Ground-based remote sensor uncertainty – a case study for a wind lidar

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Summary

A lidar of type Windcube V2 has been tested according to the new draft of the power curve measurement standard CD IEC 61400-12-1, Ed. 2 at the two test stations Rysum in Germany and Hovsore in Denmark. The test scheme includes a type specific sensitivity test aiming to examine the generic accuracy of the lidar under a wide range of environmental conditions. In this test, deviations of the lidar wind speed measurements from reference cup anemometer measurements are correlated to atmospheric conditions, finally resulting in an instrument classification. Clear and consistent trends for the influence of some important environmental variables on the accuracy of the lidar measurements have been observed at the two test sites, while some outlier results have led to partly inconsistent accuracy classes.
Furthermore, the test scheme includes a verification test aiming to trace back the individual lidar unit to national standards. The results of the verification tests were consistent at the two test sites. The full procedure for assessing uncertainties of lidar measurements according to CD IEC 61400-12-1, Ed. 2 has been tested by considering the measurements at Rysum as the required test of the lidar and the measurements at Hovsore as an application of the lidar (power curve test) and vice versa. Consistent total uncertainties in the order of 2 % to 3 % in wind speed were gained for these two examples, which are considered being typical for an application of the Windcube V2 in flat terrain.

1 Introduction

Currently, a major revision of the IEC61400-12-1 power curve standard is underway [1]. A significant feature of this revision is the likely inclusion of ground-based remote sensors (lidars and sodars) as permissible instruments for the reference wind speed measurement. In this context, a rigorous uncertainty scheme for remote sensors has been proposed combining uncertainties from instrument classification, validation and site effects. This uncertainty scheme has been applied at the example of a lidar of type Windcube V2 as tested at the two test sites Rysum in Germany [2] and Hovsore in Denmark [3].

2 Test Sites

The same lidar unit has been tested against cup anemometer measurements at a 135 m high mast in Rysum and at a 116 m high mast in Hovsore in 2011. Both test sites are located in flat terrain and are especially equipped for testing of remote wind sensing devices like lidars and sodars. The lidar has been applied directly adjacent to the masts at both sites. Main characteristics of the tests are summarised in Table 1.

test site	**Rysum**	**Hovsore**
location	North Sea Coast, Germany	North Sea Coast, Denmark
type of terrain	flat	flat
mast height	135m	116m
testing body	WindGuard	DTU
test period	2011/01/13 - 2011/03/13	2011/06/10 - 2011/12/07
available data	2195 10-minute periods	5509 10-minute periods
reference heights	35m, 72m, 104m, 135m	40m, 60m, 80m, 100m, 116m
reference cup anemometers	Thies First Class	Risoe P2546
cup anemometer calibrations	acc. MEASNET by WindGuard	acc. MEASNET by WindGuard

Table 1: Main characteristics of test sites and test periods

3 Verification Test

The traceability of the measurements of remote sensing devices according to CD IEC 61400-12-1, Ed. 2 is reached by comparing the measurements of the remote sensing device (RSD) to traceably calibrated reference sensors on masts (verification test).
The comparison is based on 10-minute averages of the measurements in the wind speed range 4 to 16 m/s as measured by the reference anemometer. The analysis is focused on bin averaging the measurements of the RSD against the measurements of the reference sensor because the result of power curve tests is a bin averaged power curve. Also in case of applying a lidar for the

purpose of site assessment, bin averaged or classified results of the measurements, e.g. in form of a joint probability distribution of wind speeds and wind directions, are of main interest. The uncertainty of the measurements of an RSD attributed to the verification test is cumulated out of:

- the bin wise deviation of RSD and reference measurements,
- the uncertainty of the reference measurements,
- the statistical uncertainty of the test.

It is pointed out that by this procedure the accuracy of a RSD is automatically limited to the accuracy of the reference measurements at the verification test (e.g. cup anemometer measurements). Furthermore, no correction of the measurements of the RSD according to the verification test is foreseen in CD IEC 61400-12-1, Ed. 2.

Overall, quite similar results of the verification tests in Rysum and Hovsore have been gained for the tested lidar unit with a typical total standard uncertainty in the range 1 % to 3 % in terms of the horizontal wind speed component. Exemplary results are shown for 104 m measurement height in Rysum and 100 m measurement height in Hovesore in Figure 1 and Figure 2, respectively.

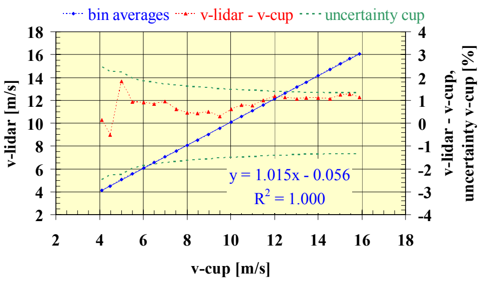

Figure 1: Result of verification test in terms of the horizontal wind speed component at Rysum at 104 m height

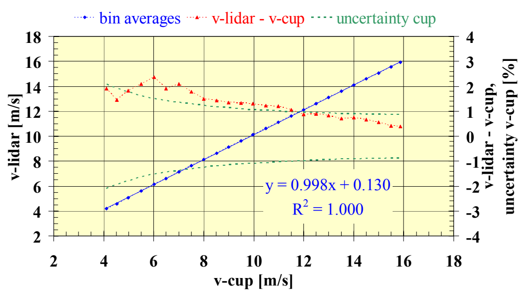

Figure 2: Result of verification test in terms of the horizontal wind speed component at Hovsore at 100 m height

4 Sensitivity Test and Classification

4.1 Sensitivity Analysis

Measurements of RSD's can be influenced by environmental conditions, like also measurements of cup anemometers. The verification test results are valid only for the environmental conditions present at the test. In analogue, cup anemometer calibrations in wind tunnels are valid only for the conditions present in the wind tunnel (e.g. low turbulence). This problem is addressed in CD IEC 61400-12-1, Ed. 2 by a type specific sensitivity analysis of the accuracy of the RSD.

As the verification test, the sensitivity test is based on the evaluation of 10-minute averages of the measurements in the wind speed range 4 to 16 m/s. The deviation of the measurements of the RSD and the reference measurements is considered as function of one environmental variable at a time. A linear regression is forced through the bin averages of the data, while special criteria for the completeness of bins and for the range covered by complete bins are applied. The regression slope is then a measure of the sensitivity of the measurements of the RSD on the considered environmental variable.

Exemplary results of the sensitivity analysis on wind shear are shown in Figure 3 and Figure 4 for 104 m measurement height at Rysum and 100 m measurement height at Hovsore, respectively. Regression slopes of all variables sufficiently covered by the tests are summarised in Table 2. The derived regression slopes are partly consistent among the two test sites and the different measurement heights and partly not.

It is pointed out that the criterion for the coverage of bins has been altered in this analysis compared to the criterion given in CD IEC 61400-12-1, Ed. 2. While CD IEC 61400-12-1, Ed. 2 requires the standard deviation of the raw data of a variable reaching 10 % of a pre-defined maximum range, here it has been required that the complete bins must cover 20 % of the maximum range. This criterion has been preferred because otherwise the wind shear would be excluded as variable sufficiently covered at Hovsore (almost excluded at Rysum), despite the fact that consistent results in terms of the shear sensitivity is reached in Hovsore and Rysum at least for some heights (outliers in terms of shear sensitivity

at 40 m at Hovsore and 72 m at Rysum may be due to mast effects).
Furthermore, the regression slopes in terms of air temperature difference at two heights and wind veer have been normalised to the same height range at the two test sites, resulting in sensitivity slopes for a temperature gradient and veer gradient.

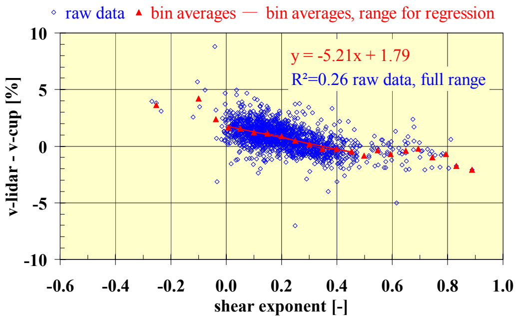

Figure 3: Sensitivity test on wind shear at 104 m height at Rysum. The regression is related to the range of bin averages covered by the line. The shown correlation coefficient is related to the raw data.

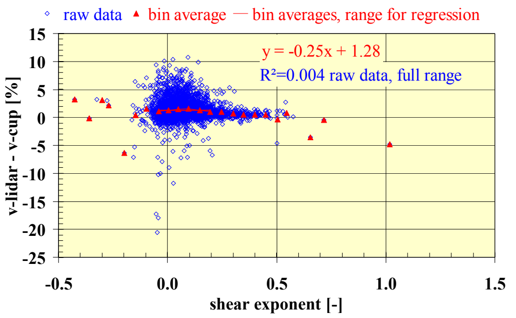

Figure 4: Sensitivity test on wind shear at 100 m height at Hovsore. The regression is related to the range of bin averages covered by the line. The shown correlation coefficient is related to the raw data.

height	wind shear	I	direction	T	T gradient	air density	wind veer	flow incl.
[m]	[%/unit var.]	[%/unit var.]	[%/unit var.]	[%/unit var.]	[%/unit var.]	[%/unit var.]	[%/unit var.]	[%/unit var.]
135	-3.720	0.188	-0.006	0.003	-0.291	11.420	-0.018	-0.053
116	-8.167	22.523	0.011	0.113	-0.823	-9.489	-0.596	
104	-5.209	0.375	0.012	0.018	-0.367	-8.130	-0.063	
100	-0.252	17.003	-0.010	0.064	-0.539	-5.058	-0.248	0.211
80	-3.448	22.246	-0.015	0.129	-0.837	-9.167	-0.374	
72	-0.808	-0.112	-0.002	-0.097	-0.205	21.168	0.011	0.345
60	-3.330	15.622	-0.016	0.120	-0.704	-2.448	-0.550	
40	-11.870	9.395	0.001	0.325	-1.031	-5.349	-1.336	
35	-2.196	0.396	-0.010	0.052	-0.445	13.858	-0.020	

Table 2: slopes of sensitivity tests on different variables gained from tests at Rysum (blue) and Hovsore (red)

4.2 Classification

A maximum range to be expected for each environmental variable is suggested by CD IEC 61400-12-1, Ed. 2 as shown in Table 3. The regression slopes derived from the sensitivity analysis are multiplied by these maximum ranges of variables in order to calculate the maximum influence of each variable on the measurements of the RSD as shown in Table 4.
Different criteria on the variables to be considered for the classification are applied (Table 5):

- criteria on the sufficient range coverage of the variables,
- criteria on the significance of the variables,
- As some of the environmental variables are correlated among each other, only sufficiently independent variables are considered. For the present analysis, variables have been considered being dependent on each other in case of a correlation coefficient of at least 0.5.

The influences of the remaining variables on the measurements of the RSD are then considered as being independent from each other, i.e. the accuracy class is calculated as square sum of the maximum influences of the relevant variables. The result is divided by the square root of 2 in order to take care for the fact that a variable being at the one end of the maximum range at the verification test and at the other end of the range at the application of the RSD is extremely unlikely. The so derived accuracy classes represent maximum percentage errors of the measurements of the RSD as in case of the accuracy classes of cup anemometers. For an assessment of the standard uncertainty of the measurements, the accuracy class should be divided by the square root of 3.
The resulting accuracy classes in terms of the horizontal wind speed component are shown in Figure 5 for the tested Windcube V2. Consistent accuracy classes between 2.7 and 4.7 are resulting from the test in Rysum for the entire height range covered by the test. Much higher accuracy classes are gained from the test in Hovsore at the heights 40 m and 116 m, what is a consequence of the high sensitivity of the measurements of the lidar on the wind shear at these heights. It is pointed out that the accuracy classes gained from the test in Hovsore get closer to the results from Rysum if the criterion on range coverage of the environmental variables as defined in CD IEC 61400-12-1, Ed. 2 is applied instead of the alternative criterion described in chapter 4.1. The derived accuracy classes refer to flat

terrain conditions, as CD IEC 61400-12-1, Ed. 2 does not allow applying RSD's in complex terrain for power curve tests (see also chapter 7).

		flat terrain			
independent variable		**max**	**min**	**range**	**source**
shear exponent alpha	[-]	0.80	-0.40	1.20	experience
turbulence intensity I	[-]	0.24	0.03	0.21	IEC 61400-12-1
rain (yes=1, no=0)	[-]	1	0	1	by definition of sensor
availability lidar	[%]	100	80	20	by definition of filter
wind direction	[°]	360	0	180	deviation of 2 directions is maximum 180°
air temperature T	[°C]	40	0	40	IEC 61400-12-1
air density	[kg/m³]	1.35	0.90	0.45	IEC 61400-12-1
T difference 133m-10m	[K]	6	-2	8	experience
flow inclination angle	[°]	3	-3	6	IEC 61400-12-1
wind veer dir133-dir35	[°]	20	-20	40	experience

Table 3: maximum expected range of environmental variables according to CD IEC 61400-12-1, Ed. 2

height	wind shear	I	direction	T	T gradient	air density	wind veer	flow incl.
[m]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
135	4.5	0.0	1.1	0.1	2.3	5.1	0.7	0.3
116	9.8	4.7	2.0	4.5	4.2	4.3	4.3	
104	6.3	0.1	2.2	0.7	2.9	3.7	2.5	
100	0.3	3.6	1.8	2.5	2.8	2.3	1.8	1.3
80	4.1	4.7	2.8	5.2	4.3	4.1	2.7	
72	1.0	0.0	0.3	3.9	1.6	9.5	0.4	2.1
60	4.0	3.3	2.8	4.8	3.6	1.1	4.0	
40	14.2	2.0	0.3	13.0	6.6	2.4	9.7	
35	2.6	0.1	1.9	2.1	3.6	6.2	0.8	

Table 4: maximum influence of variables on measurement of horizontal wind speed component from tests at Rysum (blue) and Hovsore (red)

Variable	1. Variables with Covered Range	
	Rysum	Hovsore
Wind Shear	X	X
Turbulence Intensity	X	X
Wind Direction	X	X
Temperature	X	X
Temperature Gradient	X	X
Air Density	X	X
Wind Veer	X	X
Flow Inclination	X	X
Variable	**2. Significant Variables**	
	Rysum	Hovsore
Wind Shear	X	X
Turbulence Intensity	X	X
Wind Direction	X	
Temperature	X	X
Temperature Gradient		X
Air Density	X	
Wind Veer	X	X
Flow Inclination		
Variable	**3. Independent Variables**	
	Rysum	Hovsore
Wind Shear	X	X
Turbulence Intensity	X	X
Wind Direction	X	
Temperature	X	X
Temperature Gradient		X
Air Density		
Wind Veer		X
Flow Inclination		

Table 5: Selection of variables relevant for the classification

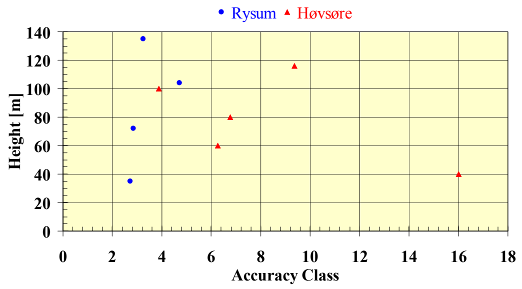

Figure 5: Accuracy classes in terms of horizontal wind speed component

4.3 Realistic Uncertainties due to the Sensitivity on Environmental Variables

The high accuracy classes are partly due to the large range of environmental variables to be considered for the classification according to CD IEC 61400-12-1, Ed. 2. The same problem exists also for cup anemometers in case of the B-class (accuracy class for complex terrain). Much more realistic uncertainties due to the sensitivity of RSD's on environmental conditions are gained if only the mean deviation of each environmental variable at the application of the RSD and at the verification test is considered. This procedure is recommended in CD IEC 61400-12-1, Ed. 2 for deriving the application oriented uncertainty due the sensitivities.

This procedure has been tested on the basis of the measurements at Rysum and Hovsore by considering the following scenarios: The measurement at Rysum has been considered as an application of the lidar based on a sensitivity test and verification test performed at Hovsore. Furthermore, the measurement at Hovsore has been considered as application of the lidar based on a sensitivity test and verification test performed at Rysum. The standard uncertainty of the applied Windcube V2 in terms of the horizontal wind speed due to the sensitivity on environmental variables is then mostly in the order of 1 % to 3 % for all cases (Figure 6).

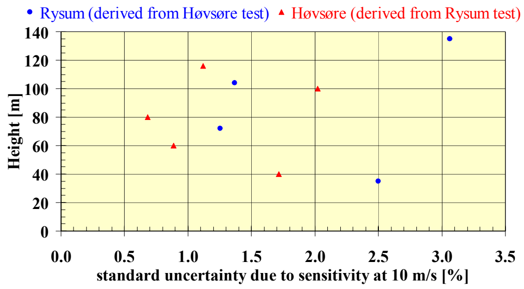

Figure 6: Standard uncertainty of the applied Windcube V2 in terms of the horizontal wind speed component due to the sensitivity to environmental variables for the case of an application at Rysum based on the tests at Hovsore and vice versa at an exemplary wind speed of 10 m/s.

5 Random Noise Error

As part of the verification test, CD IEC 61400-12-1, Ed. 2 requires the evaluation of the so-called random noise error. The random noise error describes the part of the scatter of the measurements of the RSD versus the measurements of the reference sensor (scatter of 10-minute averages, see Figure 7 and Figure 8) which is not explained by the sensitivities as derived from the sensitivity test. The random noise error is expected being instrument specific and is a relevant uncertainty only when the measurement result are single 10-minute averages of the wind speed. The random noise error is insignificant when bin-averages are the measurement result.

In case of the tested Windcube V2, the random noise errors where mostly below 1 % at the tests in Rysum and Hovsore (Figure 9).

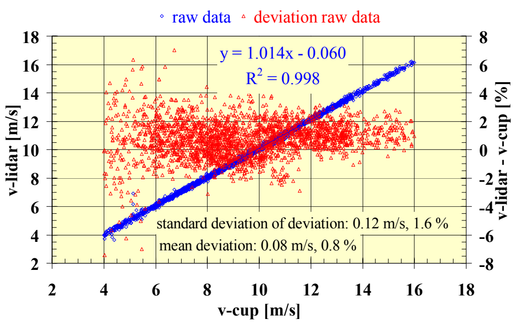

Figure 7: Raw data of verification test at 104m height at Rysum

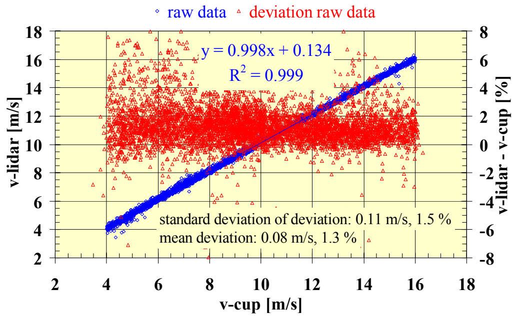

Figure 8: Raw data of verification test at 100m height at Hovsore

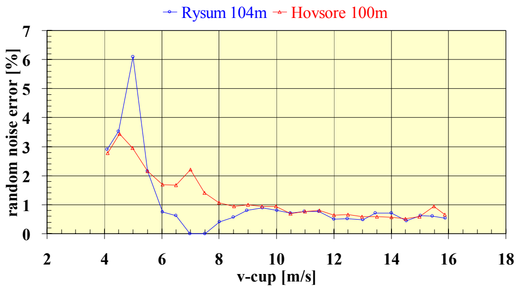

Figure 9: Random noise error at Rysum at 104 m measurement height compared to the respective error at Hovsore at 100 m measurement height

6 Control of Lidar at Application with Small Met Mast

CD IEC 61400-12-1, Ed. 2 requires the measurement of the RSD being controlled with a small met mast, which reaches at least 2/3 of the hub height of the tested wind turbine. Purpose of this control is:

- Check on obvious outlier data or malfunctioning
- Check whether systematic deviations of the RSD and the control anemometer are in the expected range under consideration of the uncertainties of the reference measurements and the sensitivities of the RSD. An additional uncertainty must be applied if the systematic deviations exceed the expectations. This feed-back algorithm helps to avoid overoptimistic classifications of the applied RSD. In the test scenario described in chapter 4.3 (test of lidar at Hovsore and application at Rysum and vice versa) the systematic deviations at the application where always within the expected ranges, i.e. no additional uncertainties from the control mast where resulting.

- Check whether the scatter of deviations of RSD and control anemometer are as expected under inclusion of the unit specific random noise error. If the respective criteria are not met, an additional uncertainty shall be applied only if 10-minute averages are the relevant result (not in case of bin averages).
- In-situ testing of the RSD (test on changes of accuracy within measurement period)

7 Inhomogeneous Airflow Over Probe Volumes

Most RSD's evaluate single wind speed components in spatially separated probe volumes under the assumption of equal wind conditions in the different volumes. This assumption can lead to significant measurement errors in complex terrain, what is the reason why CD IEC 61400-12-1, Ed. 2 allows the application of RSD's only in flat terrain. However, even in flat terrain, i.e. terrain where according to CD IEC 61400-12-1, Ed. 2 no site calibration is needed for a wind turbine power curve test, the assumption of equal flow conditions in the different probe volumes of a RSD can lead to measurement errors. Thus, CD IEC 61400-12-1, Ed. 2 requires the respective uncertainty being assessed either by means of a flow model or on the basis of the Mann-Bingöl approach [4]. As is illustrated in Table 1, even small deviations of the vertical flow inclination at opposite probe volumes of a RSD can lead to significant measurement errors.

In case of the test sites Rysum and Hovsore, the respective uncertainty is estimated being zero at least in terms of bin averages of the horizontal wind speed component.

α_1	α_2	relative lidar error
[°]	[°]	[%]
0	0.5	0.8
0	1	1.5
-1	1	3.0
1	-1	3.0
0	2	3.0
0	3	4.5

Table 6: relative lidar error in terms of the horizontal wind speed component in case of deviations of the vertical flow inclination α_1 and α_2 at opposite probe volumes according to the Mann-Bingöl approach

8 Examples of Total Uncertainties

The total uncertainty of the measurement of the horizontal wind speed component by the tested Windcube V2 has been derived for the scenarios described in chapter 4.3 (application of the lidar at Rysum based on sensitivity test and verification test at Hovsore and vice versa). Figure 10 represents the single uncertainty components and the total uncertainty as function of the wind speed for the case of an application of the instrument at Hovsore based on prior testing of the unit at Rysum. The total uncertainty is in the order of 2 % to 3 % in the entire wind speed range from 4 to 16 m/s. Table 7 illustrates the uncertainty components and total uncertainty of the tested lidar unit at a wind speed of 10 m/s for all cases where the lidar is applied at Hovsore and tested at Rysum and vice versa. A total uncertainty of about 2 % to 3 % is resulting for both application sites and all measurement heights. This illustrates the robustness of the uncertainty evaluation according to CD IEC 61400-12-1, Ed. 2.

Apart of the uncertainty components described in the previous chapters, a mounting uncertainty must be accounted for the assessment of the total uncertainty, which considers the fact that the RSD may be slightly misaligned at the application or that the alignment may change slightly during the application. This mounting uncertainty has here conservatively been assumed as 1 %. Assuming a smaller mounting uncertainty is likely justified; however the total uncertainty would hardly be changed as the uncertainty of the verification test and of the sensitivity test are prevailing.

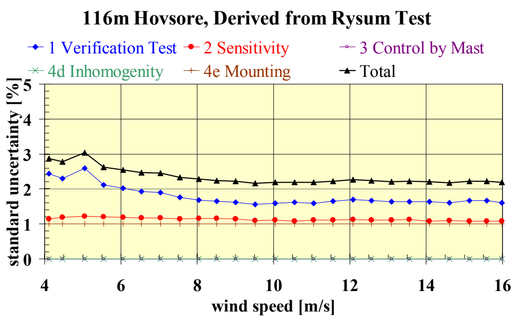

Figure 10: single uncertainty components and total standard uncertainty of the tested Windcube V2 in terms of the horizontal wind speed component in the case of an application of the instrument at Hovsore at 116m

measurement height based on a sensitivity test and verification test at Rysum

All Heights at 10m/s

Blue Heights: tested at Hovsore and applied at Rysum

Red Heights: tested at Rysum and applied at Hovsore

Height	Verification	Sensitivity	Control by Mast	Inhomogenity	Mounting	Total
[m]	[%]	[%]	[%]	[%]	[%]	[%]
35	1.6	2.5	0.0	0.0	1.0	3.1
40	1.6	1.7	0.0	0.0	1.0	2.5
60	1.7	0.9	0.0	0.0	1.0	2.2
72	1.3	1.3	0.0	0.0	1.0	2.0
80	1.8	0.7	0.0	0.0	1.0	2.2
100	1.6	2.0	0.0	0.0	1.0	2.8
104	1.0	1.4	0.0	0.0	1.0	2.0
116	1.6	1.1	0.0	0.0	1.0	2.2
135	0.9	3.1	0.0	0.0	1.0	3.4

Table 7: single uncertainty components and total standard uncertainty of the tested Windcube V2 in terms of the horizontal wind speed component at a wind speed of 10m/s in the case of an application of the instrument at Hovsore at various measurement heights based on a sensitivity test and verification test at Rysum and vice versa

9 Conclusions

- The results of the verification test of the same lidar unit at the test sites Rysum and Hovsore have led to similar results. Small deviations of these tests may be explained by the differences in the set-up of the reference measurements.
- The sensitivity analysis at the two test sites has led to similar results for some parameters but very different results for other (e.g. turbulence intensity) at the two test sites. However, partly diverging sensitivities have been observed. Critical aspects of the sensitivity analysis with potential for optimisation are:
  - sufficient coverage of ranges of environmental variables
  - significance criteria
  - correlation among environmental variables
  - mast effects on reference measurements
  - the sensitivity of the reference measurements themselves to the environmental variables
  - un-identified environmental variables
- The uncertainty assessment according to CD IEC 61400-12-1, Ed. 2 provides realistic uncertainty ranges.
- An accuracy class in the range of 3 to 6 seems being realistic for the Windcube V2, leading typically to a standard uncertainty in terms of wind speed of about 1-2% in practice.
- The total standard uncertainty of the wind speed measurements is often in the range 2-3% for a Windcube V2 in flat terrain.
- The evaluated lidar uncertainty is by definition higher than the uncertainty of reference cup anemometers.

10 References

[1] IEC 61400-12-1, Edition 2 Committee Draft, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, September 2011

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