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A Methodology Review of Uncertainty Estimation in Wind Resource and Power Performance Assessments when using LIDARs

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Offshore Wind R&D 2018, Bremerhaven

Carbon Trust has been working with government and industry to accelerate offshore wind for >10 years

The Offshore Wind Accelerator (OWA)

€100m+ Total programme spend	**60%** Industry funded
9 Leading developers	**10 yrs** Established 2008

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Contents

Background and objectives

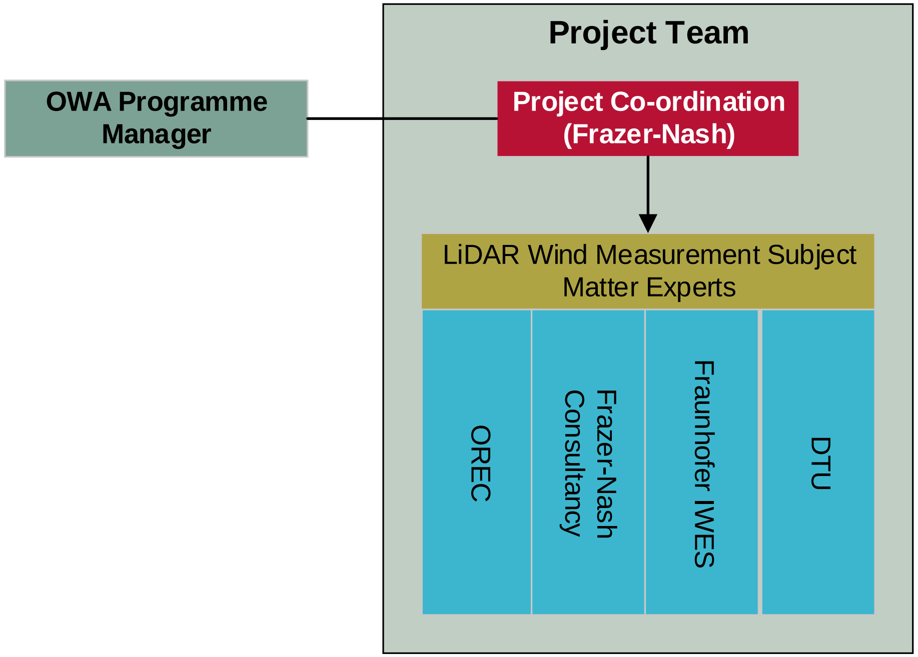
- Improvements required in the uncertainty assessment procedure for using wind LIDARs.

- Confirmed in workshop discussions on 26 January 2017 (as part of the preceding project ‘OWA LiDAR Uncertainty Reduction’) - consensus that existing IEC standard drafting of an uncertainty procedure (for power curve assessment using LiDARs) had a less than ideal basis in 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.

- Uncertainty reduction will (a) encourage use of LIDAR technology and (b) reduce quantified risk in business cases – both leading to lower cost of energy from offshore wind.

Team Structure



- Excellent working relationships and practices already established from our work on the IEA Annex 32 and subsequent OWA projects.

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Approach

- The review of the IEC 61400-12-1:2017 standard was broken into specific work packages as follows:

	Work package	Notes
1	Identify two use cases	Onshore (‘IEA Round Robin’) Offshore (FINO1 + Fraunhofer FLS)
2	Review uncertainty methodology	**This presentation.**
3	Undertake uncertainty calculations.	Webinar - 25 June 2018 Webinar. See also supporting slides.
4	Identification of improvements to uncertainty calculations.	Webinar - 25 June 2018 Webinar. See also supporting slides.
5	Dissemination.	Webinar - 25 June 2018 Webinar. **This presentation.**

- See also full report – expect to be published November 2018

Summary of revised methodology

Item	Uncertainty	Revision or Advice
1	Lidar Calibration	Revised calibration uncertainty expression
2	Classification	This project: don’t use the class number approach; use more detailed environmental variable sensitivity information (for both onshore Lidar application and FLS application). Future work: overhaul classification process altogether
3	Distance from mast & terrain complexity	Abandon (i) typical uncertainties for terrain effects of 1-3%, and (ii) calibration separation distance rule of thumb. Replace with (a) credible flow gradient values and (b) uncertainty due to induction.
4	Lidar mounting	Replace 0.1% or 0.5% which appears to be recommended in standard with advice on how to avoid such an error - then assume zero (substantiated with trigonometric argument).
5	Flow variation within control volume	2% to 3% is recommended. Replace this with zero as it appears to be unfounded, especially offshore (and anyway it is captured by “upflow” environmental variable in classification uncertainty).
6	Simultaneous use of Lidar and mast	Mandated in standard – we are happy to allow Lidar only.

Item 1: Lidar Calibration Uncertainty

Reference sensor

Standard uncertainty of measurements

Standard deviation of deviations (not included for power curve applications – could interpret as included in WRA)

Mean deviation

Original :

$$u_{\mathrm{cal}}{}^{2} = u_{\mathrm{ref}}{}^{2} + \frac{\sigma_{\mathrm{lidar}}{}^{2}}{N} + \sigma_{\mathrm{dev}}{}^{2} + \Delta v^{2}$$

Revised :

$$u_{\mathrm{cal}}{}^{2} = u_{\mathrm{ref}}{}^{2} + \frac{\sigma_{\mathrm{dev}}{}^{2}}{N} \qquad \text{for } \Delta v < u_{ref}$$

Item 2: Lidar Classification Uncertainty

- **Current advice**
  - Evaluate significant environmental variables (EVs) and their sensitivity.
  - Note average EV values during verification test.
  - During final application you have a choice:
    1. Measure EVs, multiply sensitivities by difference in EV values during application and verification.
    2. Estimate EVs, otherwise as 1.
    3. Embody uncertainty in a single Class Number – intended to envelope worst cases.

- **What is wrong with this**
  - If we know sensitivities, shouldn't we correct for them?
  - Some sensitivities more likely to be attributable to reference (e.g. temperature and cups).
  - Route 3 provides an uncertainty that is far higher (for FLS, probably for LIDARs too).

- **Revised Methodology**
  - For now, apply Route 1. Remember that if the application EVs match the verification EVs, the classification uncertainty is zero.
  - Full review of classification methodology recommended.

Item 3: Distance from mast and terrain complexity uncertainties

- **Current advice**
  - Calibration: "An additional uncertainty in the wind speed of 1% times the separation distance divided by the measurement height shall be applied".
  - Terrain complexity / power curves: 1% to 2% for offshore sites

- **What is wrong with this**
  - Calibration:
    - Intended for onshore not offshore calibrations.
    - Typical FLS application results in 5% uncertainty – too high.
    - No justification for 1% value or height divisor.
  - Terrain complexity / power curves:
    - Values not justified

- **Revised Methodology**
  - Use uncertainty based on knowledge of site or typical flow gradients (4%/km onshore; 0.5%/km coastal; 0.05%/km offshore).
  - For power curve uncertainty, add uncertainty term due to induction model.

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Impact on Uncertainty Components

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Uncertainty Component	Clarification (C) or Alternative Approach (A)	Associated Standard Uncertainty					
		Indicative from Standard	Calculated from standard approach		Calculated from recommended approach	
			Onshore	Offshore	Onshore	Offshore
1. Calibration	A	2 to 3%	N/A	5%	N/A	2%
2. Classification	A	1 to 1.5%	N/A	5%	N/A	0.4%
3. Distance from Mast*	A	5% [1]	N/A	3.5%	N/A	0.02%
3. Terrain Complexity	A	1-2% offshore, 2-3% onshore	2%	2%	1.4%	0.3%
4. Mounting	A	0.1%	0.1%	0.1%	zero	zero
5. Variation in Flow Across Site	C	See 'Distance from Mast Uncertainty' and 'Uncertainty due to Terrain Complexity'				
6. Flow variation within control volume*	A	2 to 3%	2.5%	2.5%	zero	zero

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

* Sub-components of calibration uncertainty

Summary – Floating Lidar System Use Case

Scenario	Data	Approach	Indicative Wind Speed Standard Uncertainty (%)	Indicative AEP Standard Uncertainty (%), Average WS = 7 m/s	Indicative AEP Standard Uncertainty (%), Average WS = 10 m/s
Offshore	FLS	Standard	8.0	12.7	6.8
Offshore	FLS	Revised	2.1	3.3	1.8

Note that only Category B wind speed and method uncertainties have been applied to estimate the AEP uncertainty

Impact – Floating Lidar System Use Case

1. Overall wind speed uncertainty reduced from ~8% to ~2%.
2. Recommendations made to improve and clarify Method uncertainty.
3. Flow Gradients due to Terrain uncertainty reduced from ~2% to a very small value for this far-offshore case. (Applicable to power performance scenarios)
4. Measured wind speed (thus REWS) uncertainty has been significantly reduced through reductions to a number of components.
5. One such reduction is to Calibration uncertainty, from ~5% to ~2%.
6. Another reduction is in Classification uncertainty, from ~5% to ~0.5%.
7. Most of these revised interpretations and/or methodologies are not particularly controversial, and **conservatively reductions of at least 4% in wind resource uncertainty are achievable on real projects.**
8. A number of other suggestions have been made to realise further improvements.

Summary of conclusions

- **Revised Methodology**
  - Valuable reductions in uncertainty demonstrated and justified for the following components: calibration, classification, flow gradient/terrain; flow variation in control volume; mounting.
  - These should be applied to Lidar as well as FLS applications.
- **Revision of Standard IEC 61400-12-1 ?**
  - Results have been fed back to IEC committee: typographical errors, suggested clarifications, revised methodology, further recommendations.
  - We might expect some of the less intrusive elements to appear in a revision fairly quickly.
  - In the meantime, we are recommending that the results of the present work are applied to real projects.

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Additional Slides

Supporting slides providing more detail on calculations performed follow

Summary of calculations

Data Set (On=onshore Off=offshore)	Calculation	Version	Index	Description
On	1	A	1.1.A	Verbatim application of standard, including obvious errors, using met mast data only.
On	1	B	1.1.B	Verbatim application of standard, correcting obvious errors, using met mast data only.
On	1	C	1.1.C	Modified application of standard, correcting obvious errors, using met mast data only.
On	2	A	1.2.A	Application of the standard as far as possible (with obvious errors corrected), using met mast and LIDAR data.
On	2	B	1.2.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.
On	3	A	1.3.A	Application of the standard as far as possible (with obvious errors corrected), using LIDAR data only.
On	3	B	1.3.B	Application of the standard as far as possible (with obvious errors corrected), using LIDAR data only. Use revised methodology.
Off	1	A	2.1.A	Verbatim application of standard, correcting obvious errors, using met mast data only.
Off	1	B	2.1.B	Modified application of standard, correcting obvious errors, using met mast data only.
Off	2	A	2.2.A	Application of the standard as far as possible (with obvious errors corrected), using floating LIDAR data only.
Off	2	B	2.2.B	Application of the standard as far as possible (with obvious errors corrected), using floating LIDAR data only. Use revised methodology.

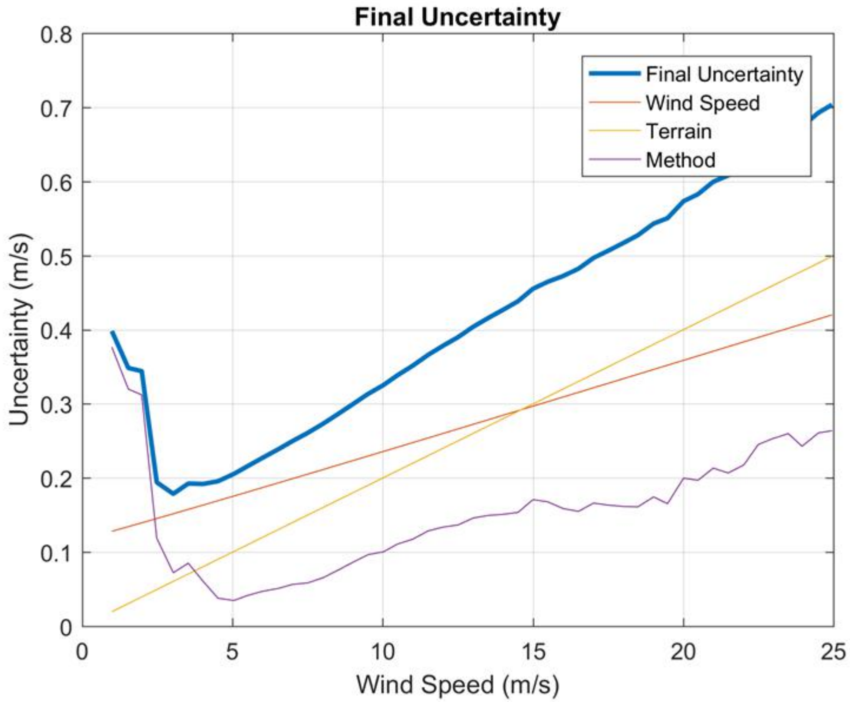
On.1 – Onshore, Mast Data Only

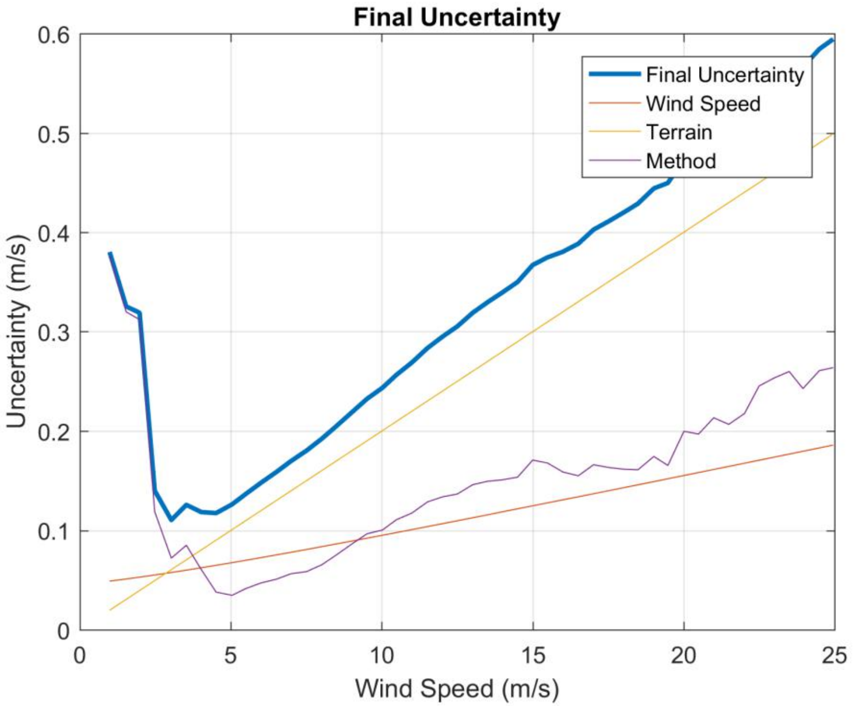
Values at V=10m/s, which are indicative

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 0.2%		
> 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)	N/A		
Rotor Equivalent Wind Speed	N/A		
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1		New approach 1.4%
Method – wind conditions			
> Shear	See E.11.2.2.2. The lower tip height anemome ~1% 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 ~0.2% rotor disc.		

<u>Combined wind speed uncertainties:</u> <u>~3.2%</u> → <u>~2.4%</u> → <u>~2.0%</u>

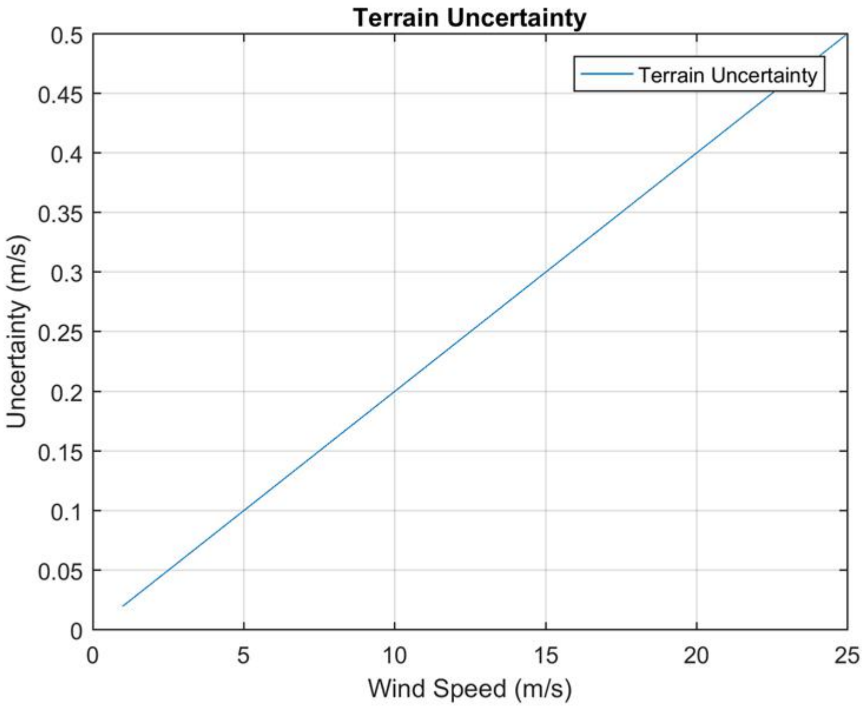
On.1.A vs On.1.B – Effect of Classification Uncertainty Error

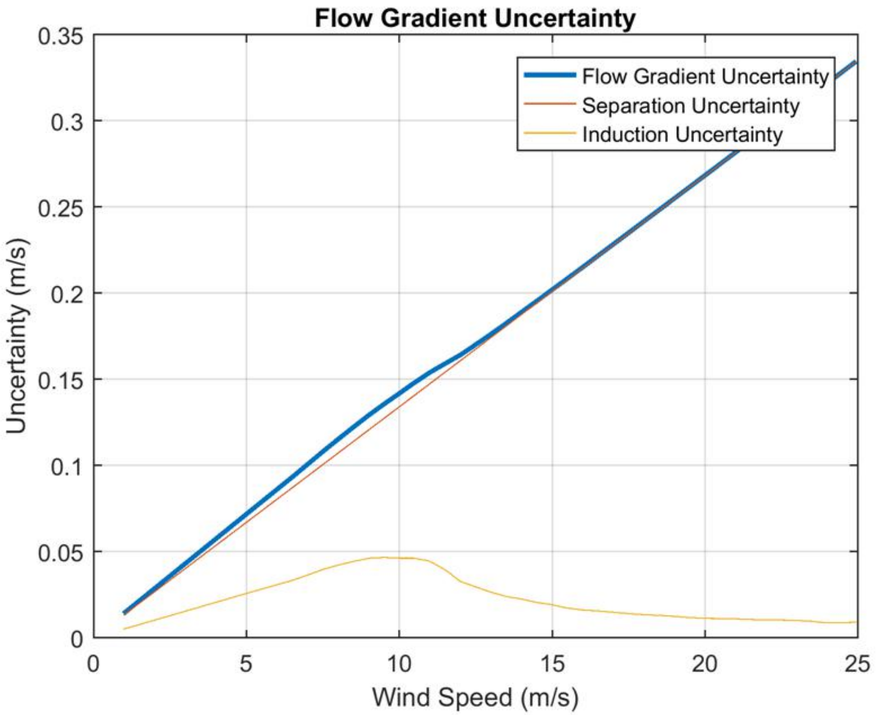




Correcting for the typographical error (in using the anemometer class number) reduces the classification error by a factor of 3.
This in turn reduces the measured wind speed uncertainty and hence the final uncertainty.

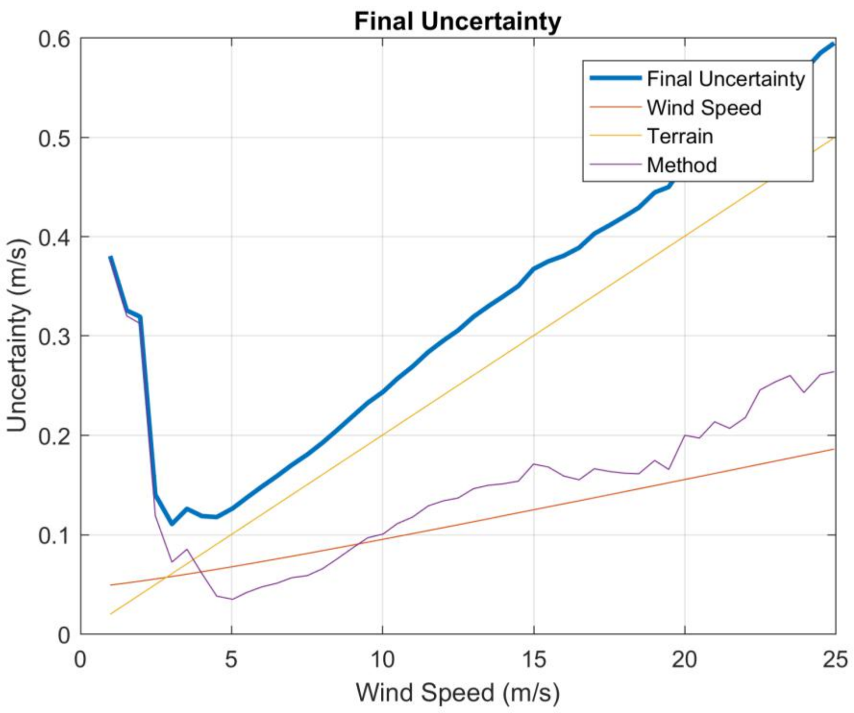
On.1.B vs On.1.C – Effect of 'Terrain Uncertainty'

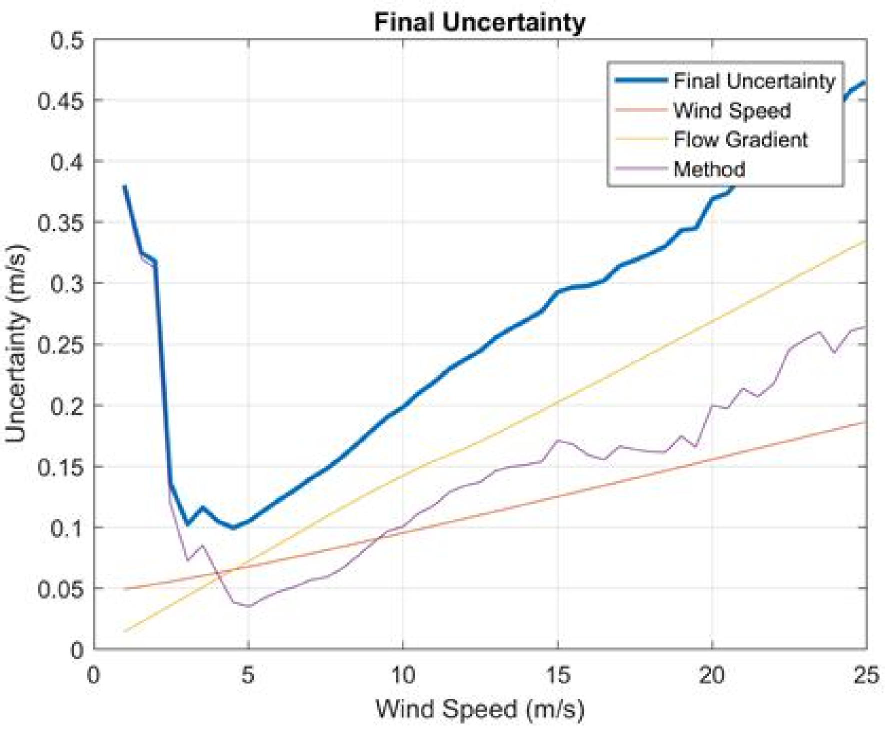




Assuming a typical flow gradient of 4%/km rather than applying a fixed 2% uncertainty has some benefit. (This is much more pronounced for offshore cases where the 0.05%/km may be assumed.)

On.1.B vs On.1.C – Effect of 'Terrain Uncertainty'





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On.2 – Onshore, Mast Data supplemented by Lidar Data

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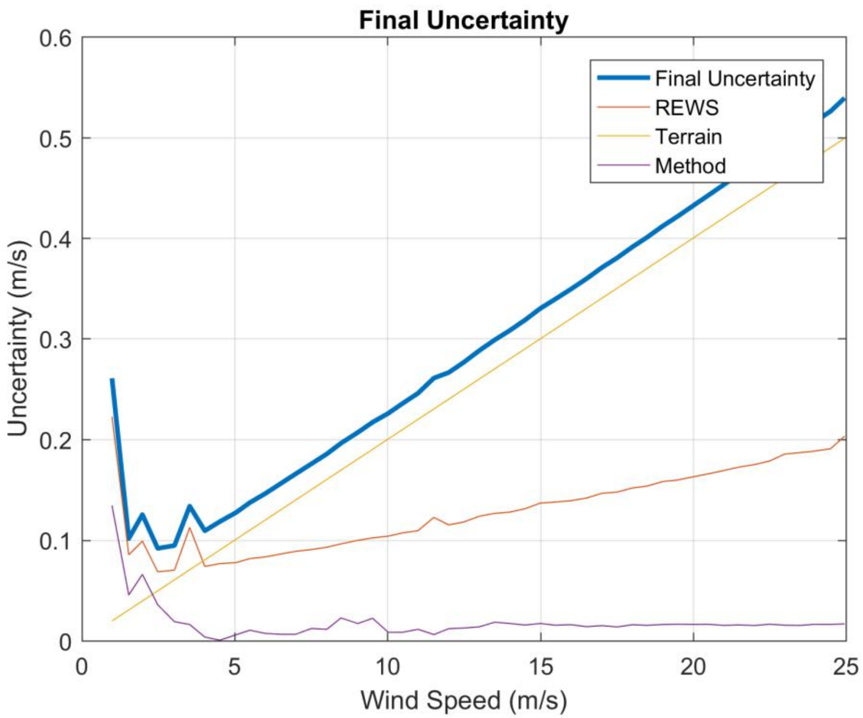
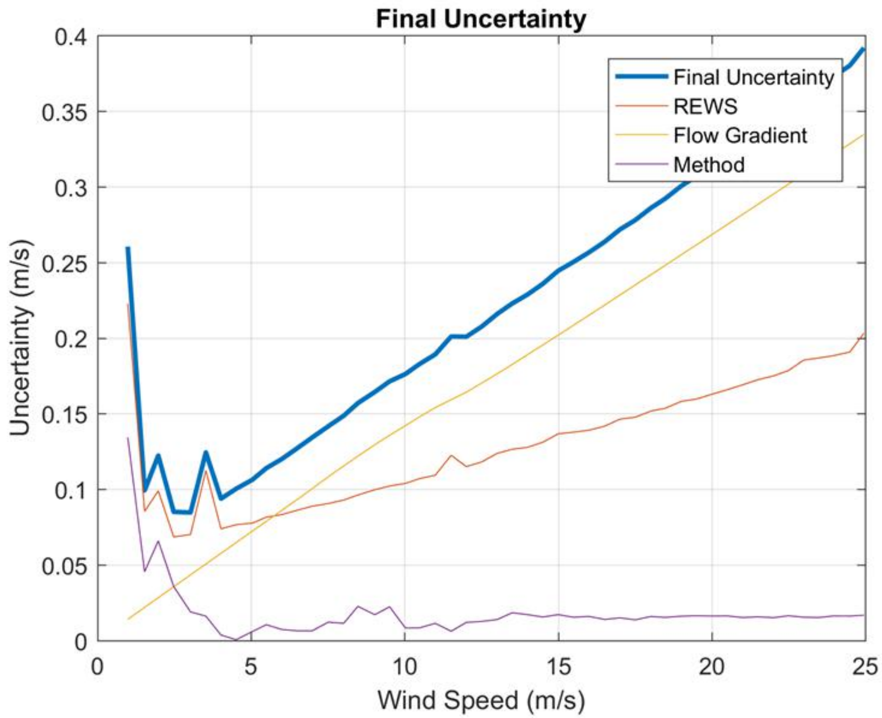
Wind Speed Uncertainty Category	On.2.A	On.2.B
Wind Speed (Cup or Sonic)	As 1.1B 0.9%	
Wind Speed (RSD)	3.5%	2.1%
> Calibration	From RSD calibration certificate, see E.7.2 2%	
> In-situ check	Zero	
> Classification	Take typical value of 1.25% from Table E.2.	Assume zero
> Mounting	Take typical value of 0.1% from Table E.2.	Assume zero
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2.	Assume zero
> Monitoring test	Zero.	
Rotor Equivalent Wind Speed	1%	
> Wind shear	Eqn E.44 (summing over Wind Speed (RSD) terms abo… provides uncertainty of the wind shear correction factor. Then us… 1%	
> Wind veer	Calculate using eqn E.50 and E.51 . Used correlation c… 0.5 in all cases. < 0.2%	
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1	New approach 1.4%
Method – wind conditions	0.1%	
> Shear	See E.11.2.2.2. RSD measurements over the full disc height were used.	
> Veer	See E.11.2.2.3. RSD measurements over the full disc height were used.	

~2.3% → ~1.7%

On.2.A vs On.2.B – Effect of 'Terrain Uncertainty'





Although the RSD wind speed uncertainty is significantly reduced, this has no impact on the REWS (or final) uncertainty as the conventional wind speed uncertainty dominates (in this case).
The reduction in final uncertainty is again down to the terrain/flow gradient uncertainty .

On.3 – Onshore, Lidar Data Only

Wind Speed Uncertainty Category	On.3.A	On.3.B
Wind Speed (Cup or Sonic)	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
> Mounting	Take typical value of 0.1% from Table E.2.	Assume zero
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2.	Assume zero
> Monitoring test	Zero.	
Rotor Equivalent Wind Speed	3.5%	2.1%
> Wind shear	Eqn E.38 assuming (a) uncertainty components are n[illegible] 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 1.4%
Method – wind conditions	0.1%	
> Shear	See E.11.2.2.2. RSD measurements over the full disc height were used.	
> Veer	See E.11.2.2.3. RSD measurements over the full disc height were used.	

~4% → ~2.5%

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On.3.A vs On.3.B – Reduced RSD Uncertainty

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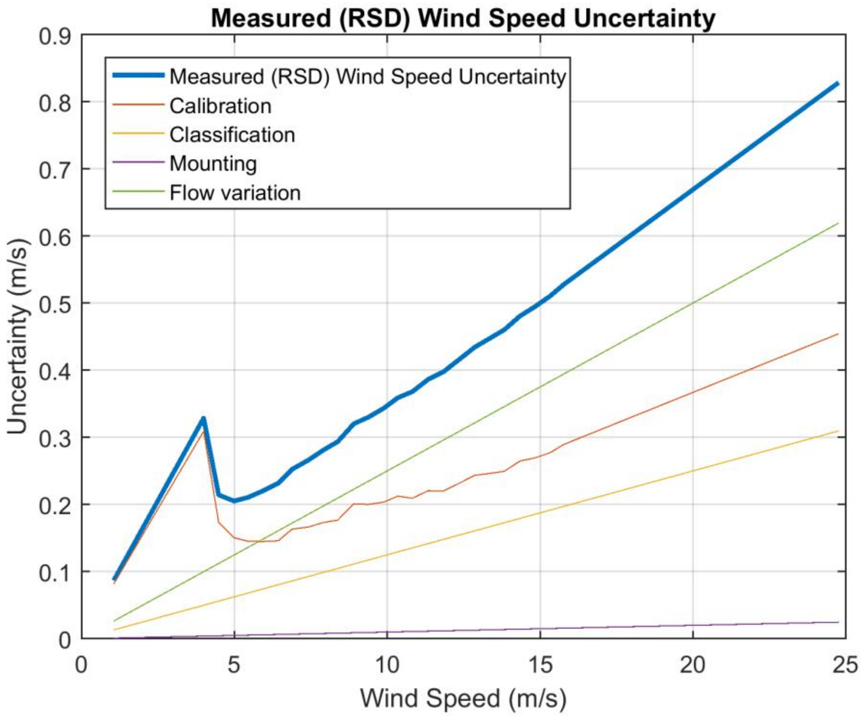
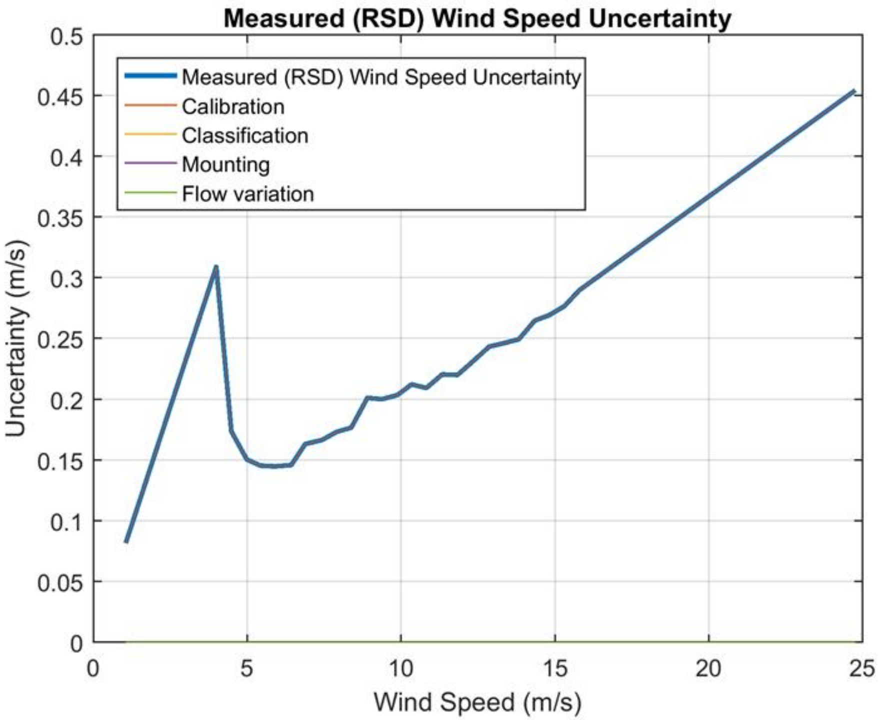
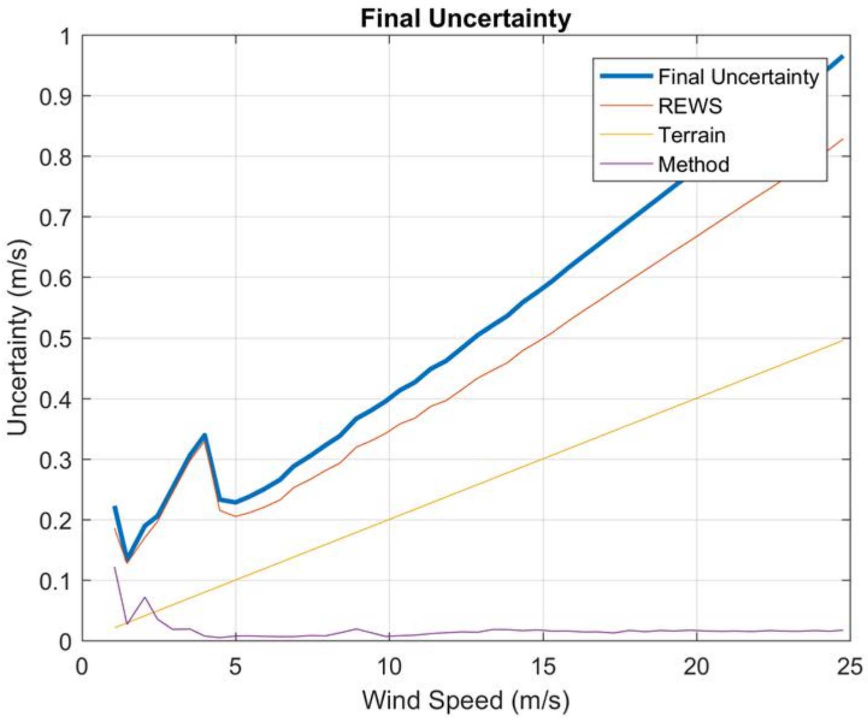
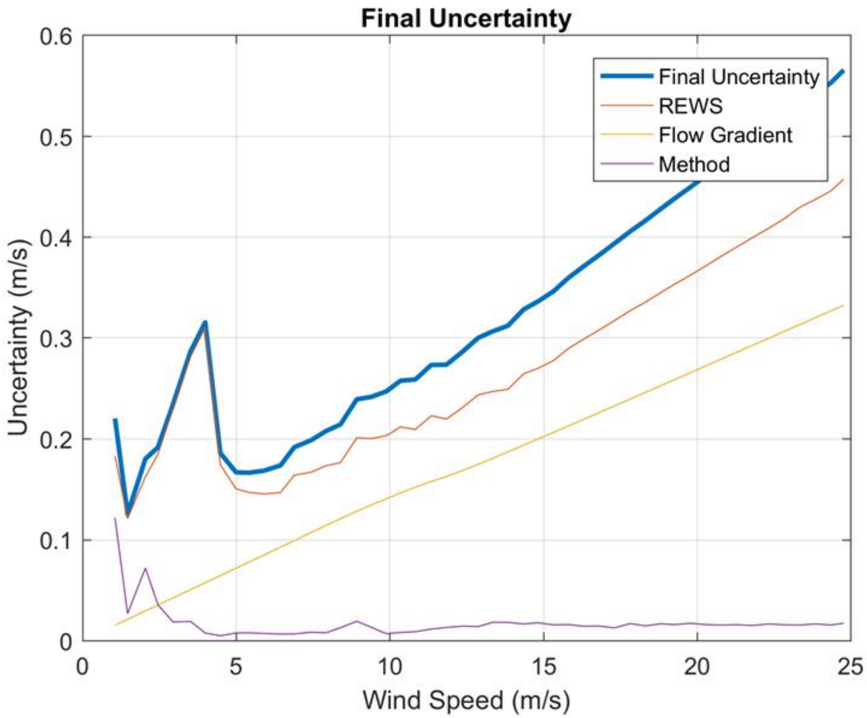




Flow variation within control volume and mounting uncertainties are assumed negligible.
Have also assumed classification uncertainty is negligible - it really should be a small value.
Therefore the calibration uncertainty dominates.
(The lidar calibration uncertainty comes from the calibration certificate, and it may be possible to further reduce with revised procedure.)

On.3.A vs On.3.B – Effect on Final Uncertainty





In this case the reduced RSD wind speed uncertainty feeds through to reduced REWS and final uncertainty.

Off.1 – Offshore, Mast Data Only

Wind Speed Uncertainty Category	Off.1.A	Off.1.B
Wind Speed (Cup or Sonic)	Assume 2% uncertainty for met mast anemometers.	
Wind Speed (RSD)		
Wind speed – terrain effects	Use 2% as Table E.2 and E.9.1 0.7%	New approach 0.3%
Method – wind conditions		
> Shear	See E.11.2.2.2. The lower tip height anemometer values were used, and a shear exponent es… for the top half of the rotor disc. 0.4%	
> Veer	E.11.2.2.3. The lower tip height wind vane values were used, and from this the veer estimate… entire rotor disc. 0.5%	

<u>~2.9%</u> → <u>~2.1%</u>

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Off.2 – Offshore, FLS Data Only

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Wind Speed Uncertainty Category	Off.2.A	Off.2.B
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 ~5.0%	Apply modified method for calibration. Assume 2% uncertainty for reference sensor. Also apply revised separation distance uncertainty. 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 p[illegible] 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
> Flow variation in different probe volumes at same height	Take typical value of 2.5% from Table E.2.	Assume zero.
> 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	New approach 0.1%
Method – wind conditions	Not included here	

<u>~8%</u> → <u>~2.1%</u>

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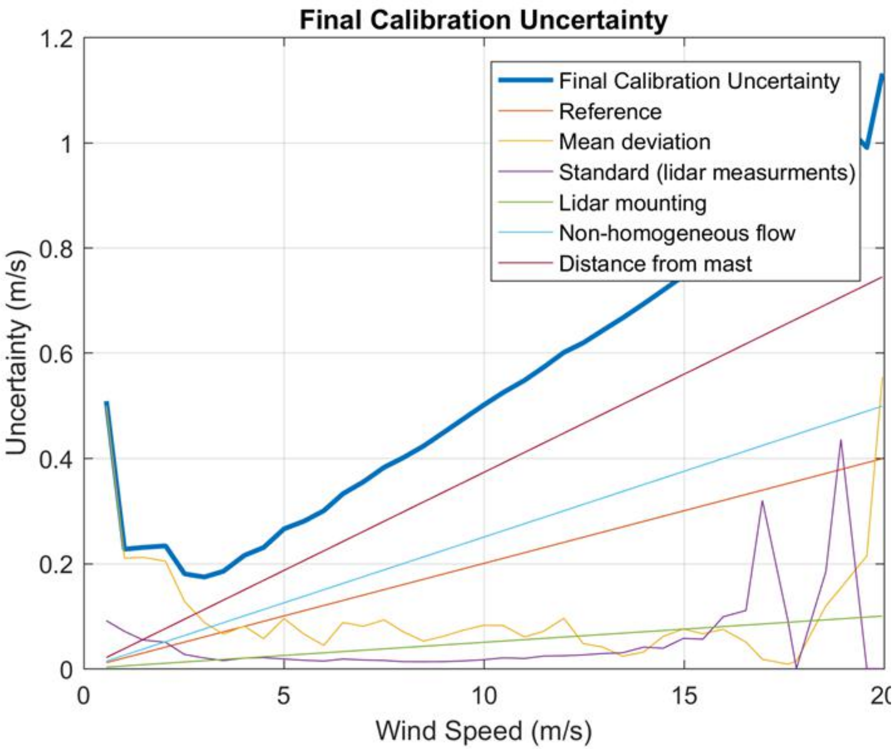
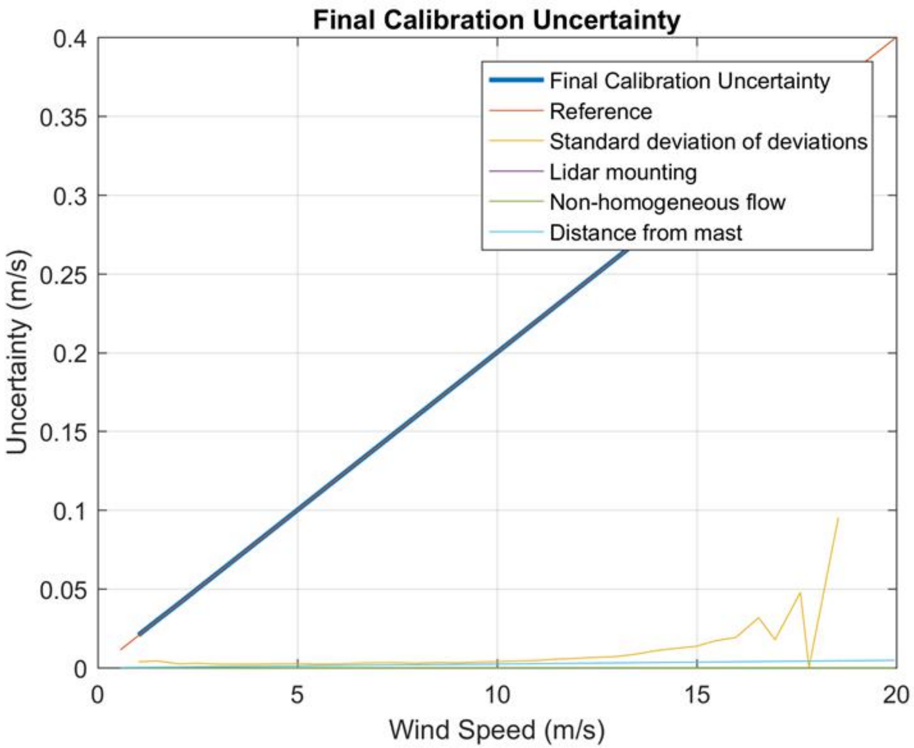
Off.2.A vs Off.2.B – Effect on Lidar Calibration Uncertainty





The expression for evaluating calibration uncertainty has been revised, and has some impact. However, the major uncertainty reductions come from (1) revised treatment of assumed flow gradient / distance from mast (2) neglecting the non-homogenous flow uncertainty.

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Off.2.A vs Off.2.B – Effect on Calibration Uncertainty

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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**

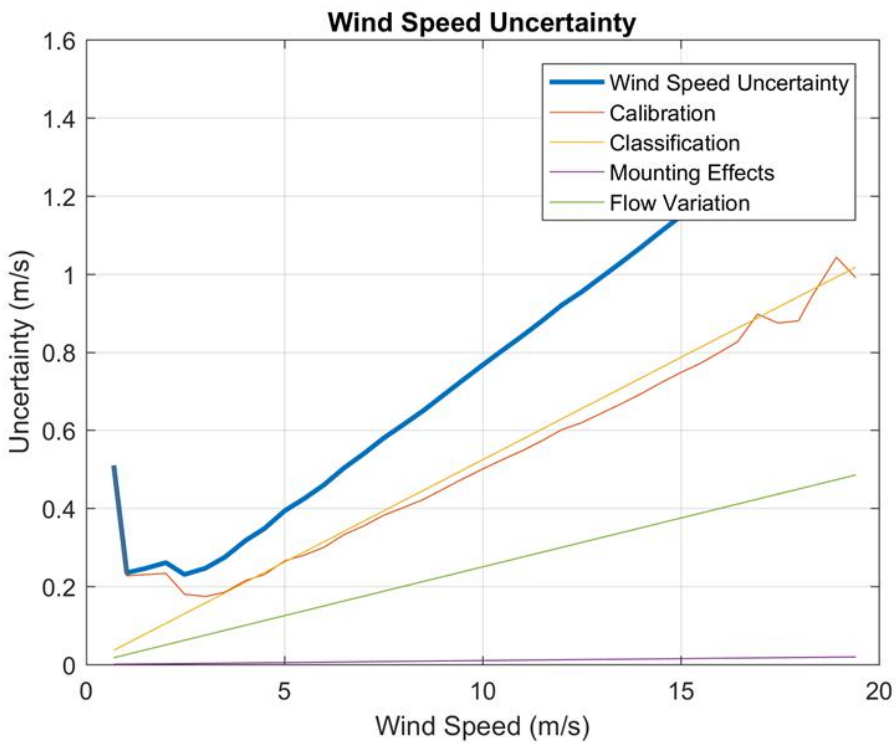
Sector = [275.5,...,350] degrees

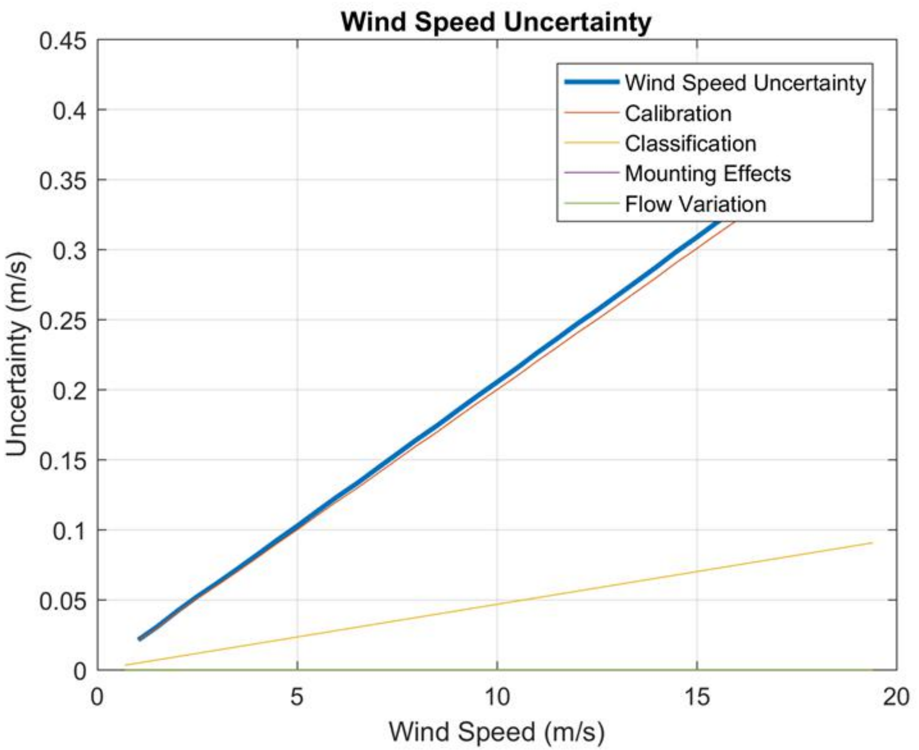
Mean	Mean difference
unit	unit
5.1384	-0.3838
8.2385	0.1595
0.0140	-0.0151
0.0697	0.0045

Classification uncertainty (%): **0.42**

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

Off.2.A vs Off.2.B – Effect on Lidar Wind Speed Uncertainty





The revised methodology allows significant reductions in all of the largest components.

Off.2.A vs Off.2.B – Effect on Final Uncertainty