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Case studies of WINDCUBE™ measurement uncertainty for complex terrain using Flow Complexity Recognition (FCR ®)

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Abstract & Objective

Wind flow around complex terrain could potentially induce significant errors in lidar wind speed reconstruction algorithm, due to the flow homogeneity assumption over the lidar volume, in estimating wind speed and direction. WINDCUBE™ lidar data in FCR® mode provides better correlation of the data with co-located anemometer measurements. In this paper, several case studies will be presented, where FCR® was applied to WINDCUBE™ V2 profiler data. The objective of this paper is to evaluate the performance of FCR in various scenarios. Success criteria for FCR performance is also presented. Case studies are classified based on terrain complexity, thermal stability observed at site (based on tower wind speed profiles or temperature [if available]), and wind direction. Wind speed uncertainties for various scenarios with and without FCR® are evaluated. The uncertainties are segregated based on various terrain classes, as mentioned above, which provides better knowledge for the value of FCR® in different scenarios. FCR® performance levels are evaluated based on the linear regression parameters after comparison to co-located tower data at various heights (slope, constant, and Pearson's correlation coefficient). It was observed that FCR® performed better than classical lidar retrievals, assuming flow homogeneity, in several scenarios. The effect of various stability classes on FCR®'s performance and uncertainty was found insignificant.

Results & Methodology

Flow Complexity Recognition (FCR®) software is a patented solution for improving lidar uncertainty in moderately complex terrains (Boquet 2009). Below we show wind speed uncertainty estimates with and without FCR and evaluate the performance of lidar for various cases.

TERRAIN CLASSIFICATION

The terrain were classified based on several factors:
1. Standard deviation of elevation (m)
2. Slope variability (deg)
3. Terrain Rugdness index (TRI) (1 = flat) and
4. Roughness length of the site (z_0)

Table 1: Terrain classification based on wind speed profiles and terrain indices

Terrain Classification	Std. Of Elevation (m)	Slope (deg)	Terrain Rugdness Index (TRI)	Z_o
Moderately Complex	< 30	< 30	< 1,5	$Z_o < 1,0$
Forested Moderately Complex	< 30	< 30	< 1,5	$1,0 < Z_o < 1,5$
Highly Complex	> 50	> 30	> 1,8	$1,5 < Z_o < 2,0$

$$TRI = \sqrt{\sum \left(x_{ij} - x_{00}\right)^2}$$

where

$$x_{ij} = elevation\ of\ each\ neighbor\ cell\ to\ cell\ (0,0)$$

$$U_Z = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right).$$

Where:
U* - Friction vecocity
K – von Karman Constant
Z – height of the profile
U_z – Mean Wind speed Profile

Based on the above classification, the sites were categorized as moderately complex or forested moderately complex or highly complex sites. The roughness length was estimated based on wind speed measurements observed at the site (from past tower/lidar measurements at various heights). Several criteria's were setup to evaluate the performance of FCR in moderately complex terrain. The stability at the site was estimated based on shear exponent values observed at the site from tower measurements (Wharton et al. 2012), and as shown in Figure 1, FCR® improves the wind speed measurements. The comparison to tower measurements in correlations, offset, mean wind speed error and standard deviation of error attain the standards of remote sensing measurements. The correction of wind direction bias in FCR results is also an indicator for FCR® improvements as shown in Figure 3. Figure 4 shows the terrain complexity and lidar location for various cases shown in this study. Results from WindCube V2 for a site assessment with FCR® option is shown in Figures 5, 6 and 7. The validation of FCR® for COWI was performed by Denmark Technical University (DTU).

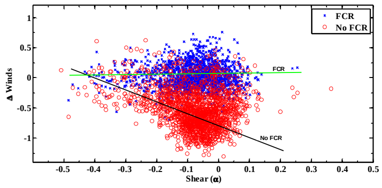

Figure 1: FCR improvement during various shear cases

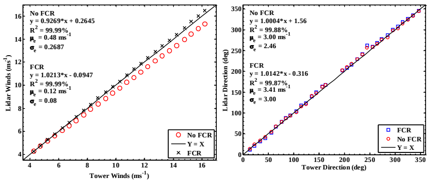

Figure 2: FCR improvement in comparison to tower measurements

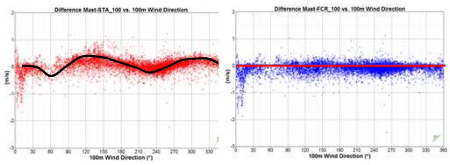

Figure 3: FCR improvement for direction bias in classical lidar measurements

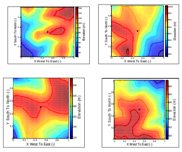

Figure 4: Terrain complexity for various sites in the analysis.

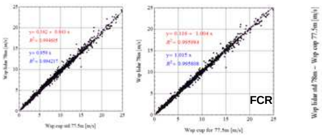

Figure 5: Scatter plots for WindCube Profiler data with and without FCR at COWI

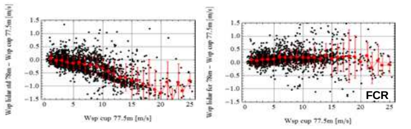

Figure 6: Sensitivity to Windspeed as observed in Bosnia with COWI for FCR and without FCR measurements

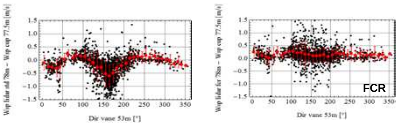

Figure 7: Sensitivity to wind direction as observed in Bosnia with COWI for FCR and without FCR measurements

Uncertainty calculation methodology[3]

$$U_{tot} = \sqrt{\sigma^2{}_e + \sigma^2{}_{reg}}$$

where

$$\sigma_{\mathrm{e}} = \text{Uncertainty due to wind variability}$$

$$\sigma_{\mathrm{reg}} = \text{Uncertainty in regression bias errors}$$

Table 2: FCR performance compared to classical lidar (no FCR) results.

Site	Complexity	R²		Slope (m)		Offset (c)		Uncertainty		Customer
		No FCR	FCR	No FCR	FCR	No FCR	FCR	No FCR	FCR	
I	Moderate	**99,99%**	**99,99%**	**0,93**	**1,02**	**0,27**	**-0,09**	**4,48%**	**2,45%**	**CRES**
II	Forested	**99,97%**	**99,92%**	**0,96**	**1,02**	**0,28**	**-0,01**	**3,66%**	**3,16%**	**Barlovento**
III	Highly Complex	97,02%	97,35%	0,96	1,20	-0,07	-0,16	3,05%	5,12%	Confidential
IV	Moderate	**99,39%**	**99,99%**	**0,94**	**0,97**	**0,23**	**0,26**	**3,5%**	**2,92%**	**Confidential**
V	Forested	**99,95%**	**99,95%**	**1,01**	**1,03**	**-0,17**	**-0,23**	**2,85%**	**2,75%**	**Gaspesie**
VI	Moderate	**99,96%**	**99,96%**	**0,99**	**0,99**	**0,19**	**0,18**	**3,75%**	**3,75%**	**JUWI**

Table 2 shows various regression parameters (Pearson's coefficient, slope and offset) and uncertainty estimates for various cases compared to tower measurements onsite. For moderately complex terrain cases, in most of the cases shown FCR® improves the wind speed uncertainty estimates, while for forested moderately complex terrain the uncertainty reduction is minimal. The reason for lower uncertainty reduction in forested regions could be due to multiple reasons (such as increased roughness at the site etc…). Since FCR® was developed for moderately complex terrain, it performs as expected in highly complex terrain conditions, as shown in site 3, where the uncertainty is higher compared to classical method. From Table 2 it can be observed that FCR® reduces the uncertainty for most of the cases analyzed or does not change the uncertainty estimated without FCR®, depending on the site conditions. FCR® is expected to reduce only bias in measurements, as shown in most cases above.

Conclusions

FCR® provides improved correlations compared to classical lidar measurements and improves project uncertainty estimates in moderately complex terrain. This would assist wind farm developers in providing higher degree of confidence in lidar measurements in moderately complex terrain. Developers can move the lidar with higher confidence to different locations in complex terrain scenarios for determining micro-siting uncertainty.

References

1. M Boquet et al., Technical report WINDCUBEv2+FCR® validation on complex sites and application for wind resource analysis
2. Wharton, S. and J. K. Lundquist. 2012a. Assessing atmospheric stability and its impacts on rotor-disk wind characteristics at an onshore wind farm. Wind Energy,15, 525–546, DOI: 10.1002/we.483
3. http://science.widener.edu/svb/stats/regress.html

Acknowledgements

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