TYPE ZX300 LIDAR

Remote Sensing Device Type-specific Classification Summary

ZX Lidars

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1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH ("GH-D"), a member of the DNV GL Group ("DNV GL"), has been assigned on 2017-09-21 by ZX Lidards, part of Zephir Ltd,. to conduct an independent classification assessment of three lidar units of type ZX300.

The performance of a remote sensing device (RSD) may be influenced by environmental variables (EV), such as wind shear and air temperature. Since the environmental conditions may differ between verification and application of the RSD, any sensitivity of its measurement accuracy to a particular EV can lead to an increased uncertainty in the measurement results of the application. The task of the classification test is to identify influential EVs and quantify the sensitivity of the RSD measurement accuracy to different EVs for a range of measurement heights. This report aims to present the quantitative uncertainty of wind measurements to be expected from the type ZX300 lidar with regards to its sensitivity to meteorological conditions.

The classification measurement campaigns took place over three sites, with one Lidar deployed at two different sites, so a total of four separate campaigns were analysed. DNV GL conducted one campaign, classifying unit ZX703 at their Janneby test-site in northern Germany [1]. ZX Lidars arranged two measurement campaigns, to classify units ZX703 and ZX716, at their Pershore test-site in the UK. The fourth campaign, to classify unit ZX537 [2], took place at the Georgsfeld test-site in northern Germany, operated by Deutsche WindGuard GmbH.

According to the IEC 61400-12-1 Ed. 2 [3], to obtain a device type-specific classification it is required to test a minimum of two units at a minimum of two different measurement sites. At least one unit has to be deployed on two sites, which results in a minimum of three classification tests for each instrument type. For the given number of classification tests of ZX300 lidars and since the unit ZX703 went through two classification trials at two different test sites, the IEC criteria for issuing the type-specific classification have been fully met.

In this report, a summary of all classification task assessments of the type ZX300 lidar are shown, and the type-specific classification figures are presented.

2 RESULTS

In this chapter, all steps and intermediate results towards the type-specific accuracy class are addressed.

2.1 Data coverage of the classification campaigns

The classification trial of unit ZX703 at the Janneby test-site took place between 09/11/2017 and 19/02/2018 for a total of 101.4 days. This trial covered a wind speed range of 3.0 to 20.2 m/s at hub height (100 m) and 3.0 to 15.2 m/s at the lowest height (29 m). The campaign data coverage, representing the number of filtered and useful concurrent measurements per wind speed bin is shown in Table 1.

	Center of WS bin / m/s																								
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
# values at 100m	221	256	321	452	551	586	544	491	413	428	374	332	320	247	254	282	305	269	246	196	185	146	147	98	92
# values at 76m	311	355	524	693	634	621	511	507	418	347	345	272	244	267	305	287	288	216	201	167	134	125	88	81	52
# values at 57m	436	605	751	742	711	557	526	418	343	312	280	279	284	318	287	251	205	189	159	126	90	85	65	28	12
# values at 29m	812	846	702	603	458	423	337	291	281	329	346	304	273	231	184	164	138	109	72	59	16	11	6	0	0

Table 1: ZX703 @ Janneby - Wind speed coverage for all assessed heights.

With regards to the classification trial of unit ZX703 at the Pershore test-site, it took place between 07/03/2018 and 16/06/2018 for a total of 102.0 days. This trial covered a wind speed range of 3.0 to 16.9 m/s at hub height (91.5 m) and 3.0 to 12.2 m/s at the lowest height (20.5 m). The campaign data coverage, representing the number of filtered and useful concurrent measurements per wind speed bin is shown in Table 2.

	Center of WS bin / m/s																								
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
# values at 91m	968	1006	1012	904	853	831	705	700	635	475	399	329	262	219	167	91	84	63	38	21	10	11	7	1	0
# values at 70m	1032	1102	1042	915	900	778	717	649	474	417	335	278	217	158	97	102	49	37	17	16	10	4	1	0	1
# values at 45m	1214	1160	1043	898	847	648	583	483	398	332	232	192	151	94	62	45	15	23	7	3	1	0	0	0	0
# values at 21m	1278	1082	885	802	638	550	449	341	281	231	150	103	50	30	20	8	6	0	0	0	0	0	0	0	0

Table 2: ZX703 @ Pershore - Wind speed coverage for all assessed heights.

When it comes to the classification trial of unit ZX716 at the Pershore test-site, it took place between 24/08/2017 and 27/11/2017 for a total of 95.0 days. This trial covered a wind speed range of 3.0 to 20.7 m/s at hub height (91.5 m) and 3.0 to 16.4 m/s at the lowest height (20.5 m). The campaign data coverage, representing the number of filtered and useful concurrent measurement per wind speed bin is shown in Table 3.

	Center of WS bin / m/s																								
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
# values at 92m	548	577	600	648	695	680	630	614	553	467	418	343	285	245	184	161	126	114	66	63	55	42	45	50	40
# values at 71m	632	643	694	699	709	676	570	570	468	399	337	273	236	181	145	132	102	76	53	49	41	48	46	35	30
# values at 46m	722	747	703	778	667	606	463	437	358	317	251	213	156	135	120	83	53	51	48	45	38	45	33	24	14
# values at 21m	754	811	673	610	494	430	406	320	268	223	169	131	120	80	53	50	45	51	43	30	19	10	8	1	2

Table 3: ZX716 @ Pershore - Wind speed coverage for all assessed heights.

The classification trial of unit ZX537 at the Georgsfeld test-site took place between 21/06/2018 and 24/09/2018 hence a total of 92.9 days. This trial covered a wind speed range of 3.0 to 18.1 m/s at hub height (135 m) and 3.0 to 14.9 m/s at the lowest height used (60 m). The campaign data coverage, representing the number of filtered and useful concurrent measurements per wind speed bin is shown in Table 4.

	Center of WS bin / m/s																							
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
# values at 135m	344	446	480	550	601	591	533	478	322	300	251	177	123	115	95	68	56	37	30	35	15	11	19	5	7
# values at 131m	358	428	498	558	614	617	546	449	312	289	248	157	122	115	89	67	54	32	32	28	17	10	18	5	6
# values at 120m	361	466	512	608	647	618	534	390	327	260	199	127	116	104	81	53	46	29	36	19	11	17	9	5	2
# values at 100m	391	510	576	679	696	649	438	378	255	180	137	121	90	87	74	50	26	32	21	16	16	8	3	3	2
# values at 82m	488	550	650	766	765	554	402	280	177	141	121	109	101	69	48	38	26	20	17	16	7	5	2	2	1
# values at 60m	582	737	807	813	620	383	260	191	141	136	93	88	70	42	46	15	19	20	10	7	4	1	3	0	0

Table 4: ZX537 @ Georgsfeld - Wind speed coverage for all assessed heights.

As observed, some wind speed bins did not completely fulfil the given IEC criteria of wind speed coverage threshold. In fact, it is challenging to find the most suitable period in which the wind speed and EVs variability are met to perform a classification test in North Europe. Usually, higher wind speeds are found in cold seasons. However, every variable that is somehow dependent on temperature is affected due to temperature ranges below zero or not higher than 10°C. Conversely, between Spring and Summer, the variability of temperature and air density increases significantly. However, it would require more than 3 months to cover the whole wind speed range due to usually lower wind speed.

Therefore, the observed wind speeds and EV range variability during the classification tests are considered significant and appropriate to provide the basis for calculating the final IEC accuracy class of the type ZX300 lidar.

2.2 Intermediate classification results

The classification results for all units were calculated based on the sensitivity analysis and on the IEC criteria for defining an environmental variable to be significant. Each classification trials identified significant environmental variables that were correlated with the size of the difference between wind speed measurements made by a type ZX300 lidar and a high-quality reference cup anemometer.

For the classification results of unit ZX703, five out of ten EVs were found to be significant and they were kept in the classification calculation. The method proposed by [4] was used to assess the intercorrelation between EVs and, in case of strong correlation, the same reference proposes a method for removing the dependence. Based on this methodology, it was observed that there was a strong intercorrelation between temperature gradient and turbulence intensity. Therefore, the decorrelation method to remove the influence of TI on temperature gradient was performed. In summary, the selected independent EVs for composing the accuracy class of unit ZX703 at the Janneby test-site were temperature gradient, temperature, turbulence intensity, wind veer and rain flag.

Table 5 lists all significant and independent EVs, their slopes and ranges. Multiplying the regression slopes by the associated range results in the maximum deviation influence of each independent variable on the RSD accuracy (Column 5). Assuming that all selected variables are fully independent from each other, to build-up the preliminary accuracy class, each individual max influence is added in quadrature (Column 6). The final accuracy class is calculated by dividing the preliminary accuracy class by $\sqrt{2}$ (Column 7) while the RSD standard uncertainty is obtained by dividing the final accuracy class by $\sqrt{3}$ (Column 8).

When it comes to the classification results for the unit ZX703 at Pershore, the selected independent EVs for composing the accuracy class were temperature gradient, temperature, turbulence intensity, wind veer and shear. Table 6 lists the selected independent EVs, their slopes and ranges along with the unit ZX703 accuracy class and standard uncertainty at the Pershore test-site.

Regarding the classification results of unit ZX716 at Pershore, the selected independent EVs for composing the accuracy class were temperature gradient, temperature, turbulence intensity, air density, wind veer and shear. Table 7 lists the selected independent EVs, their slopes and ranges along with the unit ZX716 accuracy class and standard uncertainty in Pershore test-site.

Lastly, with regards to the classification results of unit ZX537 at Georgsfeld, the selected independent EVs for composing the accuracy class were temperature, turbulence intensity, wind veer and shear, rain flag and flow inclination angle. Table 8 lists the selected independent EVs, their slopes and ranges along with the unit ZX537 accuracy class and standard uncertainty at the Georgsfeld test-site.

In summary, the selected independent and significant EVs among all the classification campaigns are temperature gradient, temperature, turbulence intensity, wind veer, wind shear, rain flag and flow inclination angle.

Height	Independent Variable	*m*	Range	Max Influence m × range	Preliminary Accuracy Class	Final Accuracy Class	Standard Uncertainty
[m]	[-]	[%/u. V.]	[u.v]	[-]	[%]	[%]	[%]
100	Temperature Gradient	-30.164	0.080	2.413	5.049	3.570	2.061
100	Air Temperature	0.107	40.000	4.291			
100	Turbulence Intensity	1.539	0.210	0.323			
100	Wind Veer	-2.644	0.400	1.057			
100	Rain (yes = 1, no = 0)	0.181	1.000	0.181			
76	Temperature Gradient	-7.043	0.080	0.563	1.980	1.400	0.808
76	Air Temperature	-0.006	40.000	0.246			
76	Turbulence Intensity	8.215	0.210	1.725			
76	Wind Veer	-1.733	0.400	0.693			
76	Rain (yes = 1, no = 0)	0.296	1.000	0.296			
57	Temperature Gradient	-10.788	0.080	0.863	3.091	2.186	1.262
57	Air Temperature	0.071	40.000	2.840			
57	Turbulence Intensity	3.867	0.210	0.812			
57	Wind Veer	-0.441	0.400	0.176			
57	Rain (yes = 1, no = 0)	0.234	1.000	0.234			
29	Temperature Gradient	-4.669	0.080	0.374	2.020	1.428	0.825
29	Air Temperature	-0.047	40.000	1.883			
29	Turbulence Intensity	-2.216	0.210	0.465			
29	Wind Veer	0.057	0.400	0.023			
29	Rain (yes = 1, no = 0)	0.420	1.000	0.420			

Table 5: Classification Results of unit ZX703 at Janneby. List of selected independent EVs along with their maximum influence on the RSD accuracy, the RSD preliminary and final accuracy class and the standard uncertainty per assessed height.

Height	Independent Variable	*m*	Range	Max Influence m × range	Preliminary Accuracy Class	Final Accuracy Class	Standard Uncertainty
[m]	[-]	[%/u. V.]	[u.v]	[-]	[%]	[%]	[%]
91.5	Temperature Gradient	-20.355	0.080	1.628	2.131	1.507	0.870
91.5	Air Temperature	-0.005	40.000	0.209			
91.5	Turbulence Intensity	5.980	0.210	1.256			
91.5	Wind Veer	-1.268	0.400	0.507			
91.5	Wind shear exponent	0.093	1.200	0.112			
70.5	Temperature Gradient	-5.795	0.080	0.464	3.321	2.348	1.356
70.5	Air Temperature	0.032	40.000	1.278			
70.5	Turbulence Intensity	3.055	0.210	0.642			
70.5	Wind Veer	-0.025	0.400	0.010			
70.5	Wind shear exponent	2.468	1.200	2.961			
45.5	Temperature Gradient	-7.548	0.080	0.604	1.880	1.329	0.768
45.5	Air Temperature	-0.001	40.000	0.042			
45.5	Turbulence Intensity	2.214	0.210	0.465			
45.5	Wind Veer	2.055	0.400	0.822			
45.5	Wind shear exponent	1.257	1.200	1.509			
20.5	Temperature Gradient	0.890	0.080	0.071	1.902	1.345	0.776
20.5	Air Temperature	-0.024	40.000	0.957			
20.5	Turbulence Intensity	4.897	0.210	1.028			
20.5	Wind Veer	0.954	0.400	0.381			
20.5	Wind shear exponent	-1.018	1.200	1.222			

Table 6: Classification Results of unit ZX703 in Pershore. List of selected independent EVs along with their maximum influence on the RSD accuracy, the RSD preliminary and final accuracy class and the standard uncertainty per assessed height.

Height	Independent Variable	*m*	Range	Max Influence m × range	Preliminary Accuracy Class	Final Accuracy Class	Standard Uncertainty
[m]	[-]	[%/u. V.]	[u.v]	[-]	[%]	[%]	[%]
92.1	Temperature Gradient	-12.383	0.080	0.991	1.980	1.400	0.808
92.1	Air Temperature	0.011	40.000	0.457			
92.1	Turbulence Intensity	6.742	0.210	1.416			
92.1	Air Density	-0.563	0.450	0.254			
92.1	Wind veer	-1.253	0.400	0.501			
92.1	Wind shear exponent	0.533	1.200	0.640			
71.1	Temperature Gradient	7.272	0.080	0.582	2.743	1.940	1.120
71.1	Air Temperature	-0.012	40.000	0.474			
71.1	Turbulence Intensity	3.926	0.210	0.825			
71.1	Air Density	0.620	0.450	0.279			
71.1	Wind veer	-0.318	0.400	0.127			
71.1	Wind shear exponent	2.073	1.200	2.487			
45.1	Temperature Gradient	10.179	0.080	0.814	3.189	2.255	1.302
45.1	Air Temperature	-0.043	40.000	1.721			
45.1	Turbulence Intensity	-3.270	0.210	0.687			
45.1	Air Density	5.037	0.450	2.267			
45.1	Wind veer	1.881	0.400	0.753			
45.1	Wind shear exponent	0.508	1.200	0.610			
21.1	Temperature Gradient	-0.421	0.080	0.034	3.361	2.377	1.372
21.1	Air Temperature	-0.011	40.000	0.436			
21.1	Turbulence Intensity	1.317	0.210	0.277			
21.1	Air Density	-4.419	0.450	1.988			
21.1	Wind veer	-1.614	0.400	0.646			
21.1	Wind shear exponent	-2.151	1.200	2.581			

Table 7: Classification Results of unit ZX716 in Pershore. List of selected independent EVs along with their maximum influence on the RSD accuracy, the RSD preliminary and final accuracy class and the standard uncertainty per assessed height.

Height	Independent Variable	*m*	Range	Max Influence m × range	Preliminary Accuracy Class	Final Accuracy Class	Standard Uncertainty
[m]	[-]	[%/u. V.]	[u.v]	[-]	[%]	[%]	[%]
135	Temperature Gradient	-23.141	0.080	1.851	3.772	2.667	1.540
135	Air Temperature	-0.045	40.000	1.807			
135	Turbulence Intensity	1.897	0.210	0.398			
135	Wind veer	1.507	0.400	0.603			
135	Wind shear exponent	-2.069	1.200	2.482			
135	Rain (yes = 1, no = 0)	-0.586	1.000	0.586			
135	Flow Inclination Angle	0.119	6.000	0.713			
131	Temperature Gradient	-25.517	0.080	2.041	3.129	2.213	1.277
131	Air Temperature	-0.034	40.000	1.361			
131	Turbulence Intensity	2.506	0.210	0.526			
131	Wind veer	1.428	0.400	0.571			
131	Wind shear exponent	-0.997	1.200	1.197			
131	Rain (yes = 1, no = 0)	-0.571	1.000	0.571			
131	Flow Inclination Angle	0.198	6.000	1.188			
120	Temperature Gradient	-23.932	0.080	1.915	2.809	1.986	1.147
120	Air Temperature	-0.028	40.000	1.134			
120	Turbulence Intensity	3.261	0.210	0.685			
120	Wind veer	1.450	0.400	0.580			
120	Wind shear exponent	-0.507	1.200	0.608			
120	Rain (yes = 1, no = 0)	-0.916	1.000	0.916			
120	Flow Inclination Angle	0.160	6.000	0.963			
100	Temperature Gradient	-26.854	0.080	2.148	3.132	2.215	1.279
100	Air Temperature	-0.005	40.000	0.185			
100	Turbulence Intensity	4.687	0.210	0.984			
100	Wind veer	1.391	0.400	0.556			
100	Wind shear exponent	1.458	1.200	1.749			
100	Rain (yes = 1, no = 0)	-0.722	1.000	0.722			
100	Flow Inclination Angle	0.092	6.000	0.549			
82	Temperature Gradient	-18.028	0.080	1.442	2.472	1.748	1.009
82	Air Temperature	0.009	40.000	0.371			
82	Turbulence Intensity	-1.008	0.210	0.212			
82	Wind veer	2.503	0.400	1.001			
82	Wind shear exponent	1.291	1.200	1.550			
82	Rain (yes = 1, no = 0)	-0.192	1.000	0.192			
82	Flow Inclination Angle	-0.107	6.000	0.639			
60	Temperature Gradient	-1.643	0.080	0.131	2.469	1.746	1.008
60	Air Temperature	0.028	40.000	1.129			
60	Turbulence Intensity	-5.991	0.210	1.258			
60	Wind veer	4.115	0.400	1.646			
60	Wind shear exponent	0.419	1.200	0.502			
60	Rain (yes = 1, no = 0)	0.154	1.000	0.154			
60	Flow Inclination Angle	-0.081	6.000	0.486			

Table 8: Classification Results of unit ZX537 in Georgsfeld. List of selected independent EVs along with their maximum influence on the RSD accuracy, the RSD preliminary and final accuracy class and the standard uncertainty per assessed height.

2.3 RSD type-specific classification results

The variation in environmental conditions between the test-site and calibration site may influence the performance of a remote sensing device. Therefore, the main objective of the classification test is to identify the environmental variables that impact the RSD horizontal wind speed measurement and therefore quantify the RSD sensitivity to these EVs for many objective heights. In summary, the classification aims to present the quantitative uncertainty of horizontal wind measurements to be expected from the RSD with regards to its sensitivity to meteorological conditions.

The IEC [3] in its Annex L.2.9 establishes a procedure to combine all the classification results for every significant independent variable,

1. Interpolate the slope to the height of interest for every classification test,
2. Combine the slope from the various classification test using the following equation

$$m_i = \frac{1}{N}\sum_{n=1}^{N} m_{i,n} + \frac{m_{i,max} - m_{i,min}}{2\sqrt{3}} \quad (1)$$

where $\boldsymbol{m_i}$ is the combined slope of environmental variable $\boldsymbol{i}$, $\boldsymbol{m_{i,n}}$ is the sensitivity slope of environmental variable $\boldsymbol{i}$ resulted from the classification $\boldsymbol{n}$. $\boldsymbol{N}$ is total number of classification tests.

With the final slopes calculated using the IEC methodology of interpolating the slope for the objective heights (Table 12 in Annex A), the max influence can be derived multiplying the final EV sensitivity slope with its range (Table 9). The max influence indicates the maximum error that can occur assuming that the calibration and application tests take place under the opposite range of an environmental variable. The preliminary accuracy class is calculated adding in quadrature every EV max influence. The type-specific class is obtained dividing the preliminary accuracy class by square root of 2.

EV (Label)	Range Limits		Range	Bin width	Max number of bins	Unit	Source
	min	max					
Temperature Gradient (*ΔT*)	-0.02	0.06	0.08	0.002	40	$K \cdot m^{-1}$	IEC
Temperature (*T*)	0	40	40	2	20	°C	IEC
Wind direction (*dir*)	0	360	180	5	72	°	IEC
RSD data quality (*ava*)	10	48	38	4	10	-	RSD Specific
Turbulence intensity (*TI*)	0.03	0.24	0.21	0.01	21	-	IEC
Air density (ρ)	0.9	1.35	0.45	0.05	9	$Kg \cdot m^{-3}$	IEC
Wind veer (*Δdir*)	-0.2	0.2	0.4	0.04	10	$° \cdot m^{-1}$	N/A
Wind shear coef. (*α*)	-0.4	0.8	1.2	0.05	24	-	IEC
Rain	0	1	1	1	2	-	Def. Sensor
Flow inclination angle (*f_inc*)	-3	3	6	1	6	°	IEC

Table 9: EVs and their parameters used in the sensitivity analysis.

Table 10 shows the results of the IEC methodology for combining the outcome of all classification tests along with the preliminary accuracy class, the type-specific class and standard uncertainty per height.

Heights \ EVs	Max influence (m x Range)								Preliminary accuracy	Type specific class	Standard uncertainty
	Temperature Gradient	Air Temperature	Turbulence Intensity	Wind Veer	Wind Shear	Air Density	Rain	Flow inclination angle			
[m]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
135	-1.85	-1.81	0.46	0.60	-2.48	*	-0.59	0.71	3.78	2.67	1.54
130	-2.03	-1.34	0.62	0.57	-1.14	*	-0.60	1.17	3.11	2.20	1.27
125	-1.80	-1.37	0.70	0.59	-1.20	*	-0.96	1.07	3.07	2.17	1.25
120	-1.91	-1.13	0.78	0.58	-0.61	*	-0.92	0.96	2.83	2.00	1.16
115	-1.97	-0.90	0.87	0.57	-0.02	*	-0.87	0.86	2.70	1.91	1.10
110	-2.03	-0.66	0.95	0.57	0.57	*	-0.82	0.76	2.71	1.92	1.11
105	-2.09	-0.42	1.04	0.56	1.16	*	-0.77	0.65	2.88	2.04	1.18
100	-1.52	2.50	1.71	0.00	1.02	-0.45	-0.01	0.55	3.61	2.55	1.47
95	-1.18	1.96	1.47	0.12	1.17	-0.33	0.20	0.22	2.99	2.12	1.22
90	-0.82	1.42	1.43	0.23	1.31	-0.20	0.23	-0.11	2.57	1.81	1.05
85	-0.46	0.91	1.40	0.34	1.52	-0.07	0.25	-0.66	2.43	1.72	0.99
80	-0.10	0.57	1.50	0.47	1.68	0.05	0.28	-0.63	2.47	1.75	1.01
75	0.11	0.61	1.61	0.60	2.23	0.18	0.30	-0.59	2.96	2.10	1.21
70	0.14	1.11	1.33	0.72	2.79	0.31	0.28	-0.56	3.43	2.43	1.40
65	0.23	1.35	1.09	0.89	2.36	0.75	0.26	-0.52	3.21	2.27	1.31
60	0.23	1.77	0.86	1.04	2.05	1.13	0.24	-0.49	3.28	2.32	1.34
55	0.25	2.07	0.71	0.45	1.91	1.51	0.23	*	3.32	2.34	1.35
50	0.28	1.03	0.52	0.61	1.60	1.89	0.28	*	2.83	2.00	1.15
45	0.32	0.41	0.39	0.77	1.29	2.27	0.31	*	2.82	2.00	1.15
40	0.16	-0.22	0.27	0.93	0.99	2.66	0.35	*	3.03	2.14	1.24
35	0.10	-0.61	0.41	0.45	0.13	0.48	0.38	*	1.07	0.75	0.44
30	0.03	-0.76	0.53	0.34	-0.44	-0.41	0.41	*	1.23	0.87	0.50
25	0.02	-0.78	0.67	0.29	-1.01	-1.30	0.45	*	2.01	1.42	0.82
20	0.00	-0.71	0.82	0.23	-1.58	-2.18	0.48	*	2.95	2.09	1.21

* EV was not assessed in the height

Table 10: Type-specific class per 5 m height.

3 DERIVING APPLICATION UNCERTAINTY – A CALCULATION EXAMPLE

The type-specific class shown in Table 10 are the maximum wind speed measurement uncertainty that can be expected from the type ZX300 lidar due to difference in environmental conditions between verification and application site. In reality, this difference is unlikely to be as great as the used EV ranges (Table 9). Therefore, the category B uncertainty of the wind speed measurement due to the influence of environmental variables on the performance of the remote sensing device is calculated as follows,

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

where

$u_{class,i}$ is the ZX300 uncertainty of wind speed measurements in wind speed bin *i* due to influence of environmental variables;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of the results from a minimum of 3 classification tests. The values derived during the type classification reported here can be found in Table 12 in Annex A of this document;

$\bar{x}_{app,j,i}$ is mean value of the environmental variable j in wind speed bin *i* as present during the application test;

$\bar{x}_{ver,j,i}$ is mean value of the environmental variable j in wind speed bin *i* as present during the verification test.

As an example of how to combine the verification and application uncertainty, Table 11 presents the environmental condition per wind speed bin from hypothetical verification and application tests. The classification uncertainty (%) column presents the derived uncertainty calculated by applying Equation 2 for combining the individual uncertainty contributions from each environmental variable. Assuming that the classification and verification uncertainty are independent, adding them in quadrature leads to the final combined uncertainty (%). This is then multiplied by the mean bin wind speed and divided by 100 to convert to a wind speed uncertainty in m/s.

Application Classification Uncertainty @ 100m																															
Wind speed				Temperature gradient			Temperature			Turbulence intensity			Air density			Wind veer			Wind shear coef.			Flow inclination angle			Rain			Uncertainty (k = 1)			
				Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Ver	App	Unc	Classification	Verification	Combined	
BIN lower [m/s]	BIN upper [m/s]	nbin ver	nbin app	[K/m *10^3]	[K/m *10^3]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[-]	[-]	[%]	[%]	[%]	[%]	[m/s]
3.75	4.25	221	579	6.4	-3.0	-0.21	3.34	16.65	0.83	0.08	0.14	0.41	1.261	1.207	-0.05	0.06	0.10	0.00	0.30	0.24	0.05	0.07	-0.24	0.03	1.00	1.00	0.00	0.96	2.28	2.47	0.10
4.25	4.75	256	735	4.6	-0.5	-0.12	3.33	16.81	0.84	0.09	0.13	0.27	1.258	1.210	-0.05	0.03	0.10	0.00	0.35	0.26	0.08	-1.22	-0.66	0.05	1.00	1.00	0.00	0.90	2.12	2.31	0.10
4.75	5.25	321	804	5.7	-0.1	-0.13	3.25	17.47	0.89	0.08	0.12	0.31	1.260	1.209	-0.05	0.06	0.10	0.00	0.31	0.24	0.06	-1.01	-0.51	0.05	1.00	1.00	0.00	0.95	2.05	2.26	0.11
5.25	5.75	452	804	6.2	-1.6	-0.18	3.49	16.93	0.84	0.07	0.13	0.39	1.260	1.209	-0.05	0.06	0.08	0.00	0.32	0.19	0.10	-0.70	-0.64	0.01	1.00	1.00	0.00	0.95	2.00	2.22	0.12
5.75	6.25	551	635	4.8	-2.6	-0.17	3.63	16.49	0.80	0.08	0.13	0.36	1.259	1.208	-0.05	0.05	0.06	0.00	0.35	0.19	0.13	-0.97	-0.86	0.01	1.00	1.00	0.00	0.91	1.93	2.14	0.13
6.25	6.75	586	374	3.5	-1.6	-0.12	3.65	15.90	0.77	0.08	0.13	0.38	1.257	1.208	-0.05	0.03	0.04	0.00	0.35	0.21	0.12	-0.94	-0.96	0.00	1.00	1.00	0.00	0.87	2.11	2.28	0.15
6.75	7.25	544	255	3.3	-3.5	-0.15	3.95	15.11	0.70	0.08	0.15	0.47	1.257	1.211	-0.05	0.03	0.03	0.00	0.34	0.22	0.11	-0.92	-0.77	0.01	1.00	1.00	0.00	0.86	2.01	2.19	0.15
7.25	7.75	491	179	3.2	-2.7	-0.13	3.88	14.77	0.68	0.08	0.15	0.51	1.256	1.213	-0.04	0.02	0.03	0.00	0.36	0.22	0.12	-1.02	-1.05	0.00	1.00	1.00	0.00	0.87	1.95	2.13	0.16
7.75	8.25	413	130	2.0	-3.1	-0.12	3.90	14.37	0.65	0.09	0.16	0.54	1.253	1.208	-0.05	0.01	0.02	0.00	0.35	0.20	0.13	-0.99	-0.76	0.02	1.00	1.00	0.00	0.86	1.68	1.89	0.15
8.25	8.75	428	133	1.4	-5.2	-0.15	3.70	14.43	0.67	0.09	0.16	0.53	1.252	1.209	-0.04	0.00	0.01	0.00	0.35	0.20	0.13	-1.07	-0.65	0.04	1.00	1.00	0.00	0.88	1.73	1.94	0.16
8.75	9.25	374	94	1.4	-5.5	-0.16	3.93	14.18	0.64	0.09	0.17	0.57	1.251	1.213	-0.04	0.00	0.01	0.00	0.34	0.19	0.13	-1.00	-0.77	0.02	1.00	1.00	0.00	0.88	1.57	1.80	0.16
9.25	9.75	332	86	0.2	-7.9	-0.18	4.00	13.54	0.60	0.10	0.17	0.49	1.250	1.213	-0.04	-0.01	0.00	0.00	0.32	0.16	0.13	-1.44	-1.16	0.03	1.00	1.00	0.00	0.81	1.54	1.74	0.17
9.75	10.25	320	70	-1.0	-7.1	-0.14	4.42	13.27	0.55	0.10	0.15	0.37	1.247	1.211	-0.04	-0.02	0.00	0.00	0.30	0.17	0.11	-1.43	-1.13	0.03	1.00	1.00	0.00	0.69	1.35	1.52	0.15
10.25	10.75	247	42	-1.7	-5.5	-0.09	4.43	13.39	0.56	0.11	0.17	0.45	1.247	1.212	-0.04	-0.02	0.01	0.00	0.28	0.20	0.07	-1.40	-1.38	0.00	1.00	1.00	0.00	0.72	1.33	1.51	0.16
10.75	11.25	254	46	-2.1	-5.1	-0.07	4.85	11.80	0.43	0.11	0.16	0.35	1.247	1.211	-0.04	-0.03	0.00	0.00	0.28	0.18	0.08	-1.22	-1.44	0.02	1.00	1.00	0.00	0.57	1.33	1.44	0.16
11.25	11.75	282	16	-2.4	-4.1	-0.04	5.09	11.74	0.42	0.11	0.16	0.39	1.247	1.209	-0.04	-0.03	-0.01	0.00	0.26	0.21	0.05	-0.59	-1.58	0.09	1.00	1.00	0.00	0.58	1.44	1.56	0.18
11.75	12.25	305	18	-2.2	-3.0	-0.02	5.69	12.73	0.44	0.11	0.15	0.31	1.243	1.203	-0.04	-0.03	0.00	0.00	0.25	0.17	0.07	-0.63	-1.68	0.10	1.00	1.00	0.00	0.55	1.49	1.59	0.19
12.25	12.75	269	21	-2.3	-3.1	-0.02	5.93	11.03	0.32	0.11	0.17	0.40	1.242	1.207	-0.03	-0.02	-0.01	0.00	0.25	0.19	0.05	-0.59	-1.52	0.09	1.00	1.00	0.00	0.52	1.27	1.37	0.17
12.75	13.25	246	10	-2.8	-0.6	-0.05	6.40	9.88	0.22	0.11	0.15	0.29	1.240	1.205	-0.04	0.01	-0.01	0.00	0.24	0.17	0.06	-0.77	-1.39	0.06	1.00	1.00	0.00	0.38	1.39	1.44	0.19
13.25	13.75	196	7	-3.2	-1.9	-0.03	6.49	9.80	0.21	0.11	0.16	0.35	1.240	1.203	-0.04	0.02	-0.01	0.00	0.24	0.14	0.09	-0.77	-2.39	0.15	1.00	1.00	0.00	0.44	1.23	1.31	0.18
13.75	14.25	185	4	-3.3	-0.9	-0.05	6.19	9.23	0.19	0.12	0.18	0.46	1.243	1.198	-0.04	-0.03	-0.03	0.00	0.24	0.17	0.06	-0.95	-2.10	0.11	1.00	1.00	0.00	0.51	1.66	1.74	0.24
14.25	14.75	146	3	-3.5	-1.0	-0.06	6.15	9.40	0.20	0.12	0.17	0.37	1.242	1.157	-0.09	-0.03	-0.03	0.00	0.23	0.19	0.04	-0.64	-1.92	0.12	1.00	1.00	0.00	0.45	1.46	1.53	0.22
14.75	15.25	147	3	-3.5	-1.1	-0.05	6.30	9.60	0.21	0.12	0.15	0.26	1.240	1.207	-0.03	0.02	-0.03	0.00	0.24	0.21	0.03	-0.62	-1.87	0.11	1.00	1.00	0.00	0.36	1.26	1.31	0.20
15.25	15.75	98	4	-3.9	-1.1	-0.06	6.27	9.50	0.20	0.12	0.15	0.23	1.241	1.201	-0.04	0.01	-0.01	0.00	0.23	0.20	0.02	-0.63	-1.86	0.11	1.00	1.00	0.00	0.33	1.06	1.11	0.17
15.75	16.25	92	5	-3.8	-1.0	-0.06	6.38	9.20	0.18	0.12	0.17	0.35	1.240	1.203	-0.04	0.02	-0.02	0.00	0.23	0.18	0.04	-0.75	-2.20	0.13	1.00	1.00	0.00	0.43	0.66	0.79	0.13

Table 11: Example of combining uncertainty of a hypothetical verification and application test.

4 IMPORTANT REMARKS AND LIMITATIONS

The final accuracy classes and standard uncertainties presented in section 2.3 of this report represent the maximum values that could be applied due to differences in environmental conditions between the verification and the application test. The example in section 3 shows how, in practice, the uncertainty due to environmental conditions can be much smaller than the standard uncertainty calculated from the accuracy class.

DNV GL have independently followed the methodology defined in the latest version of the IEC 61400-12-1. Four classification trials were analysed covering three Lidars at three locations, with one Lidar classified at two of the locations and two Lidars classified at one of the locations, fully meeting the IEC criteria for a type classification. The outcome of the given methodology is the final accuracy class per height of ZX Lidars' type ZX300 lidar, shown in Table 10.

DNV GL do not take responsibility for how these results are used.

5 CONCLUSION

A type-specific classification based on the IEC 61400-12-1, Ed. 2 [3] for the ZX Lidars' type ZX300 lidar was independently conducted by DNV GL.

The main significant environmental variables which influenced the wind measurement of the type ZX300 lidar are

- temperature gradient,
- air temperature,
- turbulence intensity,
- wind shear,
- wind veer,
- rain flag,
- and flow inclination angle.

The type-specific class numbers were given in discrete heights from 20 m to 135 m in 5 m steps. The type-class range between 0.71 % at 35 m and 2.64 % at 135 m.

6 REFERENCES

[1] DNV GL - Energy, „Classification and performance assessment of a ZX Lidars' type ZX300 lidar at Janneby - ZX703,“ Hamburg, 2018.

[2] DNV GL - Energy, „Classification and performance assessment of a ZX Lidars' ZX300 lidar at Georgsfeld - ZX537,“ Hamburg, 2018.

[3] IEC 61400-12-1 International Standard. Part 12-1, *Power performance measurements of electricity producing wind turbines,* International Electrotechnical Commission, Edition 2.0 2017-03.

[4] W. Barker, J. Gottschall, M. Harris, J. Medley, B. d. E. Roziers, C. Slinger and M. Pitter, "Correlation effects in the field classification of ground based remote wind sensors," in *Europe's Premier Wind Energy Event*, Barcelona, Spain, 2014.

APPENDIX A COMBINED SLOPES

EVs / Heights	Temperature Gradient	Air Temperature	Turbulence Intensity	Wind Veer	Wind Shear	Air Density	Rain	Flow inclination angle
[m]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
135	-23.1	-0.045	1.90	1.51	-2.07	*	-0.59	0.12
130	-25.4	-0.034	2.57	1.43	-0.95	*	-0.60	0.19
125	-22.5	-0.034	2.90	1.46	-1.00	*	-0.96	0.18
120	-23.9	-0.028	3.26	1.45	-0.51	*	-0.92	0.16
115	-24.7	-0.022	3.62	1.43	-0.02	*	-0.87	0.14
110	-25.4	-0.016	3.97	1.42	0.48	*	-0.82	0.13
105	-26.1	-0.011	4.33	1.41	0.97	*	-0.77	0.11
100	-22.8	0.062	7.11	0.01	0.85	-1.01	-0.01	0.09
95	-18.9	0.049	6.12	0.30	0.97	-0.73	0.20	0.04
90	-14.7	0.035	5.94	0.58	1.09	-0.44	0.23	-0.02
85	-10.2	0.023	5.83	0.85	1.27	-0.16	0.25	-0.11
80	-5.7	0.014	6.26	1.17	1.40	0.12	0.28	-0.10
75	-1.3	0.015	6.71	1.49	1.86	0.40	0.30	-0.10
70	1.4	0.028	5.52	1.81	2.32	0.68	0.28	-0.09
65	1.8	0.034	4.53	2.21	1.97	1.66	0.26	-0.09
60	2.9	0.044	3.57	2.61	1.71	2.51	0.24	-0.08
55	2.8	0.052	2.94	1.12	1.59	3.36	0.23	*
50	3.2	0.026	2.17	1.52	1.33	4.20	0.28	*
45	3.4	0.010	1.64	1.92	1.08	5.05	0.31	*
40	4.0	-0.005	1.11	2.33	0.82	5.90	0.35	*
35	2.0	-0.015	1.71	1.13	0.11	1.06	0.38	*
30	1.2	-0.019	2.19	0.85	-0.37	-0.91	0.41	*
25	0.4	-0.019	2.80	0.71	-0.84	-2.88	0.45	*
20	0.2	-0.018	3.40	0.57	-1.32	-4.85	0.48	*

* EV was not assessed in the height

Table 12: Combined slope using interpolation between heights.

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.