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IEC 61400-50-3 – compliant wind speed measurements with a ZX TM nacelle-mounted lidar: A case study in uncertainty analysis

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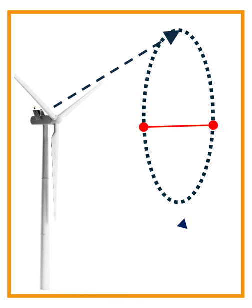
ZX Lidars

Uncertainties of 1.3% can be achieved when using a ZX TM nacelle-mounted lidar to measure wind speed. After accounting for terrain, the only significant uncertainty contribution in this case study was the uncertainty in the calibration of the lidar.

An IEC-compliant assessment of ZX TM nacelle-mounted lidar measurements has been reported by DNV [1], following the IEC 61400-50-3 standard [2].

Here we present a thorough case study deriving uncertainties for hub-height horizontal wind-speed (HWS) measurements made by a ZX TM on a 3 MW turbine in central USA.

ZX TM is a continuous-wave lidar that makes 50 line-of-sight (LOS) wind speed measurements every 1-second scan.



Precise motion sensors ensure LOS measurement data is used from locations close to hub-height.

Wind field reconstruction (WFR) is treated as a "black box" **in** IEC 61400-50-3:

Uncertainties in "final values", such as HWS, are derived from contributions from

- Intermediate value calibration;
- Intermediate value sensitivity to environmental variables (EVs);
- Terrain considerations;
- Operational conditions - the assumption of zero uncertainty due to EV effects on WFR is dependent upon a suitable evidence base.

References

[1] ***Device Type Uncertainty Assessment following IEC 61400-50-3 for the ZX TM nacelle lidar*****, DNV Report 10448127-HOU-R-1, Issue B, Nov 2023.**

[2] ***Wind energy generation systems - Part 50-3: Use of nacelle-mounted lidars for wind measurements*****, IEC 61400-50-3:2022.**

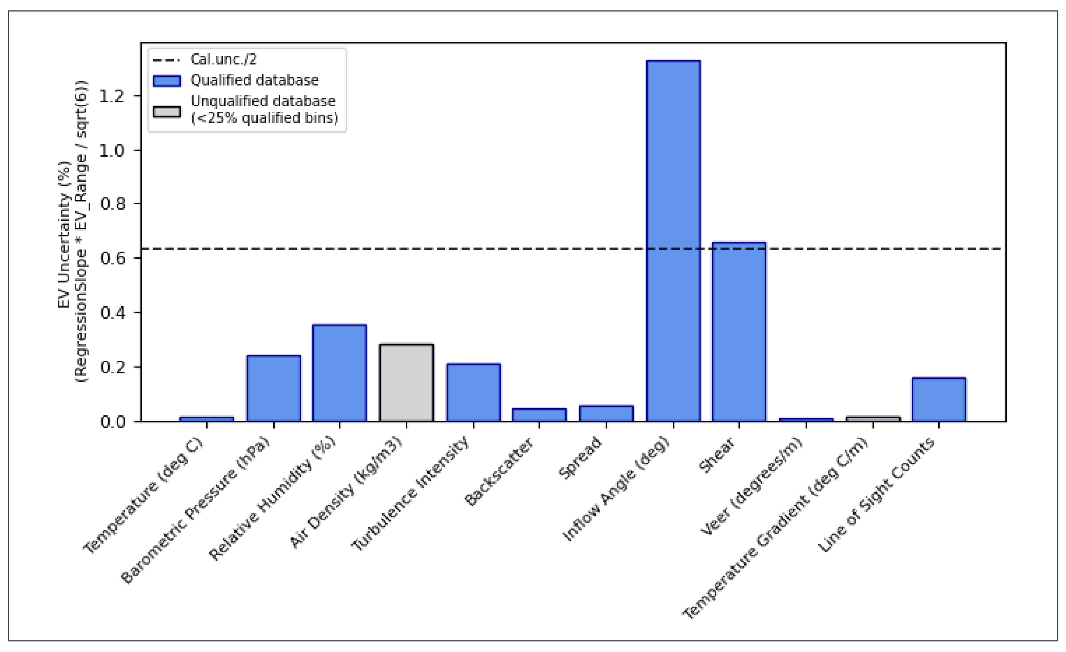
[3] ***ZX TM measurement uncertainty following IEC 61400-50-3: The influence of uncertainties in the intermediate values,*** **ZX Lidars report: ZXL/CS/RPT/00005.**

Uncertainty propagation through WFR is assessed by differentiation of the WFR algorithm with respect to intermediate values and combining the contributions:

$$U_s = \sqrt[2]{\left(\frac{\partial s}{\partial \theta_i}.U_{\theta_i}\right)^2 + \left(\frac{\partial s}{\partial \theta_c}.U_{\theta_c}\right)^2 + \left(\frac{\partial s}{\partial \varphi'}.U_{\varphi'}\right)^2 + \left(\frac{\partial s}{\partial V_L}.U_{V_L} + \frac{\partial s}{\partial V_R}.U_{V_R}\right)^2 + \left(\frac{\partial s}{\partial r}.U_r\right)^2}$$

where s is horizontal wind speed, θ_i, θ_c and φ are lidar inclination, scan-cone and scan-phase angles respectively, r is measurement range and V_L and V_R are LOS speeds from left and right of the scan. U_s, etc, denote the uncertainty in the parameter in the subscript. Note that U_{V_L} and U_{V_R} are correlated as ZX TM uses a single scanning beam.

Empirical sensitivity analysis results indicate significant correlation between LOS speed accuracy and two EVs: shear and inflow angle:



(Figure from [1], reproduced courtesy of DNV)

It is unclear how either of these EVs could affect a horizontal lidar beam, but for this study the uncertainty is assigned to the lidar measurement.

Theoretical sensitivity analysis is required for EVs that cannot be assessed empirically. From in-house analysis [3], non-linear variation of wind speed within the probe has been identified as the dominant contribution.

Analysis of the evidence base (without height correction) adds a small operational uncertainty at low wind speeds.

In this case study, a calibrated ZX TM was deployed on the nacelle of a turbine of hub height 89m, rotor diameter D=127m, measuring at a range of 283m (2.2D). Data from the sector [154°, 200°] forms part of the evidence base in [1] as the terrain is simple enough.

Analysis of terrain data in 10° sectors yields campaign mean values for inflow (assuming wind flow follows terrain along the lidar probe length) and the difference between hub and measurement heights:

Sector	154°-160°	160°-170°	170°-180°	180°-190°	190°-200°	Total / Mean
Observations	924	873	612	549	300	3258
Slope/Inflow	-0.9°	-0.1°	0.0°	+0.3°	+0.7°	-0.17°
Height difference	+3.9m	+2.9m	+1.6m	+0.6m	-0.1m	+2.3m

Uncertainty due to LOS sensitivity to EVs is calculated by multiplying the difference between campaign and calibration means by the sensitivity for the significant EVs:

EV	Calibration Mean	Campaign Mean	Sensitivity	Uncertainty
Shear	0.216	0.170	1.339	0.06%
Inflow	+0.12°	-0.17°	0.544	0.16%

Uncertainty due to measurement height difference can be assessed using equation (A.11) from [2], if no height correction is applied. Using a wind-shear exponent of 1.5 times campaign mean gives a value of 0.65%.

However, if height correction is applied, equation (A.12) from [2] should be used. As ZX TM automatically accounts for lidar inclination, measurement height uncertainty has been taken as 1 m. With a shear exponent uncertainty of 0.05 and LOS speed uncertainty of 1.3%, the resulting contribution is negligible (0.01%).

Combining contributions (assuming height correction is applied) leads to the following combined uncertainties in measured HWS:

HWS	Uncertainty contribution (%)										Combined	
(m/s)	LOS cal	LOS shear	LOS inflow	LOS nonlin	op lidar	terrain	inc	cone	phase	range	(%)	(m/s)
4.0	1.41	0.06	0.16	0.07	0.16	0.01	0.09	0.04	0.00	0.03	1.43	0.06
6.0	1.29	0.06	0.16	0.07	0.00	0.01	0.09	0.04	0.00	0.03	1.31	0.08
8.0	1.25	0.06	0.16	0.07	0.00	0.01	0.09	0.04	0.00	0.03	1.27	0.10
10.0	1.22	0.06	0.16	0.07	0.00	0.01	0.09	0.04	0.00	0.03	1.24	0.12
12.0	1.26	0.06	0.16	0.07	0.00	0.01	0.09	0.04	0.00	0.03	1.28	0.15

IEC-compliant HWS uncertainties of 1.3% have been assessed for this ZX TM deployment. This figure is dominated by the LOS speed calibration uncertainty.

For this simple site, uncertainty would increase to 1.4% if terrain effects were not accounted for. In more complex terrain, careful analysis of the influence of the terrain on HWS is recommended to avoid extra measurement uncertainty.