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Lidar Uncertainty Standard Review Methodology Review and Recommendations

Offshore Wind Accelerator – Wakes and Wind Resource

LUSR – LiDAR Uncertainty Standard Review

[June, 2018]

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1.3 DISCLAIMER

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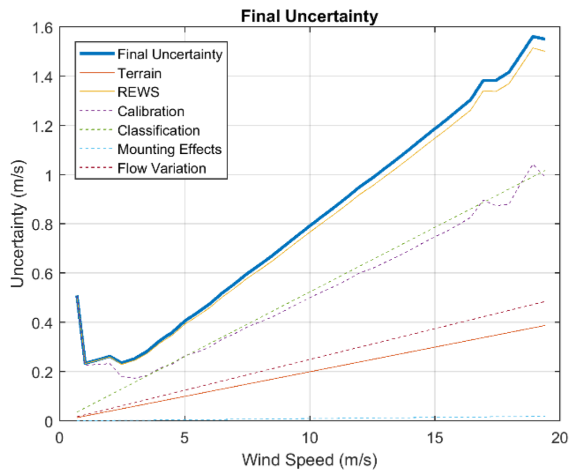
EXECUTIVE SUMMARY

It is well established in the offshore wind industry that the effective application of remote sensing wind measurement technology could be improved through improvements in the associated uncertainty assessment procedure. This was clearly underlined in workshop discussions on 26 January 2017 (as part of the preceding project 'OWA LiDAR Uncertainty Reduction'), where there was consensus that the existing IEC standard drafting of an uncertainty procedure (for power curve assessment using lidars) could be improved with respect to established theory and practice, and that a review and/or update would be of real benefit. This observation and consensus led to a clear recommendation for the OWA to carry out such a review (see reference 1). This document consists of the findings from the resulting OWA project, "Lidar Uncertainty Standard Review", which began in September 2017.

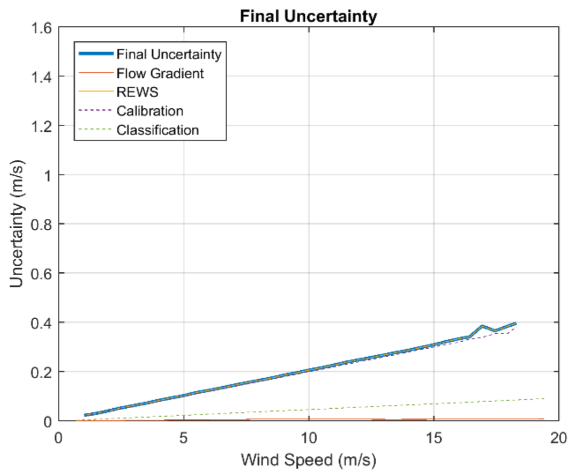
Prior to the project beginning, the updated IEC 61400-12-1 standard has progressed from draft to published status (see reference 2). This version includes many changes with respect to earlier versions. Notably for this project, there is now included a standard for the use of lidars in a new Annex L, "The application of remote sensing technology". This document describes the results of an expert review of this standard, including Annex L, to use cases of interest to the OWA partners. This includes interpretation of the standard to use case scenarios which are not directly addressed by the standard: the standard considers the use of fixed lidars for wind turbine power performance tests; this review considers floating lidars and wind resource assessment also.

This review document is structured as follows:

- The use cases of interest are described, as well as the datasets available;
- Specific recommendations and improvements are described;
- Example calculations are provided;
- Potential areas of further improvement beyond the scope of the current project are identified and recommendations made.



Example calculation, closely following the standard.



Example calculation, with revised methodology.

Combined Uncertainties for Floating Lidar Example Calculation.

Following the revised methodology proposed in this work, substantial reductions in wind speed uncertainty have been demonstrated, as summarised in the above figures. The case where this makes the largest impact is the offshore case using floating lidar data, where an overall reduction in estimated uncertainty of approximately 6% was demonstrated. The main contributors to this are:

- A revised methodology, based on expected and realistic flow gradients across the site, to estimate uncertainty due to flow gradients between the floating lidar and the reference measurement during calibration.
- A revised methodology for calibration uncertainty.
- Careful selection of the implementation route for classification uncertainty; a detailed application of environmental variable sensitivity is preferred to the class number approach. Both are allowed in the standard; the class number approach is currently more likely to be applied as it is far simpler.
- A revised methodology, based on expected and realistic flow gradients across the site and a model for the effects of induction, to estimate uncertainty due to flow gradients between the floating lidar and the turbine during the power performance test.
- The assumption that uncertainty due to flow variation within the lidar's control volume is negligible.

ABBREVIATIONS

Abbreviation	Meaning
AEP	Annual Energy Production
EV	Environmental Variable (EVs for plural)
FLS	Floating Lidar System (or Systems)
GUM	Guide to the expression of Uncertainty of Measurement
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LIDAR, lidar	LIght Detection And Ranging – a type of RSD
Met Mast	Meteorological Mast (assumed to include conventional instrumentation i.e. cup anemometers and wind vanes).
OWA	Offshore Wind Accelerator
REWS	Rotor-Equivalent Wind Speed
RSD	Remote Sensing Device
VIM	International Vocabulary of Metrology
WRA	Wind Resource Assessment

CONTENTS

2. INTRODUCTION

It is well established in the offshore wind industry that the effective application of remote sensing wind measurement technology could be improved through improvements in the associated uncertainty assessment procedure. This was clearly underlined in workshop discussions on 26 January 2017 (as part of the preceding project ‘OWA LIDAR Uncertainty Reduction’), where there was consensus that the existing IEC standard drafting of an uncertainty procedure (for power curve assessment using lidars) could be improved with respect to established theory and practice, and that a review and/or update would be of real benefit. This observation and consensus led to a clear recommendation for the OWA to carry out such a review (see reference 1). This document consists of the findings from the resulting OWA project, “Lidar Uncertainty Standard Review”, which began in September 2017.

Prior to the project beginning, the updated IEC 61400-12-1 standard has progressed from draft to published status (see reference 2). This version includes many changes with respect to earlier versions. Notably for this project, there is now included a standard for the use of lidars in a new Annex L, “The application of remote sensing technology”. This innovation pertains to the use of vertically-profiling lidars in a wind turbine power performance scenario. This is significant because this is the first IEC standard publication considering the use of lidars for power performance. It is also significant because industry-accepted good practice in the estimation of uncertainty when using lidars in other scenarios is heavily influenced by and adapted from this standard.

This document describes the results of an expert review of this standard, including Annex L, to use cases of interest to the OWA partners. This includes interpretation of the standard to use case scenarios which are not directly addressed by the standard: the standard considers the use of fixed lidars for wind turbine power performance tests; this review considers floating lidars and wind resource assessment (WRA) also. The ultimate objective of this review is to reduce the uncertainty associated with the use of lidar wind data, particularly for those scenarios. This is achieved through a detailed review of the standard, making associated clarifications, corrections and alternative recommendations; through recommendations of how it should be applied to FLS power performance and WRA scenarios; and through the generation of worked examples.

This review document is structured as follows:

- The use cases of interest are described, as well as the datasets available, in Section 3;
- Specific recommendations and improvements are described in Section 4;
- Example calculations are provided in Section 5;
- Finally, conclusions are drawn, potential areas of further improvement beyond the scope of the current project are identified, recommendations are made, and the impact summarised in Section 6.

3. USE CASES

Applicable use cases to act as demonstration calculations have been previously agreed, see reference 3. The use cases are summarised in this section for convenience. Note that the focus of the standard under review (reference 2) is on power performance, and that lidars of the vertically-profiling type only are considered; likewise this work focusses on vertically-profiling lidars in a power performance context. Section 3.4 comments on the applicability of the current work to the wind resource assessment (WRA) context and to other lidar types.

3.1 ONSHORE DATA SET: IEA WIND TASK 32 POWER PERFORMANCE WORKSHOP DATA

The onshore data set is that used in the IEA Wind Task 32 Power Performance Workshop in December 2016. The data set consists of lidar (Leosphere Windcube V2) data, met mast and wind turbine data.

The data will be used for exemplar power curve assessment uncertainty calculations in-line with the uncertainty calculation procedure specified in the IEC standard, and a parallel calculation taking into account the recommendations of this work. Note that the IEA Wind Task 32 Power Performance Workshop also included suggested values for a number of uncertainties, and that these are not necessarily the same as the values used here where the standard (reference 2) has been followed as closely as possible.

3.2 OFFSHORE DATA SET: FLOATING LIDAR POWER CURVE ASSESSMENT DATA

The offshore data set pertains to a floating lidar system (FLS) power curve assessment. This was carried out at Alpha Ventus using the Fraunhofer FLS with the FINO1 mast nearby. The data set consists of (buoy-mounted) lidar (ZephIR Z300) data, met mast and wind turbine data.

The data will be used for exemplar power curve assessment uncertainty calculations in-line with, or as an interpretation of and extension from, the uncertainty calculation procedure specified in the IEC standard, and a parallel calculation taking into account the recommendations of this work.

3.3 SUMMARY OF CALCULATIONS

A number of individual calculations have been performed as part of this study. These are comprised of:

- The use of either the onshore or the offshore data set as described above;
- The use of either met mast data alone, lidar (or floating lidar) data alone, or mast and lidar data in combination;
- A verbatim approach to the application of the standard (with and without some obvious corrections), a close as possible application of the standard but interpreted for lidar data, or a revised approach as described in this document's methodology.

How these varying elements make up the calculations performed is summarised in Table 2 of section 5, including a unique index assigned to each calculation for consistency and ease of reference. The calculations are also described in full in section 5.

3.4 NOTE ON APPLICABILITY OF CONCLUSIONS

As explained above, the current project has as its focus the application of the standard (reference 2) to power curve assessments. The use of vertically-profiling lidars to support wind resource assessments (WRAs) is also of interest, therefore the applicability of the current work to WRA is commented on here. There is no equivalent standard for WRA, and in practice the appropriate procedures for wind measurements, and for assessing their uncertainty, are adapted from the power curve assessment standard. In keeping with this, the majority of the findings of the current work is equally applicable to a WRA scenario. The exception to this is the 'Uncertainty due to Terrain Complexity' part, section 4.4, which only pertains to a power curve scenario. The WRA context to the conclusions is briefly commented on in section 6.

There is also no standard for the use of nacelle-mounted lidars for power performance assessment. In that context, most of the methodology improvements described in this work are considered to also be of value and applicable, although the worked examples provided here are of course less applicable in attempting to understand and quantify uncertainties. The 'Shear and Veer Uncertainty' part, section 4.9, is less relevant because shear and veer are typically not measured by a nacelle-mounted lidar.

Lastly, for other contexts where lidar technology may be applied for wind measurement, for example using scanning lidars for WRA, it is considered that much of the methodology discussions and improvements would remain relevant, However, the worked examples provided in this work are not necessarily representative of such an alternative scenario.

4. IDENTIFICATION OF IMPROVEMENTS

The use of an RSD for a power curve assessment is described in Annex L of IEC 61400-12-1 (see reference 2), with other parts of the standard also relevant. This section describes the authors' clarifications of, and alternative approaches to, the methodology set out in that standard, with respect to the use cases described in section 3 of this document. The remainder of this section is structured as follows:

- A summary of clarifications and alternative approaches is presented in Table 1;
- Subsequent sub-sections describe each of these in turn.

4.1 LIDAR CALIBRATION UNCERTAINTY

4.1.1 What is it now?

Uncertainty arising from lidar calibration is presently defined as deriving from five key sources (see section L.4.3 of the standard):

1. Uncertainty of the reference sensor (i.e. an anemometer mounted on a met mast), $\boldsymbol{u}_{\mathrm{ref}}^{\mathbf{2}}$
2. The mean deviation of the RSD and reference sensor measurements, $\Delta\boldsymbol{v}^{\mathbf{2}}$
3. The calculated standard uncertainty of the measurements, $\frac{\boldsymbol{\sigma}_{\mathrm{lidar}}^{\mathbf{2}}}{\boldsymbol{N}}$
4. Uncertainty due to mounting effects of the lidar (see section 4.5),
5. Uncertainty due to non-homogenous flow within the measurement volume during the calibration test (see section 4.7).

These values are combined in quadrature to generate a final calibration uncertainty.

Additionally, at the end of section L.4.3 there is a discussion of the standard deviation of the deviations of the RSD and the reference sensor ($\boldsymbol{\sigma}_{\mathrm{dev}}^{\mathbf{2}}$): this is not included as it is automatically accounted for in the category A uncertainties of the power curve. When applying the standard to WRA rather than power curve applications, one possible interpretation is that such a term should also be included in that case.

4.1.2 What is wrong with this?

The large imported uncertainty from the reference sensor calibration is a dominant factor in the final calibration uncertainty. In metrological terms, this is a relatively unusual situation (that the reference uncertainty is of the same order of magnitude, or greater, than the measurement system uncertainty) and so must be handled with care to ensure that the large reference uncertainty is not double counted with measurement error.

Currently, deviation between RSD and reference sensor is included as an uncertainty however this term appears to be an error rather than an uncertainty, and thus should either be corrected for (by application of a correction obtained by calibration, which the standard allows for) or included using a process such as that given in section F.2.4.5 in the Guide to the expression of Uncertainty of Measurement (GUM), see reference 4. However, it is considered that in this instance it may be possible to discount the reported error as an uncertainty due to the high reference uncertainty where the deviation between the RSD and reference instrument is within the uncertainty of the reference instrument. This is discussed further below.

Also, the use of the so-called calculated standard uncertainty of the measurements ($\frac{\sigma_{\text{lidar}}{}^{2}}{N}$) in the uncertainty budget does not appear to be correct. Variation in the wind speed itself should not be penalised by increased uncertainty if the reference and test instruments track perfectly (a good example could be a thought experiment in which an instrument is calibrated with itself). Rather it is the standard deviation of the difference between the reference and test instruments that is related to the uncertainty since this is indicative of how good the mapping between the test and reference instruments really is.

4.1.3 What we propose instead

When considering the calibration of remote sensing devices such as lidars, it is important to understand how the traceability to International Standards is achieved. As the unit of wind speed is ultimately distance and time, these are the base SI units to which traceability should be assured. However, it is normal practice for the lidar to be calibrated against another measurement system (the cup anemometer), which itself is calibrated against a pitot tube which should then be itself traceably calibrated.

As rotating cup anemometry is the generally accepted standard for wind measurement in the renewables industry, and because there is as yet no obvious alternative, lidars are compared with anemometers to perform their calibration. Therefore, the traceability route is via the anemometer calibration.

There are uncontrollable variables involved in the calibration of the cup anemometer (which takes place in a wind tunnel) and the calibration of the lidar (which takes place at an outside location alongside a mast with anemometers). These variables appear as uncertainties in the final values as they manifest as random error (statistical spread) in the final measurement.

There are also inherent errors due to the design of the cup anemometer against its “ideal” equivalent (e.g. the bearings are not frictionless, the rotor is neither aerodynamically perfect nor is it without inertia etc). These also will result in differences from the ideal measurement, and are taken into account in the classification of the cup and thus are accounted for in the uncertainty budget.

Measurement Uncertainty is defined in VIM (see reference 5) as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. Measurement uncertainty comprises a number of components which can be evaluated through statistical methods (such as probability density) or based on other information. The total system uncertainty is calculated using an uncertainty budget. It is important to note that during calibration, a constant bias arising from a systematic error may be present. However, this error can only be regarded as systematic (rather than random) if the reference measurement system is capable of distinguishing the true quantity value (i.e. actual wind speed) without random errors generated by another source.

Measurement bias can only be corrected for if the causes of the systematic error are known. Due to the nature and scales of the uncertainties involved in the use of anemometers to calibrate lidars, it can be difficult to envisage why this technique is so problematic. Therefore, by way of example, Annex A is a thought experiment around this type of error correction as it would apply to a mass measurement. The example shows how masses cannot be calibrated if the uncertainty of the primary reference is too great.

Much the same can be stated for lidars in the way in which the uncertainty in Annex L is stated. The formula is commonly currently represented as (note this includes the ‘standard deviation of the deviations’ term discussed in section 4.2.1):

$$\boldsymbol{u}_{\mathrm{cal}}{}^{\mathbf{2}} = \boldsymbol{u}_{\mathrm{ref}}{}^{\mathbf{2}} + \frac{\sigma_{\mathrm{lidar}}{}^{\mathbf{2}}}{\boldsymbol{N}} + \boldsymbol{\sigma}_{\mathrm{dev}}{}^{\mathbf{2}} + \Delta\boldsymbol{v}^{\mathbf{2}}, \qquad (1)$$

This incorporates both a systematic error (Δv^2), (which could be corrected for, but often lies within the uncertainty of the reference measurement and thus technically does not exist, as in the example above); and a variable term which is caused by measured variation in the reference material (i.e. the wind) which would also be observed by the reference measurement system ($\frac{\sigma_{\mathrm{lidar}}{}^2}{N}$).

Section F.2.4.5 of the GUM (reference 4) provides a methodology for correcting for situations where it is not possible to correct for *significant* systematic effects (which would normally be corrected for by application of the calibration constants). It is contended here that, due to the large reference uncertainty from the cup anemometer, it is common for the measured deviation to be smaller than the reference uncertainty and is thus not *significant*.

Thus a more sensible approximation of the uncertainty is to observe the differences between the lidar and its reference ($\sigma_{\mathrm{dev}}{}^2$) with the inclusion of the imported reference uncertainty ($u_{\mathrm{ref}}{}^2$) to give:

$$u_{\mathrm{cal}}{}^2 = u_{\mathrm{ref}}{}^2 + \frac{\sigma_{\mathrm{dev}}{}^{\mathbf{2}}}{\boldsymbol{N}} \qquad \text{For } \Delta v < u_{ref} \qquad (2)$$

There are few physical equivalents in common metrology where the calibration references have uncertainties which dominate the final calibration uncertainty in this way. However, example H6 in the GUM (reference 4) does have some similarities to the metrological challenges in creating traceable wind measurements. This example looks at hardness testing using a mechanical test device called an “indentor”. In common with wind speed measurements, the calibration takes place by comparing results obtained from 2 different reference objects (i.e. the wind at the cup is not the same wind in the lidar scan volume; and the metal indented by the calibrator is not exactly the same as the metal seen by the test machine), and thus there is a random uncertainty due to this variation in replicate measurements (H.6.3.1). Wind lidars utilise multiple measurements to form a 10 minute average which can be characterised in the same manner. The example does not, however, suffer from a poorly defined reference standard, as ultimately it can be linked to a simple distance measurement uncertainty.

4.2 CLASSIFICATION UNCERTAINTY

4.2.1 What is it now?

The purpose of an RSD classification (see L.2 of reference 2) is, as for a cup anemometer classification, to assess the sensitivity to environmental parameters (e.g. temperature, wind shear, turbulence intensity) and to account for them as an additional uncertainty (see L.4.4) if conditions during the device verifications and its final application are significantly different and a significant sensitivity has been identified. From the classification test a class number is derived that may be used to characterize (‘classify’) a certain type of system. Class numbers are always type-specific but not device-specific and shall be derived not only on the basis of one dataset and test but several tests performed for different devices and sites.

According to E.7.4 of reference 2, there are three ways to derive the uncertainty that is associated with an RSD classification:

(1) Environmental variables (EVs) found to be relevant are measured during the application and then compared (in terms of their mean values) with the conditions during the verification test performed for the applied device. The differences in the mean values of the EVs are

then multiplied with the found sensitivities (in terms of derived regression slopes) and summed up to give the uncertainty estimate.

(2) The environmental variables are not measured but certain ranges are assumed for them. Otherwise the same procedure is followed as for (1).

(3) Only the combined class number is used to derive the uncertainty (cf. equation E.19 in reference 2). For this case a fixed (and rather conservative) range of the EVs is assumed that is not further adjusted for the specific site and measurement period.

4.2.2 What is wrong with this?

- If sensitivities of the measurement accuracy to environmental variables are known, it should also be possible to correct for them at least to some extent. In general, known biases that are not corrected but translated to an uncertainty increase the total uncertainty in an unnecessary way, and moreover the best estimate data is in such a case uncorrected and therefore not in fact the best estimate.
- Some of the sensitivities typically found for RSDs are much more likely to be caused by the used reference sensor rather than the RSD itself (e.g. sensitivity to temperature and temperature differences). This is something that needs to be tackled in a different way – e.g. by correcting/calibrating the reference sensor – and should not be assigned to the RSD since this would be double-accounting (since the uncertainty due to the reference instrument sensitivities are already accounted for in the classification term of the reference instrument in the calibration).

These two points can only really be acted on through a further investigation of the physics in the RSD and reference measurements, which is not within the scope of the present project, although we consider this to be an important and necessary future step. However, the following points have been covered by the project and our proposed modified procedure (for the latter see section 4.2.3).

The RSD class numbers given in the standard as an example seem to be too high and give too high uncertainties, respectively. Furthermore, the three options outlined above may give very different results[1], where option (3) clearly seems to be the worst option. Apart from that it is not advantageous to leave the user with three options to derive the classification uncertainty and give no further guidance. We do not think that the application of a class number should be recommended to be used here at all. Site-specific ranges for the relevant environmental parameters should be known from an earlier site assessment, so that at least option (2) should be applicable.

The overall classification procedure seems to be very complex and at the same time vague. For example, section L.2 of reference 2 refers to thresholds indicating significance that are not further justified and seem to be defined in a rather arbitrary way. The probability of deriving the same results from the same dataset seems very low and the chances of obtaining consistent results from datasets from different sites seem also to be very low. This is unacceptable for an international standard.

[1] This is supported by our example calculations – see section 5.

Sub-Section Reference	Description	Clarification (C) or Alternative Approach (A)	Associated Standard Uncertainty				
			Indicative from Standard (reference 2)	Calculated from standard Approach		Calculated from recommended Approach	
				Onshore	Offshore	Onshore	Offshore
4.1	lidar Calibration Uncertainty	A	2 to 3%	N/A	5%	N/A	2%
4.2	Classification Uncertainty	A	1 to 1.5%	N/A	5%	N/A	0.4%
4.3	Distance from Mast Uncertainty	A	5%[2]	N/A	3.5%	N/A	0.02%
4.4	Uncertainty due to Terrain Complexity	A	1-2% offshore, 2-3% onshore	2%	2%	1.4%	0.3%
4.5	Uncertainty due to Mounting	A	0.1%	0.1%	0.1%	zero	zero
4.6	Variation in Flow Across Site Uncertainty	C	See 'Distance from Mast Uncertainty' and 'Uncertainty due to Terrain Complexity'				
4.7	Flow variation within control volume	A	2 to 3%	2.5%	2.5%	zero	zero

Table 1: Summary of Methodology Improvement Items. Percentage uncertainty values are approximate.

[2] Assuming a separation of 500m and a measuring height of 100m

4.2.3 What we propose instead

Generally, we recommend not to use the class number to derive a classification uncertainty for an RSD but either measure or best-estimate the EV ranges that are then combined with the derived (significant) sensitivities of the classification test. (This corresponds to option (1) or (2) above.) Our example calculations in section 5 show a possible uncertainty reduction from about 5% to 0.5% or even less for an offshore use case where a floating lidar system is applied. In order to apply the recommended options (1) or (2), it is necessary to know the sensitivities observed in the classification test. Since a complete RSD classification (as outlined in the standard) is quite costly and time-consuming – and furthermore not necessary for each RSD device but only each type – we propose that this information is to be provided by the RSD manufacturers.

Note that quantities like significant wave height and peak wave period are EVs that may be significant for an FLS applied offshore and should be added to the list of EVs given in the standard in this case.

Furthermore, we recommend to review and revise the classification procedure in more detail: if possible data should be corrected for known systematic effects and not just assigned with a higher uncertainty. The further development of corresponding methods is however not within the scope of this project but needs further investigation. The same applies to the revision of the given significance thresholds given in L.2 of the standards. We suggest that they are to be related to the reference uncertainty (following the argumentation in 4.1) but cannot provide an explicit procedure here.

4.3 DISTANCE FROM MAST UNCERTAINTY

4.3.1 What is it now?

This is an uncertainty to be added to the calibration uncertainty. It is particularly relevant for calibrations performed at a significant distance from the reference mast which will most often be the case for floating lidar. According to section L.4.3 “an additional uncertainty in the wind speed of 1% times the separation distance divided by the measurement height shall be applied”. Referring to this as U_{sep} (there is no designation in Annex L), the value is thus

$$U_{sep} = \frac{1\%.D}{H} \tag{3}$$

where $\boldsymbol{D}$ is the separation distance and $\boldsymbol{H}$ is the measuring height (both in m).

4.3.2 What is wrong with this?

Typical floating lidar calibrations will have a separation distance of several hundred metres (in order to avoid the buoy colliding with the mast). For a separation of 500m and a measuring height of 100m it is required to add an extra 5% of (standard) uncertainty. This is a very large number. It is saying that there is a 68% probability that the mean speed measured at the lidar is within ±5% of the speed measured at the reference mast, i.e. that there is a 32% probability that the speed lies outside this range. Even on a flat on-shore site, this would be extremely conservative – or more precisely, wrong as an estimate of the uncertainty. There is no consideration of the likely size of any horizontal gradient (that could give rise to a mean difference) and it is also unclear why the height enters (at all or in the denominator).

If this term was intended to cover a possible de-correlation between the lidar and test mast it is also incorrect since this will already be included in the $\frac{\sigma_{dev}}{\sqrt{N}}$ term in the calibration uncertainty (or would be if this were expressed correctly).

4.3.3 What we propose instead

All uncertainties relating to horizontal separations (i.e,. also the 'terrain complexity' term) need an estimate of any possible horizontal gradient since this is the cause of systematic speed differences. We will call this gradient G_{hor} and propose a value to be given as % wind speed change per km distance. In the case where the testing occurs with one predominating wind direction (sector), the separation uncertainty becomes

$$U_{sep} = \frac{D.G_{hor}}{1000} \tag{4}$$

We see no justification for including the measuring height in this uncertainty.

For the value of G_{hor} we suggest a value of zero if the separation is less than 50m. Otherwise, we suggest 4%/km for onshore flat sites, 0.5%/km for coastal sites (< 2km from the shore) and 0.05%/km for offshore sites (> 2km)[3]. Another possibility is that the gradient is obtained from modelling (or has been measured somehow). Using our example from before, at a coastal site using our standard values for G_{hor} the uncertainty becomes 0.25% (instead of 5%).

If the wind speed gradient across the site, how this varies with wind direction, and the distribution of wind directions during the measurement period are known with some confidence, it is preferable to correct the RSD's wind speed accordingly, and to apply a suitable uncertainty based on this correction – perhaps using the magnitude of the correction as the magnitude of the uncertainty.

4.4 UNCERTAINTY DUE TO TERRAIN COMPLEXITY

4.4.1 What is it now?

In 6.3.4, and in E.9.1, and in Table E.2 of section E.2.3, and in L.4.7, it is described how to estimate an uncertainty contribution for a power curve assessment due to flow variation across the site. This is similar to the uncertainty due to separation distance during calibration of the RSD as described above in section 4.3. It appears in so many places due to varying context as follows:

- 6.3.4: Preparation for power performance test
- E.2.3 Table E.2, and E.9.1: Complete statement of uncertainty estimate for power performance test
- L.4.7: Specific description of use of an RSD in power performance tests.

It is first advised to refer to Annex B to assess whether the flow variation due to terrain is significant enough to require a site calibration and flow correction. If this is not the case, minimum uncertainty values are stipulated according to separation distance and whether the site is onshore or offshore as follows:

- For onshore sites, this uncertainty should be a minimum of 2% (if the wind measurement and rotor turbine are between 2 and 3 diameters apart) or 3% (if they are between 3 and 4 diameters apart), unless other objective evidence can be supplied.
- For offshore sites, this uncertainty should be a minimum of 1% (if the wind measurement and rotor turbine are between 2 and 3 diameters apart) or 2% (if they are between 3 and 4 diameters apart), unless other objective evidence can be supplied.

[3] The authors are grateful to Andrew Henderson from Ørsted for suggesting these typical values for offshore.

The site calibration procedure described in Annex C should be carried out if Annex B criteria are not met, or optionally if a reduced uncertainty value below the minimum stipulated values is desired. This uncertainty term is denoted $u_{TV,I}$ .Footnotes to section 6.3.4 and Table E.2 indicate that these are 'guesstimate' values, and that the onshore case is justified from WASP flow modelling.

4.4.2 What is wrong with this?

The standard implies addition of a standard uncertainty of 1% or 2% for offshore sites, while admitting this is a 'guesstimate' and providing no specific justification. Such values may be realistic for some offshore sites, but appear to be too high for a general case. There is an option to resort to Annex C to perform a site calibration, which would enable a rational adjustment downwards of this uncertainty value. However, this entails additional wind measurements on the site so is not always practical, and is unrealistic for offshore sites. The standard does leave the option open to otherwise justify a lower uncertainty, but does not suggest how this could be achieved.

A second area of dissatisfaction is simply how these points appear in multiple locations in the standard, sometimes with an offshore/onshore distinction (E.9.1, Table E.2 of section E.2.3) and sometimes not (6.3.4 and L.4.7). This could lead to misapplication of the onshore case to an offshore scenario, and hence too high an uncertainty estimate. It is also confusing to have so many similar entries.

Lastly, it is believed by the authors that the additional uncertainty due to flow gradients (between the locations of the measurements and of the turbine in a power performance test) could be due to terrain and could be due to induction effects, and that these two separate considerations are conflated in the "1% to 2%" recommendation. It is not clear whether this is intentional.

4.4.3 What we propose instead

A justification for an uncertainty value caused by terrain can be achieved by estimating a realistic wind speed gradient (due to terrain) across the site, as described in section 4.3.3.

The lack of clarity due to multiple entries could be resolved through editorial review of the standard and clearer drafting.

In addition, where the separation distance is that between a turbine and the measurement location in a power performance test, it is recommended that the flow gradient due to induction is treated separately as an additional uncertainty term, and combined in quadrature with the wind speed gradient term, to replace the "terrain complexity" term. Recent work (see references 6,7,8,9) indicates an upwind deceleration which is significant at the separation distances recommended by the standard (i.e. at between 2 and 4 times the turbine disc's diameter, with 2.5 diameters being currently recommended, see section 6.3.2 of reference 2). The simplest model for the upstream axial wind speed U on the turbine disc's centre-line is there given as follows:

$$\frac{U}{U_\infty} = 1 - a\left(1 + \frac{2x}{D}\left(1 + \left(\frac{2x}{D}\right)^2\right)^{-½}\right) \qquad (5)$$

In the above equation x is the distance upwind and D is the turbine's diameter. The axial induction factor at the turbine disc is most simply related to the thrust coefficient as follows:

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_T}\right) \qquad (6)$$

In the above references, agreement is sought between this model, more complex models, and measured data both at full-scale and in wind tunnels. In fact although the simple model is very well matched to data from more complex models, including three-dimensional computational fluid dynamics models, the effect in full scale measurements appears to be somewhat greater than predicted, with some observations up to approximately double the upwind deceleration implied by the simple model. However, it is not currently clear whether that applies to a turbine on its own or for a turbine in a wind farm array, as the measurements were obtained only for the latter.

Another complicating factor is of course that the wind direction is not always directly from the measurement location to the turbine (see Figure 1, page 28 of reference 2). Ideally, a reliable induction model for the influence of the presence of the turbine on the freestream flow would be available for all admissible wind directions, noting that there may even be speed-ups in small measure from certain directions. Such a model could be used to correct the wind speed measurements so that the reference wind speed used in the power curve more truly represents the upstream free wind speed. In turn, the uncertainty of the correction could be added to the uncertainty budget. However, currently the literature does not yet appear to support such a deterministic model, although good metrological practice obliges us to do so even if we are unsure of the exact magnitude (the sign of the correction is not in doubt here). Nonetheless, the above cited work can be used as a rational basis for applying an uncertainty due to induction effect. The standard uncertainty of the induction effect is therefore recommended to be estimated as the percentage wind speed variation implied by equation (5), applied to each wind speed bin separately as the thrust coefficient is dependent on inflow wind speed.

For a thrust coefficient value of 0.8, and a separation distance of 2.5 times the turbine's diameter, this results in an uncertainty value due to induction effects of 0.5%. At higher wind speeds the thrust coefficient will be lower and therefore the uncertainty will be lower too.

This is an area where additional research is likely to yield a more comprehensive model for the induction effect in all wind direction sectors permissible in a power performance test. If this were achieved, then the wind speed measurements themselves should be corrected, and the associated uncertainty would be that of the correction and not of the gradient in itself, which would be of smaller magnitude. Additional research combining measurements and modelling are therefore recommended: a survey of wind speed perturbation, at the ranges relevant to power performance tests, ahead of and around (but not behind) turbines at all operating wind speeds, would be the first step; this would be followed by validation of the ability of aerodynamic models to represent the measured perturbations as a second step.

4.5 UNCERTAINTY DUE TO MOUNTING

4.5.1 What is it now?

As a contribution to the calibration uncertainty, the uncertainty in wind speed due to uncertainty in levelling the RSD appears in L.4.3 and L.4.6. This is noted as being device-specific, and a value of 0.5% appears in the example calculation of Table L.9 of section L.4.3.

During the power performance assessment, the uncertainty in wind speed due to uncertainty in levelling the RSD appears in a number of places: Table E.2 of section E.2.3 and section E.7.5. A value of 0.1% is suggested as a typical or default value, which is noted as having some objective justification, which in itself is not provided.

4.5.2 What is wrong with this?

As there is no guidance on how to estimate this uncertainty during calibration, the mounting uncertainty of 0.5% which appears in the example may be assumed to be generally appropriate and used in a new calibration uncertainty assessment. This value appears too high to be generally applicable.

A default value of 0.1%, although small, is not justified.

4.5.3 What we propose instead

The organisations who carry out RSD calibrations are well equipped to perform a mounting uncertainty estimate from first principles. That they should do so, and that the sample value of 0.5% should not be generally assumed, should be clearly stated.

For RSD mounted onshore or on a fixed platform, an appropriate procedure should be put in place to check for any displacement (e.g. due to accidental collision) of the device between the start and end of measurements. Assuming no such displacement occurs, the potential for non-ideal levelling of the device is then due to precision of the levelling equipment used.

A simple model of a tilted lidar (see Annex B) shows a cosine response of the lidar's horizontal wind speed to tilting with a small additional error introduced by the shear (relative error = $-\beta^2(½ + \alpha)$ where α is the power law exponent and β is the tilting angle in radians).

Even 1 degree out of true is very unlikely, and such a mounting error would result in very small wind speed errors: for one lidar device in common usage this would result in a wind speed error of less than 0.02%. It is therefore recommended to neglect this term, assuming such a levelling check is in place.

For buoy-mounted lidars offshore, an equivalent procedure should be adopted to ensure the device has remained appropriately levelled with respect to the buoy during the measurement period. The motion of the buoy and/or lidar with respect to the global frame of reference is accounted for by proper consideration of the floating lidar sensitivity to environmental conditions through the classification process, and through monitoring the range of environmental conditions encountered with respect to those encountered during the floating lidar's verification test. As result, it is also recommended to neglect the mounting uncertainty term.

4.6 VARIATION IN FLOW ACROSS SITE UNCERTAINTY

4.6.1 What is it now?

The term "Uncertainty due to variation in flow across the site" appears in the following places in the standard:

- L.4.1: as one of the uncertainties contributing to RSD measurement uncertainty;
- L.4.7: where it is noted that the uncertainty for RSD measurements is the same as that for mast measurements, namely 2% or 3% depending on the separation distance.

4.6.2 What is wrong with this?

This is actually the same uncertainty as that due to "the flow distortion of the wind speed between measurement point and wind turbine due to the local terrain" which is described in section E.2 of the standard and discussed in section 4.4 of this document. The use of the different term "flow variation across the site" is not helpful to the reader, especially as this has some similarity with "flow variation within control volume" (see section 4.7).

4.6.3 What we propose instead

The reader of the standard should recognise the somewhat mixed terminology and refer to section 4.4 of this document.

Ideally the drafting of the standard would be updated to make the terminology clearer.

4.7 FLOW VARIATION WITHIN CONTROL VOLUME

4.7.1 What is it now?

As a contribution to the calibration uncertainty, the uncertainty in wind speed due to variation in flow through the RSD's probe volume appears in L.4.3 and L.4.5. In the latter, the emphasis is placed on this uncertainty due to complex terrain and therefore spatially-varying flow. No specific values or approach are recommended, other than this term being taken into account.

During the power performance assessment, uncertainty in measured wind speed due to variation in flow through the RSD's probe volume appears in Table D.1's list of uncertainty components. With more detail, it also appears in Table E.2 of section E.2.3, and section E.7.6, with 2% or 3% noted as 'guesstimate' values. An expression is given for estimating this uncertainty which justifies the 2-3% 'guesstimate', having selected 1 and -1 degrees as inflow and outflow angles. This also appears in L.4.1 which refers to L.4.5.

4.7.2 What is wrong with this?

L.4.5 does not provide useful advice on offshore or simple onshore cases, where there are unlikely to be any flow gradients that are significant in this context.

The prospect of there being, during calibration at a designated calibration site, a flow gradient which is (a) significant; and, (b) not adequately captured by the RSD in any case; and, (c) where any error would somehow not show up in the data, is very remote.

4.7.3 What we propose instead

During calibration, apply a zero value for this uncertainty contribution unless there is a good reason not to.

During power performance assessment at an offshore or a flat onshore site, apply a zero value for this uncertainty contribution unless there is a good reason not to.

4.8 SIMULTANEOUS USE OF RSD AND ANEMOMETER

4.8.1 What is it now?

In earlier versions of the standard, conventional masts with anemometry were the only primary references considered for wind speed measurements. The new version of the standard still allows for the use of such conventional measurement configurations, and also introduces the use of an RSD as an integral part of the wind measurement. The configurations considered in the standard are described in section 5 of the standard and summarised in Table 1 in the same section. The use of an RSD is considered in two situations: firstly where conventional measurements are available to hub height, and second where conventional measurements are available to a lower height. Some further detail on allowable measurement configurations, considering complex and non-complex flow cases, and rotor-equivalent wind speed (REWS) or non-REWS power curves, are included in section 7.2 and Table 2 of the standard.

In Annex L.1 of the standard, it is explained how the RSD must be used with conventional measurements to at least 40m or the lower tip height of the turbine, with the conventional measurements used to monitor the RSD measurements. How this monitoring is carried out, and associated uncertainties estimated, are described in:

- L.5.2. for identification of a malfunctioning RSD;
- L.5.3 for additional uncertainties due to the conventional and RSD measurements not matching;
- L.7.1 reporting for the monitoring activity;
- E.7.7. for uncertainties related to monitoring the RSD - a typical magnitude of 0.5% is included in Table E.2 of section E.2.3.

4.8.2 What is wrong with this?

The standard does not allow for a lidar to be used on its own for a power curve assessment, mandating that a meteorological mast must be used in combination with a lidar. The leading lidar wind measurement instruments should be trusted as much as cup anemometers mounted on masts are trusted, so this restriction is not necessary.

Lidars do not have as long a track record as cup anemometers in the wind industry, and the standard's lack of acceptance of RSDs on their own for wind measurement is likely to stem from this. However, this understandable perception of risk can be tackled in a rational manner.

The risk that the lidar is not accurate is fully addressed in lidar calibration and classification. So, the desire to have an in-situ mast is driven by the desire to address the risk of the lidar somehow becoming inaccurate after its verification and before or during the power performance test. This risk is not evidenced in operational experience and is therefore thought to be low, and can be addressed by other means as follows.

4.8.3 What we propose instead

The risk that the lidar has become inaccurate after its verification and before or during the power performance test can always be fully addressed by performing a post-deployment verification (in the same manner as pre-deployment verification, see section L.3 of the standard). A risk-based approach should be adopted to ascertain whether this is necessary.

The risk-based approach should include recognition of elements of the lidar which may become inaccurate over time (for example focusing or pulse timing), and how these risks are mitigated by the lidar itself.

For a floating lidar system, in addition other risks should be considered, for example the degradation of any stability system, the development of any buoy list, or accidental impact causing a mounting error. Again, how these are mitigated during deployment or post-deployment should be understood.

If the risk analysis indicates that there is a risk in degradation in accuracy, or if sufficient information is not made available to assess the risk, then a post-deployment verification should be carried out.

With these measures in place, the risk of the lidar becoming less accurate during its application is addressed. Therefore, the lidar can be used as a primary reference source without the use of a met mast. Although the standard does not make provision for this, it can be applied in a straightforward manner by considering the lidar data as, in terms of uncertainty calculation process, equivalent to a met mast with full coverage of the rotor disc's height range.

As a further mitigation against the risk of gross error in the RSD data, the opportunity should be taken to compare RSD wind speeds with those recorded by the turbine's nacelle-mounted anemometer.

4.9 SHEAR AND VEER UNCERTAINTY

4.9.1 What is it now?

Wind shear and veer are relevant for two (sets of) uncertainty components:

- The combined REWS uncertainty outlined in section E.8 of the standard and described in more detail in E.13.6 to E.13.10 (covering more than 10 pages of the standard).
- The Method shear and veer uncertainties in E.11.2.2 and E.11.2.3 respectively.

The REWS uncertainty needs to be considered when the REWS definition is used for the power curve derivation. It includes the uncertainties of the REWS components, i.e. the individual uncertainty components of the cup and RSD wind measurements.

Method uncertainties are to be derived in any case – to reflect the limited knowledge about the wind inflow. However, it is expected that the more measurement heights (with a good distribution over the rotor area, and reflecting "good" shear/veer information) are considered for the REWS the smaller the Method shear and veer uncertainty components are.[4]

4.9.2 What is wrong with this?

It is not at all easy and straightforward (or better: extremely difficult, in our opinion) to follow the procedures for the derivation of these uncertainty components. Not every step of the procedures and every simplification is explained and justified to a sufficient degree.

Also, in many places the drafting is imprecise and results in ambiguities. For example, in the section describing how to estimate veer uncertainty when there are veer measurements across half of the rotor (see section E.11.2.3.3) it is not clear whether the veer assumed to apply across the upper half of the rotor is 1.5 times or 2.5 times that measured for the lower half. The probability of two independent attempts at calculating the uncertainty to give the same answer is practically zero. This is inappropriate for an international standard.

Furthermore, in particular for the Method uncertainties it is difficult to develop an intuitive feeling for the order of magnitude of the uncertainty components. For a full-rotor measurement with several measurement heights, the shear and veer Method uncertainties become small (and perhaps negligible) but no further guidance is given on if there is a case or threshold from which we can ignore the Method uncertainties.

4.9.3 What we propose instead

The example calculations together with the 'recipes' for the applied procedures in this report may give a good demonstration or illustration of the procedures proposed in the standard. We do not explicitly propose changes to these procedures, neither do we endorse them, but strongly recommend a revision of their description and in particular to simplify the procedure and its description. A useful element to this revision would be a threshold for when there are

[4] This is confirmed by our example calculations in 5.

sufficient measurements covering the rotor disc such that method uncertainties need not be applied.

5. EXAMPLE CALCULATIONS

The calculations performed on the datasets described in section 3 are described in this section. For ease and consistency of reference, a unique index has been assigned to each version of each calculation; these indices and their relationship to data sets and calculation methods are summarised in Table 2 below. Note that uncertainties expressed in this document are standard uncertainties.

Data Set	Calculation	Version	Index	Description
Onshore	1	A	On.1.A	Verbatim application of standard, including obvious errors, using met mast data only.
Onshore	1	B	On.1.B	Verbatim application of standard, correcting obvious errors, using met mast data only.
Onshore	1	C	On.1.C	Modified application of standard, correcting obvious errors, using met mast data only.
Onshore	2	A	On.2.A	Application of the standard as far as possible (with obvious errors corrected), using met mast and lidar data.
Onshore	2	B	On.2.B	Application of the standard as far as possible (with obvious errors corrected), using met mast and lidar data. Modifications as described in this document.
Onshore	3	A	On.3.A	Application of the standard as far as possible (with obvious errors corrected), using lidar data only.
Onshore	3	B	On.3.B	Application of the standard as far as possible (with obvious errors corrected), using lidar data only. Modifications as described in this document.
Offshore	1	A	Off.1.A	Verbatim application of standard, correcting obvious errors, using met mast data only.
Offshore	1	B	Off.1.B	Modified application of standard, correcting obvious errors, using met mast data only.
Offshore	2	A	Off.2.A	Application of the standard as far as possible (with obvious errors corrected), using floating lidar data only.
Offshore	2	B	Off.2.B	Application of the standard as far as possible (with obvious errors corrected), using floating lidar data only. Modifications as described in this document.

Table 2: Summary of calculations performed. The data sets are described in section 3.

5.1 ONSHORE CALCULATIONS USING MAST DATA ONLY: ON.1.A, ON.1.B, ON.1.C

These calculations use mast data only from the onshore data set, with a verbatim application of the standard (On.1.A), the same minus obvious typographical errors (On.1.B), and a revised approach using the methodology recommended by this study (On.1.C).

The wind speed uncertainty methodology and assumptions employed are summarised in Table 3, with distinctions made between versions A, B and C of the calculations. The overall calculation summary is presented in Figure 1 in a flowchart style; strictly speaking this is for version A and B of the calculations but also informs version C. Figure 7 to Figure 18 show the make-up of the wind speed uncertainty components for each version of the calculation in turn.

Figure 7 shows the components making up met mast wind speed uncertainty (as represented by the "*Wind Speed (Cup or Sonic)"* part of Table 3) following a verbatim application of the standard. This clearly demonstrates that the classification uncertainty is too high. On inspection, there is a typographical error in the standard for the expression used to convert an anemometer class number into an uncertainty value, see equation I.4 of reference 2: there is a square root of 3 term which appears as a multiplication factor rather than a division factor as it should be. As a consequence, the classification uncertainty is a factor of 3 too high. This correction is applied in calculation On.1.B. The large effect that this has on the classification uncertainty, and therefore on the overall met mast wind speed uncertainty is evident by comparing Figure 7 with Figure 11; the consequently large effect that this has on the overall wind speed uncertainty is evident by comparing Figure 10 with Figure 14. For the 10m/s wind speed bin, by **applying the correct expression for cup anemometer classification uncertainty, the classification uncertainty reduces from 2.2% to 0.75%, and the overall uncertainty from ~3.2% to ~2.4%.**

In this calculation the separation distance between the mast and the turbine is equivalent to 2.5 times the turbine's diameter. As discussed in section 4.4, the standard indicates a "terrain uncertainty" of 2%, which is shown in Figure 8 (for calculation On.1.A) and identically in Figure 12 (for calculation On.1.B). As described in section 4.4.3 and section 4.6.3, we are here advocating an alternative approach; by assuming a typical flow gradient of 4%/km in applying this alternative approach, the alternative wind speed uncertainty components indicated in Figure 16 is derived. Note that in this case the gradient uncertainty is dominated by the separation uncertainty and the induction uncertainty is small in comparison. The effect of this on the overall wind speed uncertainty is evident by comparing Figure 14 and Figure 18. For the 10 m/s wind speed bin, **the effect of applying a different methodology for terrain uncertainty effect is to reduce that uncertainty from 2% to 1.4%, and the overall uncertainty from ~2.4% to ~2.0%.**

In this case wind speed and direction measurements were available at the lower tip height as well as at the hub height. The standard explains how to estimate the uncertainty contribution due to this incomplete description of the shear and the veer across the rotor disc, more details being contained in Figure 1. As seen in Figure 18, this method uncertainty is a non-negligible contributor to the overall uncertainty in this case.

A second typographical error should be highlighted. **The expression for aggregating wind speed uncertainties into an Annual Energy Production (AEP) uncertainty is equation E.8 in the standard (reference 2); the end of this expression is clearly missing a close bracket and exponent 2** which is evident by inspection.

Applying the standard to an onshore data set using mast data only has been useful in highlighting some typographical errors in the standard, in allowing evaluation of the alternative approach to terrain / flow variation across site / induction related uncertainty, and in providing a baseline with which to compare subsequent calculations.

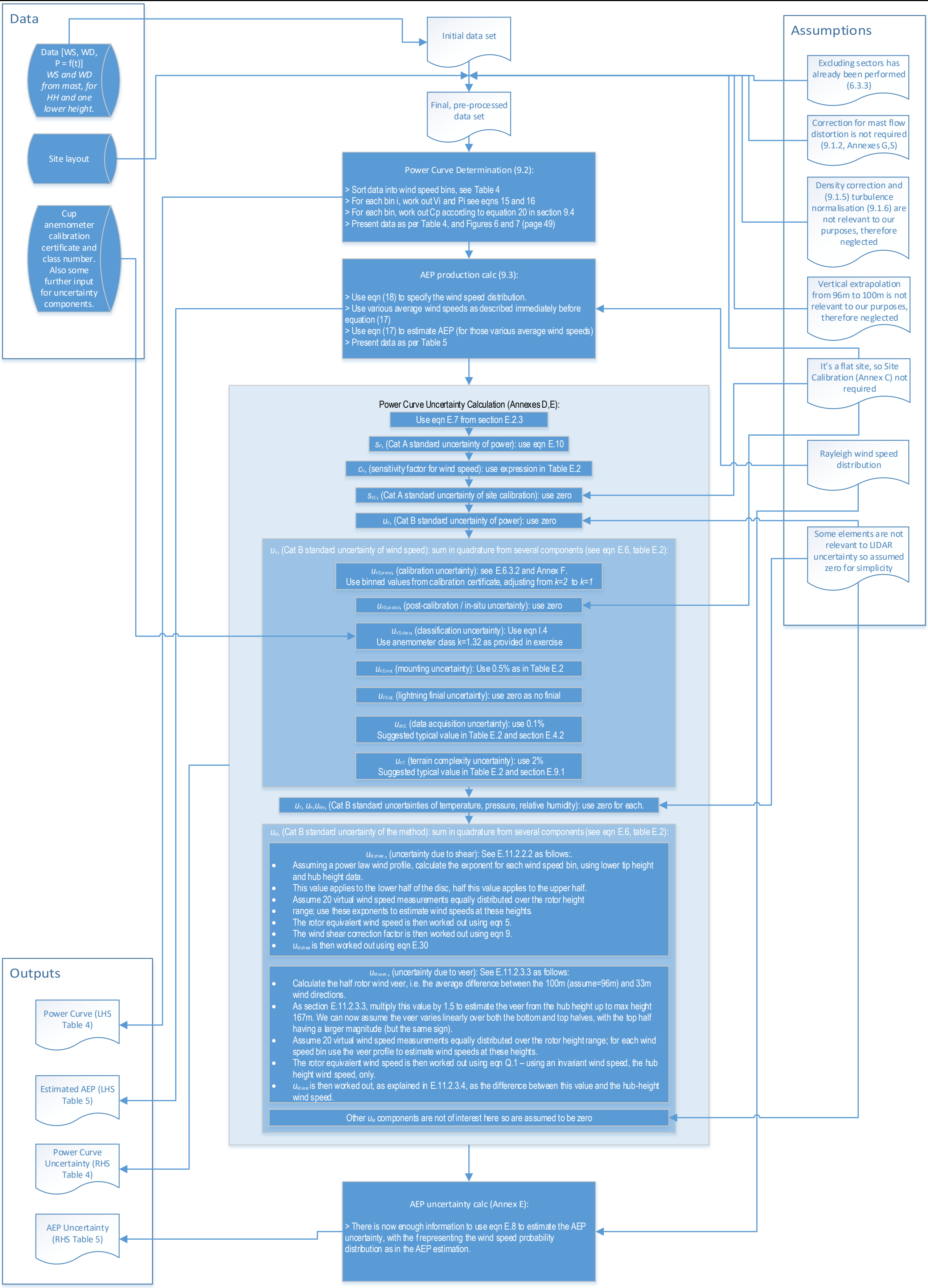


Figure 1: Calculation summary for onshore, mast only case (On.1.A, On.1.B). ***Note: Print as A3 size***

	~3.2%	~2,4%	~2.0%
Wind Speed Uncertainty Category	**On.1.A**	**On.1.B**	**On.1.C**
Wind Speed (Cup or Sonic)			
> Calibration	From anemometer calibration certificate and E.6.3.2		
> Post calibration / in-situ	Zero		
> Classification	Use equation I.4 assuming class number k=1.32 2.2%	Use corrected equation I.4 assuming class number k=1.32 0.75%	
> Mounting Effects	Use 0.5% as in Table E.2		
> Lightning finial	Use zero – no finial		
> DAQ	Use 0.1% as Table E.2 and E.4.2		
Wind Speed (RSD)			
> Calibration	N/A		
> In-situ check	N/A		
> Classification	N/A		
> Mounting	N/A		
> Flow variation in different probe volumes at same height	N/A		
> Monitoring test	N/A		
Rotor Equivalent Wind Speed			
> Wind shear	N/A		
> Wind veer	N/A		
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1 2.0%		New approach, see section 4.4 of this document 1.4%
Method – wind conditions			
> Shear	See E.11.2.2.2. The lower tip height anemometer values were used, and a shear exponent estimated for the top half of the rotor disc.		
> Veer	E.11.2.3.3. The lower tip height wind vane values were used, and from this the veer estimated for the entire rotor disc.		

Table 3: Summary of calculation methods for the onshore dataset (Dataset 1), using met mast data only (calculation 1), for 3 different versions of the calculation (A,B,C). Blank cells indicate method unchanged compared to cell to the left. Indicative numerical uncertainty values for the 10 m/s bin are annotated for selected components, and for combined uncertainty values at the top of the table.

5.2 ONSHORE CALCULATIONS USING MAST AND LIDAR DATA: ON.2.A, ON.2.B

These calculations use mast data and lidar data from the onshore data set, with a verbatim application of the standard, minus the obvious typographical errors encountered in section 5.1 (On.2.A) and a revised approach using the methodology recommended by this study (On.2.B).

The wind speed uncertainty methodology and assumptions employed are summarised in Table 4, with distinctions made between versions A and B of the calculations. The overall calculation summary is presented in Figure 2 in a flowchart style; strictly speaking this is for version A of the calculation, but also informs version B. Figure 19 to Figure 26 show the make-up of the wind speed uncertainty components for each version of the calculation in turn.

The met mast measured wind speed uncertainty (as represented by the "*Wind Speed (Cup or Sonic)"* part of Table 3) is as for calculation On.1.C using mast data only, see Figure 15. Figure 19 shows the components making up lidar measured wind speed uncertainty (as represented by the "*Wind Speed (RSD)"* part of Table 3) following a verbatim application of the standard. By comparing these figures it is clear that the uncertainty in the lidar measurement (~3.5%) exceeds that of the met mast measurement (~0.9%). However, the manner in which these are combined into a REWS uncertainty means that **the met mast measurement uncertainty dominates, and ultimately a value of around 1% is obtained,** see Figure 20. This is because the importance of lidar uncertainty in the REWS uncertainty is determined by the difference between met mast and lidar wind speed values, which in this case has a small magnitude.

For calculation On.2.A, a verbatim application of the standard was used, so the terrain complexity uncertainty (Figure 21) is simply 2%.

As will be seen in calculation On.3.A using lidar data only, the calculated method uncertainty is small. Overall, this results in a combined uncertainty for On.2.A of around 2.3%, see Figure 22. In this case, this is similar to the uncertainty values for verbatim application of the standard using mast data only in calculation On.1.B.

Calculation On.2.B applies the recommendations of this study to this scenario as follows:

- Lidar mounting uncertainty is reduced from 0.1% to zero (see section 4.5);
- The uncertainty associated with variation in flow through the probe volume is reduced from 2.5% to zero (see section 4.7);
- Supported by the result from calculation Off.2.B according to section 4.2, it seems quite possible that the classification uncertainty could be very small so is here assumed to be reduced from 1.25% to zero for the purpose of illustration (a zero or very low value is possible if the lidar calibration environmental conditions are the same as in the final application);
- A terrain complexity uncertainty of 2% is replaced with a flow gradient uncertainty according to section 4.4, which has a value of ~1.4%.

The above changes have the combined effect of significantly reducing the lidar measurement uncertainty from 3.5% to 2.1%, see Figure 20 and Figure 24. As described above, this actually has very little effect on the REWS uncertainty and hence the final combined uncertainty. However, similarly to the case where met mast data only was used (On.1.C), **the alternative approach to terrain complexity uncertainty does reduce the final uncertainty from ~2.3% to ~1.7%,** which can be seen by comparing Figure 22 and Figure 26.

Applying the standard to an onshore data set using mast data combined with lidar data has been useful in highlighting the secondary role played by the lidar data in this scenario, in further evaluation of the alternative approach to terrain / flow variation across site / induction related uncertainty, and in providing a baseline with which to compare subsequent calculations.

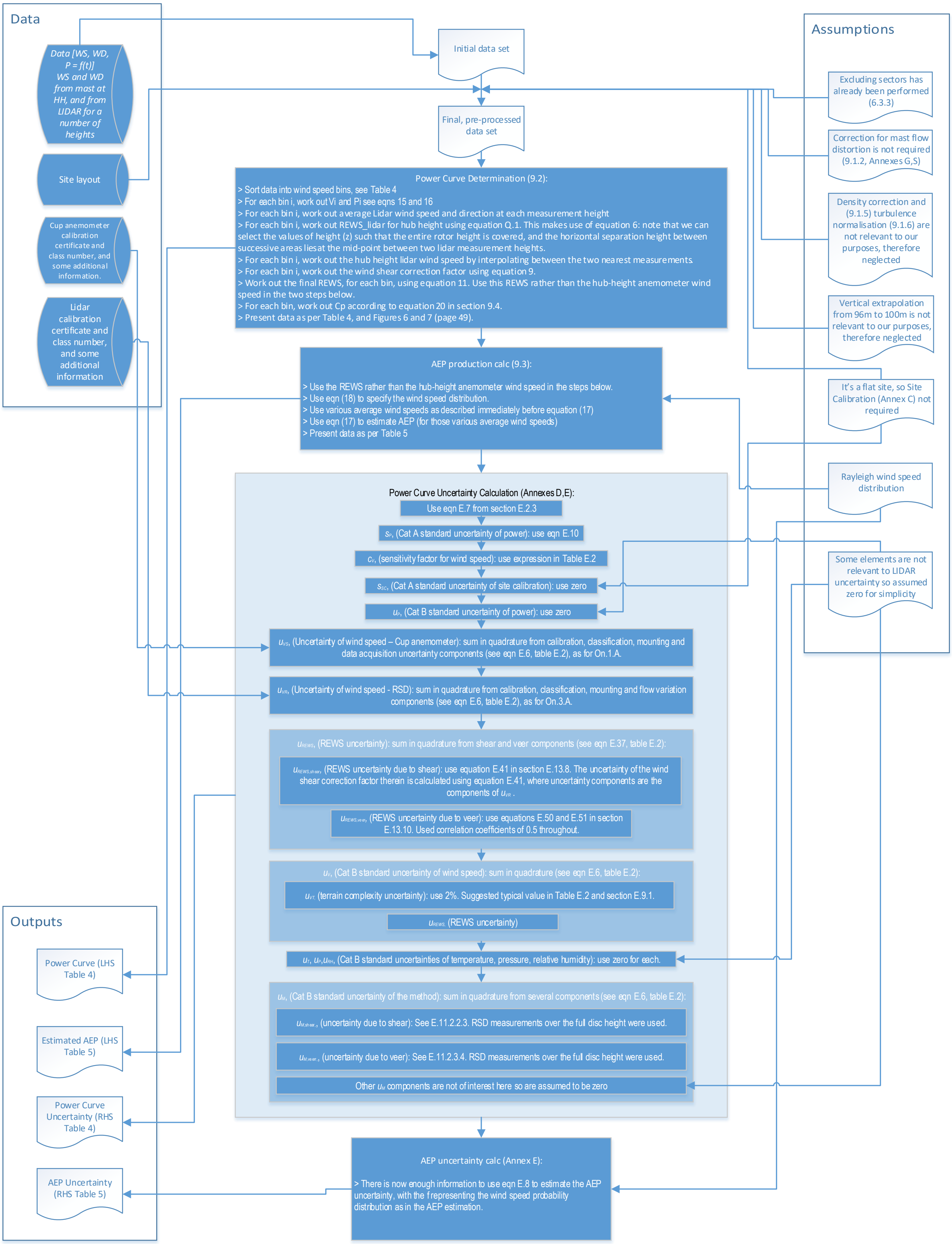


Figure 2: Calculation summary for onshore, mast and lidar data case (On.2.A). ***Note: Print as A3 size***

Wind Speed Uncertainty Category	On.2.A ~2.3%	On.2.B ~1.7%
Wind Speed (Cup or Sonic)		
> Calibration	From anemometer calibration certificate and E.6.3.2	
> Post calibration / in-situ	Zero	
> Classification	Use corrected equation I.4 assuming class number k=1.32	
> Mounting Effects	Use 0.5% as in Table E.2	
> Lightning finial	Use zero – no finial	
> DAQ	Use 0.1% as Table E.2 and E.4.2	
Wind Speed (RSD)	3.5%	2.1%
> Calibration	From RSD calibration certificate, see E.7.2	
> In-situ check	Zero	
> Classification	Take typical value of 1.25% from Table E.2.	Assume zero, see section 4.2 of this document.
> Mounting	Take typical value of 0.1% from Table E.2.	Assume zero, see section 4.5 of this document.
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2.	Assume zero, see section 4.7 of this document.
> Monitoring test	Zero.	
Rotor Equivalent Wind Speed		
> Wind shear	Eqn E.44 (summing over Wind Speed (RSD) terms above) provides uncertainty of the wind shear correction factor. Then use eqn E.41.	
> Wind veer	Calculate using eqn E.50[5] and E.51. Used correlation coefficients of 0.5 in all cases.	
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1 2.0%	New approach, see section 4.4 of this document 1.4%
Method – wind conditions		
> Shear	See E.11.2.2.3. RSD measurements over the full disc height were used.	
> Veer	See E.11.2.3.4. RSD measurements over the full disc height were used.	

Table 4: Summary of calculation methods for the onshore dataset (Dataset 1), using met mast data and RSD data (calculation 2), for 3 different versions of the calculation (A,B). Blank cells indicate method unchanged compared to cell to the left.

[5] Requires Wind Direction (RSD) uncertainty component values, see E.12.3. Here values of 1 and 2 degrees were used for verification and alignment uncertainty, all other values assumed as zero.

5.3 ONSHORE CALCULATIONS USING LIDAR DATA ONLY: ON.3.A, ON.3.B

These calculations use lidar data only from the onshore data set, with a close-as-possible application of the standard, minus the obvious typographical errors encountered in section 5.1 (On.3.A) and a revised approach using the methodology recommended by this study (On.3.B). What is meant by “close-as-possible” is of course that the standard does not allow for the use of RSD data on its own in this way; here we argue (see section 4.8) that it is permissible to do so, and apply the lidar data broadly as if it were a met mast with multiple wind measurement heights. The wind speed uncertainty methodology and assumptions employed are summarised in Table 5, with distinctions made between versions A and B of the calculations. The overall calculation summary is presented in Figure 3 in a flowchart style; strictly speaking this is for version A of the calculation, but also informs version B.. Figure 27 to Figure 36 show the make-up of the wind speed uncertainty components for each version of the calculation in turn. Figure 27 shows the components making up lidar measured wind speed uncertainty (as represented by the “*Wind Speed (RSD)”* part of Table 5) following a verbatim application of the standard. Unlike calculation On.2.A, the uncertainty in the lidar measurement (3.5%), to which there is very little addition in calculating the REWS uncertainty (Figure 30), is a significant contributor to the final uncertainty (4.0%), see Figure 31. The terrain uncertainty from a verbatim application of the standard, see Figure 28, makes the second largest contribution to the final uncertainty.

In this case, lidar measurements are available at nine heights across the rotor disc. This we would expect to represent the shear and veer profiles across the rotor disc well, and therefore the REWS and method uncertainties to be small, which is indeed the case:

- The difference between the uncertainty in the lidar measured data and the REWS uncertainty is negligible, which can be seen by comparing Figure 27 and Figure 30;
- The method uncertainty due to shear and veer (see Figure 29) makes a rather small contribution to the final uncertainty (see Figure 31).

Calculation On.3.B applies the recommendations of this study to this scenario as follows:

- Lidar mounting uncertainty is reduced from 0.1% to zero (see section 4.5);
- The uncertainty associated with variation in flow through the probe volume is reduced from 2.5% to zero (see section 4.7);
- Supported by the result from calculation Off.2.B according to section 4.2 it seems quite possible that the classification uncertainty could be very small so is here assumed to be reduced from 1.25% to zero for the purpose of illustration (a zero or very low value is possible if the lidar calibration environmental conditions are the same as in the final application);
- A terrain complexity uncertainty of 2% is replaced with a flow gradient uncertainty according to section 4.4, which has a value of ~1.4%.

The above changes have the combined effect of significantly reducing the lidar measurement uncertainty from 3.5% to 2.1%, see Figure 27 and Figure 32. Unlike calculation On.3.A, this has a direct effect on the REWS uncertainty and hence the final combined uncertainty. **The combination of reduced lidar uncertainty and the alternative approach to terrain complexity uncertainty reduces the final uncertainty from ~4.0% to ~2.5%,** which can be seen by comparing Figure 31 and Figure 36. This final value is dominated by the calibration uncertainty which is read directly from the lidar calibration certificate; if the lidar calibration data were available it may have been possible to reduce this further using the revised approach described in section 4.1.

Applying the standard to an onshore data set using lidar data only has been useful in highlighting how a final uncertainty approaching that from using mast data only can be approached using the revised methodology.

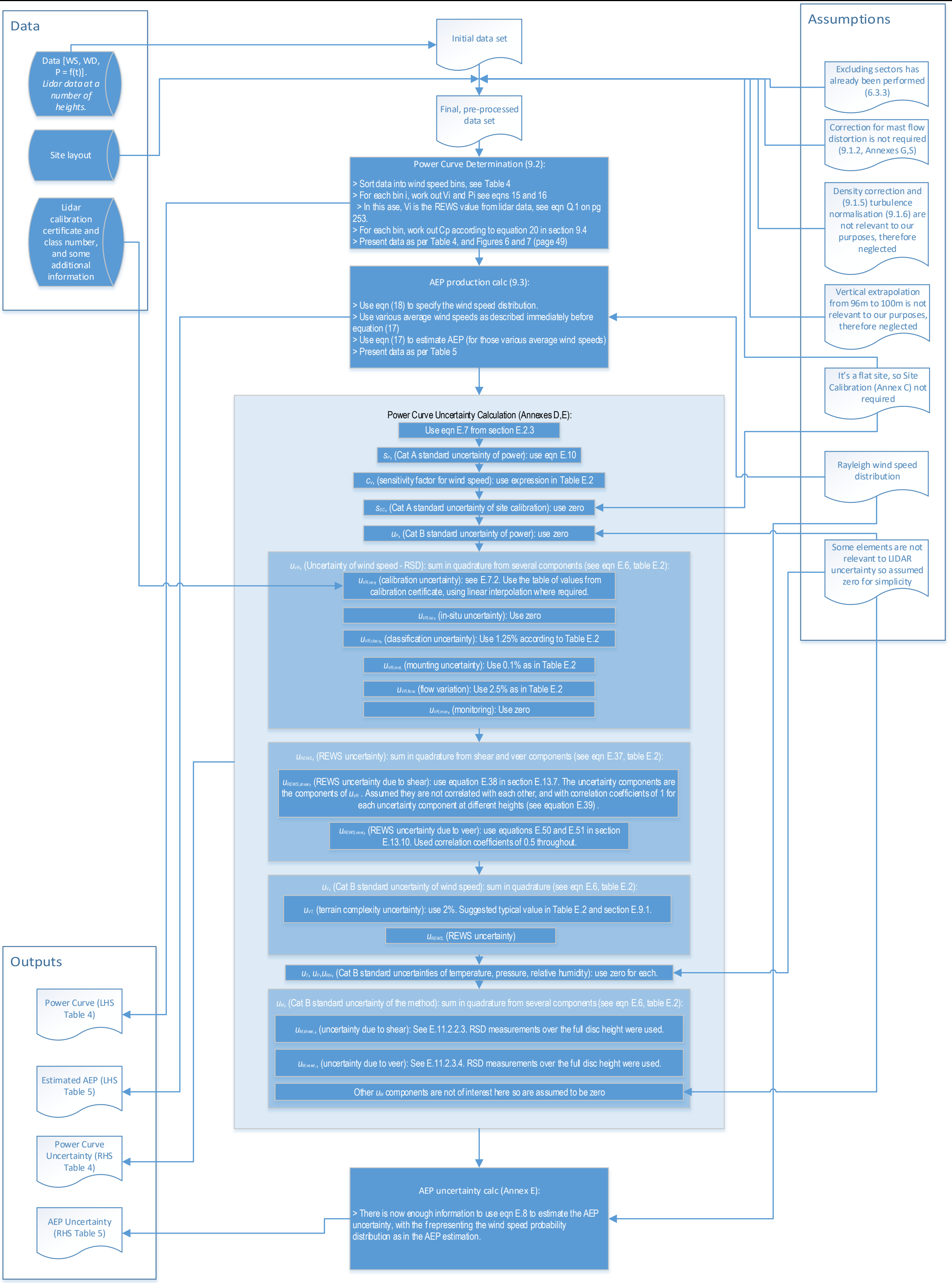


Figure 3: Calculation summary for onshore, lidar data only case (On.3.A). ***Note: Print as A3 size***

Wind Speed Uncertainty Category	On.3.A ~4.0%	On.3.B ~2.5%
Wind Speed (Cup or Sonic)		
> Calibration	N/A	
> Post calibration / in-situ	N/A	
> Classification	N/A	
> Mounting Effects	N/A	
> Lightning finial	N/A	
> DAQ	N/A	
Wind Speed (RSD)	3.5%	2.1%
> Calibration	From RSD calibration certificate, see E.7.2	
> In-situ check	Zero	
> Classification	Take typical value of 1.25% from Table E.2.	Assume zero, see section 4.2 of this document.
> Mounting	Take typical value of 0.1% from Table E.2.	Assume zero, see section 4.5 of this document.
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2.	Assume zero, see section 4.7 of this document.
> Monitoring test	Zero.	
Rotor Equivalent Wind Speed	3.5%	2.1%
> Wind shear	Eqns E.38 and E.39 assuming (a) uncertainty components are not correlated with each other and (b) with correlation coefficients of 1 for a given uncertainty component at different heights.	
> Wind veer	Calculate using eqn E.50 (see footnote to Table 4) and E.51. Used correlation coefficients of 0.5 in all cases.	
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1	New approach, see section 4.4 of this document
Method – wind conditions	2.0%	1.4%
> Shear	See E.11.2.2.3. RSD measurements over the full disc height were used.	
> Veer	See E.11.2.3.4. RSD measurements over the full disc height were used.	

Table 5: Summary of calculation methods for the onshore dataset (Dataset 1), using RSD data only (calculation 3), for 2 different versions of the calculation (A,B). Blank cells indicate method unchanged compared to cell to the left.

5.4 OFFSHORE CALCULATIONS USING MAST DATA ONLY: OFF.1.A, OFF.1.B

These calculations use mast data only from the offshore data set, with a verbatim application of the standard (Off.1.A), and a revised approach using the methodology recommended by this study (Off.1.B). The wind speed uncertainty methodology and assumptions employed are summarised in Table 6, with distinctions made between versions A and B of the calculations. The overall calculation summary is presented in Figure 4 in a flowchart style; strictly speaking this is for version A of the calculation, but also informs version B. Figure 37 to Figure 44 show the make-up of the wind speed uncertainty components for each version of the calculation in turn. Figure 37 shows the assumed met mast wind speed uncertainty (as represented by the "*Wind Speed (Cup or Sonic)"* part of Table 6); in this case this has been treated very simply, by assuming a combined uncertainty for the mast wind speed measurements of 2%. Figure 38 shows the assumed terrain complexity of 2%, as recommended by the standard.

In this case wind speed and direction measurements were available at the lower tip height as well as at the hub height. The standard explains how to estimate the uncertainty contribution due to this incomplete description of the shear and the veer across the rotor disc. As seen in Figure 29, this method uncertainty is a non-negligible contributor to the overall uncertainty in this case. The resulting final uncertainty, see Figure 40, shows wind speed and terrain uncertainty making a large and equal contribution.

The second version of this calculation, Off.1.B, applies the recommendations of this project to the same scenario. Due to the simplified approach to the met-mast wind speed uncertainty, this only results in a change to one of the components, the so-called terrain complexity uncertainty. As described in section 4.4.3 and section 4.6.3, we are here advocating an alternative approach; by assuming a typical flow gradient of 0.05%/km in applying this alternative approach, the alternative wind speed uncertainty components indicated in Figure 42 is derived. Note that in this case the gradient uncertainty is dominated by the induction uncertainty and the separation uncertainty is small in comparison. The effect of this on the final uncertainty is clear when comparing Figure 40 and Figure 44: **the effect of applying a different methodology for terrain uncertainty effect is to reduce the overall uncertainty from ~2.9% to ~2.1%.**

Applying the standard to an offshore data set using mast data only has been useful in allowing evaluation of the alternative approach to terrain / flow variation across site / induction related uncertainty, which is seen to be significant.

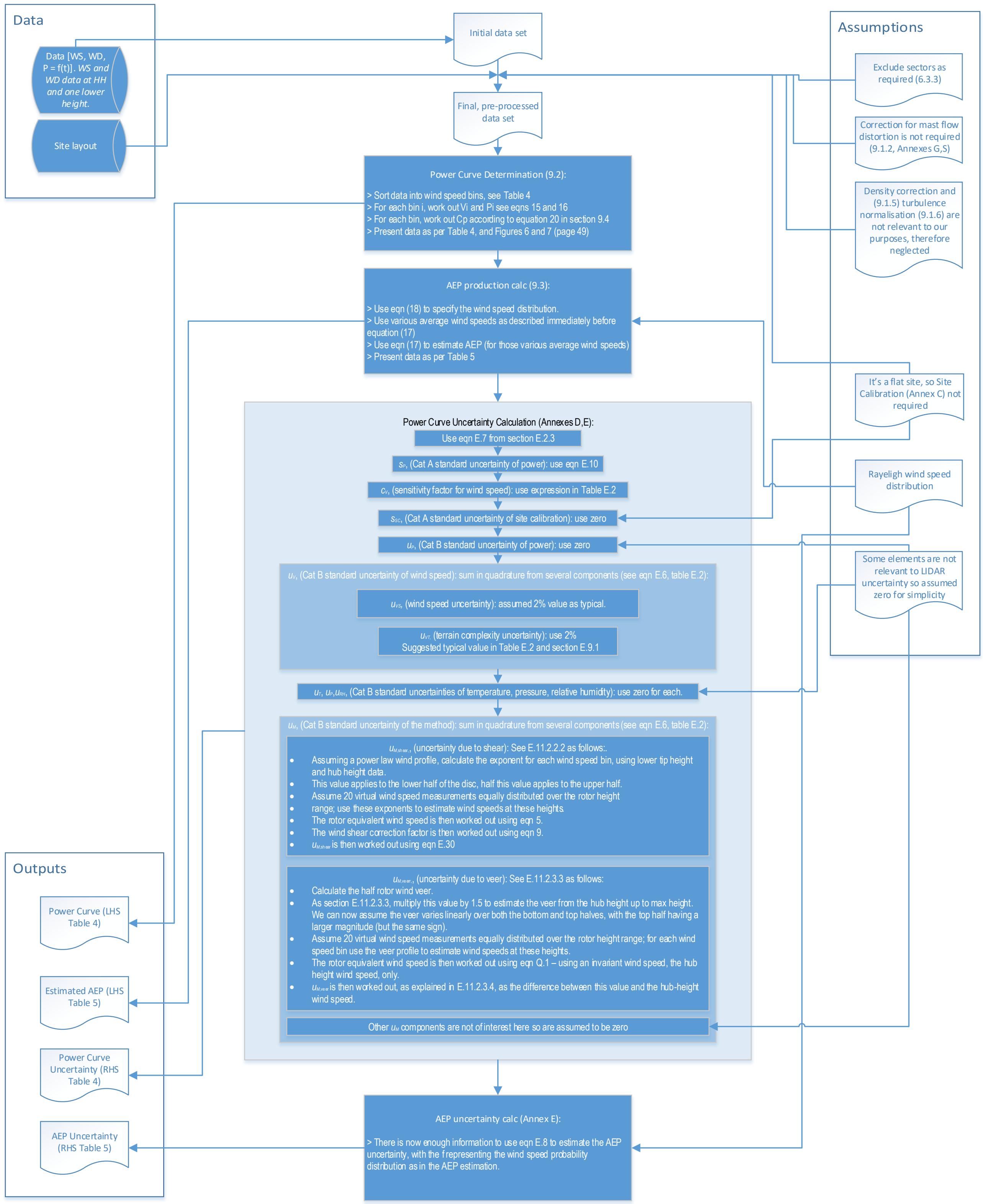


Figure 4: Calculation summary for offshore, mast data only case (Off.1.A). ***Note: Print as A3 size***

Wind Speed Uncertainty Category	Off.1.A ~2.9%	Off.1.B ~2.1%
Wind Speed (Cup or Sonic)	Assume 2% uncertainty for met mast anemometers.	
> Calibration	Not used – see above	
> Post calibration / in-situ	Not used – see above	
> Classification	Not used – see above	
> Mounting Effects	Not used – see above	
> Lightning finial	Not used – see above	
> DAQ	Not used – see above	
Wind Speed (RSD)		
> Calibration	N/A	
> In-situ check	N/A	
> Classification	N/A	
> Mounting	N/A	
> Flow variation in different probe volumes at same height	N/A	
> Monitoring test	N/A	
Rotor Equivalent Wind Speed		
> Wind shear	N/A	
> Wind veer	N/A	
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1 2.0%	New approach, see section 4.4 of this document. 0.3%
Method – wind conditions		
> Shear	See E.11.2.2.2. The lower tip height anemometer values were used, and a shear exponent estimated for the top half of the rotor disc.	
> Veer	E.11.2.2.3. The lower tip height wind vane values were used, and from this the veer estimated for the entire rotor disc.	

Table 6: Summary of calculation methods for the offshore dataset (Dataset 2), using met mast data only (calculation 1), for 2 different versions of the calculation (A,B). Blank cells indicate method unchanged compared to cell to the left.

5.5 OFFSHORE CALCULATIONS USING LIDAR DATA ONLY: OFF.2.A, OFF.2.B

These calculations use the offshore data set consisting of FINO1 metocean data and Fraunhofer FLS data. The FINO1 mast data is used to calculate the calibration and classification uncertainties, but is not used for the final application which relies on FLS data. Two versions of the calculations have been performed: a faithful application of the standard (Off.2.A), and a revised approach using the methodology recommended by this study (Off.2.B). The wind speed uncertainty methodology and assumptions employed are summarised in Table 8, with distinctions made between versions A and B of the calculations. The overall calculation summary is presented in Figure 6 in a flowchart style; strictly speaking this is for version A of the calculation, but also informs version B. Figure 45 to Figure 54 show the make-up of the wind speed uncertainty components for each version of the calculation in turn.

A schematic of the trial site layout is shown in Figure 5. For the calibration and classification stages, data from FINO1 and from the FLS were compared for the wind sector of 275.5 to 350 degrees. Note that a narrower sector was used when considering shear and veer, as the side-mounted sensors on FINO1 are influenced by the mast from certain angles. To emulate the application of the FLS to a power curve assessment, a sector of 196.5 to 343.4 degrees was used.

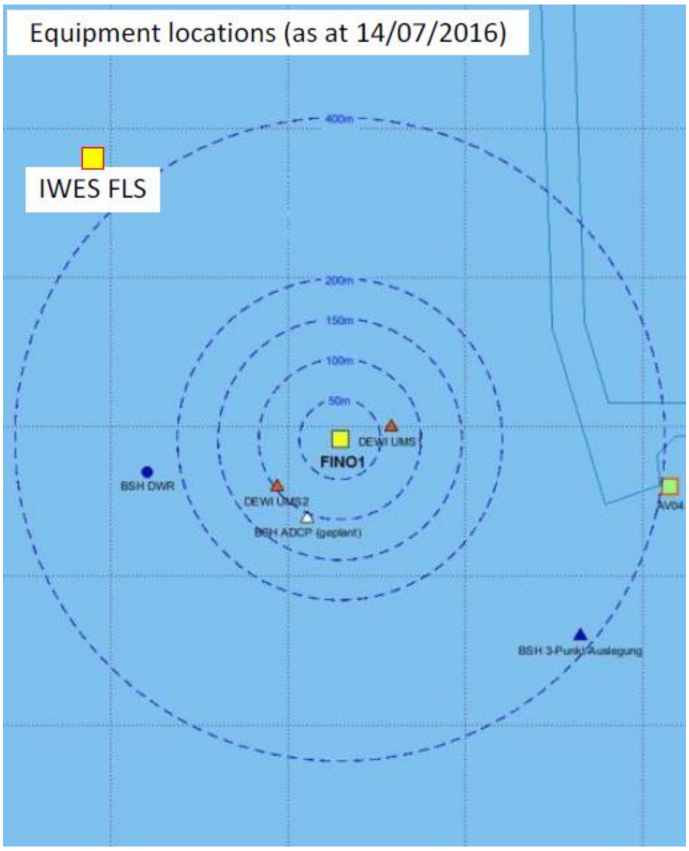


Figure 5: Schematic of trial layout. The mast is in the centre of the figure (FINO1); the FLS is marked in yellow to the north-west; and one of the Alpha Ventus turbines is evident in green to the east. The separation distance between the mast and the FLS is approximately 470m. Wave data is from a wave radar fitted to the FINO1 platform.

Figure 45 and Figure 50 show the calibration uncertainty from verbatim and revised application of the standard respectively. The distance from mast contribution is initially the largest and is considerably reduced; assuming negligible uncertainty associated with non-homogeneous flow also makes a large impact. So, before even addressing the calibration uncertainty assessment itself, large gains have been made. The revised approach to calibration uncertainty (see section 4.1) and assumption of negligible mounting uncertainty also make a contribution, and **overall the calibration uncertainty is reduced from around 5% to 2%,** the latter being driven by an assumed reference uncertainty of 2%. Please also note that the revised calibration uncertainty method dictates that when the mean deviation exceeds the reference uncertainty, that a correction is applied; in this case this condition is met (the yellow line exceeding the orange line, see Figure 45) for only quite low and high wind speeds, so such a correction has not been applied here as it has been judged to have a small impact.

Figure 46 and Figure 51 shows the calculated Lidar wind speed uncertainty (as represented by the "*Wind Speed (RSD)"* part of Table 8) from a class-number based approach and the recommended more detailed application of the standard respectively (see section 4.2 for a full description). The environmental variables which were used in these calculations, and their associated values, are summarised in Table 7. Note that the wind shear was also evaluated as being significant according to the classification procedure; however, and as permitted in the standard, this was judged to be fully correlated with turbulence intensity therefore was removed from consideration to avoid double-counting the environmental effect. **The difference in classification uncertainty value obtained from the two approaches is approximately 5%,** and as is evident from Figure 46 and Figure 51 has a strong influence on the FLS's measured wind speed uncertainty. An important detail to note is that the turbulence intensity values used for the final application are from the mast, as they are not available from the FLS data.

This reduced measured wind speed uncertainty for the FLS carries through to the eventual REWS uncertainty, see Figure 47 Figure 52. For this calculation, the associated method uncertainty has not been calculated, as this has been fully explored in the onshore case, see section 5.3.

The proposed alternative treatment of so-called terrain complexity uncertainty, already seen in section 5.4, also has the same marked impact in this case, as shown in Figure 48 and Figure 53.

The combined effect for a FLS application for following the combined revised methodologies for calibration, classification and flow gradients is to reduce the final wind speed uncertainty by almost 6%, as is shown by comparing Figure 49 and Figure 54.

Independent variable	Unit	Mean	Std	Range	Slope m	Sensitivity (m·std)	R^2	Sensitivity·R	Max. deviation (m·range)
		unit	unit	unit	% /unit	-	-	-	% /unit
Middle Wave Period	s	5.5222	0.9270	7.0135	1.0871	1.0078	0.0036	0.0607	7.6244
Wind Speed	m/s	8.0790	2.8660	19.4900	-0.1853	-0.5310	0.0122	-0.0588	-3.6112
Wind Veer	°/m	0.0291	0.1125	0.7228	6.9255	0.7789	0.0004	0.0148	5.0058
Turbulent Intensity	-	0.0652	0.0170	0.2100	39.4403	0.6689	0.0299	0.1157	8.2825

Preliminary class number: 12.84

Class number: 9.08

Classification uncertainty (%): **5.24**

Sector = [275.5,...,350] degrees

Mean	Mean difference
unit	unit
5.1384	-0.3838
8.2385	0.1595
0.0140	-0.0151
0.0697	0.0045

Classification uncertainty (%): **0.42**

Sector = [196.5,...,343.4] degrees

Table 7: Table of significant environmental variables. A classification uncertainty of around 5% was obtained following a class number approach; by evaluating the mean values of significant environmental variables in the application sector, and applying these directly to sensitivity values, a far smaller value was obtained.

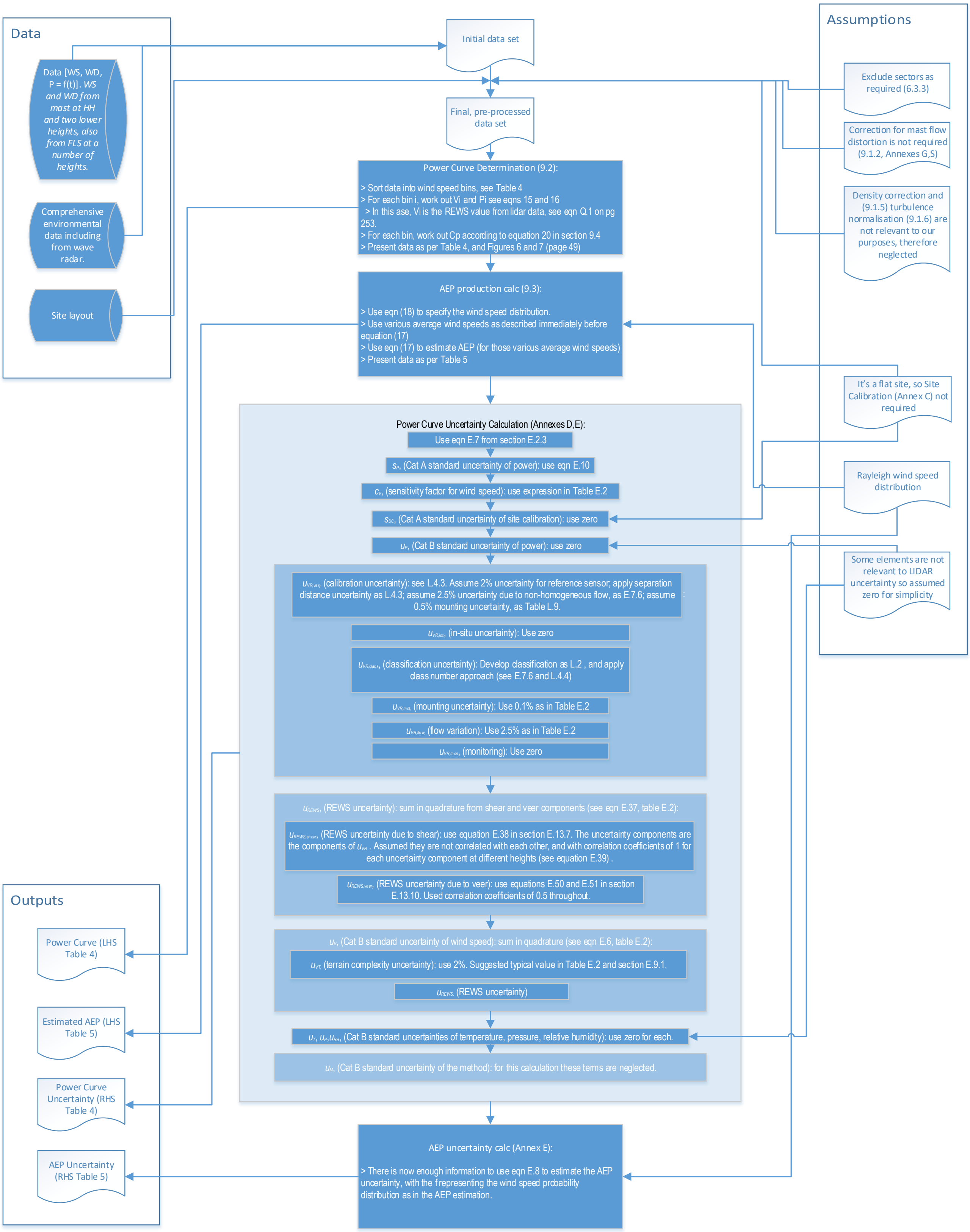


Figure 6: Calculation summary for offshore, floating lidar data only case (Off.2.A). ***Note: Print as A3 size***

Wind Speed Uncertainty Category	Off.2.A ~8%	Off.2.B ~2.1%
Wind Speed (Cup or Sonic)	N/A	
Wind Speed (RSD)		
> Calibration	Apply section L.4.3 (for RSD data) to FLS data. Assume 2% uncertainty for reference sensor. Also, apply separation distance uncertainty (section 4.3.1 of this document). ~5.0%	Apply modified method for calibration, see section 4.1 of this document. Assume 2% uncertainty for reference sensor. Also apply separation distance uncertainty as section 4.3.3. 2.0%
> In-situ check	Zero	
> Classification	From comparisons of the met mast and FLS data, and including sea state data, perform a classification calculation following L.2 of the standard. Use the class number to estimate the associated uncertainty following E.7.4 ~5.2%	Calculate the mean values of significant environmental variables during the power curve assessment. From the difference between these means and those from the verification, estimate the associated uncertainty following E.7.4 ~0.4%
> Mounting	Take typical value of 0.1% from Table E.2.	Assume zero, see section 4.5 of this document.
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2. 2.5%	Assume zero, see section 4.7 of this document. 0
> Monitoring test	Zero.	
Rotor Equivalent Wind Speed		
> Wind shear	Eqn E.38 assuming (a) uncertainty components are not correlated with each other and (b) with correlation coefficients of 1 for a given uncertainty component at different heights.	
> Wind veer	Calculate using eqn E.50 (see footnote to Table 4) and E.51. Used correlation coefficients of 0.5 in all cases.	
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1 2.0%	New approach, see section 4.4 ~0.1%
Method – wind conditions		
> Shear	Not included in this calculation.	
> Veer	Not included in this calculation.	

Table 8: Summary of calculation methods for the offshore dataset (Dataset 2), using FLS data only (calculation 2), for 2 different versions of the calculation (A,B). Blank cells indicate method unchanged compared to cell to the left.

5.6 SUMMARY OF AEP UNCERTAINTIES

A summary of the standard uncertainties in AEP resulting from the example calculations is presented in Table 9 below. The indices used in the table are those introduced in Table 2, and the example calculations are those described in section 5.1 to section 5.5 above.

This section has been up to this point primarily devoted to the estimation of uncertainty in wind speed. The results in Table 9 provide an indication of how these wind speed uncertainties translate to AEP uncertainties. To achieve this in a manner that is consistent between calculations, the wind speed uncertainties have been applied to a single power curve (in fact that derived in calculation On.1.B for a nominally 3.7 MW turbine). As described in sections 5.1 and 6.1.2, the standard has a typographical error in the expression for AEP standard uncertainty; for clarity the correct expression has been applied here. Note also that by way of illustration two Rayleigh distributions have been applied, one for an average wind speed of 7 m/s and a second for an average wind speed of 10 m/s. Finally, note also that only Category B uncertainties of wind speed and of the method are included in the indicative AEP uncertainties.

As an aside, it is also mentioned that the REWS methodology may result in reduced power scatter within wind speed bins, which could have a beneficial effect in reducing category A standard uncertainty of power; this has not been explored in this study.

Data Set	Calculation	Version	Index	Revised Methodology	Indicative Wind Speed Standard Uncertainty (%)	Indicative AEP Standard Uncertainty (%), Average Wind Speed = 7 m/s	Indicative AEP Standard Uncertainty (%), Average Wind Speed = 10 m/s
Onshore	1	A	On.1.A		3.2	5.7	3.0
Onshore	1	B	On.1.B		2.4	4.0	2.1
Onshore	1	C	On.1.C	Yes	2.0	3.3	1.7
Onshore	2	A	On.2.A		2.2	3.9	2.1
Onshore	2	B	On.2.B	Yes	1.8	3.1	1.7
Onshore	3	A	On.3.A		4.0	6.9	3.7
Onshore	3	B	On.3.B	Yes	2.5	4.7	2.4
Offshore	1	A	Off.1.A		2.9	4.7	2.5
Offshore	1	B	Off.1.B	Yes	2.2	3.4	1.8
Offshore	2	A	Off.2.A		8.0	12.7	6.8
Offshore	2	B	Off.2.B	Yes	2.1	3.3	1.8

Table 9: Summary of AEP Standard Uncertainties. Note that only Category B wind speed and method uncertainties have been applied to estimate the AEP uncertainty: refer to section 5.6 for further details.

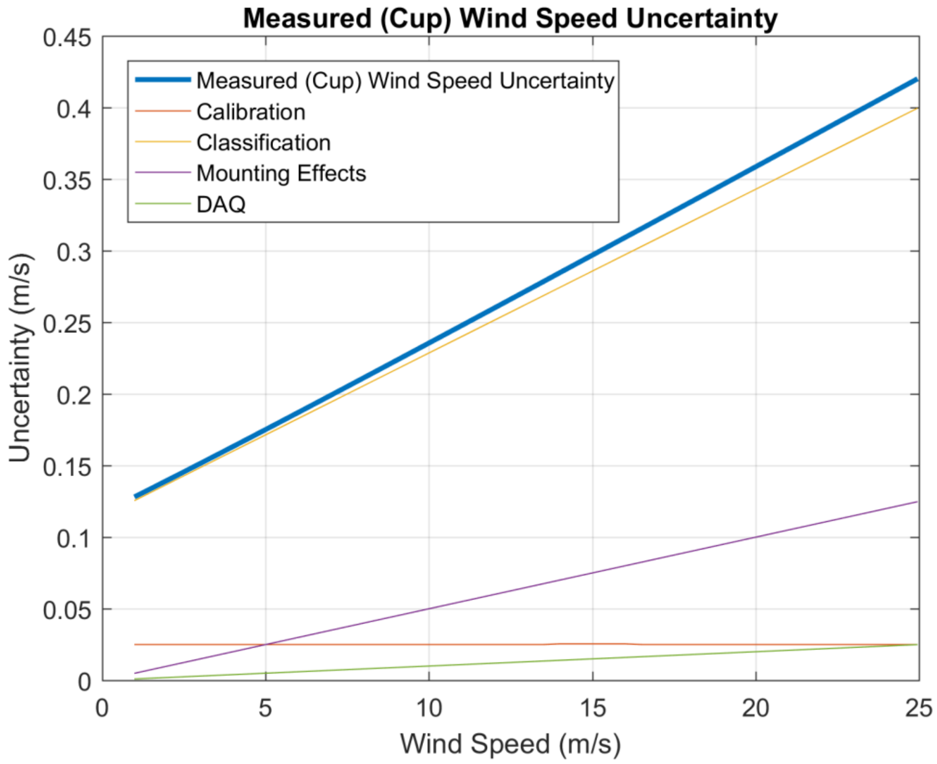


Figure 7: Measured (Cup) Wind Speed Uncertainty and components (On.1.A)

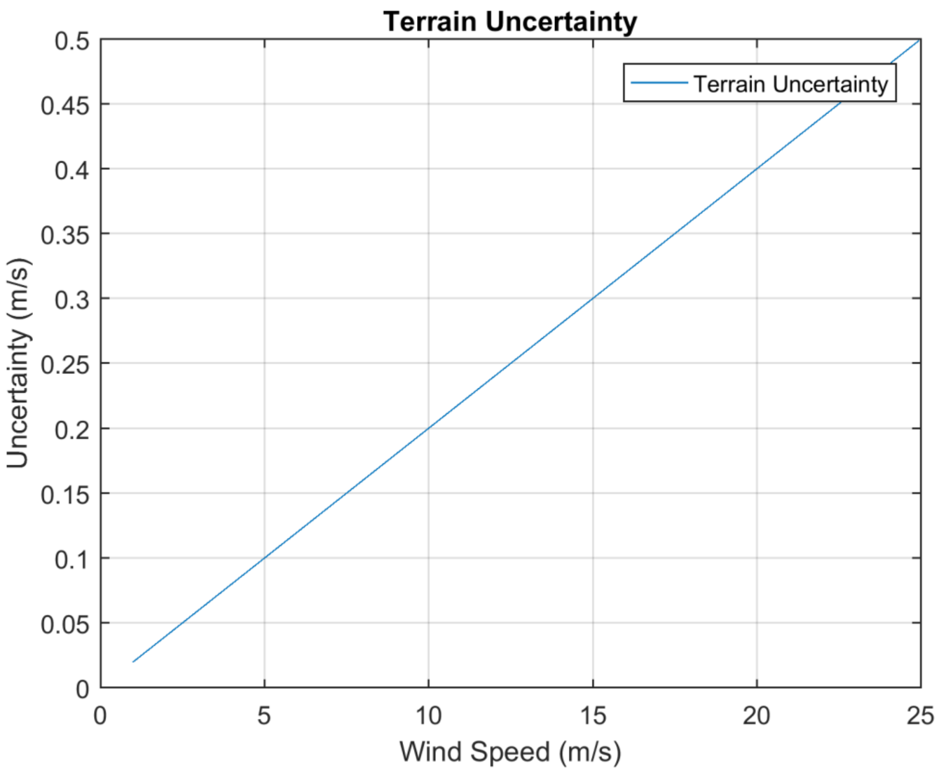


Figure 8: Terrain uncertainty (On.1.A)

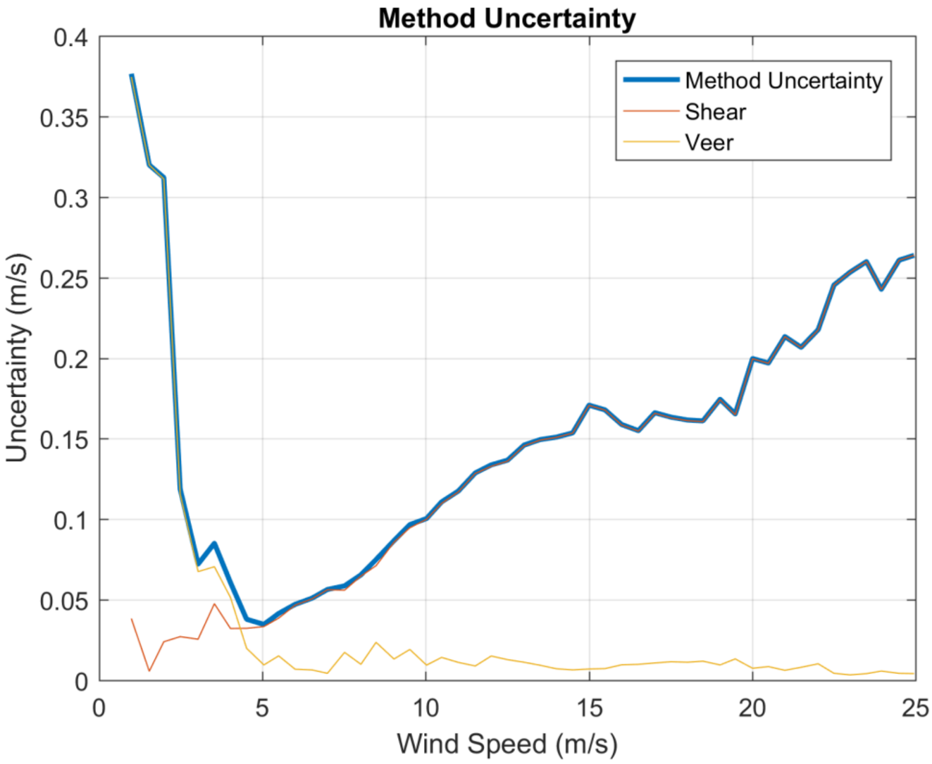


Figure 9: Method Uncertainty and Components (On.1.A)

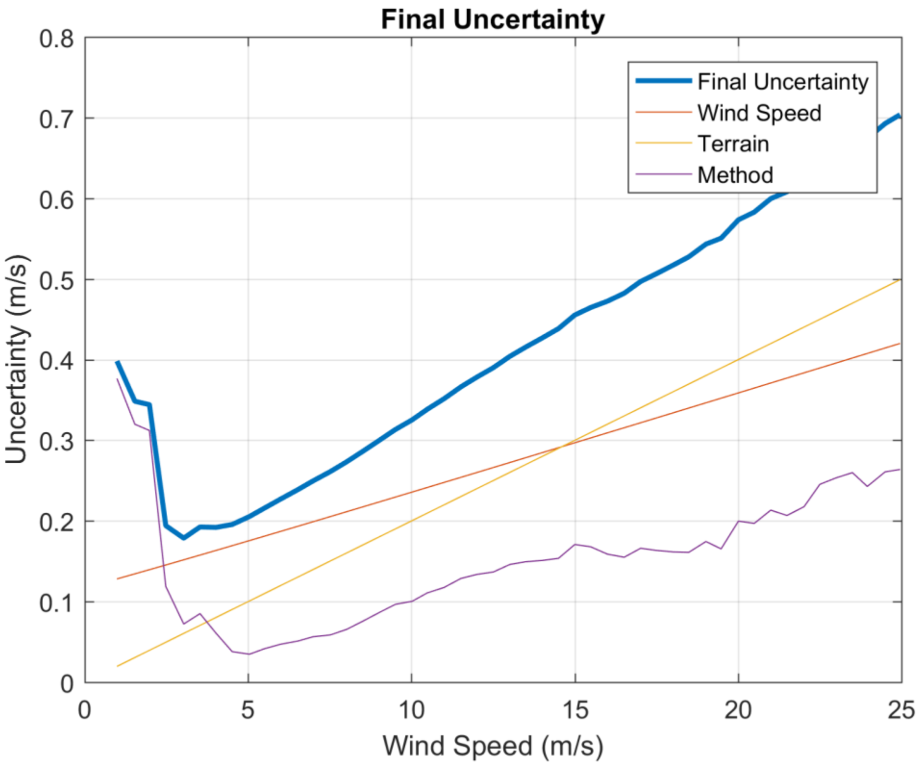


Figure 10: Final Uncertainty and Components (On.1.A)

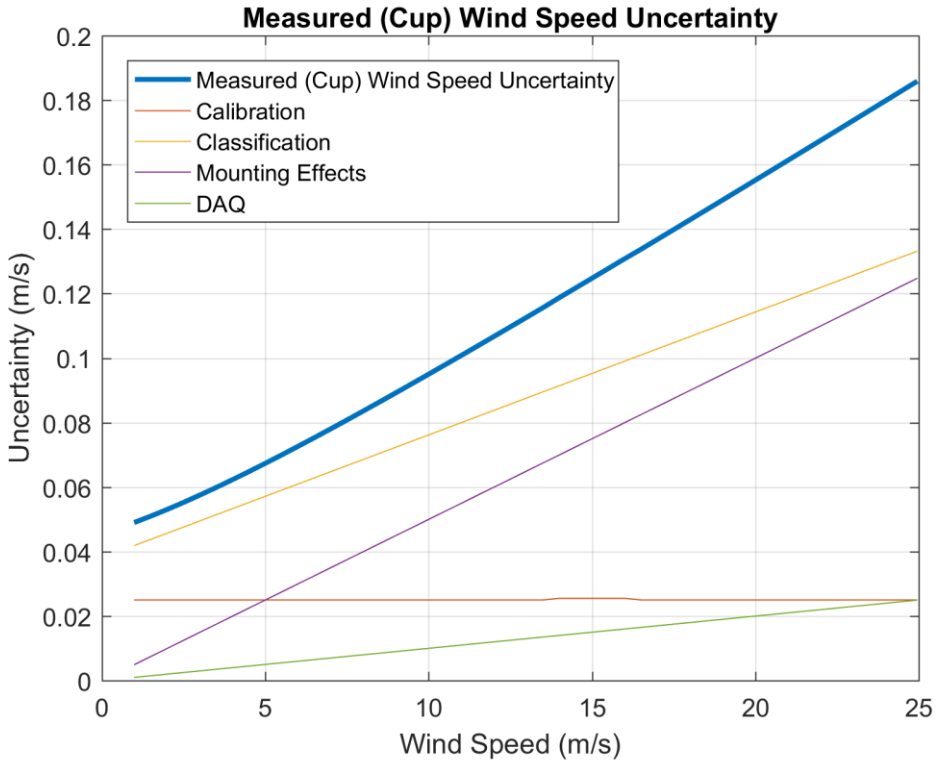


Figure 11: Wind Speed Uncertainty and components (On.1.B)

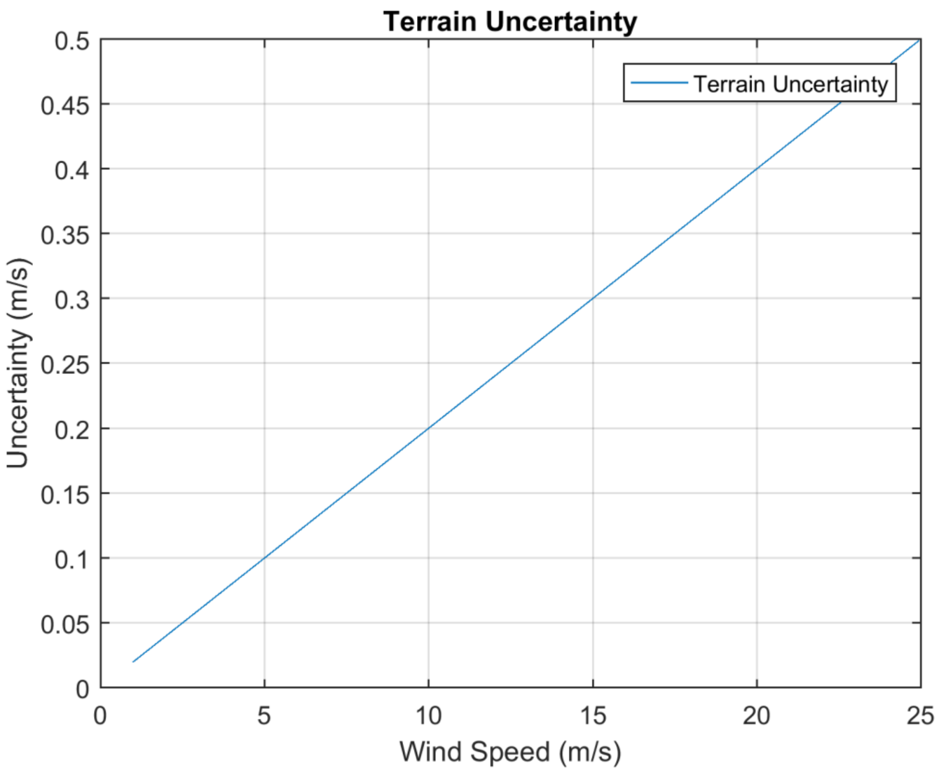


Figure 12: Terrain uncertainty (On.1.B)

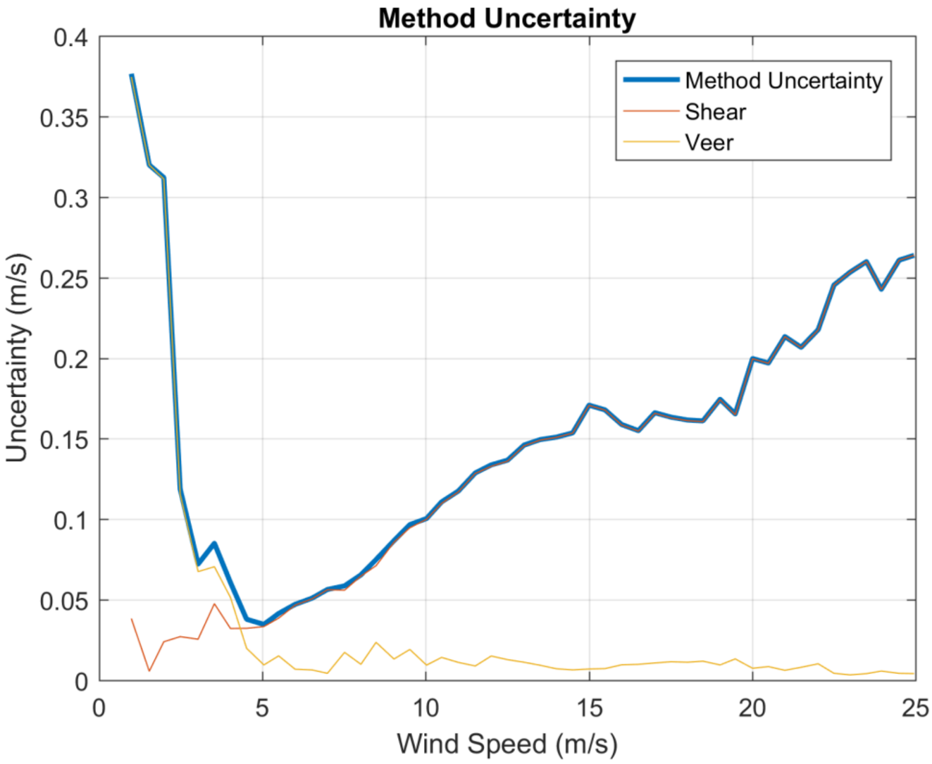


Figure 13: Method Uncertainty and Components (On.1.B)

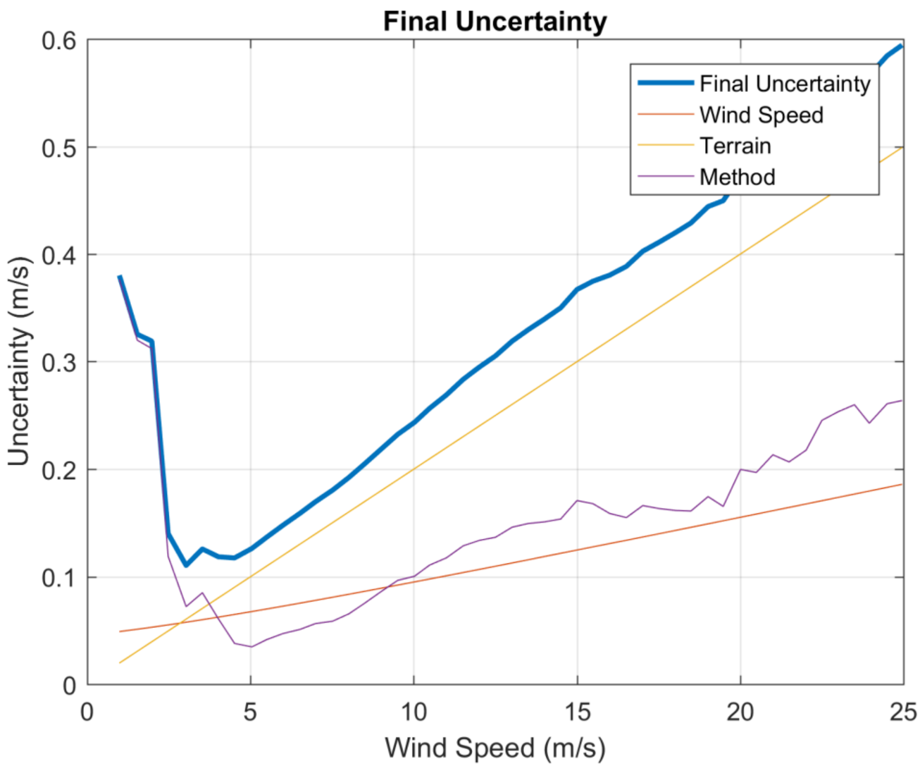


Figure 14: Final Uncertainty and Components (On.1.B)

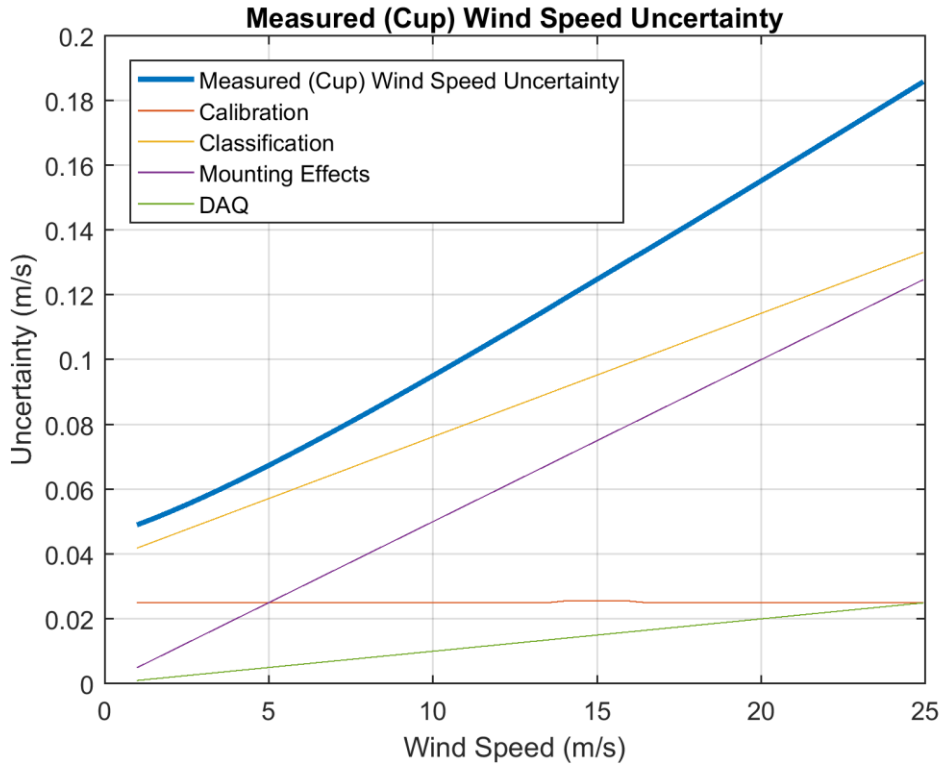


Figure 15: Wind Speed Uncertainty and components (On.1.C)

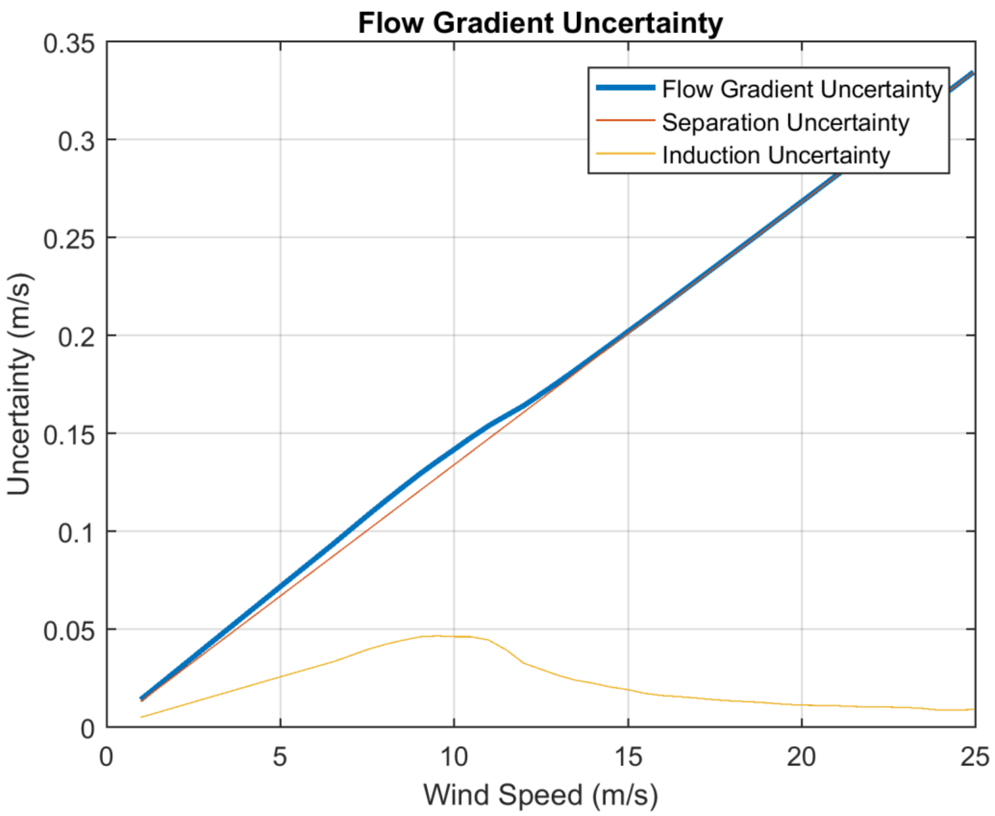


Figure 16: Flow gradient uncertainty (On.1.C)

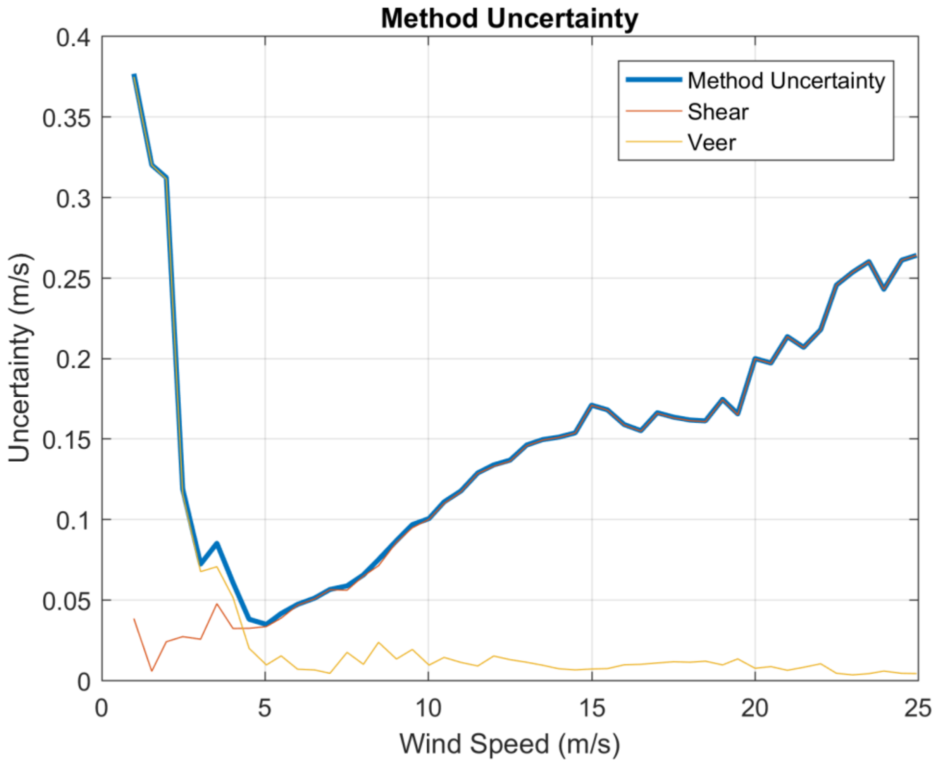


Figure 17: Method Uncertainty and Components (On.1.C)

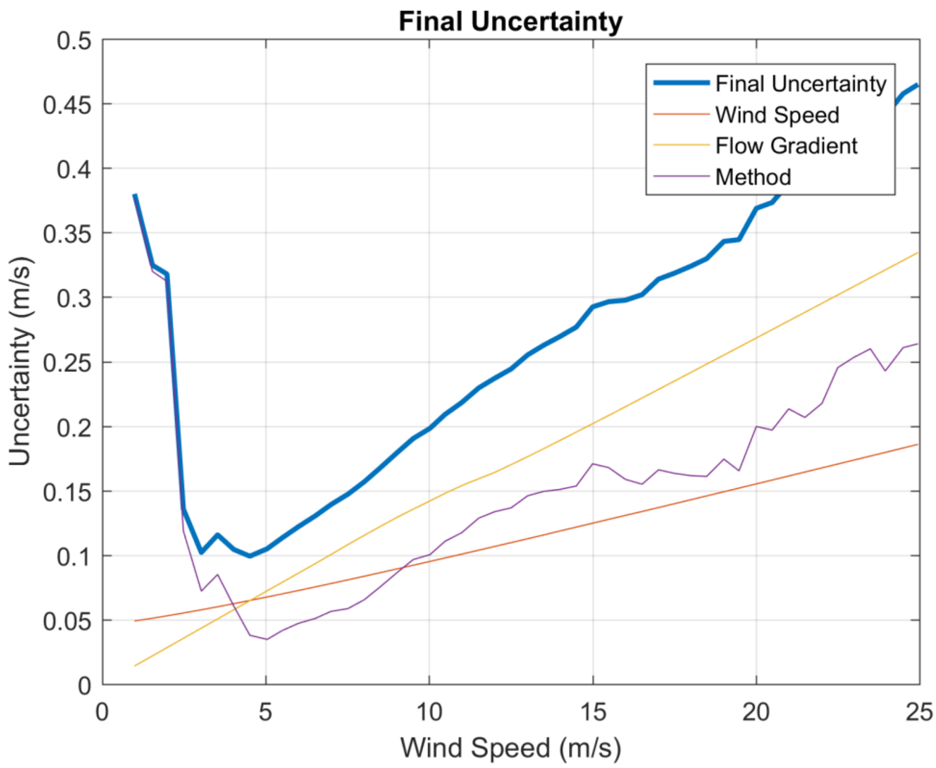


Figure 18: Final Uncertainty and Components (On.1.C)

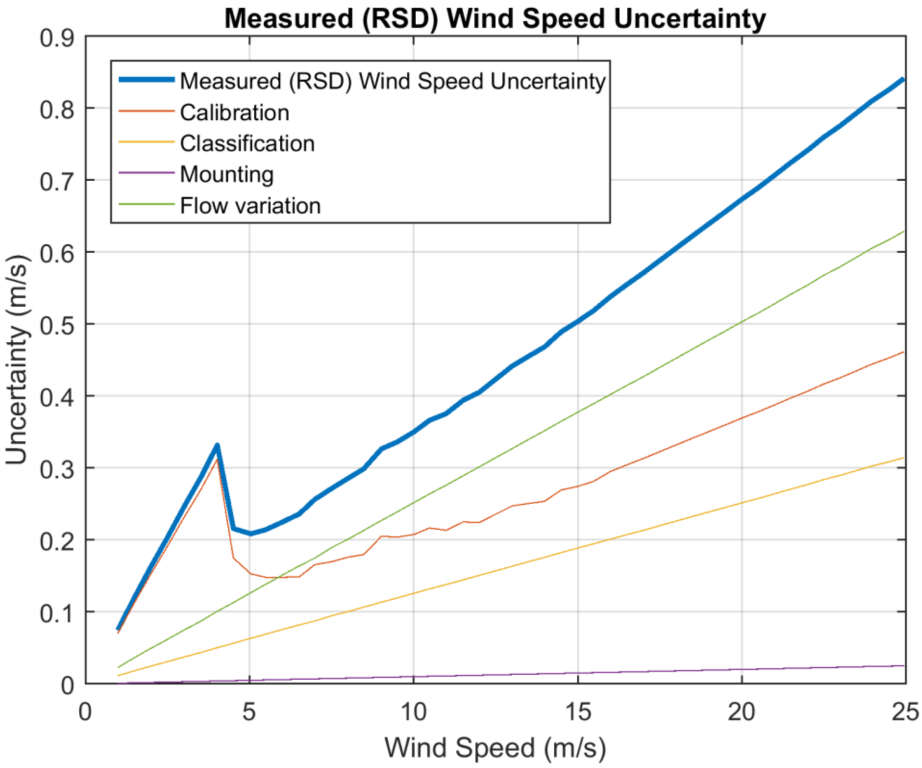


Figure 19: Lidar Wind Speed Uncertainty and components (On.2.A)

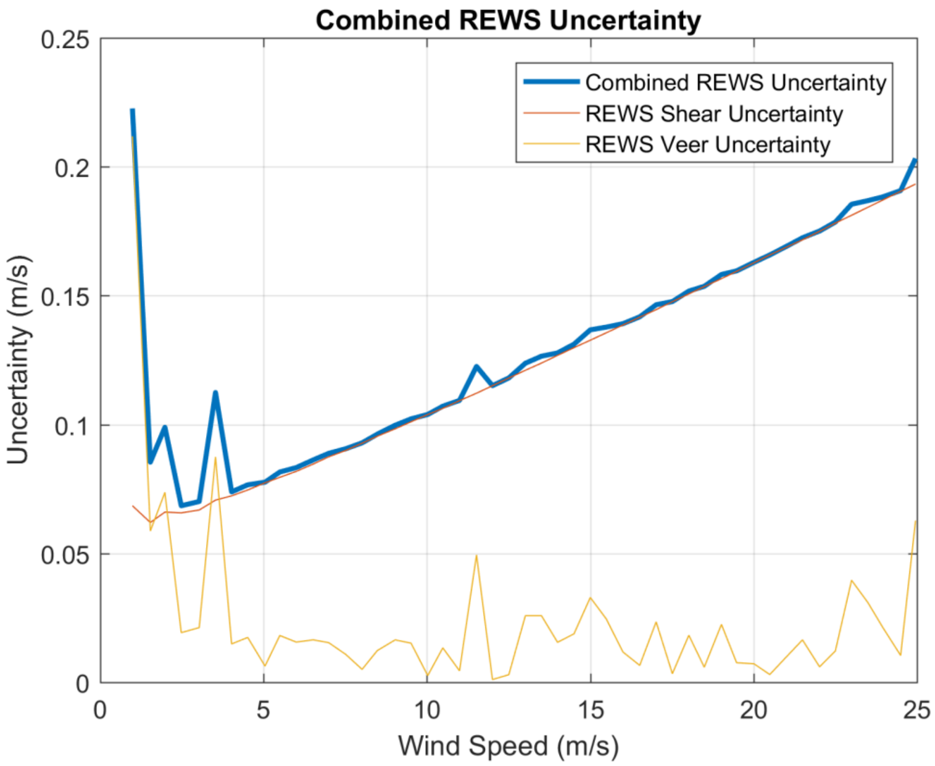


Figure 20: REWS Uncertainty and components (On.2.A)

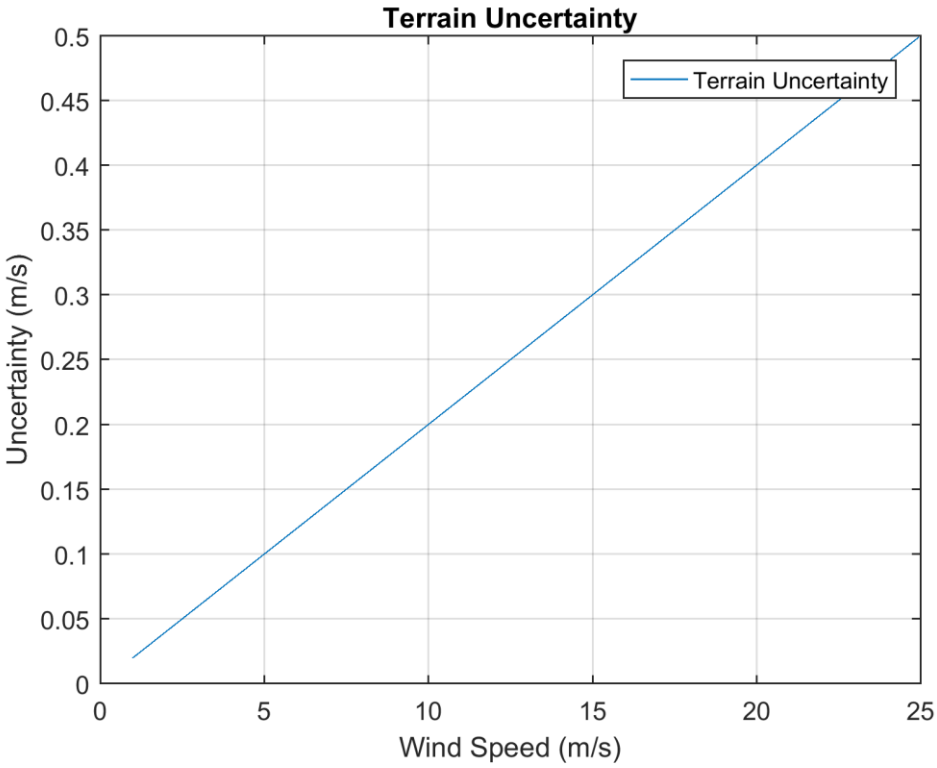


Figure 21: Terrain Complexity Uncertainty (On.2.A)

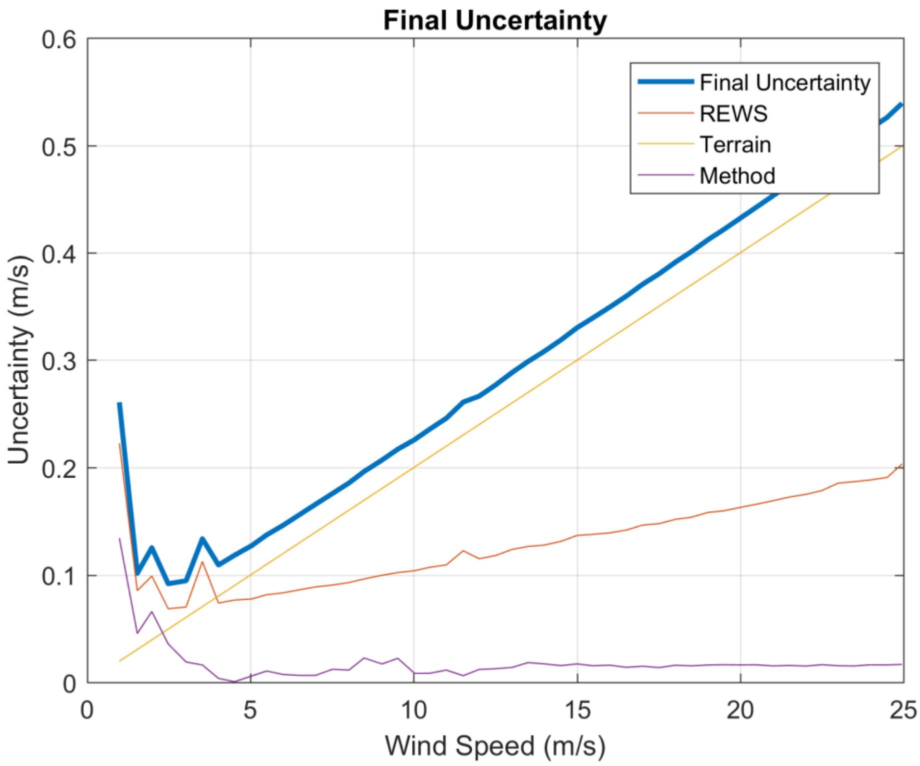


Figure 22: Final Uncertainty and Components (On.2.A)

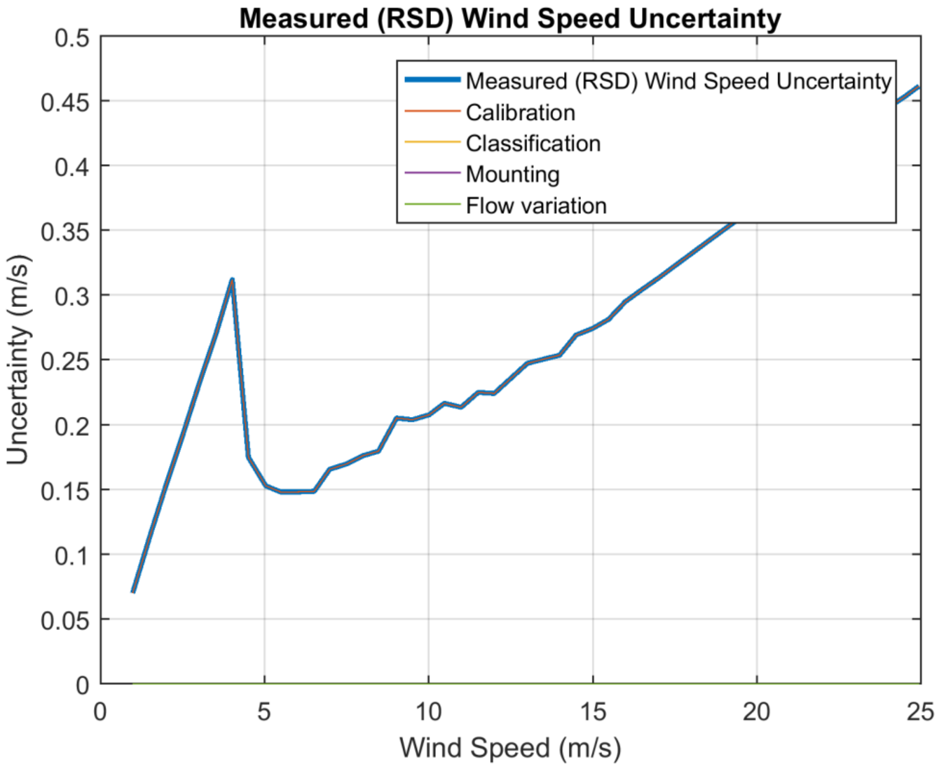


Figure 23: Lidar Wind Speed Uncertainty and components (On.2.B). Only calibration uncertainty has a contribution in this case.

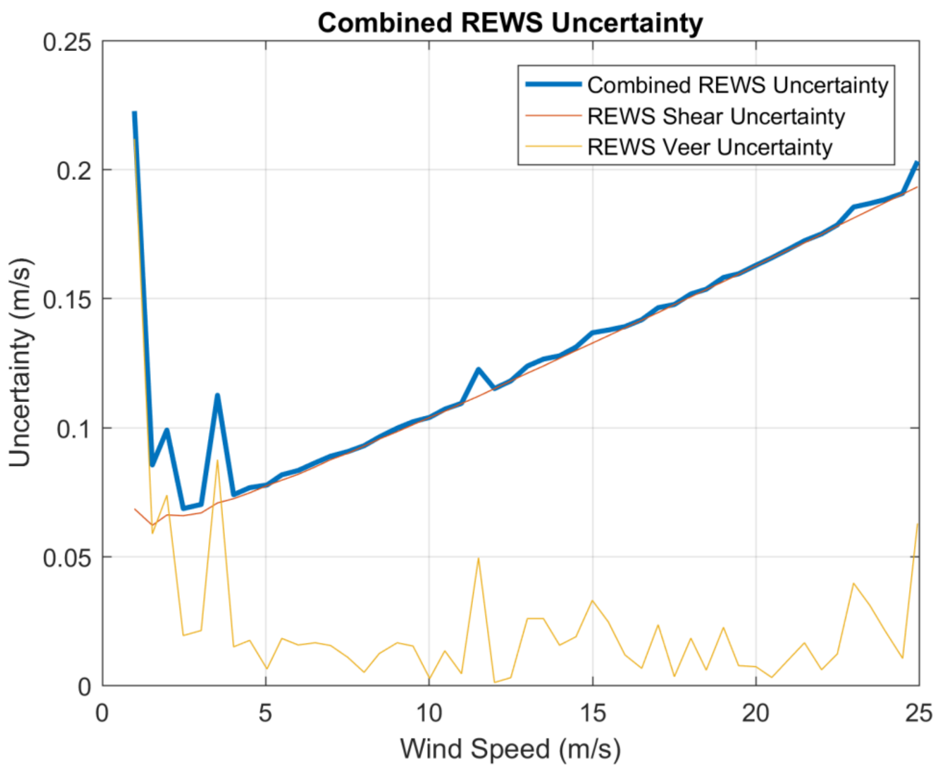


Figure 24: REWS Uncertainty and components (On.2.B)

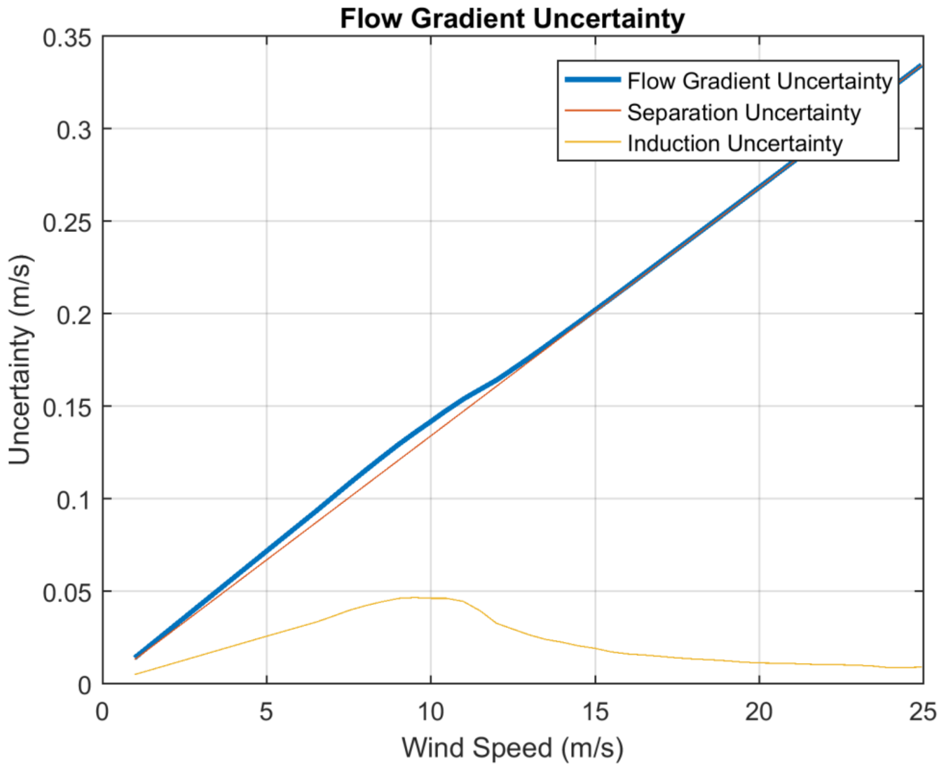


Figure 25: Flow Gradient Uncertainty and Components (On.2.B)

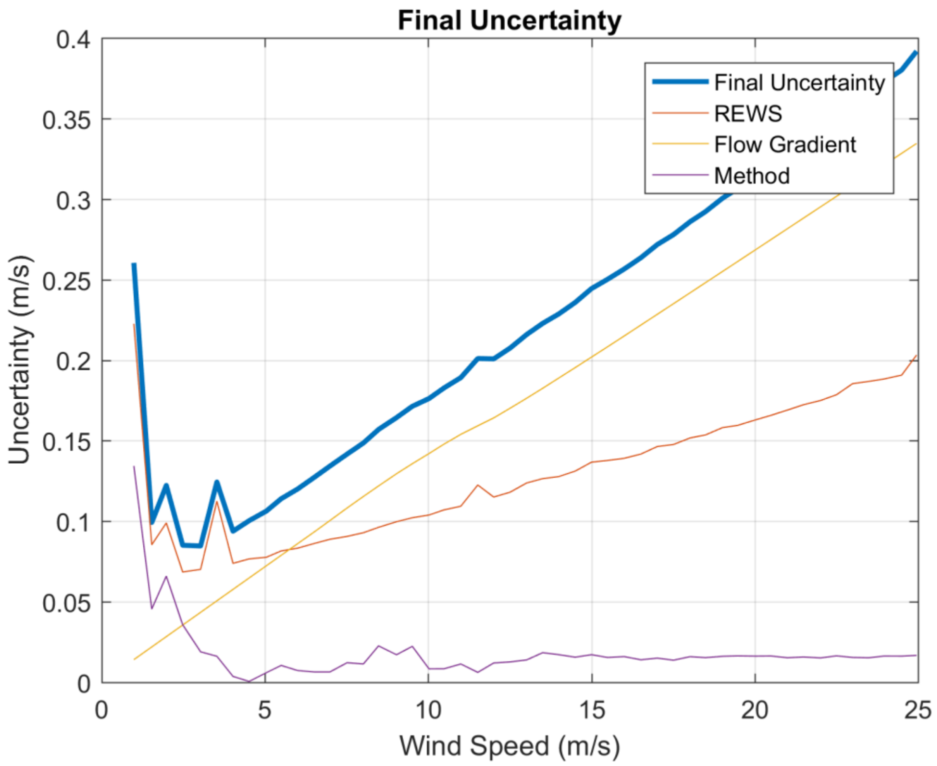


Figure 26: Final Uncertainty and Components (On.2.B)

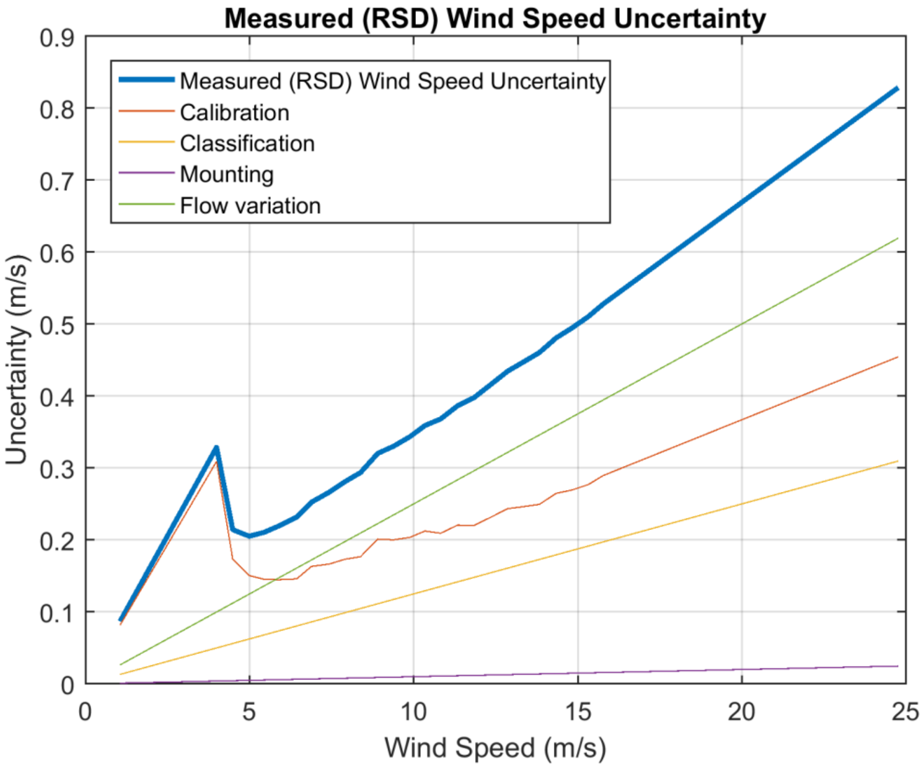


Figure 27: Wind Speed Uncertainty and components (On.3.A)

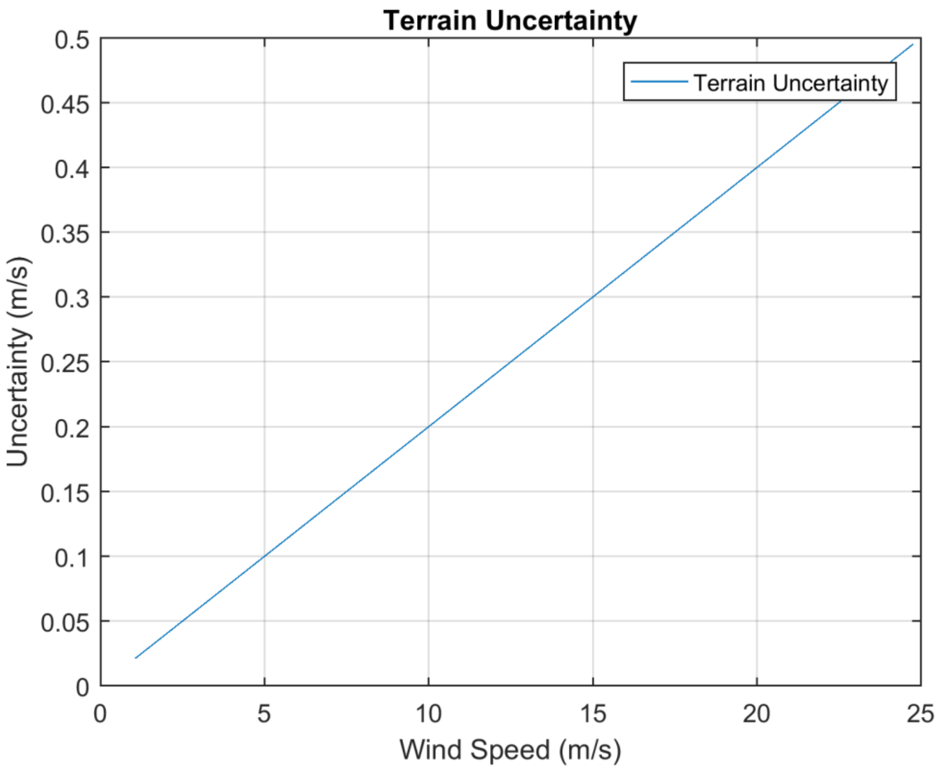


Figure 28: Terrain uncertainty (On.3.A)

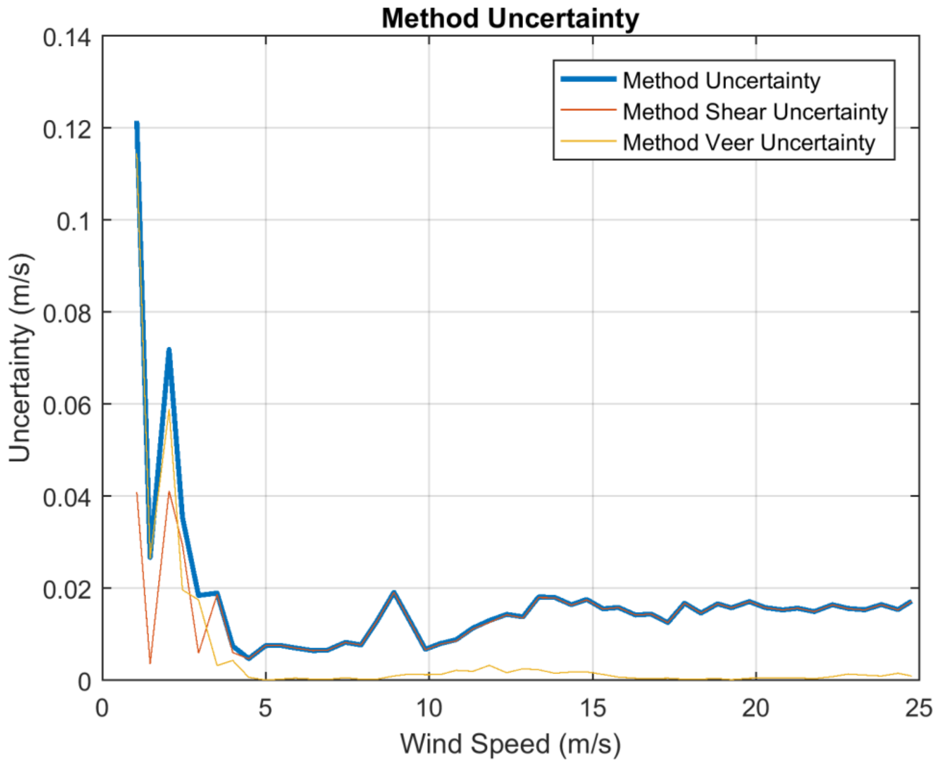


Figure 29: Method Uncertainty and Components (On.3.A)

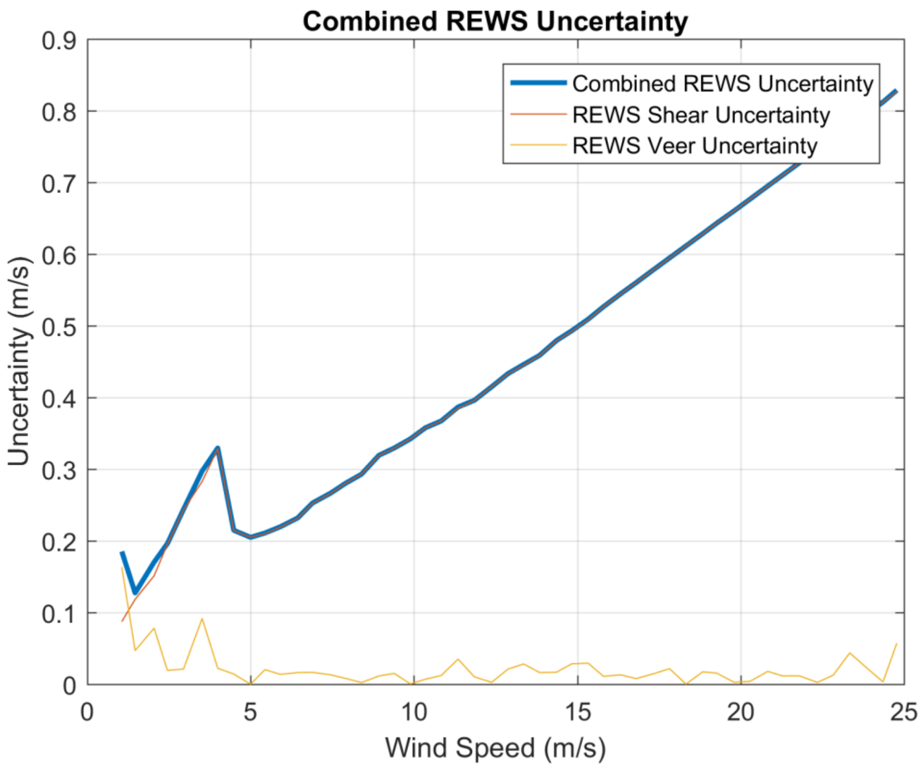


Figure 30: REWS uncertainty and components (On.3.A)

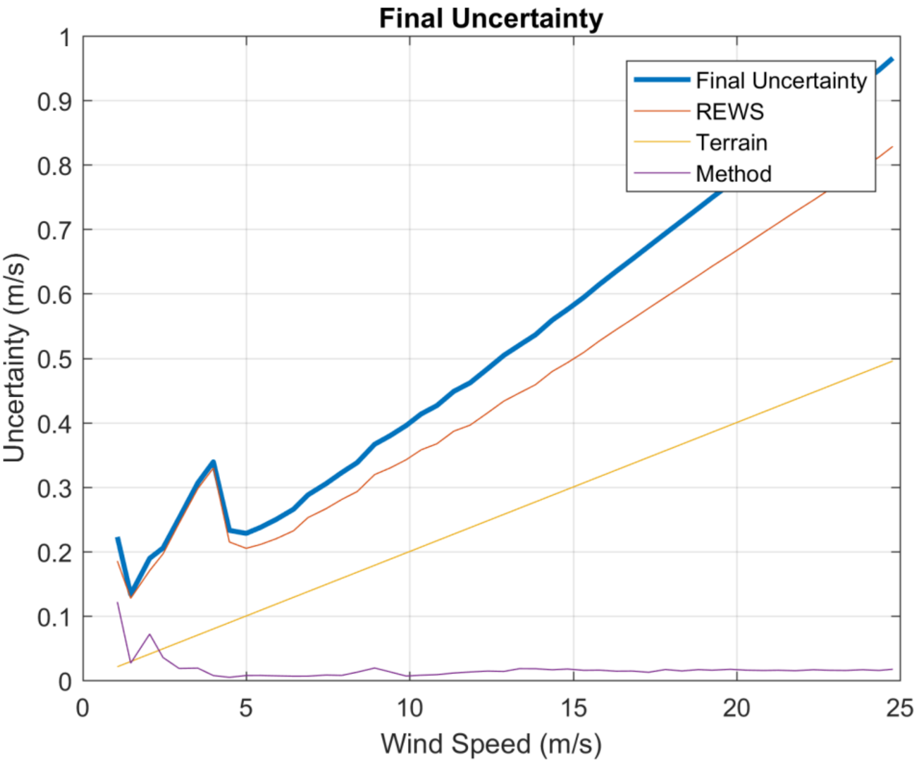


Figure 31: Final Uncertainty and Components (On.3.A)

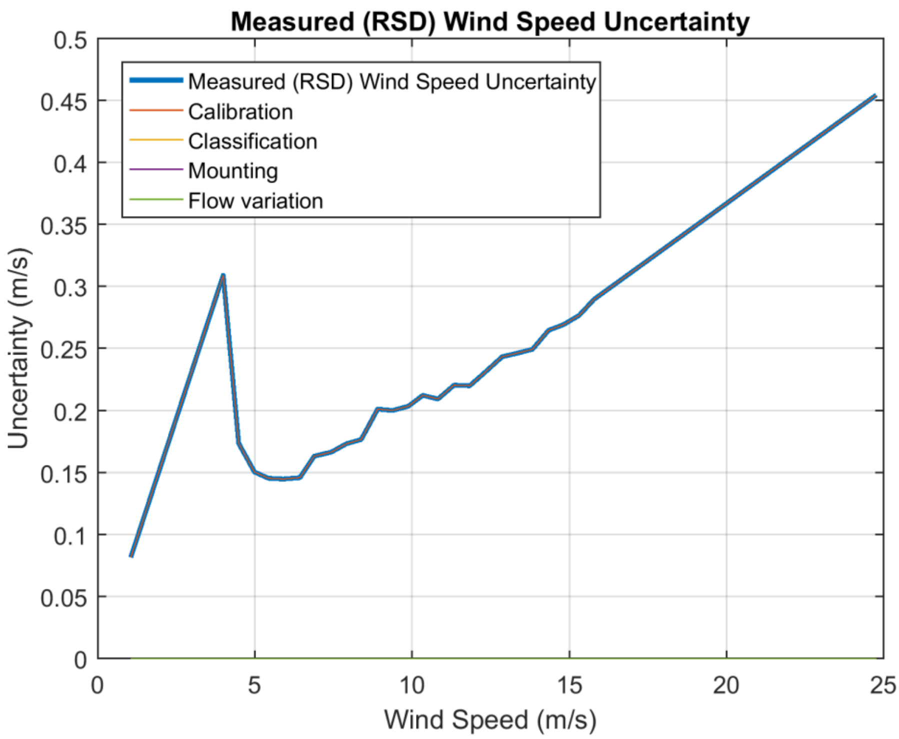


Figure 32: Wind Speed Uncertainty and components (On.3.B). Only calibration uncertainty contributes in this case.

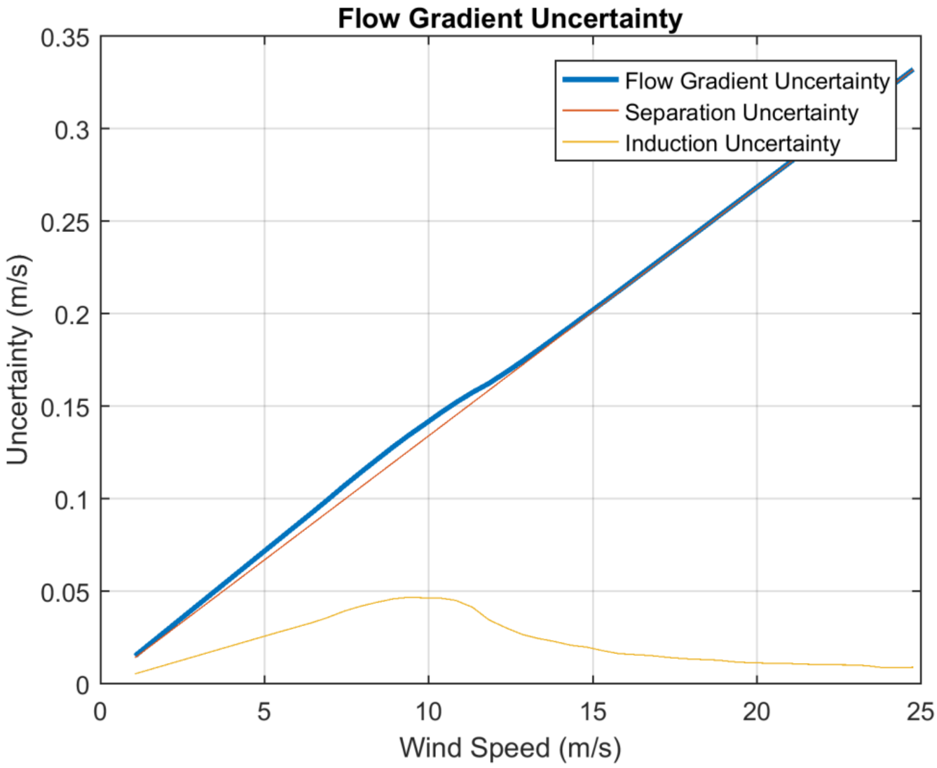


Figure 33: Flow gradient uncertainty (On.3.B)

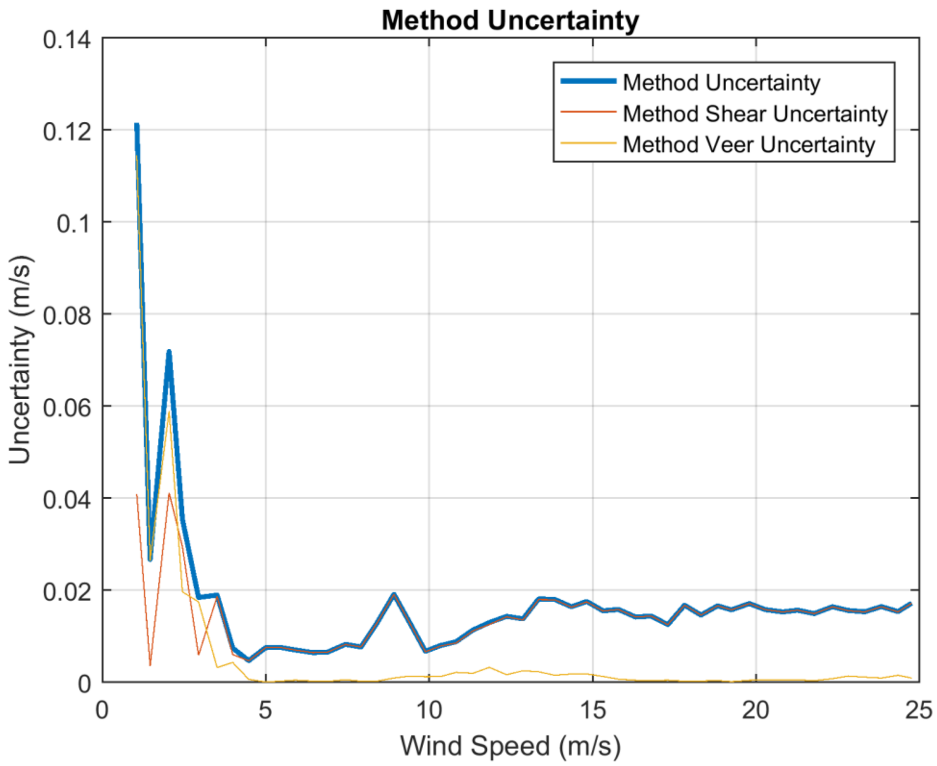


Figure 34: Method Uncertainty and Components (On.3.B)

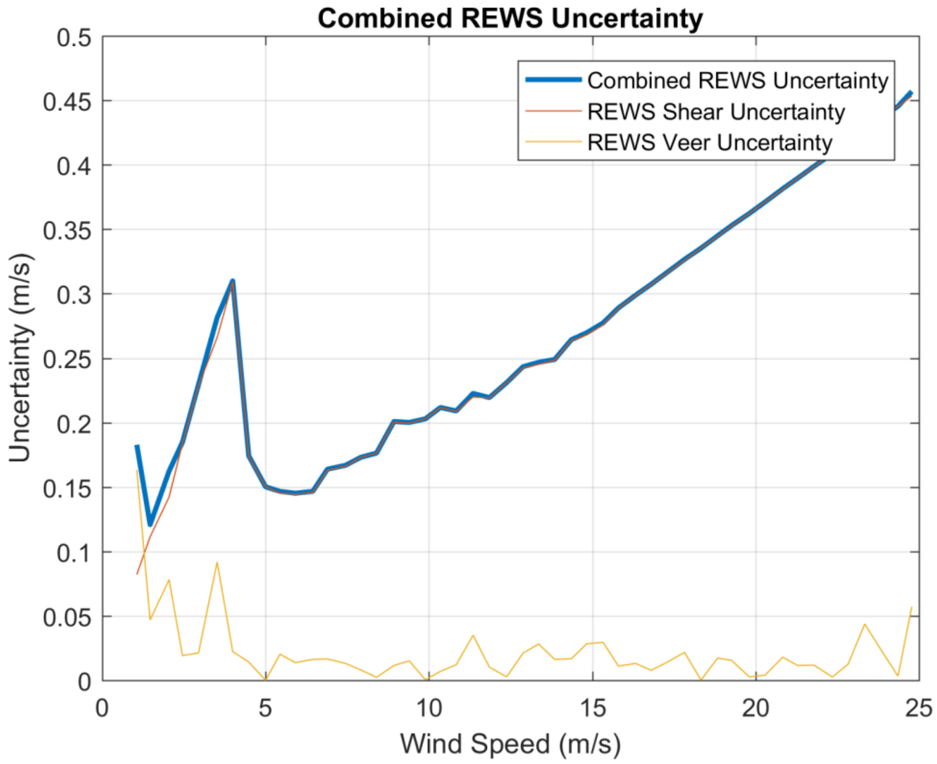


Figure 35: REWS uncertainty and components (On.3.B)

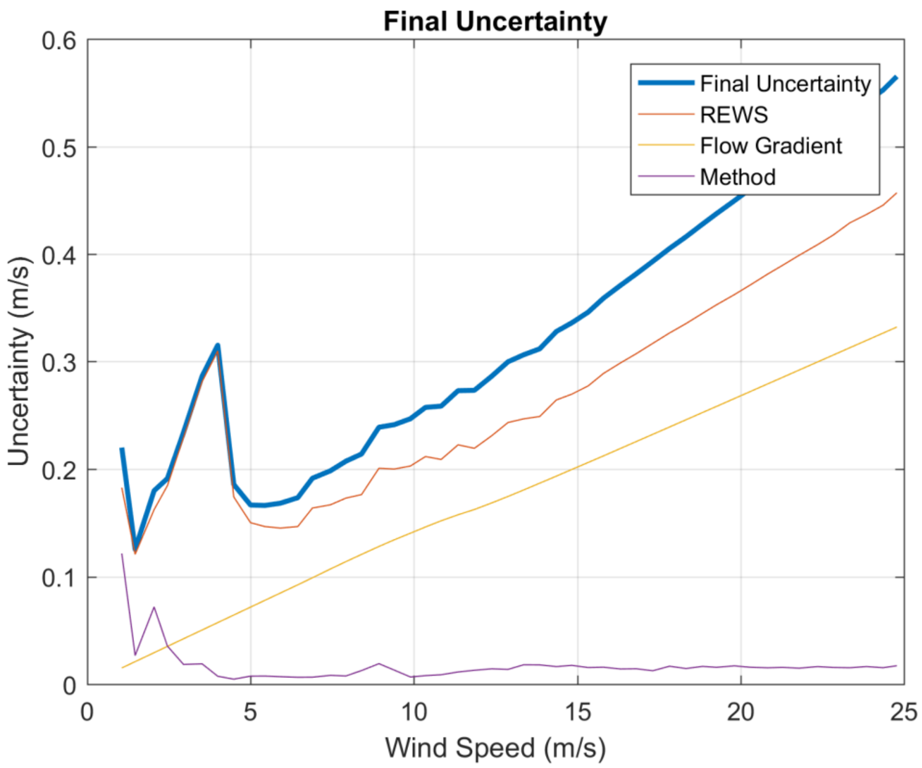


Figure 36: Final Uncertainty and Components (On.3.B)

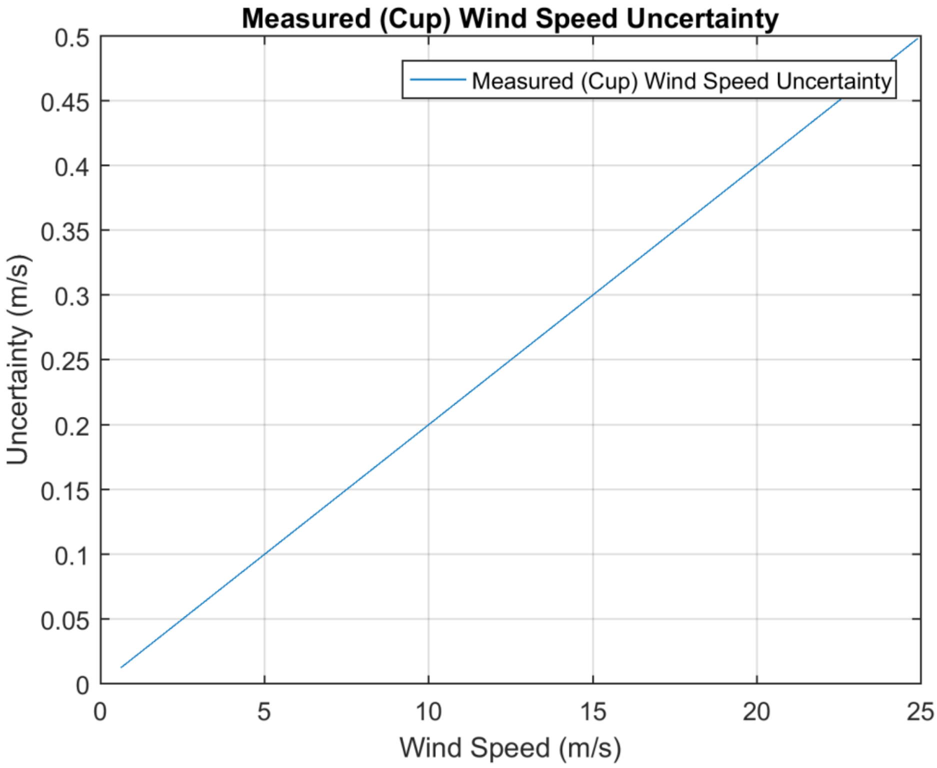


Figure 37: Wind Speed Uncertainty (Off.1.A)

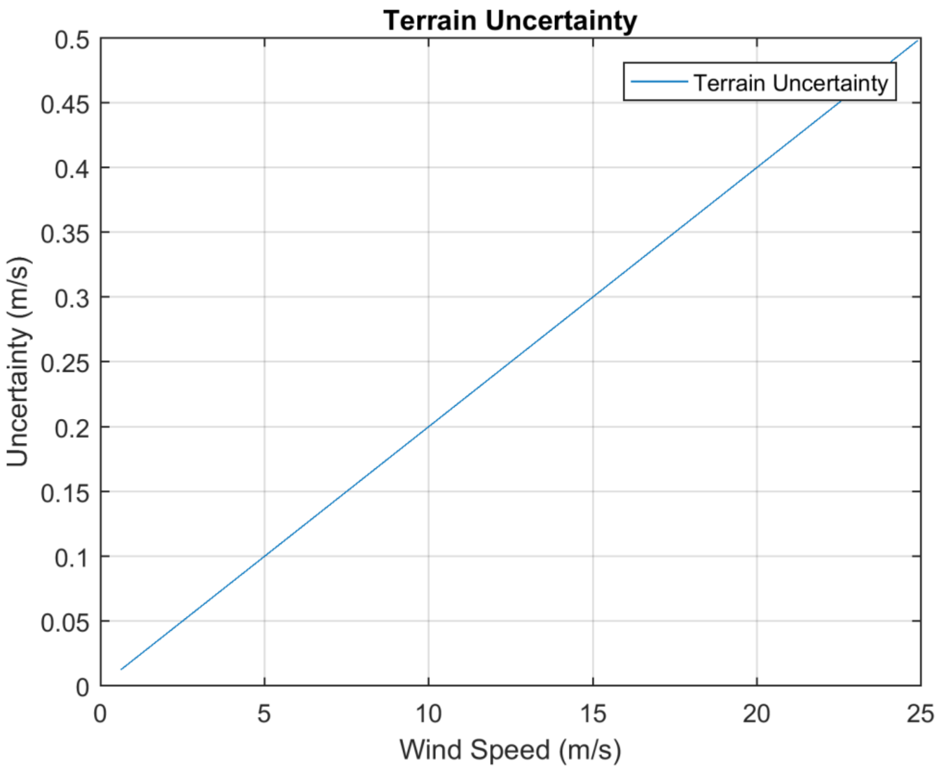


Figure 38: Terrain uncertainty (Off.1.A)

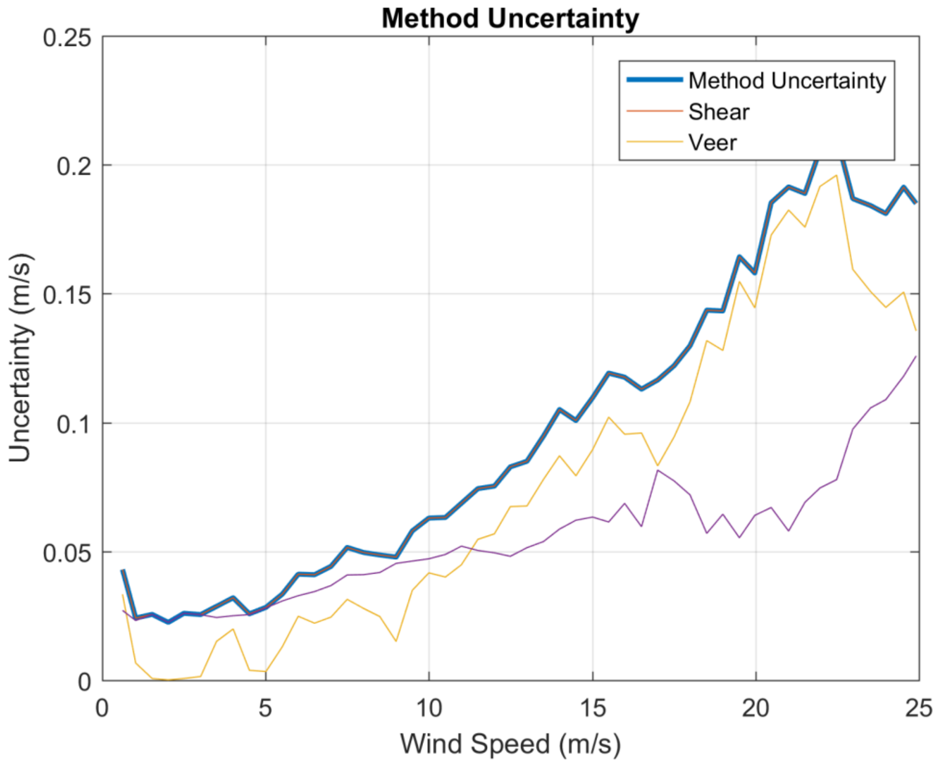


Figure 39: Method Uncertainty and Components (Off.1.A)

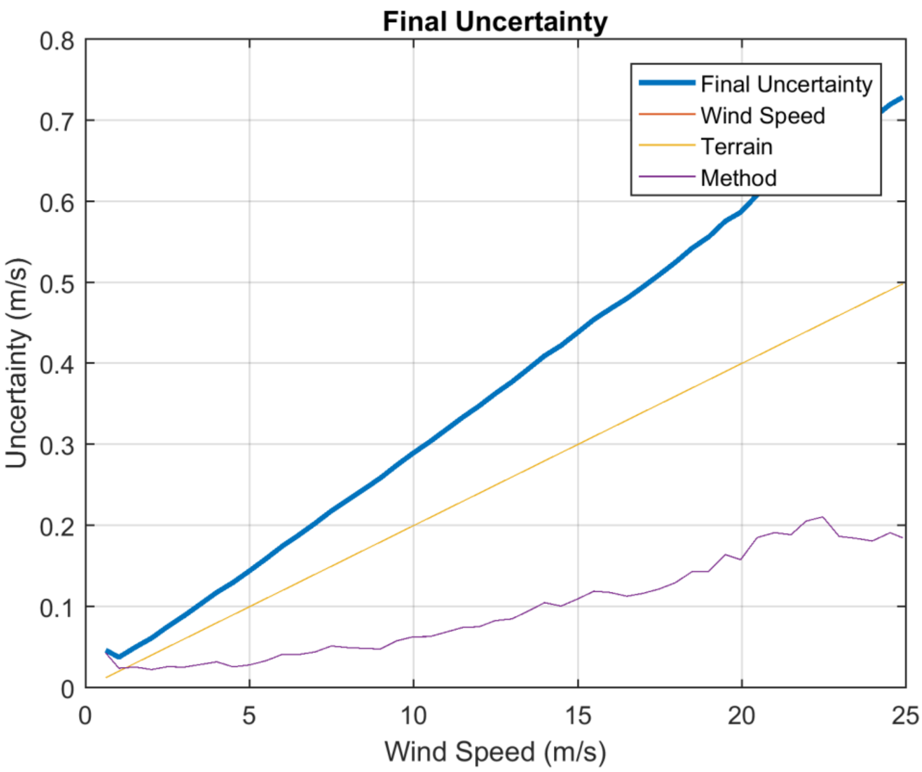


Figure 40: Final Uncertainty and Components (Off.1.A). Wind speed and terrain uncertainties are both 2% in this case.

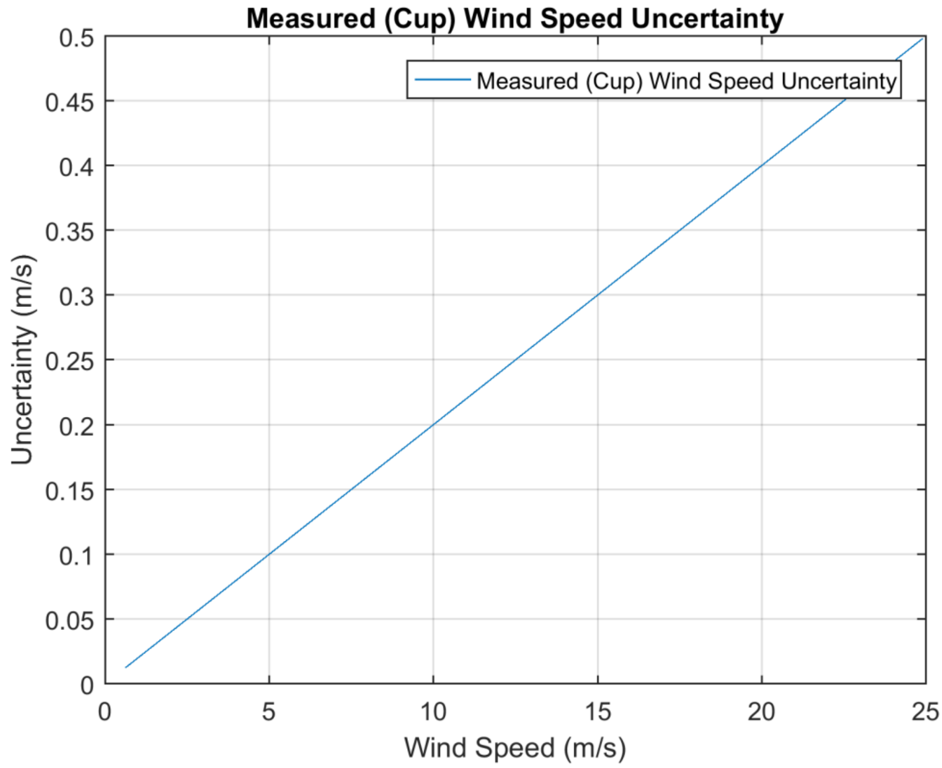


Figure 41: Wind Speed Uncertainty (Off.1.B)

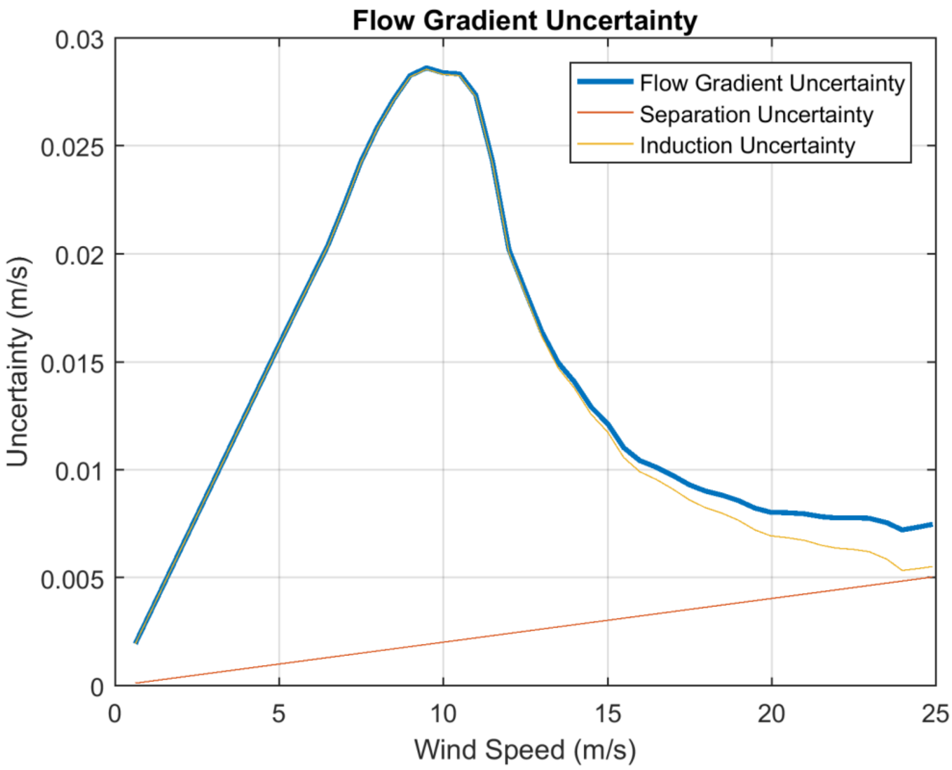


Figure 42: Flow Gradient Uncertainty and Components (Off.1.B)

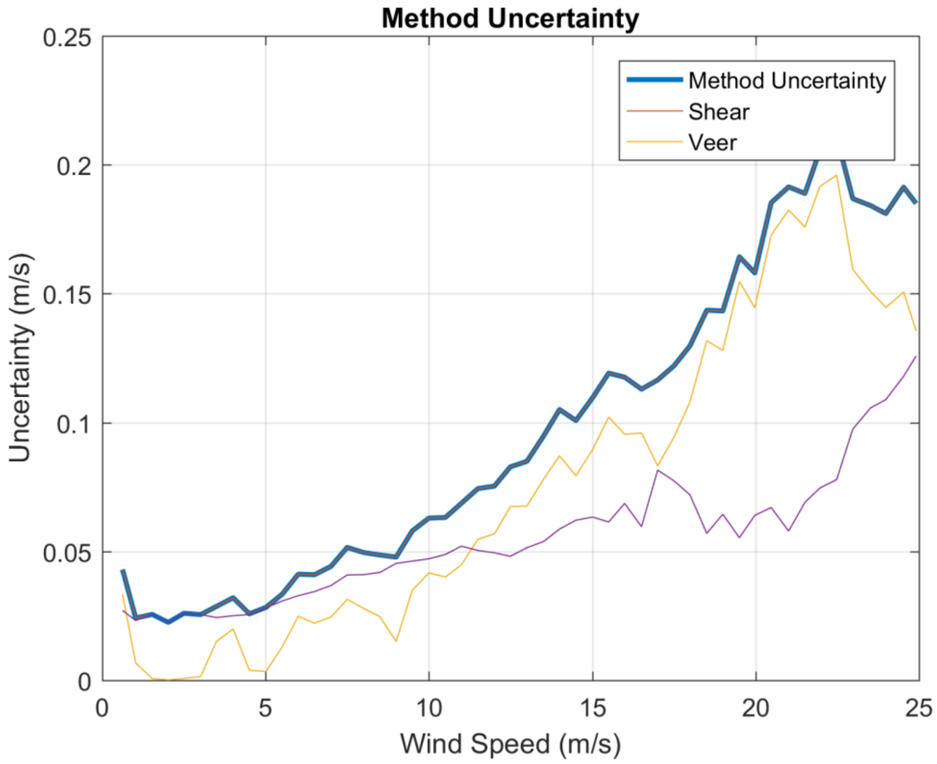


Figure 43: Method Uncertainty and Components (Off.1.B)

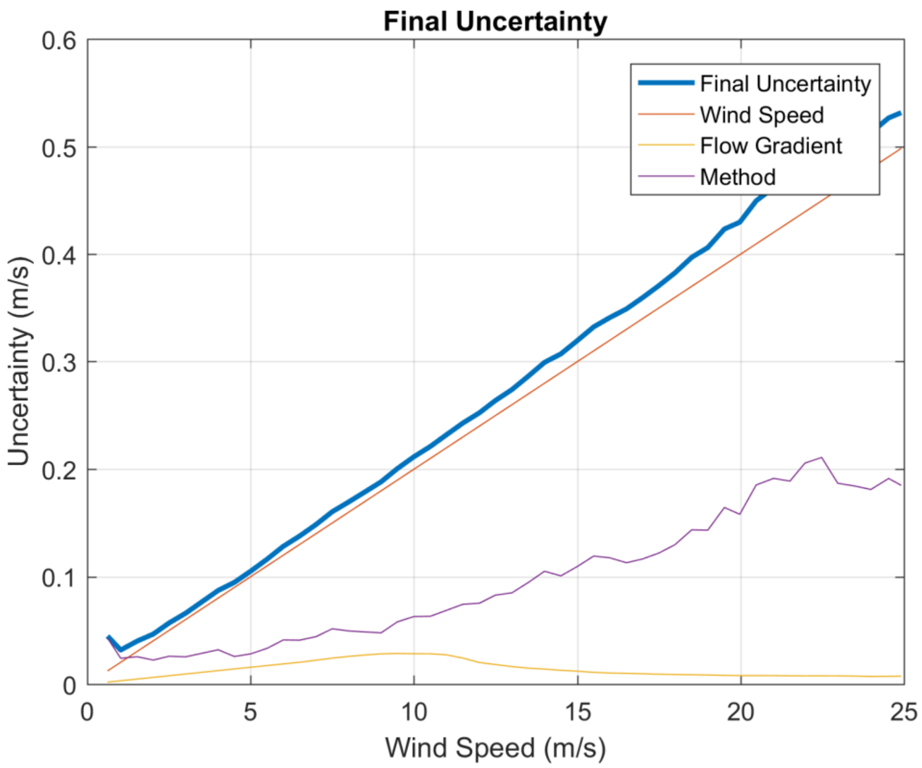


Figure 44: Final Uncertainty and Components (Off.1.B)

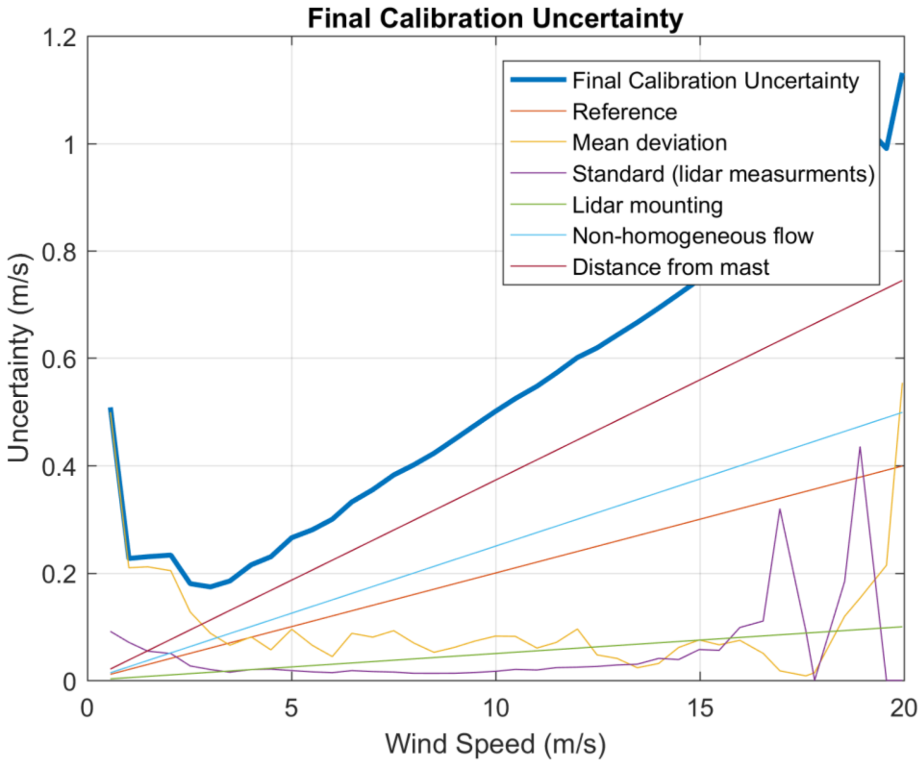


Figure 45: Calibration Uncertainty and Components (Off.2.A)

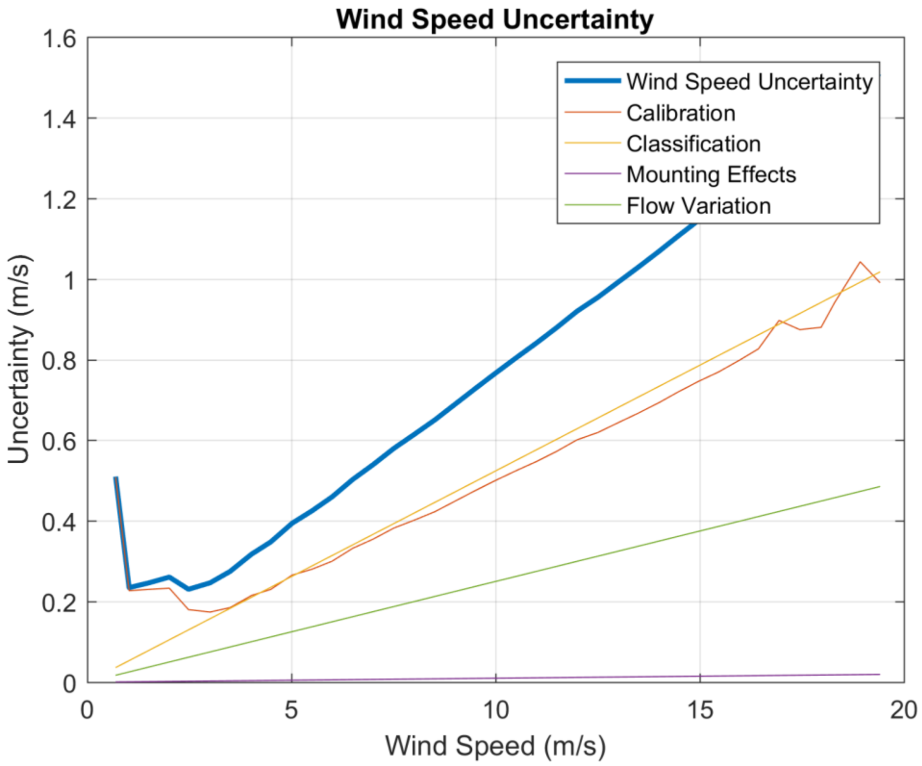


Figure 46: Wind Speed Uncertainty and Components (Off.2.A)

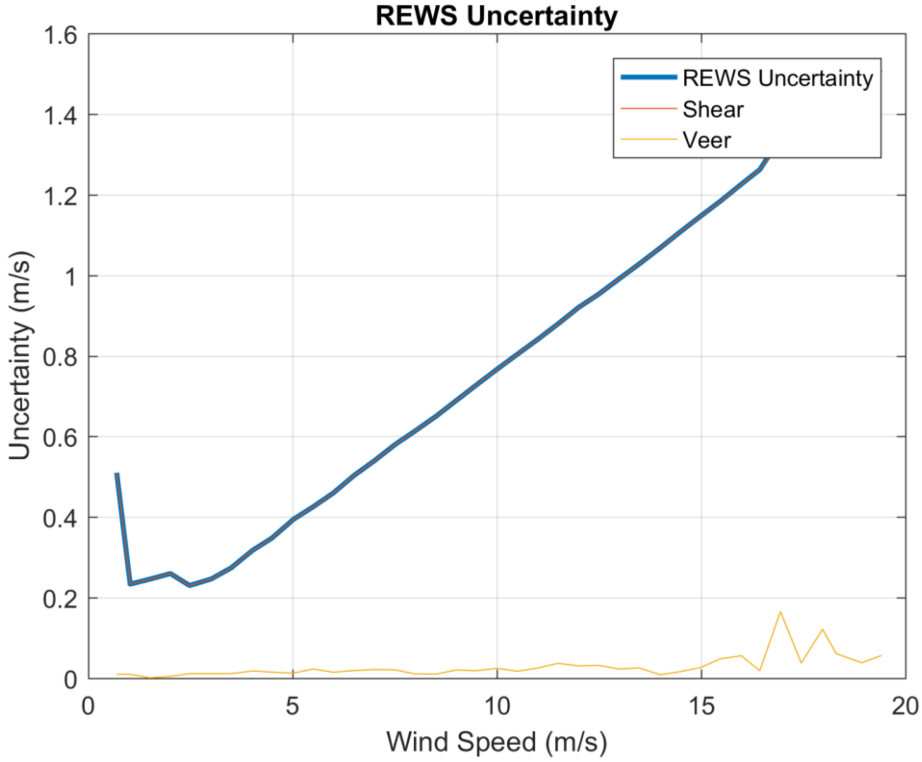


Figure 47: REWS Uncertainty and Components (Off.2.A). Note that the REWS uncertainty is here almost exactly the same as the Wind Speed Uncertainty in Figure 46.

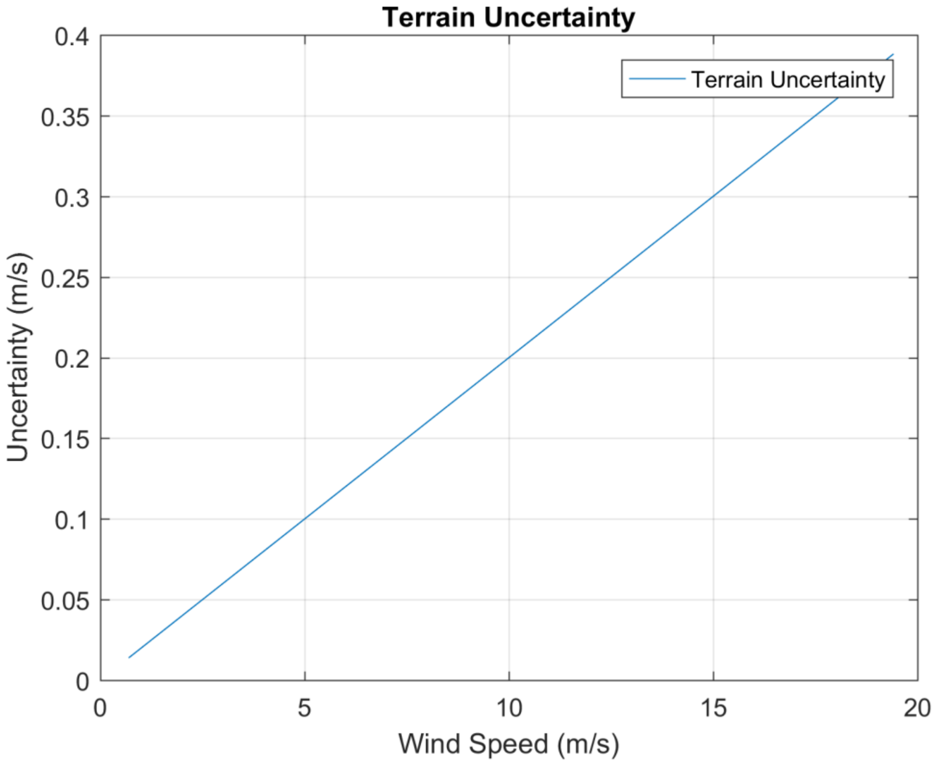


Figure 48: Terrain Uncertainty (Off.2.A)

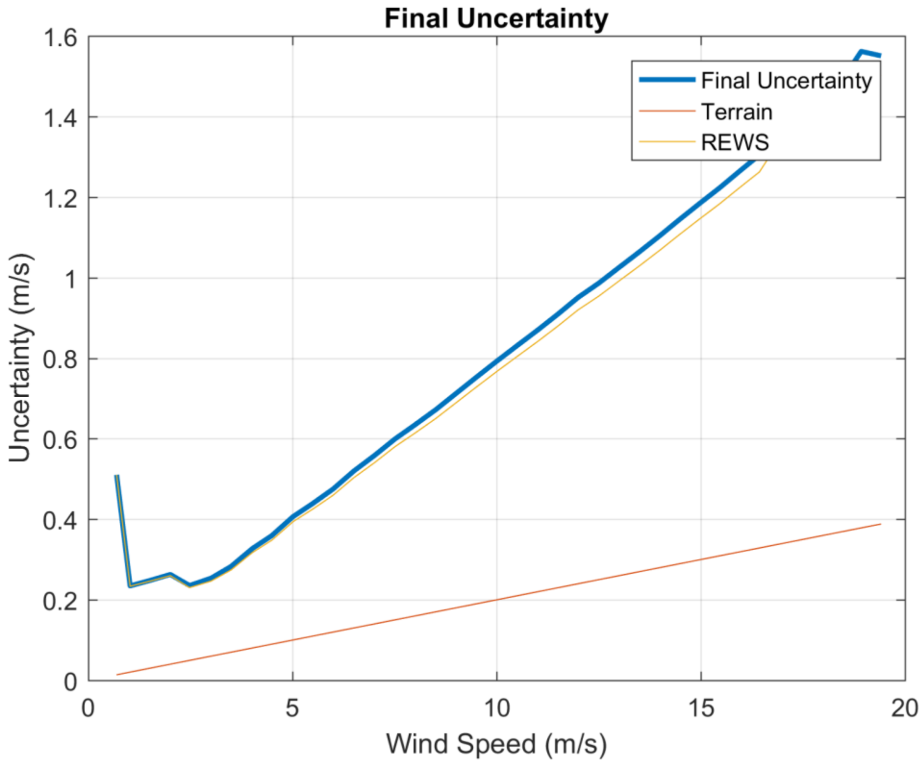


Figure 49: Final Uncertainty and Components (Off.2.A)

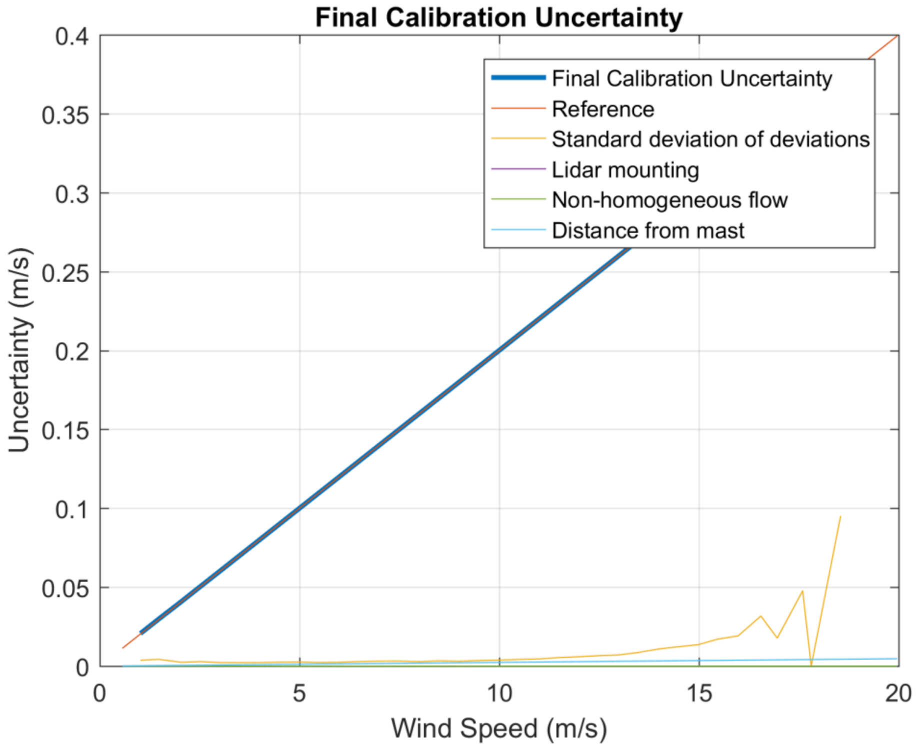


Figure 50: Calibration Uncertainty and Components (Off.2.B). Note that mounting and non-homogenous flow uncertainties are here assumed to be zero.

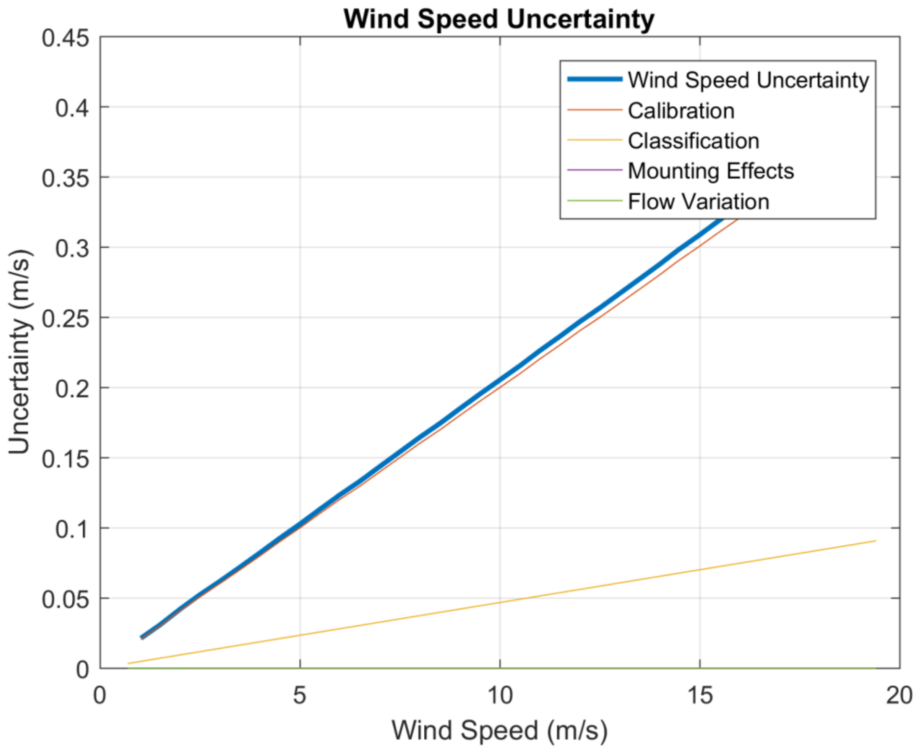


Figure 51: Wind Speed Uncertainty and Components (Off.2.B). Note that mounting and non-homogenous flow uncertainties are here assumed to be zero.

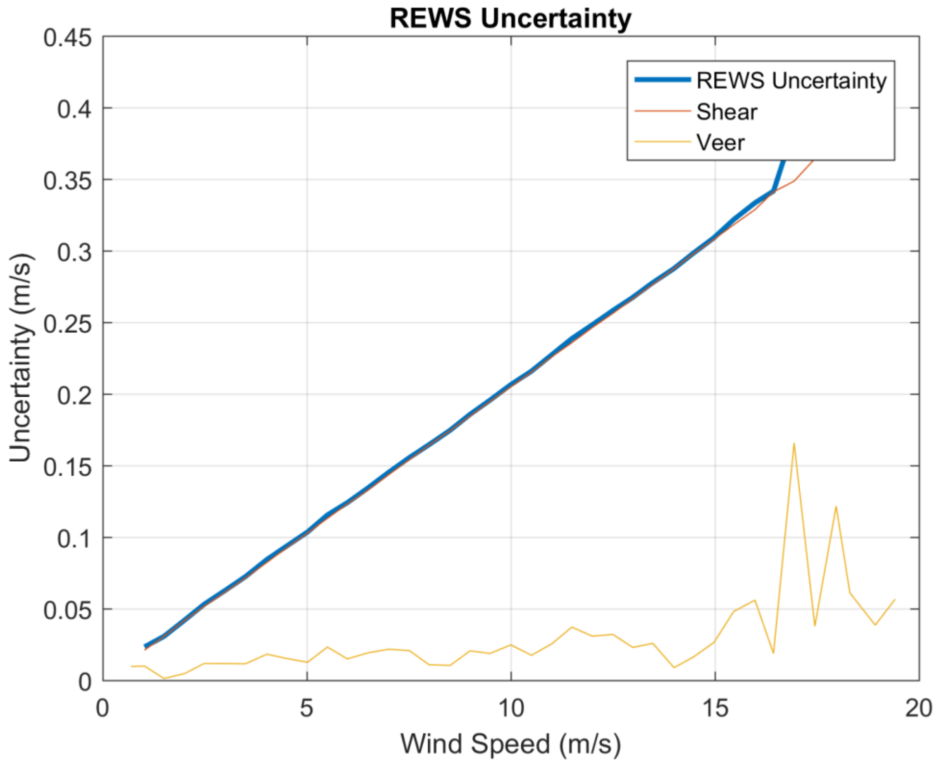


Figure 52: REWS Uncertainty and Components (Off.2.B)

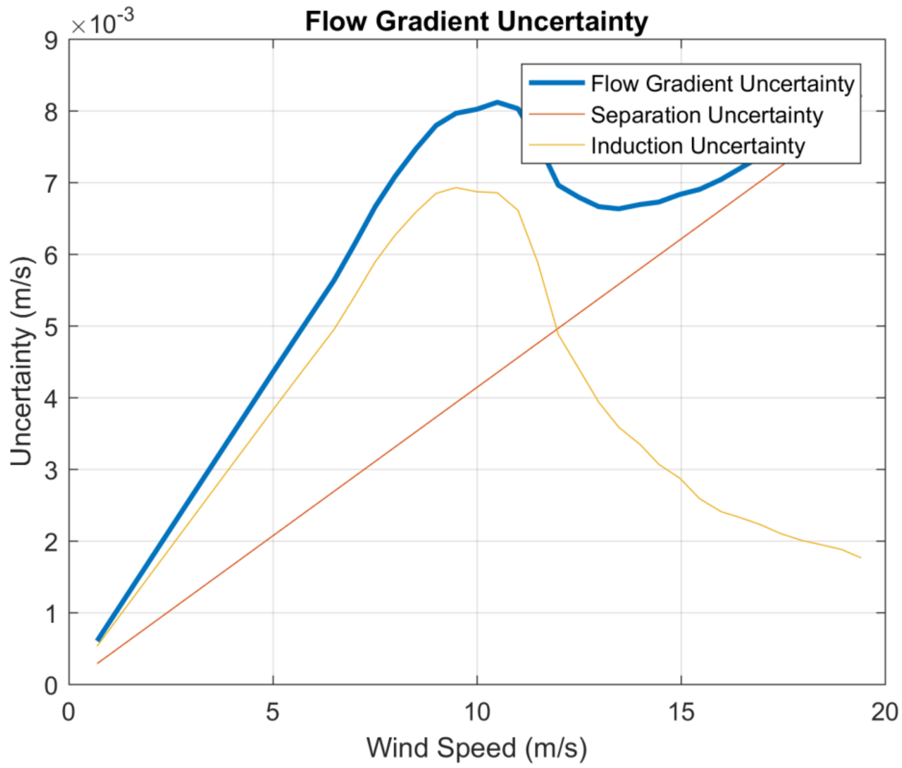


Figure 53: Flow Gradient Uncertainty and Components (Off.2.B)

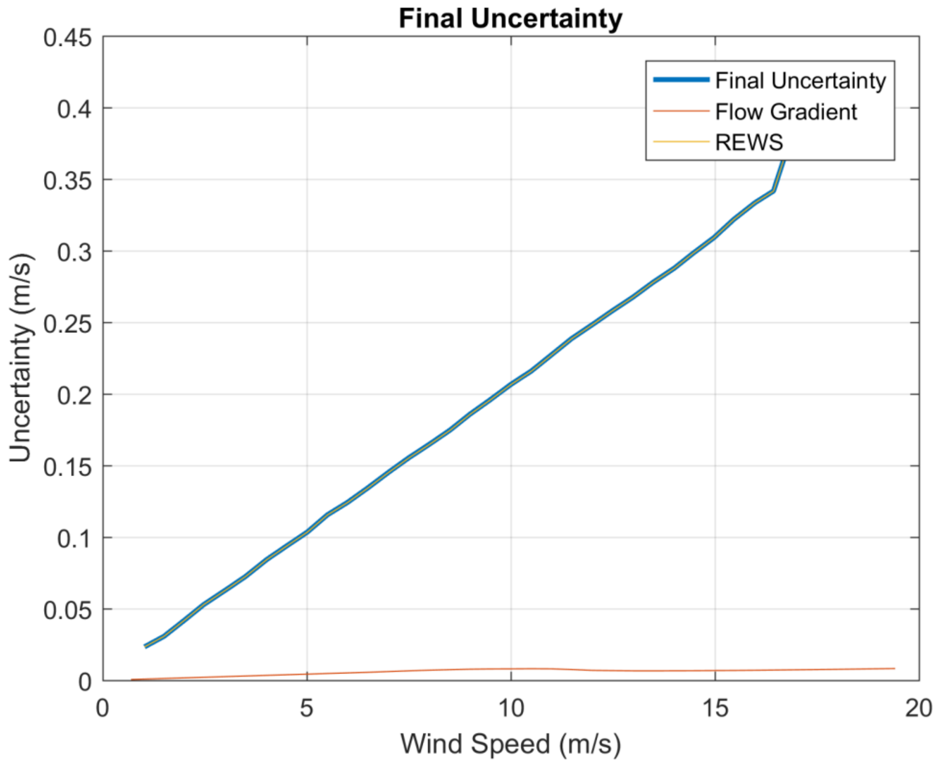


Figure 54: Final Uncertainty and Components (Off.2.B)

6. CONCLUSIONS

A review of the IEC 61400-12-1 standard has been carried out with respect to wind speed uncertainty methodology, particularly when using lidars, and with associated calculations to explore many of the pertinent issues. Clearly the recent revision to the standard which admits the use of lidars represents a significant step forward. This review has highlighted a number of areas where further progress can be made, and these are here organised under the headings of Typographical Error Correction, Revised Methodology, Ambiguity, and Complexity. Lastly, the Impact of the current work is summarised,

6.1 TYPOGRAPHICAL ERROR CORRECTION

Three instances of what appear to be straightforward typographical errors have been discovered in our copy of the standard, see reference 2.

6.1.1 Classification uncertainty and anemometer class number

On inspection, there is a typographical error in the standard for the expression used to convert an anemometer class number into an uncertainty value, see equation I.4 of reference 2: there is a square root of 3 term which appears as a multiplication factor rather than a division factor as it should be. As a consequence, the classification uncertainty is a factor of 3 too high. In the example calculation made in this study, this has an impact on the overall uncertainty being approximately 0.8% too high, see section 5.1. We recommend that users of the standard are aware of this and apply the correct expression; also, that in the next version of the standard that this is corrected.

6.1.2 Expression for AEP uncertainty

There is also a typographical error in the expression for aggregating wind speed uncertainties into an AEP uncertainty, which is equation E.8 in the standard (reference 2); the end of this expression is clearly missing a close bracket and exponent 2 which is evident by inspection. It is very unlikely that any user of the standard will apply the wrong expression without noticing this and correcting it. We recommend that users of the standard are aware of this to avoid losing time; also, that in the next version of the standard that this is corrected.

6.1.3 Expression for sensitivity factor between heights in REWS uncertainty due to veer

There is also a typographical error in the expression for the sensitivity factor between heights for the effect of veer error propagation when calculating REWS, see equation E.51 in the standard (reference 2). The left hand side of this equation should be a partial derivative with respect to wind direction, not with respect to wind speed as currently written. As the right hand side of this equation is as intended, the use of the standard wouldn’t make a calculation error as a result, however the user may be confused by the expression. We recommend that users of the standard are aware of this to avoid losing time; also, that in the next version of the standard that this is corrected.

6.2 REVISED METHODOLOGY

A number of methodology revisions have been suggested, see section 4 and the conclusions to each are discussed here in turn. The focus of the current work has been power performance assessments; the conclusions below apply equally to wind resource assessment (WRA) applications, with the exception of those relating to flow gradients, see section 6.2.3. In a WRA context, uncertainty due to flow gradients is equally applicable during calibration (when considering the effect of separation distance between the lidar being calibrated and the trusted reference), but naturally the flow gradients across the site during power performance, including induction effects, do not arise.

6.2.1 Lidar Calibration Uncertainty

An alternative approach to estimating lidar calibration uncertainty is proposed, see section 4.1. This approach is also applicable to FLS calibration uncertainty. In the representative calculation for FLS calibration uncertainty, see section 5.5, the revised approach reduced the calibration uncertainty by 2.5%. This project has not performed a similar calculation for onshore/fixed lidar calibration, but the authors would also expect a reduction in calibration uncertainty in that case, although the magnitude remains to be seen. We recommend that this revised methodology is applied when evaluating lidar or FLS calibration uncertainty. Furthermore, as a future research activity, we recommend that the impact of this for lidar and FLS applications is further explored with additional calculations.

6.2.2 Classification Uncertainty

The estimation of classification uncertainty has been reviewed, as described in section 4.2. There it is recommended that in preference to the far easier approach of basing classification uncertainty on a class number that the approach also allowed in the standard of directly measuring the environmental variables of significance in the final application is followed. In the representative calculation for FLS classification uncertainty, see section 5.5, the revised approach reduced the classification uncertainty by approximately 5%. This project has not performed a similar calculation for onshore/fixed lidar calibration, but the authors would also expect a reduction in classification uncertainty in that case. It is important to keep in mind that should the environmental conditions experienced during calibration match those in the final application, then the classification uncertainty can reduce to zero. We recommend that this revised methodology is applied when evaluating lidar or FLS classification uncertainty. It is recognised that this will necessitate release of low-level environmental variable sensitivity information by the organisations performing lidar classifications; it is the authors' understanding that there is no reason why this cannot be accomplished.

The above recommendation mainly describes how best to work with the existing standard. Furthermore, as future research activities, it is also recommended that the classification procedure should be further reviewed, especially with respect to correcting for systematic effects, and appropriate significance thresholds. It is also noted that EVs of potential significance for FLS application are listed in the recommended practice for FLS document, see reference 10.

The current drafting of the standard with respect to classification uncertainty has some problems in terms of ambiguity and complexity. The ambiguity arises from the overall drafting being difficult to follow, with many choices having to be made therein (e.g. which of three routes to follow to evaluate the classification uncertainty, how to deal with errors and sensitivities originating from the reference sensors, and how to resolve correlated EVs); and the complexity of the full calculations is such that they are difficult to reproduce reliably. As summarised in sections 6.3 and 6.4 below, the standard has similar issues in other areas and a re-drafting exercise and attempt to make the calculations more repeatable is recommended.

6.2.3 Distance from Mast Uncertainty / Uncertainty Due To Terrain Complexity / Variation in Flow Across Site Uncertainty

An alternative approach to estimating the uncertainty associated with flow gradients across either the calibration or the final application site, including the relationship with separation distance, has been proposed. These are explained in sections 4.3, 4.4, and 4.6. For the onshore calculations performed in this project, this has resulted in a reduction in the associated uncertainty (for power curve applications) of approximately 0.6%, see sections 5.1, 5.2 and 5.3.

For the offshore calculations performed in this project, the associated uncertainty for calibration of an FLS has been reduced by nearly 4% (see section 5.5) and for power curve applications by 1.7% or more, see sections 5.4 and 5.5. We recommend that this revised methodology is applied when evaluating mast/cup anemometer, lidar or FLS uncertainty. It is also recommended that the drafting of the standard is improved to simplify and clarify the terms used to refer to and explain uncertainties due to flow gradient as a number of phrases are used in different places which ultimately refer to the same issue. Furthermore, as a future research activity, we recommend that the impact of the presence of turbines on the surrounding wind flow is further studied to develop a trustworthy model that can be applied as a wind speed correction, in all directions; this can be seen as a development of the current methodology where a model for the deceleration directly upwind is used as the basis for estimating an uncertainty.

6.2.4 Uncertainty Due to Mounting

Section 4.5 makes the case for neglecting uncertainty due to mounting, for both lidar and FLS applications. The value indicated in the standard is small in any case so the impact of this change is small. We recommend that this revised methodology is applied when evaluating lidar or FLS calibration uncertainty.

6.2.5 Flow Variation Within Control Volume

Section 4.7 makes the case for neglecting uncertainty due to flow variation within a control volume for offshore, coastal and flat onshore applications. The values indicated in the standard suggest a range of 2% to 3% so the impact is appreciable. We recommend that this revised methodology is applied when evaluating uncertainties using lidar data.

6.2.6 Simultaneous Use of RSD and Anemometer

The standard allows for RSD data to be used only in combination with mast data. In section 4.8 it is proposed that lidar data can be used on their own as the primary source of wind measurements. We recommend that they are used as such, and that the drafting of the standard is updated to reflect this.

6.2.7 Shear and Veer Uncertainty

The topic of how shear and veer measurements, or more properly the lack of a sufficient number of shear and veer measurements, gives rise to REWS uncertainty and method uncertainty in the standard has been reviewed in this project. This is the most difficult part of the standard to follow; it is not at all clear which route to follow, and the development of the various equations used is neither evident nor well referenced in many cases. For the time being, we recommend that the user of the standard uses the “flowchart” figures in this document as an aid to planning their own implementation of the standard. Furthermore, it is strongly recommended that these sections of the standard are revised and updated for improved clarity. Lastly, if we assume that the rather complex methodology therein will be retained, it must be recommended that tools are developed or other means put in place to support accuracy and repeatability of individual calculations.

6.3 AMBIGUITY

The standard as currently drafted is difficult to follow, and in many places the user has to rely on their own judgement as to how to implement the standard, or which parts to implement. A number of such areas have been highlighted in the Revised Methodology section above: classification uncertainty (6.2.2), uncertainties related to flow gradient (6.2.3), shear and veer uncertainty (6.2.7). Moreover, the standard would be improved with better signposting and visual representations of the various calculation routes, akin to the “flowchart” approach taken for the calculations in this report, see for example Figure 1. It is our recommendation that the next revision of the standard addresses these issues and removes ambiguity as a result.

6.4 COMPLEXITY

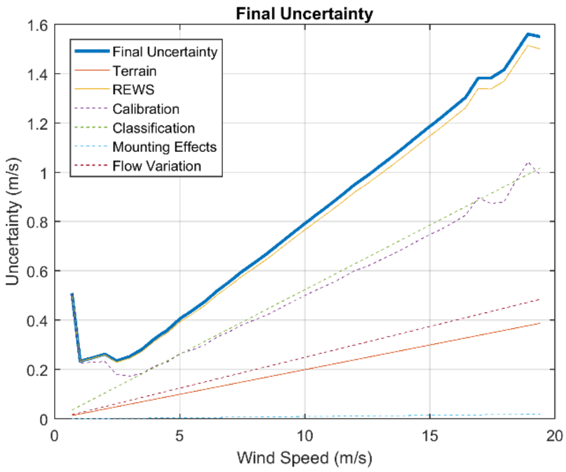
During the course of this project the project team has carried out a number of calculations. In most cases these have been carried out by two different individuals in parallel, and it has been our experience that it is very difficult to ensure consistency. Even when setting aside ambiguity issues, it is our conclusion that it is unrealistic to expect repeatable calculations due to the level of complexity entailed in the standard. Two such areas have been highlighted in the Revised Methodology section above: classification uncertainty (6.2.2) and shear and veer uncertainty (6.2.7). It is our recommendation that during the development of the next revision of the standard an attempt to address the complexity challenge is made; it is likely that improvements can be made to reduce the complexity in the methodology should the authors acknowledge reduced complexity as a goal. If this is not sufficient in itself, we recommend that common tools are developed to support accuracy and repeatability of individual calculations. At the time of writing it is not clear how this can be accomplished as we do not expect that the IEC committee responsible for the standard would see development of supporting tools as part of their remit; it is possible that IEA Wind or some other industry body would be motivated to undertake such an initiative.

6.5 IMPACT

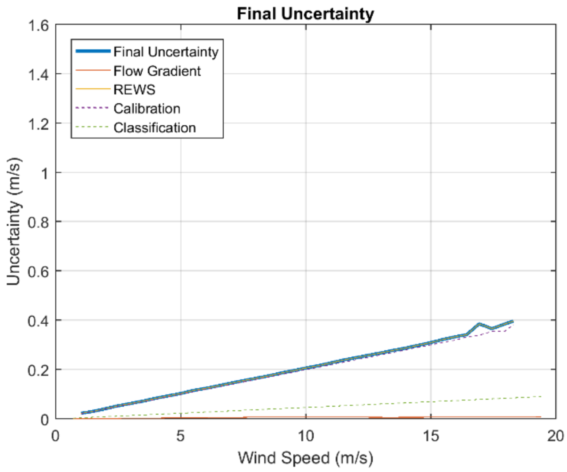
Figure 55 below attempts to summarise the impact of the current study, which can be usefully arranged in the following main points:

1. For an indicative use case, where a floating LIDAR data set is employed for a power performance study, the overall wind speed uncertainty has been reduced from approximately 8% to approximately 2%.
2. The so-called Method uncertainty was not included in that particular case, but specific recommendations have been made to improve and clarify the treatment of Method uncertainty in the standard.
3. A significant contributor to this reduction is the uncertainty resulting from Flow Gradients due to Terrain: this has been reduced, due to a revised methodology, from a value of approximately 2% to a very small value for this far-offshore case. This is applicable to power performance scenarios, but not to WRA scenarios.
4. The measured wind speed uncertainty (and hence REWS uncertainty) has been significantly reduced through reductions to a number of components.
5. One such reduction is to the Calibration uncertainty, which has been reduced from around 5% to around 2% through a revised methodology.

6. Another reduction is in Classification uncertainty, from around 5% to around 0.5%, which has been achieved through a careful evaluation, consistent with the standard, which avoids the catch-all ‘class number’ approach.
7. Uncertainties due to lidar mounting and flow variation within the lidar’s control volume are considered negligible, which also reduces the measured wind speed uncertainty.
8. Most of these revised interpretations and/or methodologies are considered to be not particularly controversial, and therefore it is the authors’ expectation that they will be adopted in the industry, and that conservatively reductions of at least 4% in wind resource uncertainty are achievable on real projects.
9. A number of other suggestions have been made to realise further improvements.



Off.2.A



Off.2.B

Figure 55: Combined Uncertainties for Floating Lidar Example Calculation. These figures summarise the following example calculations:

- Left: Off.2.A, following the standard as closely as possible, see Figure 45 to Figure 49;
- Right: Off.2.B, revised methodology, see Figure 50 to Figure 54.

7. REFERENCES

1. “Reducing Lidar Uncertainty – Project Recommendations”, M Courtney, D Stein, S Webb. FNC 52885/45692R Issue 1, 30-Mar-2017.

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8. “Offshore Compression zone measurement and visualisation”, M. Asimakopoulos, P. Clive, G. More, R. Boddington.

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10. IEA Wind, Expert Group Report On Recommended Practices, 18. Floating Lidar Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

ANNEX A - WEIGHT UNCERTAINTY EXAMPLE

Measurement bias can only be corrected for if the causes of the systematic error are known. To give an example from a more everyday situation – if you were to try and calibrate a set of scales using a traceably calibrated 1.000kg mass correct to 0.001kg, you would be able to write down the factors which may generate errors in your measurement (differences in temperature, air pressure, humidity, levelness of the scales etc) and fix them such that they are known (i.e. remove the random element), or correct for the systematic components (e.g. apply a constant to correct for changes in air buoyancy). You then place the 1kg mass outside for 3 days and then immediately bring it back to the scales and calibrate them, recording the difference in measurements as error (1.030kg). You now have a number of uncontrolled random error sources (changed temperature and humidity of the mass, oxidation of the mass etc) even though you believe you have controlled all of the variables where your scales are located. You continue to take measurements until such time as the scales read 1.000kg. In this instance, it is likely that the errors observed in the scales are actually more to do with the reference mass changing but can only be regarded as part of the random error of the scales (because their systematic effects cannot be quantified). This presents the difficult situation that you have a total error spread of 0.030kg recorded on your scales likely only due to errors in the reference. This error cannot be corrected for in the scales as cannot be proven to be systematic, but is not truly an uncertainty because it is an error due to the reference. One approach would be to record this only as an uncertainty of the reference (1kg +/- 0.03kg) and import it into the total uncertainty budget. The consequence of this is that you cannot calibrate the scales with any precision lower than 0.03kg. Therefore if we, in a final step, try and calibrate a 1kg mass using our scales, we still import the 0.03kg uncertainty from the initial calibration of the scales and any measurement below 0.03kg (such as 1.0001kg) cannot be faithfully recorded as the offset exists within the stated uncertainty of the reference measurement system.

ANNEX B - SPEED ERROR FOR A TILTED GROUND-BASED LIDAR

B.1 INTRODUCTION

A simple model is presented of a ground-based lidar measuring wind speed in a plane (one horizontal and one vertical wind speed component) and then introducing a small tilting error. Our purpose is to determine the magnitude of the resulting error on the horizontal wind speed. This will be used to assign an appropriate ‘mounting’ uncertainty to lidars of this type.

B.2 NON-TILTED MODEL

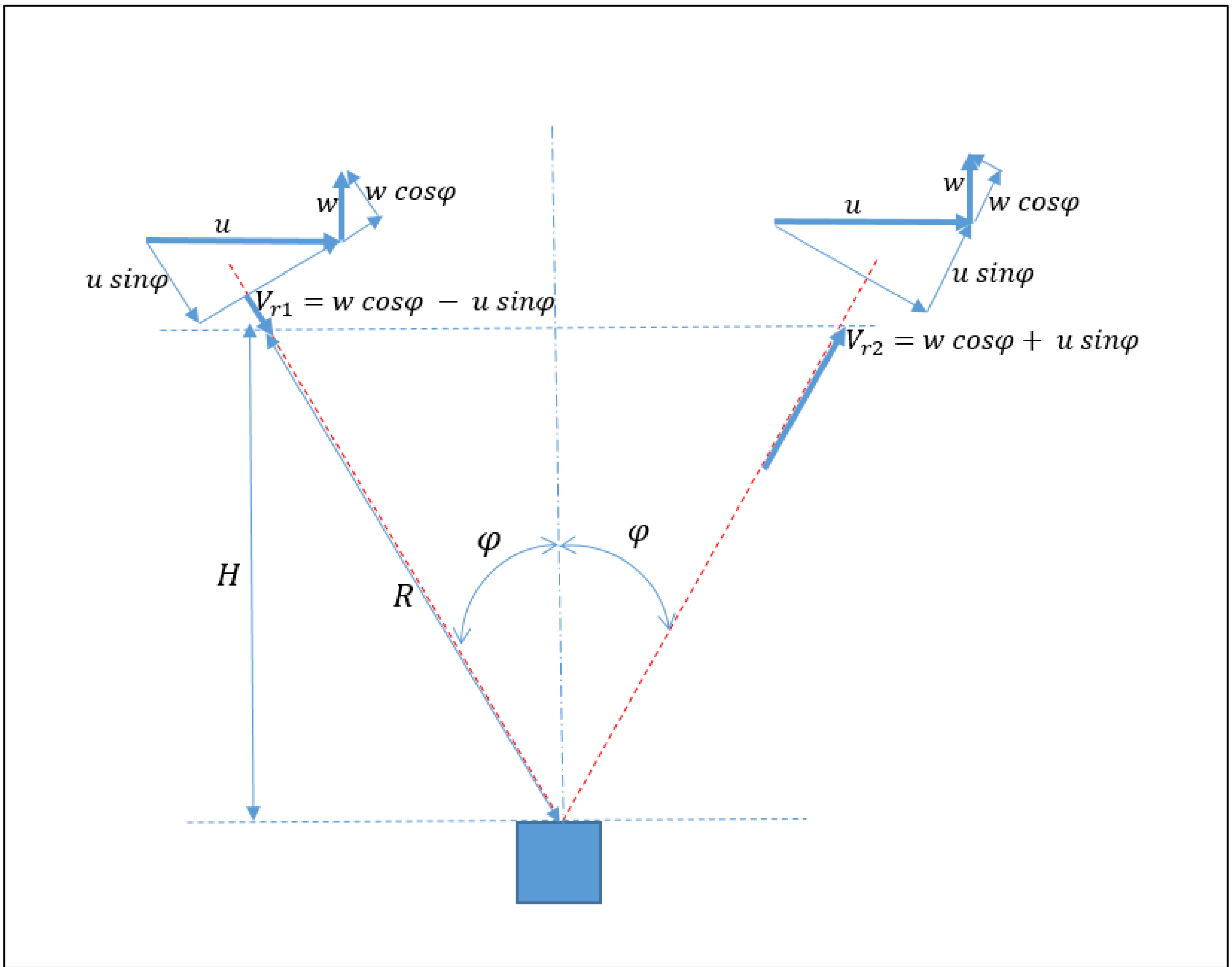

Figure B1: Geometry and radial wind speed components for the un-tilted model.

Our un-tilted model is shown in Figure B1. This corresponds to the standard reconstruction of one of the two horizontal wind speed components in a Doppler Beam Swinging lidar such as the Leosphere Windcube. The necessary assumption is that the wind speed components sensed by the left beam (here denoted 1) are the same as those sensed by the right beam (beam 2). As shown in the figure, the corresponding radial wind speed components V_{r1} and V_{r2} can be readily seen to be

$$V_{r1} = w \cos\varphi - u \sin\varphi \tag{B1}$$

and

$$V_{r2} = w \cos\varphi + u \sin\varphi \tag{B2}$$

where u is the horizontal wind speed component, w is the vertical component and φ is the half-opening angle of the lidar beams. Radial wind speeds are here defined as positive away from the lidar.

Subtracting the two radial speeds from each other gives a solution for u -

$$u = \frac{(V_{r2} - V_{r1})}{2\sin\varphi} \tag{B3}$$

Adding the two radial speeds gives a solution for w –

$$w = \frac{(V_{r2} + V_{r1})}{2\cos\varphi} \tag{B4}$$

B.3 MODEL WITH LIDAR TILTING

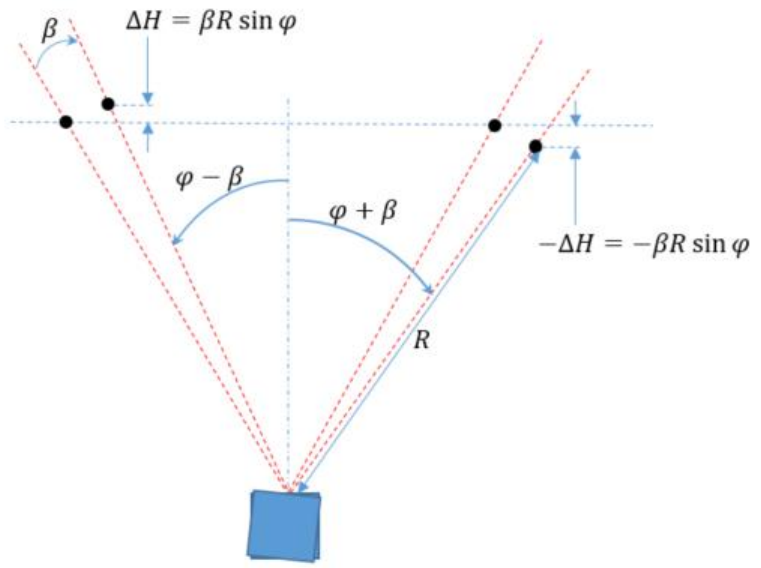

Figure B2: Tilted lidar model.

We now introduce a small tilting of the lidar with angle β as shown in Figure B2. The tilting has two effects. Firstly the heights at which the beam is sensed (actually the centre of the range gate) is lifted on the left and reduced on the right. For a measurement at range R, ΔH is simply

$$\pm\Delta H = \pm\beta R \sin\varphi \tag{B5}$$

To account for the changed sensed horizontal wind speed, we will introduce a locally linearized wind speed gradient G given by

$$G = \frac{1}{u}\frac{du}{dH} \tag{B6}$$

The sensed horizontal wind speeds on left and right u_1 and u_2 will be

$$u_1 = u(1 + \Delta HG) = u(1 + \beta RG \sin\varphi) = uK_1 \qquad \text{(B7)}$$

and

$$u_2 = u(1 - \Delta HG) = u(1 - \beta RG \sin\varphi) = uK_2 \qquad \text{(B8)}$$

The second effect of the lidar tilting is that the elevation angles of the beams are altered; reduced by β on the left and increased by β on the right. Where previously the radial speeds were given by equations 1 and 2, the tilt affected radial speeds V'_{r1} and V'_{r2} are now

$$V'_{r1} = w\cos(\varphi - \beta) - uK_1 \sin(\varphi - \beta) \qquad \text{(B9)}$$

and

$$V'_{r2} = w\cos(\varphi + \beta) + uK_2 \sin(\varphi + \beta) \qquad \text{(B10)}$$

B.4 ERROR WITH PURELY HORIZONTAL FLOW

We will proceed by examining the case where there is no vertical component (e.g. offshore). The difference of the radial speeds (required for equation 3) becomes

$$V'_{r2} - V'_{r1} = u(K_2 \sin(\varphi + \beta) + K_1 \sin(\varphi - \beta))$$

$$= u\{K_2 (\sin\varphi\cos\beta + \sin\beta\cos\varphi) + K_1(\sin\varphi\cos\beta - \sin\beta\cos\varphi)\} \qquad \text{(B11)}$$

Rearranging (B11) we get

$$V'_{r2} - V'_{r1} = u\{(K_2 + K_1)\cos\beta\sin\varphi + (K_2 - K_1)\sin\beta\cos\varphi\} \qquad \text{(B12)}$$

Noting that $(K_1 + K_2) = 2$ and $(K_2 - K_1) = -2\sin\beta\, RG\sin\varphi$, substituting in (B12) and dividing through by $2\sin\varphi$ we find that the horizontal speed resolved from the tilted lidar u' will be

$$u' = \frac{(V'_{r2} - V'_{r1})}{2\sin\varphi} = u\{\cos\beta - GR\cos\varphi\sin^2\beta\} \qquad \text{(B13)}$$

For a power law profile with exponent α we have $G = \frac{\alpha}{H}$ and noting that $R\cos\varphi = H$, equation (B13) simplifies to

$$u' = u\{\cos\beta - \alpha\sin^2\beta\} \qquad \text{(B14)}$$

For small tilting angles ($\cos\beta = 1 - \frac{\beta^2}{2}$ and $\sin\beta = \beta$), the relative error $\Delta u_t/u$ introduced by the tilting is

$$\frac{\Delta u_t}{u} = -\beta^2(½ + \alpha) \qquad \text{(B15)}$$

Interesting things about this result:

- Doesn't depend on height or opening angle or sign of the tilting
- It's just a cosine response (equation B14) plus a small shear effect

- Is quadratic and therefore always negative – any tilting will give a negative bias (relevant for floating lidar)
- Its pretty small for typical ‘mounting’ errors. At 1^0 and alpha=0.14 it is only 0.02%
- Most of the error is due to the changing angles, not the shear.

B.5 ERROR WITH PURELY VERTICAL FLOW

Here we calculate the error in the horizontal speed due to the component of vertical speed w. Our assumption is that the vertical speed does not change with height. From (9) and (10) we can see that the difference in the radial speeds is now

$$\begin{aligned} V'_{r2} - V'_{r1} &= w\{\cos(\varphi+\beta) - \cos(\varphi-\beta)\} \\ &= -2w \sin\varphi \sin\beta \end{aligned} \qquad \text{(B16)}$$

Dividing through by $2\sin\varphi$ (in accordance with (B3)) gives the erroneous component of horizontal wind speed $u_w{}'$ that is due to the response of the tilted lidar to the vertical wind speed component

$$u'_w = -w\sin\beta \qquad \text{(B17)}$$

This is simply a sine response to the vertical wind speed component.

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