Comparison of wind speed measurements over complex terrain using a LIDAR system

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***Abstract*—An analysis of the feasibility of using new technologies based on remote sensing for measuring wind speed and wind direction at different heights has been performed. A remote sensing equipment, specifically a WindCube Lidar one scanning at different cone angles, a common cup anemometer, and a propeller anemometer have been used. Comparisons over complex terrain are presented of wind speed and wind direction at 69 m and 45 m above ground level. Results show excellent correlation between the Lidar and the common wind speed meters. Apart from those sectors affected by tower shadow, wind speed correlation results are in line with previous contributions. In the same way, wind direction registered by WindCube shows good agreement with the other anemometers, although some requirements must be taken into account.**

***Keywords*—Remote wind measurement, cup anemometer, propeller anemometer, complex terrain.**

NOMENCLATURE

N	Number of measurements during test period
V_{MM}	Wind speed measured by meteorological mast
V_{WC}	Wind speed measured by WindCube
$RMSE$	Root mean square error

I. INTRODUCTION

Unlike conventional power plants, the production of wind farms depends on meteorological conditions, specifically the magnitude of the wind speed, which can not be directly influenced by human intervention. Hence, in wind energy systems, wind speed plays the most important role. Due to the cubic relationship between velocity and power, it is expected that a small variation in the wind speed will result in a large change in the power generated by a wind turbine. Therefore, good quality anemometers which are sensitive, reliable and properly calibrated must be used for wind measurements.

The calibration is done under ideal conditions against a benchmark anemometer, which is considered as the reference one. Even with proper calibration, some errors may appear in the measurements. One of these important errors is the tower shadow. The nearby obstacles, or even the anemometer tower itself, may disturb the instrument, tending to mislead. In order to minimize the risk of tower shadow, guyed towers are preferred to lattice ones.

There are several types of anemometers, [1], [2]. The first anemometer appeared as early as in 1450, and was a pressure plate one. Nevertheless, the most commonly used for wind energy resource assessment is the cup anemometer, which is basically a drag device. It consists of several equally spaced cups connected to a rotating vertical axis. This anemometer can sustain a variety of harsh environments. Though, it has some limitations. It accelerates quickly with the wind but retards slowly when the wind stops. Cup anemometer thus does not give reliable measurement in wind gusts. Moreover, the air density of the particular location where it is put up affects it.

Another anemometer commonly used in wind energy applications is the propeller one, which works predominantly on lift force. This measures wind speed parallel to its axis. Wind direction can be measured as well. Therefore, three propellers must be used to measure the horizontal and vertical components of wind.

Apart from its technical drawbacks, a functional disadvantage of the anemometers presented before is that both of them need met masts for their mounting and the costs associated with the purchase, erection and instrumentation of the met masts increases rapidly with height. The evolution of new multi-MW wind turbines has resulted in increased hub heights and increased rotor diameters, thus making remote sensing an important issue for wind energy applications. Remote sensing techniques offer the ability to determine wind speed and direction at several heights using a ground-based instrument which operates via the transmission and detection of light (LIDAR) or via the transmission and detection of sound (SODAR). As well as the economic difficulties, there is a mounting pressure within the wind energy industry in order to find a new method that takes into account the wind speed over the swept rotor area instead of hub height only, [3]–[9].

Considering previous works and contributions, the aim of the present paper is to analyse, through measurements

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performed on a meteorological mast equipped with a cup anemometer and a propeller one, the similarity degree between these equipment and a WindCube Lidar system scanning at different cone angles. Firstly, section II summarizes the most important contributions related to Lidar experiments for wind energy applications. Then, section III shows a brief description of the test site. Next, section IV analyses the measurements performed by both equipment according to wind speed and wind direction, both at 45 m and 69 m above ground level. Finally, section V outlines all the ideas found in the work.

II. PREVIOUS EXPERIMENTS PERFORMED WITH LIDAR

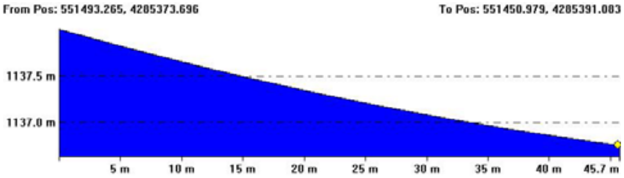
Although remote sensing for wind energy applications is a recent issue, several approaches have been performed in order to assess the behaviour of these instruments versus common wind speed meters. In [10], after solving a problem with the focus of a ZephIR Lidar located in flat terrain, the measurements on a meteorological mast instrumented with several cup anemometers at different heights during a period of three weeks revealed very good correlations at all heights. In [11] measurements with a Lidar and two Sodar in an offshore wind farm during two months showed that remote sensing could be used to supplement met mast measurements for offshore applications. The work developed in [12] points out high correlations between a Lidar and a cup anemometer, both in flat and complex terrain, though it must be noticed that the measurements performed in complex terrain had short duration. In [13], a longer test period over complex terrain shows a good correlation degree. In general, it can be seen that Lidar's results are in good agreement with classical wind speed meters.

It can be stated that all the works mentioned before used only one type of Lidar, a Zephir one. Whereas in [8] was used by first time a WindCube Lidar for wind energy purposes. It was compared with a Zephir one, a Sodar and a cup anemometer in the power curve performance scope. It was concluded that the WindCube offered good results, very similar to the Zephir ones, and better than the Sodar and cup ones. Since light can be much more precisely focused and spreads in the atmosphere much less than sound, Lidar instruments have higher accuracy than Sodar ones. In [14] similar results are shown with a WindCube and a cup anemometer. Moreover, in [15], a depth comparison between the two commercial Lidars present at moment, Zephir and Windcube ones, is performed.

III. REAL DATA MEASUREMENTS

The experiment is carried out in a wind farm from Spain. Specifically, the measurements have been performed in the south of Castilla-La Mancha, the second region of Spain with the highest wind installed capacity (data obtained from the National Energy Commission of Spain in November 2010). Three equipments have been used, namely: a WindCube Lidar, a cup anemometer and a propeller anemometer (these installed at the meteorological mast of the wind farm). The distance between the met mast and the remote sensing instrument is lower than 50 m, and no obstacles were set out between both equipments. Figure 1 shows the equipments used and the difference in ground level between them. It can be seen that the met mast is located 1 m over the WindCube. Though, this difference was corrected in the beginning of measurements. For the current analysis, two different measurement heights have been selected. One measurement height is related to the hub height of the wind turbines, 69 m above ground level. Whereas, the other height is found at a lower height, 45 m.

(a) Equipment at test site: WindCube (left) and Met Mast (right)



(b) Difference in ground level between met mast (up) and WindCube (down)

Fig. 1. Layout of test site

The test covered a period of 52 days of wind measurement data during the summer of 2010. However, the measurements were not continuous. In fact, the WindCube was set to measure during three weeks with a 30° cone angle. The following 31 days the focus of the Lidar was changed by a smaller cone angle, 15°.

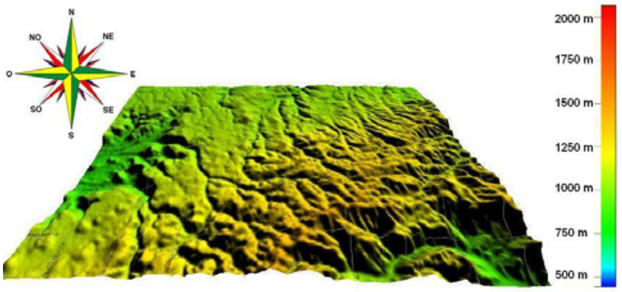
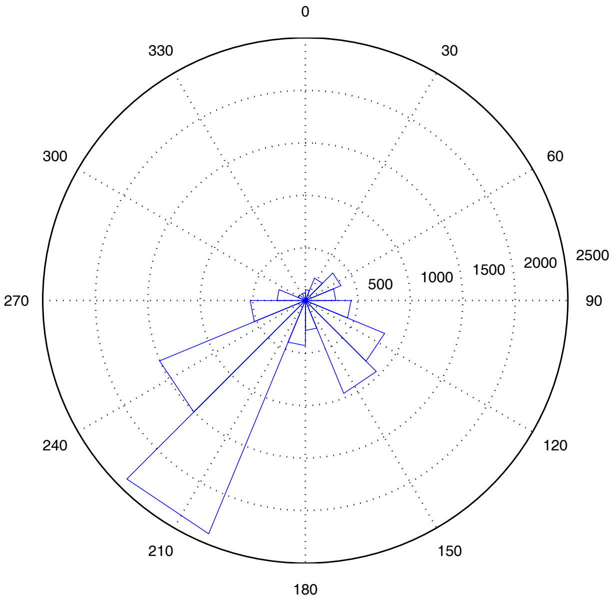


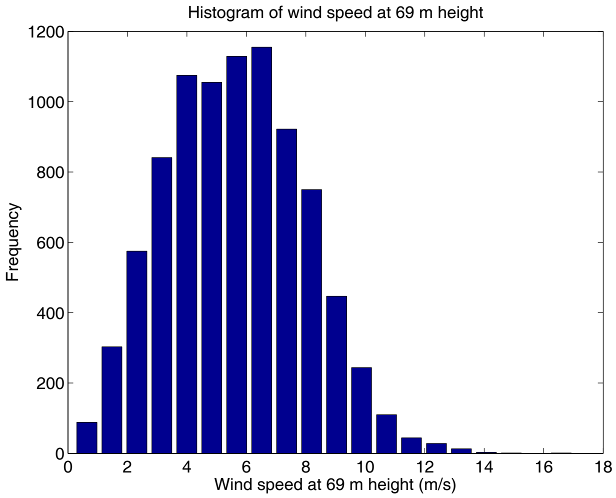
Fig. 2. Test site 3D topographical map

One of the major concerns related to remote sensing equipments is their ability to perform measurements over complex terrain. Hence, the topographical features of the terrain must be depicted. According to [16], when the differences in elevation exceeded 60 m within a radius of 11.5 km in the surroundings of the wind turbine, that terrain must be considered as complex terrain. Therefore, in figure 2, the 3D topographical map of the experimental site is shown through one square of 25 km wide. It thus can be concluded that the terrain over all the measurements were performed is a complex one.

Although the main object of the present paper is to analyze the difference in the measurements performed by remote sensing equipments and common wind speed meters, a slight description of the wind resource at test site is depicted in figure 3. The upper part of the figure points out southwest direction as the main wind speed direction, and the lower graph depicts the frequency of wind speeds taken at 69 m height by cup anemometer. It thus is clearly seen that these values fit perfectly with the ones expected in an onshore wind farm.



(a) Wind rose



(b) Histogram

Fig. 3. Wind resource parameters at test site

IV. Results and Discussion

Wind speed and wind direction are exoposed for the different periods in the present section.

Firstly, in order to make an estimation of the similarity degree of the three equipments, the root mean square error ($RMSE$) was calculated, both for wind speed and direction, equation (1):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (V_{WC} - V_{MM})^2}{N}} \tag{1}$$

Where, V_{MM} is the wind speed recorded by any of the common wind speed meters installed at the meteorological mast. Obviously, the calculation of the $RMSE$ related to wind direction is performed replacing wind speed with wind direction in equation (1).

Before showing the results achieved, it is important to point out that what is done here is a comparison between two different measurement methods, because on the one hand it is measured over a volume with significant vertical and horizontal extent, and on the other hand it is taken into account essentially a point measurement (the measurement volume of the cup anemometer becomes insignificant in comparison with Lidar one).

A. *First Measurement Period*

The first measurement period covered 21 days during June 2010. Since 10 min. average value is chosen for wind speed and wind direction, 3024 measurements were expected. However, due to some communication troubles with the remote sensing equipment, 2946 measurements were performed.

1) Wind Speed Analysis: By applying equation (1) to the wind speed measured by the three equipments during the first test period, tables I and II show the $RMSE$ related to each measurement height.

This result shows an error rather low between equipments, taking into account the complex topography of the terrain

Equipments	*Cup Anemometer*	*Propeller Anemometer*
WindCube	0.2882 m/s	0.4055 m/s

TABLE I
WIND SPEED $RMSE$ AT 69 M HEIGHT

Equipments	*Cup Anemometer*	*Propeller Anemometer*
WindCube	0.2467 m/s	0.2749 m/s

TABLE II
WIND SPEED $RMSE$ AT 45 M HEIGHT

and no filter has been applied. However, a relevant error appears in the measurements performed by the propeller anemometer at 69 m height, which is due to some technical problems in the beginning of measurements. Apart from this particular instance, a slight increase of the error with height is found. Moreover, the behavior of the common speed meters is different, the cup anemometer matches the remote sensing equipment better than the propeller anemometer.

In order to deeply analyse the behaviour of the several instruments, the $RMSE$ has been calculated according to wind speeds. Thus, 4 m/s wind speed intervals have been chosen, figure 4.

There are three different coloured lines in figure 4 showing three different amounts of data chosen. The blue line depicts RMSE calculation taking into account the data both from WindCube and cup anemometer that fits within each interval. Thus, the RMSE obtained with this method is the one which has lower amounts of data. The black line depicts RMSE calculation with the values measured from the cup anemometer fitted within each interval. And the red line shows RMSE calculation with the values measured from the WindCube fitted within each interval. The upper and central part of figure 4 shows the RMSE in each wind speed interval, in absolute and relative values, respectively. Relative values are obtained by dividing absolute RMSE values into the mean wind speed registered within each speed interval. Whereas, the lower part shows the amounts of data used for each calculation. Looking at the central part of the figure, it can be stated that the higher the wind speed, the lower the RMSE.

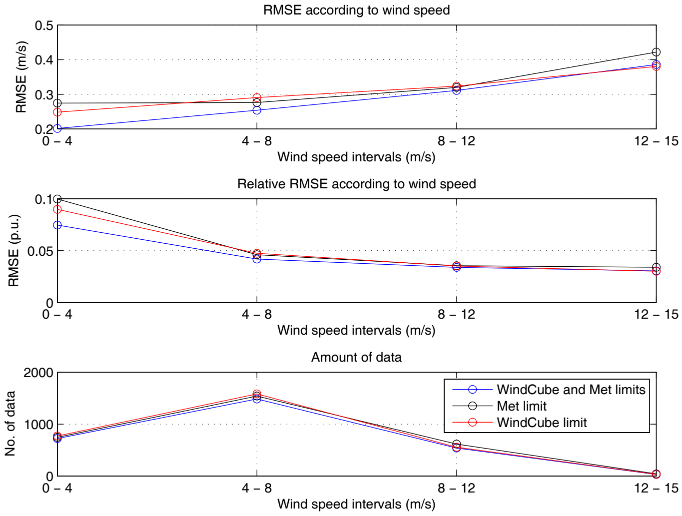


Fig. 4. Wind speed $RMSE$ between WindCube and cup anemometer at 69 m height, according to wind spweed intervals

Hence, WindCube measurements reflects at high wind speeds very similar results to common wind speed meters. However, in [15] it is said that the WindCube can measure in complete wind still without losing accuracy. Therefore, it must be pointed out that the results shown in the present paper, on the one hand, are based on complex terrain and, on the other hand, the cup anemometer loses accuracy at low speed because its rotating inertia. Moreover, it must be taken into account that current wind turbines does not start working until the wind speed has exceeded 4 m/s. Thus, the error appeared at low wind speeds is less relevant than the one found at higher speeds. The conclusions for the propeller anemometer are the same than the ones presented before for the cup anemometer.

Apart from studying the $RMSE$ between equipments according to the wind speed, the $RMSE$ related to wind directions has been calculated as well. Next requirements have been taken into account:

- Wind directions measured by both instruments have been divided among six sectors, starting with -30º, and with a width of 60º. Table III depicts the measurement sectors.

Sectors					
S1	S2	S3	S4	S5	S6
-30º:30º	30º:90º	90º:150º	150º:210º	210º:270º	270º:330º

TABLE III
WIND DIRECTION SECTORS SELECTED

- Four wind speed filters have been used to split wind speed in four. Firstly, no filter is considered. Subsequently wind speeds lower than 2 m/s, 4 m/s and 6 m/s have been filtered.

Taking into account previous requirements, figure 5 shows the $RMSE$ between WindCube and cup anemometer at 69 m height and the amount of data used for each assessment.

Three wind direction sectors where the RMSE is greater than the other ones are noticed, even a difference greater than three times is found within wind speed filter higher than 6 m/s between sectors S1 and S6. This result may be caused because sectors S1 to S3 the tower is shadowing the Windcube. Though, it is important to point out that the results of sectors S1 and S2 for the pink line are not relevant due to its low amount of data involved (9 and 21 measurement points, respectively).

The results for the $RMSE$ according to wind direction sectors at 45 m height and propeller anemometer follow the same pattern.

Once the RMSE has been analysed both according to wind speed and wind direction, a correlation analysis is performed. Thus, Figure 6 shows the measurements performed by WindCube and common wind speed meters, together with the linear

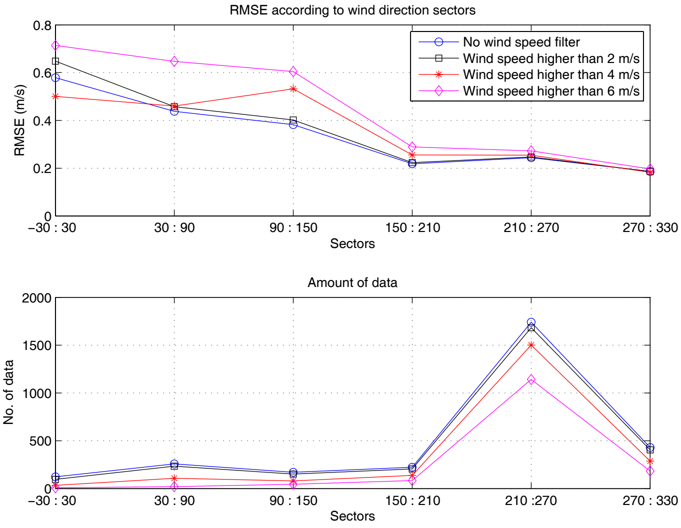


Fig. 5. Wind speed $RMSE$ between WindCube and cup anemometer at 69 m height according to wind direction sectors

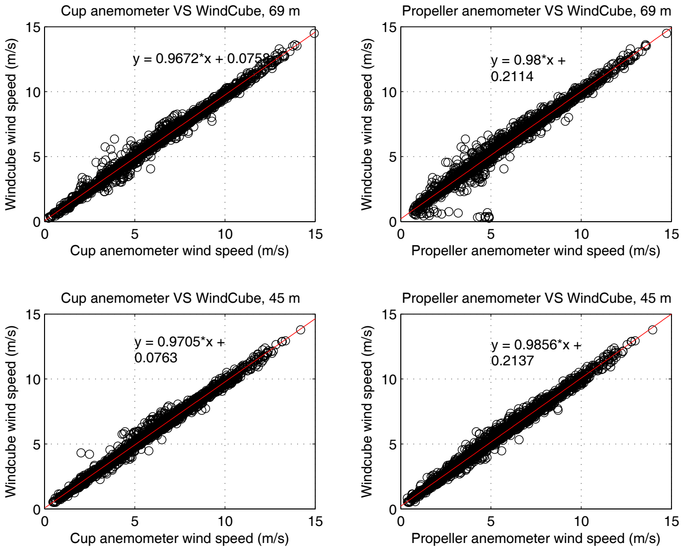


Fig. 6. Wind speed correlation

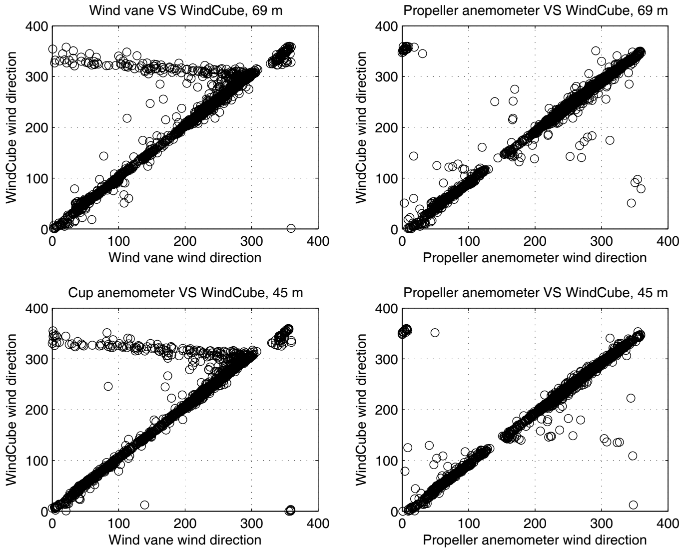


Fig. 7. Wind direction correlation

regression adjustment. Since the slope of the regression line is close to 1, good results are noticed from this figure.

2) Wind Direction Analysis: Figure 7 shows wind direction measured by WindCube, propeller anemometer and a common wind vane at all measurement heights. A wide spread of data is depicted and could mislead. But, in fact, the spread is not significant because when one instrument measures a value closeness to 360º at one moment and the other instrument a closeness to 0º one at the same moment, really the correlation performed by the instruments is good although appears some spread in the figure (for example, all the points located in the left upper corner depicts this characteristic).

Hence, in order to improve wind direction correlation, in figure 8 two filters have been applied. On the one hand, a filter that adds 360º to the lower measurement when the difference between each pair of wind directions is higher than 180º has been improved. On the other hand, all the wind speeds lower than 4 m/s have been filtered in order to avoid the great variances in wind direction that occurs at low wind speeds. Taking into account these improvements, the propeller anemometer shows a certainly excellent slope (0.9942 and 1.0011 for each measurement height). Thus, an acceptable correlation degree is found over the wind direction registered by the WindCube.

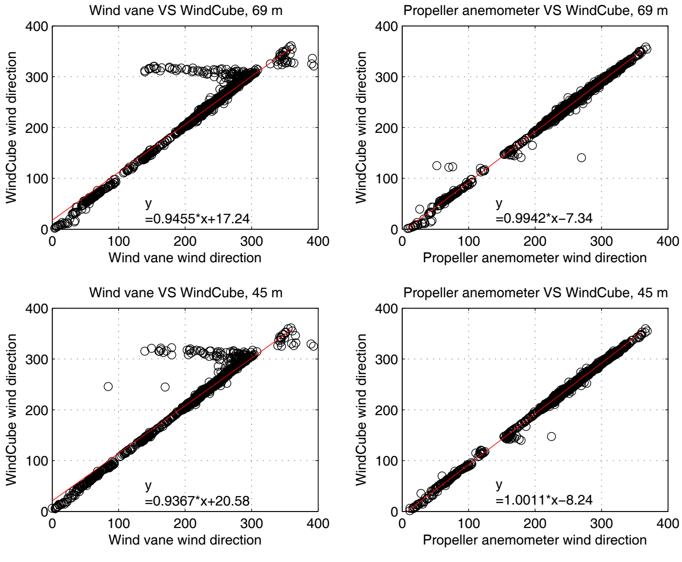


Fig. 8. Filtered wind direction correlation

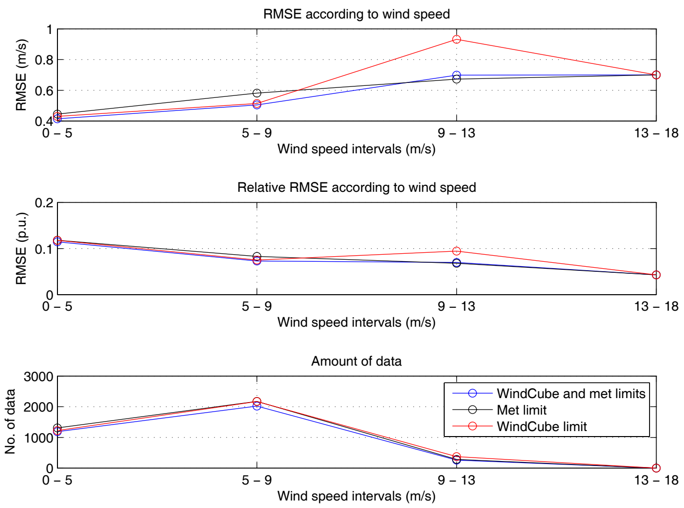


Fig. 9. Wind speed $RMSE$ between WindCube (using 15^o cone angle) and cup anemometer at 69 m height

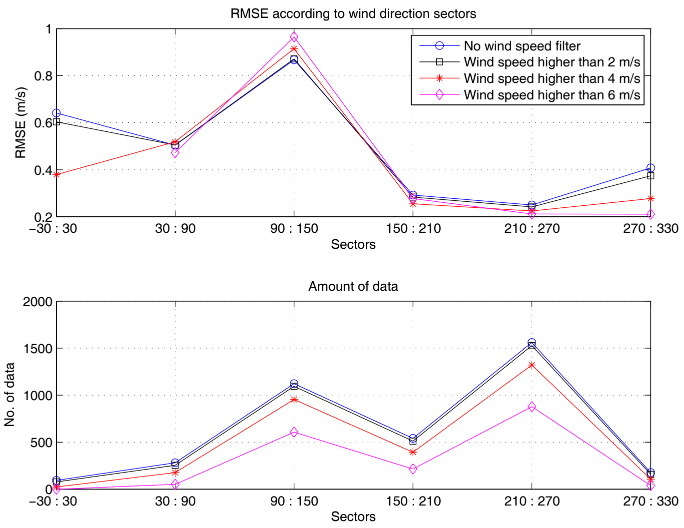


Fig. 10. Wind speed $RMSE$ between WindCube (using 15^o cone angle) and cup anemometer at 69 m height according to wind direction sectors

B. Second Measurement Period

The second measurement period covered 31 days during July 2010, using the 15^o cone angle of the remote sensing instrument. Therefore, 4464 measurements were expected. However, due to some communication troubles with the remote sensing equipment, 3770 measurements were performed.

1) Wind Speed Analysis: By applying equation (1) to the wind speed measured by the three equipments, tables IV and V show the $RMSE$ related to each measurement height.

Equipments	***Cup Anemometer***	***Propeller Anemometer***
WindCube	0.5465 m/s	0.6039 m/s

TABLE IV
WIND SPEED $RMSE$ AT 69 M HEIGHT

Equipments	***Cup Anemometer***	***Propeller Anemometer***
WindCube	0.5002 m/s	0.4751 m/s

TABLE V
WIND SPEED $RMSE$ AT 45 M HEIGHT

The results show similar behavior when the 30^o cone angle was used. A moderate increase of the error with height is found as well. Though, the value is approximately two times higher than the measurements performed with the 30^o cone angle.

Furthermore, the $RMSE$ has been calculated according to wind speed intervals. Thus, 4 m/s wind speed intervals have been chosen, figure 9. The information offered by the coloured lines depict the same than figure 4. The central part of the figure shows that the higher the wind speed, the lower the RMSE.

Apart from studying the $RMSE$ between equipments according to the wind speed, the $RMSE$ related to wind directions has been calculated with the lower cone angle as well. The same requirements depicted in section IV-A have been taken into account. Figure 10 shows the $RMSE$ between WindCube and cup anemometer at 69 m height. Although a low $RMSE$ is found, sector S3 provides a higher error. However, in this sector and two previous ones the met mast is shadowing the remote sensing equipment.

As well as the RMSE analysis related to wind speed and wind direction, the correlation analysis using 15^o cone angle is presented, figure 11. The comparison versus the measurements performed using the 30^o cone angle shows that better slope is found between cup anemometer and remote sensing instrument using the 15^o cone angle. Whereas, the correlation degree between the propeller anemometer and the WindCube improves using the 30^o cone angle.

2) Wind Direction Analysis: Taking into account two filters commented during the first measurement period for wind direction analysis, figure 12 shows wind direction measured by WindCube, propeller anemometer and a common wind vane at all measurement heights. An anomalous result for the propeller anemometer is found. Though, it must be pointed out that this anemometer underwent several disconnections during the test period. Since results of the left side of figure 12 are in line with previous works, and the three equipments were set to measure at the same time, the anomalous behavior it thus attached to the propeller anemometer.

V. CONCLUSIONS

Generally, remote sensing results based on Lidar instruments are intended to be very good and promising. One of the major advantages of these systems is their easy and quick deployment, which can make this equipment a relevant tool for use in wind energy issues, like wind resource assessment and power curve performance. However, due to its recent

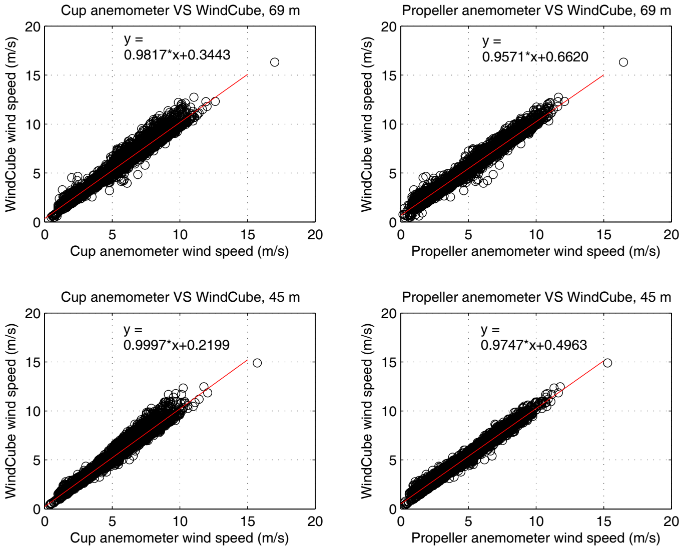


Fig. 11. Wind speed correlation using 15° cone angle

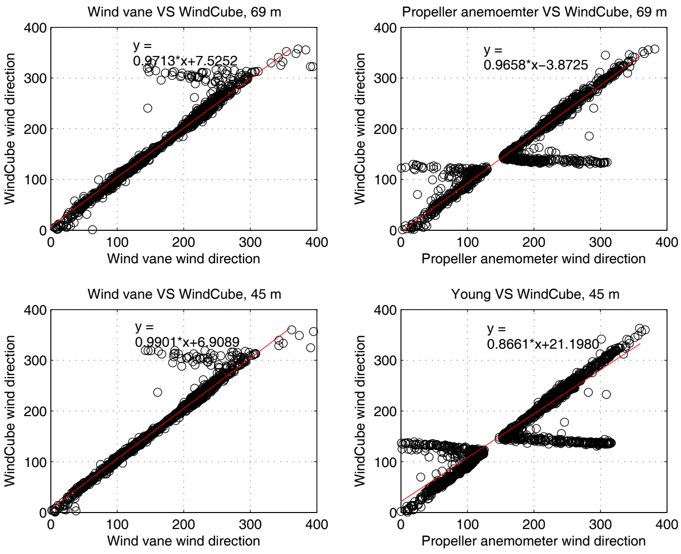


Fig. 12. Filtered wind direction correlation using 15° cone angle

application in the wind energy scope, further research is needed.

A WindCube Lidar system and two common wind speed meters (a cup anemometer and a propeller anemometer) have been deployed in a wind farm in order to analyse their correlation degree in a very complex terrain. Two measurement heights have been chosen to assess wind speed and wind direction during 52 days.

WindCube shows high correlations to the common cup anemometer mounted on a meteorological mast. Apart from those sectors affected by tower shadow, wind speed correlation shows good results. Firstly, a higher RMSE is found in the measurements performed at greater height above ground level over the whole measurement period. According to wind speed level, the higher the wind speed, the lower the RMSE between WindCube and common wind speed meters.

In the same way, the wind direction registered by the WindCube shows good agreement with common wind direction vanes, although some variation on the dispersion between both devices has been found, and this matter needs further attention. A possible reason lies in the measuring method (volume versus point measurements). Thus how to interpret the difference between these two methods of measurements is not fully understood.

In spite of the previous trouble, the work developed in the present paper states that WindCube instruments can be used in the same way than common wind speed meters. Furthermore, it seems that new ideas (alternative scanning modes, different cone angles, ...) are necessary to improve the accuracy of remote sensing instruments over complex terrain.

REFERENCES

[1] S. Mathew, *Wind Energy: Fundamentals, Resource Analysis and Economics*. Springer, February 27 2006.

[2] A. L. R. James F. Manwell, Jon G. McGowan, *Wind Energy Explained: Theory, Design and Application*. WileyBlackwell, April 19 2002.

[3] A. Honrubia, A. Vigueras-Rodríguez, E. Gómez-Lázaro, D. Rodríguez, M. Mejías, and I. Lainez, “The influence of wind shear in wind turbine power estimation,” *European Wind Energy Conference*, 2010.

[4] R. Wagner, I. Antoniou, S. M. Pedersen, M. S. Courtney, and H. E. Jorgensen, “The influence of the wind speed profile on wind turbine performance measurements,” *Wind Energy*, vol. 12, pp. 348–362, 2009.

[5] I. Antoniou, R. Wagner, S. M. Pedersen, U. Paulsen, H. A. Madsen, H. E. Jorgensen, K. Thomsen, P. Enevoldsen, and L. Thesbjerg, “Influence of wind characteristics on turbine performance,” *European Wind Energy Conference*, 2007.

[6] R. Wagner, M. Courtney, J. Gottschall, and P. Lindelow-Marsden, “Improvement of power curve measurement with lidar wind speed profiles,” *European Wind Energy Conference*, 2010.

[7] N. Stefanatos, D. Zigras, D. Foussekis, F. Kokkalidis, P. Papadopoulos, and E. Binopoulos, “Revising reference wind-speed definition for power performance measurements of multi-mw wind turbines,” *European Wind Energy Conference*, 2008.

[8] R. Wagner, H. E. Jørgensen, U. S. Paulsen, T. J. Larsen, I. Antoniou, and L. Thesbjerg, “Remote sensing used for power curves,” *International Symposium for the Advancement of Boundary Layer Remote Sensing*, 2008.

[9] K. Bleiber, T. Kramkowski, N. Cosack, and K. Braun, “The influence of meteorological parameters on the operational behavior of multimegawatt wec,” *German Wind Energy Conference*, 2006.

[10] D. A. Smith, M. Harris, A. S. Coffey, T. Mikkelsen, H. E. Jørgensen, J. Mann, and R. Danielian, “Wind lidar evaluation at the danish wind test site in høvsøre,” *Wind Energy*, vol. 9, no. 1, pp. 87 – 93, 2006.

[11] I. Antoniou, H. E. Jørgensen, T. Mikkelsen, S. Frandsen, R. Barthelmie, C. Perstrup, and M. Hurtig, “Offshore wind profile measurements from remote sensing instruments,” *European Wind Energy Conference*, 2006.

[12] I. Antoniou, M. Courtney, H. E. Jørgensen, T. Mikkelsen, S. V. Hunerbein, S. Bradley, B. Piper, M. Harris, I. Marti, M. Aristu, D. Foussekis, and M. P. Nielsen, “Remote sensing the wind using lidars and sodars,” *European Wind Energy Conference*, 2007.

[13] D. Foussekis, F. Mouzakis, P. Papadopoulos, and P. Vionis, “Wind profile measurements using a lidar and a 100m mast,” *European Wind Energy Conference*, 2007.

[14] A. Honrubia, A. Vigueras-Rodriguez, and E. Gomez-Lazaro, “Comparative analysis between lidar technologies and common wind speed meters,” *World Wind Energy Conference*, 2010.

[15] M. Courtney, R. Wagner, and P. Lindelöw, “Testing and comparison of lidars for profile and turbulence measurements in wind energy,” *International Symposium for the Advancement of Boundary Layer Remote Sensing*, 2008.

[16] W. Frost, B. H. Long, and R. E. Turner, “Engineering handbook on the atmospheric enviromental guidelines for use in wind turbine development,” NASA, Tech. Rep., 1978.