SafeWind

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"Site calibration using equivalent wind speeds"

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Abstract: This report analyses whether the concept of the equivalent wind speed can be used to reduce the uncertainty of a site calibration in complex terrain. It is shown that the scatter of the flow correction factors is slightly lower using the equivalent wind speed than using the wind speed at a single height. The improved correlation between the two equivalent wind speeds indicates that this concept might also be useful in short-term forecasting using upstream remote sensing systems in front of wind farms.

AUTHORS[1], REVIEWERS				
MAIN AUTHOR/EDITOR:	Paula Gómez			
AFFILIATION:	CENER			
ADDRESS:	Pol. Rocaforte, Parcelas G2-H1. 31400 Sangüesa, Spain			
TEL.:	+34 948 87 17 45			
EMAIL:	pgomez@cener.com			
FURTHER AUTHORS:				
PEER REVIEWERS:	Mike Courtney DTU (WPL) ; Robin Girard			
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STATUS:				CONFIDENTIALITY:				ACCESSIBILITY:		
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S1	Reviewed			**R1**	Restricted to project members			Public web site	
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PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

[1] **The authors of this document are solely responsible for its content, which does not represent the opinion of the European Community and the European Community is not responsible for any use that might be made of data appearing therein.**

[2] **VERSION NAMING : V0.x** draft before peer-review approval, **V1.0** at the approval, **V1.x** minor revisions, **V2.0** major revision

Contents

1. Introduction

Wagner et al. showed in [1] that the use of an equivalent wind speed, representing the whole wind speed profile within the span of a turbine rotor, can improve the power curve measurement as it accounts for the variations of wind shear during the measurement. This equivalent wind speed is a better representation of the available energy than the wind speed at hub height when there is some shear (i.e. the wind speed is not constant with height).

When performing power performance measurements on wind turbines, it is common practice to measure the reference wind speed from a hub-height meteorological mast standing 2.5 rotor diameters upwind of the turbine under test. However, in complex terrain it is likely that the wind conditions at the reference mast position differ from the ones seen by the wind turbine. In the particular case of a power performance measurement, the IEC 61400-12-1 standard [2] requires a "site calibration" prior to the power curve phase. The aim of such a calibration is to establish the correlation between the wind speeds measured by cup anemometers, installed at hub height, at the reference mast and at another temporary mast at the wind turbine position. The result is a set of flow correction factors for a set of wind directions.

In this report we will make a preliminary investigation of whether the concept of the equivalent wind speed can be used to improve site calibrations. A site calibration in complex terrain is performed at different heights following the method laid out by the IEC standard. In addition to the standard method using two cup anemometers at one (hub) height, results are presented using two non-standard methods:

- The use of a lidar to provide the wind speed at hub height at the reference position
- Obtain flow correction factors based on equivalent wind speeds (obtained from wind profile across the whole rotor area), with both lidar and masts.

The aim is to check whether a reduction of the site calibration uncertainty (and consequently of power performance measurement uncertainty) can be achieved.

A reduction in the site calibration uncertainty by using an equivalent wind speed could also be an indication that the equivalent wind speed method could increase the correlation between an observed and a predicted wind speed over several hundred meters in complex terrain. This has relevance to the use of the equivalent wind speed for short-term forecasting by using remote sensing devices.

2. Measurement campaign description

This measurement campaign was carried out simultaneously to the first stage of site calibrations (eastern wind turbine positions: A6, A5 and A4, see Figure 1) in CENER's Alaiz test station, between November 2009 and June 2010. The test site and terrain characteristics are described in [3].

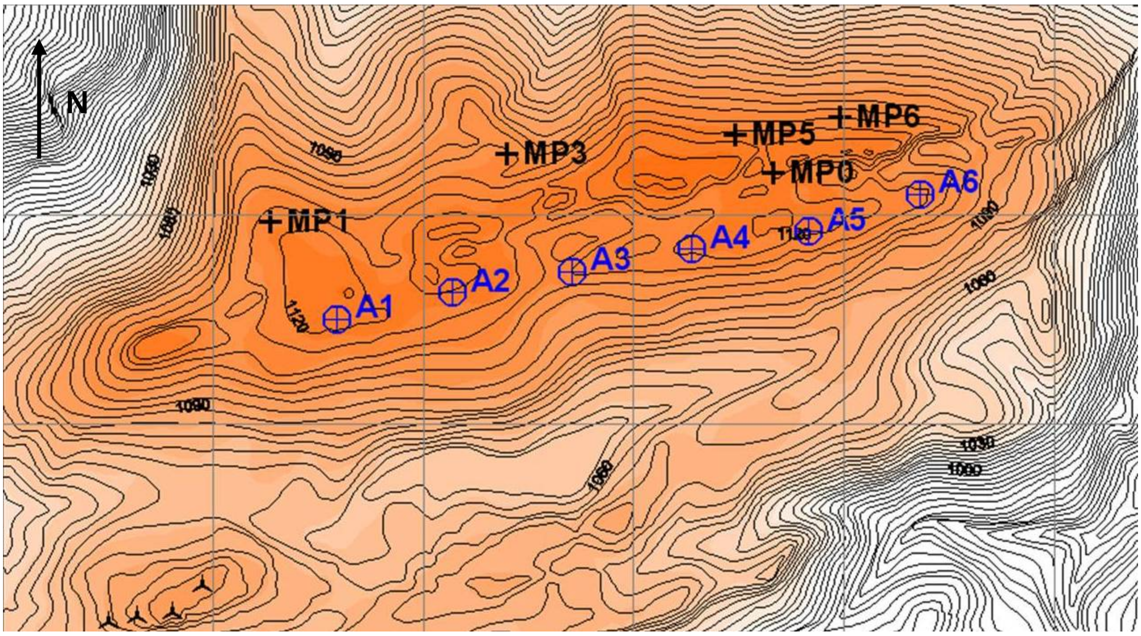

Figure 1 – Layout of wind turbine stands and reference meteorological mast positions in Alaiz test station.

Each of the wind turbine positions A6, A5 and A4 is calibrated at 4 heights (118m, 102m, 90m and 78m), to allow for the future installation of wind turbines of different hub heights. Temporary meteorological masts (or "calibration masts"), named MC6, MC5 and MC4 are installed at A6, A5, A4 respectively. Reference meteorological masts are installed at MP6, MP5 and MP0. This analysis focuses on the pair **MP5-MC5**. The distance between these two masts is 290m.

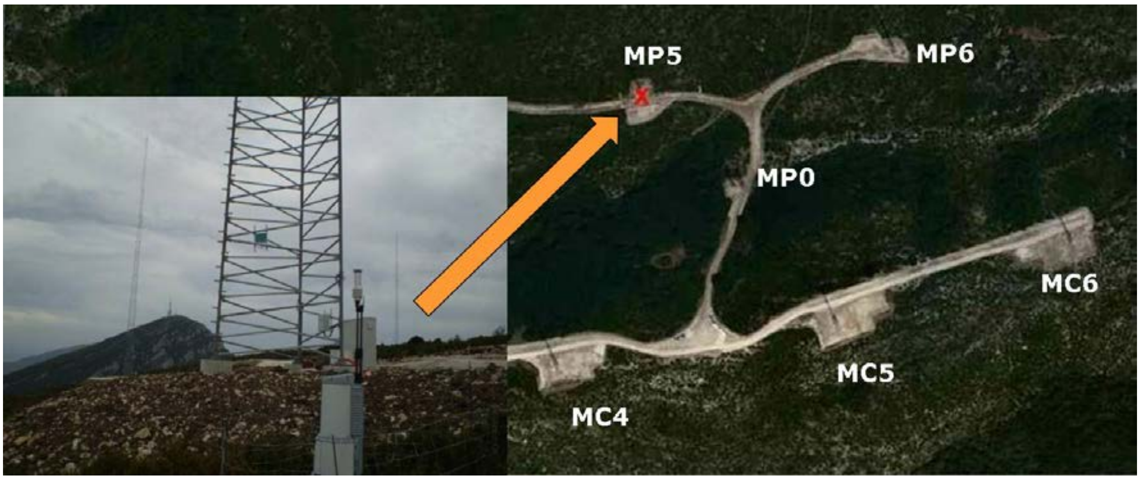

Figure 2 – Aerial view of the test station (December 2009) and positions of the meteorological masts installed at the site during the site calibrations. View of ZephIR deployed near MP5.

Figure 3 – Test site view, looking eastwards. From left to right: masts MP6, MP5, MP0, MC6, MC5 and MC4.

MP5 and MC5 have the same dimensions, orientation and instrumentation (Table 1). More details about the meteorological mast can be found in [3].

The lidar is installed close to MP5 and is configured to measure at heights 40m, 78m, 90m, 102m and 118m.

All data from masts and lidar are post-processed to 10min average statistics, and filtered. Lidar and mast are synchronized by GPS.

Sensor	Height a.g.l. (m)	Boom orientation (º)
Cup anemometer (main)	118	260
Cup anemometer (control)	116	260
Wind Vane	118	80
Propeller	116	80
Humidity & Temperature sensor	113	--
Cup anemometer (main)	102	260
Cup anemometer (control)	100	260
Wind Vane	102	80
Propeller	100	80
Humidity & Temperature sensor	98	--
Cup anemometer (main)	90	260
Cup anemometer (control)	88	260
Wind Vane	90	80
Propeller	88	80
Humidity & Temperature sensor	81	--
Cup anemometer (main)	78	260
Cup anemometer (control)	76	260
Wind Vane	78	80
Propeller	76	80

Cup anemometer	40	260
Humidity & Temperature sensor	38	--
Rain sensor	5	--
Humidity & Temperature sensor	2	--
Pressure sensor	1.5	--

*Table 1 – I*nstrumentation of masts MP5 and MC5

Type of Sensor	Model
Cup anemometer	Vector A100LK-PC3
Wind Vane	Thies-Compact
Propeller	Young 27106T
Humidity & Temperature sensor	Ammonit P6312
Pressure sensor	Vaisala PTB110
Rain sensor	Lambrecht 15152

*Table 2 –S*ensor models

3. Results

In this section results obtained at measurement heights 40m, 78m and 118m are presented. For illustrative purposes, wind speed measurements from 40m are also analysed although distance restrictions (290m > 4D) do not formally permit an IEC standard compliant site calibration at this height. This allows obtaining results for a wider range of heights although with a larger uncertainty from the 40m level. The wind vane at 78m on MP5 is used for wind direction binning at all heights.

Only wind direction sectors within the free measurement sector [305º, 30º) (derived from obstacle assessment [1]) with a representative amount of data are presented in the following results. The criterion used is that a sector should have a minimum amount of 144 datasets corresponding to wind speeds between 4 and 16m/s, and in those there must be at least 36 datasets below 8m/s and 36 datasets above 8m/s.

The following filters were applied to the dataset:

- Dates: 2009-11-24 08:50 to 2010-06-02 10:10
- Temperature>2ºC (T sensor at 113m, MP5)
- Lidar quality filters (must be fulfilled at <u>all</u> 5 measurement heights): PiF≥50, PiA≥30, Spatial variation parameter<0.1
- Lidar fog filter: Scaling38>50

3.1 Lidar performance

Here we compare the lidar wind speed measurements with those from the same heights at the adjacent mast (MP5). This will give us an indication of the measurement performance of the lidar which is relevant in assessing the site calibration results obtained when using this instrument as the reference sensor.

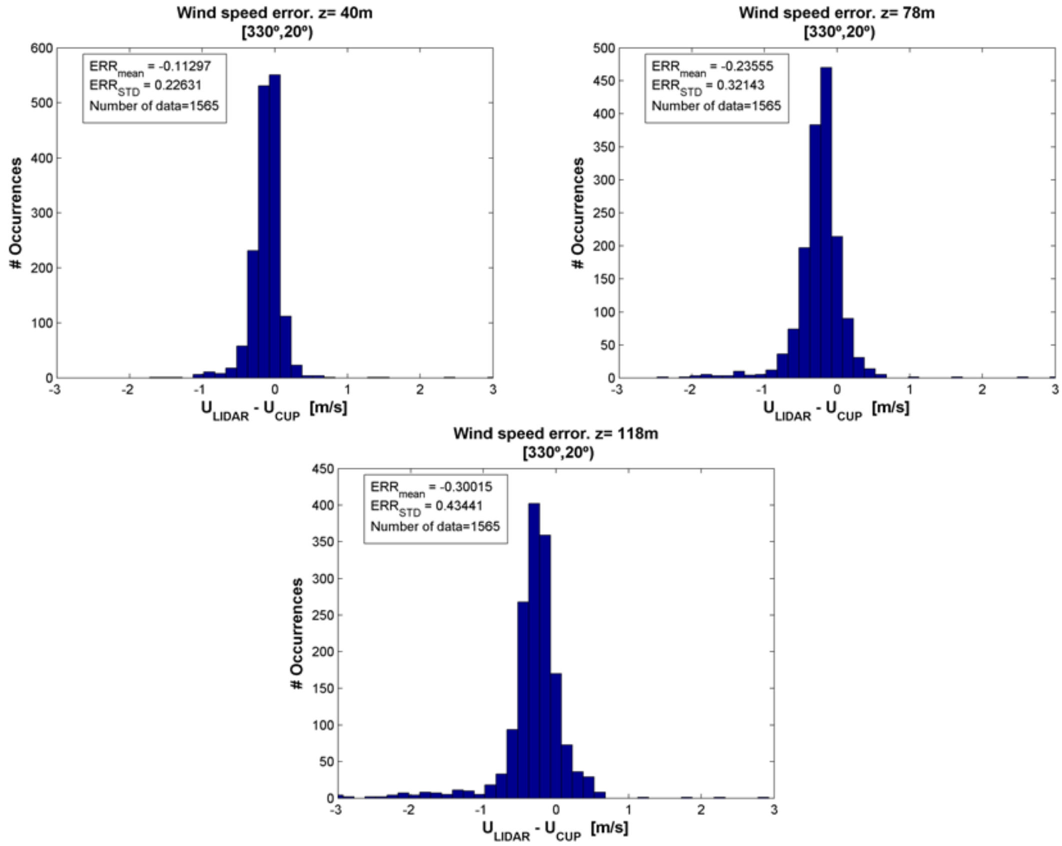

Figure 4 – Wind speed difference (U_{LIDAR}-U_{CUP}) between lidar and reference mast (MP5) cup anemometers at different heights: 40m, 78m and 118m.

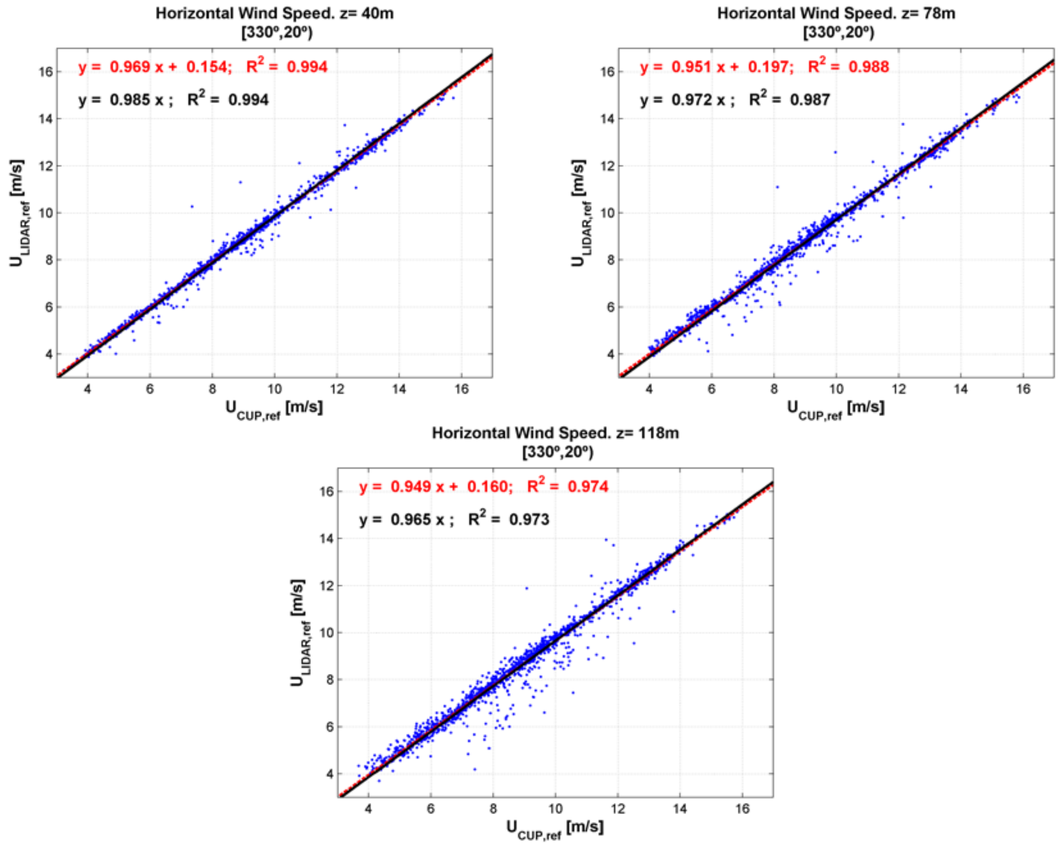

Figure 5 – Lidar vs cup anemometer wind speed at reference mast (MP5) at different heights: 40m, 78m and 118m.

Both the scatter plots and the histograms show that lidar underestimates wind speed, and the disagreement between lidar and cup anemometers increases with height. The scatter increases drastically with height, probably due to cloud contamination. This is unusually poor lidar performance as can be seen by the comparative measurements at the same site in [4].

Figure 6 shows how the ratio of the lidar wind speed to the cup anemometer wind speed changes with wind direction. Most of deviation between the lidar and the cup is accounted for by terrain effects.

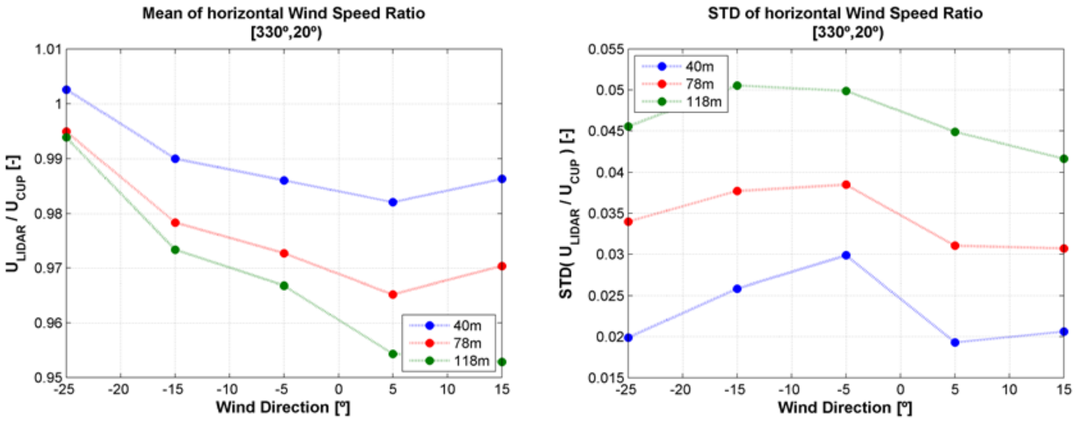

Figure 6 – Left: Mean of the ratio between lidar and cup wind speed, per direction bin. Right: Standard deviation of the ratio between lidar and cup wind speed, per direction bin

3.2 Profile classification

The wind speeds at heights 40m, 78m and 118m measured by

- the lidar
- the cup anemometers on the reference mast
- the cup anemometers on the calibration mast

are fitted to the power law model:

$$U_{fit}(z) = U(z_{hub}) \cdot \left(\frac{z}{z_{hub}} \right)^{\alpha} \qquad (1)$$

Where z_{hub} =78m, U is the wind speed, z is the height (a.g.l.), and α is the shear exponent. This model is simple and widely used to quantify wind shear. However, not all wind profiles would be well described by this power law. For this reason, the residual of the fit to the power law is used as an estimator of the goodness of the fit. This residual is calculated using the following definition:

$$RES = \frac{\sqrt{\sum_i \left(U_{fit,i} - U_i \right)^2}}{3} \qquad (2)$$

Where i=1..3; U_i is the wind speed measured by the lidar or the cups at height z_i, and $U_{fit,i}$ is the wind speed value given by the power-law fitting function at height z_i.

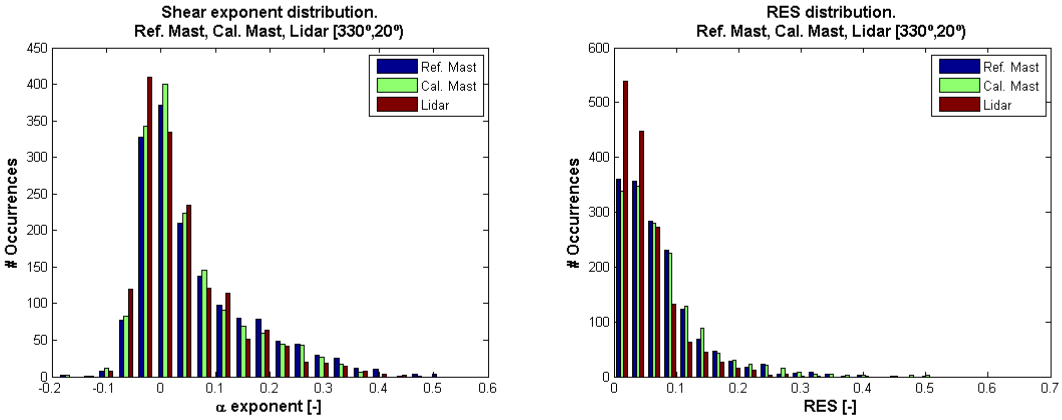

Figure 7 – Frequency distribution of shear exponent α (left) and residual of the fit to the power law (right) obtained from wind profiles measured by the reference mast (blue), the calibration mast (green) and the lidar (red).

3.3 Flow correction factors for wind speeds at hub height

In this section, each height is treated independently. That is, we suppose 3 independent calibrations are made, corresponding to hub heights 40m[3], 78m and 118m.

At each height, wind speed ratios are calculated in two different ways:

$$\frac{U_{CUP,cal}}{U_{CUP,ref}}$$ is the ratio between the wind speed measured by the cup anemometer in the calibration mast (MC5) and the wind speed measured by the cup anemometer in the reference mast (MP5) and

$$\frac{U_{CUP,cal}}{U_{LIDAR,ref}}$$ is the ratio between the wind speed measured by the cup anemometer in the calibration mast (MC5) and the wind speed measured by the lidar.

The flow correction factors are the average of those ratios in each wind direction bin. Since the lidar underestimates the wind speeds (Section 3.1), it is of little use to compare the factors obtained using lidar wind speed as reference to the factors obtained with cups, since as expected the ratios obtained with lidar are bigger. Instead, the standard deviation of the flow correction factors in each direction is compared:

[3] The use of this height, as mentioned earlier, is just an approximation for illustrative purposes (40m height does not fulfil with the requirements of required instrumentation, neither the 2D to 4D separation requirement).

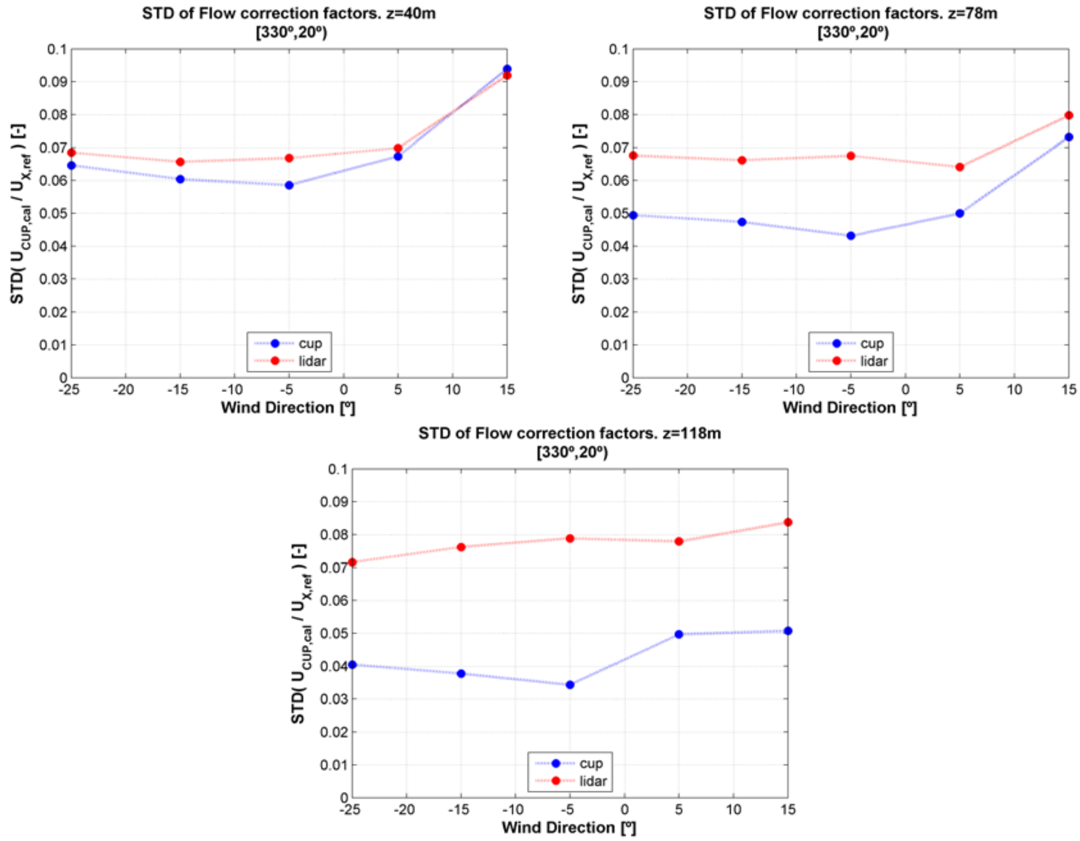

Figure 8 – Standard deviation of flow correction factors obtained at three different hub heights, using cup (blue) or lidar (red) as the reference wind speed.

The use of the lidar as the reference wind speed at hub height increases the uncertainty (standard deviation) of the flow correction factors. This is to be expected from the poor correlation of the lidar to the adjacent mast that we saw in Section 3.1.

Since the use of the lidar as the reference wind speed did not represent an improvement (i.e. reduction of the standard deviation of the flow correction factors), it is next investigated if the use of equivalent wind speeds can improve the results..

3.4 Flow correction factors for equivalent wind speeds

In this section we will investigate if using the equivalent wind speed, an area-weighted average of the wind speed profile, instead of the wind speed at individual heights can decrease the scatter in the flow correction factors. Note that since we had only one lidar device available, the equivalent wind speeds are calculated using cup anemometers at each mast position. This is possible due to the generous height of the Alaiz met masts.

Considering the available measurement heights, we assume that we are performing the site calibration, for the power performance verification of a hypothetical wind turbine of 78m hub height and 80m rotor diameter.

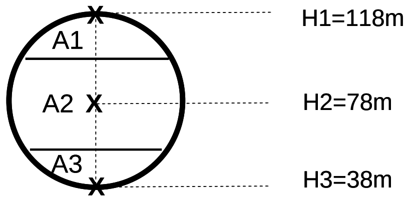

Figure 9 – Measurement heights and their corresponding sections of rotor area.

The rotor swept area is divided as indicated in Figure 9, where the upper and lower limits of area A2 are respectively (H1+H2)/2 and (H2+H3)/2.

The equivalent wind speed is defined as:

$$Ueq = \left(\sum_i U_i^{\,3} \frac{A_i}{A} \right)^{1/3} \qquad (3)$$

Where U_i (with i=1...5) is the wind speed at height H_i, and A_i is the portion of rotor area corresponding to H_i.

Next, flow correction factors are calculated according to the following two expressions. The results are compared to what was obtained in Figure 8 at 78m, see Figure 9.

$\frac{Ueq_{CUP,cal}}{Ueq_{CUP,ref}}$ is the ratio between the equivalent wind speed measured by the cup anemometers in the calibration mast (MC5) and the equivalent wind speed measured by the cup anemometers in the reference mast (MP5) and

$\frac{Ueq_{CUP,cal}}{Ueq_{LIDAR,ref}}$ is the ratio between the equivalent wind speed measured by the cup anemometers in the calibration mast (MC5) and the equivalent wind speed measured by the lidar.

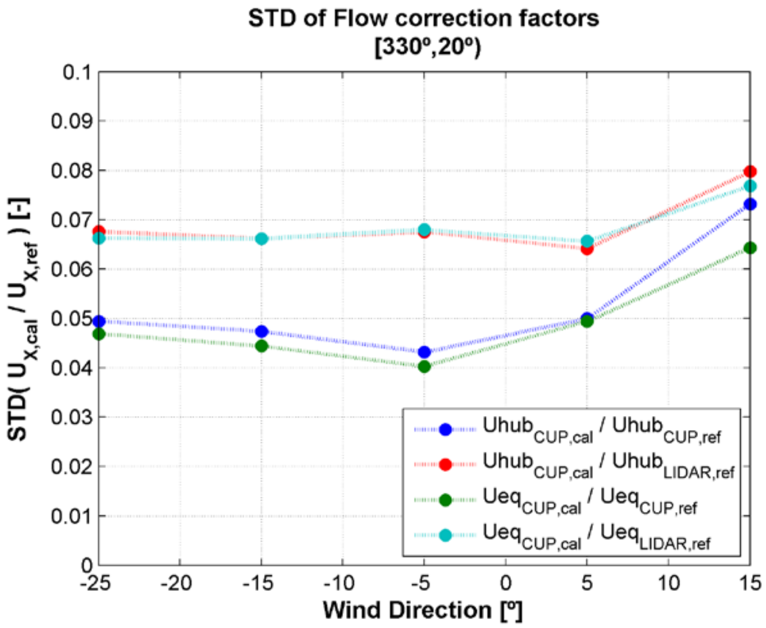

Figure 10 – Standard deviation of flow correction factors obtained from hub height wind speeds (using cup –dark blue- or lidar -red- as reference), and from equivalent wind speeds (using cup –green- or lidar -light blue- as reference).

We can see from Figure 10 that in comparison with the hub-height to hub-height flow correction factors (blue dots), the equivalent wind speed flow correction factors (green dots) have a slightly lower standard deviation.

4. Conclusions

- Using lidar wind speed at hub height as the reference wind speed in this site calibration does not produce any improvement. On the contrary, the site calibration uncertainty (i.e. standard deviations of the flow corrections factors) is increased. This is probably due to the poor performance of this particular lidar under the cloudy and foggy conditions at the test site.

- Using flow correction factors obtained from equivalent wind speeds measured with cup anemometers (across the rotor swept area), a reduction in the scatter of the flow correction factors (and therefore in the statistical uncertainty of the site calibration) is observed.

- This improvement is however small, perhaps because, as seen from the profile classification results, the Alaiz profiles are not very extreme - they do not deviate much from a power law and the shear exponents are quite modest. It may be possible that this methodology presents a bigger improvement in sites were extreme profiles are more common.

- It remains to be demonstrated whether the benefits of using an equivalent wind speed methodology for site calibration can also be obtained when using remote sensing devices to measure the wind profiles. Although the results from this experiment are not

encouraging, more modern versions of this lidar and different lidar types can be expected to give much higher correlations in comparable conditions. A second issue to resolve is how to handle the measuring errors in the remote sensing devices arising from the flow curvature at complex sites.

References

[1] Wagner R. et al., Accounting of for the wind speed shear in power performance measurement, Wind Energy 2011; 14:993--1004.

[2] IEC 61400-12-1: *Power performance measurements of electricity producing wind turbines.* Edition 2005.

[3] Gómez P. "*Measurement campaign in Alaiz – Overview*". SafeWind Deliverable Dc-2.3 Overview.

[4] Borbon F. "*Results of the measurement campaign in complex terrain – Assessment*". SafeWind Deliverable Dc-2.3 Assessment.