Post conversion of Lidar data on complex terrains

Stéphane SANQUER [(1)], Alex WOODWARD[(2)]

(1) Meteodyn (2) ZephIR Lidar

1. Introduction

Data from remote sensing devices (RSD) are now widely accepted for use in wind resource assessment campaigns. Once installed, both the position and height of conventional anemometry such as cups are fixed, limiting the measurements to certain turbine locations and dimensions. RSD are portable and user configurable meaning they can overcome this issue. These benefits, including the ability to measure at greater heights than current masts are generally capable of, reduce project development risks and help secure investment. The ability of RSD to produce reliable measurements in the upper atmosphere also future proofs them against ever increasing wind turbine hub heights and rotor swept areas.

Ground-based vertically-scanning RSD, whether based on sodar or lidar principles, calculate a mean wind speed vertically above the sensor location on the basis of measurements around a scanned area that typically encompasses a diameter comparable to the measurement height. This process relies on an assumption that the line-of-sight Doppler shifts measured around the circumference of the sampling disk are representative of the wind speed at the centre; however this assumption breaks down in strongly non-uniform flow leading to possible differences in measured horizontal wind speed. By using a flow model, such as Computational Fluid Dynamics (CFD), it is possible to compute a set of factors that enable the conversion of RSD measurements to a comparable point measurement similar to that of conventional anemometry [1]. This process is key to ensuring continued project financing based on data from RSD alone by reducing the uncertainty between a RSD and traditional anemometry.

This work demonstrates a transparent methodology used in the application for CFD conversion of measurements from a Continuous Wave (CW) lidar, ZephIR 300, in varying terrain complexities.

The current draft of the IEC standards [2] includes guidance on how to deploy a RSD for the purpose of turbine power performance measurement. The standards currently limit the use of RSD to flat terrain. This work demonstrates that ZephIR 300 lidar can produce reliable measurements in terrain not considered to be simple; the draft standards limit this to terrain that does not require a site calibration.

The complexity of terrain can be described by the ruggedness index (RIX) [3], [4], which is defined as the fractional area of the terrain within the circular vicinity of a point of interest that exceeds a steepness threshold or critical slope. Mortensen *et al.* [5] investigates the relationship between WAsP prediction errors and site ruggedness. The main drawback in applying RIX is the necessity to choose the reference critical slope and the fact that forestry influences on the wind flow are ignored. Site specific ruggedness classes were suggested by Bingöl [6] to define the complexity of a site. Table 1 summarises this interpretation of site complexity. These classes were applied in this study.

	Class 0 z0<0.01 m	Class 1 z0 in [0.01m;0.05m]	Class 2 z0 in [0.05m; 0.4m]	Class 3 z0>0.4m
Flat without vegetation	Simple	Simple	-	-
Hilly sites (Hhill<100 m, slope in [5°, 10°])	Moderately complex	Moderately complex	Moderately complex	Complex
Vegetated flat sites (Hcanopy in [5m, 10m])	-	Moderately complex	Moderately complex	-
Montains without forest (solpe > 10°)	Complex	Complex	Complex	-
Forests (Hcanopy >10m)	-	-	-	Complex
Montains and forests	-	-	-	Highly-complex

Table 1: complexity classes according to [5]

The purpose of this research work is to:

- Assess the differences between ZephIR 300 and mast data in various complexity classes
- Highlight the categories where CFD conversion is needed
- Provide a methodology for CFD conversion of ZephIR 300 measurements in complex terrain, which will allow the use of ZephIR 300 data at sites other than those considered simple.

Ten sites will be tested and their results presented in the final paper, ranging from very simple through to extremely complex terrain.

2. Why conversion may be needed in complex terrain?

ZephIR 300 is a CW ground-based vertically scanning Lidar. Figure 1 demonstrates how the upwind and downwind components of the wind may not be horizontal as a result of terrain induced flow distortion. Depending on the terrain at site, these non-homogenous flow vectors can be a function of both direction and height above the sensor. The conversion method used here considers only the main direction i.e. along a line parallel to the wind at the center of the scan disk.

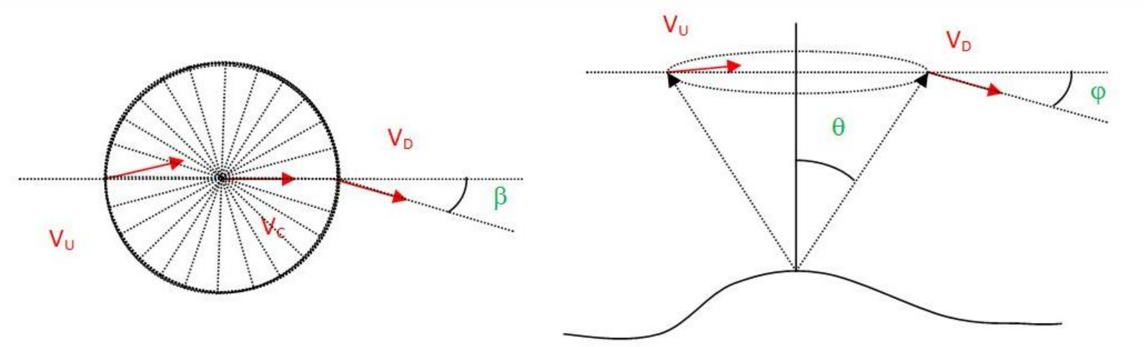

Figure 1: View of the Lidar cone of measurement

Θ is the scanning angle, i.e. the angle between the lidar scanned beam and the vertical axis, which for a ZephIR 300 is 30°. β and ϕ represents the wind incidence and wind inclination. The lidar velocity, V_L, is defined as:

$$V_L = \frac{V_r(down) - V_r(up)}{2\sin(\theta)} = \frac{\vec{V_d}.\vec{\imath} - \vec{V_u}.\vec{\jmath}}{2\sin(\theta)}$$

The methodology considers the relationship between the horizontal wind speed by comparing the measured velocity (V_L) and the horizontal wind speed (V_C) at the centre of the lidar scan, which is calculated from the upstream (V_U) and downstream (V_D) vectors. α is the CFD conversion factor and is defined as the ratio V_C / V_L.

The Lidar velocity in this case is defined as follow:

$$\begin{aligned} V_L = \frac{1}{2\sin(\theta)} (&V_d \cos(\beta_d)\cos(\varphi_d)\sin(\theta) + V_d \cos(\beta_d)\sin(\varphi_d)\cos(\theta) \\ &+ V_u \cos(\beta_u)\cos(\varphi_u)\sin(\theta) - V_u \cos(\beta_u)\sin(\varphi_u)\cos(\theta)) \end{aligned}$$

Where β_u and β_d are the deviation of the wind in the horizontal plane according to the direction defined by the upstream and downstream points. ϕ_U and ϕ_D are the incidence of the wind in the vertical plane.

Assuming that the horizontal deviation is negligible across the lidar disk, the general equation becomes:

$$V_L = \frac{1}{2\sin(\theta)}\left(V_d \sin(\theta + \varphi_d) + V_u \sin(\theta - \varphi_u)\right)$$

An incident angle of +/- 3^o can lead to differences of up to 10% between measurements of horizontal wind speed between RSD and conventional anemometry, something which the application of CFD conversion can address. Flow features associated with complex terrain such separation and recirculation can be modelled accurately through the application of advanced numerical techniques, producing high confidence in the conversion factors they generate. CFD approaches are one solution [6]. It has been demonstrated that CFD models are more appropriate than linear models in complex terrain since accurate predictions of both wind speed and inflow angle are needed to apply complex terrain conversion to measurements from RSD.

3. Computation of the conversion factors for several sites

The conversion factors in this study were deduced from the CFD code Meteodyn WT. Meteodyn WT solves the Reynolds Averaged Navier-Stokes (RANS) equations, using a refined mesh at the ZephIR 300 location and computing wind speed and inflow angle. Orographic and roughness data from SRTM and Corine Land coverage database were used as model inputs for defining the site in the CFD software (Figure 2).

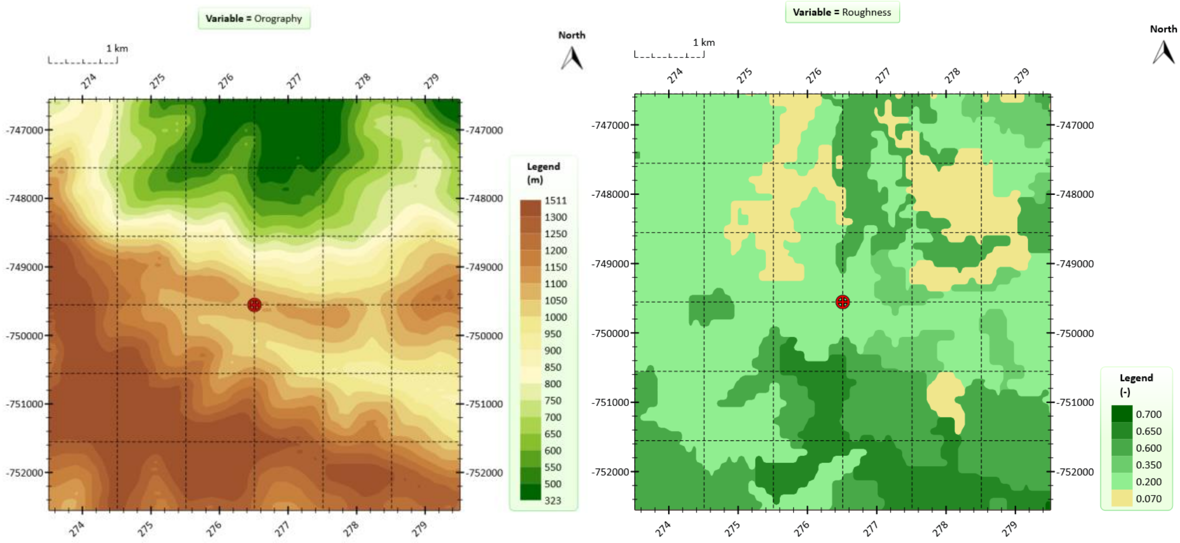

Figure 2: Orography and roughness around the LIDAR (highly complex site n°3)

A standard mesh resolution is used (4 m in the vertical and 25 m in the horizontal) to model the wind flow over the site. This high resolution allows the wind flow over complex and forested areas to be modelled accurately. Around the RSD location, the mesh is refined so that the variation in flow can be correctly modelled. To assess the directional influence on α , computations were performed in 10° steps for neutral stability.

A conversion factor rose (Figure 3) is deduced from the directional analysis at a site automatically in the CFD model. Figure 3 is an example of a conversion factor rose at a highly complex site, showing a variation in α from 0.97 (East wind) to 1.116 (North wind). For the simplest site investigated here, conversion factors in the range 0.99 to 1.01 were calculated. These values lie well within the standard uncertainty associated with a Class 1 anemometry and it is recommended not to apply the conversion factor to data in cases such as this. The Final paper will present a range of conversion factor from ten sites of varying complexity.

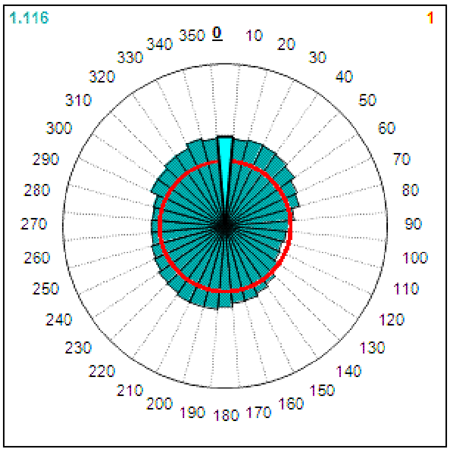

Figure 3: conversion factor for the highly complex site

4. Results

Improved agreement between the ZephIR 300 and mast measurements was achieved by applying the conversion factors to the ZephIR 300 measurements. The coefficients of determination (R^2) from the forced fit regressions were close to unity for all the sites looked at. Table 2 summarizes the results from four sites ranging in complexity from very simple (flat without forest) to extremely complex (mountainous and with forestry).

Site 1 - Simple terrain

Height (m)	Pre-conversion R^2	Pre-conversion correlation	Post-conversion R^2	Post-conversion correlation
91	0.99	1.00	0.99	1.00
70	1.00	1.00	1.00	1.00
45	1.00	1.00	1.00	1.00
20	1.00	1.00	1.00	1.00

Site 2 - Moderately Complex Terrain

Height (m)	Pre-conversion R^2	Pre-conversion correlation	Post-conversion R^2	Post-conversion correlation
61	0.99	0.98	0.99	0.99

Site 3 –Complex Terrain with Forest

Height (m)	Pre-conversion R^2	Pre-conversion correlation	Post-conversion R^2	Post-conversion correlation
80	0.99	0.98	0.99	0.99
60	0.99	0.98	0.99	0.99
40	0.99	0.98	0.99	0.99
20	0.99	1.00	0.99	1.00

Site 4 – Highly Complex Terrain

Height (m)	Pre-conversion R^2	Pre-conversion correlation	Post-conversion R^2	Post-conversion correlation
45	0.99	0.91	1.00	0.98
40	0.99	0.92	1.00	1.00
20	0.99	0.93	0.99	1.01

Table 2: results about conversion for three cases: simple, moderate complex and highly complex

5. Analysis and conclusions

Applying CFD conversion to data from RSD in complex terrain improves the agreement between wind speed measurements from RSD and masts – one example reduced the difference from 10% to less than 1%. For moderately complex terrain and simple sites with forestry, CFD conversion of RSD measurements should be considered a standard process when the coefficient of determination is very close to unity (> 0.98). For extremely complex terrain, CFD conversion of RSD measurements showed good results also. The limit to the application of this methodology should only be governed by the ability of the numerical model to accurately predict the flow characteristics at the site in question.

ZephIR 300 data is considered by DNV GL to be at Stage 3 under "benign" conditions, meaning its data is accepted for use in bankable / finance-grade wind speed and energy assessments with either no or limited on-site met mast comparisons. With this approach it has been demonstrated that ZephIR 300 data, coupled with CFD based conversion, can be extended and treated as finance-grade in complex terrain also.

6. Bibliography

[1] F. Bingöl, J. Mann, D. Foussekis, *Conically scanning Lidar error in complex terrain.* s.l. : Meteorol. Z. 18 189-195, 2

[2] IEC 61400-12-1 *Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines*. CDV Draft Document Edition 2. 22 July 2015.

[3] E. Berge, F. Nyhammer, L. Tallhaug and O. Jacobsen, *An evaluation of the WAsP Model at a Coastal Mountainous site in Norway*, Wind Energy 9, pp 131-140

[4] A.J. Bowen, N.G. Mortensen, *Exploring the limits of WAsP: the wind Atlas Analysis and application program*, European Union Wind Energy Conference, 1996

[5] N.G. Mortensen, A. Tindal, L. Landberg, *Field validation of the RIX performance indicator for flow in complex terrain*, EWEA Conference 2008

[6] F. Bingöl *Complex Terrain and Wind Lidars*. Risø-PhD-52(EN) August 2009

[7] C. Bezault, S. Sanquer, M. Nadah, Correction tool for LIDAR in complex terrain based on CFD outputs Correction tool for Lidar in complex terrain based on CFD EWEA Conference 2012