compliance with the condition.
3. Instead of applying a correction, an additional uncertainty may be applied for bins where the condition is not met. A consistent approach for quantifying the additional uncertainty is not known to the authors.

This situation is being discussed by the group developing the new standard IEC 60400-50-4 so there is nothing to be gained in attempting to pre-empt the outcome here. Instead, in the worked example provided below in Section 3, where the conditions implicit in equations E1 and /or E3 are not met, this will simply be clearly indicated.

2.4. Final uncertainty of FLS Wind Speed Data at Development Site

Summary of approach

A calibration has been performed for an FLS as described in Section 2.3. In the final application of the FLS when it is deployed to the site of interest, uncertainty estimates should be made for the resulting wind speed measurements. This is accomplished by combining in quadrature the FLS calibration uncertainty with the FLS classification uncertainty. An uncertainty due to mounting may also be added, but it is expected that normally this will be neglected. This is summarised in Figure 2 below, which has been updated from the Recommended Practice document [3].

Method

The combined wind speed uncertainty in the final application is estimated as

$$u^2_{VF,final,,i} = u^2_{VF,cal,i} + u^2_{VF,class,i} + u^2_{VF,mnt,final,i} \qquad \text{E4}$$

Some commentary on individual components is as follows:

1. The FLS calibration uncertainty, $u_{VF,cal,i}$, is obtained from equation E3.
2. For $u_{VF,class,i}$, the FLS classification uncertainty, akin to in Section 3.3.2, we here assume that an FLS classification test is also performed, allowing $u_{VF,class,i}$ to be estimated as described in section 4.2 of LUSR (which refers to and is consistent with section L.2 of IEC 61400-12-1). Note that this necessitates recording the values of any significant environmental variables during the final FLS deployment, otherwise the more conservative class number approach would need to be applied.
3. Uncertainty due to mounting effects in the final application, $u_{VF,mnt,final,i}$, should be considered but is normally assumed to be small and therefore neglected (see section 4.5 of LUSR).
4. Unlike section L.4.1 of IEC 61400-12-1, and in a consistent manner with section 4.9 of LUSR, there is no significant contribution attributed to inhomogeneous flow within the lidar's measurement control volumes.

Classification Tests

As described in Section 2.2, estimating the calibration uncertainty for an FLS (in this two-stage process context) requires use of fixed lidar classification information. Likewise, as described in Section 2.3, estimating the FLS wind speed uncertainty in the final application requires use of FLS classification information. Thus it is clearly implied that the two-stage process requires both calibration and classification tests to be carried out for Stage 1 (lidar versus tall met mast) and Stage 2 (FLS versus lidar) at all heights of interest.

It is industry practice for classification information to be aggregated from at least three trials. It should be expected that before such information is accumulated, to be pragmatic, it will be necessary to estimate classification uncertainty from a smaller number of trials and/or established classification information from lower heights.

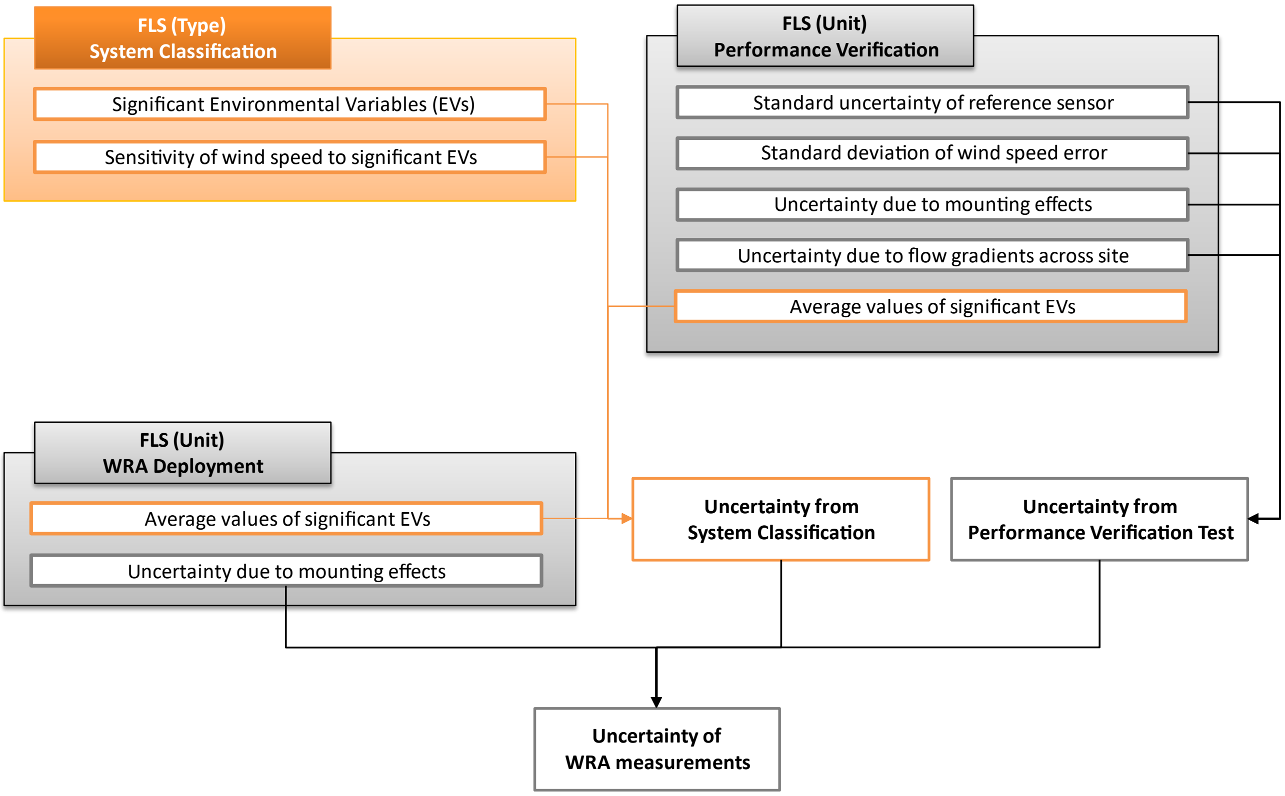

Figure 2: Flow chart summarising the estimation of wind speed uncertainty in the final FLS application. Note that "Uncertainty due to flow gradients across site" should be more fully described as "Uncertainty due to separation distance between FLS unit and reference measurement system in the presence of flow gradients across site".

3. Worked Example

3.1. Introduction

In this section a worked example of the method described in Section 2 is provided. The data for 'Stage 1' in the two-stage process (Calibration of Lidar using Reference (Onshore) Meteorological Mast), is taken from the calibration of a Windcube V2 profiling lidar at DTU's Østerild test site [5], and is provided with permission by Ørsted. The data from the highest height of 244 m is used here. The data for 'Stage 2' in the two-stage process (Calibration of FLS using Reference Lidar) is taken from a measurement campaign comparing data from a reference Vaisala Windcube V2 mounted on the FINO3 research platform with data from a nearby Fraunhofer IWES Lidar Buoy also equipped with a Vaisala Windcube V2. That offshore measurement campaign has been described in a conference paper [6], and the data is provided to this OWA project courtesy of Fraunhofer IWES. The data from a height of 231 m is used here as the closest match in height to the Stage 1 data. In the intended real-world application, the lidar unit being calibrated in Stage 1 would be the reference unit for Stage 2, which is not the case here; this inconsistency is not considered important for the current purpose of providing a realistic worked example.

In the final application, the calibration uncertainty is combined with classification uncertainty and mounting uncertainty as described in Section 2.4 . A worked example is not provided here as this is independent of the two-stage process; in other words, the same process as is already familiar from typical single stage (i.e. FLS versus mast) application is applicable. It is useful to note that if mounting uncertainty is assumed negligible and there are no significant environmental variables (in the classification sense), then the final application uncertainty may simply be assigned to the calibration uncertainty resulting from Stage 2.

3.2. Calibration of Lidar using Reference (Onshore) Meteorological Mast

As described in Section 2.2, the reference uncertainty, $u_{VS,i}$, for the cup anemometer mounted on the mast is made up of a number of components. The calculation of that uncertainty is not of direct interest in this context, so here we simply present the reference uncertainty values, taken verbatim from the calibration report, in Table 2 and Figure 3.

Here the lidar mounting uncertainty, $u_{VR,mnt,i}$, is assumed to be negligible. Uncertainty $u_{VR,sep}$ due to flow gradients across the site and separation distance between the mast and lidar is also assumed to be negligible as this appears to be the implicit assumption from the test report from DTU.

The other components from the equation E1 are available from the test campaign itself. The resulting estimation of calibration uncertainty for the lidar, $u_{VR,cal,i}$, is tabulated in Table 2 and plotted in Figure 3. As noted in Section 1 and summarised in Table 1, there are differences between the 'LUSR' approach recommended here and the 'standard approach'. For comparison, results for the 'standard' approach to aggregation of uncertainty components for the same data are presented in Table 3 and Figure 4.

As expected, the 'LUSR' approach yields a lower uncertainty (e.g. 1.3% at 10 m/s) dominated by the reference uncertainty, whereas the 'standard' approach yields a higher value (e.g. 2.6% at 10 m/s) where reference uncertainty, mean deviation and standard deviation of deviations all play important roles. The condition $\left|\Delta v_{VF,i}\right| < \ u_{VR,i}$ is not met for roughly half of the bins in the 'LUSR' approach, which is evident from Figure 3 in particular. Similarly, the condition that the so-called reduced uncertainty (i.e. having removed the mean deviation contribution) does not exceed the mean deviation is also the case for several bins in the 'standard' approach, although not evident in the figures. As there is no industry consensus on how to manage these exceedances, and the topic is currently under debate in the development of the IEC 61400-50-2 standard, this is left here simply as an observation.

3.3. Calibration of FLS using Reference Lidar

As described in Section 2.3, the reference uncertainty, $u_{VR,i}$, for the reference lidar is made up of a number of components. In this case the only non-zero component is the lidar calibration uncertainty: the lidar classification is assumed to have shown no significant environmental variable sensitivity (and the lidar deployed in similar conditions to the calibration test) therefore the classification uncertainty is zero; uncertainties due to non-homogenous flow and lidar mounting are also assumed negligible. The reference uncertainty is tabulated in Table 4 and plotted in Figure 5.

Here the floating lidar mounting uncertainty, $u_{VF,mnt,i}$, is assumed to be negligible. Uncertainty $u_{VF,sep}$ due to flow gradients across the site and separation distance between the reference lidar and FLS is estimated from the LUSR guidance: for a far offshore site we assume 0.05% uncertainty per kilometre of separation, and in this case the separation distance is 400 m.

The other components from the equation E3 are available from the test campaign itself. The resulting estimation of calibration uncertainty for the FLS, $u_{VF,cal,i}$, is tabulated in Table 4 and plotted in Figure 5. As noted in Section 1 and summarised in Table 1, there are differences between the ‘LUSR’ approach recommended here and the ‘standard approach’. Results for the ‘standard’ approach to aggregation of uncertainty components for the same data are presented in Table 5 and Figure 6.

As expected, the ‘LUSR’ approach yields a lower uncertainty (e.g. 1.3% at 10 m/s) dominated by the reference uncertainty, whereas the ‘standard’ approach yields a higher value (e.g. 4.6% at 10 m/s) where mean deviation and standard deviation of deviations are dominant.

3.4. Comments

As is well known, any successive step in a traceable uncertainty chain can only increase or at best not increase the estimated uncertainty. For this reason, it has always been a concern that the two-stage process may elevate uncertainties to levels well beyond the levels the industry is accustomed to with a single stage (i.e. FLS versus mast) calibration process. Here we have an example of the two-stage process where the resulting uncertainty levels scarcely differ from those which would be attained in a single stage. On the other hand, we must acknowledge that the ‘standard’ approach, which is surely being phased out in the industry, does indeed result in significant uncertainty increases at each stage.

Wind speed at bin centre	Average measured wind speed in bin (cup)	Average measured wind speed in bin (lidar)	Reference uncertainty	Number of data points in bin	Standard deviation of deviations	Std dev of deviations / square root number points	Lidar mounting uncertainty	Uncertainty due to separation distance	Calibration uncertainty	Absolute value of mean deviation	Check
v_i	$v_{cup,i}$	$v_{R,i}$	$u_{VS,i}$	$N_{VR,i}$	$\sigma_{VRdev,i}$	$\sigma_{VRdev,i}/\surd N_{VR,i}$	$u_{VR,mnt,i}$	$u_{VR,sep,i}$	$u_{VR,cal,i}$	$\lvert \Delta v_{VR,i} \rvert$	$u_{VS,i} - \lvert \Delta v_{VR,i} \rvert$
m/s	m/s	m/s	m/s	count	m/s	m/s	m/s	m/s	m/s	m/s	m/s
4.0	4.14	4.34	0.07	32	0.19	0.03	0	0	0.08	0.21	-0.14
4.5	4.50	4.69	0.07	88	0.18	0.02	0	0	0.08	0.19	-0.12
5.0	5.00	5.23	0.08	93	0.16	0.02	0	0	0.08	0.22	-0.14
5.5	5.50	5.70	0.08	96	0.17	0.02	0	0	0.09	0.20	-0.12
6.0	5.99	6.20	0.09	101	0.15	0.01	0	0	0.09	0.22	-0.13
6.5	6.50	6.72	0.09	128	0.16	0.01	0	0	0.09	0.23	-0.14
7.0	7.02	7.24	0.10	137	0.16	0.01	0	0	0.10	0.22	-0.12
7.5	7.49	7.69	0.10	154	0.15	0.01	0	0	0.10	0.20	-0.10
8.0	8.02	8.22	0.11	247	0.14	0.01	0	0	0.11	0.20	-0.09
8.5	8.50	8.72	0.11	265	0.16	0.01	0	0	0.11	0.21	-0.10
9.0	8.99	9.19	0.12	330	0.18	0.01	0	0	0.12	0.20	-0.08
9.5	9.50	9.70	0.12	328	0.18	0.01	0	0	0.12	0.20	-0.08
10.0	10.00	10.17	0.13	333	0.15	0.01	0	0	0.13	0.17	-0.04
10.5	10.48	10.65	0.13	281	0.16	0.01	0	0	0.13	0.17	-0.04
11.0	10.99	11.14	0.14	208	0.15	0.01	0	0	0.14	0.14	0.00
11.5	11.49	11.61	0.14	183	0.14	0.01	0	0	0.14	0.12	0.02
12.0	12.00	12.15	0.15	172	0.17	0.01	0	0	0.15	0.14	0.01
12.5	12.51	12.64	0.15	172	0.14	0.01	0	0	0.15	0.13	0.02
13.0	13.00	13.11	0.16	168	0.17	0.01	0	0	0.16	0.11	0.05
13.5	13.51	13.63	0.16	146	0.16	0.01	0	0	0.16	0.11	0.05
14.0	14.00	14.11	0.17	129	0.15	0.01	0	0	0.17	0.11	0.06
14.5	14.52	14.58	0.17	118	0.19	0.02	0	0	0.17	0.06	0.11
15.0	14.99	15.05	0.18	96	0.15	0.02	0	0	0.18	0.06	0.12
15.5	15.49	15.57	0.18	93	0.20	0.02	0	0	0.18	0.07	0.11
16.0	15.86	15.94	0.19	34	0.24	0.04	0	0	0.19	0.08	0.11

Table 2: Stage 1 worked example, following ‘LUSR’ approach for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. Note that negative values in the last column indicate mean deviation exceeding reference uncertainty. See equation E1 and Figure 3.

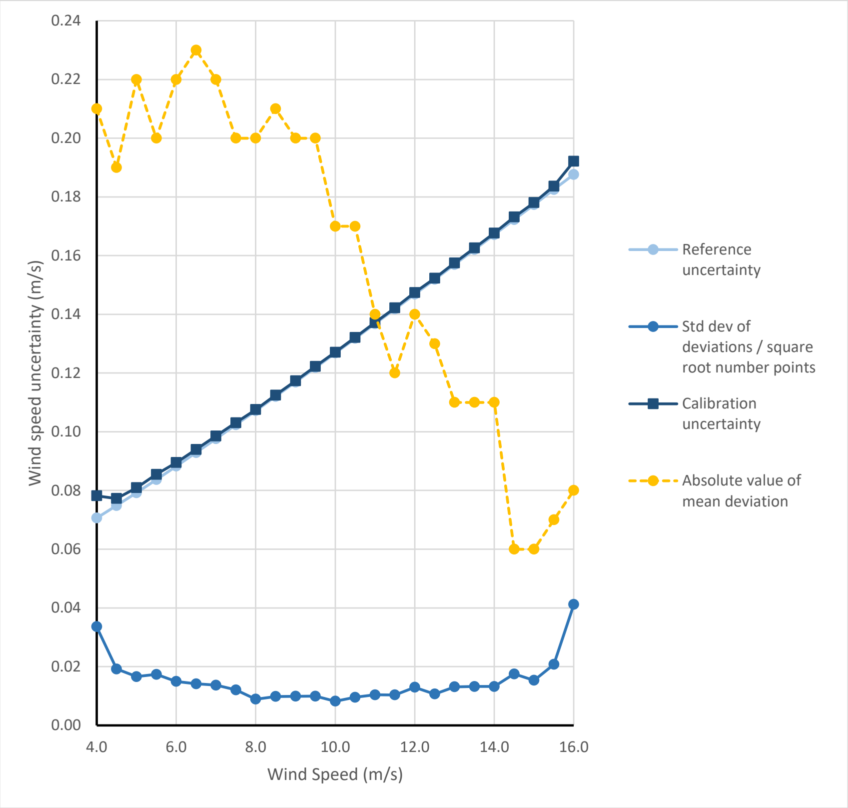

Figure 3: Stage 1 worked example, following ‘LUSR’ approach for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. Mean deviation exceeding reference uncertainty for lower wind speeds is clearly visible. See equation E1 and Table 2.

Wind speed at bin centre	Average measured wind speed in bin (cup)	Average measured wind speed in bin (lidar)	Reference uncertainty	Absolute value of mean deviation	Number of data points in bin	Standard deviation of lidar data	Std dev lidar / square root number points	Standard deviation of deviations	Lidar mounting uncertainty	Uncertainty due to separation distance	Calibration uncertainty
v_i	$v_{cup,i}$	$v_{R,i}$	$u_{VS,i}$	$\lvert \Delta v_{VR,i} \rvert$	$N_{VR,i}$	$\sigma_{VR,i}$	$\sigma_{VR,i}/\sqrt{N_{VR,i}}$	$\sigma_{VRdev,i}$	$u_{VR,mnt,i}$	$u_{VR,sep,i}$	$u_{VR,cal,i}$
m/s	m/s	m/s	m/s	m/s	count	m/s	m/s	m/s	m/s	m/s	m/s
4.0	4.14	4.34	0.07	0.21	32	0.20	0.04	0.19	0	0	0.29
4.5	4.50	4.69	0.07	0.19	88	0.25	0.03	0.18	0	0	0.27
5.0	5.00	5.23	0.08	0.22	93	0.22	0.02	0.16	0	0	0.28
5.5	5.50	5.70	0.08	0.20	96	0.23	0.02	0.17	0	0	0.28
6.0	5.99	6.20	0.09	0.22	101	0.21	0.02	0.15	0	0	0.28
6.5	6.50	6.72	0.09	0.23	128	0.21	0.02	0.16	0	0	0.30
7.0	7.02	7.24	0.10	0.22	137	0.22	0.02	0.16	0	0	0.29
7.5	7.49	7.69	0.10	0.20	154	0.21	0.02	0.15	0	0	0.27
8.0	8.02	8.22	0.11	0.20	247	0.21	0.01	0.14	0	0	0.27
8.5	8.50	8.72	0.11	0.21	265	0.21	0.01	0.16	0	0	0.29
9.0	8.99	9.19	0.12	0.20	330	0.21	0.01	0.18	0	0	0.29
9.5	9.50	9.70	0.12	0.20	328	0.23	0.01	0.18	0	0	0.30
10.0	10.00	10.17	0.13	0.17	333	0.21	0.01	0.15	0	0	0.26
10.5	10.48	10.65	0.13	0.17	281	0.22	0.01	0.16	0	0	0.27
11.0	10.99	11.14	0.14	0.14	208	0.19	0.01	0.15	0	0	0.25
11.5	11.49	11.61	0.14	0.12	183	0.21	0.02	0.14	0	0	0.23
12.0	12.00	12.15	0.15	0.14	172	0.24	0.02	0.17	0	0	0.27
12.5	12.51	12.64	0.15	0.13	172	0.20	0.02	0.14	0	0	0.24
13.0	13.00	13.11	0.16	0.11	168	0.23	0.02	0.17	0	0	0.26
13.5	13.51	13.63	0.16	0.11	146	0.20	0.02	0.16	0	0	0.25
14.0	14.00	14.11	0.17	0.11	129	0.20	0.02	0.15	0	0	0.25
14.5	14.52	14.58	0.17	0.06	118	0.24	0.02	0.19	0	0	0.26
15.0	14.99	15.05	0.18	0.06	96	0.21	0.02	0.15	0	0	0.24
15.5	15.49	15.57	0.18	0.07	93	0.25	0.03	0.20	0	0	0.28
16.0	15.86	15.94	0.19	0.08	34	0.26	0.05	0.24	0	0	0.32

Table 3: Stage 1 worked example, following ‘standard’ approach (see Table 1) for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. See equation E 1 and Figure 4.

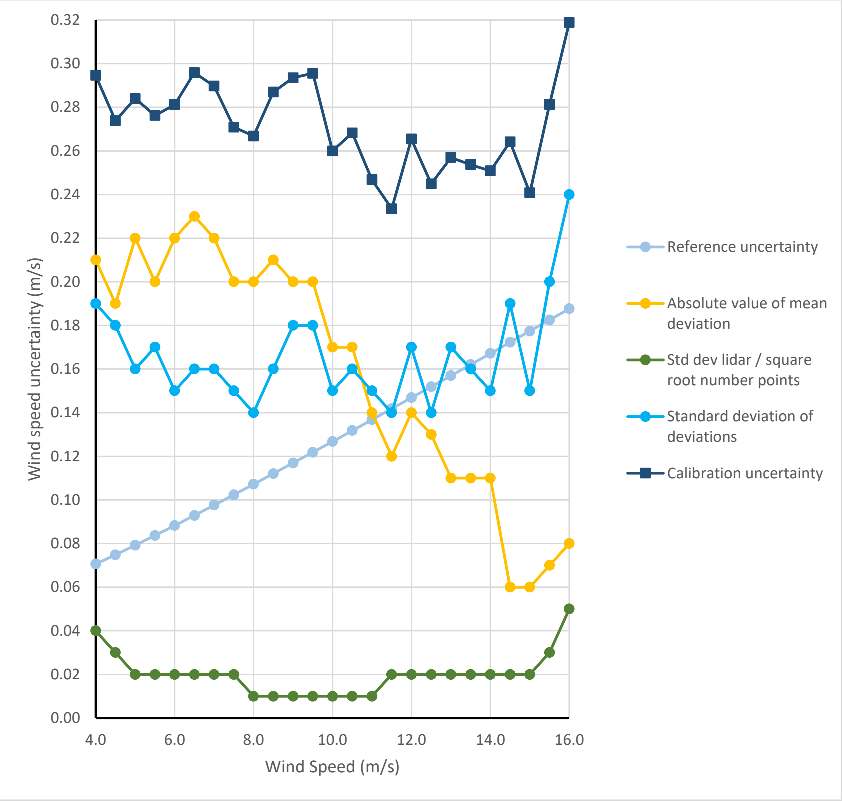

Figure 4: Stage 1 worked example, following ‘standard’ approach (see Table 1) for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. See equation E 1 and Table 3.

Wind speed at bin centre	Average measured wind speed in bin (lidar)	Average measured wind speed in bin (FLS)	Reference uncertainty	Number of data points in bin	Standard deviation of deviations	Std dev of deviations / square root number points	FLS mounting uncertainty	Uncertainty due to separation distance	Calibration uncertainty	Absolute value of mean deviation	Check
v_i	$v_{R,i}$	$v_{F,i}$	$u_{VR,i}$	$N_{VF,i}$	$\sigma_{VFdev,i}$	$\sigma_{VFdev,i}/\sqrt{N_{VF,i}}$	$u_{VF,mnt,i}$	$u_{VF,sep,i}$	$u_{VF,cal,i}$	$\lvert\Delta v_{VF,i}\rvert$	$u_{VR,i} - \lvert\Delta v_{VF,i}\rvert$
m/s	m/s	m/s	m/s	count	m/s	m/s	m/s	m/s	m/s	m/s	m/s
4.0	4.00	4.06	0.08	140	0.20	0.02	0	0.001	0.08	0.05	0.03
4.5	4.49	4.55	0.08	175	0.21	0.02	0	0.001	0.08	0.06	0.02
5.0	4.99	5.04	0.08	230	0.23	0.02	0	0.001	0.08	0.05	0.03
5.5	5.50	5.54	0.09	207	0.23	0.02	0	0.001	0.09	0.04	0.04
6.0	6.00	6.03	0.09	227	0.24	0.02	0	0.001	0.09	0.03	0.06
6.5	6.49	6.51	0.09	233	0.22	0.01	0	0.001	0.10	0.01	0.08
7.0	7.00	7.06	0.10	274	0.27	0.02	0	0.001	0.10	0.05	0.04
7.5	7.48	7.53	0.10	309	0.25	0.01	0	0.002	0.10	0.05	0.06
8.0	8.00	8.08	0.11	326	0.30	0.02	0	0.002	0.11	0.08	0.02
8.5	8.48	8.52	0.11	350	0.30	0.02	0	0.002	0.11	0.04	0.07
9.0	9.00	9.01	0.12	322	0.30	0.02	0	0.002	0.12	0.01	0.11
9.5	9.52	9.51	0.12	393	0.36	0.02	0	0.002	0.12	0.00	0.12
10.0	10.00	10.03	0.13	484	0.37	0.02	0	0.002	0.13	0.04	0.09
10.5	10.50	10.53	0.13	483	0.36	0.02	0	0.002	0.13	0.02	0.11
11.0	10.99	10.99	0.14	464	0.36	0.02	0	0.002	0.14	0.01	0.13
11.5	11.49	11.51	0.14	482	0.37	0.02	0	0.002	0.14	0.03	0.11
12.0	11.99	12.03	0.15	421	0.40	0.02	0	0.002	0.15	0.03	0.12
12.5	12.51	12.55	0.15	401	0.39	0.02	0	0.003	0.15	0.05	0.11
13.0	13.00	13.01	0.16	469	0.43	0.02	0	0.003	0.16	0.01	0.15
13.5	13.50	13.54	0.16	446	0.43	0.02	0	0.003	0.16	0.04	0.12
14.0	14.00	14.02	0.17	455	0.47	0.02	0	0.003	0.17	0.02	0.15
14.5	14.49	14.50	0.17	464	0.45	0.02	0	0.003	0.17	0.00	0.17
15.0	14.99	14.96	0.18	371	0.46	0.02	0	0.003	0.18	0.03	0.15
15.5	15.50	15.46	0.18	336	0.45	0.02	0	0.003	0.19	0.04	0.14
16.0	15.99	15.99	0.19	371	0.48	0.03	0	0.003	0.19	0.00	0.19

Table 4: Stage 2 worked example, following 'LUSR' approach for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. Negative values in the last column indicate mean deviation exceeding reference uncertainty – and in this case there are none. See equation E3 and Figure 5.

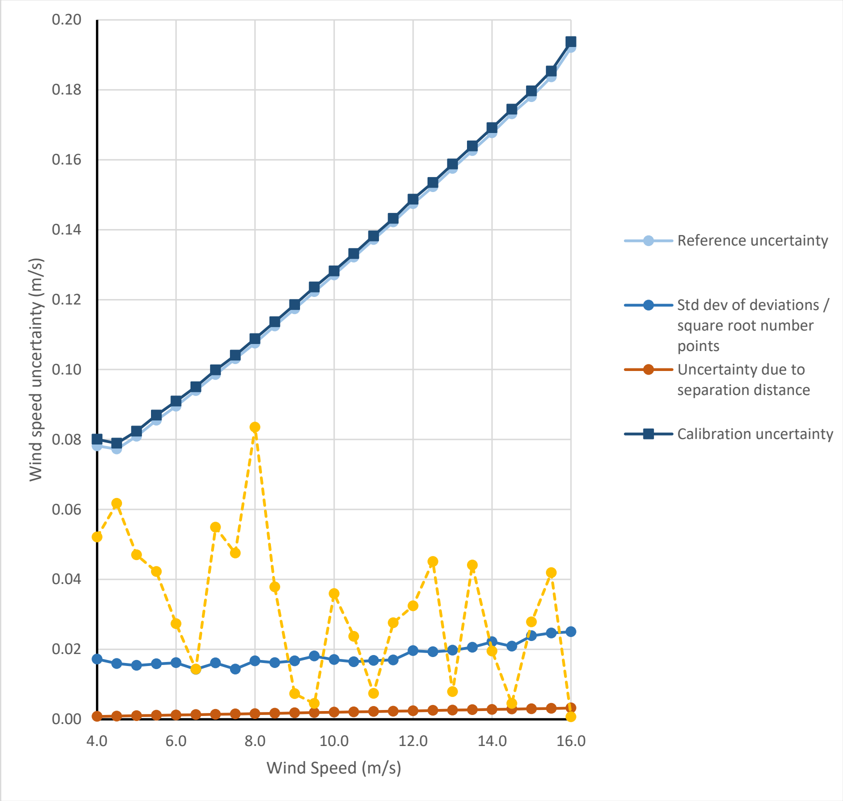

Figure 5: Stage 2 worked example, following 'LUSR' approach for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. It is clearly visible that mean deviation does not exceed reference uncertainty. See equation E3 and Table 4.

Wind speed at bin centre	Average measured wind speed in bin (lidar)	Average measured wind speed in bin (FLS)	Reference uncertainty	Absolute value of mean deviation	Number of data points in bin	Standard deviation of FLS data	Std dev FLS / square root number points	Standard deviation of deviations	FLS mounting uncertainty	Uncertainty due to separation distance	Calibration uncertainty
v_i	$v_{R,i}$	$v_{F,i}$	$u_{VR,i}$	$\lvert\Delta v_{VF,i}\rvert$	$N_{VF,i}$	$\sigma_{VF,i}$	$\sigma_{VF,i}/\sqrt{N_{VF,i}}$	$\sigma_{VFdev,i}$	$u_{VF,mnt,i}$	$u_{VF,sep,i}$	$u_{VF,cal,i}$
m/s	m/s	m/s	m/s	m/s	count	m/s	m/s	m/s	m/s	m/s	m/s
4.0	4.00	4.06	0.29	0.05	140	0.25	0.02	0.20	0	0.001	0.36
4.5	4.49	4.55	0.27	0.06	175	0.26	0.02	0.21	0	0.001	0.35
5.0	4.99	5.04	0.28	0.05	230	0.28	0.02	0.23	0	0.001	0.37
5.5	5.50	5.54	0.28	0.04	207	0.26	0.02	0.23	0	0.001	0.36
6.0	6.00	6.03	0.28	0.03	227	0.28	0.02	0.24	0	0.001	0.37
6.5	6.49	6.51	0.30	0.01	233	0.26	0.02	0.22	0	0.001	0.37
7.0	7.00	7.06	0.29	0.05	274	0.31	0.02	0.27	0	0.001	0.40
7.5	7.48	7.53	0.27	0.05	309	0.28	0.02	0.25	0	0.002	0.37
8.0	8.00	8.08	0.27	0.08	326	0.33	0.02	0.30	0	0.002	0.41
8.5	8.48	8.52	0.29	0.04	350	0.34	0.02	0.30	0	0.002	0.42
9.0	9.00	9.01	0.29	0.01	322	0.33	0.02	0.30	0	0.002	0.42
9.5	9.52	9.51	0.30	0.00	393	0.39	0.02	0.36	0	0.002	0.46
10.0	10.00	10.03	0.26	0.04	484	0.40	0.02	0.37	0	0.002	0.46
10.5	10.50	10.53	0.27	0.02	483	0.39	0.02	0.36	0	0.002	0.45
11.0	10.99	10.99	0.25	0.01	464	0.38	0.02	0.36	0	0.002	0.44
11.5	11.49	11.51	0.23	0.03	482	0.40	0.02	0.37	0	0.002	0.44
12.0	11.99	12.03	0.27	0.03	421	0.43	0.02	0.40	0	0.002	0.48
12.5	12.51	12.55	0.24	0.05	401	0.41	0.02	0.39	0	0.003	0.46
13.0	13.00	13.01	0.26	0.01	469	0.46	0.02	0.43	0	0.003	0.50
13.5	13.50	13.54	0.25	0.04	446	0.47	0.02	0.43	0	0.003	0.51
14.0	14.00	14.02	0.25	0.02	455	0.50	0.02	0.47	0	0.003	0.54
14.5	14.49	14.50	0.26	0.00	464	0.47	0.02	0.45	0	0.003	0.52
15.0	14.99	14.96	0.24	0.03	371	0.48	0.03	0.46	0	0.003	0.52
15.5	15.50	15.46	0.28	0.04	336	0.47	0.03	0.45	0	0.003	0.53
16.0	15.99	15.99	0.32	0.00	371	0.49	0.03	0.48	0	0.003	0.58

Table 5: Stage 2 worked example, following 'standard' approach (see Table **1**) for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. See equation E 3 and Figure 6.

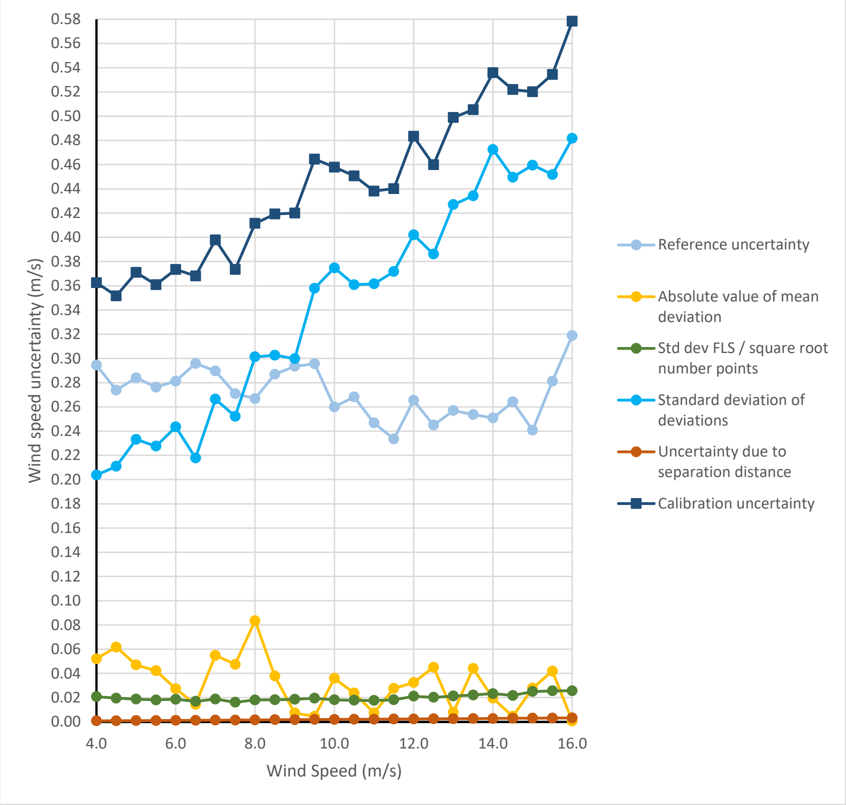

Figure 6: Stage 2 worked example, following 'standard' approach for aggregations of uncertainty components into lidar calibration uncertainty. Uncertainty values shown are standard uncertainties. See equation E3 and Table 5.

4. References

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