Summary of Classification of Remote Sensing Device

Type: Vaisala Windcube V2.1 XP

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Contents

1 Abstract 6
2 Introduction 8
3 Measurement Results 9
4 Calculation of Classification 12
5 Example Calculation 15
6 Deviation to IEC 61400-12 and IEC 61400-50 Series 17
7 Conclusions 18
8 References 19

This report covers 19 pages.

1 Abstract

Deutsche WindGuard Consulting GmbH (DWG) analysed classification measurement data on the remote sensing device (RSD) of type Vaisala Windcube V2.1 XP. The data was provided to DWG by the measuring institutes once the measurements were completed. According to IEC 61400-50-2:2022 [1], a full classification of a type of remote sensing device requires measurements on at least two different units and one unit at two different sites, i.e. at least three measurements. This is fulfilled by the measurements reported in the references [2], [3] and [4]. It was found that the environmental variable wind shear is influencing the accuracy of the Vaisala Windcube V2.1 XP. It was noted that the sensitivity slope was dependent on the way wind shear was characterised. Key results of the classification are the sensitivity slopes and class numbers presented in Table 1. This report summarises the derivation of these results and gives an example of usage.

Note: The given sensitivity slopes and class are valid for a symmetric characterisation of wind shear using wind profile information above and below the height of interest.

Height	Slopes m_j Wind Shear	Final Class
[m]	[%]	[%]
200	0.71	0.60
195	0.69	0.59
190	0.68	0.57
185	0.66	0.56
180	0.64	0.54
175	0.49	0.42
170	0.36	0.30
165	0.23	0.20
160	0.14	0.12
155	0.25	0.21
150	0.46	0.39
145	0.67	0.56
140	0.87	0.74
135	1.08	0.91
130	1.28	1.08
125	1.48	1.25
120	1.69	1.43
115	1.80	1.53
110	1.95	1.66
105	2.11	1.79
100	2.26	1.92
95	2.39	2.03
90	2.52	2.14
85	2.70	2.29
80	2.88	2.44
75	2.93	2.49
70	3.01	2.55
65	3.12	2.65
60	3.25	2.76

Table 1 Final sensitivity slopes with symmetrically determined wind shear (above and below target height) for every 5 m of measurement height between 60 m and 200 m. Grey marked heights do not have the full set of three measurements. Above 180 m, the wind sheer definition as used here could not be applied (missing upward measurement height).

2 Introduction

The Vaisala Windcube V2.1 XP is a ground based Doppler lidar system (LiDAR = Light Detection And Ranging) for wind measurements in the lower atmosphere. The standard IEC 61400-50-2:2022 [1] sets a scheme to assess the uncertainty of remote sensing devices (RSD), involving a calibration test for every unit and a classification for every type of instrument.

The calibration describes the accuracy of the measurements of the RSD for the environmental conditions present at the test site during the calibration period. The environmental conditions present at an application of the RSD may deviate from the conditions present at the calibration. To assess the influence of changing environmental conditions on the accuracy of a device, a sensitivity analysis or classification of the instrument is needed. The procedure for such a classification is set out in Chapter 6 of [1]. Basically, the deviation between the RSD and reference mast measurements is analysed with regard to different environmental variables.

DWG was given the data of three classification measurements performed by third party institutes. Two units were tested on the same test site and one of those units was tested on a second test site. Thusly, the minimum requirements of a full classification are met. Based on the delivered data and documentation, DWG performed classification analysis [2], [3] and [4]. This report combines the results of these measurements to receive a final classification result (Table 1)

3 Measurement Results

The performed measurements are summarised in Table 2. All these measurements identified environmental variables that impact the measurement of horizontal wind speed of the RSD. This was achieved by performing a linear regression between the deviation of wind speed measured by the RSD from the wind speed of a calibrated cup anemometer and the investigated environmental variable. The slope of this regression is the sensitivity. In this way, *wind shear* was identified as significant and independent variable impacting the measurement accuracy of the RSD.

The IEC 61400-50-2:2022 [1] does not specify how wind shear has to be calculated. During the measurement it was noticed that the sensitivity slope is highly dependent on the way wind shear is characterised, i.e. from which anemometers the power law exponent was calculated. The following possibilities exist:

wind shear (up & down): The wind shear exponent is calculated from the linear regression of the logarithms of wind speed and height using three cup anemometers: the one at the height of interest together with the ones 20 m above and below.

wind shear (up): only the cup anemometers at the measurements at height of interest and 20 m above is used.

wind shear (down): only the cup anemometers at the measurements at height of interest and 20 m below is used.

At the topmost height of 200 m, only wind shear (down) is available. At both sites, an additional anemometer 20 m below the lowest assessed height was used for characterising wind shear. Therefore, all three wind shear values are available at the lowest height of the site.

Table 3, Table 4 and Table 5 summarise the observed sensitivity slopes with regard to the three wind shear parameterisations above. In addition, the combined sensitivity slopes calculated as described in Chapter 4 are given. These combined sensitivity slopes are compared in Figure 1. While the resulting slopes are consistent between units and measurement sites, they differ between the characterisation of wind shear. Within the presented study it could not be determined whether this is a mathematical consequence of using different x-axis for the linear regression or if there is a hidden physical reason. As the probe volume of the lidar extends both above and below, it is here decided to use for the following classification the symmetric definition wind shear (up& down).

Location	Serial Number	Reference	Abbr.	Lowest Height	Period
Janneby	WLS7-9982	[2]	J I	60 m	2024-02-22 - 2024-05-31
Janneby	WLS7-9983	[3]	J II	60 m	2024-02-22 - 2024-05-31
Rodewald	WLS7-9982	[4]	R I	80 m	2024-08-08 - 2024-11-17

Table 2 Performed classification measurements. Lowest height denotes the lowest height at which mast and RSD are compared.

Measurement Height	Slopes $m_{(Shear\ up\ \&\ down)}$			
	J I	J II	R I	All
[m]	[%]	[%]	[%]	[%]
200	0.80	0.58	0.46	0.71
180	0.72	0.52	0.42	0.64
160	0.07	0.01	0.18	0.14
140	0.75	0.98	0.35	0.87
120	1.70	1.67	1.60	1.69
100	1.96	2.27	2.28	2.26
80	2.82	2.94	2.47	2.88
60	2.84	3.23	3.29	3.25

Table 3 Measured sensitivity slopes with regard to wind shear calculated from three anemometers, one placed at measurement height, one 20 m below and the third at 20 m above. Grey cells are not derived from measurement at that hight but scaled values from the closest available measurement height. The sensitivity slopes combined with formula (1) are given in the rightmost column.

Measurement Height	Slopes $m_{(Shear\ up)}$			
	J I	J II	R I	All
[m]	[%]	[%]	[%]	[%]
200	1.23	1.33	1.04	1.29
180	1.11	1.20	0.93	1.16
160	0.83	1.01	0.86	0.95
140	1.25	1.57	0.83	1.43
120	2.23	2.32	2.12	2.28
100	2.96	3.19	3.16	3.17
80	3.25	2.88	3.95	3.67
60	3.99	4.27	5.26	4.87

Table 4 Same as Table 3, but for wind shear calculated from two anemometers, one placed at measurement height and one at 20 m above.

Measurement Height	Slopes $m_{(Shear\ down)}$			
	J I	J II	R I	All
[m]	[%]	[%]	[%]	[%]
200	-0.14	0.05	0.02	-0.08
180	0.24	0.28	-0.20	0.25
160	-0.56	-0.29	-0.51	-0.53
140	0.25	0.43	-0.21	0.34
120	0.73	1.17	0.79	1.02
100	0.92	1.19	0.98	1.11
80	2.19	2.02	1.15	2.09
60	1.28	1.31	1.53	1.45

Table 5 Same as Table 3, but for wind shear calculated from two anemometers, one placed at measurement height and one 20 m below.

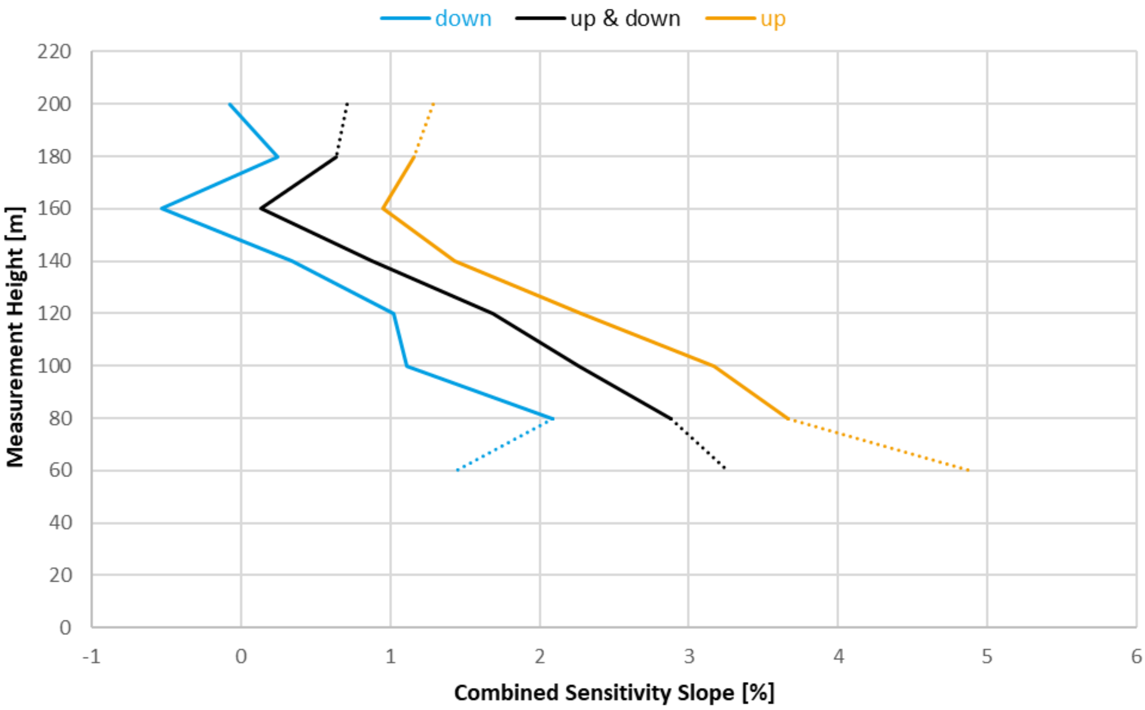

Figure 1 Combined sensitivity slopes with regard to wind shear for different derivations of wind shear. *Down* (*up*) represents the slopes resulting with shear calculated with the anemometer at the height of interest and the one below (above). *Up & down* uses all three anemometers. Dotted lines mark heights were at least one part of the calculation uses a scaled slope from 20 m below or above (corresponding to grey values in Table 3, Table 4 and Table 5.

4 Calculation of Classification

The aim of a classification is to quantise the possible measurement error due to changing environmental variables between calibration and application of an RSD. To achieve this, sensitivity slopes from all three measurements have to be calculated at the measurement height used during application. Chapter 6.9 of [1] describes the following procedure:

1. Interpolate the sensitivity slopes of every classification test to the target height. If a target height is above the highest one of the classification test, the slope of the last covered measurement height is increased with the ratio of target height and the last covered height. If a target height is below the lowest one of the classification test, the slope of the last covered measurement height is increased with the ratio of last covered height and target height.
2. Combine the slopes with the following formula:

$$m_j = \frac{1}{N}\sum_{n=1}^{N} m_{j,n} \pm \frac{\max(m_{j,n}) - \min(m_{j,n})}{2\sqrt{3}} \quad (1)$$

   where m_j is the final slope for variable j, $m_{j,n}$ is the sensitivity slope of variable j measured during classification n, N is the total number of classification measurements (here N=3). The sign for the right part of the formula is the same as that of the average slope (i.e. the magnitude of the slope always increases).

Table 1 summarises the interpolated and combined slopes for every 5 m of measurement height between 60 m and 200 m. In addition, the final accuracy class is shown, which calculates as follows:

For the significant variable the slope is multiplied with the range according to Table 6 to assess the impact of the variable if calibration and application occur on opposite ends of the range. This results in a preliminary class. To take into account that in the majority of cases neither calibration nor the application are performed under conditions at either end of the ranges, the final class is derived by division through the square root of 2. Table 7 and Figure 2 show the intermediate steps of the class calculations.

Variable	Unit	Min	Max	Range
Wind Shear	[-]	-0.40	0.80	1.20

Table 6 Ranges of the variables considered in the calculation of final class.

Height	Slopes m_j x Range Wind Shear (up & down)	Preliminary Class	Final Class
[m]	[%]	[%]	[%]
200	0.85	0.85	0.60
195	0.83	0.83	0.59
190	0.81	0.81	0.57
185	0.79	0.79	0.56
180	0.77	0.77	0.54
175	0.59	0.59	0.42
170	0.43	0.43	0.30
165	0.28	0.28	0.20
160	0.16	0.16	0.12
155	0.30	0.30	0.21
150	0.55	0.55	0.39
145	0.80	0.80	0.56
140	1.05	1.05	0.74
135	1.29	1.29	0.91
130	1.53	1.53	1.08
125	1.77	1.77	1.25
120	2.03	2.03	1.43
115	2.16	2.16	1.53
110	2.34	2.34	1.66
105	2.53	2.53	1.79
100	2.72	2.72	1.92
95	2.87	2.87	2.03
90	3.03	3.03	2.14
85	3.24	3.24	2.29
80	3.45	3.45	2.44
75	3.52	3.52	2.49
70	3.61	3.61	2.55
65	3.75	3.75	2.65
60	3.90	3.90	2.76

Table 7 Calculation of final accuracy class. Grey marked heights are outside the range of one measurement site.

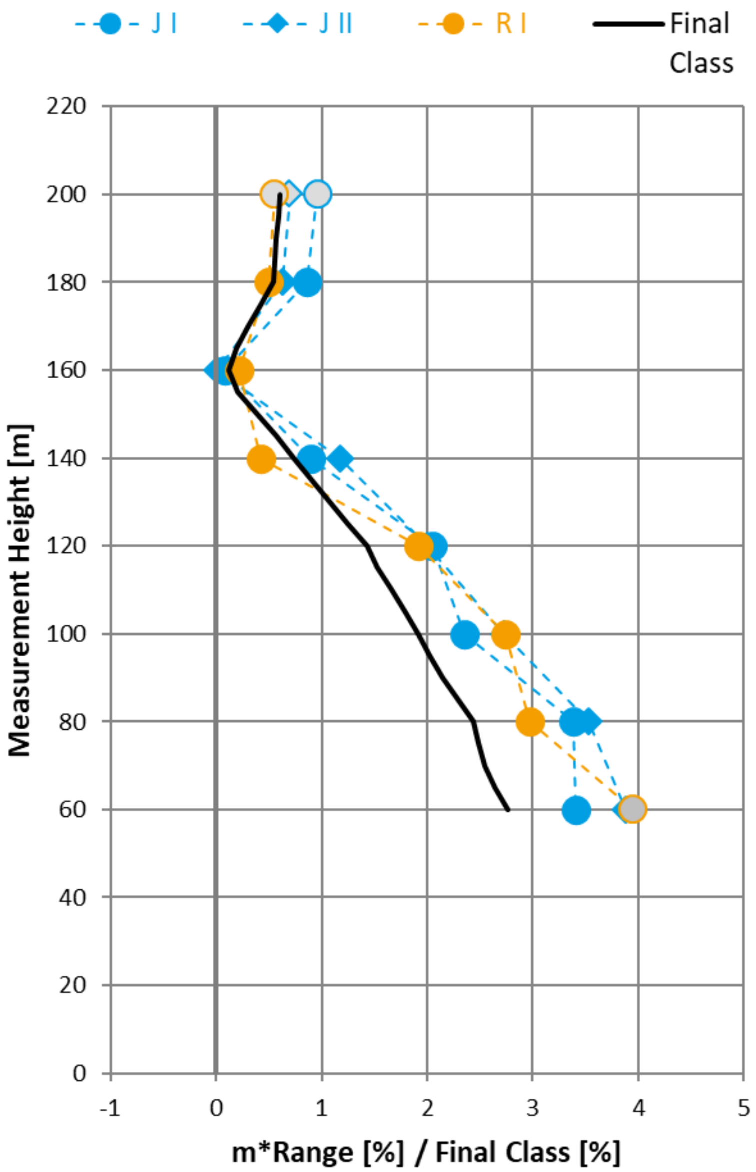

Figure 2 Graphical representation of the magnitude of slope multiplied by range for every measurement campaign (thin) and the final classes (bold).

5 Example Calculation

The accuracy classes given in Table 1 represent the maximum uncertainty due to different environmental conditions. In practice, the conditions at the verification test and the application of the instrument will not differ by the complete ranges described in Table 6. Therefore, the error of the instrument at the application is calculated from

$$u_{\mathrm{class,i}} = v_{\mathrm{i}} \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \left| \overline{x}_{\mathrm{app},j,i} - \overline{\mathrm{x}}_{\mathrm{ver},j,i} \right| \right)^2} \quad (2)$$

where

$u_{\mathrm{class,i}}$ uncertainty of the RSD in wind speed bin i due to the influence of environmental variables,

v_i average wind speed in wind speed bin *i*,

M number of significant and independent variables,

m_j slope describing the sensitivity of the RSD due to environmental variable *j*,

$\overline{x}_{\mathrm{app},j,i}$ mean value of variable *j* in wind speed bin *i* during the application

$\overline{x}_{\mathrm{ver},j,i}$ mean value of variable *j* in wind speed bin *i* during the verification test.

To illustrate the procedure for the classification at hand, Table 8 shows the environmental conditions at hypothetical calibration test and application for the height of 80 m. Equation (2) is then used to derive the uncertainty due to different environmental conditions.

For the example at hand, it can be seen that the actual uncertainty of 0.23% to 0.64% due to the influence of environmental variables can be smaller than the standard uncertainty of 1.4% that would be derived from the accuracy class of 2.4.

Wind Speed	Wind Shear			Uncertainty		
	Cal.	App.	Unc.	Classification	Calibration	Combined
[m/s]	[-]	[-]	[%]	[%]	[%]	[%]
4.01	0.25	0.37	0.34	0.3	1.6	1.6
4.49	0.30	0.42	0.33	0.3	1.3	1.4
5.01	0.31	0.44	0.36	0.4	1.2	1.3
5.50	0.31	0.47	0.45	0.5	1.2	1.3
6.00	0.29	0.49	0.59	0.6	1.1	1.3
6.48	0.30	0.50	0.57	0.6	1.1	1.3
6.99	0.31	0.47	0.46	0.5	1.1	1.2
7.49	0.31	0.44	0.37	0.4	1.1	1.1
8.01	0.28	0.40	0.34	0.3	1.1	1.1
8.52	0.28	0.40	0.36	0.4	1.1	1.1
9.01	0.27	0.36	0.26	0.3	1.1	1.1
9.49	0.26	0.34	0.23	0.2	1.0	1.1
9.98	0.24	0.34	0.30	0.3	1.0	1.1
10.48	0.21	0.33	0.32	0.3	1.1	1.1
11.02	0.20	0.33	0.39	0.4	1.1	1.1
11.51	0.20	0.32	0.36	0.4	1.1	1.2
11.97	0.18	0.29	0.33	0.3	1.2	1.2
12.47	0.18	0.31	0.37	0.4	1.2	1.2
13.03	0.18	0.35	0.50	0.5	1.1	1.2
13.52	0.18	0.36	0.54	0.5	1.5	1.6
13.96	0.17	0.39	0.64	0.6	1.3	1.4
14.41	0.17	0.31	0.39	0.4	1.5	1.5
14.99	0.17	0.39	0.64	0.6	1.3	1.4
15.51	0.17	0.31	0.39	0.4	1.5	1.5

Table 8 Example calculation of the uncertainty due to the influence of environmental variables. For the four significant and independent variables, the average values of the variables during a hypothetical calibration and at a hypothetical application site are shown together with the resulting uncertainty. Additionally, the resulting classification uncertainty, the uncertainty due to calibration, and the combined uncertainty from both calibration and classification are presented. The uncertainties in this example are standard uncertainties (k=1).

6 Deviation to IEC 61400-12 and IEC 61400-50 Series

- The smallest distance of any probe volume to the closest turbine at the site Janneby is less than 2 rotor diameters of that turbine. According to IEC 61400-12-5:2022 [5] this would lead to a 360° exclusion sector. However, DWG did not observe large deviations of the wind speed measured by a lidar with probe volumes closer than 2 D in the past. For the calculation of the exclusion sector the formula given in Figure 1 of IEC 6140012-5:2022 [5]is used also for distances below 2 D.
- Precipitation and flow inclination were not assessed at the Rodewald test site. These two variables were not significant at the other two classification measurements in Janneby. As the results of Rodewald agree well with the results of Janneby, it is not expected that these variables would have been significant at Rodewald.

7 Conclusions

A full classification according to IEC 61400-50-2:2022 [1] for the remote sensing device of type Vaisala Windcube V2.1 XP was performed. The main results of this classification test are:

1. As significant and independent variables influencing the accuracy of the tested RSD the following were identified:

   Wind Shear
2. The used wind profile information has a significant impact on the resulting sensitivity slopes. Only using measurement heights at and below the height of interest underestimates the sensitivity while using only heights above the height of interest leads to higher sensitivity slopes.
3. Using wind shear exponents derived from measurement heights above and below the target height, accuracy classes from 0.1 to 2.4 were derived between 180 m and 80 m. with the lowest class at 160 m measurement height. Highest class numbers were observed at the lower measurement heights at 80 m.
4. It has to be mentioned that the actual uncertainty from the classification during an application will usually be smaller than indicated by the class numbers. In an example application it could be seen that the actual uncertainty of 0.23% to 0.64% due to the influence of environmental variables can be smaller than the standard uncertainty of 1.4% that would be derived from the accuracy class of 2.4.

8 References

[1] IEC 61400-50-2, Wind energy generation systems - Part 50-2: Wind measurement – Application of ground-mounted remote sensing technology; Edition 1.0, 2022-08

[2] K. Franke, D. Trabucchi: Classification of Remote Sensing Device, Type: Vaisala Windcube V2.1 XP, Serial Number: WLS7-9982, Site: Janneby, Germany, DWG-Report PP25007.A0, 2025-05-20

[3] K. Franke, D. Trabucchi: Classification of Remote Sensing Device, Type: Vaisala Windcube V2.1 XP, Serial Number: WLS7-9983, Site: Janneby, Germany, DWG-Report PP25008.A0, 2025-05-20

[4] K. Franke, D. Trabucchi: Classification of Remote Sensing Device, Type: Vaisala Windcube V2.1 XP, Serial Number: WLS7-9982, Site: Rodewald, Germany, DWG-Report PP25009.A0, 2025-05-20

[5] IEC 61400-12-5, Wind energy generation systems - Part 12-5: Power performance - Assessment of obstacles and terrain; Edition 1.0, 2022-08

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