ZX Lidars

New Continuous Wave Lidar Performance Verifications at 200m and 300m

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Contents

Uncertainty

ZX Lidars

14/11/2025

- Uncertainty is the key tool available to Developers to justify measurement costs.

- Several elements contribute to the uncertainty of a Lidar at the device level:

    - Calibration (verification) uncertainty
    - Off site
    - On site

- Classification uncertainty
- Mounting uncertainty
- Flow complexity uncertainty

Classification results

- Three ZX 300e Lidars were deployed in five campaigns across three test sites during 2025.
- Approved IEC test sites: Hanover (Geo-Net), Janneby (Pavana) and the UK Remote Sensing Test Site (ZX & DNV).
- Classification spans 21m to 200m, methodology complies with IEC 61400-50-2 standard. Sensitivities were measured for three lidars down to 21m at the UK Remote Sensing Test Site.
- **No significant environmental variables were found resulting in a final accuracy class and standard uncertainty of 0% at all heights from 21 – 200 m**
- **A very extensive Lidar Classification covering the widest height range to date, and many data sets / Lidars included.**
- **Result = Lowest standard uncertainty possible.**

Height (m)	Class (%)	Std Uncertainty (%)
200	0	0
190	0	0
180	0	0
170	0	0
160	0	0
150	0	0
140	0	0
130	0	0
120	0	0
110	0	0
100	0	0
90	0	0
80	0	0
70	0	0
60	0	0
50	0	0
40	0	0
30	0	0
21	0	0

IEC test site Janneby (Pavana) with Lidars and 200m met mast, and ZX 300e's 20-200m IEC Classification

Performance verifications

- **Many ZX 300e's have already been extensively verified during 2025.**
- **Best practice criteria: Correlation gradients within +/-1% of unity with correlation coefficients greater than 0.985.**
- At 200m masts, mast-lidar correlation parameters met **all** wind industry best practice criteria with **data availability above 85% at all heights up to 200m.**
- A fleet of ZX 300e units verified at a 91m mast in the UK. The mast-lidar correlation parameters from all the units met **all** wind industry best practice criteria with **data availability above 97% at all heights.**
- The same fleet were also verified against Midar ('Mast' + 'Lidar') up to 200m. Midar-lidar correlation parameters from all the units also met **all** wind industry best practice criteria with **data availability above 95% up to 300m.**
- At a highly complex site, CFD correction factors were successfully applied to the wind speeds. This yielded mast-lidar correlation parameters that met **all** wind industry best practice criteria.

21/06 - 23/09/25				Hanover	ZX6003			
Height (m)	59	79	99	119	139	159	179	199
Gradient [0.98<X<1.02]	1.008	1.005	1.000	1.002	0.999	0.999	0.996	0.992
R-squared [>0.98]	0.989	0.990	0.990	0.990	0.989	0.990	0.988	0.986
Direction accuracy (%)	99.9	100.0	99.9	99.9	100.0	100.0	100.0	99.9
Availability (%)	99.1	99.1	98.8	98.0	97.6	97.2	96.8	96.6

23/05 - 13/08/25				Hanover	ZX6004			
Height (m)	59	79	99	119	139	159	179	199
Gradient [0.98<X<1.02]	1.011	1.007	1.001	1.002	1.000	1.000	1.000	0.996
R-squared [>0.98]	0.991	0.991	0.989	0.989	0.989	0.987	0.987	0.986
Direction accuracy (%)	100.0	100.0	100.0	100.0	99.9	100.0	99.9	99.9
Availability (%)	99.6	99.6	99.2	98.2	97.4	97.1	97.3	97.5

17/02/25 - 18/05/25				Pavana	ZX6002				
Height (m)	39	59	79	99	119	139	159	179	199
Gradient [0.98<X<1.02]	1.008	1.010	1.004	1.001	1.003	1.005	1.000	0.999	0.994
R-squared [>0.98]	0.997	0.996	0.995	0.994	0.995	0.994	0.991	0.992	0.992
Direction accuracy (%)	99.8	99.8	99.8	99.8	100.0	99.8	99.7	99.7	99.8
Availability (%)	99.0	98.2	96.4	94.9	93.3	92.0	91.0	89.4	86.8

19/02/25 - 20/05/25				Pavana	ZX6003				
Height (m)	39	59	79	99	119	139	159	179	199
Gradient [0.98<X<1.02]	1.004	1.007	1.001	0.998	1.001	1.002	0.997	0.995	0.991
R-squared [>0.98]	0.996	0.996	0.994	0.993	0.994	0.993	0.990	0.991	0.991
Direction accuracy (%)	99.8	99.9	99.9	99.9	100.0	99.8	99.7	99.7	99.7
Availability (%)	98.9	98.1	96.3	94.4	93.1	91.6	90.8	88.8	86.1

23/05 - 13/08/25		Janneby	ZX6101	
Height (m)	28	56	74	102
Gradient [0.98<X<1.02]	0.999	1.007	0.998	0.993
R-squared [>0.98]	0.983	0.992	0.991	0.990
Direction accuracy (%)	99.9	100.0	100.0	99.9
Availability (%)	99.6	99.3	98.8	98.3

10/05 -13/08/25	Pershore	ZX6104		
Height (m)	20	45	70	91
Gradient [0.98<X<1.02]	1.008	1.001	1.001	0.994
R-squared [>0.98]	0.995	0.997	0.996	0.996
Direction accuracy (%)	100.0	100.0	100.0	100.0
Availability (%)	99.9	99.9	99.9	99.8

Lifting the limits on Lidar verifications due to mast heigh

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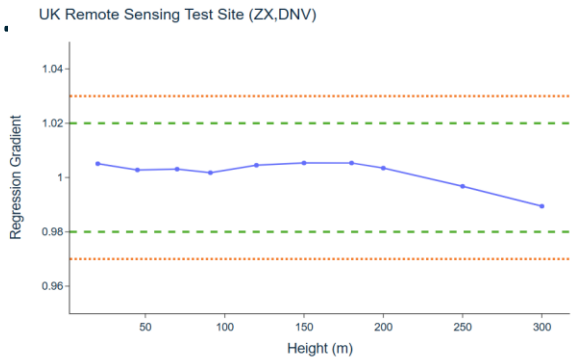
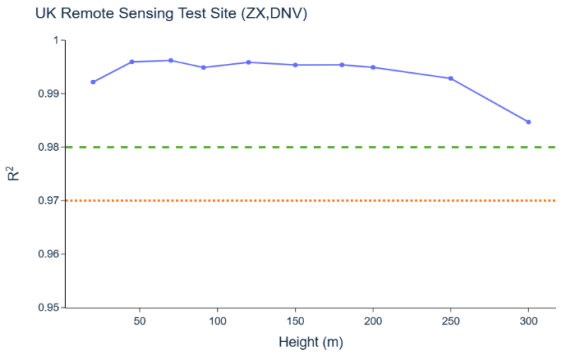
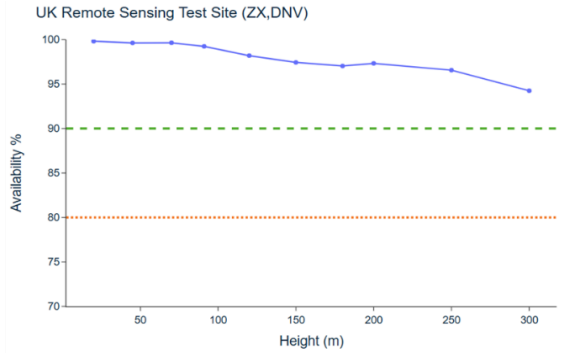
- **Could collective trust in Lidar be leveraged to go beyond existing mast verification heights?**
- At Pershore (IEC compliant site) a Lidar was verified against the 91m met mast, and against reference Lidars (200m mast traceability with known and low uncertainties, 0% standard Classification uncertainty.)
- Verified Lidar then mounted at the top of the 91m met mast to extend the mast range.
- This **Midar** (‘Mast’ + ‘Lidar’) configuration allows additional ground-based lidar verifications to be traceable against verified references (mast and Midar) up to 300m above ground level
- **Accuracy and data availability analysed across a ZX300e fleet with all industry KPI’s met and exceeded up to and including 300m.**
- Green = DNV best practice, Orange = DNV minimum acceptance criteria







ZX300e

ZX Lidars

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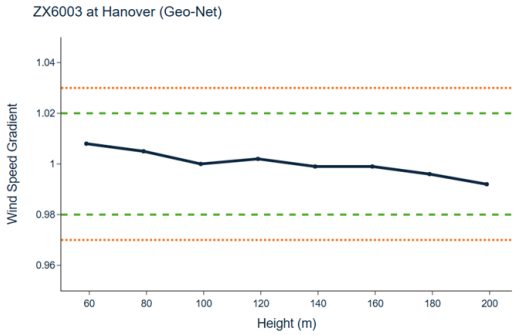
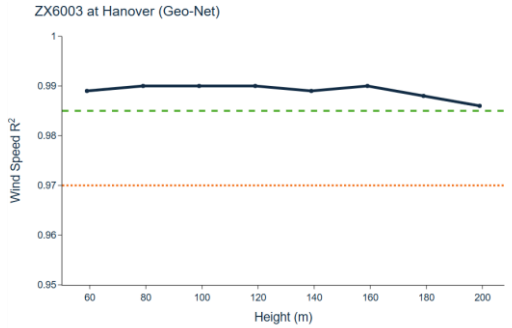
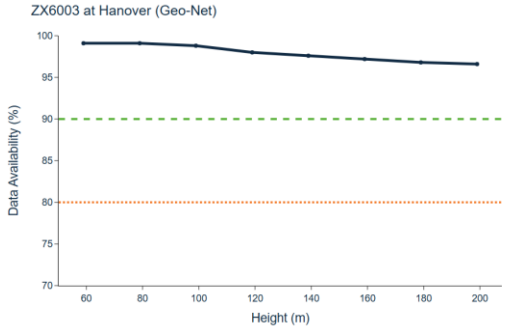
Performance verifications

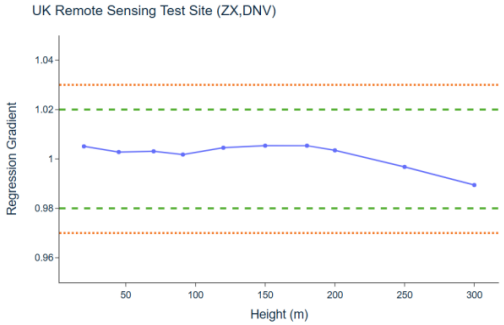
200 metres

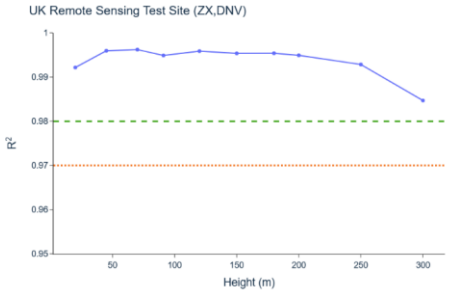


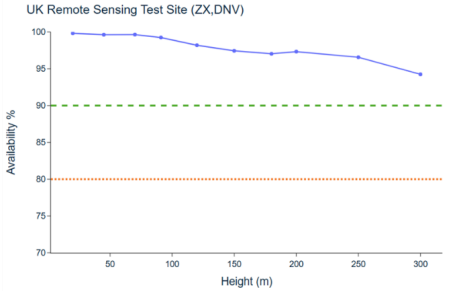




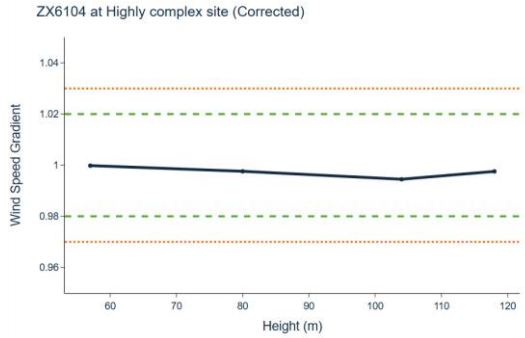
300 metres (fleet average)

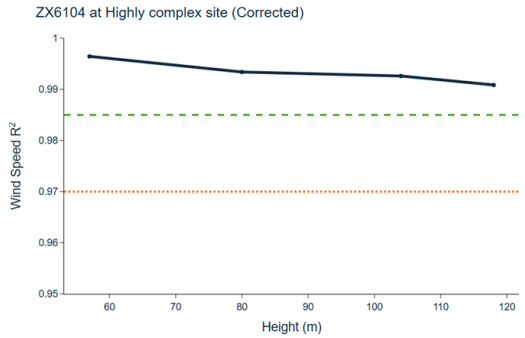


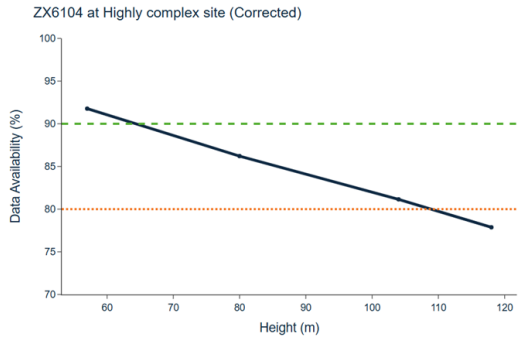




Complex terrain







Eliminating CW directional uncertainty

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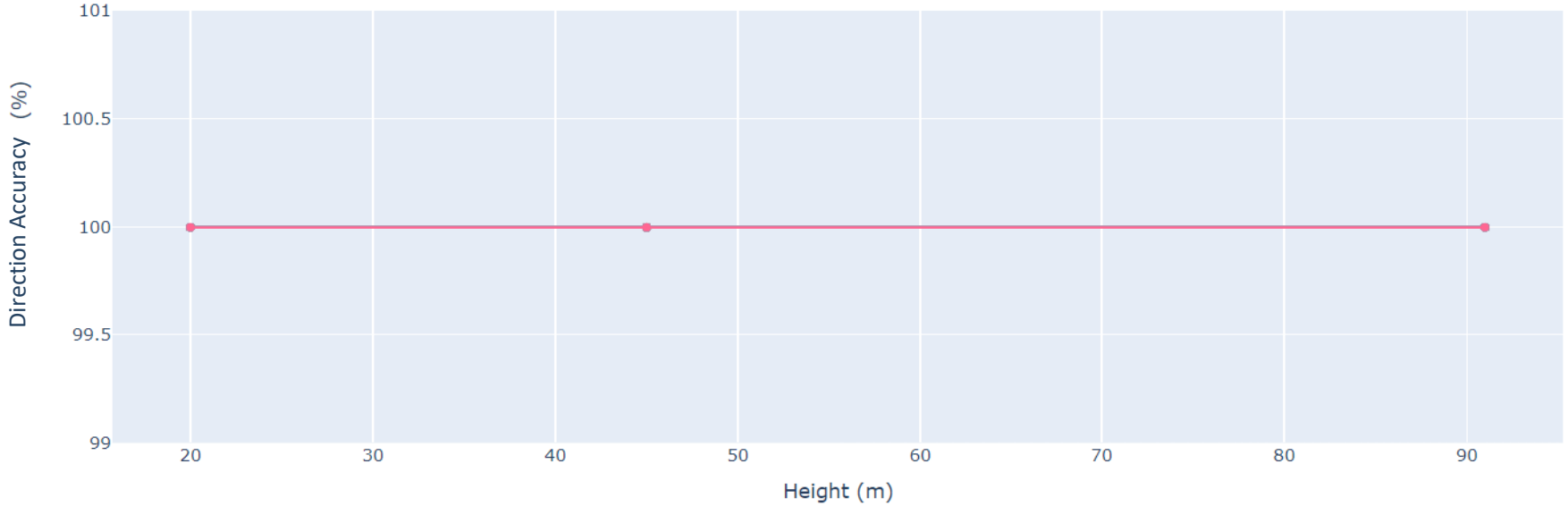
- Previous CW Lidars have occasional directional ambiguity under certain wind flow conditions
- Extra processing required, generally no additional uncertainty added
- Using the mast as a reference the differences between 10-minute averaged wind directions measured by the mast and the fleet of lidars was computed
- **ZX 300e accurately measures wind direction to within +/- 0.5 degree**
- No direction ambiguity, no need to further process any measured data
- Onboard met station still available (temperature, pressure, humidity, GPS)

- **Makes handling of data easier.**



Cup-equivalent Turbulence Intensity validation

ZX Lidars

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- **A fresh approach to comparison between cup TI and Lidar TI.**
- **ZX 'METICE'**: Multi-site Ensemble Turbulent Intensity Cup Equivalence leveraging Artificial Neural Network and Models.
- Can be used on any ZX Wind10 data file to produce new TI outputs.
- Evaluated across more than 17 sites…and counting, simple and complex terrain, and with varying stability conditions.

- **We need more data, more ZX data sets, more 'high quality mast datasets.**
- **Why? To support ongoing wind turbine OEM acceptance of Lidar TI and address barriers for adoption.**
- **Use cases: EYA, power performance measurement, load calculation, lifetime extension.**

21/06 - 23/09/25				Hanover	ZX6003			
Height (m)	59	79	99	119	139	159	179	199
TI Gradient [0.95<X<1.05]	1.000	1.004	1.001	0.988	0.987	0.962	0.960	1.000
TI R-squared [X > 0.7]	0.934	0.925	0.904	0.884	0.876	0.770	0.718	0.785
TI R-squared (DNV)	0.989	0.984	0.977	0.970	0.967	0.934	0.915	0.932

23/05 - 13/08/25				Hanover	ZX6004			
Height (m)	59	79	99	119	139	159	179	199
TI Gradient [0.95<X<1.05]	0.999	1.000	1.008	0.999	0.993	0.993	0.992	1.012
TI R-squared [X > 0.7]	0.919	0.915	0.900	0.888	0.869	0.824	0.799	0.751
TI R-squared (DNV)	0.990	0.986	0.980	0.976	0.970	0.957	0.948	0.930

17/02/25 - 18/05/25				Pavana	ZX6002				
Height (m)	39	59	79	99	119	139	159	179	199
TI Gradient [0.95<X<1.05]	0.990	0.983	1.007	1.011	0.998	1.002	1.030	1.024	1.020
TI R-squared [X > 0.7]	0.901	0.907	0.879	0.852	0.847	0.821	0.777	0.765	0.744
TI R-squared (DNV)	0.991	0.987	0.980	0.973	0.970	0.962	0.945	0.939	0.928

19/02/25 - 20/05/25				Pavana	ZX6003				
Height (m)	39	59	79	99	119	139	159	179	199
TI Gradient [0.95<X<1.05]	0.998	0.993	1.013	1.019	1.005	1.014	1.039	1.032	1.031
TI R-squared [X > 0.7]	0.893	0.907	0.883	0.844	0.844	0.812	0.783	0.758	0.735
TI R-squared (DNV)	0.991	0.987	0.981	0.972	0.970	0.960	0.947	0.938	0.928

10/10/24 - 08/01/25		Pershore	ZX6101	
Height (m)	20	45	70	91
TI Gradient [0.95<X<1.05]	0.998	0.985	0.990	1.006
TI R-squared [X > 0.7]	0.792	0.879	0.861	0.817
TI R-squared (DNV)	0.991	0.991	0.985	0.976

23/05 - 13/08/25		Janneby	ZX6101	
Height (m)	28	56	74	102
TI Gradient [0.95<X<1.05]	0.934	0.958	0.961	0.968
TI R-squared [X > 0.7]	0.671	0.847	0.852	0.828
TI R-squared (DNV)	0.986	0.985	0.982	0.975

Thank you

ZX300e