VALIDATION OF LIDAR MEASUREMENTS IN EXTREMELY COMPLEX TERRAIN

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Abstract

The aim of this study is to analyse the adequacy of using ground base continuous wave LIDAR technologies in very complex sites, for reproducing critical wind variables in wind resource analysis and site assessment. As a test, an extremely complex site was selected, with a mean altitude of 1100 m and slopes that can reach 30 deg. near the LIDAR device.

Comparisons between horizontal wind speed, wind direction, turbulence intensity, and vertical wind speed and inflow angle measured values in the LIDAR and in a nearby mast were carried out.

Due to the existing extreme climatic and topographic conditions, a LIDAR detailed data treatment and validation, directional analysis of wind speed and significant variables, and in-depth study of correction factors to apply (using a CFD model in this case) was required. Detailed results of the data analysis carried out and magnitude and behaviour of correction factors are presented.

Relevant and positive conclusions concerning the accuracy of LIDAR measurements when reproducing the mean and directional behaviour of wind speed were obtained.

Relative deviations between LIDAR and mast measurements were significant in the case of turbulence intensity and maximum wind speed values, therefore the validity of the analysed LIDAR technology for site assessment studies in very complex sites could not be confirmed.

A considerable decrease of LIDAR data availability with height was detected, probably due to the low aerosol presence at such altitude and the unfavourable climatic conditions present at site (fog and others).

Abbreviations

CFD: Computational Fluid Dynamics

IEC: International Electrotecnical Commision

LIDAR: Light Detection and Ranging

WS: Wind Speed

TI: Turbulence Intensity

VWS: Vertical wind speed

1. Introduction

Currently, RSD (Remote Sensing Devices) technologies such as LIDAR are expected to reduce the measurement uncertainty and improve the annual energy production estimation.

However, in complex terrain the problem of a ground base continuous wave LIDAR, is that non-uniform flow across the LIDAR scan disk may result in a breakdown of the model assumptions and lead to a different measurement when compared to a single point mast located with cup anemometers.

The LIDAR error in complex terrain depends mainly on the curvature of the flow (not on the opening angle or other issues) therefore an analysis with a CFD (Computational Fluid Dynamics) model can be performed with the aim of applying a correction factor to the LIDAR measurements which could reduce the existing bias.

Meteodyn^{WT} CFD model, which has a specific module for analysing LIDAR complex terrain corrections, was run internally in the present work in order to obtain a suitable set of correction factors.

Therefore, one of the required activities of this study was the calculation of correction factors with the CFD model, and the analysis of the most suitable model parametrization for this extremely complex site.

Results of the validation tests of a ground base continuos wave LIDAR in complex terrain are presented in next sections, once the LIDAR measurements have been corrected by the suitable factors. The selected site for validation was an Iberdrola operational wind farm located in north of Spain (Cantabria), which has very high terrain complexity.

Wind data (horizontal wind speed, vertical wind speed, wind direction and other variables) obtained by the LIDAR and by conventional meteorological sensors installed next to the LIDAR in an IEC compliant meteorological mast were compared.

2. Methodology

2.1 Test site description

The main differentiating feature of the present study is the extreme complexity and harsh climatic conditions of the analysed site. However surface roughness is not significant and there are no obstacles at the site. Next figure shows the wind farm area, LIDAR location and slopes at site.

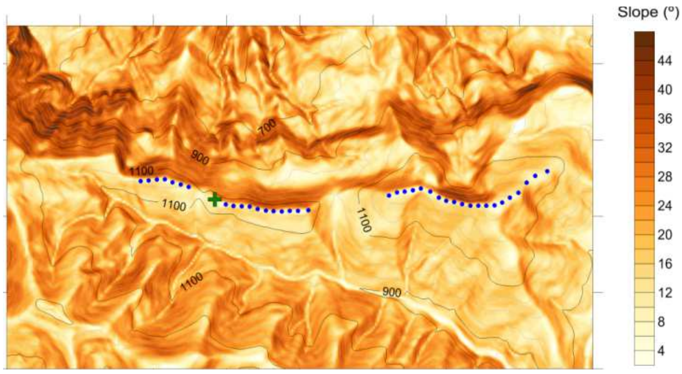

Figure 1: Slopes at site in degrees. Blue points represent the installed wind turbines and green cross marks the LIDAR position.

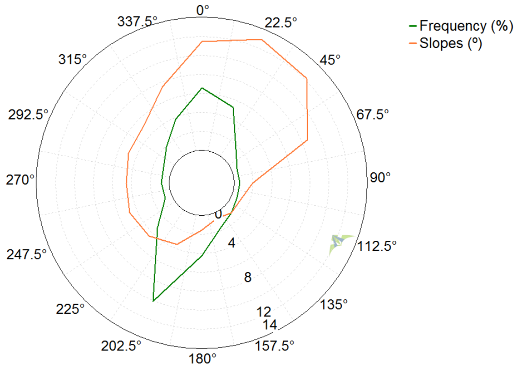

Figure 2: Wind frequency (green) and slopes (orange) at site. Slopes correspond to a 50m radius from LIDAR position.

A meteorological mast is available at site from October 2014. The analysed LIDAR device was installed next to this mast from May 2015 to January 2016. Therefore a significant period of about 8 months was available for the comparison.

Figure 3: Relative position of LIDAR and mast.

Distance between mast and LIDAR device is about 8m, enough to avoid tower induced distortions in LIDAR measurements, following manufacturer indications.

2.2 Measurement equipment

The analysed RSD device is a ground-based continuous wave LIDAR model Zephir 300.

In this case, the scanning cone angle programed was 30º and the sampling rate configured was 1 second. Several common mast-LIDAR heights were programmed for better comparisons.

On the other hand, the meteorological mast consists of a lattice structure of 45 m height, located next to one of the turbines of the Iberdrola operational wind farm used for testing. The logger programed sample rate is 1 second. The different recorded variables are ten minute averaged. The mounting of instruments on the meteorological mast meets Annex G requirements of IEC 61400-12-1 [1]. All sensors were calibrated according to Annex F of IEC 61400-12-1 [1].

Sensor	Model	Height (m)	Boom azimut (º)
Anemometer	Thies Advanced	45	TOP
	Thies Advanced	40	250
	Thies Advanced	20	250
	Ultrasonic Vaisala 2D	40	70
	Ultrasonic NRG 3D	40	70
Wind Vane	Thies Classic	43.5	250
	Thies Classic	38	250
Barometer	SETRA	43	
Datalogger	Campbell CR1000	1	
Thermohigrometer	Serie CP 1	41	
	Serie CP 1	11	

Table 1: Mast configuration

Mast and LIDAR had a common measurement period with good availability that goes from May 2015 (14/05/15) to January 2016 (15/01/16).

Common height levels of the different analysed devices and variables are shown in next table.

Level	Variable		
	WS	Dir	VWS
20	C, L	L	L
25	L	L	L
40	C, L	C, L	L, US
45	C, L	C, L	L
65	L	L	L
98.8	L	L	L
132.5	L	L	L
166.3	L	L	L
200	L	L	L

L (LIDAR), C (Cup), US (Ultrasonic)

Table 2: Variables measured at different heights with LIDAR, cup (C) and ultrasonic anemometer (US).

2.3 Data treatment

Average and standard deviation values of horizontal wind speed, wind direction and vertical wind speed recorded by the LIDAR and the reference met mast sensors were treated. The data treatment method is described in next sections.

2.3.1 Cup anemometers wind data filtering

A detailed wind data filtering is crucial in this kind of tests. The filtering criteria considered for cup anemometers were:

- All erroneous or out of range data were filtered through the whole data series.
- Icing of cup anemometers. All data with a temperature below 2ºC with simultaneously humidity higher than 80% are discarded in order to make sure the reference cup anemometers are not affected by icing [1].
- Tower induced distortions. Cup anemometers of 40 and 20 m levels were affected between 35-85º, and ultrasonic anemometer between 205-245º. Cup anemometer of 45m level is TOP mounting therefore there is no distortion affection.

2.3.2 LIDAR wind data filtering

LIDAR's internal processing identifies high uncertainty conditions and rejects the corresponding measurements from the output data file, marking them with relevant Quality Codes. Two types of Quality Codes are used in the output file:

- 9999: High quality wind speed measurement is not possible. This is often caused by very low wind speed, or due to partial obscuration of the LIDAR window, or significant interference with the laser beam at the specified height.
- 9998: the LIDAR automatically detects atmospheric conditions which adversely affect LIDAR wind speed measurements. For example, in thick fog, beam from LIDAR device may not be able to reach the measurement height. Also in certain cases when affected by significant precipitation, Zephir300 will also reject the vertical wind speed records.

On the other hand, all data in which the variable Packet in Average (PiA) or number of samples included in the 10-min average, was less than or equal to 50 % were rejected.

2.3.3 Site conditions

It has to be noted that some wind turbines are near the test site. This requires a valid sector analysis in order to exclude wind data coming from sectors in the wake of an operating wind turbine or a significant obstacle.

Exclusion of affected sectors was carried out following Appendix A of IEC 61400-12-1 [1] requirements. The valid measurement sectors for IEC compliance at met mast position are 317º-62º and 145º-270º. It was checked that valid measurement sectors for IEC compliance at LIDAR position had the same direction range.

Finally, taking into account both operating turbines and tower distortion effects described in previous section, the valid sector considered in the test for every wind speed sensor is shown in next table.

Anemometer	Height	Final valid sectors (º)
Lidar	20-200	317-62, 145-270
Cup	20, 40	317-35, 145-270
Ultrasonic	40	317-62, 145-205, 245-270

Table 3: Valid sectors for each sensor and height.

2.4 Conversion factors

Conversion (or correction) factors are the result of Computational Fluid Dynamics (CFD) analysis and allow the conversion of LIDAR volume measurements at each height to point measurements more representative of a cup anemometer sited on a met mast. The conversion factors are typically provided for each defined measurement height in 36 sectors of 10° width and centered on the bin. For a given wind direction and measurement height above ground level, the measured horizontal 10-min wind speed should be multiplied by the corresponding conversion factor.

Meteodyn^{WT} CFD (5.0.3 version) is available at Iberdrola and has a specific module for analysing LIDAR complex terrain corrections. In order to correct the wind speed estimation at the centre of the cone of measurements, this LIDAR correction tool uses the directional results issued from the CFD modelling that are wind speed up coefficient and inflow angle [6].

As it was explained previously, the presence of sharp topography in main wind directions makes necessary a precise parametrization of the CFD model in order to avoid steady state solutions. Also mesh size and number of cells were selected in order to have an acceptable number of nodes into LIDAR scan cone. Summary tables with main model parametrizations and directional values of dynamic conversion factors are included in Appendix A.

In next graph, dynamic conversion factors derived for the different LIDAR heights are shown.

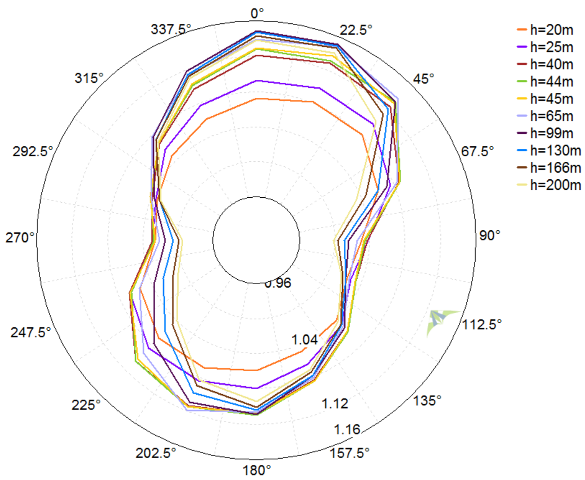

Figure 4: Directional dynamics correction factors at different heights (36 sectors from 20 to 200m).

It can be appreciated that correction factors are higher towards 20 ad 200 º approximately, following the existent hillsides at LIDAR position. The highest frequency of data correspond also to these sectors, therefore the influence of correction factors is significant in this study case.

On the other hand, it can be observed that the evolution of wind speed factors with height has also a directional behavior. Typically, conversion factors decrease with increasing height as the effect of terrain reduces and geostrophic effect begins to dominate [7]. However, in this case due to the nearby steep slopes the effects could be unpredictable.

3. Comparison of LIDAR and mast measurements

3.1 Data availability

For the LIDAR-cup data availability comparison, all sectors were included and tower distortion filters were not considered, but LIDAR data with PiA < 50 % were rejected. The data availability at the different measurement heights, and for the common available period (May15-Jan16), is shown in the table below.

Height (m)	LIDAR		Cup [1]	
	N data	Avail. (%)	N data	Avail. (%)
20	33452	86.2	37400	96.3
25	33514	86.3		
40	28496	73.4	37384	96.3
45	27717	71.4	37390	96.3
65	25522	65.7		
98.8	23621	60.8		
132.5	22427	57.8		
166.3	21511	55.4		
200	20914	53.9		

[1] Data without valid sector and tower distortion filters

Table 4: Number of data and availability at every wind speed measurement level. LIDAR and cup.

As it can be seen in the table above, the mast wind speed availabilities had very high values (higher than 95 %) in every case. For LIDAR top height of 200 m the data availability is about 54 %, increasing when the height decrease until a value of about 86 % at the lowest analysed heights (20-25 metres).

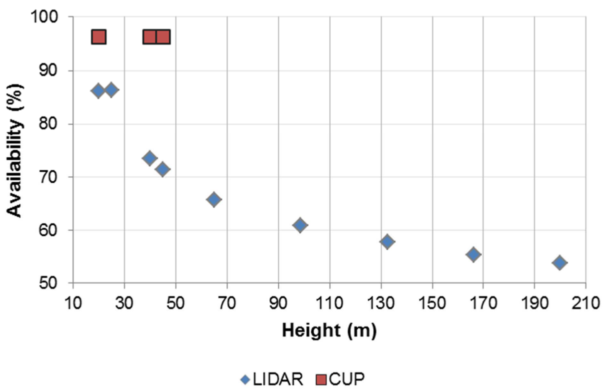

Figure 5: Availability at every height (Cup and LIDAR).

This decrease in LIDAR data availability was analyzed in detail in terms of the quality codes of data rejected by LIDAR´s internal processing (see section 2.3.2). As it is shown in next figure, the number of filtered data is mainly related with adverse meteorological conditions at site (9998 described code).

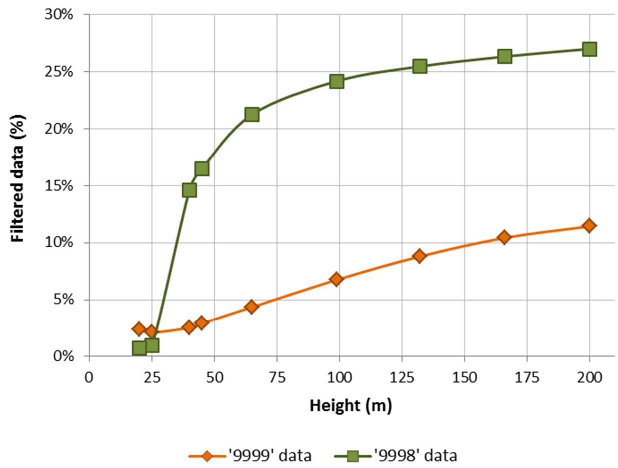

Figure 6: LIDAR filtered data in terms of internal quality codes.

3.2 Validation of wind speed measurements

Hereinafter, horizontal wind speed, vertical wind speed and turbulence intensity from met mast and LIDAR were compared, in order to establish the LIDAR device accuracy.

Dynamic conversion factors obtained were applied to LIDAR measurements in order to carry out the different comparatives.

Only concurrent 10 minute data in the final valid sector (Table 3) will be considered for the different validation tests.

3.2.1 Horizontal wind speed

The mean, maximum and minimum wind speeds, as well as wind speed BIAS[1], are shown in next table for LIDAR and cup anemometers. However, due to the usually high turbulence present at low wind speeds, only wind speeds higher than 2m/s were considered for the analysis. Cup anemometer was considered the reference to apply the necessary wind speed filters.

		Data	WS_{cup} (m/s)	WS_{lidar} (m/s)	BIAS (%)
Horizontal WS at 45m (m/s)	**Mean**	17349	10.9	10.8	-0.6
	Max		37.0	33.3	-10.0
	Min		2.0	1.9	-6.7
Horizontal WS at 40m (m/s)	**Mean**	16408	11.3	11.4	0.6
	Max		36.3	33.9	-6.8
	Min		2.0	1.7	-15.0
Horizontal WS at 20m (m/s)	**Mean**	19221	11.2	11.1	-0.7
	Max		37.4	34.3	-8.2
	Min		2.0	1.8	-10.8

Table 5: Mean, minimum, maximum WS and BIAS.

For all measurement heights, the LIDAR-cup mean WS BIAS is very low (lower than 1% in absolute value in all cases).

However maximum and minimum WS were not correctly reproduced by LIDAR device, with LIDAR max. WS values about 4m/s below the ones registered by cup anemometers.

[1] The so-called BIAS was calculated as a percentage error: $\frac{(\text{Variable}_{\text{lidar}} - \text{Variable}_{\text{cup}})}{\text{Variable}_{\text{cup}}} \cdot 100$

A regression analysis was carried out in order to establish the degree of correlation between LIDAR and cup anemometer horizontal wind speed measurements. Tabular and graphical results are shown in Appendix B.

Additionally, the wind speed range between 4-16 m/s was considered for this regression analysis. This range is the standard cup anemometer range in a calibration procedure, and it is also the wind speed range for which the LIDAR site verification must be carried out according to the IEC standard [2]. However, the correlation coefficients and mean wind speed BIAS are almost independent from the considered wind speed range. Correlation factors are higher than 0.98 in all cases.

Due to the complexity of the analysed area a directional correlation analysis was carried out. Taking into account the bi-directional wind rose at the site with main frequencies towards north and south directions, two great direction sectors were considered for the analysis: 315-45º and 135-225º. Results are shown in Appendix B. Correlation coefficients obtained at northern sector, are slightly lower than southern ones. But the most significant result is the difference in the wind speed BIAS obtained. Northern wind speeds are lower than southern ones (less than half), and its LIDAR-cup BIAS is significantly higher reaching about 4% at 20m level.

On the other hand, the wind speed distribution and the Weibull fitting were also analysed. The scale and shape parameters of the Weibull best fitting distribution can be seen in next table.

Height (m)	A_{LIDAR} (m/s)	A_{CUP} (m/s)	k_{LIDAR}	k_{CUP}
45	10.6	10.6	1.33	1.23
40	11.5	11.4	1.43	1.39
20	11.1	11.1	1.35	1.34

(1) WAsP methodology

Table 6: Scale and shape Weibull parameters.

As expected, the scale parameter (A) is similar in all levels. However, the shape parameter (k) takes a slightly different value, being lower in the case of the cup anemometers. Next figure shows the WS frequency distribution at 45m level.

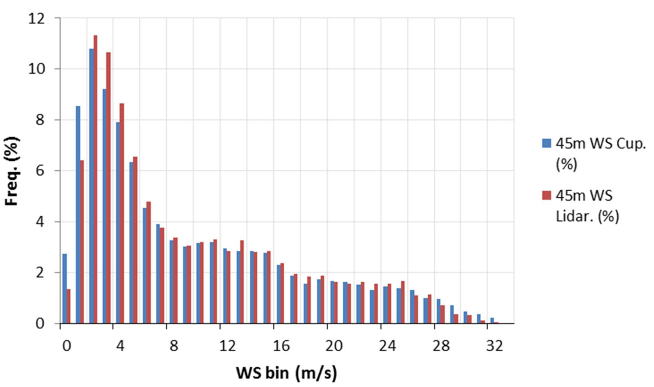

Figure 7: WS distribution at 45m level.

Differences are encountered, mainly in the 4-8 m/s productive wind speed bins where LIDAR frequencies are higher. These discrepancies lead to significant differences in the calculated annual energy production that can reach about 4% at 45m height.

3.2.2 Turbulence intensity (TI)

Turbulence intensity (TI)[2] values obtained with LIDAR and cup anemometer data series were compared.

Mean, maximum and minimum TI, number of data and BIAS are shown in next table.

		Data	TI_{cup} (%)	TI_{lidar} (%)	BIAS (%)
Turbulence intensity at 45 m (%)	**Mean**	17331	13.1	14.3	9.2
	Max		72.4	73.4	1.4
	Min		1.3	1.0	-20.3
Turbulence intensity at 40 m (%)	**Mean**	16408	12.7	14.1	11.2
	Max		70.1	67.5	-3.8
	Min		1.2	1.2	-3.4
Turbulence intensity at 20 m (%)	**Mean**	19221	12.9	14.4	12.1
	Max		78.5	77.5	-1.2
	Min		2.2	2.0	-10.4

Table 7: Mean, minimum, maximum TI and BIAS.

Obtained BIAS were significant, taking into account that in general BIAS of about 10% could predetermine the type of power curve to select for certain energy assessment. It can be appreciated in previous table that BIAS tends to decrease with height for mean values, being LIDAR mean TI measurements higher in all cases.

A regression analysis was carried out in order to establish the degree of correlation between LIDAR and cup horizontal TI measurements. In Appendix C, tabular and graphical results for the different height levels are shown. TI correlations show a significant scatter in general, and correlation results do not depend on the analyzed WS range. TI correlation results show however a significant directional behavior. Northern sectors show higher TI values and BIAS about 13% at 45m, however southern sectors show significantly lower TI values with BIAS of about 5% at the same level. Also correlation coefficients obtained were significantly high in southern sectors. This result confirms the importance of considering a directional analysis in order to validate LIDAR measurements in complex terrains. However, in spite of the directional treatment, deviations in TI global mean values were significant. Also, as it is shown in next paragraph, TI analysis by wind speed bins showed differences in the obtained curves that would be crucial for site assessment purposes.

Therefore, the measured representative TI by wind speed bins is compared with the representative TI that defines the A, B and C IEC standard subclasses [3]. It can be noted in next figure the significant difference obtained with LIDAR and cup anemometers.

[2] The ambient turbulence intensity is a derived variable defined as follows: TI= σ_{WS}/ WS. With σ_{WS} = relative deviation of WS.

This formulation was applied to 10 minute data at every analysed sensor for the different comparatives.

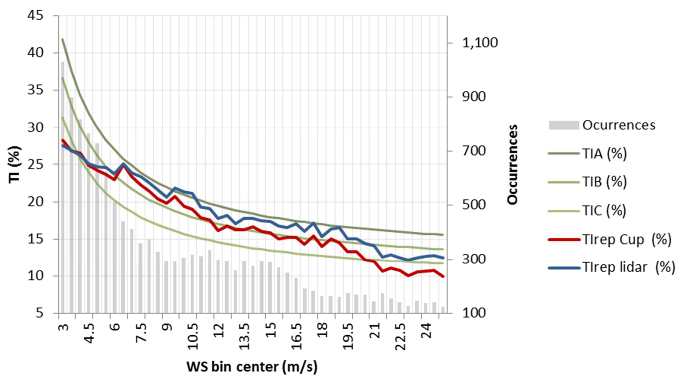

Figure 8: Representative TI calculated with LIDAR data (blue line) and with cup data (red line).

3.2.3 Vertical wind speed and inflow angle

The considered mast is equipped with an ultrasonic anemometer (US) that registers vertical wind speed.

Ten minute vertical wind speed and inflow angle[3] comparisons between US anemometer and LIDAR closest measurement level were carried out. Mean, maximum and minimum vertical wind speed and inflow angle values, number of data and BIAS for mast and LIDAR is shown in next table.

		Data	VWS_{US} (m/s)	VWS_{LIDAR} (m/s)	BIAS (m/s)
VWS at 40m (m/s)	Mean	7108	-0.1	-0.1	0.1
	Max		3.3	3.5	0.2
	Min		-3.4	-3.5	-0.1
Inflow angle at 40m (m/s)	Mean	7115	0.3	0.9	0.6
	Max		24.9	14.5	-10.5
	Min		-22.5	-16.3	6.2

Table 8: Mean, minimum, maximum VWS and BIAS.

The mean vertical wind speed value obtained with LIDAR is similar to the US sensor one, with a BIAS of 0.1 m/s. Maximum and minimum vertical wind speed values are also very similar in both cases.

Maximum and minimum inflow angle values present significant discrepancies in this case. It is important to emphasize that inflow angle values depend also on the horizontal wind speed values.

The VWS and inflow angle behavior was also very directional and surprisingly well reproduced by LIDAR device, as it can be seen in Appendix D results. Northern vertical wind speeds and inflow angle values were positive and southern negatives, with BIAS almost null in both cases.

4. CONCLUSIONS

Results showed good correlations and acceptable values of relative deviations between LIDAR (after applying the adequate CFD dynamic correction factors) and mast horizontal and vertical wind speed measurements at the analysed extremely complex site.

An important result is that obtaining a set of dynamic factors with an adequate model parametrization leads to WS BIAS lower than 1% in such a complex site.

However, a significant decrease in data availability (filtered by LIDAR's internal processor) with height was found, with about 30% LIDAR data missed from 20 to 200m height. This can provide indication of the expected percentage of LIDAR data available in harsh climate sites, probably due to the low aerosol presence at such altitude and the unfavourable climatic conditions present at site (fog and others).

Due to the directional behavior of the flow at complex sites, a directional analysis was found to be crucial in the analysis of variables as turbulence intensity.

Site assessment variables as representative turbulence intensity or maximum wind speed values obtained in LIDAR and mast presented significant deviations; therefore the validity of the analysed LIDAR technology for site assessment studies in very complex sites could not be confirmed.

References

[1] IEC 61400-12-1. "Power performance measurements of electricity producing wind turbines". Ed1, 2005.
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[3] IEC 61400-1. "Wind turbines-Part 1: Design requirements". Ed3 Amendment 1, 2010.
[4] MEASNET "Power Performance Measurement Procedure". Version 5, December 2009.
[5] ISO 2533 "Standard atmosphere". Addendum 2, 1997.
[6] Guillaume Dupont, Céline Bezault, Stéphane Sanquer. "Meteodyn Correction Tool for LIDAR in complex terrain based on CFD outputs". EWEA, 2012.
[7]. Mark Pitter, Claude Abiven, Klaus Vogstad, Michael Harris, Will Barker and Oisin Brady. "LIDAR and computational fluid dynamics for resource assessment in complex terrain". EWEA, 2012.
[8]. M. Pelletier, D. Faghani, M. Boquet, R. Dexter, B. Boucher, E. Osler, C. Masson, L. Landberg. "LIDAR validation in complex terrain". EWEA, 2011.
[9]. Peter Argyle, Simon Watson. "Validation of measurements from a Zephir LIDAR". EWEA, 2015.

[3] The inflow angle is a derived variable defined as $tg^{-1}(v_3/v_1)$. With v_3= Vertical wind speed and v_1= Horizontal wind speed.

This formulation was applied to 10 minute data at every analysed sensor for the different comparatives.

Appendix A

Dynamic correction factors by 10º direction sector and for the different heights

Dynamic correction factors										
Sector (º)/ Height (m)	**20**	**25**	**40**	**44**	**45**	**65**	**99**	**133**	**166**	**200**
0	1.073	1.096	1.120	1.130	1.132	1.142	1.152	1.150	1.145	1.140
10	1.075	1.091	1.123	1.132	1.132	1.144	1.151	1.151	1.146	1.138
20	1.079	1.094	1.129	1.131	1.140	1.150	1.159	1.158	1.158	1.154
30	1.084	1.102	1.130	1.133	1.137	1.150	1.146	1.144	1.138	1.129
40	1.086	1.102	1.129	1.137	1.136	1.143	1.138	1.132	1.125	1.111
50	1.075	1.095	1.124	1.131	1.127	1.136	1.129	1.112	1.105	1.094
60	1.067	1.083	1.102	1.103	1.105	1.102	1.087	1.079	1.061	1.052
70	1.054	1.068	1.070	1.072	1.069	1.065	1.054	1.042	1.030	1.016
80	1.048	1.056	1.047	1.045	1.046	1.041	1.028	1.020	1.011	1.004
90	1.025	1.034	1.035	1.033	1.031	1.020	1.010	1.004	0.996	0.992
100	1.016	1.022	1.026	1.023	1.019	1.013	1.008	1.006	1.001	0.998
110	1.020	1.023	1.028	1.027	1.025	1.019	1.018	1.018	1.014	1.011
120	1.025	1.030	1.038	1.039	1.039	1.030	1.023	1.024	1.020	1.019
130	1.038	1.040	1.053	1.050	1.050	1.044	1.046	1.040	1.037	1.032
140	1.042	1.054	1.061	1.066	1.064	1.057	1.058	1.054	1.055	1.052
150	1.045	1.059	1.071	1.071	1.071	1.071	1.068	1.069	1.065	1.063
160	1.049	1.068	1.093	1.096	1.096	1.088	1.087	1.085	1.081	1.077
170	1.053	1.076	1.105	1.104	1.102	1.099	1.101	1.097	1.094	1.088
180	1.058	1.081	1.107	1.105	1.104	1.102	1.107	1.102	1.099	1.094
190	1.063	1.079	1.111	1.119	1.115	1.117	1.116	1.110	1.106	1.098
200	1.068	1.081	1.115	1.120	1.122	1.124	1.120	1.114	1.105	1.098
210	1.066	1.086	1.112	1.111	1.109	1.115	1.100	1.083	1.074	1.066
220	1.072	1.082	1.110	1.107	1.103	1.094	1.081	1.063	1.052	1.045
230	1.064	1.087	1.100	1.104	1.100	1.092	1.072	1.053	1.041	1.032
240	1.060	1.076	1.086	1.084	1.090	1.064	1.050	1.037	1.024	1.016
250	1.048	1.057	1.048	1.045	1.043	1.046	1.023	1.015	1.003	0.999
260	1.038	1.043	1.041	1.037	1.037	1.030	1.020	1.008	1.001	0.996
270	1.022	1.026	1.026	1.025	1.022	1.018	1.010	1.004	0.997	0.991
280	1.016	1.019	1.020	1.020	1.018	1.015	1.012	1.004	0.998	0.996
290	1.027	1.028	1.031	1.034	1.034	1.028	1.027	1.020	1.017	1.016
300	1.039	1.041	1.046	1.049	1.050	1.054	1.045	1.042	1.045	1.041
310	1.042	1.054	1.060	1.061	1.059	1.070	1.065	1.063	1.063	1.060
320	1.052	1.061	1.075	1.075	1.077	1.087	1.090	1.082	1.083	1.079
330	1.056	1.070	1.090	1.094	1.095	1.105	1.110	1.107	1.106	1.102
340	1.065	1.085	1.105	1.109	1.112	1.122	1.129	1.124	1.120	1.119
350	1.068	1.091	1.120	1.124	1.124	1.132	1.145	1.140	1.140	1.137

Model parametrization

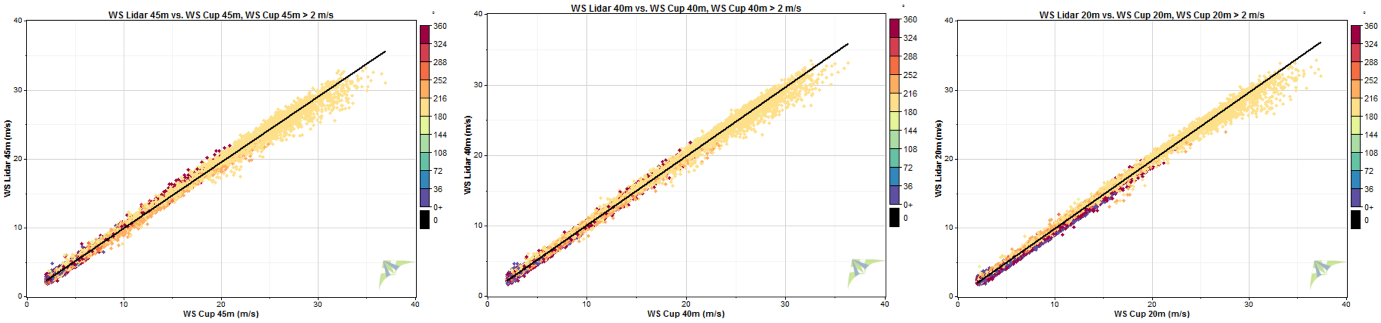
CFD model parametrization (Meteodyn^{WT} 5.0.3)	
Properties	
Direction	36 sectors
Thermal stability class	2
Smoothing - Whole domain	1
Forest model	Dissipative
Mesh	
Minimum horizontal resolution	25
Maximum vertical resolution	4
Horizontal expansion coefficient	1.1
Vertical expansion coefficient	1.2
Verticality parameter	0.5
LIDAR	
Minimum horizontal resolution	5
Maximum vertical resolution	1.1

Appendix B

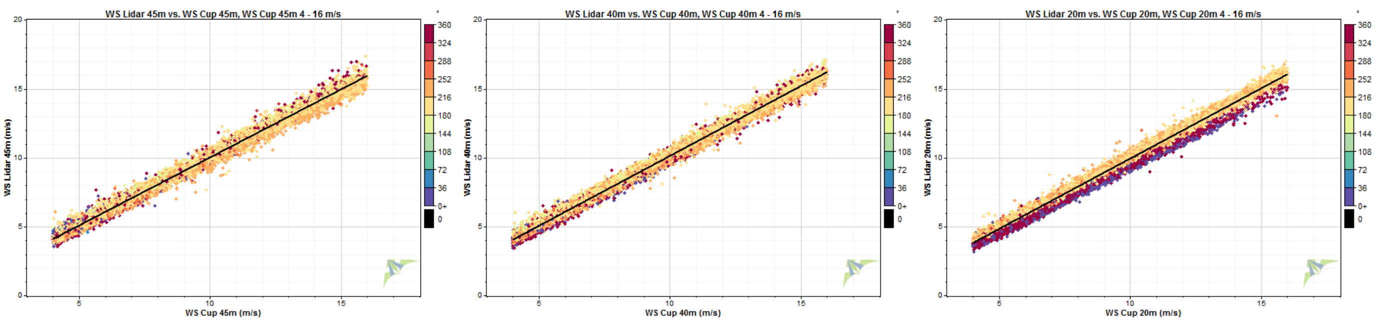
Horizontal WS correlation results for different WS ranges

Wind speed range at 45 m	WS_{lidar}= slope·WS_{cup} + offset			Data	WS_{cup} (m/s)	WS_{lidar} (m/s)	BIAS (%)
	R^2	Slope	Offset				
WS_{cup} > 2 m/s	0.9953	0.9541	0.4395	17349	10.90	10.84	-0.6
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.9898	0.9866	0.1888	9179	8.9	9.0	0.8
Wind speed range at 40 m	**WS_{lidar}= slope·WS_{cup} + offset**			**Data**	**WS_{cup} (m/s)**	**WS_{lidar} (m/s)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
WS_{cup} > 2 m/s	0.9960	0.9787	0.3137	16408	11.30	11.38	0.6
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.9919	1.0121	0.0414	9000	9.1	9.2	1.8
Wind speed range at 20 m	**WS_{lidar}= slope·WS_{cup} + offset**			**Data**	**WS_{cup} (m/s)**	**WS_{lidar} (m/s)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
WS_{cup} > 2 m/s	0.9962	0.9857	0.0765	19221	11.19	11.11	-0.7
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.9897	1.0189	-0.2363	10378	9.0	8.9	-0.8

Linear regression results for WS_{cup} > 2m/s – All direction sectors – 45, 40 and 20m levels



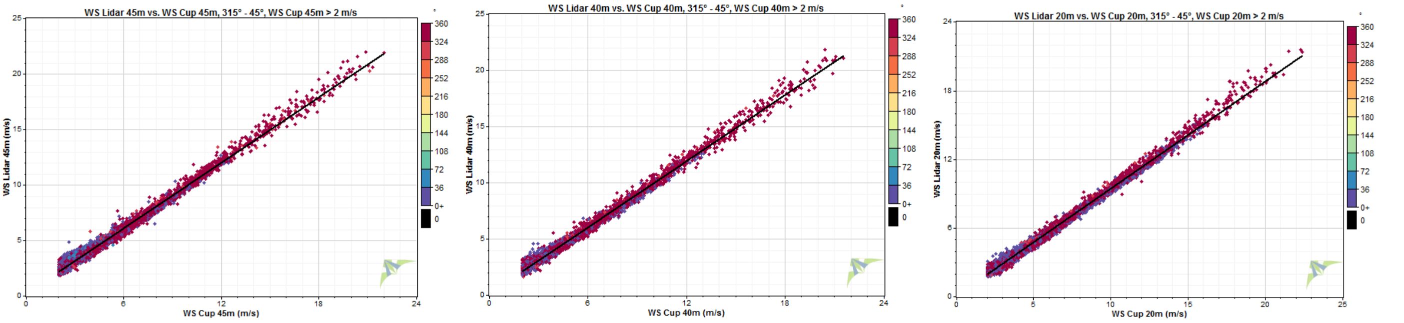
Linear regression results for 4 ≤ WS_{cup} ≤ 16m/s – All direction sectors– 45, 40 and 20m levels



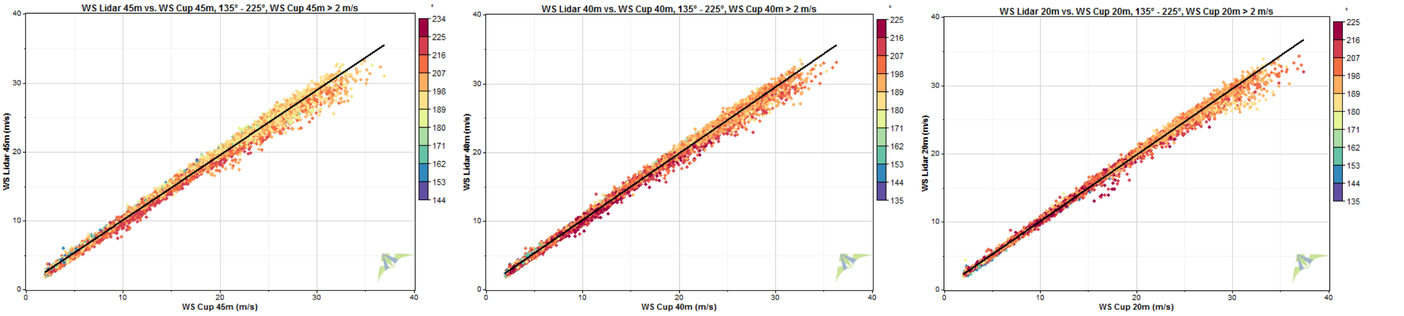
Horizontal WS correlation results for different direction ranges

Wind speed range at 45 m	WS_{lidar}= slope·WS_{cup} + offset			Data	WS_{cup} (m/s)	WS_{lidar} (m/s)	BIAS (%)
	R^2	Slope	Offset				
Dir_{cup} 43.5m 315-45º	0.9895	0.9842	0.2429	6488	5.1	5.2	3.2
Dir_{cup} 43.5m 135-225º	0.9931	0.9444	0.6277	10080	14.9	14.7	-1.3
Wind speed range at 40 m	**WS_{lidar}= slope·WS_{cup} + offset**			**Data**	**WS_{cup} (m/s)**	**WS_{lidar} (m/s)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
Dir_{cup} 39m 315-45º	0.9915	0.9818	0.1825	5472	5.4	5.5	1.5
Dir_{cup} 39m 135-225º	0.9947	0.9676	0.5467	10205	14.7	14.8	0.7
Wind speed range at 20 m	**WS_{lidar}= slope·WS_{cup} + offset**			**Data**	**WS_{cup} (m/s)**	**WS_{lidar} (m/s)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
Dir_{cup} 39m 315-45º	0.9930	0.9345	0.1358	7357	5.7	5.4	-4.2
Dir_{cup} 39m 135-225º	0.9957	0.9702	0.4508	11100	15.1	15.1	0.0

Linear regression results for WS_{cup} > 2m/s – 315-45 º– 45, 40 and 20m levels



Linear regression results for WS_{cup} > 2m/s – 135-225 º– 45, 40 and 20m levels

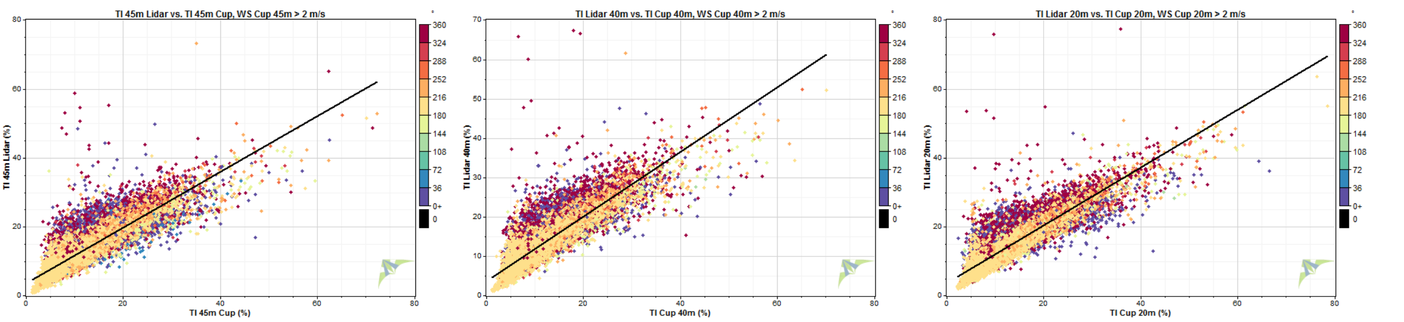


Appendix C

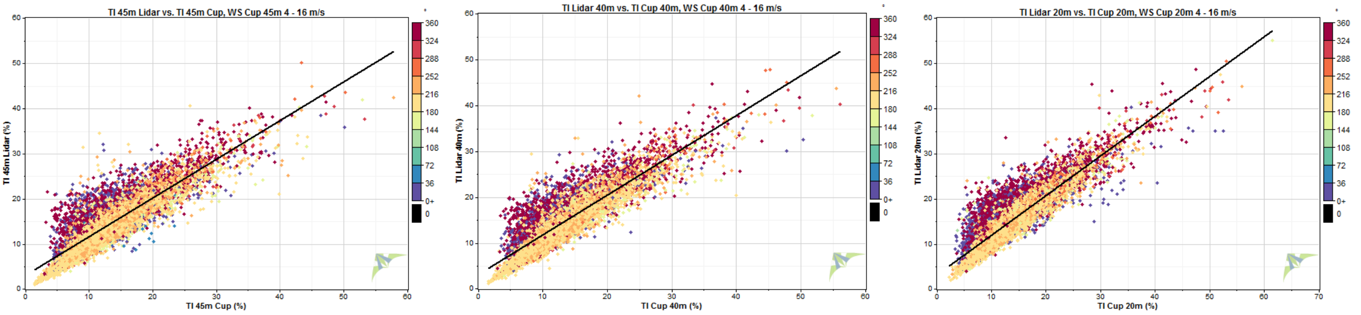
TI correlation results for different WS ranges

WS range at 45 m	TI_{lidar}= slope·TI_{cup} + offset			Data	TI_{cup} (%)	TI_{lidar} (%)	BIAS (%)
	R^2	Slope	Offset				
WS_{cup} > 2 m/s	0.7313	0.8068	3.7399	17331	13.1	14.3	9.2
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.7576	0.8581	3.1479	9178	13.3	14.6	9.8
WS range at 40 m	**TI_{lidar}= slope·TI_{cup} + offset**			**Data**	**TI_{cup} (%)**	**TI_{lidar} (%)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
WS_{cup} > 2 m/s	0.7412	0.8223	3.6716	16408	12.7	14.1	11.2
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.7768	0.8683	3.1547	9000	13.2	14.6	10.6
WS range at 20 m	**TI_{lidar}= slope·TI_{cup} + offset**			**Data**	**TI_{cup} (%)**	**TI_{lidar} (%)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
WS_{cup} > 2 m/s	0.7736	0.8394	3.6276	19221	12.9	14.4	12.1
4 m/s ≤ WS_{cup} ≤ 16 m/s	0.8058	0.8773	3.2786	10378	13.1	14.8	13.0

Linear regression results for WS_{cup} > 2m/s – All direction sectors



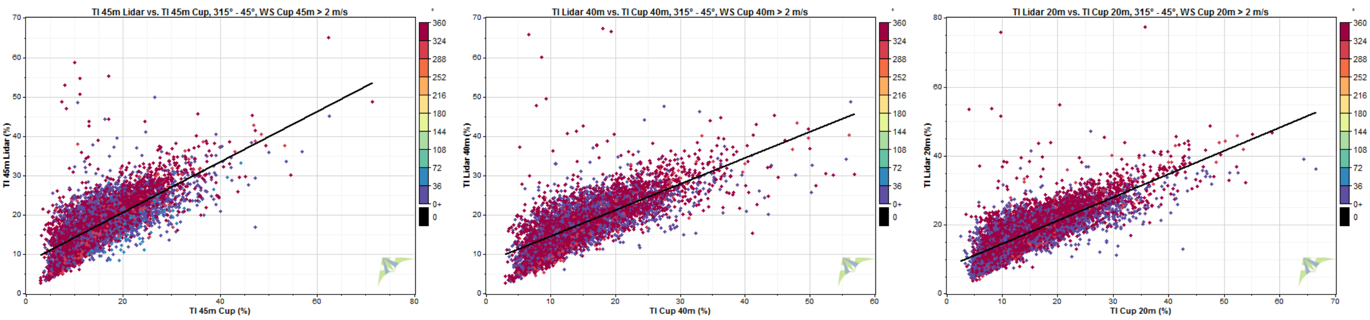
Linear regression results for $4 \leq WS_{cup} \leq 16$m/s – All direction sectors



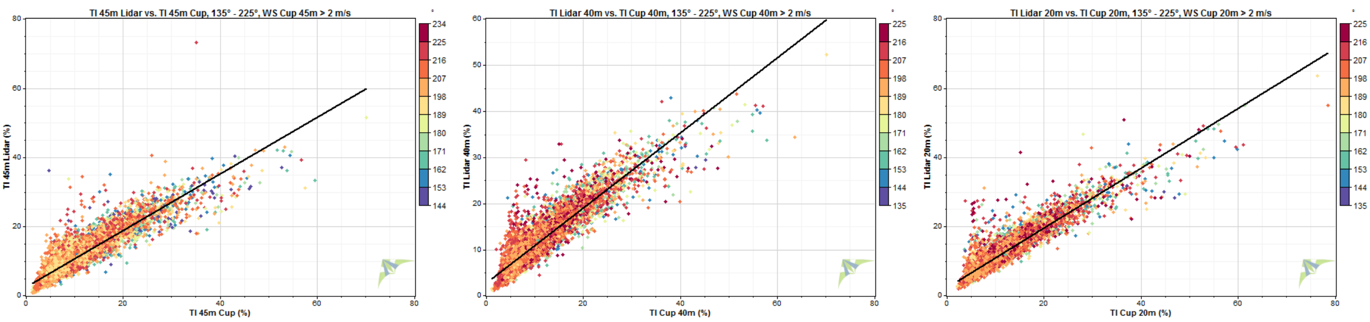
TI correlation results for different direction ranges

Dir range at 45 m	TI_{lidar}= slope·TI_{cup} + offset			Data	TI_{cup} (%)	TI_{lidar} (%)	BIAS (%)
	R^2	Slope	Offset				
Dir_{cup} 43.5m 315-45º	0.5316	0.6394	7.9897	6488	16.0	18.2	13.8
Dir_{cup} 43.5m 135-225º	0.8236	0.8184	2.6049	10063	10.9	11.5	5.5
Dir range at 40 m	**TI_{lidar}= slope·TI_{cup} + offset**			**Data**	**TI_{cup} (%)**	**TI_{lidar} (%)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
Dir_{cup} 43.5m 315-45º	0.5453	0.6635	8.0158	5472	15.5	18.3	18.1
Dir_{cup} 43.5m 135-225º	0.8382	0.8150	2.7438	10205	10.8	11.6	7.4
Dir range at 20 m	**TI_{lidar}= slope·TI_{cup} + offset**			**Data**	**TI_{cup} (%)**	**TI_{lidar} (%)**	**BIAS (%)**
	R^2	**Slope**	**Offset**				
Dir_{cup} 43.5m 315-45º	0.6080	0.6763	7.7947	7357	15.5	18.3	18.1
Dir_{cup} 43.5m 135-225º	0.8727	0.8662	2.2919	11100	10.7	11.6	8.4

Linear regression results for $WS_{cup} > 2$m/s – 315-45 º



Linear regression results for $WS_{cup} > 2$m/s – 135-225 º



Appendix D

VWS correlation results for different direction ranges

Dir range at 40 m	VWS_{lidar}= slope·VWS_{US} + offset			Data	VWS_{US} (m/s)	VWS_{lidar} (m/s)	BIAS (m/s)
	R^2	Slope	Offset				
Dir_{cup} 38m 315-45º	0.9146	0.9324	0.1056	3674	0.43	0.35	-0.1
Dir_{cup} 38m 135-225º	0.9310	0.9449	0.0106	3202	-0.66	-0.71	0.0

Dir range at 40 m	$Inflow_{lidar}$= slope·$Inflow_{US}$ + offset			Data	$Inf._{US}$ (º)	$Inf._{lidar}$ (º)	BIAS (m/s)
	R^2	Slope	Offset				
Dir_{cup} 38m 315-45º	0.8101	0.6202	2.1289	3674	4.5	3.7	-0.7
Dir_{cup} 38m 135-225º	0.9340	0.8369	-0.2530	3209	-3.1	-3.4	-0.3