ZX300E

Classification of the ZX Lidars ZX300e lidar, summary report according to IEC 61400-50-2

ZX Lidars

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Task and objective:
Lidar classification summary report in accordance with IEC 61400-50-2 for five ZX300e lidars tested at 3 different sites. This document is intended to provide all interested parties with the classification results and methodology.

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It consists of 18 pages excluding title and back cover pages.

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EXECUTIVE SUMMARY

The ZX Lidars ZX300e lidar has undergone five measurement campaigns with three different lidar units at three different test sites. This report presents the summary results as per the IEC 61400-50-2:2022 [1].

Campaigns took place in the period between the 28.03.2024 and the 27.08.2025 at two sites in northern Germany equipped with 200 m tall reference met masts and one site in the UK with a 92 m tall reference met mast. The classification covers the range of heights from 20 m to 200 m.

The classification is considered valid for wind field reconstruction algorithm versions 3.09 and 3.10. The version 3.10 includes an additional feature for computing cup-equivalent TI based on the 10-minute wind statistics results.

No EVs were found to be significant according to the criteria set out in the IEC 61400-50-2:2022 [1].

1 INTRODUCTION

ZX Lidars contracted DNV Energy Systems Germany GmbH, a member of the DNV Group ("DNV"), to complete a classification of the ZX300e lidar (a ground based vertical profiling lidar) in accordance with the IEC 61400-50-2:2022 [1]. This report summarises the results of the five individual campaigns and presents the final combined classification results.

The individual campaigns were conducted at two 200 m tall reference met masts and one 92 m tall reference met mast. The two trials at Rodewald (operated by GEO-NET Umweltconsulting GmbH) covered the height range from 60 m to 200 m. The one trial at Janneby (operated by Pavana GmbH) covered the height range from 40 m to 200 m. The two trials at Pershore (operated by ZX Lidars) covered the height range from 20 m to 92 m. Two lidar units (SN ZX6003 and ZX6004) were tested at the Rodewald site, one unit (SN ZX6003) was tested at the Janneby site, and two units (SN ZX6003 and ZX6101) were tested at the Pershore test site. This is considered sufficient to provide representative results covering the full range from 20 m to 200 m.

Further details to the individual trials are contained in the individual campaign sensitivity reports [2,3,4,5,6].

DNV is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements, energy assessments and lidar verifications and classifications. DNV is also a full member of the network of measurement institutes in Europe 'MEASNET' and in the FGW (Fördergesellschaft Windenergie und anderer Erneuerbaren Energien).

The work has been conducted in compliance with all relevant health and safety legislation. DNV Energy Systems Germany GmbH operates an Occupational Health and Safety Management System certified according to the OHSAS 18001:2007.

2 SITE INFORMATION

The following section briefly describes the three test sites at which the measurement campaigns were completed. All three test sites meet the requirement of IEC 61400-12-5:2022 [7] for simple terrain and the sensors on the meteorological masts are regularly calibrated in accordance with the MEASNET requirements.

The met masts at all test sites had 2 side boom mounted cup anemometers at each height. At each height, the reference wind speed was calculated as the average of the primary and control anemometers, except where either of the anemometers was in the wake of the mast. For those wind direction, only the measurement from the free anemometer was used. Further details can be found in the individual reports [2,3,4,5,6].

The five campaigns covered all four seasons. An overview of the campaign periods is provided in Table 2-1.

Table 2-1 Overview of the campaign periods

	Lidar serial number	Site	Start	End
Campaign 1	ZX6003	Rodewald	22-Jun-2024	29-Sep-2024
Campaign 2	ZX6004	Rodewald	23-May-2025	24-Aug-2025
Campaign 3	ZX6003	Janneby	06-Nov-2024	01-Apr-2025
Campaign 4	ZX6003	Pershore	28-Mar-2024 12-Jun-2025	02-Jun-2024 27-Aug-2025
Campaign 5	ZX6101	Pershore	18-Nov-2024	07-Mar-2025

2.1 Rodewald

The Rodewald test site is located in the North-West of Germany, as shown in Figure 2-1. The Rodewald test site is operated by GEO-NET Umweltconsulting GmbH and has a 200 m tall met mast with boom mounted anemometers every 20 m starting from 60 m. There are wind turbines to the East of the test site leaving a free sector from 121° to 90°. An overview of the sensors and heights used to obtain the environmental variables (EV) is provided in Table 2-2.

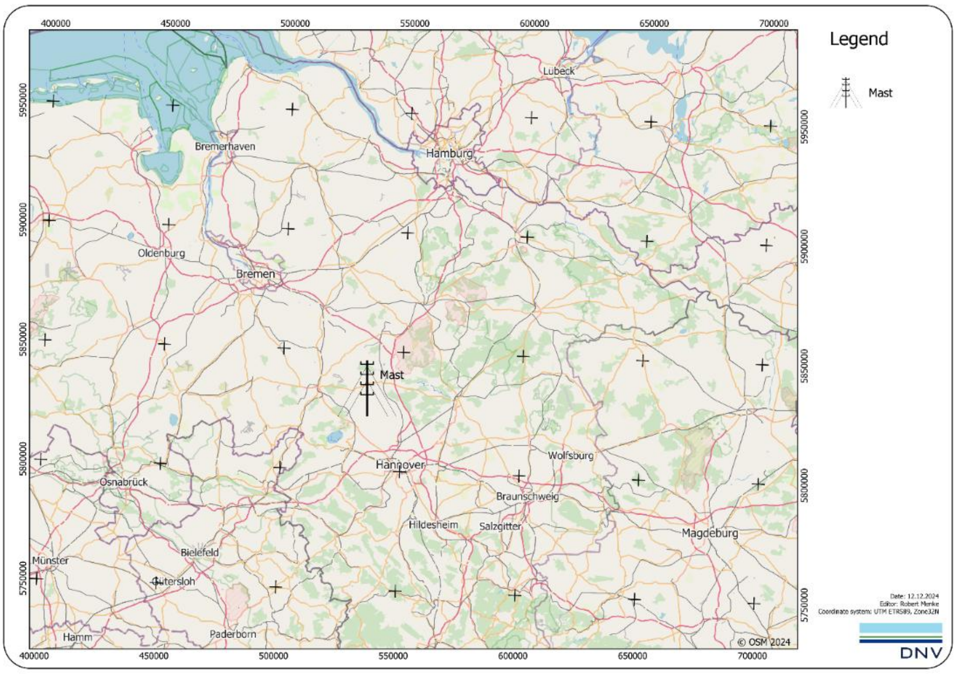

Figure 2-1 Location of the Rodewald test site (N52° 39.53', E 009° 31.29')

Table 2-2 Description of sensor and height pairing for environmental variables at Rodewald

EV	Associated measurement/sensor height [m]*							
Height	**200**	**180**	**160**	**140**	**120**	**100**	**80**	**60**
Temperature gradient	Temperature at 192 and 30							
Air temperature	192	192	155	155	155	95	95	55
Air density	Temperature at 155, humidity at 155, pressure at 133							
Wind veer	Wind vanes at 77 and 197							
Wind direction	197	177	157	137	117	97	77	77
Wind shear	200, 180	200, 180, 160	180, 160, 140	160, 140, 120	140, 120, 100	120, 100, 80	100, 80, 60	80, 60
Flow inclination	197		177		117		77	
Packets in average	200	180	160	140	120	100	80	60
Turbulence intensity	200	180	160	140	120	100	80	60
Rain	3.5							

* rounded to the nearest m

2.2 Janneby

The Janneby test site is located in the north of Germany as shown in Figure 2-2. The Janneby test site is operated by Pavana GmbH and has a 200 m tall met mast side boom mounted anemometers every 20 m starting at 20 m. There are wind turbines to the North of the site leaving a free sector from 74° to 308°.

The sensors on the Janneby mast are provided in [4] and a description of the EVs paired with specific wind speed measurement heights are provided Table 2-3.

Figure 2-2 Location of the Janneby test site (N 54° 36.64' E 009° 18.70')

Table 2-3 Description of sensor and height pairing for environmental variables at Janneby

EV	Associated measurement/sensor height [m]*								
Height	**200**	**180**	**160**	**140**	**120**	**100**	**80**	**60**	**40**
Temperature gradient	Temperature at 199 and 10								
Air temperature	199								
Air density	Temperature interpolated between 10 and 199 to the respective height, humidity at 10 and pressure interpolated between 2 and 199 to the respective height.								
Wind veer	Wind vanes at 58 and 198								
Wind direction	197	177	157	137	117	97	77	57	37
Wind shear	200, 180	200, 180, 160	180, 160, 140	160, 140, 120	140, 120, 100	120, 100, 80	100, 80, 60	80, 60, 40	60, 40
Flow inclination	177			117			77		
Packets in average	200	180	160	140	120	100	80	60	40
Turbulence intensity	200	180	160	140	120	100	80	60	40
Rain	4								

* rounded to the nearest m

2.3 Pershore

The Pershore test site is located on a disused airfield near the village in Worcestershire UK as shown in Figure 2-3. The Pershore test site is operated by ZX Lidars and has a 92 m tall met mast with side boom mounted anemometers at 20.5 m, 45.5 m and 70.5 m, and a pair of goal post mounted anemometers at 91.5 m.

An overview of the sensors and heights used to obtain the environmental variables (EV) is provided in Table 2-4.

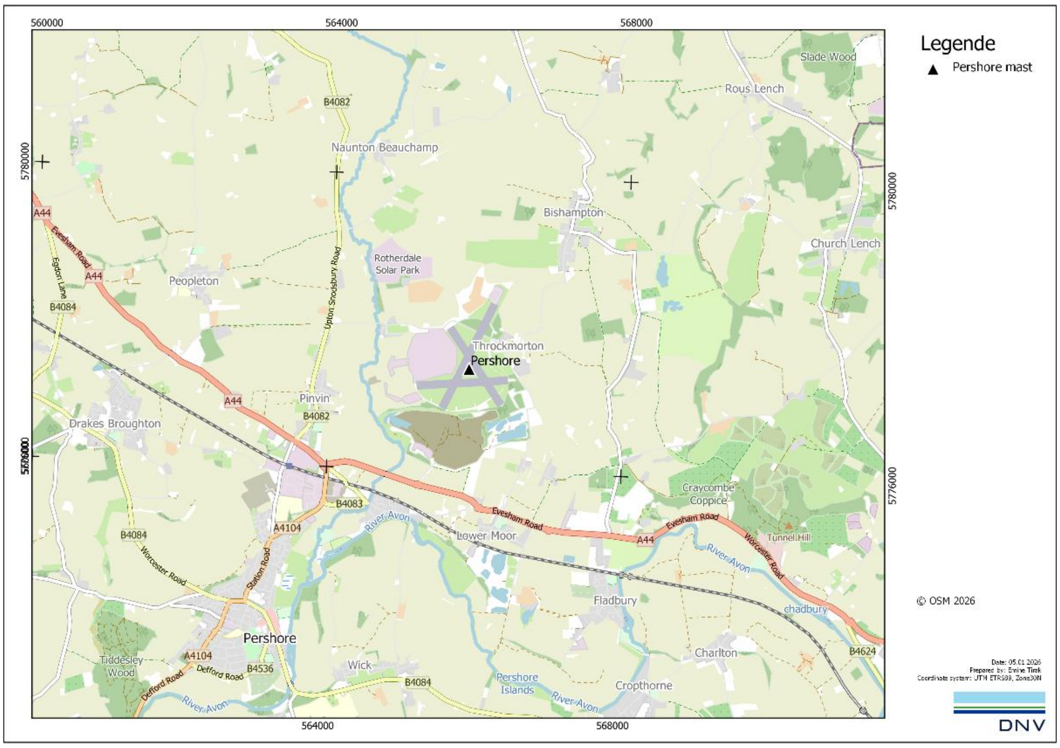

Figure 2-3 Location of the Pershore test site (N 52° 08’ 35.1”, W 002° 02’ 13.7”)

Table 2-4 Description of sensor and height pairing for environmental variables at Pershore

EV	Associated measurement/sensor height [m]*			
Height	**92**	**71**	**46**	**21**
Temperature gradient	Temperature at 44 and 88			
Air temperature	88		44	
Air density	Temperature at 88, Humidity at 88, Pressure at 2		Temperature at 44, Humidity at 44, Pressure at 2	
Wind veer	Wind vanes at 43.5 m and 88 m			
Wind direction	88		44	
Wind shear	92, 71	92, 71, 46	71, 46, 21	46, 21
Flow inclination	88		21	
Packets in average	92	71	46	21
Turbulence intensity	200	180	160	140
Rain	3.5			

* rounded to the nearest m

3 LIDAR CLASSIFICATION APPROACH

The lidar classification approach is provided in IEC 61400-50-2 [1] in Chapter 6. A summary of key evaluation steps and criteria are described in this section.

IEC standard [1] requires three campaigns to be conducted at two different sites with at least two different lidar units of which one unit is tested at two of the sites. Each campaign must last for at least 3 months (or 90 days).

The classification is evaluated for wind speeds from 4 m/s to 16 m/s in bins of 0.5 m/s width (total range 3.75 m/s to 16.25 m/s). For each 10-minute data pair (lidar and reference wind speed) the deviation is calculated as the difference between the reference sensor and the lidar wind speeds as a ratio of the reference sensor for each 10-minute mean value and expressed as a percentage.

$$deviation = \frac{(v_{RSD} - v_{reference})}{v_{reference}}$$

The IEC prescribes a number of EVs (listed in Table 3-1) against which the deviation should be evaluated to determine if it has a significant influence on the measurement accuracy. The sensitivity of the deviation to a given EV is defined as a two-variant linear relationship fitted to the binned deviations. Binning of the deviation and EV data is done as per the specifications detailed in Table 3-1.

Bin-average deviation and EV values are considered valid if the bins meet criteria requiring (a) minimum data counts; and (b) constraints on the variability of the within-bin deviation data, per 50-2 equations 3 and 4 respectively. Data bins that meet these criteria are considered “qualified,” and the sensitivity results are considered valid if at least 25% of the possible bins (as defined by the bin width and range) are qualified (IEC 61400-50-2:2022 [1] Clause 6.5.).

Table 3-1 List of EVs defined in the IEC standard including defined ranges and bin widths

EV (Label)	Min	Max	Range	Bin width	Max number of bins	Unit	Source of range definition
Temperature gradient	-0.02	0.06	0.08	0.002	40	$K\ m^{-1}$	IEC
Air temperature	0	40	40	2	20	°C	IEC
Wind direction	0	360	180	5	72	°	IEC
Availability	80	100	20	1	20	%	Sensor specific
Turbulence intensity	0.03	0.24	0.21	0.01	21	-	IEC
Air density	0.9	1.35	0.45	0.05	9	$Kg.m^{-3}$	IEC
Wind veer gradient	-0.2	0.2	0.4	0.04	12	°/m	IEC
Wind shear exponent	-0.4	0.8	1.2	0.05	24	-	IEC
Rain	0	1	1	1	2	no/yes	Sensor specific
Flow inclination	-3	3	6	0.2	30	°	IEC

Using the above criteria, significant EVs are then assessed for intercorrelation. The aim is to avoid double counting the uncertainties from correlated EVs. This process is conducted independently for each measurement campaign.

If an EV is identified as being significant in one campaign, then the results for this EV from all campaigns are carried forward for the further evaluation.

The output of the sensitivity analysis is then evaluated for convergence to identify if any of the test campaigns should be considered as an outlier. According to the IEC, if the magnitude of the sensitivity derived from any individual campaign differs by more than 50% from the mean value across all campaigns for a particular significant EV, then the campaign can be considered not be representative and can be excluded from the classification.

To calculate the final accuracy class for the lidar type, the slopes of the significant EVs are first interpolated to a set of common heights. The slopes from the individual campaigns are then combined to give the final slope as follows:

$$m_{final} = \frac{1}{N_{CT}} \sum_{n=1}^{N_{CT}} m_n + \frac{m_{max} - m_{min}}{2} \times \frac{1}{\sqrt{3}}$$

where N_{CT} is the number of classification tests, m_n is the slope of the *n*th test, and m_{max} and m_{min} are the maximum and minimum slopes of the N_{CT} campaigns.

The maximum influence of each EV is then calculated as the final slope times the range defined in Table 3-1. The preliminary accuracy is given by the summing the maximum influences of all EVs in quadrature. The type class is the preliminary accuracy divided by the square root of 2, and the standard uncertainty the preliminary accuracy divided by the square root of 3. Thus, an uncertainty is calculated for each measurement height separately.

3.1 Deviations from the IEC Standards

As presented in the sensitivity reports [2,3,5], the database requirements for wind speed bin completion was not fulfilled for some of the upper wind speed bins for both lidar campaigns at Rodewald and one of the two campaigns at Pershore. The missing wind speed bins are not expected to have a significant influence on the results; however, the wind speed distribution as a whole was strongly biased to very low wind speeds. Therefore, any phenomena that may be more prevalent at low wind speeds will be more strongly represented in the results.

Wind direction has not been considered as an EV. With the symmetrical arrangement of 50 beams around the cone, a directional effect cannot occur other than due to terrain or mast flow distortion. Furthermore, a linear fit as described in the standard, and the methods for calculating the impact on measurement uncertainty are not suited to periodic relationships.

4 RESULTS

4.1 Summary of the sensitivity results from the individual campaigns

During the individual trials, no EVs were identified as having a significant sensitivity. More details can be found in the individual campaign reports. For the sake of a quick overview, the sensitivity and sensitivity x R for all campaigns and all EVs are presented graphically in the following figures.

Only sensitivities for which the number of qualified bins criteria (at least 25% of bins as specified in Table 3-1) has been fulfilled are presented. For the EV rain, only two campaigns had sufficient rain events to permit sensitivity to be calculated. For the EV density, only one campaign had enough significant bins.

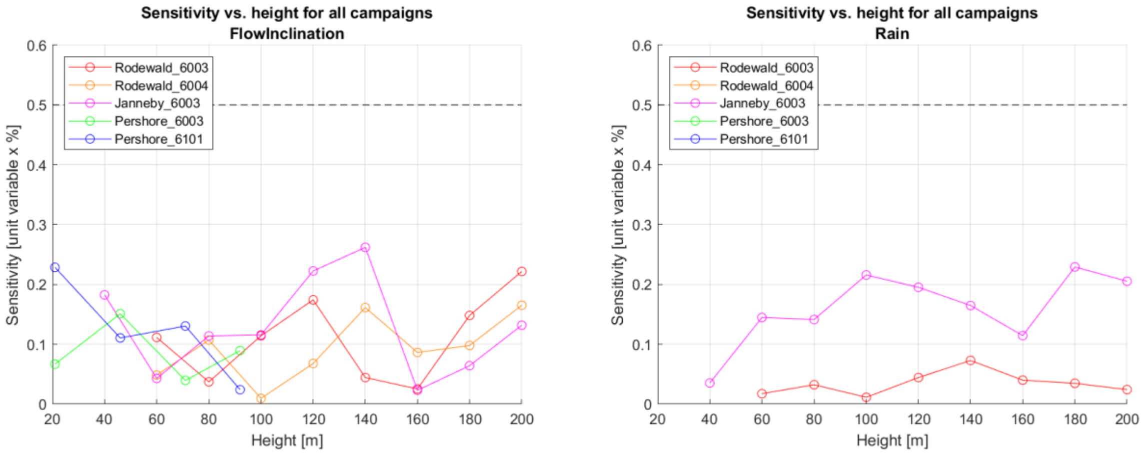

Figure 4-1 Plot of sensitivity to flow inclination (left) and rain (right) for all campaigns and all heights

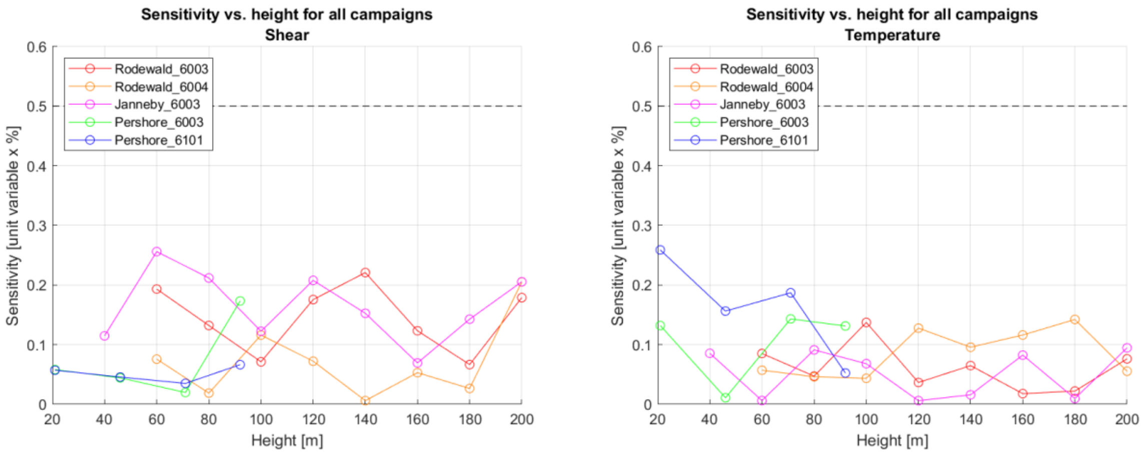

Figure 4-2 Plot of sensitivity to shear (left) and temperature (right) for all campaigns and all heights

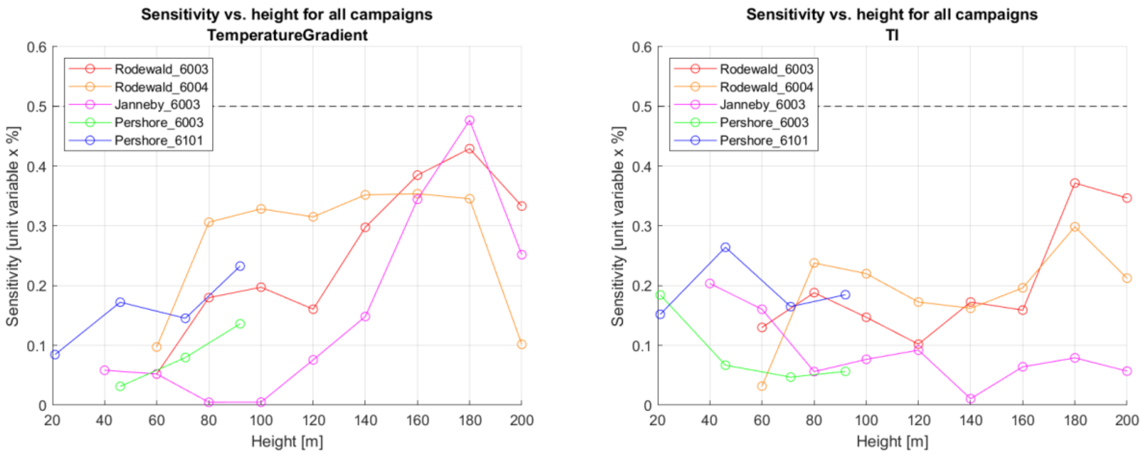

Figure 4-3 Plot of sensitivity to temperature gradient (left) and TI (right) for all campaigns and all heights

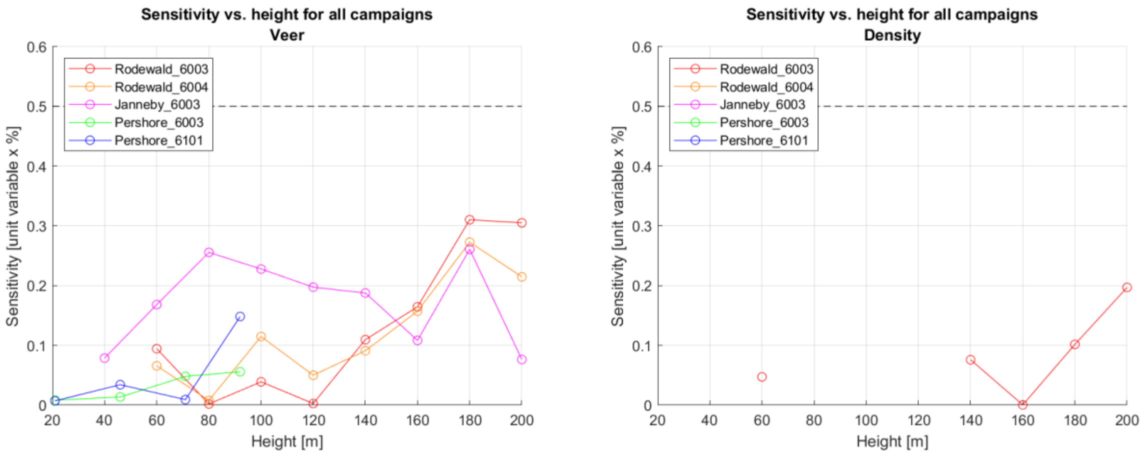

Figure 4-4 Plot of sensitivity to veer (left) and density (right) for all campaigns and all heights

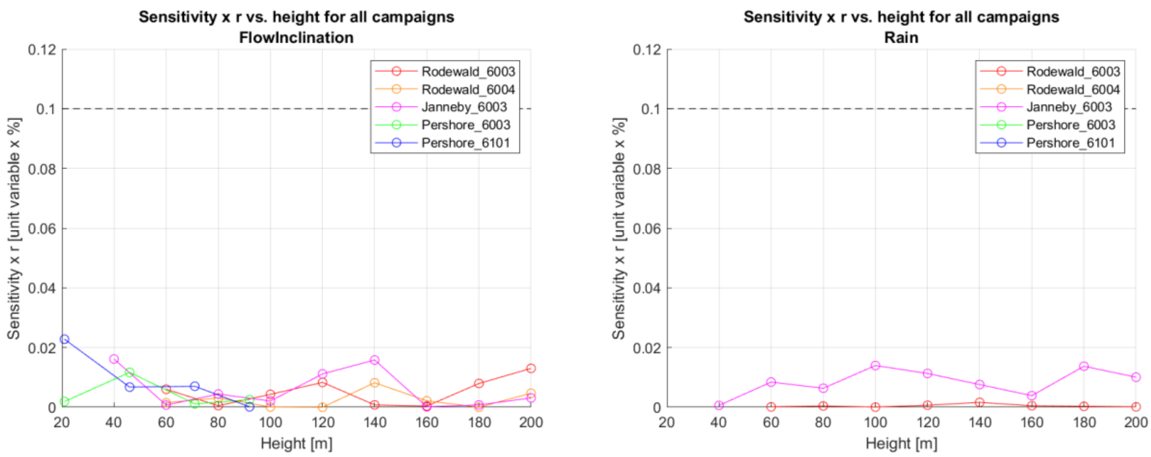

Figure 4-5 Plot of sensitivity x R to flow inclination (left) and rain (right) for all campaigns and all heights

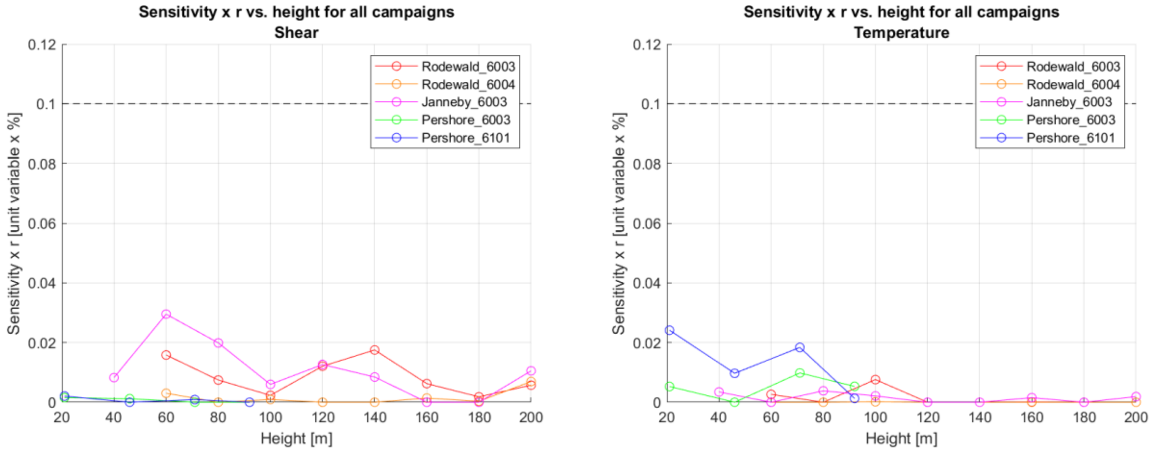

Figure 4-6 Plot of sensitivity x R to shear (left) and temperature (right) for all campaigns and all heights

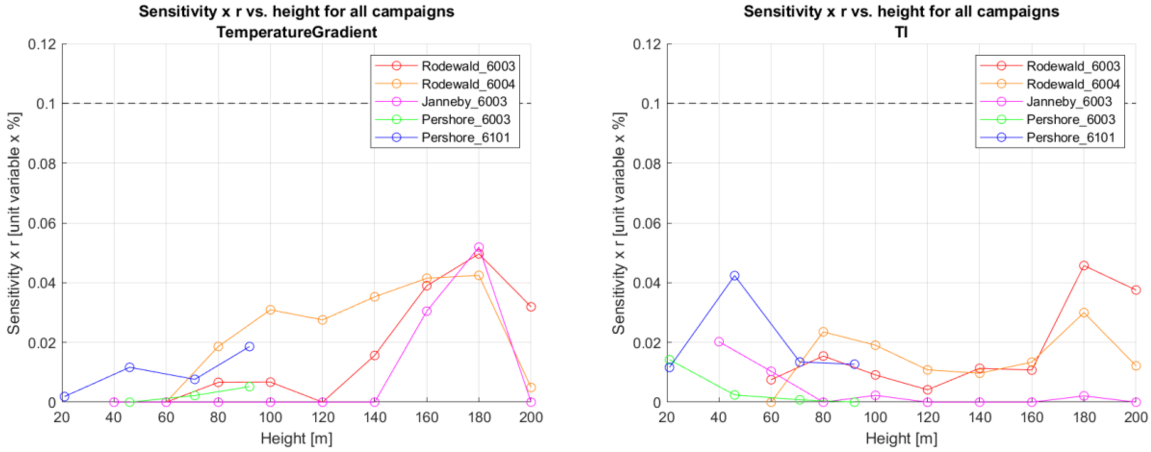

Figure 4-7 Plot of sensitivity x R to temperature gradient (left) and TI (right) for all campaigns and all heights

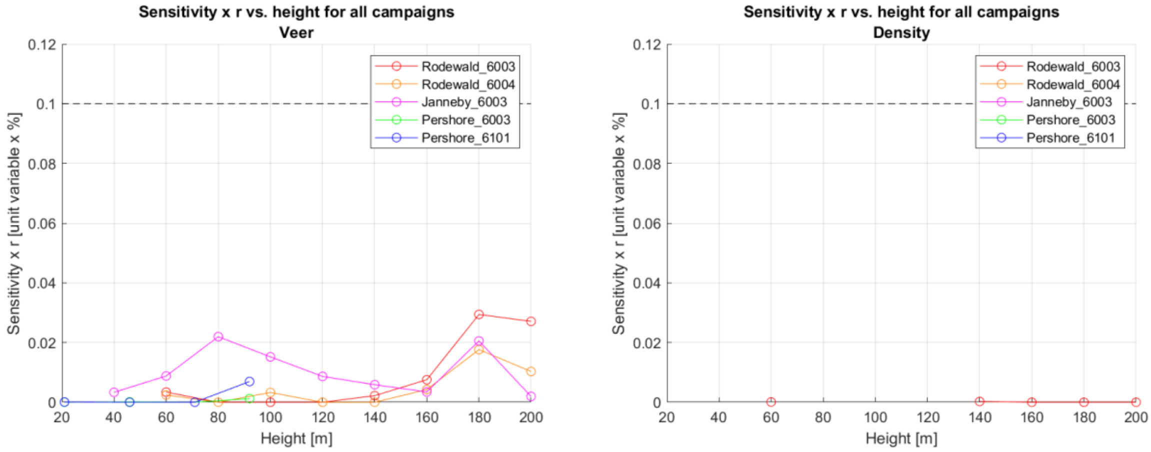

Figure 4-8 Plot of sensitivity x R to veer (left) and density (right) for all campaigns and all heights

4.2 Convergence test

A convergence test was conducted for all EVs. The scatter in the results was such that the IEC criteria for outliers were breached for at least one measurement height for all campaigns. This finding is in keeping with the result that no EV was found to be significant.

4.3 Intermediate results

During the individual trials, no EVs were identified as having a significant influence on the lidar measurements. Accordingly, there are no intermediate results to present.

4.4 Type specific classification results

Since no EVs were found to be significant, the resulting class number is zero. This means that the calibration uncertainty obtained for a given lidar is applicable to the specific measurement campaign without additional uncertainty due to differing environmental conditions between the calibration and specific measurement campaigns.

5 DERIVING APPLICATION UNCERTAINTY

The type-specific class and standard uncertainties are the maximum wind speed measurement uncertainty that may be expected from the lidar due to differences in the environmental conditions between a verification and specific measurement campaign. However, it is likely that the differences are smaller than those assumed in the calculation of the type-class and standard uncertainties. In this case the category B uncertainty of the wind speed measurement due to the influence of EVs on the performance of the remote sensing device is calculated as follows,

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

where:

$u_{class,i}$	is the type-specific class uncertainty in wind speed bin i,
M	is the number of significant EVs,
m_j	is the slope describing the sensitivity of the wind speed measurement of the remote sensing device on the EV j,
$\bar{x}_{app,j,i}$	is the mean value of the EV j in the wind speed bin i as present during the specific measurement campaign,
$\bar{x}_{ver,j,i}$	is the mean value of the environmental variable j in wind speed bin i as present during the verification test.

When evaluating the measurement uncertainty in a specific measurement campaign, several uncertainty components are added in quadrature. The classification uncertainty is only one of several uncertainty components.

6 CONCLUSION

No EVs were found to be significant. This results in a class number of zero for the ZX300e lidar for heights from 20 m to 200 m. The classification is considered valid for wind field reconstruction algorithm versions 3.09 and 3.10. The version 3.10 includes an additional feature for computing cup-equivalent TI based on the 10-minute wind statistics results.

The final accuracy classes and standard uncertainties presented in this report reflect the measurements conducted in five measurement campaigns at three locations and with three different lidar units. The range of conditions experienced during these campaigns resulted no observed significant sensitivities to EVs listed in Table 3-1. While this indicates that the measurement is not significantly impacted by the EVs investigated herein, this should not be misinterpreted as indicating that there is no measurement uncertainty but rather, that the measurement uncertainty can be assumed not to vary significantly with changing environmental conditions.

The range of environmental conditions across all the individual trials met the significance threshold for almost all EVs. The exceptions were 10-minute data availability (packets in average), the air density and for 3 out of 5 campaigns also rain. These did not show sufficient fluctuation during the individual campaigns to enable a sensitivity to be determined.

In two campaigns were the database completion criteria met for all heights, covering the range from 20 m to 200 m. Only in one campaign were the criteria no met across all heights. In general, the range of wind speeds covered across all campaigns is considered representative of the full range as specified in the IEC, from 4 to 16 m/s.

The use of the classification at heights greater than 200 m is permitted for power performance testing applications according to the IEC up to 267 m (hub height ±25%) provided a suitable additional uncertainty is applied. A suitable method of defining the additional uncertainty is not provided in the IEC 12-1 or IEC 50-2 standard.

For other applications and measurement heights, the user is advised to exercise engineering judgment.

7 REFERENCES

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