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WP6.6
Remote Sensing – CRES activities:
Measurements & inter-comparisons in Complex Terrain

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Abstract: The present report presents measurement comparisons between remote sensing devices and mast mounted cup anemometers, in complex terrains.

Several commercially available remote sensing devices were deployed (one monostatic sodar, three lidars), operating in different modes, in order to investigate how well they can perform in complex terrains, where the sensed flow is not (expected to be) uniform.

The report is more focused on lidars performance, because, quite early, it was revealed that comparisons between mast mounted cup anemometers and sodars are inevitably “unfair”. This is due to the fact that, (monostatic) sodars’ results are affected by high metal structures (i.e.: mast) and when installed away from them, then they provide different results since the flow properties are different.

Lidars can be installed next to the mast’s basement but, it was proved that in complex terrains this is not sufficient in order to provide identical results to a cup anemometer. However, the high data availability, the wide wind speed range and the very high correlation to cups, are (among others) strong arguments in their favour.

The first campaign presents simultaneous comparisons between one sodar, one lidar and two meteorological masts, all within ~1km2. Practically, it provided the first strong indication (in 2006 already), that comparisons have limitations. The second campaign focused on comparisons among different lidars, using various scanning angles and a 100m mast. The last part of this report, focuses on wind flow results, presenting wind profiles that were measured in various complex sites, in the framework of site assessment studies. There it is shown that sometimes, even a hub-height mast, is not sufficient to reveal the complete wind profile.

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STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	**X**		**R0**	General public			Private web site	**X**
S1	Reviewed			**R1**	Restricted to project members	**X**		Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

The present report presents measurement comparisons between remote sensing devices and mast mounted cup anemometers, in complex terrains.

Several commercially available remote sensing devices were deployed (one monostatic sodar, three lidars), operating in different modes, in order to investigate how well they can perform in complex terrains, where the sensed flow is not (expected to be) uniform.

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2. Remote Sensing at Panachaiko mountain

Figure 1: *A general view of the Wind Farm from NW.*

An experimental campaign using a sodar unit started during November 2006 at Panachaiko mountain, which is located NE of the Peloponnesus peninsula, near the city of Patras, in Greece. The altitude of the site is approximately 1800m and at that moment a nearby a 35 MW wind farm (41 wind turbines) was operating since 2005. An extension of the wind farm was foreseen (another 13.6 MW, 16 wind turbines) at that time and the sodar campaign was realised within the site of the extension.

CRES for the needs of this project used a SFAS sodar, a commercially available unit, manufactured by Scintec (www.scintec.com), from the series of flat array sodars. Its main technical specifications are summarized in the table below.

Number of elements	64
Frequency range	2525 – 4850 Hz
Acoustic output power	2.5 W
Electric output power	20 W
Multi-frequency operation	Up to 80 frequencies, 10 within a single sequence
Multi-beam operation	Up to 9 beams
Beam angles	0°, ± 19°, ± 24°
Number of range gates	100
Vertical resolution	5 m
Lowest measurement height	20 m
Maximum range	500 m
Averaging time	1 min – 1 hour
Accuracy of Horizontal wind speed	0.1 – 0.3 m/s
Accuracy of Vertical wind speed	0.03 – 0.1 m/s
Accuracy of wind direction	2° - 3°
Measurement range horizontal	0 to 50 m/s
Measurement range vertical	-10 to +10 m/s
Operational temperature range	-35 to 50°C
Power requirements DC operation	±12 V, 4 A peak, 1 to 2 A average
Power requirements AC operation	100 to 240 V, 200 W
Size	44 x 42 x 16 cm
Weight	11.5 kg

Technical characteristics of the Scintec's SFAS SODAR.

2.1 Sodar principle of operation

The operation principle a sodar can be summarized as follows: A sodar antenna emits short acoustic pulses into the atmosphere. The acoustic waves are backscattered at temperature inhomogeneities in the air. The antenna receives the backscattered signals and the subsequent electronics and digital processing evaluates the amplitudes and frequencies. The duration between emission and reception provides the height information about the area to be evaluated. Since the temperature inhomogeneities move with the wind, a Doppler frequency shift is observed revealing the wind speed relative to the beams axes. If this Doppler shift is measured at different beam directions, the three-dimensional wind profile is obtained. The amplitude of the backscattered signals supplies information about the strength of the thermal turbulence.

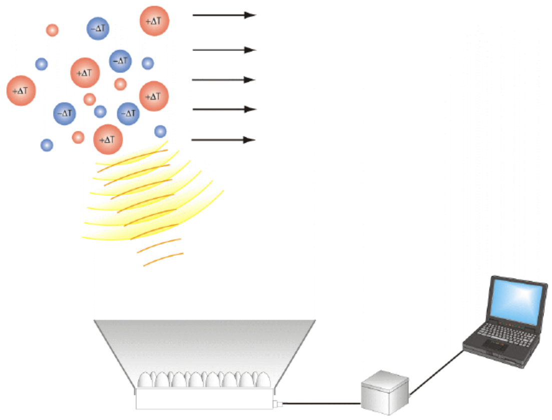


Figure 2: *Principle of operation of SODAR.*

The Scintec FAS (Flat Array Sodars) series are of monostatic type, i.e. the same antenna is used for emission and reception of sound. It generates different beam angles during emission and reception by phase-delayed driving and sensing, respectively, of the rows or columns of an array of 64 acoustic transducers. The phase delays in the emission and reception modes are produced digitally, resulting in long-term stability of the phase shift and related performance. General advantages of phased array systems over 3-component horn antenna systems are a smaller antenna size and a more flexible use.

The height resolution is gathered by range gating, i.e. by considering the time the pulse needs to propagate from the antenna to the measured layer and back to the antenna. From the amplitude of the backscattered wave, detailed information about the turbulence structure in the atmospheric boundary layer can be obtained. By evaluating the spectrum of the backscattered wave, the wind speed is determined. This is possible because of the Doppler frequency shift resulting from the movement of the scattering temperature inhomogeneities with the mean wind. When at least 3 beams are emitted at different angles, a vertical profile of the 3D wind vector can be derived. The spectra of the acoustic signals received are determined using a Fast Fourier Transform process.

2.2 First unlucky attempt

The measurements started on November 8, 2006 and lasted until November 21, 2006. Along with the SODAR unit, a custom system (designed by CRES) was installed in order to supply the SODAR unit and the laptop which controls its operation, with the necessary electrical power (~300W). The system consisted of a trailer and a small wind turbine of 500kW (Figure 4). Within the trailer there were six 12V batteries of 105Ah, connected per 2, in 3 parallel series, to get 24V. Next there was a 24V inverter of 350W and a Charger 24V-16A. The batteries were charged by a ~2kW electrical generator (with unleaded fuel) and the small wind turbine. Finally, a Stylitis data logger (which includes a GSM modem) was used to remotely log (mainly) the voltage of the batteries. Just before the SODAR unit, a ~1000VA Line-Interactive UPS was connected, in order to "absorb" elec. instabilities of the system output, since that resets SODAR resulting to 10min data loss.

The premature end of the measurements was due to the damage of the enclosure panels of the sodar, after severe wind speed gusts (exceeding 30m/s). The amount of the collected data is insufficient to perform any type of statistical analysis and correlations to the neighbour meteorological masts. The weather conditions at that time (snow ~0.5m high) did not even permit for several months to access the remaining equipment of the measurements. A new measurement campaign was scheduled in summer 2007, with the repaired sodar.

Figure 3: *Views of the 2 prevailed wind directions of the measurement site.*

<u>Left:</u> WSW view with the sodar (right arrow) and its distant (~50m) supporting units to ensure low-level background noise (left arrow).
<u>Right</u>: ENE view of the site.

Figure 4: *<u>Left:</u> View of the autonomous power supply system*
<u>Right:</u> Inside view of the trailer assuring the power supply
(batteries, inverter, data logger, generator, small wind turbine controller).

Figure 5: *The destruction of the acoustic enclosure and the damaged units of sodar after severe wind gusts (estimated at above 30m/s).*

2.3 Measurements using a sodar and a lidar and two reference masts

2.3.1 Campaign description

The second phase of the measurement campaign at Panachaiko mountain started in September 2007 and lasted up to the end of November 2007, when both remote sensing devices were uninstalled due to snow conditions (Figure 8). Panachaiko mountain (1800m asl) is usually covered by snow, during several months in winter and the risk of losing the devices into the snow was quite high.

Meanwhile, the extension of the wind farm (13.6MW, 16 wind turbines) started to be realized and the foreseen wind turbines were erected in the nearby of the measurement point. However, during the entire period of measurements they were <u>not operating</u> because of grid connection issues.

Figure 6: *A general view of the measurements area showing the 55m lattice mast, the sodar and the lidar.*

Given the experience "gained" from the first sodar campaign at the specific site, it was decided to move the unit to a more protected spot (Figure 6). It is clear now that, the enclosure surface of the sodar cannot sustain gusts of ~30m/s (frequent to that site), because in such a case the panel either will bend or will be de-anchored.

Additionally, two masts were also already erected: a tubular one (53m high) serving as permanent reference mast of the wind farm and a lattice one (55m high) installed in the future position of a wind turbine (for site calibration and power performance reasons). Both masts were equipped with calibrated Vector A100LK cup anemometers and the mounting of all sensors was following the IEC 61400-12-1 recommendations. The distance between the two masts was 122m.

Figure 7: *Concurrent view of the two both Masts during ZephIR's installation.*

Figure 8: *Another view of the measurement set-up showing the sodar and the 53m tubular Mast.*

During the entire experiment sodar was configured to emit the so-called “polyphonic” acoustic pulses. The default setting is “monophonic” pulses i.e. the pulse sequence is emitted strictly in sequence - one frequency at a time. This is the preferred option for maximum range but provides less data quality in the lower range. “Polyphonic” pulses involve several frequencies at a time like in a chord. This slightly decreases performance in the upper height range, but greatly improves the performance in the lower height range. However, it is underlined the “polyphonic” option in the specific sodar and software (APRUN version 1.18) means that the first pulses are emitted monophonically to provide a good height coverage and the later ones are emitted polyphonically.

Another important point to be documented concerns the orientation of the unit. Given the surrounding “obstacles”, specific attention was paid to orientate the unit (not the enclosure, since it is a symmetric octagon) in a way that the 4 acoustic beams are “free” i.e. they were not emitted in the direction an obstacle.

2.3.2 Results

Given the fact that data from two reference masts were available, the first result concerns the wind speed comparison between their top anemometers (Figure 9).

☞ The wind speed comparison results confirm the flow difference that often occurs in very complex terrains in just 122m. They also confirm the necessity of performing site calibration studies, before evaluating the power performance of a wind turbine in complex terrain.

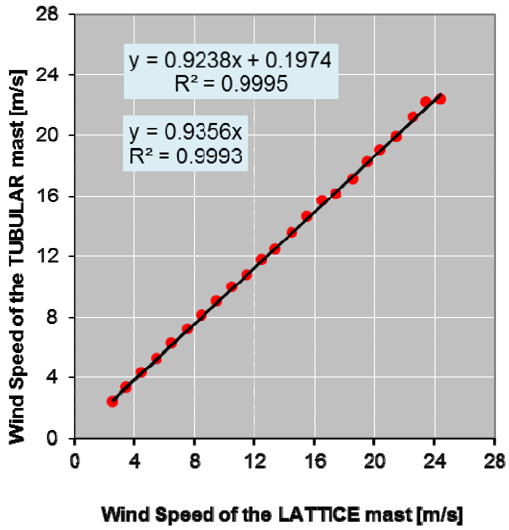


Figure 9: *Wind speed comparison between the top anemometers of the 2 Masts (6956 10min-average data, W direction sector, 1m/s bins, 53m and 55m heights agl).*

During the experiment, the weather conditions were very difficult, varying from clear skies (few days only) and rains, to conditions with very low visibility (mist – fog – low clouds) and snow (Figure 8b). Consequently, both the sodar and the lidar were operating in particularly low signal to noise ratios and data filtering was necessary.

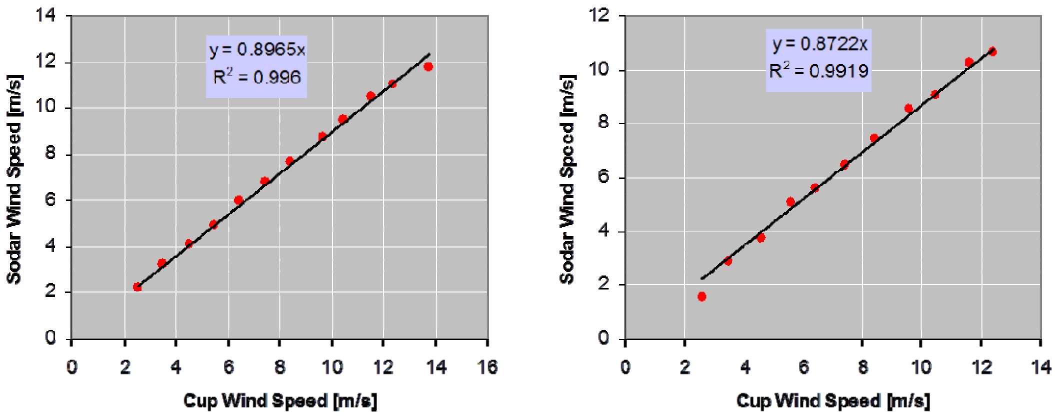


Figure 10: *Cup – Sodar wind speed comparison at 55m height (516 1h-average data, 1m/s bins)*
Left: *Relative to Tubular Mast* ***Right:*** *Relative to Lattice Mast*

Sodar data filtering was mainly performed during the post-processing by the APRUN software, which also controls the unit's operation. After several configurations were tried, finally the most trustworthy database was created using 1hour average results, imposing thus correlations of hourly-averaged data.

Figure 10 shows the sodar comparison to the top cup anemometers of the two masts. Apart the 1h-averaging, binning the results in 1m/s wind speed bins, greatly improved the results scattering and lead to higher R^2 values. However, this had a negligible effect on the regression slopes which remained unchanged and, in any case, deviated "considerably" from 1.0, while maintaining a satisfactory linearity. Given the flow complexity (as proved also by the two masts comparisons - Figure 9) the results are not surprising, but as discussed hereafter, the complex flow may not be the only reason for that.

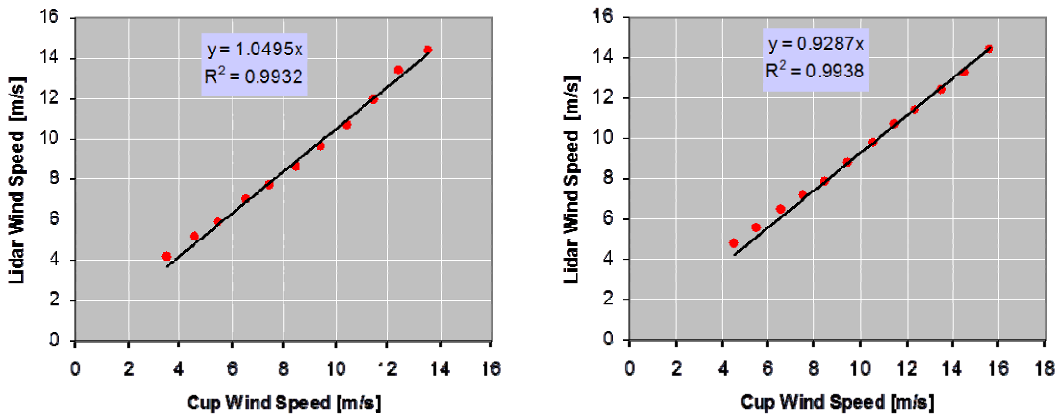


Figure 11: *Cup – Lidar wind speed comparison (935 10min-average data, 1m/s bins)*
Left: Relative to Tubular Mast (122m away from the lidar)
Right: Relative to Lattice Mast (close to lidar)

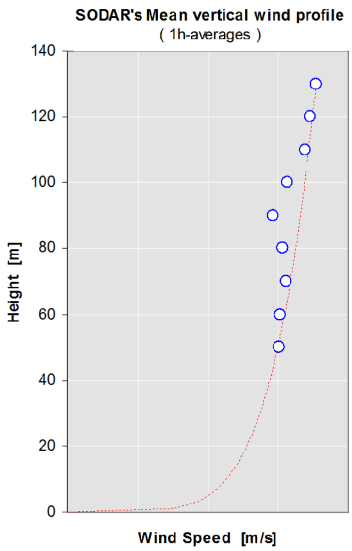


Figure 12: *Sodar mean vertical profile, showing a possible interference with the two nearby Masts and the wind turbine.*

Figure 13: *ZephIR operating in fog / low cloud conditions*

2.3.3 Conclusions of the “Panachaiko” campaign

CRES’ first remote sensing campaign was performed under very difficult conditions at the Europe’s highest wind farm (1800m asl). Both sodar and lidar operated in harsh environments and revealed that a key parameter in such conditions is the power supply unit. This not only in terms of cost, but also in terms of functionality (frequent restart problems, when the units were left out of use for 1-2 days in freezing temperatures and high humidity). Fuel cells are expected to extend the uninterrupted operation of sodars and lidars from 4-5 days (our case) to more than a month, reducing thus the probability for “frozen” unit.

Sodar results require further investigation, since it is not clear to which degree they are affected by the two surrounding masts and the nearby standstill wind turbine (Figure 12). It is reminded here that, during the second experimental campaign, the safety of the unit was considered more than the optimum SODAR position. This induced a considerable complexity in the raw data. A first database analysis showed that advanced data filtering is needed in order to extract results with a high degree of confidence. The analysis needs to involve not only the directional filtering (due to topography variations), but also but also the distance filtering in respect to the surrounding “obstacles”. Therefore, the results will be furthermore analyzed in the future, when the required effort will be supported financially.

Lidar results were more satisfactory, but the frequent low visibility conditions (Figure 13) influenced considerably the data quality and availability. In any case, it is clear now that continuous-wave (CW) lidars are penalized in high mountainous sites (except summers), because they will operate for considerable periods of time in low visibility conditions.

During this entire lidar campaign, the ZephIR’s “cloud correction” algorithm (running in real-time in the unit’s firmware), was undergoing a major revision and (in agreement with the other project parties) it was decided to disable it, mainly for comparison reasons. Despite the reduced number of data, a sufficient amount remained to safely conclude that in the specific complex terrain, the lidar-cup comparisons fail systematically in the entire range of wind speeds by a relatively small, but non negligible, percentage (~7%).

The previous concluding remark, lead us to design a new experimental campaign in a milder complex terrain with easier access and power supply conditions, using different types of lidars and a high mast, in order to investigate in detail, not only the average horizontal wind speed, but also the vertical component and some turbulence properties.

3. Verification of various LIDARs using a 100m Mast

3.1 Description of the Measurement Campaign

3.1.1 Site location

CRES Test Station is situated approximately 100km SE of Athens (37° 44’ 47 N, 24° 03 58 E). The facility is divided in two parts: The first and bigger part comprises a commercial Wind Farm with 5 HAWTs (Enercon E40-500kW, Neg-Micon 48/750kW, Vestas V47-660kW, Pyrkal OA-500kW and Pyrkal OA-600kW). The second part, situated in the north of the Wind Farm, comprises a 100m meteorological mast (37° 46’ 04 N, 24° 03 44 E or 37.767958, 24.062226) and two small and very old wind turbines (Wincon 110kW and a downwind 50kW). The elevation of the site is approximately 112m and the sea coast is at 1km east. The landscape could be characterized as complex terrain (rather mild), surrounded by hills with rather gentle slopes, low vegetation (more bushes, few trees). A roughness value of 0.15 (or less) represents rather well the entire site.

Figure 14: *A general view of the Wind Farm from NW.*

The annual average wind speed of the site, measured at 78m, is 6.9m/s with mean turbulence intensity 11% in the range 9-11m/s. The Weibull fit of the wind speed distribution results in k=1.7 and C=7.8m/s. The main wind direction sectors are N and S (2.5:1 occurrence ratio).

3.1.2 Description of the 100m Mast

The reference mast of the CRES Test Station is a lattice one, guiwired, weighting 13tn, with an equilateral triangular cross-section, the same from bottom to the top. It is made up from identical modules, each of 1200m high. The stiffening rods of each side are 1300mm long having an angular section of 60mm wide and 60mm tall. The round legs have a diameter of 114.3mm. The cross-bracings form 45deg with the horizontal level (having the same angular form of 60x60mm).

Mast type	Triangular lattice, guiwired
Mast Height	100m
Mast weight	13tn
Distance of anchors	48m / 65m
Side length	1.3m
Structural member (leg) diameter	114mm

Cross-bracing angle	45°
Vertical distance between horizontal stiffening rods	1.2m
Width and height of horizontal & stiff. rods	60x60mm
Solidity	0.41
Thrust coefficient. CT	0.51
Boom length(from the outer leg)	3.0m
Max. theoretical flow induction (distortion) at free flows	-1.4%

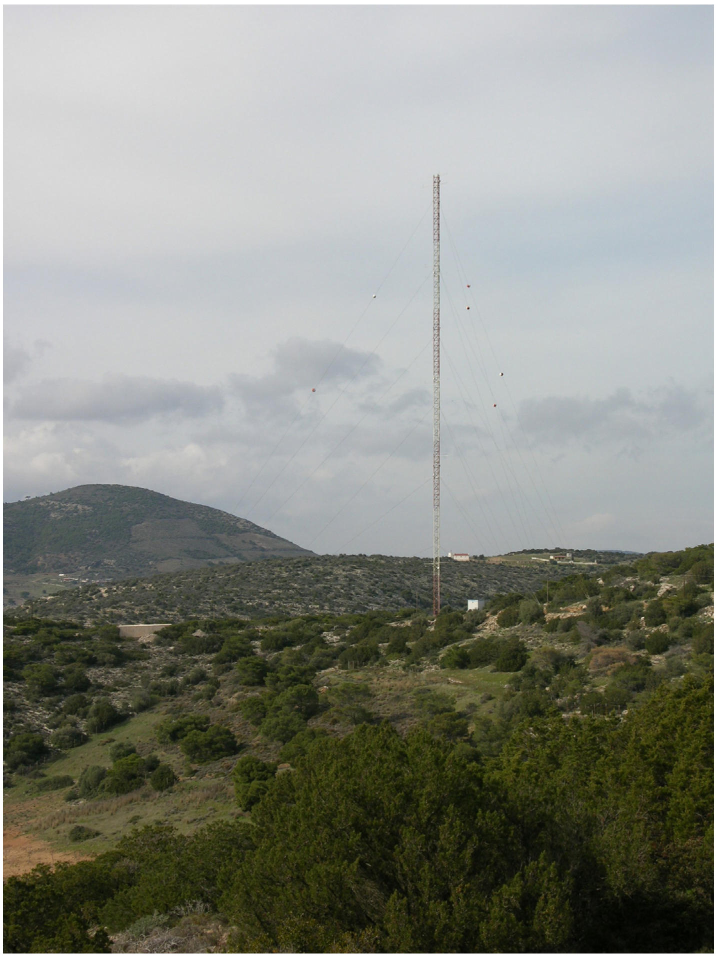


Figure 15: *The 100m reference mast (S view).*

The north part of the triangular section points the North with an average[1] 4° offset. The sensors are supported on the Mast, by the aid of separate telescopic booms, fixed at the two legs of the triangular section which are opposite to the one pointing to the North. The booms have a rectangular cross-section, made of high strength aluminium alloy. Their cross-section is 50mmX50mm at base (Mast side) and 30mmX30mm at the end, where the sensors are

[1] Due to a slight twist of the mast

supported. All wind sensors (even the top ones) are mounted at a height of 45cm above the boom and at a distance of 3.0m from the outer mast leg.

Following the formulation proposed in the Appendix of the IEC standard for wind turbine power performance [1], the Mast (erected 6 years earlier…) has a solidity of 0.41 and a thrust coefficient of 0.51, yielding to a (maximum theoretical) flow induction of -1.4%[2] for free flows (i.e.: when wind direction is perpendicular to the boom). Finally, a lightning arrestor is situated on the top of the Mast (north leg).

3.1.3 Description of the Sensors

Five Vector A100LK cup anemometers are mounted at 12m, 32m, 54m, 76m and 100m heights, E-side of the Mast. In the opposite side (Mast's W-side) and at the same heights except the top one, five Vector W200P wind vanes are mounted, using identical booms. The highest vane is placed at 98m (E-side). Mast's top configuration is shown in … All the anemometers are calibrated according to MEASNET procedures [3], before their installation and right after their replacement. For the purpose of this project, 3 pairs of anemometers were used per each height and the results of the anemometers recalibration[3] are presented in Figure 16.

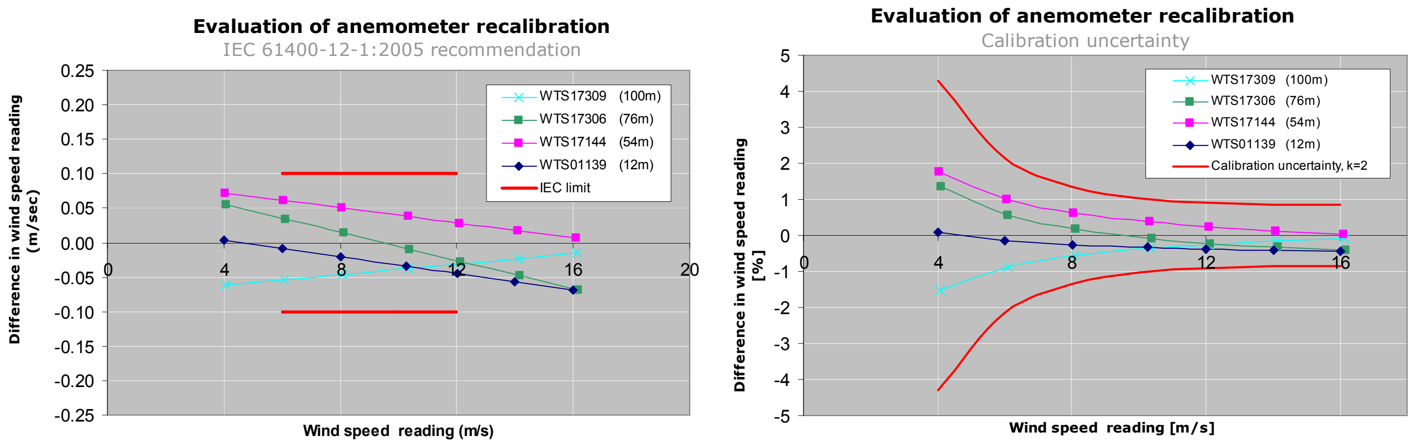


Figure 16: *Results of the anemometers recalibration.*

Since the aim of this work is to compare lidars to cup anemometers, the following should be noted: MEASNET calibration procedure defines the calibration range from 4m/s to 16m/s. Consequently, the fair comparison of cups-lidars/sodars should be restricted to the above range. However, sometimes is of great interest to expand this range to higher and lower wind speeds, assuming that the calibration coefficients of the cups remain the same. In the present work, when comparisons include larger ranges, this assumption is adopted, because this could be easily a subject for a separate project.

Two Gill WindMaster Pro ultrasonic anemometers, capable of measuring the three components of the wind speed vector, are mounted at 78m and 98m heights, using the same booms as for the cups, but in the W-side of the Mast. The sonics were also calibrated at CRES wind tunnel, in steps of 60° azimuth angles and 5° inclination angles. Two identical sets of sonics anemometers were used; the first one was dismounted and re-calibrated in November 2009 and the second one was calibrated and installed in September 2010.

[2] For comparison reasons, the flow induction at RISO's 116m reference mast is -1.1% at 80m height [2].
[3] Only 4 were recalibrated, the one at 32m height was defective and not operating anymore.

Finally, the Mast is also equipped with dedicated sensors for temperature, atmospheric pressure, rain, relative humidity, as well as, with a global and reflected radiation pyranometer.

3.2 Results from the reference sensors

The particular experimental campaign started at Sep. 9, 2008 and ended at Jan. 29, 2009. Results are based on 10min averaged data, unless otherwise stated. Figure 17 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 18 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.

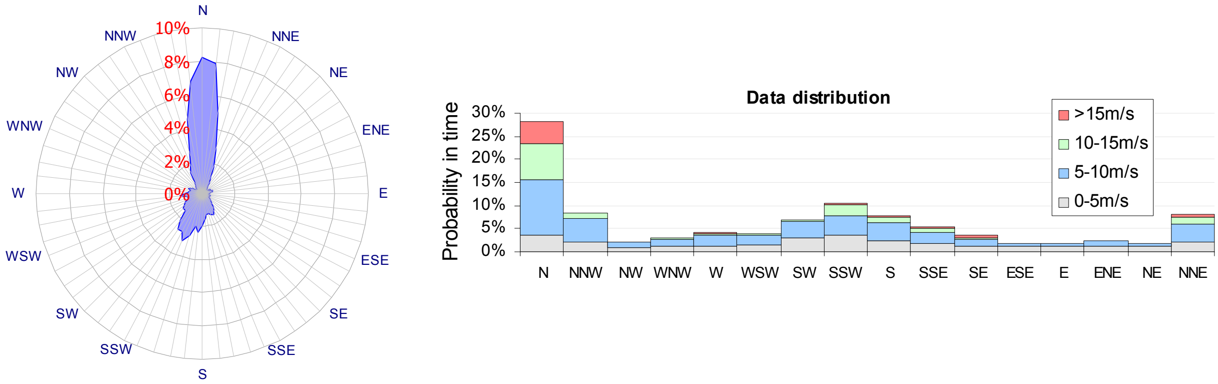


Figure 17: *Data distribution (wind rose) during the experiment. The average wind speed at 100m height was 7.2m/s*

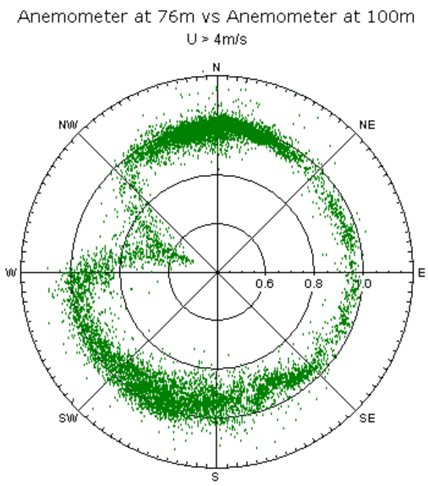


Figure 18: *Influence of the Mast tower*[4]

Figure 19 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 R2 value well above 0.99. The same picture is obtained when

[4] In this lattice tower, there is no free top-mounted anemometer. The ratio "drop" seen at ~293° is explained by the "obstacle" difference at 100m height (lightning arrestor) and at 78m height (front northern leg of the mast). It is reminded that the cup booms are mounted on the two south (SE and SW) legs of the triangular mast.

comparing the standard deviations although the slope and the regression coefficient R2 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.

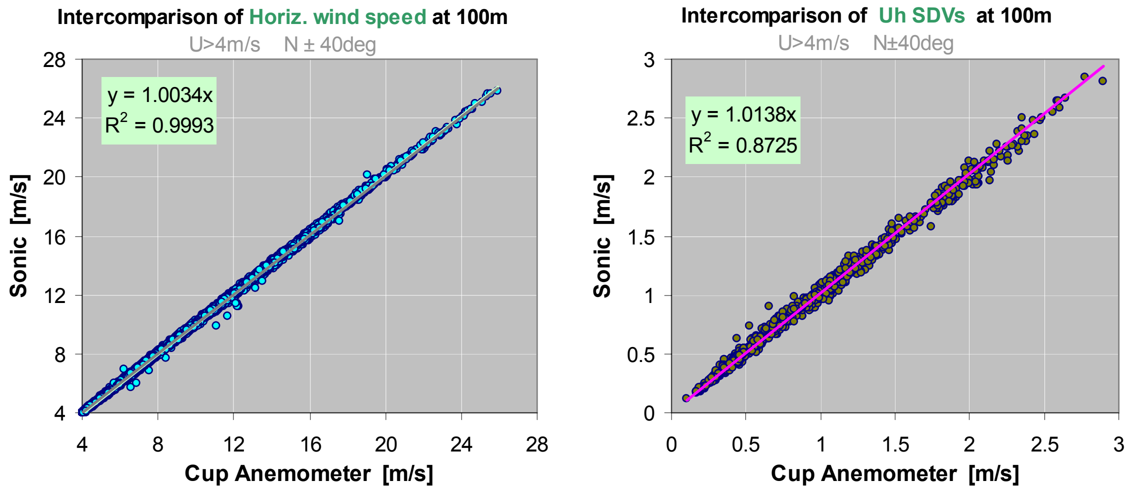


Figure 19: *Comparison of the horizontal wind speed's average (left) and SDV values (right), between Sonic and Cup anemometer at 100m.*

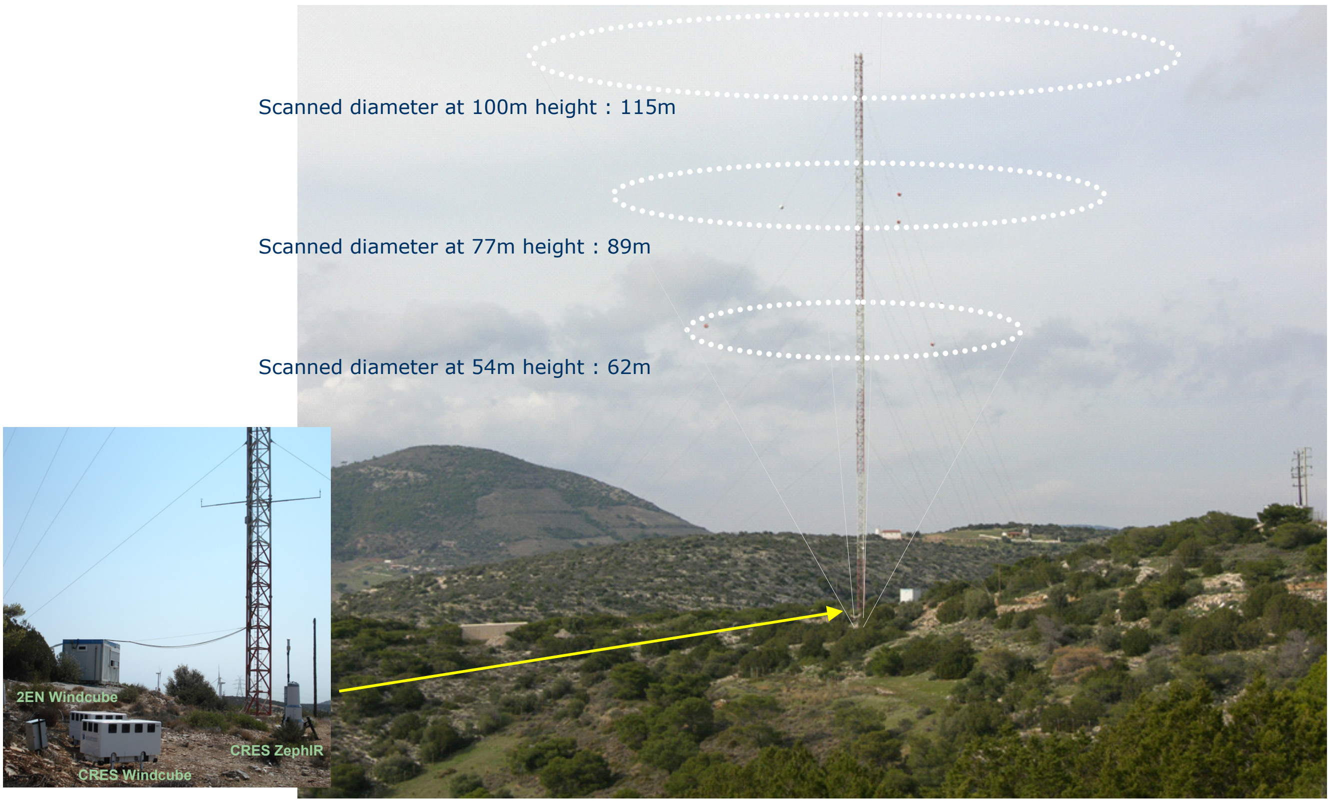


Figure 20: *Schematic representation of the lidars scanning areas (30° prism).*

3.3 ZephIR results

The emphasis on this work 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), practically eliminated data at wind speeds lower that 4m/s. Thus, comparison results exclude wind speeds lower than 4m/s. Figure 21 shows how ZephIR compares to cup anemometers at 3 different heights (10min averaged values).

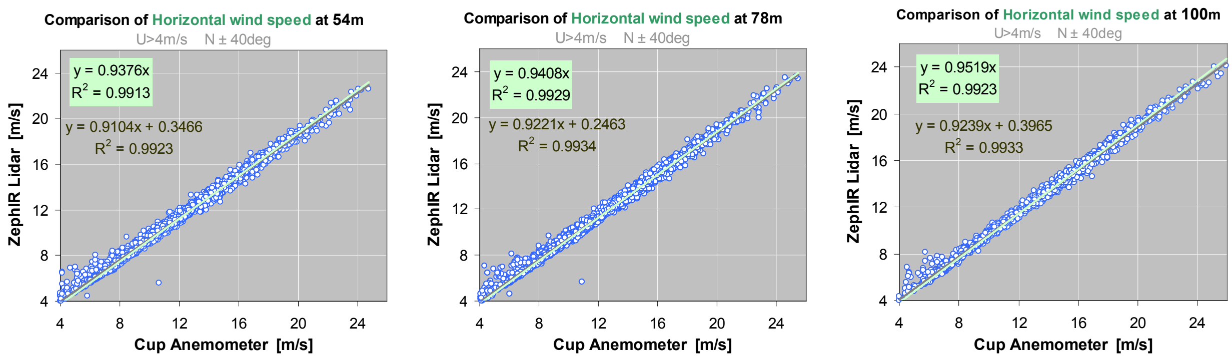


Figure 21: *Comparison of the horizontal wind speed between ZephIR and Cup anemometers*

Figure 5 presents the comparison of the standard deviation of the horizontal wind speed between ZephIR and cup anemometers. The same behaviour 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 for the σ_U underestimation by the ZephIR. In contrary to a cup anemometer, which measures only temporal fluctuations, a lidar (and a sodar) measures and includes in σ_U also the spatial fluctuations of the wind speed.

“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 23). 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 24).

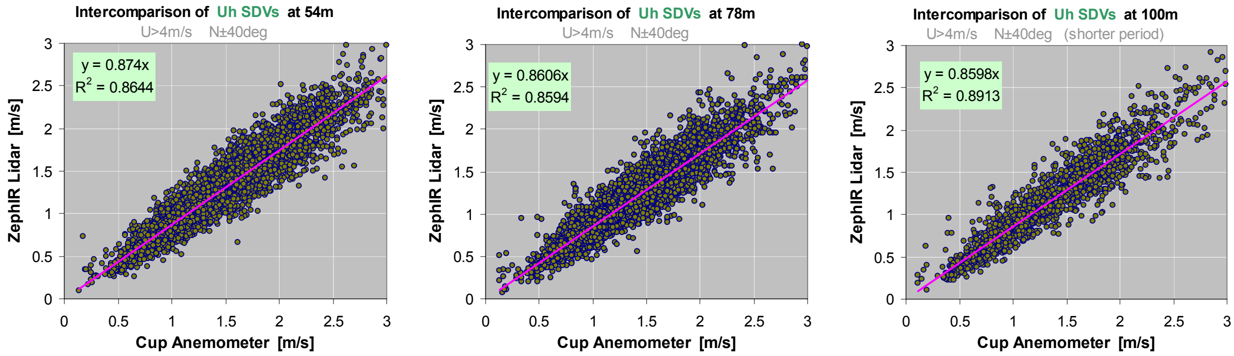


Figure 22: *Comparison of the SDV of the horizontal wind speed between ZephIR and Cup anemometers*

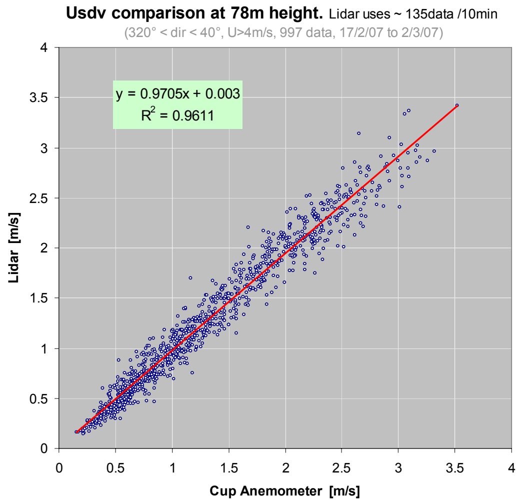


Figure 23: *Improved wind speed's SDV results are obtained when "fixing" ZephIR at one height.*

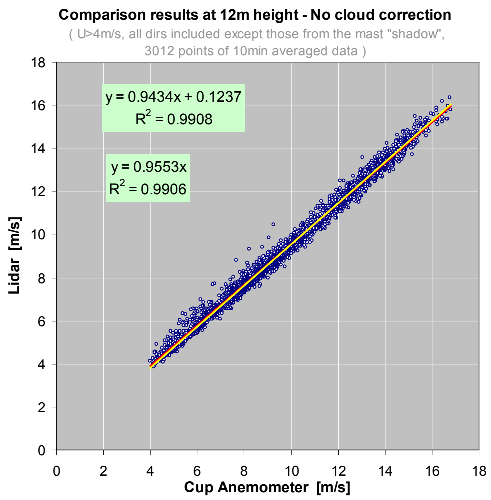


Figure 24: *Cup-ZephIR comparisons at the lowest height of the Mast (12m).*

3.4 Windcube with 30° prism results

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. The two Windcubes are considered almost identical, as they were manufactured recently (separated by some weeks only) and they have neighbour serial numbers (WLS7-0012 vs WLS7-0015).

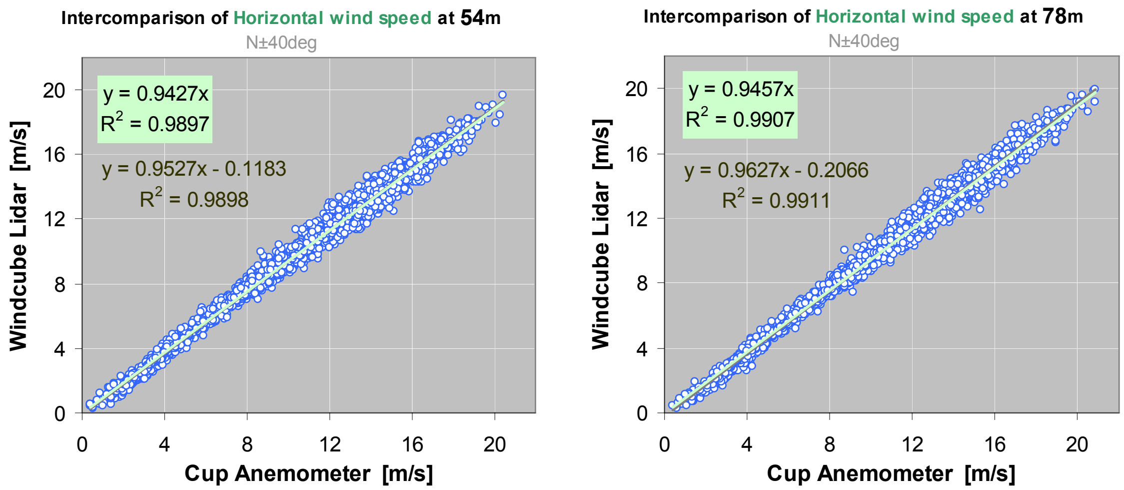


Figure 25: *Comparison of the horizontal wind speed between Windcube and Cup anemometers*

Figure 25 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.

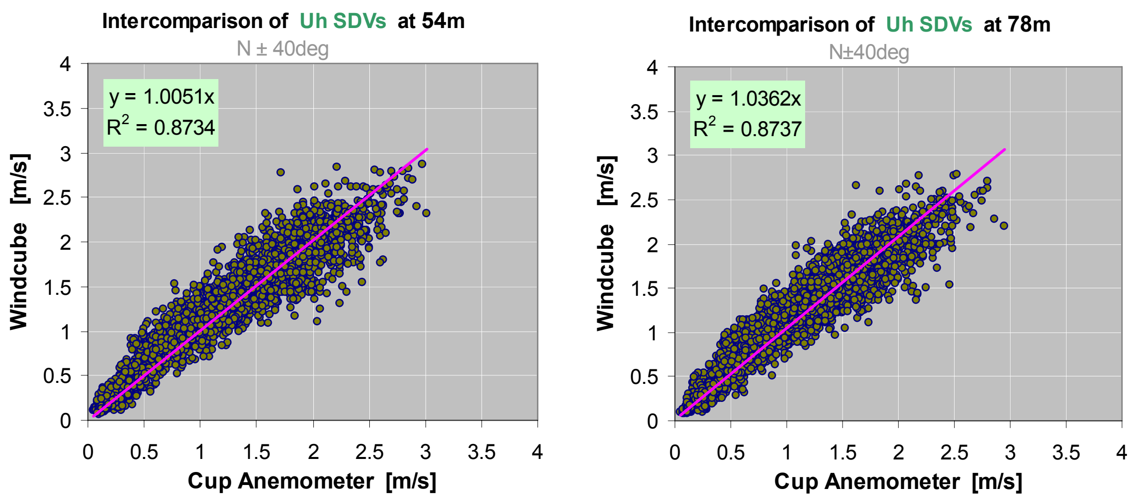


Figure 26: *Comparison of the SDV of the horizontal wind speed between Windcube & Cup anemometer*

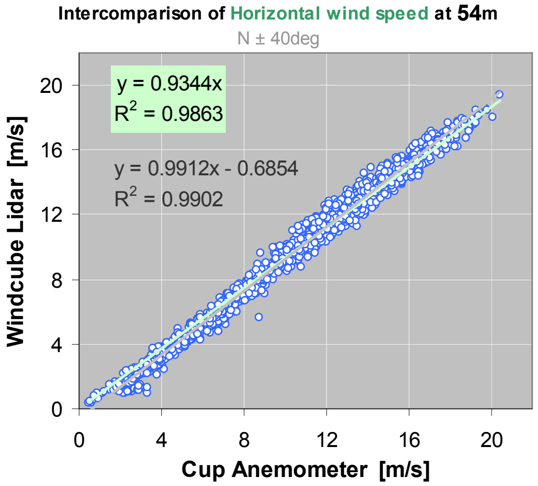
Unlike the ZephIR, Windcube does not rotate continuously but the prism stands still, while sending a stream of pulses, waiting for the backscattered signal. Then, it rotates by 90°. In order to produce a single value, Windcube combines the latest four radial velocities to deduce the wind speed vector. 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 25 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 |Δσfreq|>0.4 (variance of the signal broadening).

3.5 Windcube with 15° prism results

Figure 27 and Figure 28 are the equivalent figures, 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).



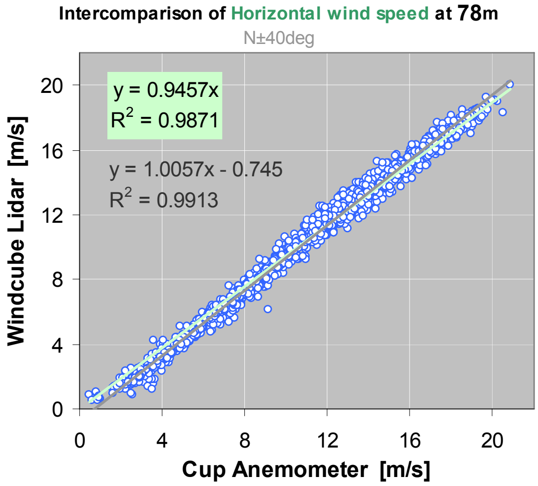


Figure 27: *Comparison of the horizontal wind speed between Windcube with the 15° prism and Cup anemometers*

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 behaviour, 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 [8].

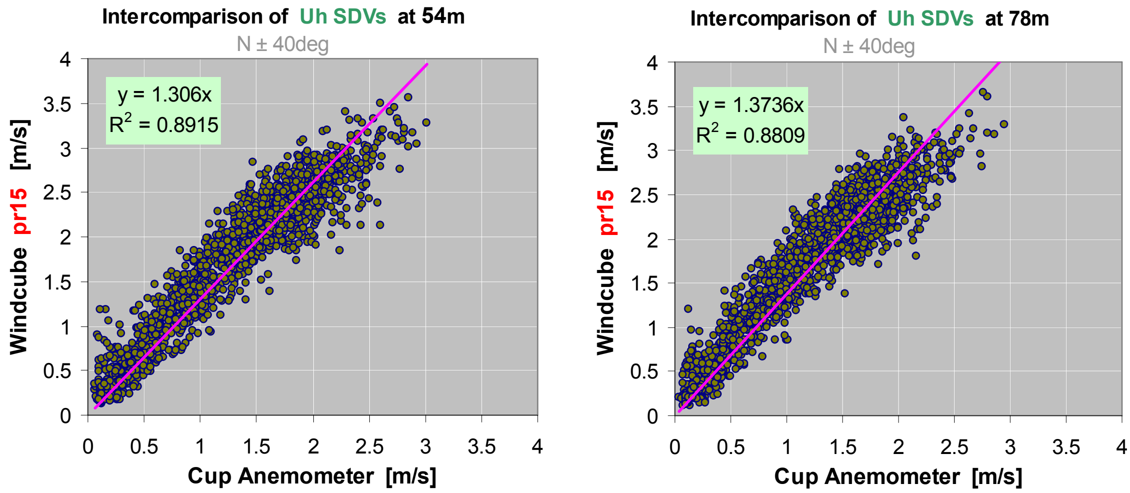


Figure 28: *Comparison of the SDV of the horizontal wind speed between Windcube with the 15° prism and Cup anemometers*

3.6 Flow tilt angles results

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 29 shows that practically equivalent results are obtained by the two Windcubes, independently of the prism angle they use.

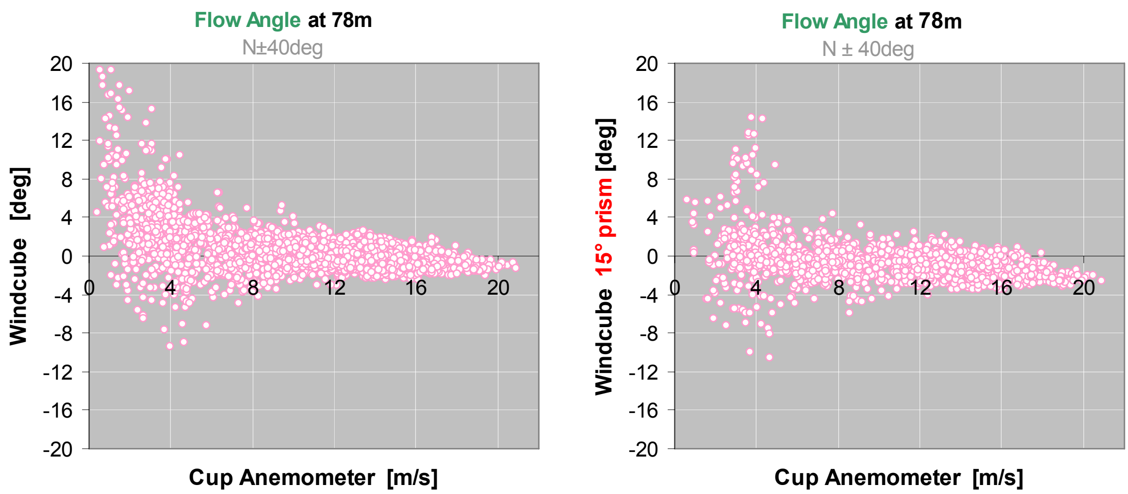


Figure 29: *Comparison of the flow inclination angle (10min averages) at 78m height, as measured by the two Windcubes using 30° prism (left) and 15° prism (right).*

Given the flow complexity, additional information is obtained when presenting distributions of instantaneous data, instead of just average values. Thus, in Figure 30 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.

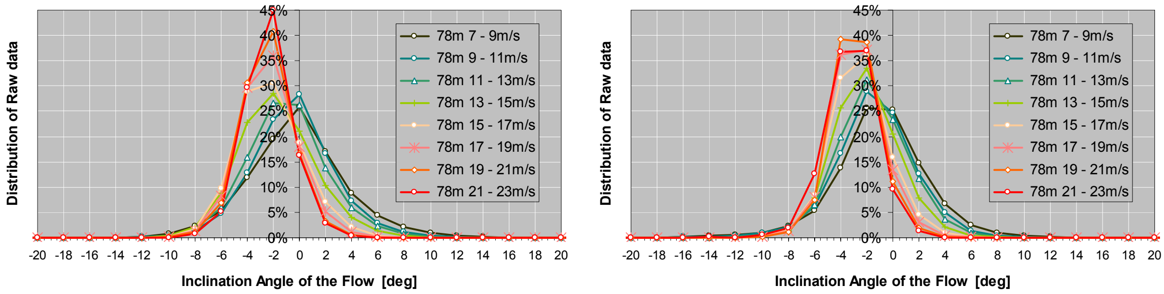


Figure 30: *Distribution of instantaneous flow inclination angles per wind speed bin, as calculated by the two Lidars, using the raw data.*

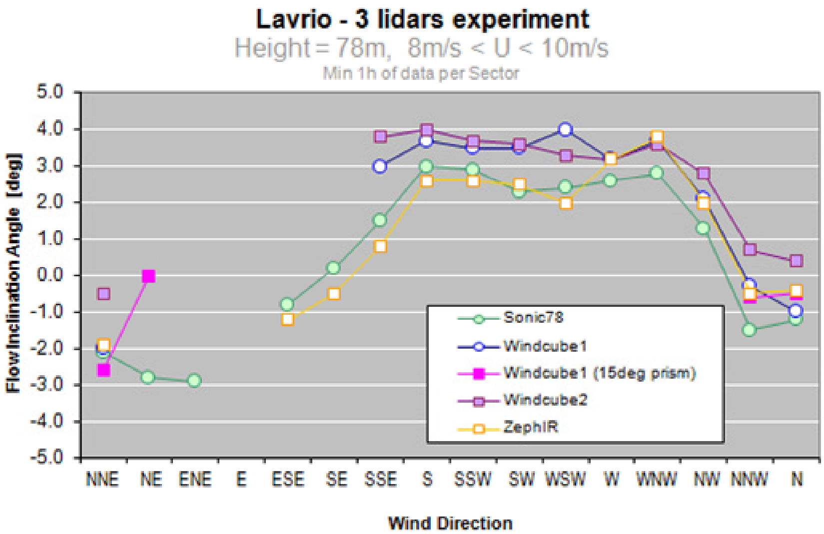


Figure 31: *Variation of the flow tilt angle with wind direction Comparison between Sonic and 3 Lidars (ZephIR and 2 Windcubes)*

4. Vertical wind speed – Windcube vs Sonic results

Having confirmed that, when considering the horizontal wind speed, all lidars systematically deviate from the ideal regression slope (1.0), a new measurement set-up was defined to attempt comparisons of the vertical wind speed component, between Sonic and Lidars.

This campaign started at March,31 2009 and lasted 10 days. Two Windcube lidars were employed; the first one was operating with its standard configuration (30° prism) and the other one without a prism (scanning vertically at 0°). Figure 32 shows the wind conditions during these days. It was discovered later that during these days, the Sonic at 78m height was functioning sporadically and irregularly, thus the comparison height was restricted only to 100m agl.

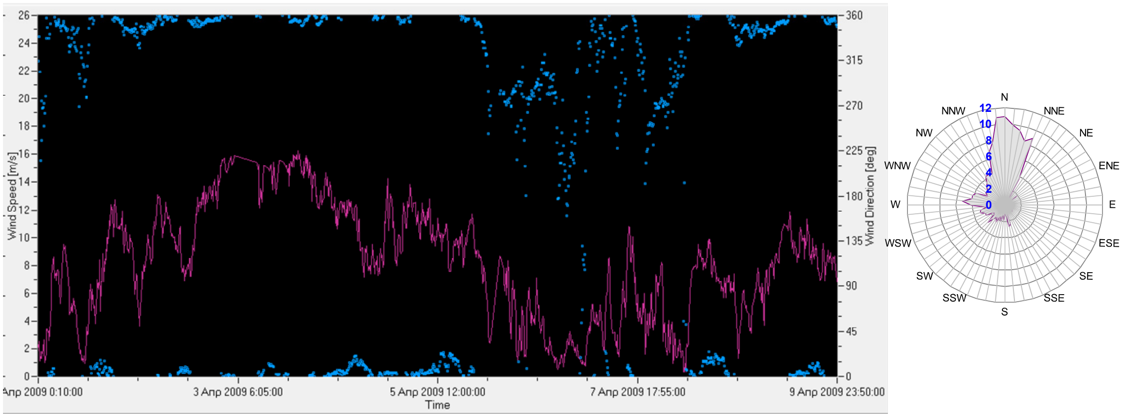


Figure 32: *Wind conditions during the specific experiment (10min average wind speed time-series and wind rose).*

The initial position of the two Windcubes was not changed. Specific attention was given to maintain the same horizontal level for the two Windcubes; the error is estimated to less than 0.3°. Obviously, the measurements area (volume) of the two lidars is not the same; the one without prism measures in the centre of the other's lidar scanning cone. The guiwires of the mast did not permit to place the Windcube without prism, in such a way, so it senses the area right in front of the Sonic anemometer. However, the distance between the measurement area of the Sonic and the Windcube without prism was <10m (Figure 20).

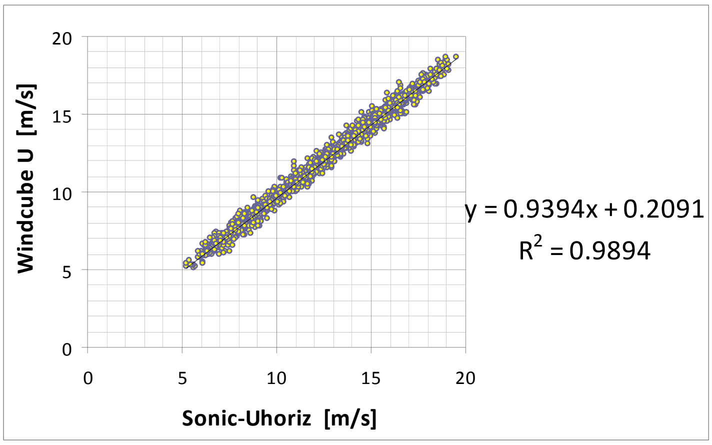


Figure 33: *Horizontal wind speed comparison during the experiment; Sonic vs Windcube Lidar at 100m height 2076 1min data, U>5m/s, 6deg wide sector (357 ° - 3°).*

Given the short duration of the measurement campaign and the necessary data filtering, it was chosen to present 1min average data (instead of 10mim average) in order to use a meaningful number of data. The synchronization of the raw data was checked and re-confirmed during the data analysis, by verifying the time-shift that maximizes the correlation coefficient of the two time-series.

Figure 33 confirms that in case of data shortage, using 1min-average data, does not modify the general picture of the lidars performance in complex terrain. The regression slope and the determination coefficient R^2 are very similar to those calculated from 10min-average values.

Figure 34 shows that (as somehow expected) measurements of the vertical wind speed using a no-prism Windcube are very close to those taken from the Sonic anemometer. This is clearly manifested by the undoubted improvement of the σ_W comparisons (Figure 35). In this graph, not only the regression slope is improved significantly (0.58 vs 0.98), but also the coefficient of determination R^2 drastically increases (0.71 vs 0.87).

☞ This worth noting result denotes that, despite the measurements difficulty (low range of wind speeds: max. ±2m/s, small amount of data), the vertical component of the wind speed can be also measured by a lidar with a vertical beam and that a 3D Sonic is not the only serious alternative, as up to date.

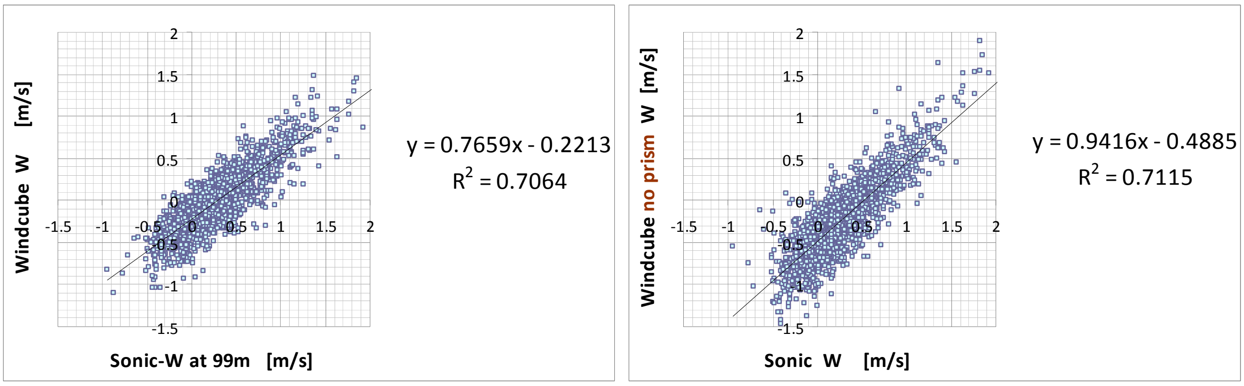


Figure 34: *Measurements of w-component at 100m agl*
30°-prism (left) and no-prism (right) Windcube vs Gill WindMaster Sonic
2076 1min data, U>5m/s, 6deg wide sector (357 ° - 3°)

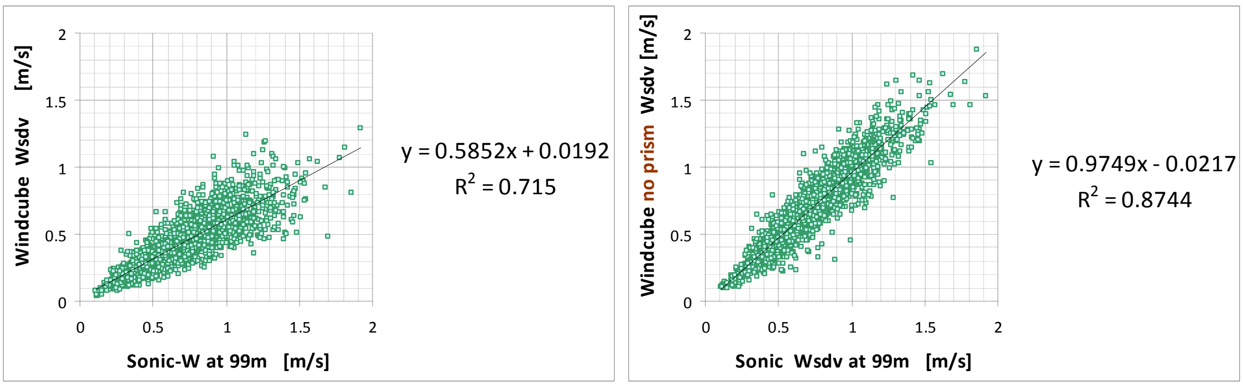
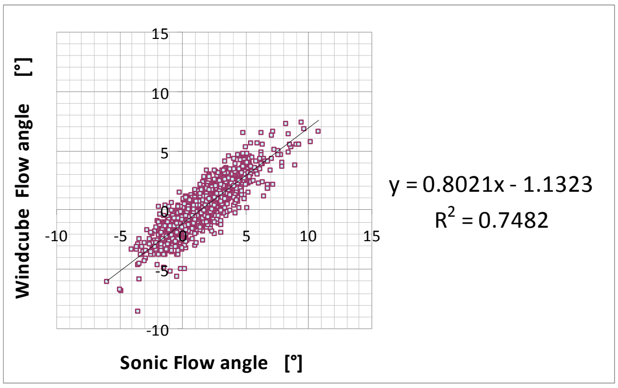


Figure 35: *Measurements of SDV of the w-component at 100m agl*
30°-prism (left) and no-prism (right) Windcube vs Gill WindMaster Sonic
2076 1min data, U>5m/s, 6deg wide sector (357 ° - 3°)

The previous result could also be a sort of confirmation that, decomposing and simply averaging measurements at 4 azimuth points (almost 115m away one from the other) is of limited validity in complex terrain. Such distances in complex terrain, often contain different topography slopes affecting inevitably the flow angle.

Figure 36 confirms that the Sonic's flow angle measurements are much better approximated by no-prism Windcube, than the one with the standard 30° prism.



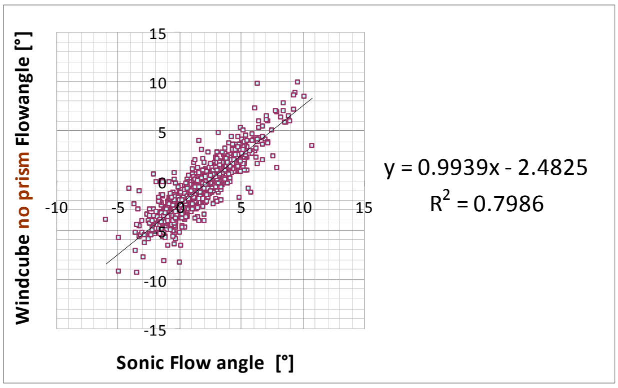


Figure 36: *Measurements of Flow angles at 100m agl*
30°-prism (left) and no-prism (right) Windcube vs Gill WindMaster Sonic
2076 1min data, U>5m/s, 6deg wide sector (357 ° - 3°)

It remains to be examined, whether the above results can be further improved, if a tilt offset was introduced to correct for the small, but inevitable, horizontal misalignment between the 2 Windcubes and the Sonic. This could be done during the post-processing by introducing two separate offsets for pitch and roll misalignment (or for E-W and N-S directions). However, it is not expected that the general picture will change significantly.

5. Other short LIDAR deployments in Complex Terrains

Since the acquisition of the ZephIR and Windcube lidars several measurement campaigns were conducted all over Greece, mainly in order to assess in detail the wind shear. These relatively short campaigns (approx. 2months) are generally sufficient to depict the general trend of the shear (e.g: regions of negative shear due to flow acceleration at low heights, etc).

In the following campaigns, it has to be pointed out that, wherever CRES was not responsible for the erection and operation of the masts, this was done by a certified Laboratory according to ISO-17025 standards. Additionally, CRES obtained full access to raw data and reconfirmed the necessary boom length and positions, calibration certificates, etc.

5.1 Central mountainous Greece 1500m asl – ZephIR deployement

The specific measurement campaign was conducted during spring (2009). The site at its present form is not accessible during winter months. The small photo at left of the Figure 37, shows the deployed equipment (lidar and fuel generator) and the nearby 20m mast.

Figure 37: *A general view of the site and of the installed equipment (within the grid) comprising the ZephIR and the unit assuring its power autonomy.*

As easily observed in Figure 38, the velocity “deficit” of the lidar appears once more, when comparing the 10min averages of the (horizontal) wind speed. The regression slope of the standard deviations is very close to 1.0 (independently of the constant term presence), nevertheless, the comparison is not 100% fair since (as repeated before) lidar fluctuations include apart the temporal ones (as cup does) the spatial ones too.

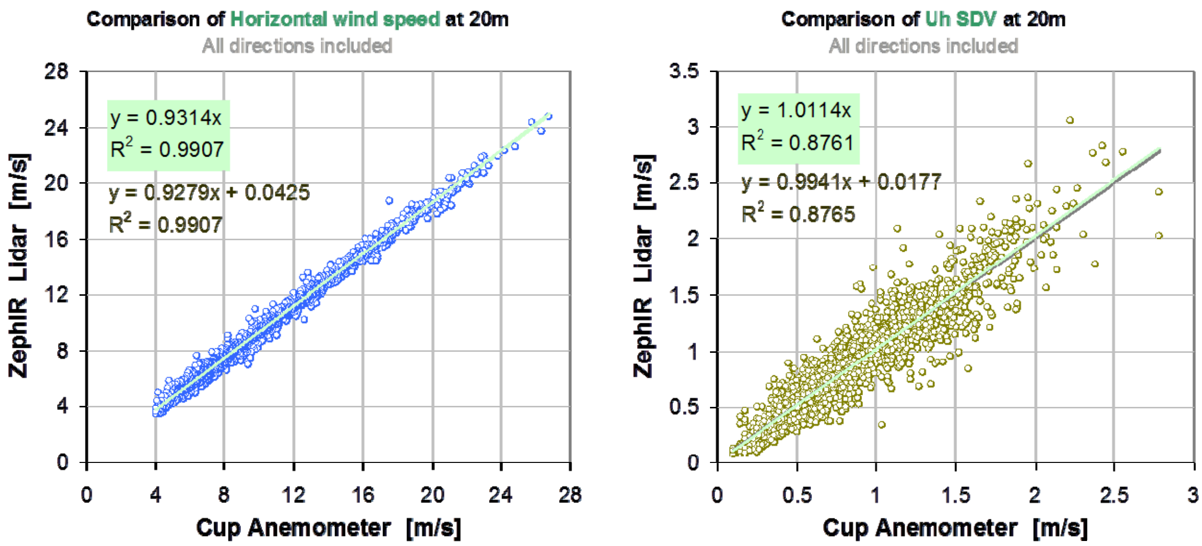


Figure 38: *ZephIR-cup comparisons of the average (left) and SDVs (right) values at 20m agl*

Figure 39 (left) displays the 10min-average flow angles occurred at 20m height, during the entire measurement campaign. The right one is for a specific direction sector, at 55m height and presents the distribution of the 3sec-raw data, per wind speed bins (of 2m/s). The last one clearly shows that flow angles increase with the wind speed, following most probably the terrain slope, while at low wind speeds, heat dissipation from the ground reduce this effect.

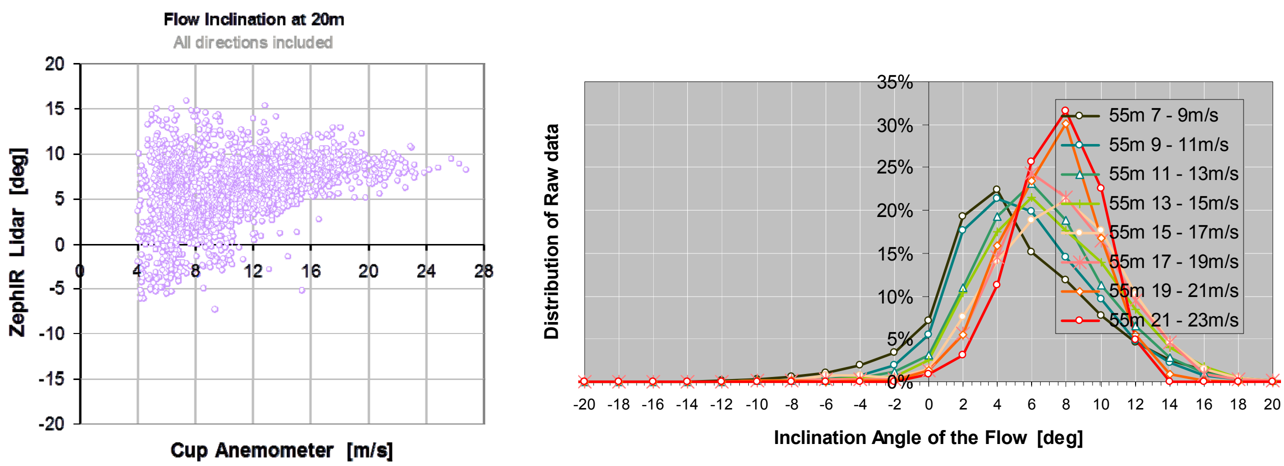


Figure 39: *ZephIR's flow inclination results*
Left: 10min average values at 20m agl. Right: distribution of raw (3sec) data at 55m agl

5.2 Coastal Greece 1000m asl – Windcube deployment

Another measurement campaign was conducted in spring-summer 2009 using the Windcube lidar, in a coastal part of Greece. The terrain was again very complex and the measurement location was at 1000 asl. Cup-lidar comparisons were again performed and the results are summarized in Figure 41.

Figure 40: *CRES' Windcube lidar at 1000m asl:*
General view of the site (above) and close view of the lidar and the mast (left).

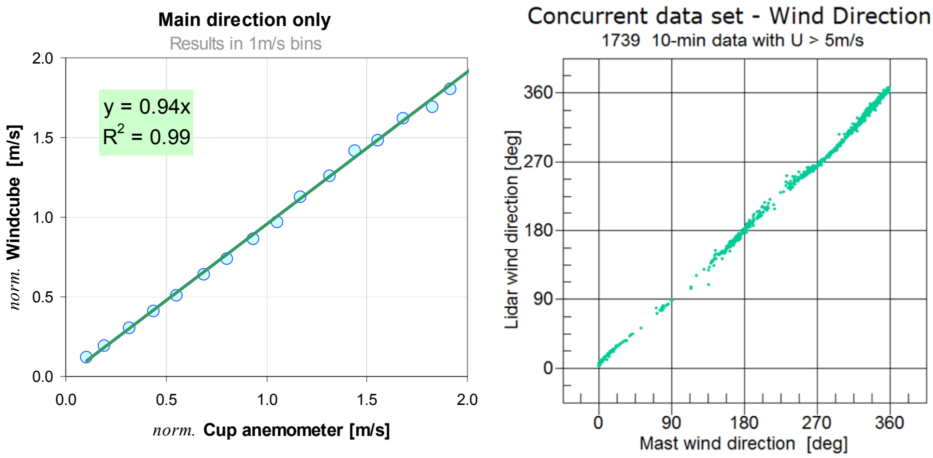


Figure 41: *10min average wind speed (normalized) and direction comparisons Windcube vs Cup anemometer at 40m agl and 1000m asl*

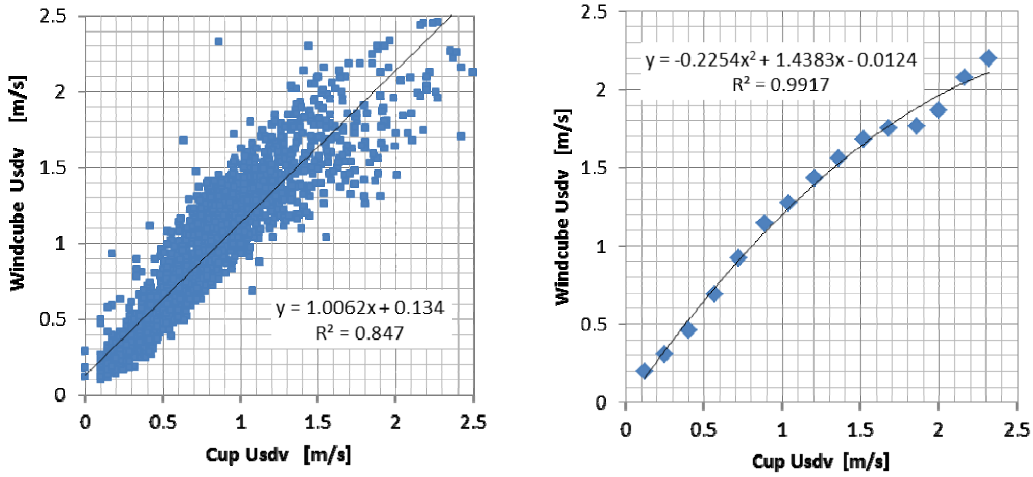


Figure 42: *Wind speed's SDV values comparisons: All data (left) and binned data (right) Windcube vs Cup anemometer at 40m agl and 1000m asl*

5.3 Frequent wind speed profiles in complex terrain

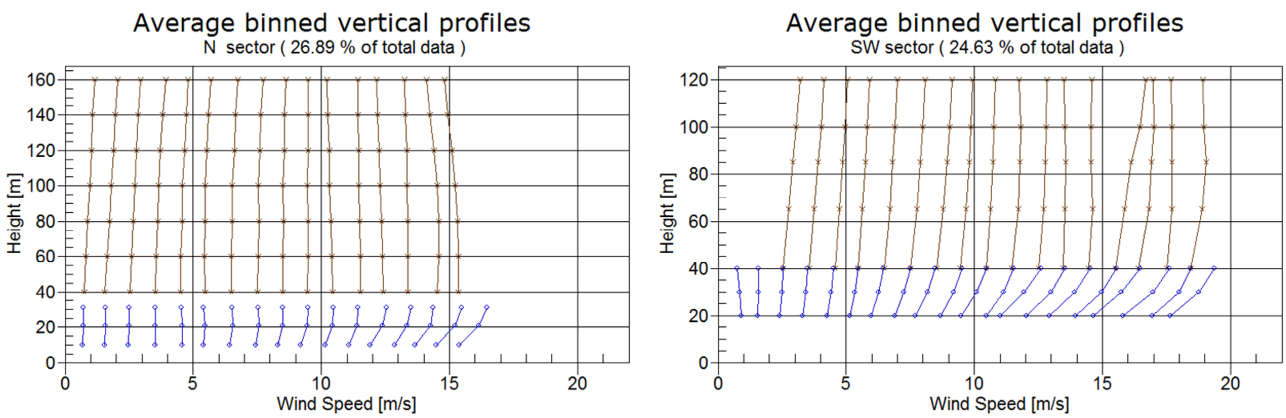


Figure 43: *Representative vertical profiles (from main directions) as measured by cups and lidars*

(Cup anemometers in blue colour, Lidars in brown colour)

6. Extreme events recorded by lidars

During the several campaigns performed in complex terrain, some exciting results (unfortunately not for the developers…) were obtained by the lidars. The results presented below were obtained concurrently by both cups and the lidar and concern the horizontal wind speed variation with height (10min averaged values). It is suspected that, instantaneous results might have revealed even more pronounced phenomena, but Masts' data-loggers were not storing 1sec raw data.

The developers' decision to perform a lidar campaign in those sites was strongly influenced by some "strange" results, already recorded by cup anemometers at low heights. The Figures below present such cases and reveal why lidar campaigns should be strongly recommended in complex topographies. It is underlined that, these extreme events appear within the main wind direction sectors of the sites, so the probability of their occurrence is not at all negligible.

☞ Notice that, even if the height of the Mast was equal to that of a WT's tower (as recommended by the standards), it would be insufficient to reveal the complete picture of the phenomenon, which covers the entire rotor.

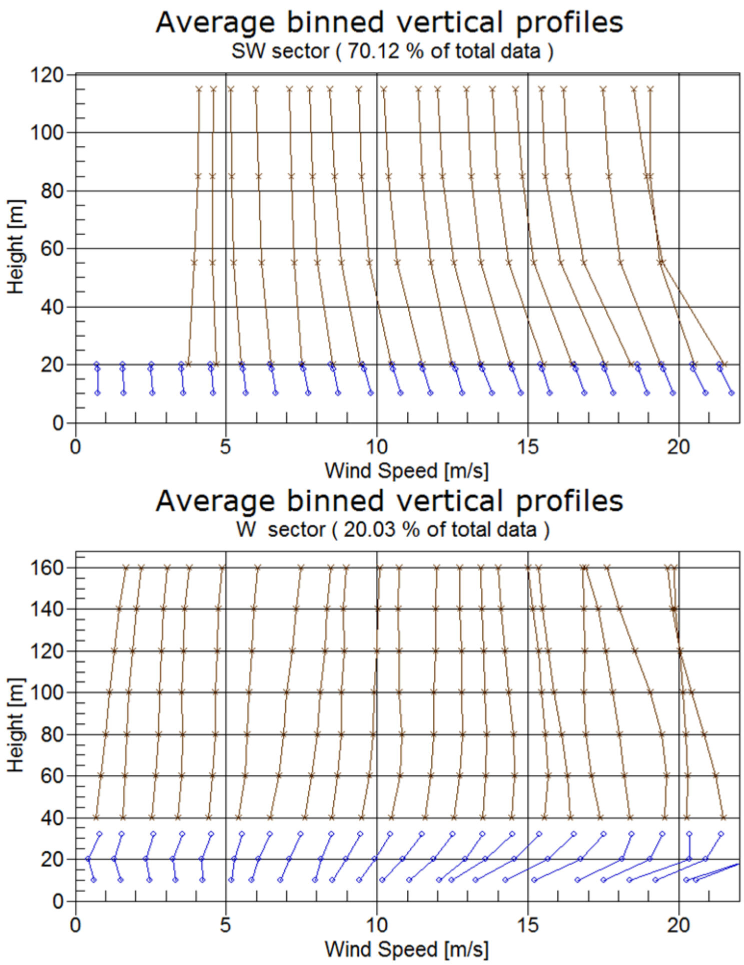


Figure 44: *Lidar results alerting for blade-tower collision*
(Cup anemometers in blue colour, Lidars in brown colour)

Figure 44 warns for uncommon rotor loads, which might lead to blade-tower collisions, a phenomenon already occurred in several places worldwide (and of course never predicted!).

Figure 45 presents another uncommon case in which, the rather “smooth” velocities profiles occurring at low wind speeds, change to “wild” at high wind speeds. It is underlined that, this time the phenomenon was captured already at low heights by the cup anemometers, but the lidar revealed the entire “picture” of this severe profile.

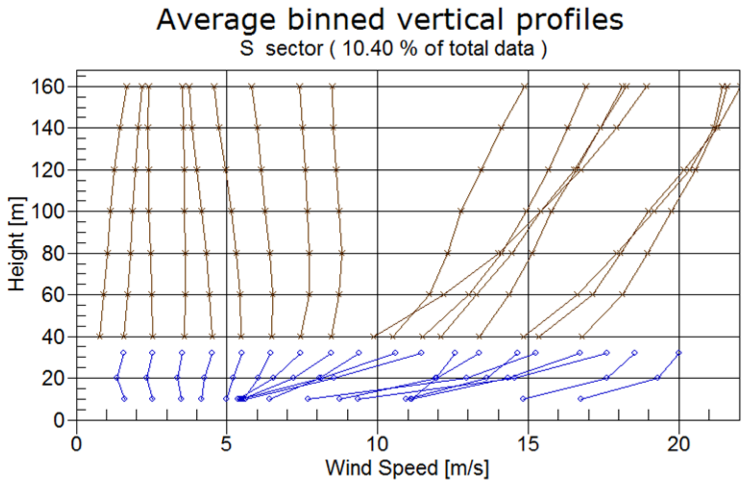


Figure 45: *Wind profiles alerting for heavy WT loading*
(*Cup anemometers in blue colour, Lidars in brown colour*)

7. Conclusions

This report has focused on the comparisons between remote sensing units (sodar/lidars) and mast mounted (calibrated) anemometers, operating in various complex terrains.

The acquainted knowledge during these measurement campaigns leads to the following concluding remarks, concerning the operation of remote sensing devices in complex terrain:

- Comparison of sodars to mast-mounted cup anemometers most likely will fail, since the sodar has to be installed at a considerable distance from the mast (>150m) to avoid acoustic interference, therefore losing the flow representability. Consequently, the results are easily misinterpreted leading to wrong judgments concerning the accuracy of either the unit or the wind speed. A possible alternative could be bi-static sodars (separated emitter/receiver), for which the above constraint applies in a lesser degree.

- Lidars installations do not suffer from the above limitation, since they can be installed at the mast's basement. Additionally, they can measure at low heights (10m for the CW lidars) and practically the entire wind speed range (>25m/s), in contrary to sodars that are "blinded" by the surrounding noise. Despite these advantages, wind speed comparisons between lidars and mast-mounted cup anemometers systematically deviate from the ideal regression slope (1.0) from 4% to 7%. It was proven here, that this is independent of the lidar technology (CW or PW), the prism angle, the cup anemometer manufacturer, or even the body issued its calibration certificate. The presented measurement campaigns included a mixture of all the above configurations, but the results remained consistent.

- Remote sensing devices are called to operate in sites, where flow conditions change significantly with distance. Such a case was presented in §2.3.2, where in just a hundred meters distance, two cup anemometers at 55m height exhibited 7% deviations (Figure 9). Consequently, a lidar (or in general a conically scanning remote device), if installed next to one's or to another's basement, will inevitably sense this deviation and provide it as a velocity deficit. This velocity deficit by no means should be interpreted as "inaccuracy" of the remote sensing device. After all, this flow complexity exists and a ≥2MW-size wind turbine senses it, despite the fact that a single cup anemometer cannot reveal it.

- Reducing the scanning cone angle of the remote sensing devices, not only does not improve the horizontal wind speed comparisons, but it deteriorates its standard deviations. This was proved experimentally for the first time and the theoretical background is given in 6] and [7].

- Also for the first time, convincing results were obtained from a lidar (scanning vertically without a prism), regarding the measurement of the vertical component of the wind speed and the flow angle.

The relatively easy installation of lidars in sites where high masts cannot practically erected, provided some unique velocity profiles. Up to now, almost in every wind farm, the tallest measuring device before the wind turbines erection was a hub-height mast. Consequently, the upper rotor disk was "covered" only by numerical models or simple extrapolations. Lidars (and sodars in some extend) can now provide this kind of information. During these measurement campaigns, some "unique" velocity profiles were recorded and presented in this report. It remains to be seen, the degree to which the lidar technology will change the way we perform a site assessment today, as well as, its foreseen adoption as an onboard measuring device and control of the wind turbines.

8. References

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