Investigation of sources for lidar uncertainty in flat and complex terrain

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Summary
The main sources of lidar uncertainty have been studied for two consecutive measurement campaigns in flat and complex terrain conditions. The same two lidar equipment have been used and compared to standard cup anemometry. It has been verified that non-uniform wind flow plays a very important role in lidar uncertainty. In this study, the non-uniform wind flows were caused by multi-MW wind turbine wakes at the flat terrain site and by orography properties at the complex terrain site. Under these conditions, lidar bias from standard anemometry showed values of up to 30% and 5% respectively.
The presence of low clouds or foggy conditions has been found to affect the lidar availability and the measurements' quality as well. Continuous wave lidars are in special more sensitive to these effects. The bias introduce by these conditions can be in an order of magnitude higher than those caused by the terrain conditions, which are the main interest of this article. For this reason, the effects of foggy conditions have been filtered out as much as possible.

Keywords
Remote sensing, lidar, complex terrain, measurement uncertainty, wind resource.

1 Introduction

The present work shows the results observed from two subsequent wind speed measurement campaigns using the same lidar equipment and compared to standard cup anemometry. The first campaign was performed at flat terrain conditions and the second one in complex terrain conditions. The main sources of lidar uncertainty are studied and special attention is paid to the sources of non-uniform wind flow, which has been accredited to play a major role on lidar uncertainty.
Literature indicates that lidar technologies have close correlation to standard cup anemometer measurements in flat terrain conditions. However, in complex terrain, the performance is degraded. Bingöl et al. [1] have defined the vertical wind speed gradient as the main source of deviation in lidar measurements with bias in the mean wind speed in the order of 5% to 10%. Still, some considerable work has to be done in order to reduce the lidar uncertainty [2].

2 Measurement campaigns

2.1 Risø Høvsøre test site: Flat terrain conditions.

Risø's test site at Høvsøre is located in a flat terrain region, close to the coast line. It is surrounded by crop fields and two big water masses, as represented in the map of Figure 1 (left). There are few farm buildings in the surroundings and basically the biggest structures around are those of the six multi MW wind turbines and their corresponding met masts as seen in Figure 1 (center). The mast and turbine locations are indicated by two rows of colored points in Figure 1 (right). At the west side of the turbine and mast rows, the lidars and the reference mast locations are indicated. The lidar scanning discs at several heights are also represented in the latter figure.

The reference met mast is instrumented with a top mounted cup anemometer at 91 meters height. Additional anemometers are installed on southern booms at 89, 71, 51 and 31 m. Moreover, two cup anemometers are installed on northern booms at 71 and 51 m. There is a wind vane at 89 m on the northern boom as the only wind direction reference. Furthermore, pressure and absolute temperature sensors are installed at 89 m. Finally, at 3 m there are installed relative humidity, rain and temperature sensors to complete the mast instrumentation.

Figure 1. Høvsøre test site. Location map, aerial view and lidar sitting.

2.2 CENER Alaiz: Complex terrain conditions.

The second measurement campaign is currently been performed at CENER's Alaiz test site which is located at the top of a mountain of approximately 700 m height above surrounding plateaus. The mountain has a uniform slope facing north which extends nearly parallel to the west-east direction. The remote sensing devices are installed on the ridge top, as seen in Figure 2. Towards the south-east end of the ridge, the orography becomes more complex. The met mast has been equipped with cup anemometers to sense the horizontal wind speed, propeller anemometers to sense the vertical wind speed and wind vanes to sense the horizontal wind direction at 78, 90, 102 and 118 m height. Also temperature, rain and atmospheric pressure sensors are present at several heights.

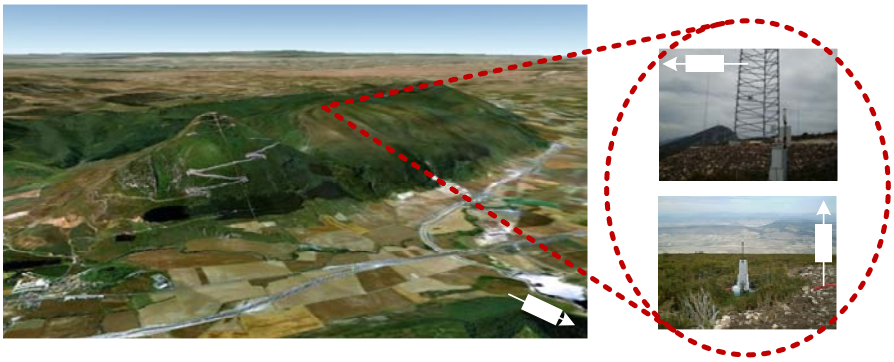


Figure 2. CENER's Alaiz test site. Lidars and met mast location indicated.

Correspondingly, the lidars were programmed to sense the wind velocity at the four different heights coinciding with those from the met mast instrumentation. Measurements have been recorded during a period of approximately five months.

3 Theory

Lidar devices measure wind velocity component parallel to the laser beam direction (so called radial or line of sight velocities). These measurements are spatially located in the perimeter of a horizontal circle situated at the desired height, as indicated by the points A and B in Figure 3 where the actual wind vectors are inserted. Based on these measurements, an internal algorithm estimates the wind velocity. In flat terrain conditions where the wind flow is supposed to be highly spatially homogeneous (see wind flow streamlines in Figure 3); the calculated wind vector (indicated by C in the same figure) is not so different from the measured wind vectors.
Conversely, the presence of big obstacles as a multi MW wind turbine can alter considerably the wind flow sensed by the lidar. Therefore, this can introduce more uncertainty in the measurements. For the case of complex terrain conditions, the uniform wind flow is disturbed by the irregular terrain orography or for instance by the presence of forest regions. Therefore, changes in direction, vertical tilt, turbulence, flow acceleration and wind profile changes are present. Subsequently, the measured vectors at points A and B can be considerably different both in direction and magnitude and do not necessarily represent properly the wind vector at the

circle centre. As expected, the calculated wind velocity (based on the assumption of a homogeneous wind field) results in more discrepancy when compared to point measurements at the desired height; obtained with a cup anemometer installed in a met mast.
Furthermore, lidars work emitting laser beams that find it difficult to propagate in air with strong humidity condensation. Rain and especially low clouds or ground fog can affect negatively the lidar performance and reduce its availability. The use of rain and cloud detectors like ceilometers can be of great benefit to filter out time periods with adverse atmospheric conditions.

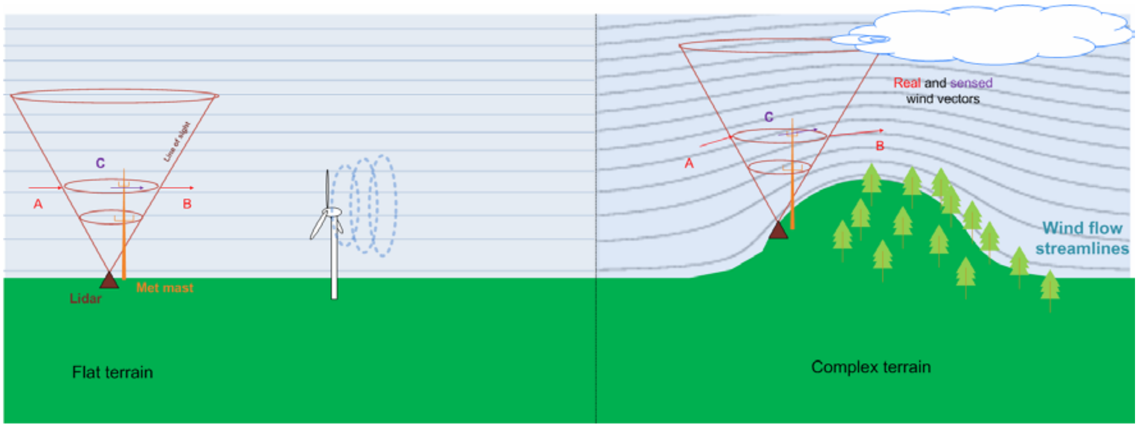


Figure 3. Lidar and met mast located in flat terrain and complex terrain conditions. Wind flow streamlines are shown. The wind velocity vector is drawn in locations A and B at spatial points where the lidar scans the radial velocity component. The velocity vector calculated by the lidar is drawn at the circle centre marked as C.

4 Results

4.1 Correlation lidar cup and data filtering

The present work summarizes the partial results from two measurement campaigns using the same two lidar equipments. As indicated above, the first campaign was performed in flat terrain and the second one is being performed in complex terrain conditions. In both cases, the reference wind speed is taken as the one given by the cup anemometer at the corresponding measurement height. From the two campaigns, the only coincident measurement height is at 90 m. Therefore, the inter-comparison has been done using measurements at this height, unless indicated otherwise.

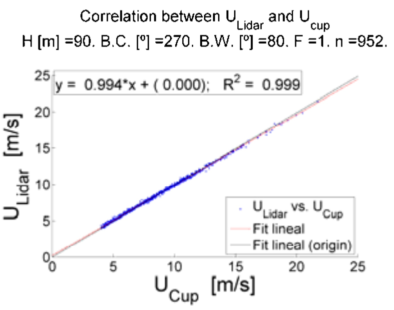
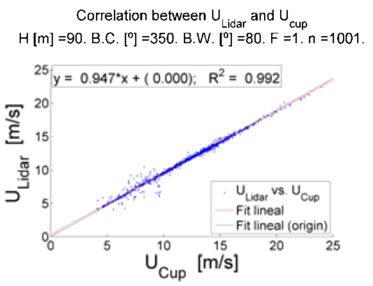
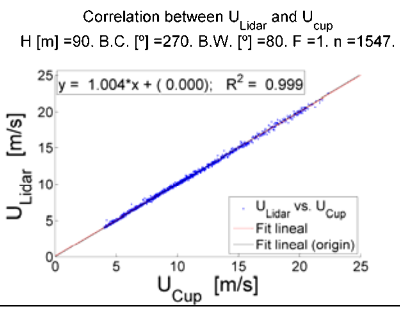
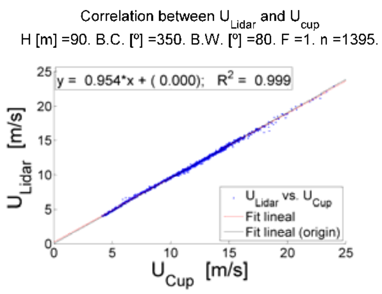
Firstly, the correlation of the horizontal wind speed (U) between cup anemometer and the lidars is presented in Table 1. As can be seen, the ZephIR and Windcube measurements for the horizontal wind speed are compared with those from cup anemometers for flat and complex terrain conditions. Notice that in the four figures, the correlation is generally good once some data quality filters have been applied. The sources of bias in the lidar measurements will be explained in section 4.2.

Regarding the data filtering criteria, there are some variables in common and some others very specific for each kind of device. For the cup anemometer data, the first filtering criterion is that the ambient temperature must be higher than 2 ºC to avoid frozen or braked anemometers. Also, only wind speeds higher than 4 m/s are considered due to the calibration range of the cup anemometers. The higher limit of this calibration range is normally 16 m/s, however data above this limit was still considered in order to assess the lidar performance at these velocity values.

For the case of lidar data, rainy periods are filtered out since rain affects lidar measurements (vertical wind speed component and data availability) [3]. Additionally, each lidar registers several signals apart from the measured wind speed. These signals offer the chance to filter out the data based on the device individual properties. For instance, at each 10-min period, the ZephIR records the number of circular scans at each height that are accomplished during each 10-min period. A minimum amount of scans is selected to assure that enough data was recorded and the 10-min period average is representative of the wind conditions during that period. This amount depends whether the ZephIR is scanning once (as in Alaiz) or three times per height (as in Høvsøre). Respectively, 28 or 50 scans-in-average are chosen as a quality filter. There is not a 3 factor difference since the scanning time increases but the lens focusing time between heights remains constant.

Moreover, the average number of radial velocities retrieved at each circular scan is used as a filter since this allows determining whether there was enough backscatter from the atmosphere from all directions or whether there was any obstacle for the laser beam. This is important since the ZephIR's processing algorithm performs a fit to a rectified cosine function based on the number of points-in-fit. If there are few points, the uncertainty of the fitted function is higher and that is why a minimum requirement of 35 (one scan per height) or 105 (three scans per height) is selected as a data filter.

Table 1. Correlation of the horizontal wind speed (U) between lidars and cup anemometer at 90 m height for flat and complex terrain conditions. The lidar data filters applied are indicated in the "Comments" column.

	Flat terrain	Complex terrain	Comments
ZephIR			Filters: No rain Scans_in_Average >= 28 / 50 Points_in_Fit >= 105 / 35 U >= 4 m/s Turb < 0.10 Scaling >= 25 / 50 Wind dir West / North (+/- 40º) Windcube availability = 100%
Windcube			Filters: No rain U >= 4 m/s Wind dir West / North (+/- 40º) Availability = 100%

For the ZephIR, there is an additional parameter that helps to identify the goodness of the fitting function. The turb parameter indicates how much deviation was there in general from the measured points to the estimated function to be fitted. The turb parameter gives information with resemblance to what in statistics offers the sum of squared residuals. Consequently, higher values of the turb parameter can be an indication of considerable un-uniformity of the wind velocity field where the ZephIR was scanning. This can help to identify very turbulent wind flows. Additionally, the turb parameter can be an indicator of noise in the retrieved signal. For this study, only datasets where the turb value was 0.1 or less have been taken into account.

Furthermore, the ZephIR's scaling factor is a parameter related to the strength of the backscattered signal. It can be understood as the gain that has to be added to the incoming signal in order to detect it properly. A weaker signal would need a higher scaling factor. Normally, weak signals indicate very clear air where low aerosol concentration backscatters just a small part of the energy. On the other hand, a low scaling factor value indicates that the returning signal was strong enough to be easily detected. This can reveal the presence of higher aerosol concentration and most importantly for our interest, the presence of low clouds or fog at ground level. In general, a scaling factor higher that 25 or 50 from the lowest measuring height (38 m as default) can help to filter out periods with high presence of foggy conditions. For the case of Alaiz test site, since it is a considerably high mountain surrounded by flatter regions, ambient humidity frequently condensates around its top conducing to highly foggy conditions during winter months.

In respect to the specific Windcube data filtering criteria, this is basically reduced to the device availability. This parameter indicates how much of the time during each 10-min period, the device was able to properly measure the signal backscatter and estimate an equivalent wind vector. In this study, only periods with 100% of lidar availability where chosen. The reasons of lower availability can be due to signal obstruction due to foggy conditions or low clouds.

It is important to notice that the Windcube availability has been used as a filtering criterion for the ZephIR as well. The hope is that most of low availability periods are caused by the presence of fog or very low clouds and consequently this help us to filter out data that can negatively affect the ZephIR performance[1].

As a final filtering criterion that in general affects the performance of all the devices is the presence of obstacles that obstruct the free wind flow and can produce wind acceleration or form wakes with considerable wind speed reduction and turbulence intensity. The first example is the presence of the met mast itself that directly affects the flow around with distortions that reach the cup anemometer location. It is necessary to filter out data based on the wind direction in order to reduce as much as possible the met mast effects. It has been seen that the mast wake effect differs depending on the mast structure. Additionally, for those wind directions where there is not direct wake incidence in any of the cup anemometers, the mast effects are still noticeable. For instance, if plotting the ratio of two cup anemometers (at the same height but at opposite sides of the met mast) as function of the wind direction, a kind of sinus wave shape reflects how the flow is disturbed by the mast presence. This information could be used to "correct" the cup anemometer measurements in order to reduce the mast effects [4]. Nevertheless, this approach has not been performed for the present study.

Other aspect taken into account when selecting the wind direction sectors to be used for the lidar-cup correlation is the presence of any big structure nearby, or of especial terrain conditions. These structures can produce strong wind turbulence or flow obstruction at several scales affecting differently the cup anemometers and the lidars. This is explained with more detail in section 4.2.

Despite applying the mentioned filters, still there exists some dispersion in the correlation graphs, especially at complex terrain conditions. A first attempt to identify the main lidar bias sources affecting the lidars in flat and complex terrain is introduced in section 4.2. As a final remark for this section, the present study is based on two early lidar units and therefore the results might differ to some extent if a different device would be used. Furthermore, second generation lidar devices of each brand are already available in the market and performance improvements can be expected.

4.2 Lidar bias sources

When facing the task of comparing the lidar performance in flat and complex terrain conditions, it is necessary to identify what are the main sources of bias between lidar and cup anemometer measurements. It can result in a big challenge since diverse variables can affect cups and lidars differently and some others can affect them simultaneously. Ideally, it should be possible to identify the individual effect of each variable over each device, however some bias

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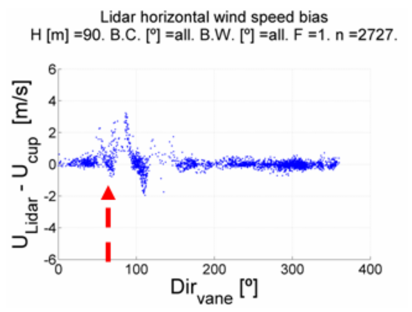
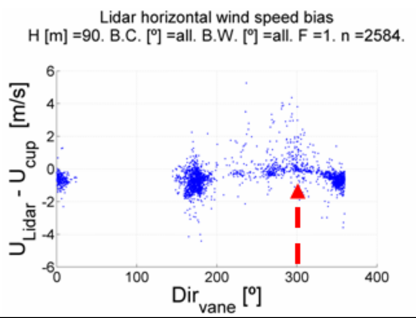
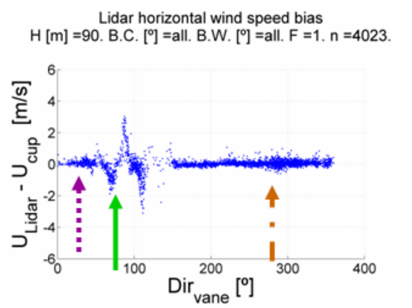
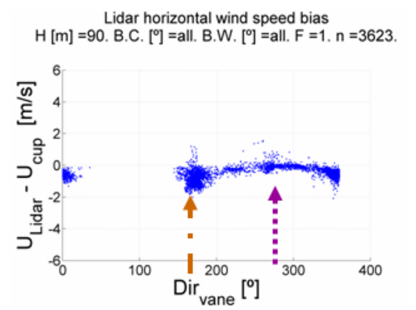
[1] Differently to continuous wave lidars as the ZephIR, the Windcube is a pulsed wave lidar. The main difference in the working principle is that continuous wave lidars sense the signal backscatter constantly. The main assumption is that the returning signal comes from the desired measuring height which is achieved by using lens to focus the laser energy there. If the signal is actually backscattered from a different height, there is no a direct way to detect it. Contrary, the pulsed lidar emit a signal pulse of a specific length and calculates the time necessary to reach and return from the desired measuring height. Then it opens a temporary sensing window to measure the backscatter. If the laser signal is blocked before reaching the desired height or if there is almost not backscattered at all due to very clear air, during the sensing window there is be nearly no signal at all to be measured and a "null" registry is recorded. These two sensing approaches have both advantages and disadvantages as have been previously discussed by other authors [5], [6].

sources can appear simultaneously and therefore separating their influence becomes a difficult assignment.

For the case of flat terrain as shown in figures from Table 2, there is a wind direction sector from which the lidar bias is more obvious (saw shape). It was identified that from this direction region, the presence of turbine wakes affected both the cup and lidar measurements. Depending on the direction angle, the wake could be impacting only the cup and not the lidar and vice versa, therefore the big positive or negative differences in the wind speed values sensed by them. Other issue is that the lidars are scanning a perimeter whose diameter length scale is comparable to the one of the turbine wake, while the cup anemometer can be considered as a point in space.

Table 2. Lidar horizontal velocity bias vs. wind wane direction.

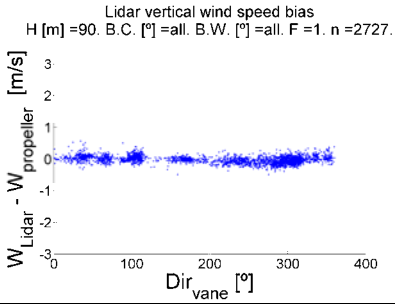
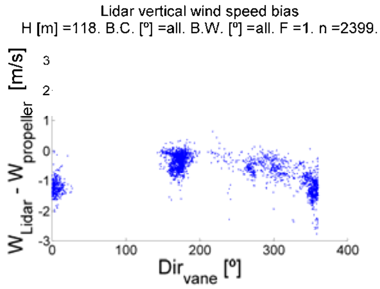
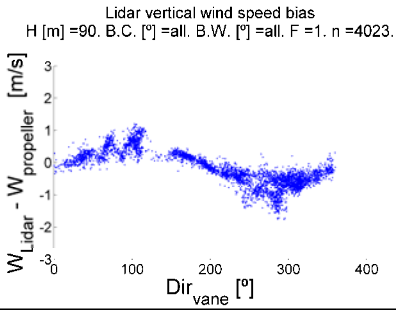
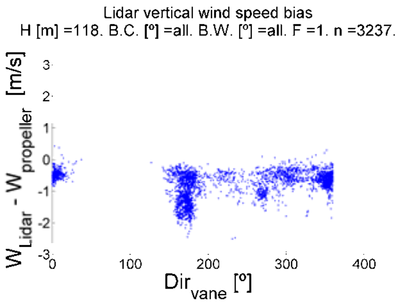
	Flat terrain	Complex terrain	Comments
ZephIR			Filters: Scans_in_Average >= 28 / 50 Points_in_Fit >= 105 / 35 U >= 4 m/s turb < 0.10 scaling >= 25 / 50 Windcube availability = 100%
Windcube			Filters: U >= 4 m/s Windcube availability = 100% **Bias sources:** **Wakes** **Clouds** **Mast effects** **Roughness / Orography?**

As mentioned before, some variables are difficult to separate when studying the bias sources. During the measurement campaign at Høvsøre, it was found that most of the low cloud presence was precisely when wind was blowing from the sector with turbine wakes. Therefore, the influence of clouds in the lidar measurements (especially in the continuous wave lidar) was difficult to separate from the turbulence and speed deficit due to the turbine wakes.

The complex terrain graphs show that the lidars tend to underestimate the wind velocity from northern and southern sectors, precisely where the there is more tilt in the flow due to the alignment with the mountain slope. As the wind direction changes and the tilt angle is reduced as wind flows parallel to the mountain flatten top (eastern and western sectors), the lidar bias is reduced. At 270º there is a group of data revealing the mast effect. Here the cup anemometer might be sensing a reduced wind speed due to the wind flow obstruction caused by the mast.

Additionally to the horizontal component of the wind vector, the lidars are also able to determine the vertical component (W). Unfortunately, at the flat terrain campaign there were no sensors at the met mast to measure the vertical wind velocity. For this reason, just the absolute value of the vertical component sensed by the lidars is presented in left figures from Table 3. Notice here the difference between the ZephIR and the Windcube measurements in terms of magnitude. The sinuous wave curve seen in the Windcube data is suspected to be caused by a mis-aligned internal mirror that was removed and replaced during a previous experiment. It is probably not typical of a standard Windcube. Though, this figure helps to highlight the importance of correct leveling (use an accurate level sensor) when installing any lidar. Notice again the saw shape in the curve due to the turbine wakes.

Table 3. Lidar vertical velocity bias vs. wind wane direction.

<table>
<tr><th></th><th>Flat terrain
- just W_lidar, not bias -</th><th>Complex terrain</th><th>Comments</th></tr>
<tr><td>ZephIR</td><td>
</td><td>
</td><td>Filters:
Scans_in_Average >= 28 / 50
Points_in_Fit >= 105 / 35
U >= 4 m/s
turb < 0.10
scaling >= 25 / 50
Windcube availability = 100%</td></tr>
<tr><td>Windcube</td><td>
</td><td>
</td><td>Filters:
U >= 4 m/s
Windcube availability = 100%</td></tr>
</table>

At the complex terrain site in Alaiz, the mast has installed vertical propeller anemometers at several heights. The two graphs at the right of Table 3 show the lidar bias of the vertical wind velocity at 118 m height. The reason of using this height instead of 90 m as previously is that data availability from the propeller at 90 m is much reduced. In this set of graphs is difficult to identify a clear behavior due to the data dispersion in the plots. However, observed that when wind blows from south (180º) the lidars tend to overestimate the vertical component (with negative magnitude in this case). Contrary, when wind blows from north, the lidars seem to underestimate the vertical component, and therefore the bias is negative too. The gap in the data from around 25º to 145º is simply because there is almost no wind blowing from that sector at this site. The wind rose is very directional north/south for Alaiz.

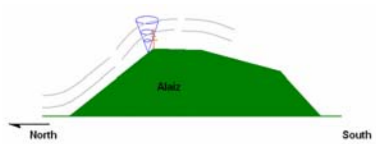
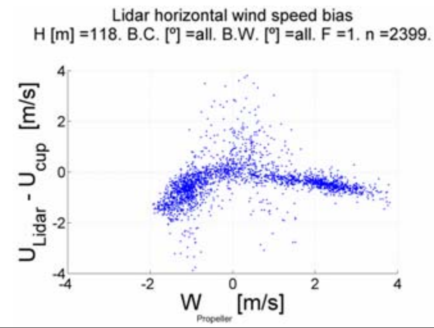
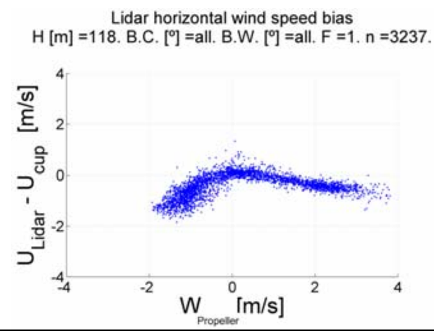
Remember that the lidars and the mast are installed precisely at the mountain edge where the northern uniform slope gives place to a flatten hill top. So the lidar beams are sensing radial velocities above and incline surface at north and at a flat surface at south. This result in measuring different wind vectors assuming the flow follows the ground contour as in left figure from Table 4. Besides, it is important to mention that the Windcube vertical component is recorded with the opposite sign as the ones registered by the ZephIR and the propeller anemometers [3]. For this reason the Windcube value of –W has been used instead.

Several authors have pointed out that the main lidar source of uncertainty in complex terrain conditions is the vertical wind speed gradient [1], [7]. To verify this hypothesis, the lidar horizontal velocity bias is plotted as function of the vertical velocity (not the gradient since it is not possible yet to estimate it from the available sensors at Alaiz) in figures from Table 4. As explained above, since the lidars are installed at the mountain edge, this is precisely the location where we expect the highest vertical speed gradient.

The two graphs show very concise information about the effect of the vertical component at this siting for the lidar measurements. Very similar results are obtained if the tilt angle is used instead of W. It is clear that when the vertical component increases in magnitude, the lidars tend to underestimate the horizontal wind speed. Different slopes are observed whether the wind is blowing uphill or downhill. The reason of this behavior is not totally understood yet and further analysis is needed.

In previous paragraphs, the influence of wind turbulence was indicated to play an important role in lidar uncertainty. With that purpose the lidar bias is plotted as function of the turbulence intensity measured by the cups as shown in Table 5. Figures from flat terrain conditions show there is not a perfect correlation, but at least it is clear that the highest lidar bias occurs in periods when there is high turbulence intensity. The graphs include all the wind directions. Here it is important to mention that the definition of turbulence intensity is the wind speed variance divided by the mean wind speed during each 10-min period. Using this concept and based on cup anemometer measurements, it is not possible to know if the wind flow was for example very uniform and even uni-directional and the only parameter changing was the wind speed magnitude or if the flow was very spatially chaotic like that one inside a turbine wake. In the case of point measurements like the cup anemometers there is no a big impact but for volume measuring lidars this distinction should be more relevant to take into account.

Table 4. Lidar horizontal velocity bias vs. propeller vertical velocity.

<table>
<tr><th></th><th></th><th>Complex terrain</th><th>Comments</th></tr>
<tr><td>ZephIR</td><td rowspan="2">
</td><td>
</td><td>Filters:
Scans_in_Average >= 28 / 50
Points_in_Fit >= 105 / 35
U >= 4 m/s
turb < 0.10
scaling >= 25 / 50
Windcube availability = 100%</td></tr>
<tr><td>Windcube</td><td>
</td><td>Filters:
U >= 4 m/s
Windcube availability = 100%</td></tr>
</table>

In the case of complex terrain conditions, there were no big structures in the surroundings and the wind turbulence can be considered as ambient and terrain contributions only. Here the correlation between lidar bias and turbulence intensity measured with the cups is once again not very clear and using another variable related to the wind flow uniformity might be more useful.

A final variable studied for this work is the influence of the wind shear over the lidar bias. Since probe length can be of the order of several meters ate the studied heights, the wind shear might have an impact in what the lidar is measuring since the volume average of the wind speeds is at this region might differ from the actual speed at precisely the desired height. In Table 6, the lidar bias distribution at the lowest measuring height, for the two locations, is presented at the left column. Notice that in flat terrain the bias distribution is centred at zero while in flat terrain at a negative value. This means in the complex terrain site, lidars mostly underestimate the wind speed. The second column shows the lidar capability to sense the wind shear. In the flat terrain site the wind shear is in general very vertically straight but in the complex terrain site is possible to find higher (even negative) differences between the speed at higher and lower heights. The two lidars in general show similar results to cup anemometers but still seem to be slightly less sensible to detect the wind speed differences at different height when they are in the range from 0 to 1.2 m/s.

Fitting the measured wind profiles to the power law function U(z) = Ur (z/zr)^α, we obtain the parameter that helps to characterize the wind profiles. Plotting the lidar bias as function of this α parameter can reveal how the wind shear affects the lidar bias. This is shown in the right column figures of Table 6. There seems to be a not a clear correlation for the flat terrain case, but for the complex terrain site, the lidar underestimation of the wind speed seems to be reduced as the α parameter increases, this means, when the wind speed is faster at higher heights than at lower heights. This insight gives an important motivation to further study the influence of the atmospheric stability over the results obtained so far.

Table 5. Lidar horizontal velocity bias vs. turbulence intensity.

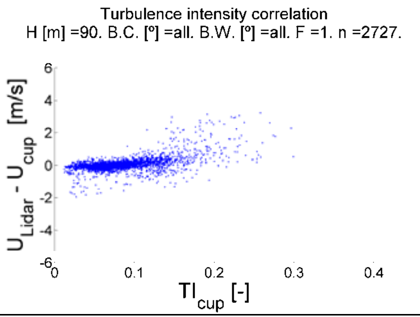
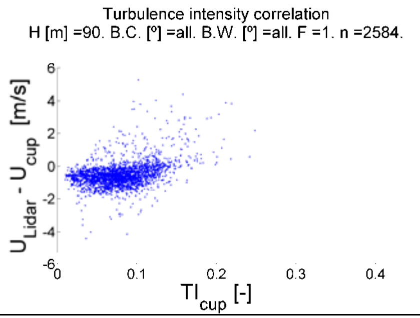
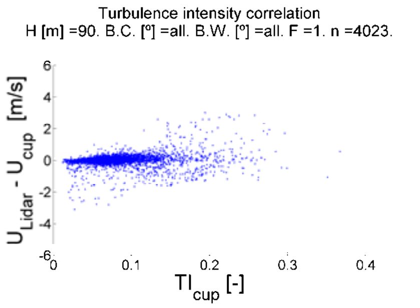
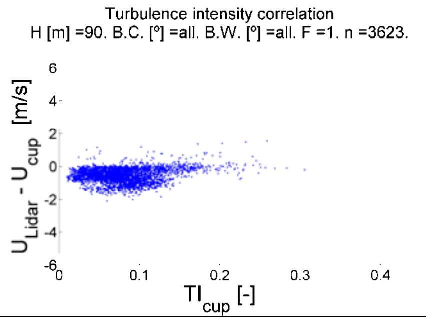
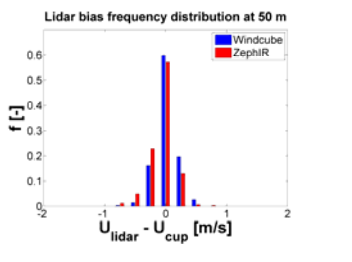
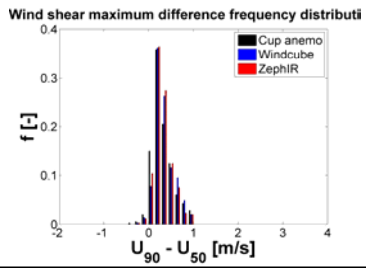
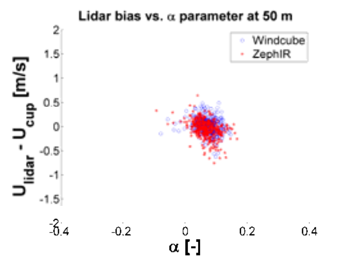
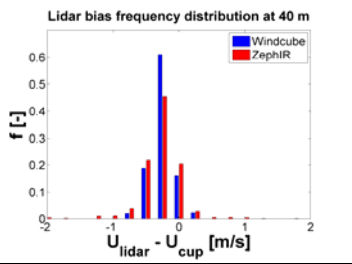
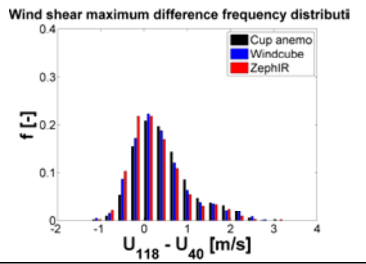
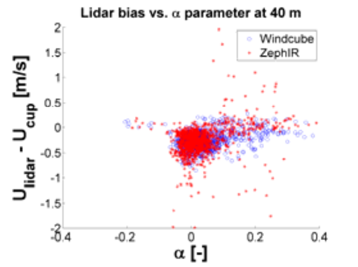
	Flat terrain	Complex terrain	Comments
ZephIR			Filters: Scans_in_Average >= 28 / 50 Points_in_Fit >= 105 / 35 U >= 4 m/s turb < 0.10 scaling >= 25 / 50 Windcube availability = 100%
Windcube			Filters: U >= 4 m/s Windcube availability = 100%

Table 6. Lidar horizontal velocity bias at 40m as function of the wind shear properties.

	Ubias frequency distribution	Shear difference frequency distribution	Ubias vs. α
Flat terrain			
Complex terrain			

5 Conclusions

The performance of two different lidar systems has been compared to cup anemometer measurements at two different locations. The first measurement campaign was realized at flat terrain conditions while the second one at complex terrain conditions.

Identifying the main sources of lidar uncertainty (assuming lidars and cups are properly calibrated) is a difficult task since the studied bias sources can affect the measurements simultaneously and identifying their individual contribution is sometimes not possible.

Lidar measurements have shown to be sensitive to the wind flow uniformity (i.e. spatial wind velocity field variation). The origin of non uniform flows can be due to the presence of big structures like multi MW wind turbines or due to orography conditions like the presence of mountains, hills, forests, etc. It was shown that the variation of the vertical component of the wind velocity plays an important role in the lidar bias occurrence for the Alaiz campaign. It is still necessary to verify if this relationship is causal or if at the lidar siting (mountain edge) the vertical velocity gradient dW/dx scales with W.

Since lidars work emitting a laser beam, the presence of low clouds or foggy conditions can be an issue that affects the availability of the device and the quality of the measurements. For the case of the continuous wave lidar used during the measurement campaign, the bias due to very low clouds of foggy conditions can reach an order of magnitude greater that the other bias sources. Therefore a proper methodology to identify the occurrence of these conditions is very important to assure the quality of the collected data. The continuous wave lidar has been recently upgraded with a new firmware version that is expected to reduce these effects. Yet, more data is necessary to be collected in coming months to asses its effectiveness.

It is important to remember that comparing the lidar data to cup anemometer data, there is always uncertainty in both sensing devices and certain factors can affect their performance either separately or simultaneously. For the cup anemometer, it is of great significance to asses the influence of the met mast where it is installed, the response to the wind flow tilt angle and the effects of icing that can not only stop completely, but also slow down the normal anemometer rotation.

Further lidar bias analysis is under development and new variables will be integrated, mentioning with special importance the influence of the atmosphere stability conditions. Furthermore, the use of fast data will be implemented in order to compare instantaneous lidar and cup anemometer data rather than 10-min averages. The purpose of this study is the development of a lidar bias correction methodology for complex terrain conditions.

6 Acknowledgement

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