Investigating Wind Flow properties in Complex Terrain using 3 Lidars and a Meteorological Mast

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SUMMARY

Three simultaneously operating lidars of both technologies (continuous and pulsed wave), scanning at different cone angles (30deg and 15deg), were deployed next to a 100m meteorological mast, situated in a complex terrain. Results include comparisons between the lidars and the Mast's anemometers (cups and sonics) at various heights.

Despite the excellent correlation of the wind speed between lidars and cup anemometers, a systematic velocity deficit of approx. 6% is noted for all the lidars. This difference is attributed to the lidars principle of measurement**:** they scan conically large areas above the ground and in order to deduce the wind speed vector, they assume flow homogeneity, which is not valid for flows over complex terrains.

Finally, a worth note result concerns the rather insignificant influence of the lidar's prism angle on the results of the average horizontal wind speed. However, a significant increase of the standard deviation of the horizontal wind speed is noted, when measuring with the 15deg prism, relatively to the 30deg prism. Again, the lidar's principle of measurement is believed to be the reason of that, however further analysis of the instantaneous radial velocities is needed to support this point of view.

DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

Lidar devices permit wind profile measurements at heights practically unachievable by meteorological masts. This is particularly interesting when dealing with complex topographies, where it remains unknown the extend of the terrain influence to the wind flow.

In case of complex mountainous topographies, lidars can provide more realistic results than cup anemometers, since they scan large areas which are comparable to the surfaces of the wind turbine rotors. However, it is questionable if lidars provide ideal results to "point" devices (i.e. cup anemometers) for non-homogeneous wind fields, usually present in complex terrains.

This experiment, in contrary to some previous ones which already revealed this problem [[1] [2]], aimed to examine this behavior in a more systematic way. Consequently, three lidars were deployed, representing all the commercially existing models and technologies, up to now:

- a ZephIR with the standard 30° prism (continuous wave laser beam)
- a, Windcube with the standard 30° prism (pulsed wave laser beam)
- a Windcube with a 15° prism (pulsed wave laser beam)

Moreover, new cup anemometers were installed, having been calibrated according to MEASNET procedures, as well as, two 3D ultrasonic anemometers (Gill Windmaster) for the measurement of the vertical component of the wind speed.

CRES Test Station is situated approximately 100km SE of Athens and it The 100m triangular lattice reference meteorological mast is equipped with calibrated cup anemometers (Vector A100K) and vanes (Vector W200P) at 5 heights (10m, 32m, 54m, 76m, 100m) and with ultrasonic anemometers at 2 heights (78m, 98m). Additionally, the temperature profile is measured using differential thermometers, as well as, the atmospheric pressure and the solar radiation. Dedicated instrumentation is used for signal protection, filtering and conditioning. The sensors are supported on the Mast by the aid of telescopic booms of rectangular cross-section, made of high strength aluminum alloy. Boom cross-section is 50mmX50mm at base and 30mmX30mm at the end where the sensors are supported. All wind sensors (even the top ones) are mounted at a height of 45cm above the boom and at a distance of 310cm from the outer mast leg.

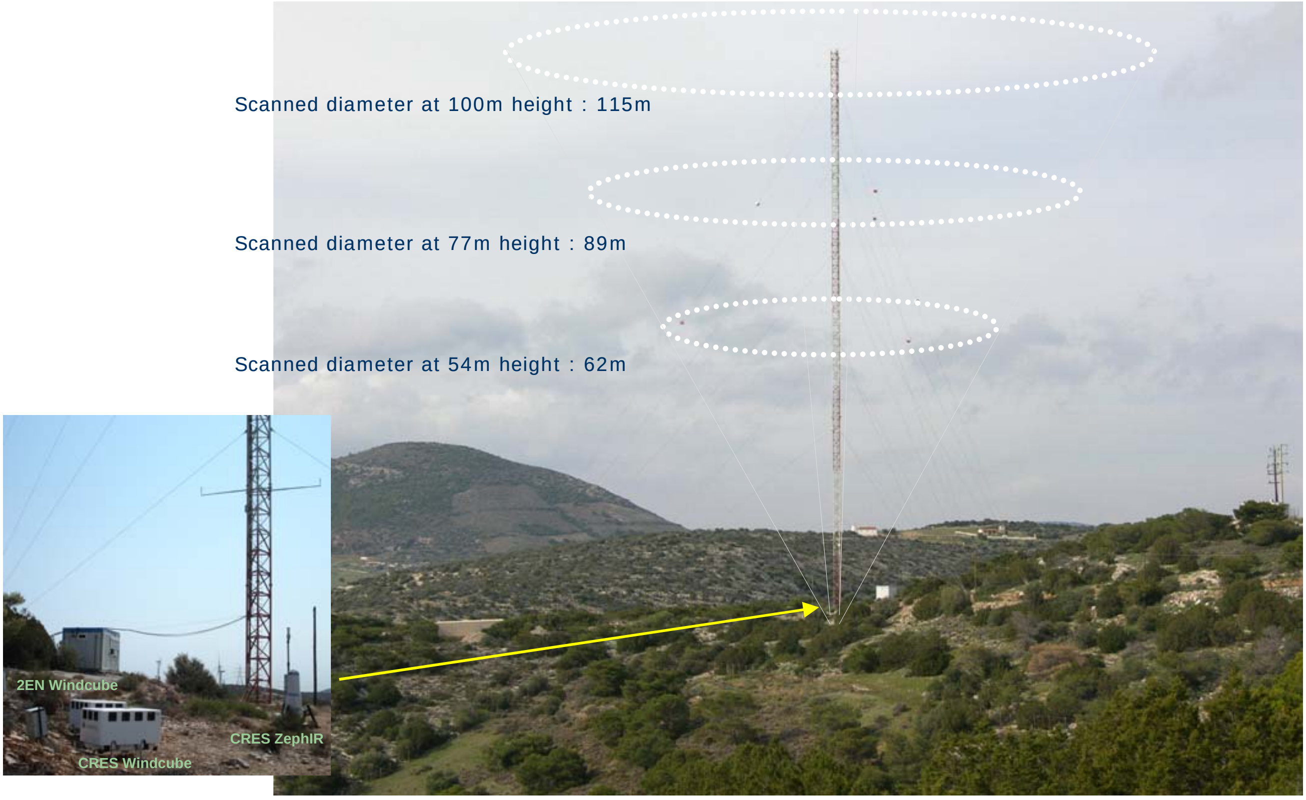

Photo 1: *The 100m meteorological mast at CRES Test Station and the 3 Lidars. The surfaces scanned by the Lidars with a 30° prism are given schematically.*

RESULTS

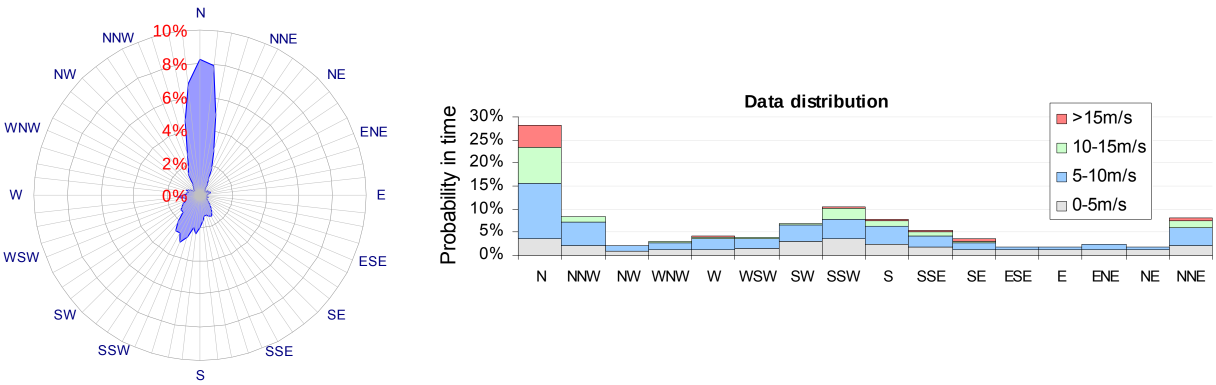

Figure 1: Data distribution (wind rose) during the experiment. The average wind speed at 100m height was 7.2m/s.

The experimental campaign started at Sep. 9, 2008 and ended at Jan. 29, 2009. Results are based on 10min averaged data, unless otherwise stated. Figure 1 shows the data distribution during this period. For this experiment, data only from a narrow sector (320°-40°) are processed, in order to minimize terrain induced effects. Figure 2 shows that within this wind direction range the “shadow” of the Mast is negligible. Additionally, this sector is free when considering the ultrasonic brackets, permitting thus to safely compare ultrasonic and cup anemometers.

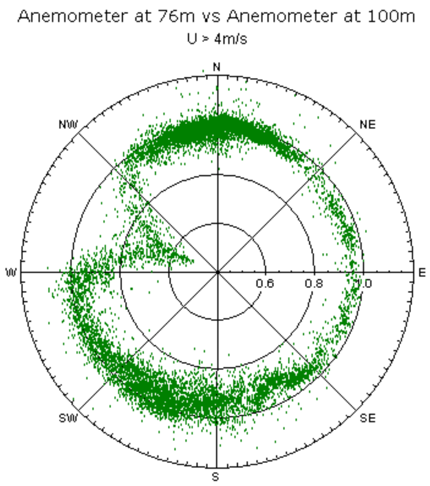

Figure 2: Influence of the Mast tower (free top anemometer at 100m versus boom mounted anemometer at 76m)

Figure 3 shows how the ultrasonic anemometer compares to the cup anemometer at 100m height. Comparison of the average horizontal wind speed is considered excellent and its linearity is characterized by a R^2 value well above 0.99. The same picture is obtained when comparing the standard deviations although the slope and the regression coefficient R^2 are slightly deteriorated. Considering that, standard deviation values deal with fluctuations, it is believed that the different sampling rates (1Hz for cup, 4Hz for sonic) is the reason of that.

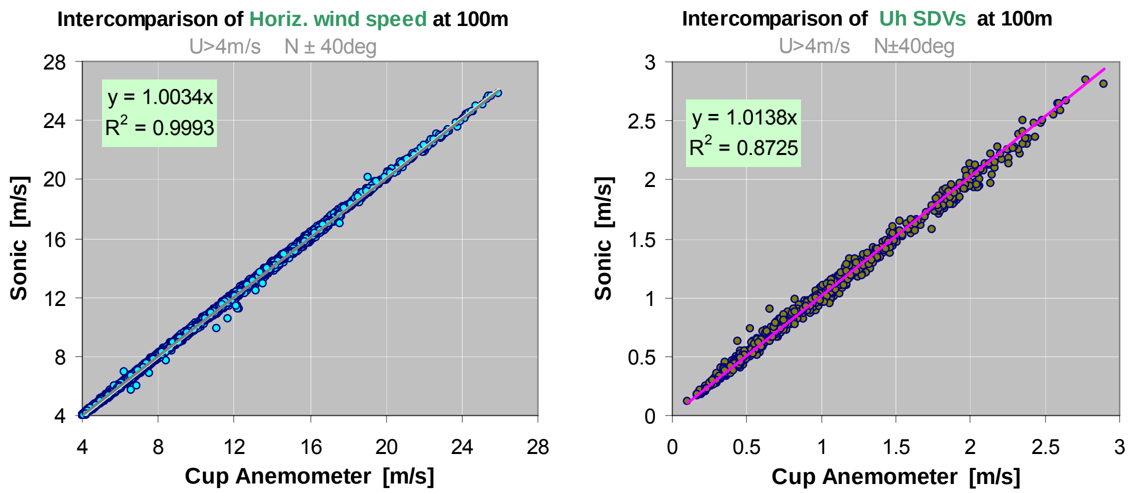

Figure 3: Comparison of the horizontal wind speed between Sonic and Cup anemometer at 100m.

The emphasis on this paper is given in wind speed comparisons between the three lidars and cup anemometers. Wind direction comparisons results between all lidars and wind vanes are found excellent and for brevity reasons are not shown here.

During the entire experiment ZephIR was operated with software version 2.0 which includes a new "cloud correction" algorithm to compensate the influence of the low clouds on the Doppler shift of the laser beam. It is believed that although enabled, this option had no practical effect due to the meteorological conditions of the specific site (low altitude and next to the sea). ZephIR data were filtered according to following condition: a sequence of all measured "valid" heights was required, each height was considered "valid" if at least 140 (radial) points in fit were used, when deducing the wind speed vector. This filtering condition combined with the fact that ZephIR is "blinded" at low Doppler frequency shifts (due to the RIN -relative intensity noise- which is caused by rapid variations in the emitted power[3]), practically eliminate data at wind speeds lower that 4m/s. Thus, comparison results exclude wind speeds lower than 4m/s. Figure 4 shows how ZephIR compares to cup anemometers at 3 different heights (10min averaged values).

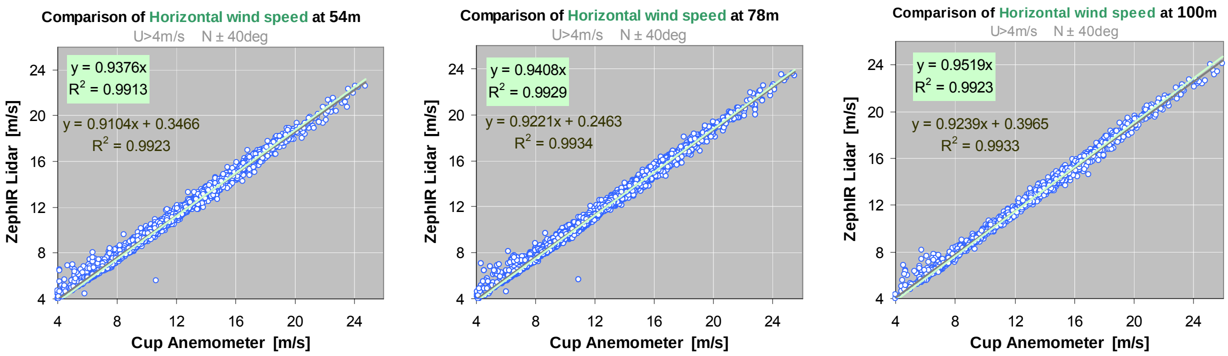

Figure 4: Comparison of the horizontal wind speed between ZephIR and Cup anemometers

Figure 5 presents the comparison of the standard deviation of the horizontal wind speed between ZephIR and cup anemometers. The same behavior is noted for all heights: both the slopes and the regression coefficients are slightly lower than 0.9. However, here the undersampling of ZephIR has to be taken into account. When scanning 4 heights, the sampling frequency is ~0.05Hz (approx. 40 points per 10min), a significantly different value from that of a cup (1Hz, 600 points per 10min). The lower sampling rate is not the only reason of this: ZephIR's measurements are 3sec averaged values and include the spatial fluctuations of the wind speed in contrary to cup which measures only temporal fluctuations. "Fixing" ZephIR at only one height for a short period, increased the sampling rate (approx. 135 points per 10min) and improved also the slope and the R2 values (figure 6). Finally, it is worth noted that the same picture concerning the comparison of the average wind speed, is obtained at 12m height (approx. 6% velocity deficit, R2>0.99).

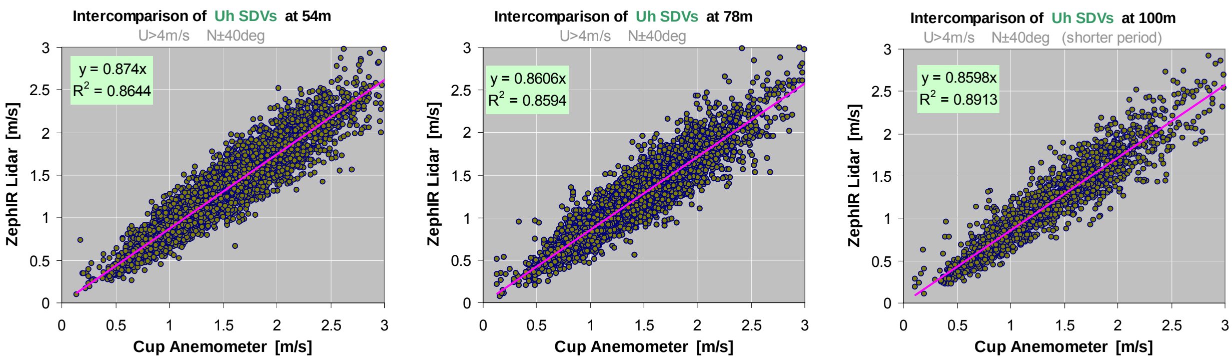

Figure 5: Comparison of the SDV of the horizontal wind speed between ZephIR and Cup anemometers

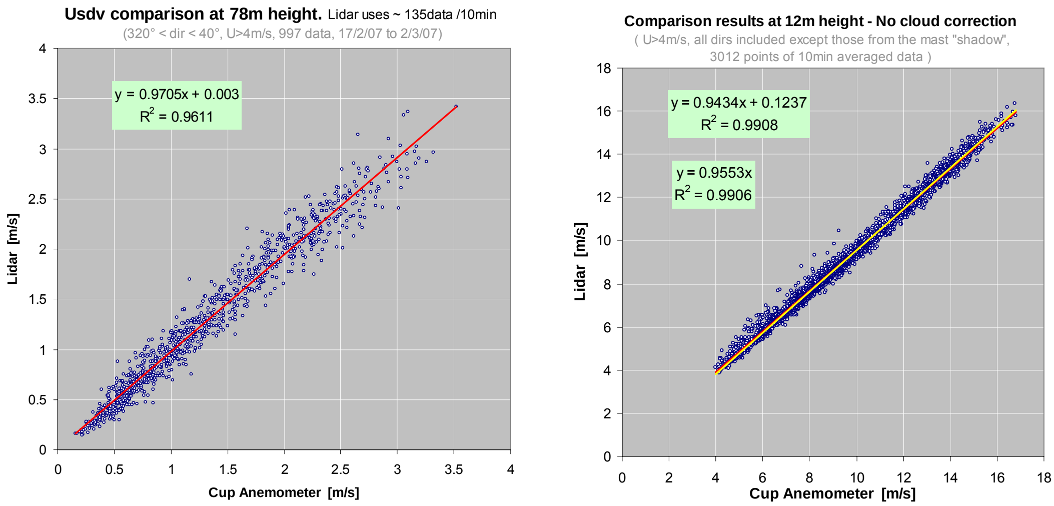

Figure 6 **(left):** Improved wind speed's SDV results are obtained when "fixing" ZephIR at one height. **(right):** Comparison of the horizontal wind speed at 12m height between ZephIR and Mast.

During one month, the two Windcube lidars were cross-checked using their standard prism of 30° (actually ≈27.7°), in order to assure perfect data comparability. Then, a 15° prism was introduced into the Windcube of CRES, up to the end of the experiment. Some data losses (cup at 100m and Sonic at 78m), as well as, different weather conditions reduced the comparison heights from 3 to 2, but this did not affect the general picture of the results.

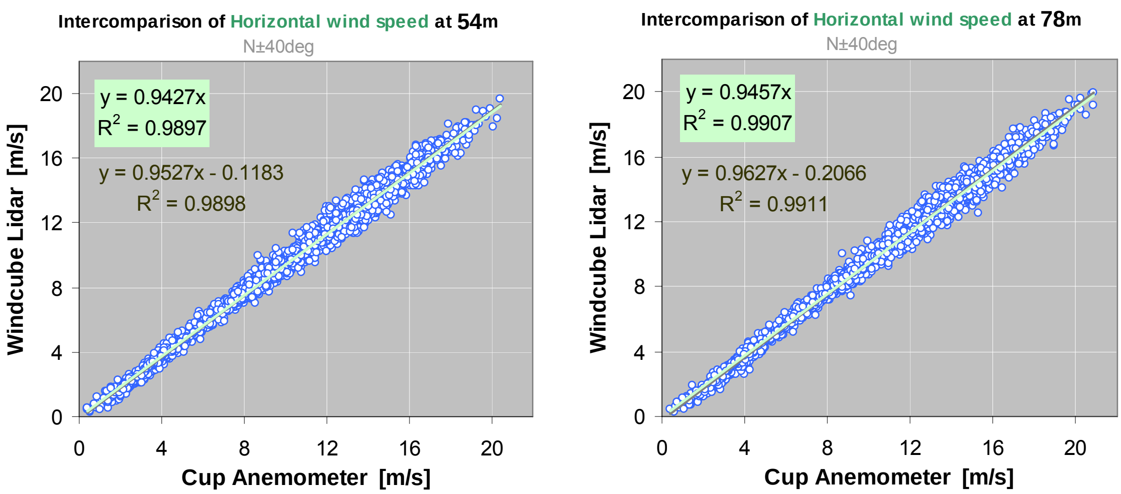

Figure 7: Comparison of the horizontal wind speed between Windcube and Cup anemometers

Figure 7 shows the comparison of the horizontal velocity between the Windcube (using the standard prism) and cup anemometers. Note that comparisons start slightly above 0m/s since Windcube due to its measurement principle (it mixes the laser's frequency with a precise offset and by heterodyning it obtains a "net" Doppler shift), it can measure during calms.

Unlike the ZephIR, Windcube does not rotate continuously but the prism stands still, while sending a stream of pulses, waiting for the backscattered signal. Then, it rotates by 90°. In order to produce a single value, Windcube combines the latest four radial velocities to deduce the wind speed vector. Given the fact that at each wedge rotation Windcube calculates the wind speed at 10 heights simultaneously, its sampling rate is ≈0.7Hz (approx. 400 points per 10min).

Figure 8 presents the comparison results for the standard deviation of the wind speed. Although satisfactory slopes are obtained (given the comparable sampling rates), the relative wide scattering is attributed to the spatial fluctuations (apart the temporal ones) of the wind speed, which are inevitable due to the lidar's operation principle.

All the Windcube results (independently of the prism angle) were filtered by CNR>-20 (carrier to noise ratio) and $|\Delta\sigma_{freq}|>0.4$ (variance of the signal broadening).

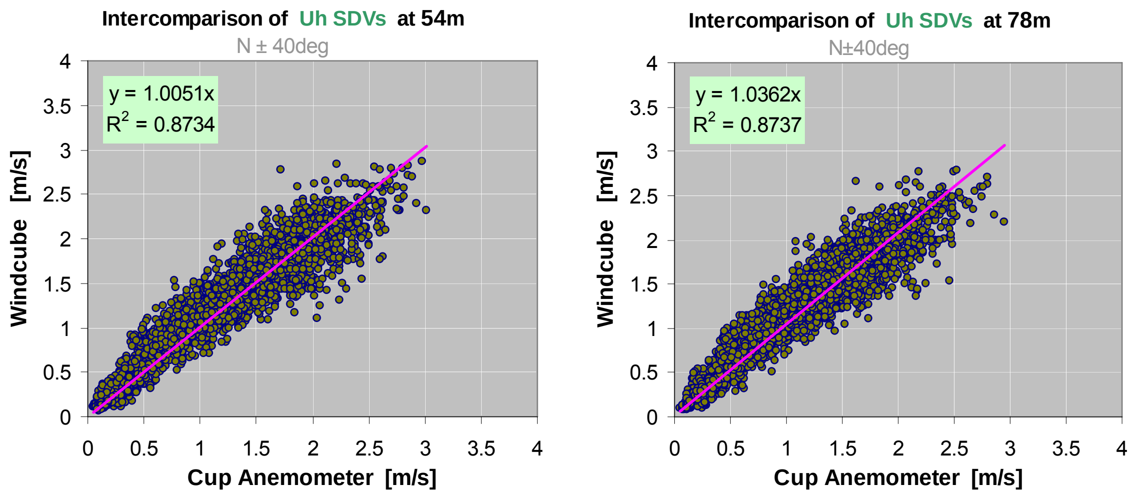

Figure 8: Comparison of the SDV of the horizontal wind speed between Windcube & Cup anemometer

Figures 9 and 10 are the equivalent figures of 7 and 8, for the Windcube using the 15° prism. Despite the narrower scan cone, it is noted that the velocity deficit in respect to the cup anemometer remains, either in form of a slope deviating from 1.0 or in form of a constant negative slope (if a regression with a constant term is used).

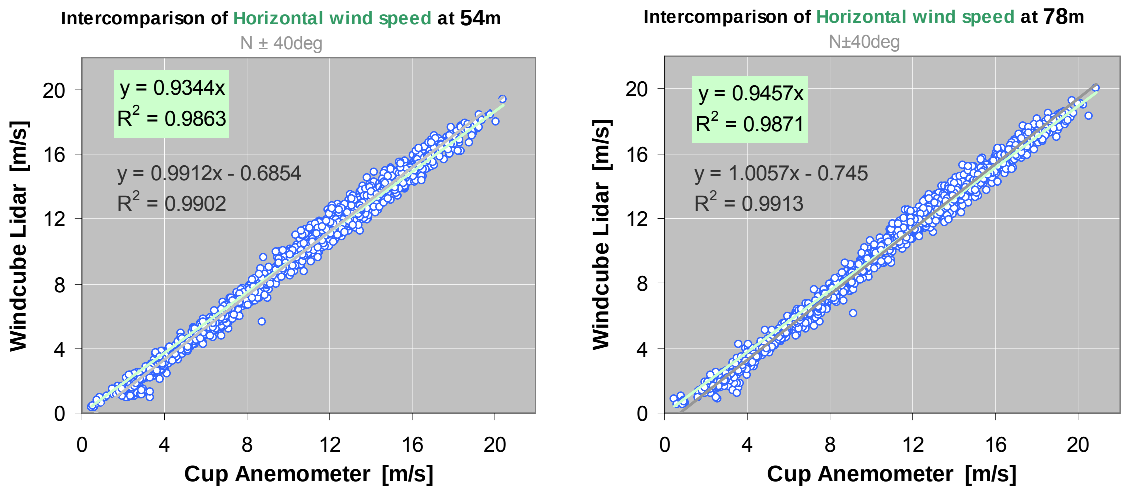

Figure 9: Comparison of the horizontal wind speed between Windcube with the 15° prism and Cup anemometers

The rather insignificant influence of the prism angle on the comparison results, concerning the horizontal wind speed, agrees well with a previous theoretical approach (F. Bingol *etal*[4],[5]) dealing with conically scanning lidars in complex terrains.

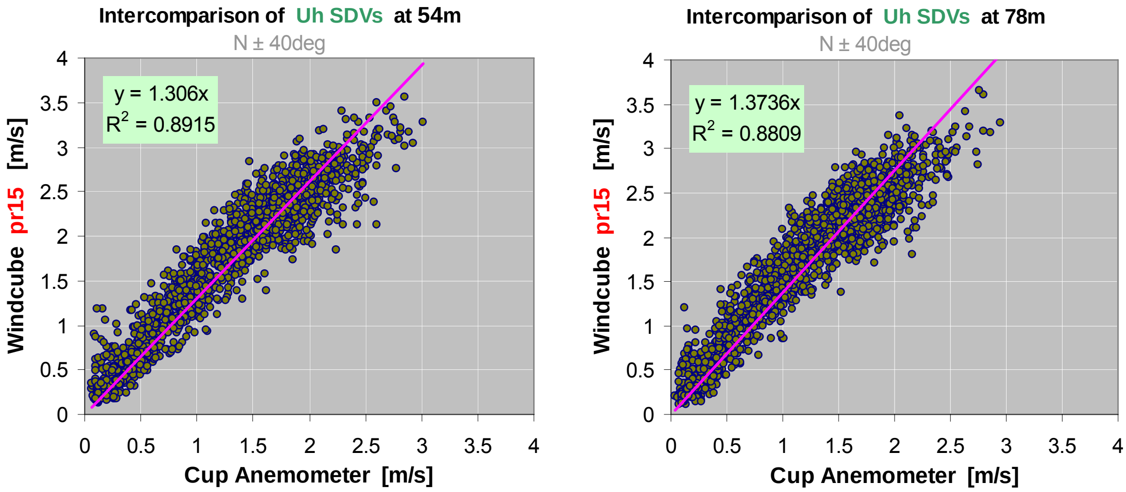

Figure 10: Comparison of the SDV of the horizontal wind speed between Windcube with the <u>15° prism</u> and Cup anemometers

Another important result is the significant increase (by ~30%) of the Lidar's standard deviation of the horizontal wind speed, when using the 15° prism. Although further data analysis is needed to investigate this behavior, a possible explanation deals with the involvement of both of σ_U and σ_W of the (true) wind speed vector, together with the prism angle, into the calculation of the lidar's standard deviation, due to the spatial nature of measurement (J. Mann [6]).

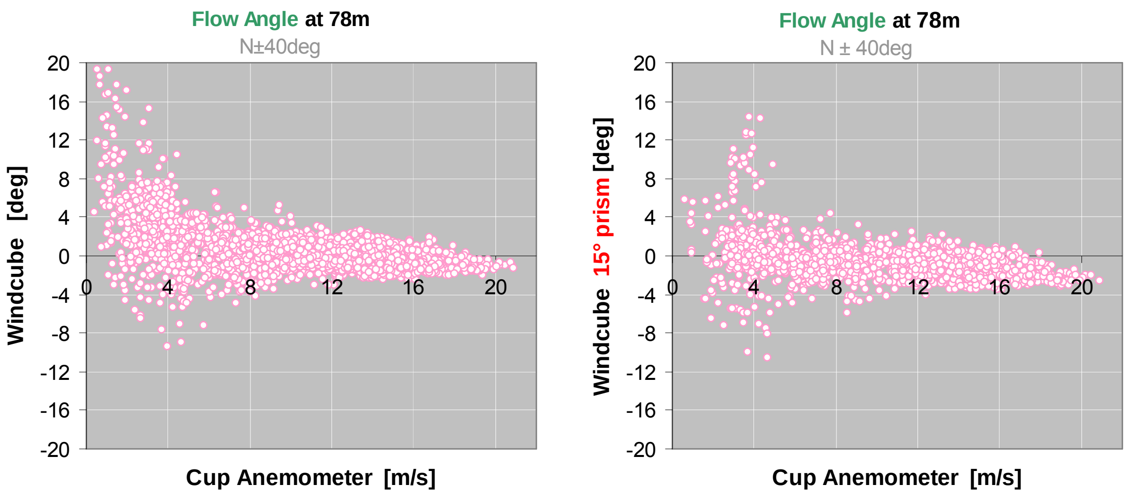

Figure 11: Comparison of the flow inclination angle (10min averages) at 78m height, as measured by the two Windcubes using 30° prism (left) and 15° prism (right).

Lidars are capable to measure the 3 components of the wind speed vector and this is very important in complex terrain areas where flow is affected by the topography. Here, it was chosen to present the vertical component of the wind speed in the form of flow inclination angle. Figure 11 shows that practically equivalent results are obtained by the two Windcubes, independently of the prism angle they use. Comparisons with Sonic results are not presented, mainly because of data losses (Sonic at 78m) but also since the variation of the wind speed's vertical component is very pronounced by the complex topography, especially at high heights where lidars are scannning areas above neighbour hills (photo 1). Given the flow complexity, additional information is obtained when presenting distributions of instantaneous data, instead of just average values. Thus, in figure 12 the distribution of the instantaneous flow angles is presented (per wind speed bins for fairer comparison) for both the ZephIR and the Windcube. Obviously, these results concern the specific site and a very good agreement is noticed, concerning both the shapes and the trend relatively to the horizontal wind speed.

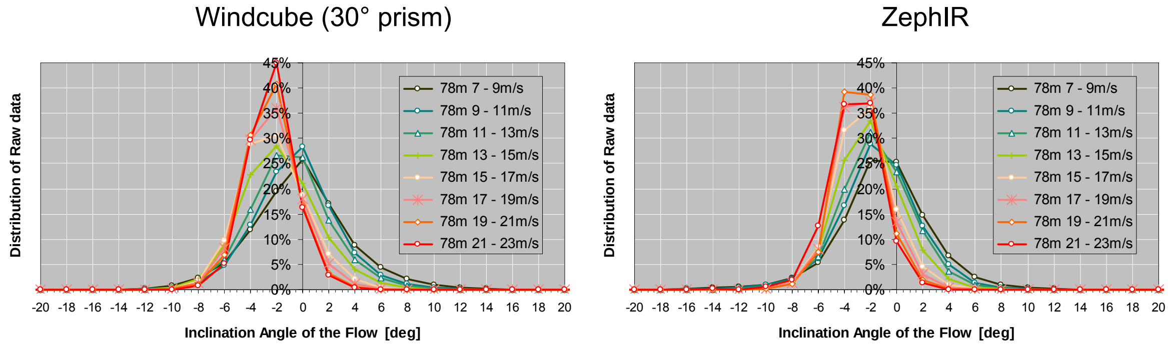

Figure 12: Distribution of instantaneous flow inclination angles per wind speed bin, as calculated by the two Lidars, using the raw data.

CONCLUSIONS

The present work confirmed that in complex terrain sites, both types of lidars (ZephIR and Windcube) exhibit a velocity deficit (~6% in this specific site), compared to cups and sonics anemometers. This behavior found to be independent of the height, as verified from 12m to 100m. However, this systematic behavior is characterized by remarkable correlations (>0.98) proving that lidars provide high quality data. This velocity deficit is attributed to their principle of measurement: lidars scan conically large areas above the ground, assuming flow homogeneity in order to deduce the wind speed vector, which is not always true for flows over complex terrains. On the other hand, lidars may sense more representatively the wind flow over the rotor of a multi-MW WT, operating in complex terrain. If this is true, then it is questionable whether a cup anemometer (point measurement) fairly represents the reference wind speed, during WT Power Performance evaluation.

This unique experiment provided some new results concerning the influence of the prism angle on the lidars performance. It was found that regarding the mean horizontal wind speed, the velocity deficit remains practically unaffected. Unexpectedly, a significant increase was noted concerning the lidar's wind speed standard deviation. This is explained by the fact that lidars s.d.v. is marked by the spatial character of the measurement and may not be directly comparable to that of Cup anemometers.

Finally, it seems that new ideas (algorithms, alternative scanning modes, new prisms,…) are necessary to further improve the accuracy of lidars in complex terrain.

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