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Risø-R-Report

UpWind
D1. Uncertainties in wind assessment with LIDAR

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Abstract (max. 2000 char.):

In this report sources influencing wind assessments with lidars are listed and discussed. Comparisons with mast mounted cup anemometers are presented and the magnitudes of the errors from the listed error sources are estimated. Finally an attempt to define uncertainty windows for the current state of the two commercial wind sensing lidars is presented.

The results in this report give important feedback on system improvements to manufacturers and an estimation of the current ability for wind farm developers which are potential users.

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Preface

In this report sources influencing wind assessments with lidars are listed and discussed. Comparisons with mast mounted cup anemometers are presented and the magnitudes of the errors from the listed error sources are estimated. Finally an attempt to define uncertainty windows for the current state of the two commercial wind sensing lidars is presented.

The factors which give rise to uncertainties in wind assessment with lidars are to a large extent identical for sodars. However, in addition to these problems sodars have for example wind speed dependent beam deviations and availability. This report focuses on lidars since they have shown on much smaller uncertainties in comparisons with mast mounted cup anemometers. Most of the comparisons shown in this report are with Windcubes. Windcubes have generally shown on slightly lower standard uncertainty in cup comparisons and the experimental extraction of cone angle errors and range errors are therefore of higher quality. From comparisons in Høvsøre it is estimated that the difference in accuracy between the two systems is due to a higher sensitivity to inhomogeneous aerosol concentration and a non-optimal extraction of the significant wind velocity from the Doppler spectra. However, as an outcome of this work the test conditions and the Zephirs have improved since the most recent Zephir was tested in Høvsøre.

1.1. Content

This report starts with a short background on the measurement principle of conically wind sensing lidars. This background will not give the reader a comprehensive understanding of the lidar technology but will provide sufficient information to understand how the uncertainties arise.

Following the background, the factors which might influence wind assessment with lidars are listed and discussed. This list might, even at this point, not be conclusive.

The systems used in the comparative tests are then described. System errors detected and resolved during the test campaigns are also described here. The test site and data screening parameters are introduced as well as the uncertainties in the reference sensor, mast mounted cup anemometers.

Finally, the results from the comparative tests of lidars with mast mounted cup anemometers are presented. The magnitudes of the influencing factors are extracted from these data. An attempt to define a general uncertainty window of remote wind assessment with lidars is drawn from the experiences obtained during these comparisons.

1 Measurement principle of conically scanning lidars sensing wind over flat terrain.

A coherent LIDAR can only measure the wind speed vector in its pointing direction, the so called radial velocity. It will simultaneously measure a weighted distribution of all the wind speed vectors within the sample volume, see Figure 1. The sample volumes can roughly be described as a Lorentzian or Gaussian like profile with FWHM of about 20-30 m. The wind speed distribution can typically be sensed at a range of slightly less than 200 m, which in standard configurations corresponds to about 150 m height. One measurement of the radial wind speed distributions takes about 500-5 ms to perform.

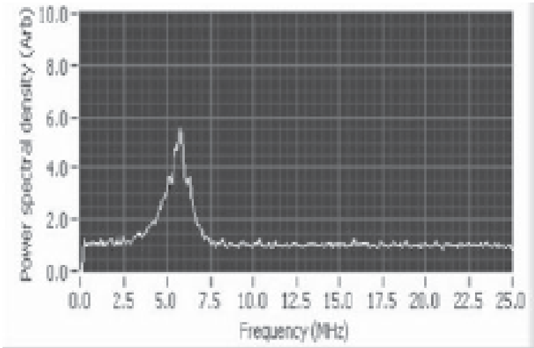


Figure 1 : A smooth almost symmetric measured wind speed distribution. Note the high frequency resolution obtained with the continuous wave Zephir.

However, in wind energy it is typically the 10 minute average horizontal wind speed and direction at a specific height which is sought. A conically scanning lidar estimates the horizontal wind velocity, speed and direction, at the intended sensing range by interpolating at least 3 measurements of the wind speed distribution in the beam direction along the circumference of the scanned circle, Figure 2. The interpolation is made over up to about 100 m horizontally.

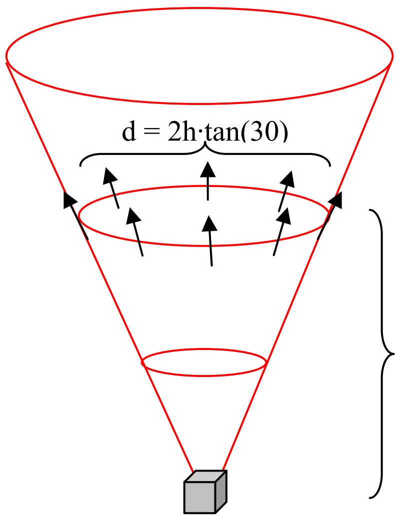


Figure 2: Radial wind speed distributions are measured typically along the perimeter of a conical scan. The cone angle is typically 30 degrees. The radial velocities are in this case collected over a circle with a diameter, d, of about 100 meters for typical hub heights, h.

The coherent lidar measurement principle has been described in detail elsewhere [i,ii]. Coherent detection is fairly straightforward in fiber based lidar systems. The reference line and the search line have the same laser source and the set up is therefore self-calibrating the Doppler shift, i.e. the drift in carrier frequency appear on both lines and are therefore cancelled out. The uncertainties in the Doppler shift measurement therefore lie in determining the laser wavelength and, if applied, the frequency offset of the reference line. This can easily be done with insignificant uncertainty.

Apart from the measurement, the extraction of the one radial wind velocity at the intended measurement height from the weighted wind distribution within the sample volume and the interpolation of at least three extracted radial velocities are important steps in finding the horizontal wind speed. The latter two steps, in which the largest amount of uncertainties is introduced, are shortly described in the following.

1.1 Extraction of the radial wind velocity at the intended measurement height from the weighted wind distribution within the sample volume.

From each measured wind speed distribution, one for each beam direction, the lidar wind velocity estimator tries to extract the wind speed component at the set measurement height. The value taken is typically the peak, the centroid or a value extracted from a maximum likelihood estimator.

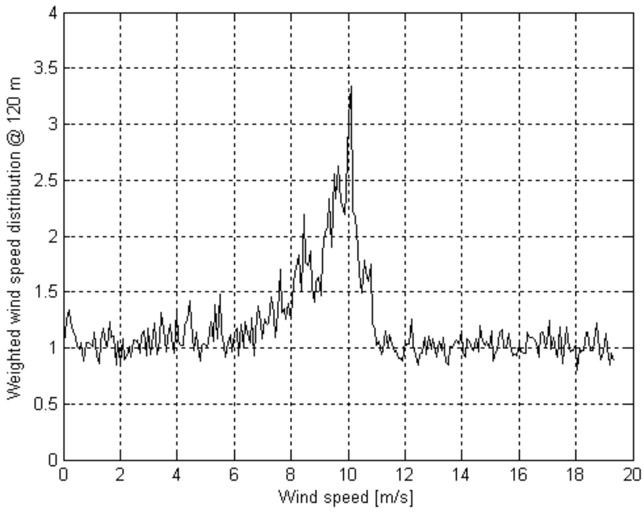


Figure 3 : The measured Doppler spectrum, here from a Zephir focused at 120 m, is noisy due to the randomness in the speckle pattern and shot noise from the detector. However, after sufficient averaging, typically over a few ms, the measured Doppler spectrum will represent the weighted wind speed distribution within the sample volume. This distribution is non-symmetric unless the wind shear and wind veer are symmetric around the measurement height. It is thus non-trivial to make an accurate estimate of the wind velocity at the set measurement height from the weighted wind distribution measurement.

The weighting function of the sample volume is difficult to model or measure with high accuracy. It also changes with sensing range. Further on, it is described under the assumption of homogeneously distributed aerosols, both in context of backscatter coefficient, correlated scatter duration and a fully developed speckle over the sample duration. The assumption that the aerosols within the sample volume are homogeneously distributed is likely to be valid for pulsed lidars which sense the 10 minute average wind in typical atmospheres. For cw systems clouds, fog etc introduces significant changes to the weighting function of the sample volume and specific considerations, which will be described later, have to be taken.

An ideal lidar should therefore not introduce biases in the extraction of the wind speed at the set measurement height. Longer sampling volumes could introduce larger standard deviations from the wind at the intended height since the assumption of homogeneously distributed aerosols is less fulfilled.

However, the significantly contributing sample volume typically stretches over about 50 m, depending on sensing distance and lidar system. It is therefore not straightforward to pick the wind speed, from the measured wind distribution which corresponds to the wind at the intended height. It is likely that estimators which try to pick the wind velocity at the set measurement height are influenced by wind veer, i.e. directional change with sensing range, or wind shear, i.e. velocity change with sensing range. These effects could easily be non-linear, different for different sampling volumes, i.e. ranges, and therefore only mitigated to a certain level. It is therefore not unlikely that they will introduce shear and veer dependent biases on the measurements.

1.2 Interpolation of the horizontal wind velocity vector at the center of the cone from the radial velocities measured at the scan perimeter.

The wind velocity (vertical wind speed, horizontal wind speed and horizontal wind direction) at the chosen measurement height is constructed by interpolating at least three radial wind speed vectors picked by the estimator. Different interpolation techniques are used mainly depending on the number of radial vectors available. For fully conically scanning lidars, like the Zephir, a sine wave is fitted to the 50 extracted radial speeds as a function of scan direction[iii], see Figure 4.

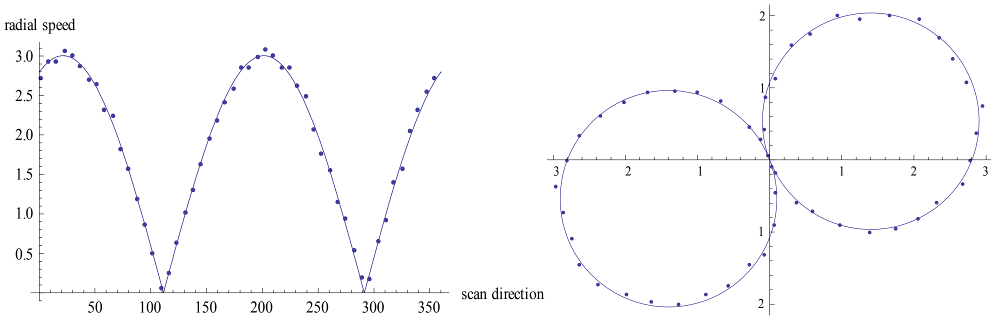


Figure 4 : Fits to the measured radial wind speeds as a function of the scan direction, represented as the sine function and as the radial "figure of eight" plot.

It is believed that the Windcube, which only measures in four directions shifted with 90° (N, E, S, W), calculates two horizontal velocity vectors, u_1 and u_2, from the two opposing sensing directions, r_1 and r_3 respectively r_2 and r_4 and combines these to find the vertical and horizontal wind speed, w and u, and the wind direction (theta).

$u1 = (r1-r3)/2\sin(30)$
$u2 = (r2-r4)/2\sin(30)$
$u = \mathrm{sqrt}((u1)^2+(u2)^2)$
$w = (r1+r3)/2\cos(30) = (r2+r4)/2\cos(30)$

Theta = arctan(u2/u1)

n.b. theta must be assigned to the correct quadrant, for example with a atan2 function.

These simple interpolation techniques are assuming that the wind velocity (vertical wind speed, horizontal wind speed and horizontal wind direction) on average will be homogeneous over the scanned volume.

In flat terrain this is a good assumption. The interpolation is therefore non-complex and an ideal lidar will not be biased. The standard deviation of the interpolated value from that measured by a cup in the center of the scanned ring will depend on the turbulence of the site and the circumference of the scan. A turbulent site and a large circumference will introduce larger standard deviations.

In complex terrain the interpolation is less straightforward and has to be supported by wind models which can describe for example veer, flow angles and speed up/down effects. If the modeling is unsuccessful the lidar could make biased interpolations. The biases will depend on the terrain and sensing height and will be different for different wind directions. In general modeling will be connected with higher uncertainties in the interpolated wind. If the complex wind flow is ignored and the simple interpolation schemes for flat terrain is used errors estimated to be up to 10 % can be expected in moderately complex terrain. However, the uncertainties of conically scanning lidars in complex terrain need more investigation.

Conically scanning lidars can to some degree sense the spatial wind variations over the scan perimeter by considering the distortion of the “figure of eight”, i.e. the residuals in the fitting of the sine wave, or the variation of the velocity sensed in opposite directions. The turbulence in flat sites or flow inhomogeneities over complex sites can be done from these values.

Currently the commercial lidar systems do not employ advanced modeling but will simply make interpolations based on homogeneous flow. The user is however provided with the extracted radial velocities which can be used for modeling.

The uncertainties in model assisted interpolation in complex terrain are not further treated in this report. This report considers the inherent uncertainties of the lidar system and the experimentally derived estimations have been done over flat terrain. Uncertainties in flow modeling are not estimated for the general case but have to be considered for the individual site.

The measurement of the radial wind velocity distribution, the extraction of the wind radial wind velocity component at the intended measurement height and the interpolation for the horizontal wind speed and direction are made with uncertainties. These uncertainties will be listed, explained and quantitatively estimated in the following sections.

2 Factors influencing the accuracy of wind sensing lidars

There are several factors which will influence the accuracy of a lidar. Some can be tied to uncertainties in the hardware, for example uncertainties in the cone angle, while others are spurred by atmospheric effects, like rain or clouds. Plausible factors have been divided into two sections according to the previous reasoning. The influence of each factor is qualitatively discussed below.

In the result sections some of these factors have been quantitatively estimated. However, many of the errors react to the same input. It is therefore not always possible from mast comparisons to breakdown the uncertainties and couple them to specific factors. Some of the lidar uncertainties are better estimated from the uncertainties in the direct measurements of the hardware, however experience have showed that in the development of the lidars it has been very valuable to have independent measurements both directly on the hardware and from cup anemometer comparisons. The total effect of the complete chain can be found from comparative studies, for example the actual cone angle after mounting of the wedge. Some work still remains to sort between significant and less significant uncertainty factors, nor is it at this point certain that the list of uncertainties is conclusive.

2.1 Uncertainties connected to errors in lidar hardware

Coherent lidars are based on heterodyne detection and their wind speed accuracy is therefore practically independent of drifting laser quantities such as power and wavelength which are extremely sensitive parameters in direct detecting lidars. Heterodyne detection is therefore many times referred to as a calibration-free technique. Furthermore is the bandwidth of the detected wind signals typically in a frequency range of 0 – 50 MHz where sampling is fairly straightforward and the accuracy much greater than the 100 kHz which corresponds to about 0.1 m/s. However, there is more to a wind sensing lidar than heterodyne detection. A list of uncertainty sources due to errors in the lidar hardware are presented in Table 1. Each of the sources are discussed in the following subsections.

Uncertainty	**Could affect**	**Implication**	**Improvements**
Sensing range error - Range gate trigger - Focusing - Range gate distortion	 - Pulsed systems - Focus system - Range gated with fixed focus	Wind shear dependent error	Methods for estimating sensing range errors from lidar-cup comparisons have been established.
Cone angle	Both systems	1 Speed proportional bias 2 Small range bias	Calibration at fabrication improved. Up to 3% removed after mast verifications
Tilted mounting	Both systems	Direction dependent errors	
Wind estimator	Both systems		Non-linear error in Windcube estimator removed.
Pulse Chirp	Pulsed system	Bias on vertical and radial velocity	
RIN	System without offset on ref	Overestimation of low wind velocities	Lasers improved and specifications tightened.

Table 1: List of uncertainties connected to the lidar hardware.

Errors in sensing range

One inherent problem with remote sensing is to accurately know the distance you are sensing at. Since the wind on average increases significantly with height an error in sensing distance will introduce a measurement bias. An average error of 5 m in the sensing height can easily introduce a bias of 0.2 m/s in typical shear conditions (average of 0.04 m/s wind speed increase per m in sensing range).

For continuous wave systems, which rely on a variable focus for changing sensing range, biased sensing range can be due to errors in the translation stage which controls the lens to source distance, or the focal length of the lens. In the current cw system the focus settings are calibrated by maximizing the return from a hard target. The accuracy of the translating stage has to be better than 5 μm for a 1 m range accuracy at 100 m sensing range.

For pulsed systems the trigger time, i.e. the time the pulse leaves the lidar, has to be known to a higher accuracy than 10 ns to get an accuracy for the range gating, i.e. sensing range, with a 1 m/s accuracy. This is not difficult to measure but it is not trivial to define since the pulse start and center of a pulse can be difficult to define, see Figure 5.

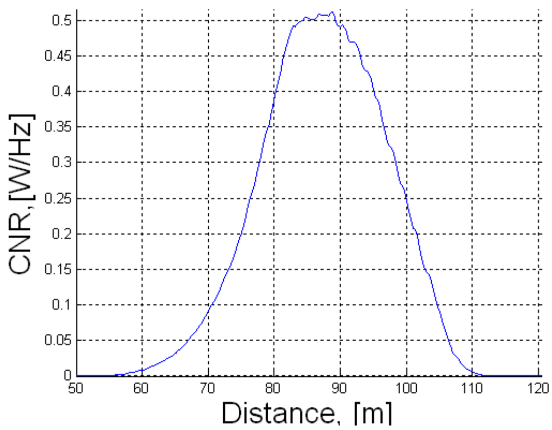


Figure 5 : The CNR obtained from different distances in the range gate. The peak is rather flat and the start and end of the pulse are ambiguous.

Pulsed systems, for example the Windcube, will typically be focused at a fixed distance at about 100 m in order to increase the CNR in the first few hundred meters in comparison with a collimated system. The telescope effects on fixed focus range gated systems, should be accounted for to avoid sensing range errors in the order of a few meters[iv].

A sensing range error will introduce errors on the estimated radial wind speed which for limited errors, e.g. < 10 m, in a first approximation are linearly proportional to the wind shear at that sensing range, see Figure 6. Since wind shear and wind speed typically are related it is important to separate errors which depend on wind speed, for example cone angles errors, and errors which depend on wind shear, for example sensing range errors, in verification tests. This can be done either by screening or, preferably, in a 2-parametric regression analysis. Limited sensing range errors can be extracted, in meters, from cup comparisons as the regression coefficient, k_s, of the lidar error, lidar-cup in m/s, as a function of wind shear, m/s wind increase per m sensing range.

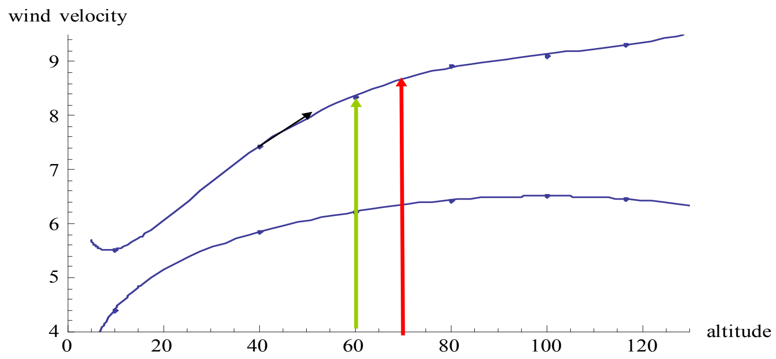


Figure 6 : The errors introduced by sensing at an erroneous height are in a first approximation linearly dependent on sensing range.

The uncertainties due to sensing range errors cannot be estimated individually in cup comparisons, since there are other factors which introduce errors which also are wind shear dependent, those are introduced later in this text. However, the combined effect of wind shear on the lidar assessment can be estimated experimentally from cup comparisons while the sensing range can with some uncertainty be calibrated for on hard target measurement.

Cone angle errors

Since a lidar only can measure the wind speed in the beam direction, i.e the radial wind speed, and from at least three measurments needs to construct the horizontal wind velocity it is important to know the cone angle with high accuracy. A likely source of uncertainty in conically scanning lidars is uncertainty in the intended cone angle, φ, see Figure 7. An error in cone angle, $\Delta\varphi$, is transferred to an error in the sensed horizontal wind speed, u_{meas}, which is linearly proportional to the wind velocity, u. The lidar error, ε_{lidar}, due to a cone angle error can be expressed as

$$\varepsilon_{lidar} = u_{meas} - u = \left(\frac{\sin(\varphi - \Delta\varphi)}{\sin(\varphi)} - 1 \right) \cdot u = k_u \cdot u \qquad (1)$$

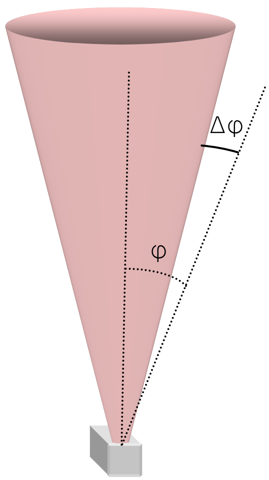


Figure 7 : Illustration of the cone angle error. The intended cone angle is shown as a dotted line, the actual cone angle is illustrated by the pink cone.

Typically lidars use a cone angle of about 30°. An error in the cone angle of a mere 0.5° will induce a k_u of -1.5%, see Figure 8. A lidar suffering uniquely from a cone angle error should have a k_u which is constant with sensing range.

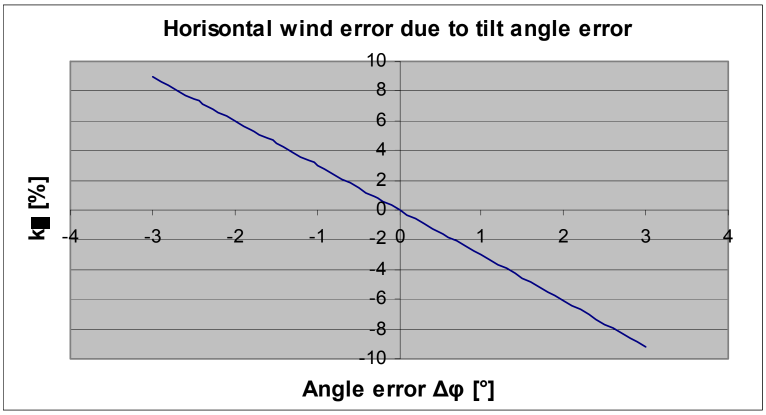


Figure 8 : The error in the horizontal wind velocity due to a cone angle error, Δφ, of a lidar with an intended cone angle of 30 °.

An error in cone angle will also introduce a small error in sensing sensing range since the lidar will measure at a sensing sensing range which corresponds to the intended height and the actual cone angle. This sensing range error, Δh, increases with sensing sensing range according to

$$\Delta h = \left(\frac{\cos(\varphi - \Delta\varphi)}{\cos(\varphi)} - 1 \right) h_i \qquad (2)$$

For typical wind shears the error in sensing range, due to the cone angle error, will to a small degree balance the wind velocity error. For example, a cone angle error of -0.5°, on an intended 30°, will induce a k_u of 1.5% but also an overestimation of the actual sensing sensing range of 0.5 m when intending to sense at 100 m. A 10 m/s wind with a wind shear increasing with 0.05 m/s per meter sensing range would thus be sensed with an effective error of 10·0.015 - 0.5·0.05 = 0.125 m/s.

As a result of the UpWind project errors in cone angles inflicting biases of up to 3% on the wind velocity has been revealed, explained and resolved. The cone angles are today carefully assessed in fabrication, in the Zephir's case by velocity measurements on a hard target and for the Windcube by internal wedge calibrations, i.e. measurements of wedge angle and refractive index. Although cone angle accuracy has been addressed by the manufacturers on several occasions the uncertainty in these direct cone angle calibrations has to be further investigated.

Tilted mounting

The mounting of a lidar is equally important as mounting of cup anemometers and wind vanes. The centerline of the cone should to the highest degree be vertical. A tilted lidar will experience significant cone angle and limited sensing range errors which are different for the different sensing directions. The errors introduced will lead to direction dependent biases both on speed and direction. If the lidar is mounted off the vertical this will be seen as an atypical wind speed dependent bias on the vertical wind velocity. A good practice is therefore to observe the vertical wind speed during mounting. The uncertainty and magnitude of the influence of the mounting accuracy has to be further investigated. To minimize these effects both commercial systems are checked with digital water passes during mounting.

Wind estimator

The frequency resolution of pulsed lidars, like the Windcube, are extremely limited, in the order of a few MHz. High level estimators has to be deployed to described the wind distribution which typically will not stretch over more than 3 m/s, corresponding to a Doppler shift range of about 4 MHz, within the sample volume. The uncertainty of such estimators has been theoretically estimated[v]. However, since the commercial system's estimator is not public it is not possible to directly estimate its uncertainties. In course of the UpWind project a severe non-linear error, dependent on wind speed and direction, in the estimator was revealed, explained and corrected. This correction seems to have approximately halved the standard deviations obtained from the cup comparisons.

Cw systems, like the Zephir, have a higher frequency resolution, in the order of a few 100 kHz. Nevertheless, a higher resolution will to a smaller degree average out effects from for example scatter with uncharacteristic correlation duration[ii].

The uncertainty in the estimator's ability to pick the velocity corresponding to the velocity in the center of the sample volume is also influenced by shear and veer effects as will be discussed in 0.0 and 0.0.

Pulse Chirp

Chirping, i.e. frequency drift of the carrier wavelength throughout a pulse, is a common problem in steep laser pulses. This effect can to some degree be calibrated for from measurements of hard targets. However, how such correction transfer to measurements in the atmosphere is not totally concluded. Calibration can also be done after deployment in flat terrain by studying the average offset on the vertical wind velocity. Care must be taken in order not to confuse the vertical wind velocity offset introduced by chirping and the wind speed and direction dependent vertical wind velocity offset introduced by tilted mounting. Chirping effects will also introduce difficulties in predicting the estimator response from different shear or veer.

Chirping will introduce an offset on the radial velocity sensed by a pulsed lidar if not accounted for. Nevertheless, the chirping effect on the estimated horizontal wind velocity should average out since the Windcubes interpolation technique is based on wind velocity vectors obtained from opposite directions.

Relative Intensity Noise

A significant source of uncertainty at low wind velocities for lidars which do not employ an offset on the reference channel, like the Zephir, is Relative Intensity Noise (RIN). RIN is pink noise and arises from fast power variations in the emitted light, see Figure 9.

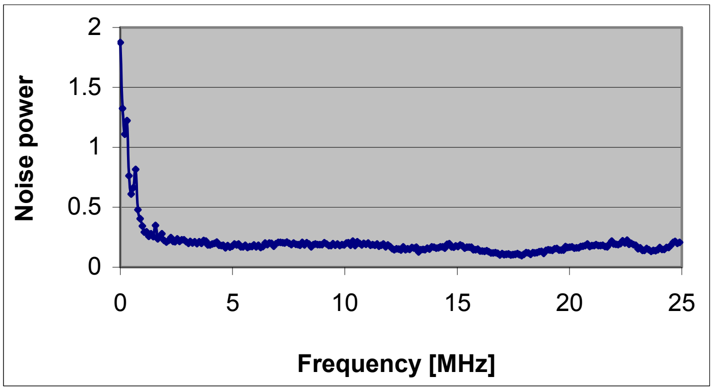


Figure 9: Noise reference measured in Zephir prototype. Note the strong RIN at low frequencies.

RIN is treated by detracting reference noise measurements and by blanking the lowest velocity bins, typically up to 0.6 m/s. However, this procedure has introduced a positive bias in the estimations of the low radial velocities. This has been mitigated by excluding the low radial velocities when interpolating the horizontal wind. In strong wind there are a higher number of points in the interpolating wind which statistically should lead to less uncertainty. This bias is typically not present on horizontal wind velocities which are stronger than 4 m/s.

However, the RIN has differed from laser to laser and in some occasions the screening criteria has not always been sufficiently high. This has introduced further uncertainties. Recently, the fiber lasers employed in the Zephirs have developed and quality restrains have increased. After these improvements we expect these problems to be insignificant.

2.2 List of uncertainties connected to atmospheric phenomena

The uncertainty in the wind sensed by a coherent lidars will also depend on the atmospheric conditions, for example to what degree the assumptions on a horizontally uniform flow and homogeneity of the aerosol distribution are fulfilled. The magnitude of the errors in the lidar hardware will also depend on for example wind speed and shear. A list of uncertainty sources due to atmospheric phenomena are presented in Table 2. Each of the sources are discussed in the following subsections.

Uncertainty	Could affect	Implication	Improvements
Turbulence over scan perimeter, flat terrain	Conically scanning systems	Standard deviation. No bias.	
Turbulence over scan perimeter, complex terrain	Conically scanning systems	Standard deviation. Direction dependent biases if interpolation unsuccessful.	
Inhomogeneous aerosol scatter distribution	Both	Standard deviation.	
Clouds	Continuous wave system	Positive bias if untreated. Lower and possibly wind speed dependent availability if clouds are screened. No biases with cloud correction. Higher standard deviation during	Improvement of cloud correction algorithm.

		clouds than in cloud free.	
Rain	Both	Standard deviation increase. Bias on w.	
Shear	Both	Non-linear errors, the bias due to sensing range errors increases with shear.	
Veer	Both	Non-linear errors with veer.	

Table 2: List of uncertainties connected to atmospheric phenomena.

Turbulence over the scan perimeter

The differences of the wind sensed over the scan perimeter is both due to spatial turbulence and that the radial measurements are taken at different times. In flat terrain the turbulence is nominally random and will only introduce a standard deviation on the measurement1. In complex terrain veer, flow angles, speed up/down effects can introduce significant biases.

The standard deviation will depend on the turbulence at the site, biases in complex terrain on the success of the interpolation.

A conically lidar can to some degree evaluate the turbulence at a flat site by studying the variability of the wind velocity sensed in different, for example opposing, directions. In most complex terrains it will, with the same approach, be able to reveal that the flow over the site is non-homogenous. More advanced flow models can be used in combination with the radial velocities to estimate three dimensional flows also in complex terrain

Inhomogeneous aerosol scatter distribution

The weighting function of the sample volume, which is used to set the sensing range, is calculated for a homogeneous aerosol distribution. This is probably unlikely in a real atmosphere especially since the number of collected photons is limited. However, in a clear atmosphere, i.e. one without clouds or fog, the atmosphere can be considered as homogeneous over ten minutes.

Clouds

Continuous wave systems will be influenced by clouds since the weighting function of the sample volume is erroneous in the presence of significantly non-homogeneous backscatter distributions[vi]. A significant part of the measured wind distribution will be taken at the cloud height and not at the intended measurement height. Positive biases on the wind horizontal wind speed are introduced in cloudy weather since clouds predominantly are above and the wind thus typically stronger at the cloud height than at the set sensing height.

Some different approaches for corrections of the cloud algorithms have been tested[vii]. These algorithms are based on making a measurement with the lidar telescope collimated. This measurement intends to give a measurement of the wind

1 The calculation of the horizontal velocity, as described on page 8, from the radial vectors which vary due to measurement uncertainty and turbulence over the scan perimeter introduces a positive bias on the horizontal wind velocity. In Høvsøre the variation in the Windcube's two opposing radial velocity is measured and it is estimated that it can be described as a Gaussian distribution which during high turbulence could have a standard deviation of 1 m/s. The bias is mostly significant at very low wind speeds. At 1-2 m/s this would introduce a bias of about 0.3 m/s, however this high turbulence is unlikely at low wind speeds and at 10 m/s the bias seems to be limited to 0.04 m/s. The exact method of how the Windcube constructs a horizontal velocity of 4 radial Windcube velocities is not publicly available.

distribution at the height with strongest backscatter, i.e. the cloud height. This distribution is then deducted from the measurement taken with the focus at intended height. Since the two measurements are taken at different times the correction will not be without uncertainty, however, it is likely that positive biases are removed. Another approach is to detect clouds with a ceilometer and screen the wind data. This screening approach could however be wind speed dependent. A more powerful cloud correction algorithm, which only applies the cloud correction in the presence of clouds, has been developed during the UpWind project.

Rain

Rain will give a strong negative bias on the vertical velocity since the lidar will dominantly measure the raindrops fall velocity. Although the raindrops horizontal velocity might not coincide with the horizontal wind velocity, since they accelerate less quickly than aerosols, the ten minute averaged interpolated horizontal velocity seems to be insignificantly biased in flat terrain. However, raindrops increase the randomness of the origin of scatter and increasing standard deviations in the measurement error has been observed rain.

Shear

Since a wind sensing lidar has a substantial sample volume the measured radial wind speed distribution is different for different wind shear conditions although the wind speed at the measurement height is the same. A simple estimator, e.g. a peak finder, will thus return a different radial wind velocity for different shear conditions even if the wind velocity at the set measurement height is the same, for example as in Figure 10.

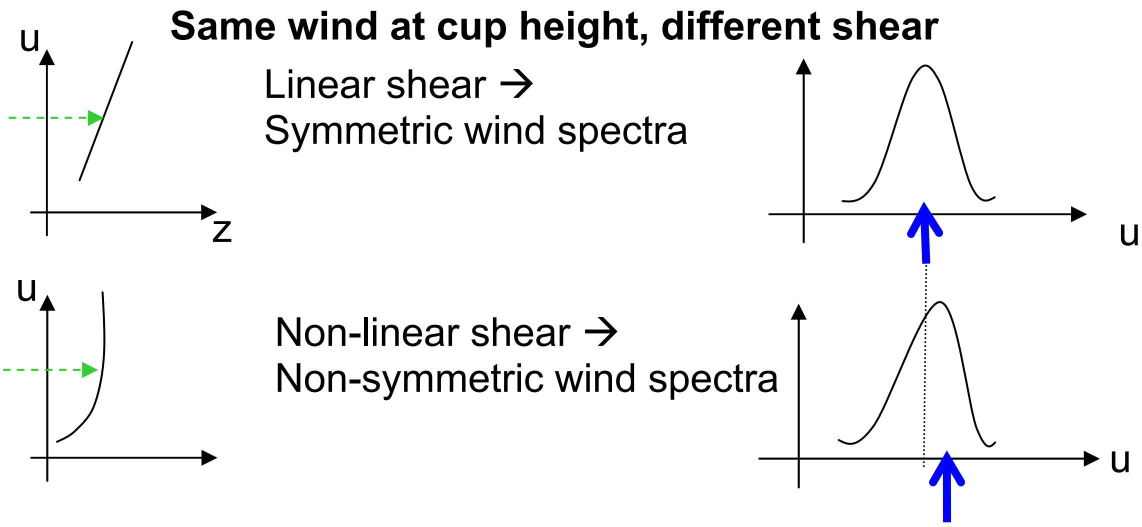


Figure 10 : Linear shear gives a symmetric radial wind velocity spectrum if the sample volume is symmetric. Non-linear shear, which is more typical, gives rise to slightly skewed radial velocity spectra. An estimator will typically return a different win velocity at the set measurement height for different shear conditions Even though the wind velocity at the set measurement height is the same.

Wind sensing lidars typically employ more advanced estimators which to some degree try to balance the wind shear dependency. However, the estimation of the radial velocity is still prone to be slightly affected by shear effects and the errors introduced can easily be non-linear towards wind shear.

Since shear typically decreases with sensing range it is likely that the wind spectra will be shifted to a higher wind velocity and that estimators are likely to overestimate the velocity at the set measurement height. The errors made by the estimator will depend on the weighting function of the sample volume and will thus be different at different sensing ranges. In the case of focused systems the increase of sample volume with height will to some degree probably be balanced by a smaller wind gradient.

In difference to limited sensing range errors which typically will be linear with wind shear. Furthermore are sensing range errors not depending on the relation between beam and wind direction. Experimentally it will be extremely difficult to separate the influence of these two effects.

Veer

The measured radial wind velocity distribution depends on the wind veer, directional change with sensing range, over the sample volume in a similar manor as for shear. The estimator might therefore make the same kind of errors in strong veer. The magnitude of these errors could in a first approximation be of slightly smaller magnitude since typical wind shear over 50 m could be 2.5 m/s while strong wind veer over 50 m could be 30 degrees, inducing a radial velocity spread of about 1.5 m/s at 10 m/s winds.

2.3 General considerations on uncertainty

Uncertainty with increased height

As a general rule the CNR will decrease as the sensing range increases. At the same time the interpolation will be more uncertain. For a continuous wave variable focus system the weighting function of the sample volume will flatten out with height and the sensitivity for inhomogeneous aerosol distributions, like clouds, will increase. All of these factors talk for higher uncertainty at higher heights.

On the other hand turbulence, shear and veer will typically decrease with altitude, the uncertainties connected to these phenomena will therefore decrease.

In comparisons with mast mounted cup anemometers there is a higher uncertainty in the cup anemometry for cups mounted on booms at the lower heights.

Uncertainty with increased wind speed

The uncertainty connected to the uncertainty in cone angle is linearly dependent on the wind velocity. Turbulence is typically independent of wind speed. Shear typically increases with wind velocity while veer decreases. While estimator errors can be relatively big at low wind speeds it is not unlikely that the uncertainties in total will grow with wind velocity.

3 Uncertainties in comparisons with mast mounted cup anemometers

There are several uncertainties related to the cups and masts when lidar precision is assessed in mast comparisons. The uncertainties in the lidar measurement are bigger than the uncertainties in cup anemometry but the accuracy of lidars has now reached a stage where cup uncertainties cannot be excluded. It is also important to consider the effects of the mast on the lidar in comparisons.

It is sometimes suggested that the volume measurement made by a lidar better represents the wind flow in terms which are more suited for wind energy applications than the, in comparison point measurements, made by a cup anemometer. However, for site evaluations it can be difficult to interpret the radial wind distributions into available wind energy within the sample volume without extraction and interpolation of radial velocity components.

It is possible that lidars in other applications, for example staring lidars mounted in the nacelle of a turbine, will make a measurement which is more useful than that obtained by a cup anemometer.

3.1 Distance between lidar and mast

A first issue in lidar-cup comparisons is the closeness of the mast and the lidar. Lidars do not have secondary beams and will therefore not, as opposed to sodars, capture echoes from targets outside the pointing direction. It is therefore possible, and often best, to place the lidar in direct closeness to the mast. The comparisons of the cup and the interpolated value obtained from the radial wind speeds collected over the scan perimeter will then in flat terrain have minimal standard deviation.

The standard deviation in the comparison of a cup and a lidar will depend on the turbulence over the scan perimeter during the test. Tests performed in sites with higher turbulence will result in higher standard deviations in the comparison.

For imperfect lidars the standard deviation in the error will also depend on the spread of the influencing factor, for example a lidar with a cone angle error will give a larger standard deviation if the spread of wind velocities are large. Likewise for a lidar with a sensing range error which is evaluated during a period with a large spread in wind shear. In the same way will mean errors depend on the wind conditions during the test, for example cone angle errors will give higher mean errors in strong winds.

3.2 Influence of the mast on the lidar

One advantage with lidar anemometry is that they can sense the wind profile, i.e. velocity and direction at several heights, without being shaded by a mast. The wake effect on a cup anemometer from a lattice mast can take away 20-30% of the wind velocity. However, when the lidar is placed in the vicinity of a mast for comparisons with cups it is important to determine, and screen, the wind directions for which the mast wake passes through the lidar sample volume, particularly at low heights and lidars in direct vicinity of the mast when the sample volume is closest to the mast.

It is typically only the mast wake that has to be considered. Other flow distortions, in the order of a few percent, around the mast are expected to have recovered after 10 m. Wake effects of up to 10 % can be observed with lidars at distances of 25 m behind a lattice mast with a base side of 7 m, see Figure 11. A good practice in lidar-cup comparisons is therefore to screen out the wind-directions which give rise to a tower wake within the sample volume. The sensitive directions will alter slightly with sensing height, at 60 m height the geometry of the test setup gives sensitive directions at 60, 120, 200 and 340°, which confers with the observations.

The Windcube, which senses radial wind velocities in four directions, will experience mast wakes in four small wind sectors. These directions will be slightly shifted for different sensing heights.

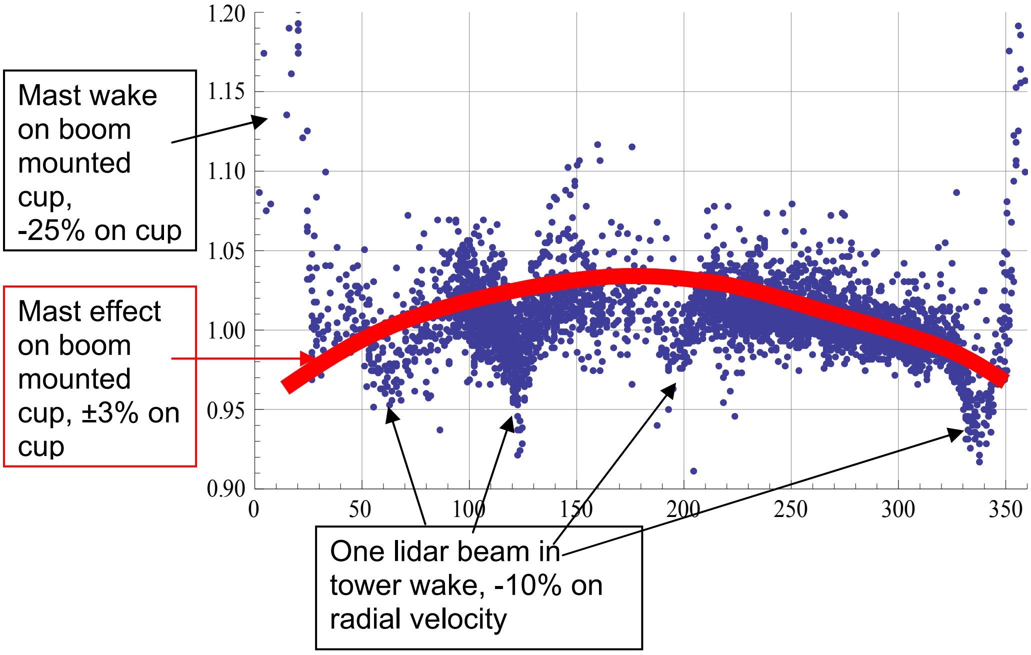
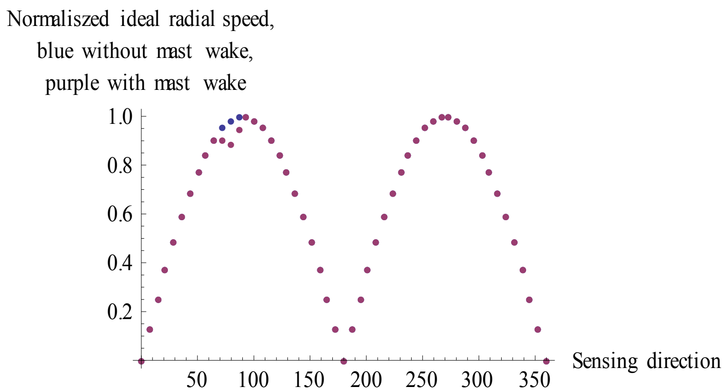


Figure 11 : The mast wake effects on a Windcube set to measure at 60 m can roughly be estimated to reach 10 % from this diagram which plots the lidar/cup ratio. The distance between center of the sample volume and the mast is about 25 m.

The Zephir which senses in 50 directions has the peculiarity that it will, for any wind direction, experience a mast wake close to the direction where it senses the maximum down wind. The wake might affect a few measurement points around the down wind peak where the fit sensitivity is greatest. Although only a few points are affected this could give rise to a 1 % underestimation of wind speed in the comparison, see Figure 12.



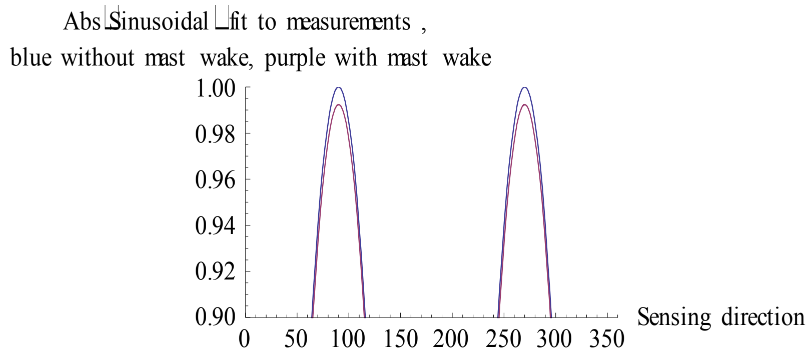


Figure 12 : Theoretically estimation of mast wake effects on a Zephir. In this model it is estimated that the Zephir measures 10% loss in a direction close to the max down wind and 5% in the two neighboring directions due to the mast wake. This affects the fit considerably, and the lidar-cup comparison would show on a 0.8% underestimation in wind speed.

3.3 Uncertainties and errors in the cup measurement

Cup anemometry is a relatively mature technology. Uncertainties and errors have been rigorously examined and standardized calibration methods and model classifications are available. In this report we have followed the guidelines in Appendix E.5.3 of the IEC 61400-12-1 standard for power performance measurements[viii].

Uncertainty in anemometer calibration.

The cup anemometer is sufficiently small to be calibrated in wind tunnels where the wind flows are well described. Each cup is calibrated with a gain and an offset constant. In spite of the accuracy of the calibrations the standard uncertainty of the anemometer calibration is usually estimated to 0.1 m/s, see for example Figure 13.

Uncertainty due to flow distortions caused by mounting effects

In wind energy it is best practice to use top mounted anemometers since they suffer insignificantly from mast wakes. However, in many cases the wind at lower levels is also interesting and in those cases cups are mounted on shafts, with a length exceeding 15 boom diameters, on booms (5 times the tower diameter).

Typically, the lidar is evaluated at several sensing heights. It is therefore also compared to boom mounted anemometers. Cups mounted on booms feel flow distortions due to the mast and boom. Most significant (typically about 20-30% for a lattice tower) is the effect of tower wake, i.e. when the wind passes through the mast before it hits the cup anemometer. However, the mast has a non-negligible effect on boom mounted cups even when the wind approaches the tower, see reference viii for a theoretical estimation and Figure 14 for the mast effects extracted from measurements at 80 m height on the metrology mast in Høvsøre.

Mast effects on boom mounted cups can be extracted from the measured ratio of two cups mounted on booms in different directions, see Figure 13. The boom effect on each cup is modeled as phase shifted sinusoidals. The mast effect extracted from the cup ratio measurement on the mast in Høvsøre can be seen in Figure 14.

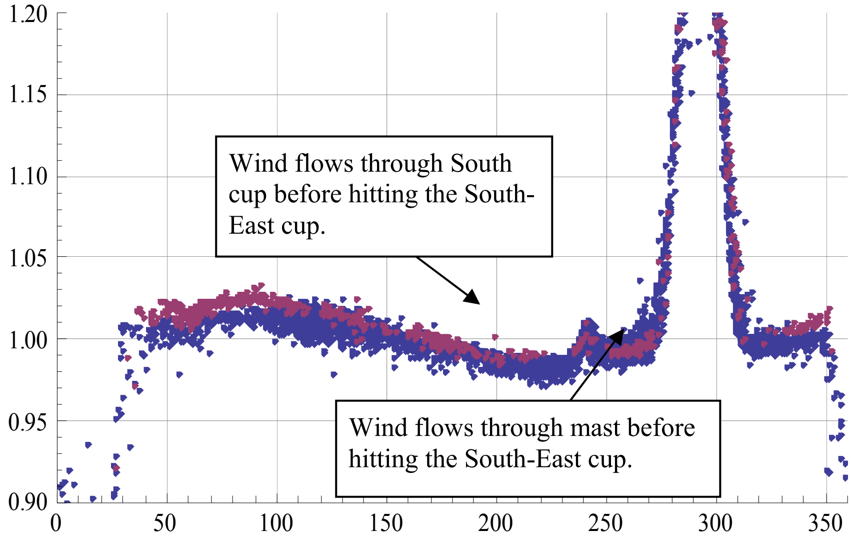


Figure 13: 10 minute average horizontal wind velocity ratios of South Cup and a South-East Cup as a function of wind direction. The cups are mounted at 80 m on a lattice tower according to the standard for power curve measurements. Note the large tower wakes and the sinusoidal behavior of the errors do to flow distortion around the mast. The different colors show the ratios for two different South cups compared to the same South-East cup. This comparison supports the typical assumption that the cup calibration uncertainty can reach 0.1 m/s.

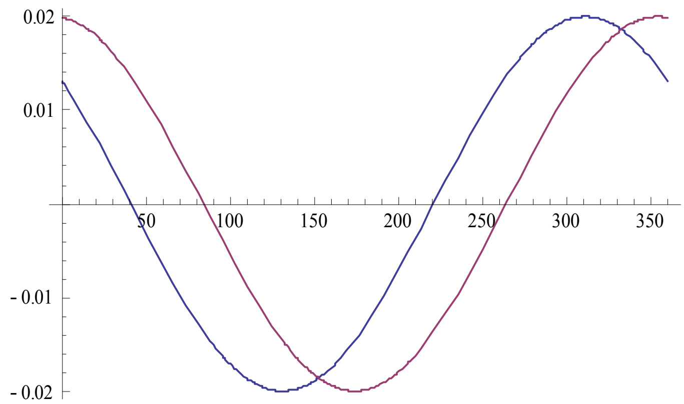


Figure 14 : Extracted cup error due to boom effects as a function of wind direction for the South pointing (red) and South east pointing (blue) cups mounted on booms at 80 m on the metrology lattice tower in Høvsøre.

The best practice in lidar comparisons with boom mounted cup anemometers is to try and correct for the effect of the mast. A good practice is to only include values which are in a narrow symmetrical sector around the direction in which the cup is unaffected by the mast. This direction can be difficult to find, but the errors involved in using a narrow sector, e.g. ± 20° around the wind direction which is perpendicular to the boom direction will be very small, e.g. <0.5%.

The standard uncertainty due to mounting effects on a top mounted cup is often estimated as 1 % of the wind speed. On boom mounted cups the uncertainty can reach 3% but can be mitigated by calibration to about 1.5%. It is not unlikely that boom mounted cups in addition to the sinusoidal behavior also have a small negative bias, in comparisons with top mounted cups, this offset has been estimated to be smaller than 1%.

Uncertainty due to operational characteristics

Cup anemometers are very reliable instruments for wind measurements however they are not flawless. Due to the inertia and friction it will experience acceleration and deceleration effects which make them measure less accurately in very turbulent flow. However at wind velocities over 4 m/s these effects are typically small. A cup will neither respond correctly to off horizontal flows and a third uncertainty is degradtion.

The uncertainty due to operational characteristics is estimated for different classes of anemometers, the uncertainty of a top mounted Risø cup anemometers[ix], class 1, used in these intercomparisons is 0.16 m/s.

Uncertainty in the data acquisition system

A usual estimate of the typical standard uncertainty in the data acquisition system is 0.03 m/s.

Total cup uncertainty of the cup anemometers used for lidar testing in Høvsøre

The uncertainties listed above are all considered to be independent and the total cup uncertainty is given as the square root of the sum of the squared individual uncertainties.

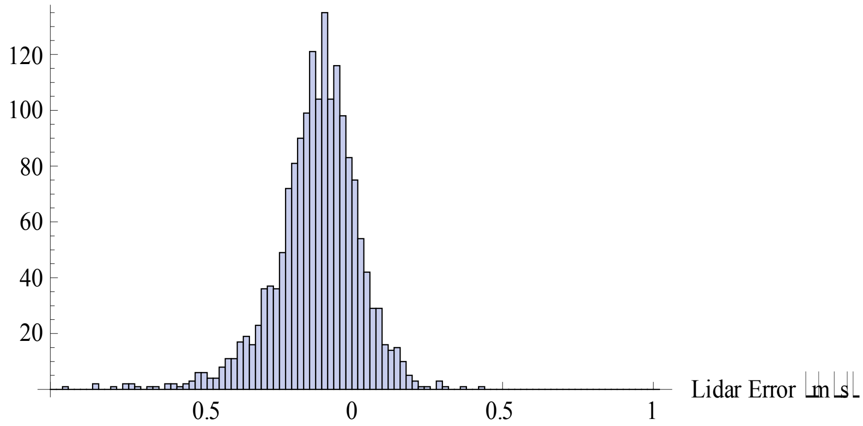
In the test facility in Høvsøre which use well calibrated class 1A anemometers which are replaced every 6 months. The total uncertainty of a top mounted cup is estimated to

$$Cup\_uncert = \sqrt{(0.1)^2 + (0.03 + 0.003 \cdot u)^2 + (0.01 \cdot u)^2 + (0.03)^2} =$$

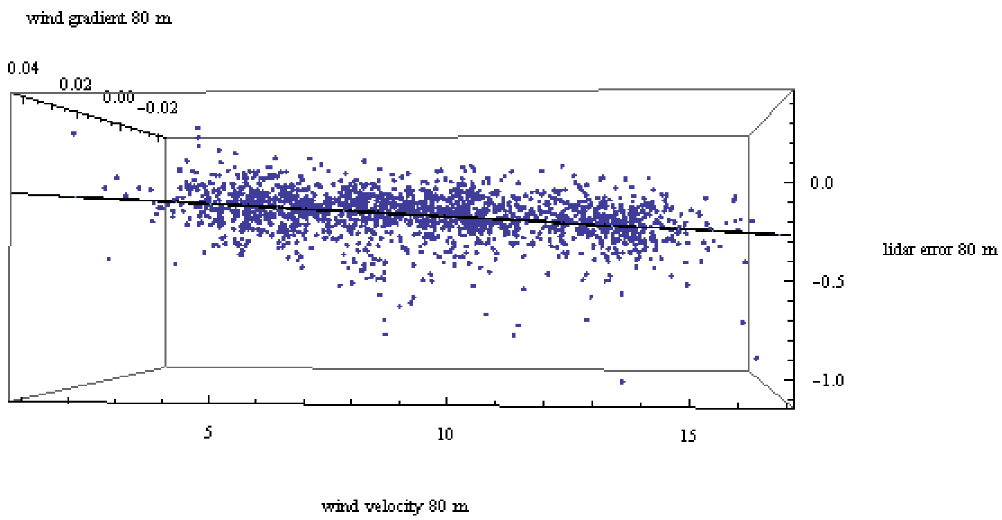
$$\sqrt{0.0118 + 0.00018u + 0.000109u^2}\, m/s$$

Which for example at 10 m/s wind gives an uncertainty of 0.16 m/s, which can be compared to about 0.2 m/s for a corrected boom mounted cup.

Some of the uncertainty in the lidar verification due to the uncertainty of the cups can be estimated by studying the lidar – cup values for two different cups at the same height and in the same period, see Figure 15 and Figure 16. The cups are boom mounted, boom effects have been corrected for. The wind sectors are chosen such as tower wakes in the lidar beam do not interfere with the measurement. Note that the South-East reference cup is placed in a direction where the predominant winds will pass through the tower before they hit the cup, the data set is therefore considerably smaller for the South East cup comparison. The uncertainty due to operational characteristics does not shine through in this comparison.

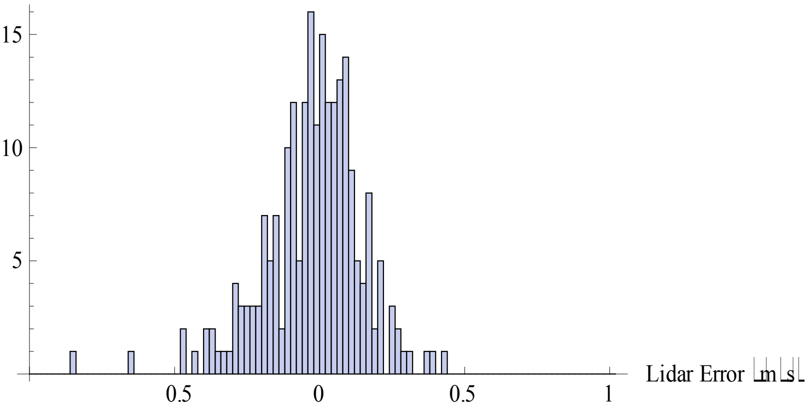



```
Mean: -0.12 m/s
Standard deviation: 0.14 m/s
```

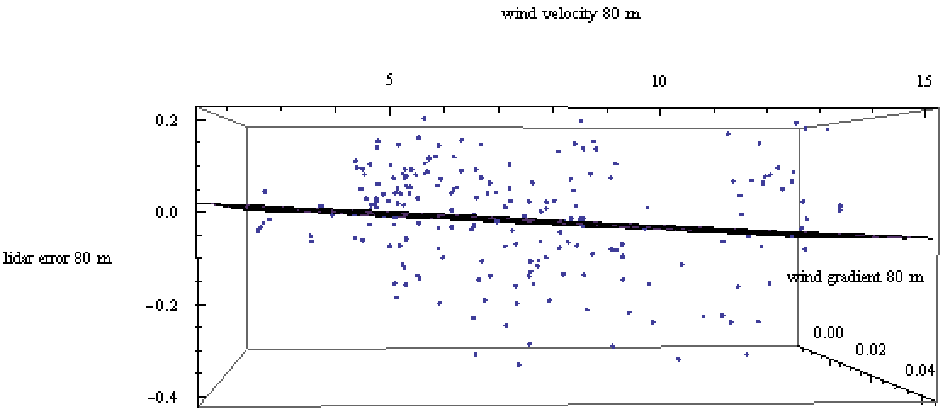


Parameter	Estimate	90%-confidence interval
Offset [m/s]	0.003	[-0.01..0.02]
Wind shear dependence, k_s [m/s per m]	-1.1	[-2.3..0.1]
Wind velocity dependence, k_u [%]	-1.3	[-1.5 ..-1.1]

Figure 15 : Histogram and two parametric regression analysis on wind shear and speed of WC2 - South cup at 80m. Wind sector 140-200° and 230-300°. The boom mounted cup is corrected for flow distortions around the tower according to Figure 14.




```
Mean: -0.03 m/s
Standard deviation: 0.21 m/s
```



Parameter	Estimate	90%-confidence interval
Offset [m/s]	0.004	[-0.07..0.08]
Wind shear dependence, k_s [m/s per m]	0.6	[-2.4..3.6]
Wind velocity dependence, k_u [%]	-0.6	[-1.5 ..0.4]

Figure 16: Histogram and two parametric regression analysis on wind shear and speed of WC2 – Southeast cup at 80 m. Wind sector 140-200°. The boom mounted cup is corrected for flow distortions around the tower according to Figure 14 .

The difference in mean error, -0.12 and -0.03 m/s, lies within the cup uncertainty of 0.11-0.2 m/s for the wind speed range 0 to 15 m/s. The estimate of the `Wind velocity dependence` k_u, of -0.6% and -1.3%, lies within the calibration uncertainty for the wind range in the data set. The data set for the South East cup includes relatively more wind from land 140-180° where the turbulence is stronger and shear has a wider range, this could be reflected in slightly the higher standard deviation in the comparison with the South East cup.

4 Test description

Lidars have been tested at the Test Station for Large Wind Turbines at Høvsøre in western Jutland, Denmark since 2005. So far 20 lidars, 11 Zephirs and 9 Windcubes, have been tested and a total of 50 months of comparative data have been collected.

Due to the relatively simple homogeneous flow, high sensor maintenance level and the well documented wind conditions with a large range of wind speeds and shears, the Høvsøre test station is an almost ideal site for evaluation and comparison of different remote sensing techniques and models. However, the presence of the turbines to the north of the meteorological mast precludes testing with wind from the northerly sectors, 330-360° and 0-30°. Winds from this sector are relatively uncommon, less than 10% yearly.

Lidar anemometry has developed considerably during these years. Cloud correction algorithms have been tuned, estimators improved and hardware precision increased. The reliability and quality control has also gone through much needed progress.

4.1 Test site

The test site is located in very flat terrain, with no major obstacles, but with somewhat inhomogeneous roughness, see Figure 17 and Figure 18. To the south is the lagoon ‘Nissum Bredning’, at the closest point, only 900 m from the meteorological mast and 1.8 km to the west, the North Sea, separated from the land by a strip of sand dunes 10-20 m high. The most homogeneous fetch is from the east – mostly open farmland.

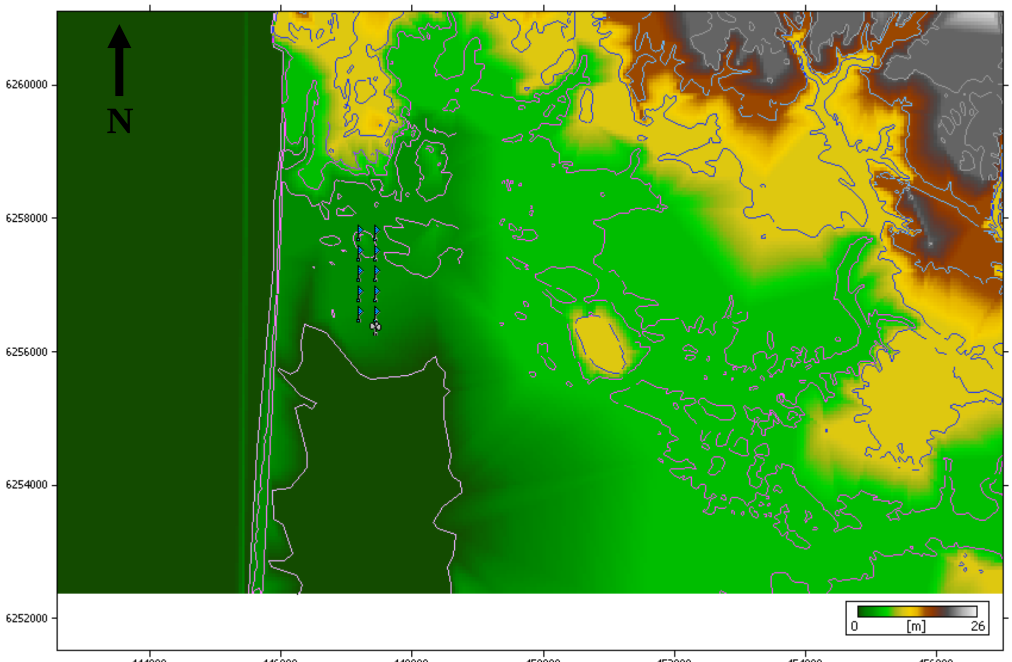


Figure 17 : Elevation map at the Test Station. The distance from the met mast to the coast to the west is 1.8 km. The row of turbines and towers are marked with blue flags.

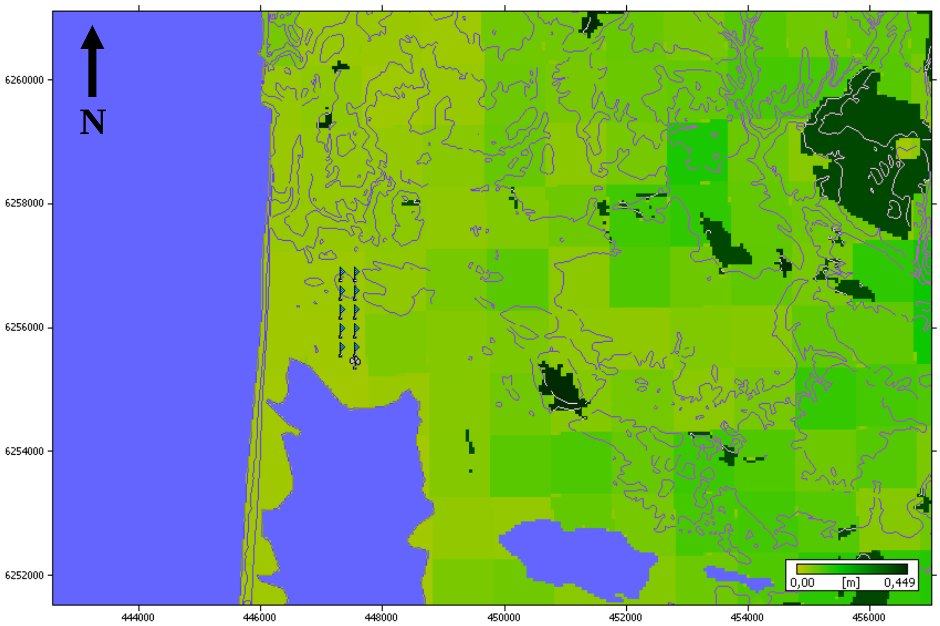


Figure 18 : Roughness map at the Høvsøre Test Station.

The facility comprises a line of five test stands for MW class wind turbines. The turbines are aligned in a north–south direction, parallel to the coastline, and are separated by 300 m from each other. At the southern end of the line, 200m from the closest wind turbine, there is an intensively instrumented 116 m meteorological mast, Figure 19. In addition, each stand has a dedicated measuring mast located 240 m to the west of each turbine. These masts are ranging from 80 to 107 m height.

Since there is no problem with backscatter from the mast structure (unlike fixed-echo problems when testing sodars), it is possible and indeed advantageous to place the lidars under test close to the reference mast. Lidars under test are placed along the road next to the 116 m metrology mast as shown in Figure 19. The distance from tested lidars to the centre of the tower is 15 m. Turbine wakes from the north of the meteorological mast precludes testing with wind from the northerly sectors, 330-360° and 0-30°.

Figure 19 : The row of wind turbines at Høvsøre with the 116.5 m meteorological tower in the foreground. Lidars under test are placed along the road next to the metrology tower as indicated by red circles. The picture is taken from a low flying aircraft to the south-west of the mast. The five westerly masts dedicated for turbine studies cannot be seen in this picture.

Two technicians are permanently stationed at Høvsøre in order to service the copious instrumentation and to assist with other research and development activities. There is excellent infrastructure including network over the entire site, offices, a workshop and meeting rooms.

Wind conditions in Høvsøre

The wind is predominantly westerly in Høvsøre (see Figure 20). The wind velocities have a good spread which is important for lidar testing (see Figure 21). The wind rose and Weibull fits have been generated in the WaSP program Wind Climate Analyst from measurements of speed and direction at 100 m at the metrology tower in Høvsøre from December 2005 to December 2008. The boom mounted cup anemometer was corrected for mast effects. Note that the northerly winds from 0-30° and 330-360° are significantly underestimated due to tower and turbine wakes.

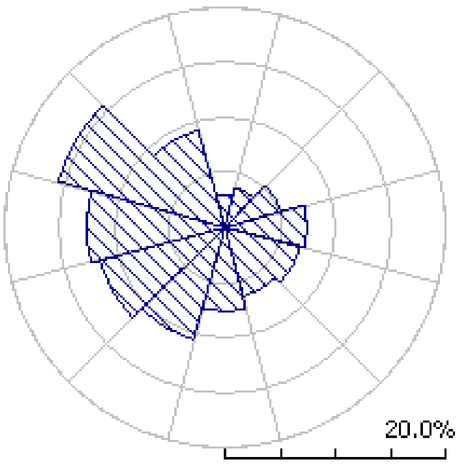
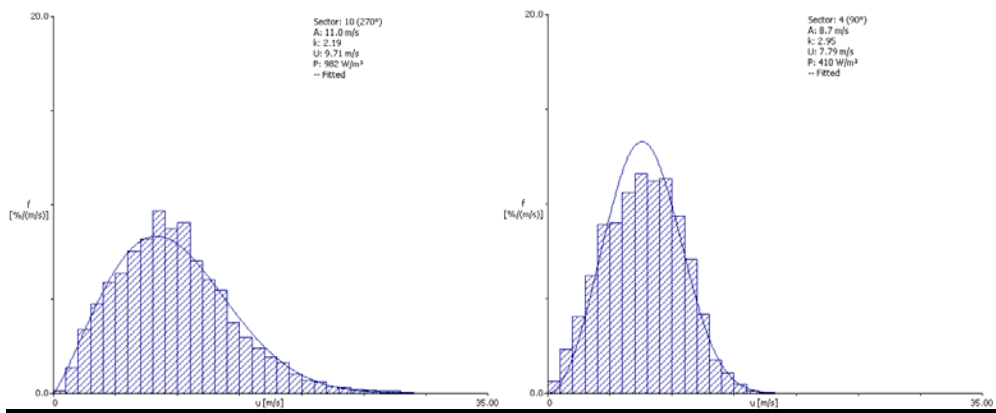


Figure 20 : Wind rose from measurements at 100 m in Høvsøre from December 2005 to December 2008. The northerly winds from 0-30° and 330-360° are significantly underestimated due to tower and turbine wakes.



	0	*30*	*60*	*90*	*120*	*150*	*180*	*210*	*240*	*270*	*300*	*330*	*All*
A	5.0	8.0	8.0	8.8	8.8	8.8	11.0	12.1	12.3	11.3	11.7	11.4	10.5
k	1.47	2.09	2.57	3.00	2.90	2.99	2.18	2.61	2.63	2.16	2.12	2.00	2.07
U	4.48	7.05	7.11	7.90	7.88	7.87	9.76	10.73	10.93	10.04	10.35	10.13	9.29
E	155	394	340	423	429	421	1002	1160	1218	1097	1225	1215	907
f	3.0	3.7	5.2	7.5	7.1	6.4	7.6	10.6	11.8	12.4	15.6	9.1	100

Figure 21 : Wind velocity histogram and fitted Weibull distributions, 255 to 285° westerly to the left, and 75 to 105° easterly to the right, from measurements at 100 m in Høvsøre from December 2005 to December 2008. The northerly winds from 0-30 and 330-360° are significantly underestimated due to tower and turbine wakes.

The westerly winds coming in over the North Sea are fairly non-complex with low shear and little veer, especially during summer, while easterly winds typically have a large spread in shear, Figure 22, and can have strong veer, Figure 23. Note the strong correlation between shear and wind speed and the inverse correlation between veer and speed.

The wind shear, given as m/s wind velocity increase per meter height, has been calculated as the derivative of a wind profile fitted to the cup measurements at 10, 40, 60, 80, 100 and 116 m.

The wind veer is given as the wind direction at 100 m – the wind direction at 60 m. The 3° offset is most likely due to, and lies within the uncertainty, an offset in set north of the two wind vanes.

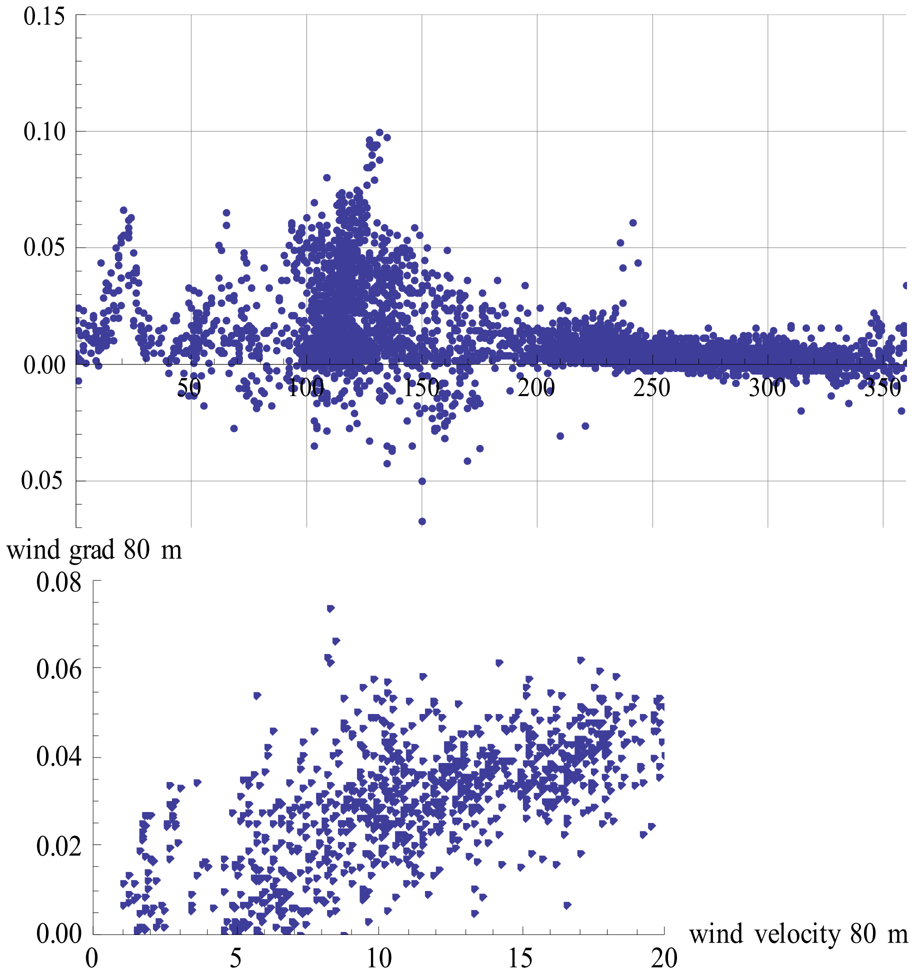


Figure 22: Summertime wind sheard in m/s per m height at 100 m as a function of wind direction, only for velocities above 4 m/s, top, and as a function of wind speed at 80 m when the wind comes in over land, bottom. Measurements are taken at metrology mast in Høvsøre.

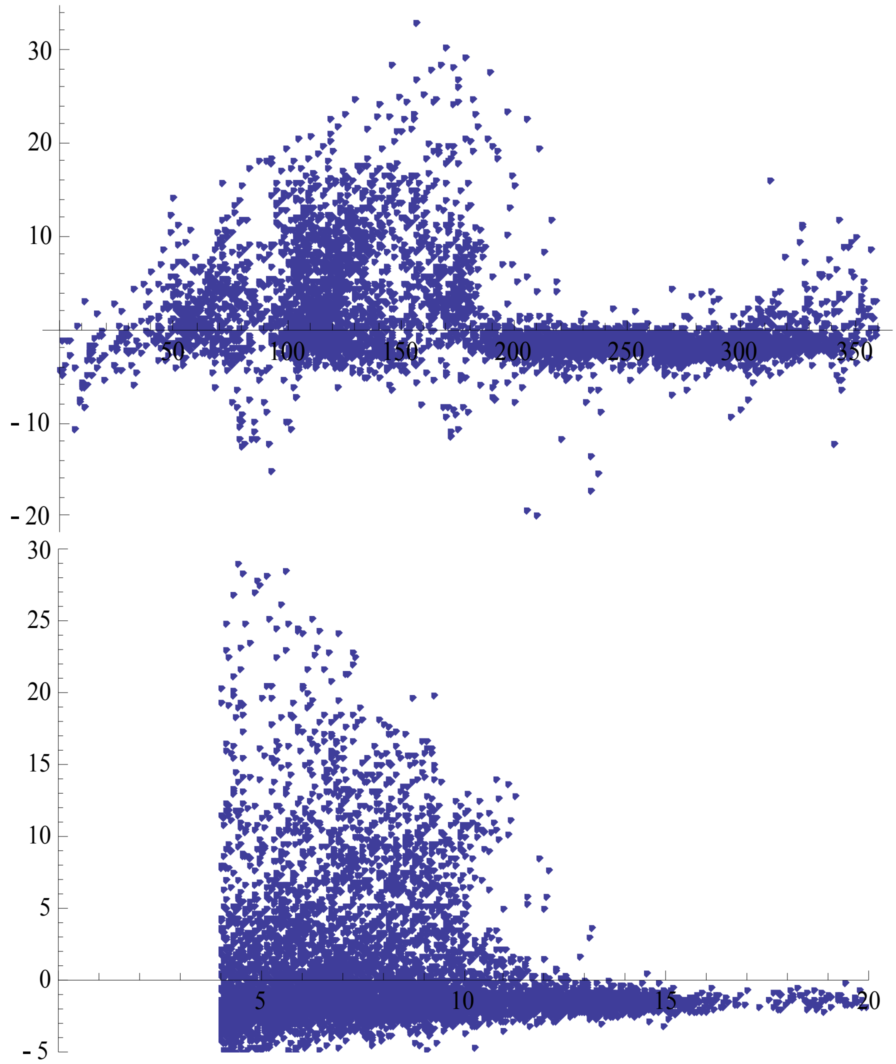


Figure 23 : Summertime wind veer, i.e wind direction at 100 m – wind direction at 60 m as a function of wind velocity and direction, only for velocities above 4 m/s. Note that there seems to be an offset of about 3° between the two wind vanes. Measurements are taken at the metrology mast in Høvsøre.

Turbulence in Høvsøre

The turbulence at the site is limited. For lidar comparison it is not the temporal turbulence i.e the standard deviation of the wind during ten minutes which is most important but the spatial turbulence, i.e. the ten minute averaged flow inhomogenity over the scan perimeter.

A qualitative measurement of the ten minute flow inhomogenity can be found by studying the wind difference of two closely spaced equally high masts, in this case two 80 m high reference masts. The two reference masts are placed 300 m away from each other and about 300 respectively 600 m away from the metrology tower. Since the cups are influenced by turbines wakes from the east the inhomogenity from interesting easterly sector where wind comes in over land cannot be done. The data was collected from the two top mounted cups during September to November 2008, see Figure 24 for speed differences and Figure 25 for difference in direction.

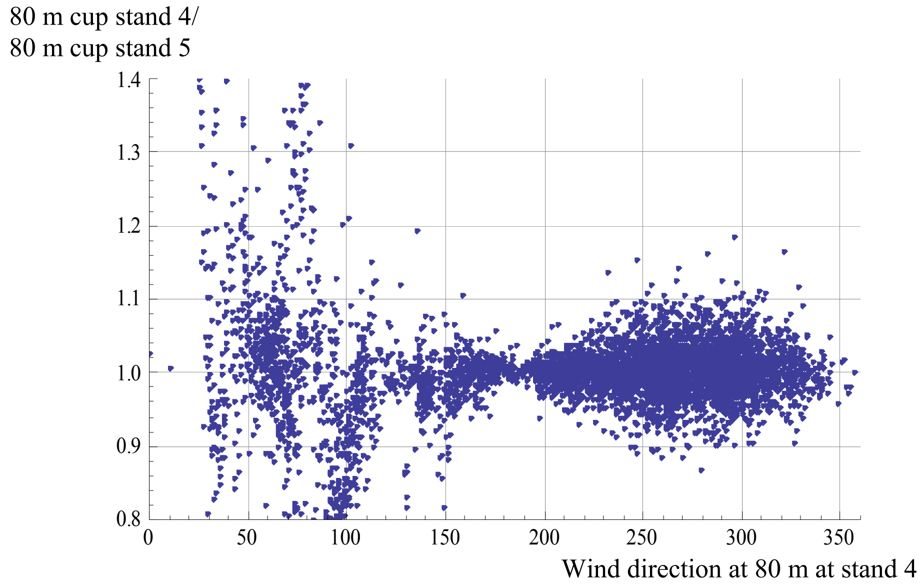


Figure 24 : Ratio between the two top mounted cups at the 80 m reference masts at stand 4 and 5, separated with 300 m. Note that the wind from the easterly sector includes wakes from the turbines and will not give a true picture of the inhomogenity of the wind which flows around the metrology tower.

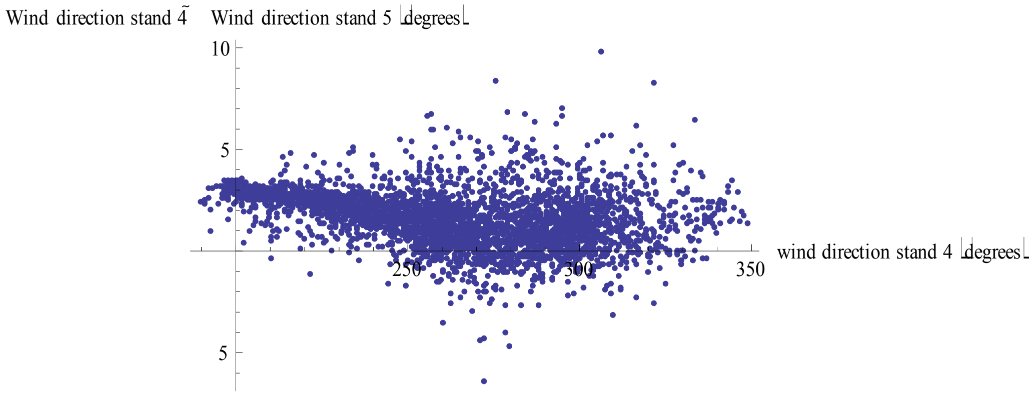


Figure 25 : Difference between the wind vanes at the 80 m reference masts at stand 4 and 5, separated with 300 m.

The difference in the ten minute average wind speed from sector 190-350° measured with the two cups has a standard deviation of 0.35 m/s and a negligible mean error of 0.03 m/s, see Figure 26. The mean difference cannot be excluded to arise from differences in the cup calibrations but the spread between the two cups should not exceed 0.1 m/s. The difference in wind direction has a mean error of 1.3°, within the typical accuracy of 3°, and a spread of 1.6°, see Figure 27. The data set has been screened so that only wind velocities higher than 4 m/s are included to avoid over spinning of the cups.

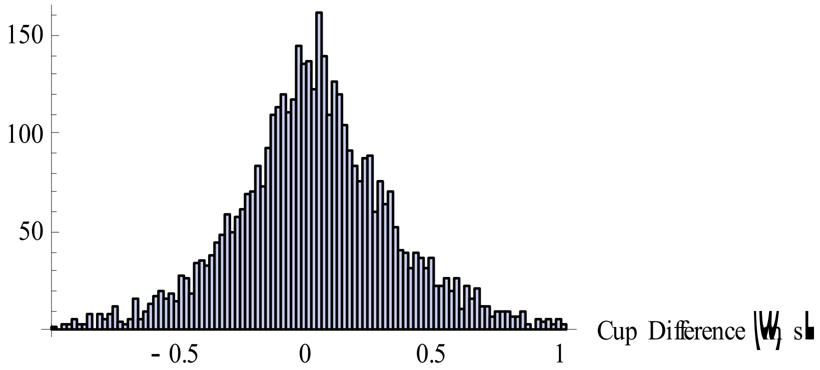


Figure 26 : Histogram over difference in ten minute average wind velocity at stand 4 and stand 5 in Høvsøre. The two masts are separated with 300 m.

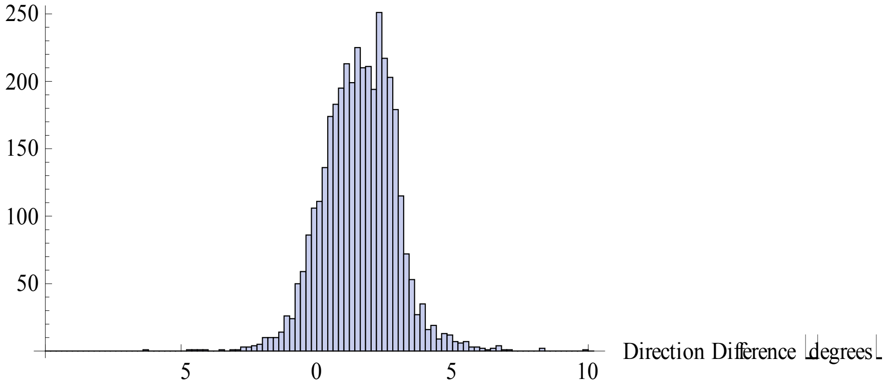


Figure 27 : Histogram over difference in ten minute average wind direction at stand 4 and stand 5 in Høvsøre. The two masts are separated with 300 m.

4.2 The metrological mast, the cup anemometers and other sensors

Due to its height, intensity of instrumentation and high data quality, most lidar testing is made with the metrology mast as reference. The original purpose of this mast is to supplement the wind measurements at the turbine test stands, to provide additional information about the climatology at Høvsøre and as a source of meteorological data for boundary layer research.

The mast has a top-mounted anemometer at 116.5 m and boom mounted cups and 3D ultrasonic anemometers at 100 m, 80 m, 60 m and 40 m. The boom mounted instrument faces directly south. There is a redundant reference cup at 114 m and at 80 m a cup has been installed in a south-easterly direction as a supplement and for deduction of the mast effects on boom mounted sensors. All cup anemometers, class 1 Risø P2546[x], are regularly exchanged for re-calibrated units and a rigorous QC is implemented. In addition wind speed measurements at 160m height (both cup and ultrasonic anemometers) are available from a light beacon mast, some 300m north of the meteorological mast.

The metrology mast is furthermore equipped with wind vanes at 60 and 100 m height and a range of other sensors measure temperature, pressure and rainfall, see Figure 28 for a blue-print of the instrumentation. Next to the met mast tower is a ceilometer which can sense the cloud base height.

All sensors are mounted according to the high demands set by the IEC standard for power curve measurements.

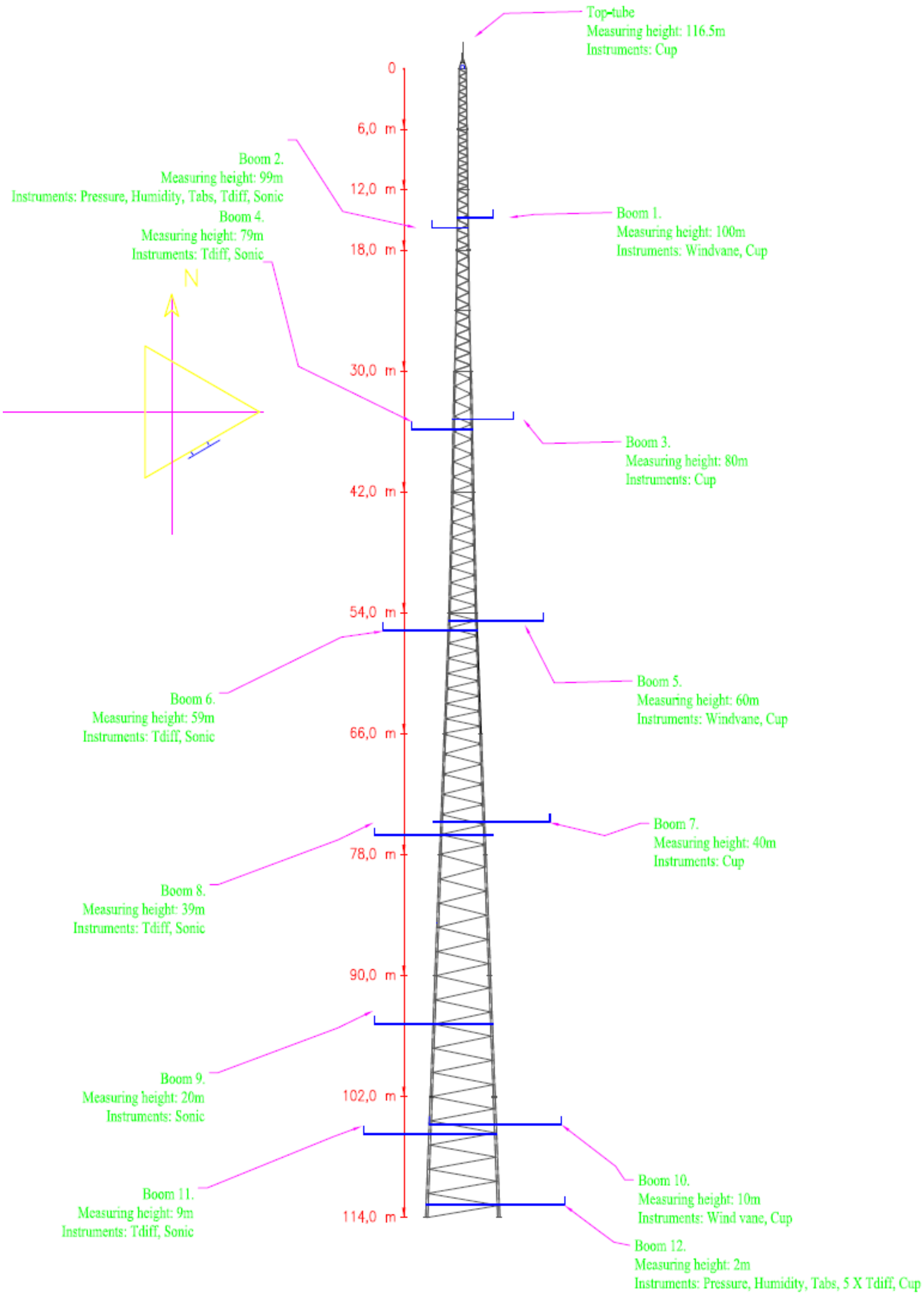


Figure 28: Instrumentation of the 116.5 m metrology mast in Høvsøre. The tower has since tha drawing was made also been equipped with a boom mounted reference cup anemometer at 114 m and a supplementary cup anemometer at 80 m pointing in the south east direction.

4.3 Tested systems

11 Zephirs and 9 Windcubes have been tested at Høvsøre. Since the two tested systems differ significantly in weighting of sample volume, acquisition rate,

interpolation techniques, coherent sampling duration etc the magnitude of the influencing factors will be quite different. The two tested systems are shortly introduced below. A detailed description is available[xi].

Windcube lidar

The Windcube is a pulsed system with a nominal pulse width of 200 ns. It has a fixed focus at about 100 m height to increase the CNR from ranges below 500 m. Thus it is expected to have highest accuracy at this height. It senses the radial wind velocity in four directions and makes independent wind measurement at all set heights every 6 s. It uses a cone angle of about 30°.

Zephir

The Zephir is a continuous wave, variable focus system with an efficient lens radius of about 2.2 cm. It uses a cloud correction algorithm to mitigate the influence of clouds. It senses the radial velocity in 50 directions at one height in 1 s. It can change height in about 1 s. The cone angle is about 30°.

4.4 Experienced and solved problems

The development and market introduction of lidars have been fast. In the end of 2008 it is estimated that about 100 Zephirs and Windcubes have been sold worldwide. In 2009 two new systems, the Galion and the Vindicator from Sgurr Energy and Catch the Wind Inc. respectively, will be introduced to the market. Reliability and accuracy has improved significantly during the three last years, see Figure 29. In 2006 the commercial Zephir model was introduced. In 2007 a ceilometer was installed, comparison was screened on clouds and deficiencies in the original cloud correction algorithm was revealed. The positive bias and high standard uncertainty due to cloud influence was reduced, however the availability dropped. Once the positive bias from clouds where removed a negative gain, i.e. was seen which later was found to be due errors in the calibration of the cone angle. In 2008 the Zephir cloud correction algorithm was tuned, which meant that the lower bias and standard uncertainty could be maintained also in cloudy conditions. Shortly after this cone angles were corrected and the bias error reduced even further.

In 2007 Leosphere introduced the Windcube. Also the Windcube improved the calibration procedure of the cone angle which reduced the bias and in the summer of 2008 improvements in the wind estimator removed a non-linear error which almost halfed the standard uncertainty. Several improvements in hardware, software and in comparison techniques are expected in 2009.

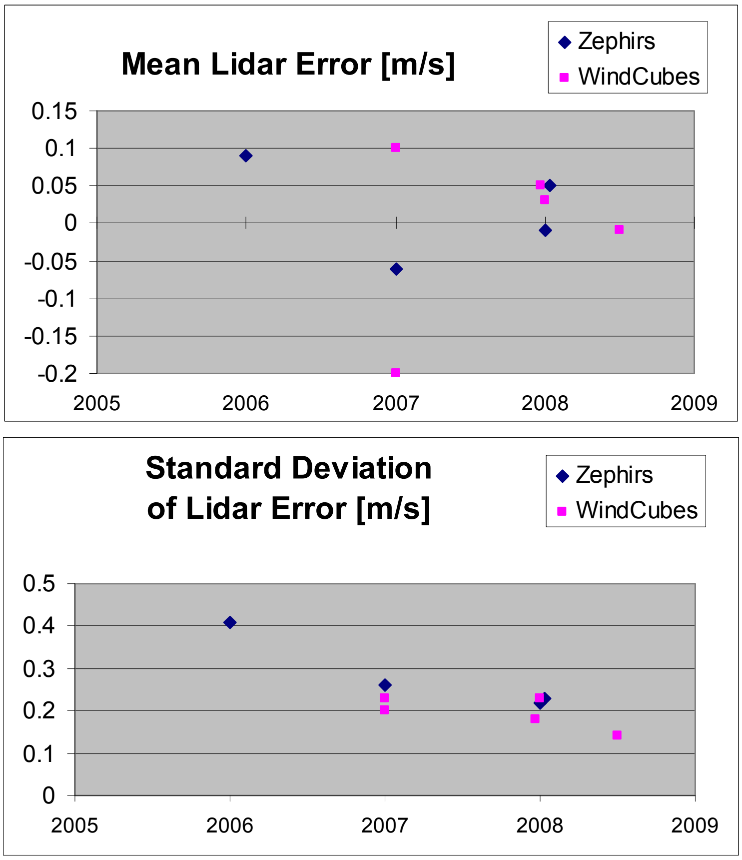


Figure 29 : Development of lidar anemometry in 2005 to 2008.

Cone angle calibrations

Both Natural Power and Leosphere have after comparisons with mast mounted cup anemometers review the calibration procedure of the cone angles in the Zephirs and Windcubes. Corrections in the Windcubes of about 0.5° improved the gain with 1.5 %, while Natural power experienced errors in the original calibration procedure with up to 1° causing a gain error of 3%.

Cloud corrections

With the current cloud correction algorithm the Zephir makes a measurement with the focus set at 800 m. This measurement will almost exclusively pick up a signal from a strong scatterer, e.g cloud. If the power in the 800 m measurement is sufficiently strong the radial signals will be deduct from the radial signals with the focus at the set measurement height. If no significant signal is detected with the focus at 800 m no correction is made. Since the measurement at 800 m and the measurement at the set height can be taken with up to 21 seconds lag the correction is made with some uncertainty, however, it is estimated that significant biases will be avoided.

The Courtney bump, a non-linear error on radial wind speed in the Windcube estimator

In the spring of 2008 the Windcube and the comparison with cup anemometers had reached such detail in the lidar-cup measurements that signature pattern was obtained when plotted towards cup speed, see Figure 30.

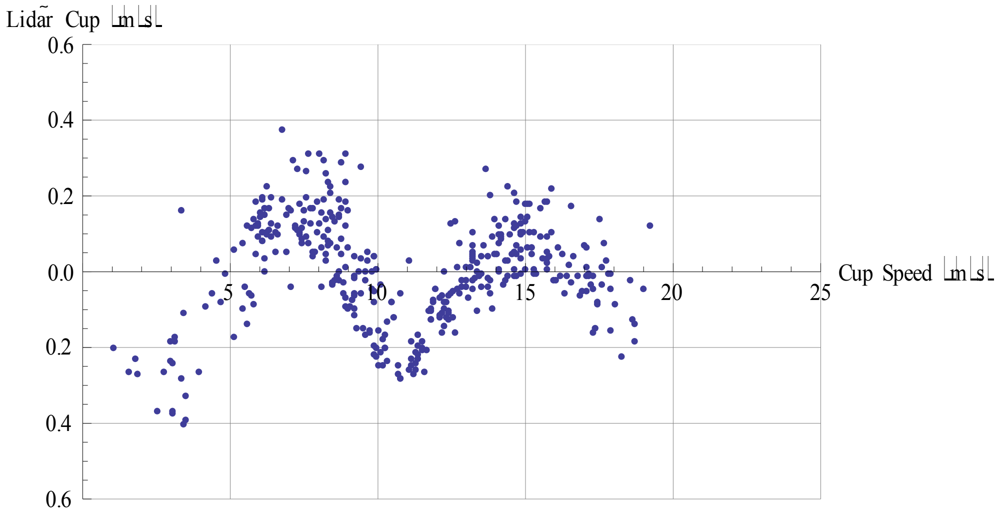


Figure 30 : Windcube-cup at 116 m vs cup speed at 116 m. Note the sinusoidal error with a period in the order of 7 m. The non-linear relation has been connected to an error in the original Windcube estimator. The estimator has now been improved and these non-linear errors have disappeared.

These errors where judged to arrive due to an error in the estimator. The estimator had an increased probability to estimate wind speeds which coincided with the frequency resolution of 5 MHz. This gave higher probability to find horizontal wind velocities in the beam direction every 5MHz*1.55µm/2cos(60)=7.75 m/s. These errors are smudged when the assessed wind has a high standard deviation in speed and direction during the ten minute average.

4.5 Uncertainties in lidar-cup comparisons in Høvsøre

The cup anemometers are expected to have a bias which lies within ±0.5% in typical flow conditions and a standard uncertainty of about 0.2 m/s. The uncertainty due to distance between cup and lidar is negligible and the flow in Høvsøre has, at least for the westerly directions, proved to be without significant flow distortions in average and should in a sufficiently large comparative data set ensure that no biases are introduced due to complex terrain.

Some degree of uncertainty is also introduced since some of the errors, due to cups, flow distortions due to masts or lidar errors, are non-linear while a 10 minute average is linear. For example if a ten minute period has a strong wind direction variability the flow distortion due to masts and booms can vary significantly. In some extreme cases the lidar could or the cup could even measure in a tower wake but the ten minute average could lie inside the accepted sector. In this experiment the wind sectors have been screened with large boarders to mitigate such effects.

5 Experimentally estimated uncertainties in lidar anemometry

This section gives experimentally estimations of uncertainties in lidar anemometry. The influences of different factors are treated in different sub-sections. It is mostly the results on the uncertainty in the ten minute horizontal wind velocity that are reported here.

All experiments have been screened on rain unless otherwise stated. Rain is specifically treated in 0.0. The wind sector in use has been carefully chosen, to avoid wakes from towers and turbines. Mast effects on boom mounted cup anemometers have been corrected for. Wind speeds below 4 m/s are excluded in order to avoid cup overspinning.

5.1 Uncertainty in radial wind speed distributions

The fundamental value obtained in lidar anemometry is the weighted radial wind speed distribution within the sample volume. The uncertainty factors in this measurement have been described in this report. Experimental comparison with cup anemometers is imprecise as a cup anemometer cannot measure the vertical flow and makes a significant smoothening of turbulence due to sensor inertia. Comparisons are instead made with ultra-sonic anemometers which measure the 3D flow and can measure small scale wind turbulence. It is widely regarded that ultra-sonic anemometers cannot give as high accuracy as cup anemometers in stable flow, see for example Figure 31. In addition there is also some difference in the principally instantaneous spatial wind distribution measured by a lidar and the temporal wind distribution measured by a sonic anemometer.

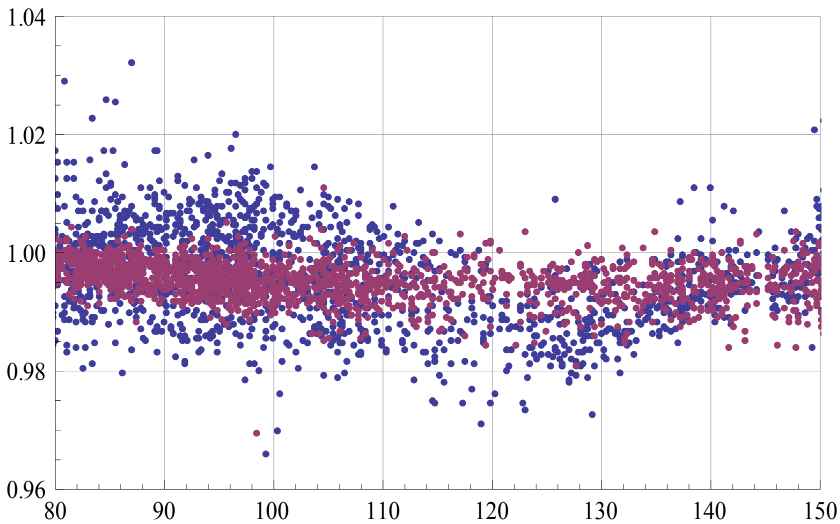


Figure 31 : Sonic-cup ratio, blue, and cup-cup ratio, red, of the ten minute average horizontal wind speed vs direction. Measurements taken during autumn 2008 in Høvsøre at 80 m height.

Since it is difficult to define the spatial weighting function of the lidar measurement and spatially resolve the wind from the measured wind distribution it has been the extracted wind velocity at the set measurement height which until now has been assessed, see chapter 5.2. In the case of pulsed lidars the frequency resolution is not sufficient to give more than a rough estimate of the wind distribution width.

5.2 Uncertainty in extracted radial wind speed

A simplification, to working with the full radial wind spectra, is to work with the radial wind velocity extracted from the wind distribution. It is generally assumed that this velocity represents the radial velocity at the set measurement height.

Two experiments, one with Windcubes and one with Zephirs, have been done. In these particular experiment the lidars were aimed next to a sonic anemometer. The Windcube estimator was at this time suffering from the non-linear error described in 0.0. Since it is difficult to verify the lidar staring angle at high altitudes the staring angle was found by correlating the lidar measurement to the sonic data. The data was also corrected for pulse chirp which was estimated by studying the long term average difference in two opposing directions[xii, xiii].

Further experiments of this type with new and improved lidar systems are underway.

Chirp

The chirp in pulsed lidars will affect the radial velocity. The effect of chirp, vertical wind influence and other biases in construction of the horizontal velocity can be reduced in flat terrain by using opposite directions to give wind vectors in the horizontal plane. The chirp is calibrated in manufacturing.

The effect of chirp was estimated on four Windcubes tested in the same period in December 2007, see Table 3. An average offset was measured by studying the difference of the two opposing directions during ten different rain free periods. The accuracy of this estimate is limited since the Windcubes at this time suffered from a significant non-linear error.

Windcube	Unit 1	Unit 2	Unit 3	Unit 4
Average offset [m/s] Beam direction 0 and 180	1.07	-0.02	-0.1	0.42
Average offset [m/s] Beam direction 90 and 270	1.08	0.01	-0.08	0.45
Standard deviation of offset in [m/s]	0.3	0.2	0.2	0.4

Table 3 : Estimate of the chirp influenceon radial wind velocity in the Windcube systems

The effect of tilted mounting would also induce offsets on the radial velocity but these would be much smaller than those observed for unit 1 and 4. It is also unlikely that they would be similar for both sets of oppsite directions.

5.3 Uncertainty in constructed horizontal velocity

Even if the uncertainty in the radial velocity can be made small, commercially it has been the uncertainty in the ten minute horizontal wind velocity which has been required. It will probably be the construction of a wind vector from the radial measurements that will set the limitations in accuracy, especially so for conically scanning systems measuring in complex terrain.

It will probably be the construction of a wind vector from the radial measurements that will set the limitations in accuracy, especially so for conically scanning systems measuring in complex terrain. However, it is not impossible that some of the uncertainty seen in this experiment are averaged out when several extracted radial velocities are combined, notably, chirp, angle errors and vertical wind influences.

With Turbulence

It is likely that the uncertainty in the lidar measurement increases in high turbulence. This can be studied as the lidar deviation vs the standard deviation in the wind velocity during ten minutes or as in figure Figure 32 where the lidar error is plotted against the difference of the cups at 80 m at stand 5 and stand 4 which are separated with 300 m. However, no clear relation can be seen in this graph.

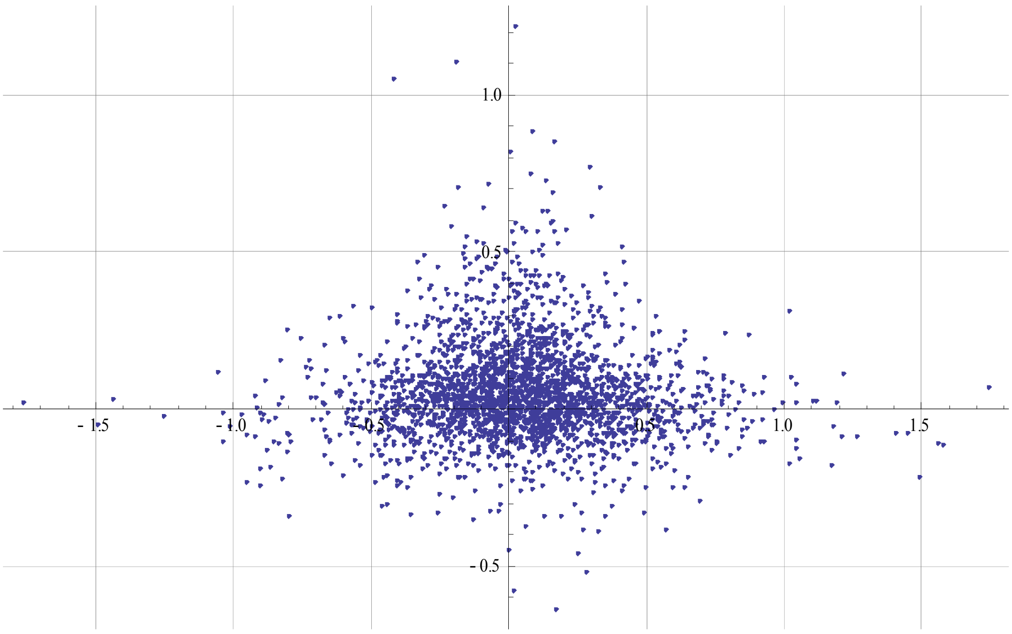


Figure 32 : Lidar –cup at 116 m vs cup stand 5 –cup stand 4 at 80 m. All top mounted cups, no rain and wind speeds faster than 4 m/s.

In complex terrain

Lidars have also been assessed in complex terrain. The errors, made by a conically scanning lidar interpolating the horizontal wind velocity under assumption of horizontally homogeneous flow in average, will depend on the site and lidar setup. An experimental estimation of the uncertainties in complex terrain is therefore difficult to make.

The example given here is wind sensed with a non cloud corrected Zephir in Lavriov, Greece[xiv]. The lidar was compared to a top mounted cup at 99 m height, see Figure 33. Data has been screened to include only 4 m/s winds and the wind sector is chosen so that mast wakes on the cups are avoided. The data set has not been screened for rain.

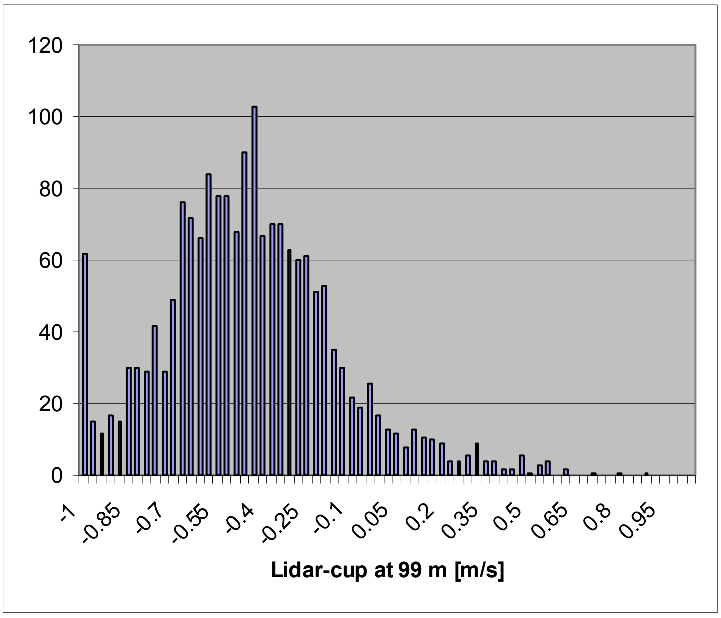


Figure 33 : Histogram over the lidar cup deviation at 99 m height in complex terrain. The data was collected with a non-cloud corrected Zephir in Lavriov.

Despite the fact that the lidar is not cloud corrected, which normally would give a positive bias, the lidar to cup comparison gives a large negative mean, Mean = -0.46 m/s with a standard deviation of 0.31 m/s.

However, the available data set is taken with an older version of the Zephir where contemporary systems showed on differences to cups in Høvsøre with mean errors of 0.15 m/s with standard deviations of about 0.35 m/s. There is much need of an updated campaign using improved systems and intercomparisons techniques.

Cone angle errors

Cone angle errors will manifest themselves as wind speed dependent errors which are similar at all heights. For high accuracy in the comparisons it is important to screen the data set so that other error sources do not influence the fit.

In this example the errors have been screened on rain, shear, veer, CNR and availability and corrections for mast effects on boom mounted cups are done. (No rain +- 30 min, shear < 0.03 m/s per m, veer < 3 degrees from 60 to 100 m, CNR > -15, availability > 80%, wind sector 240-290° and wind speed>4 m/s). The data has been collected with a Windcube in July to September. This estimator in this Windcube is updated and does not make the non-linear errors explained in 0.0.

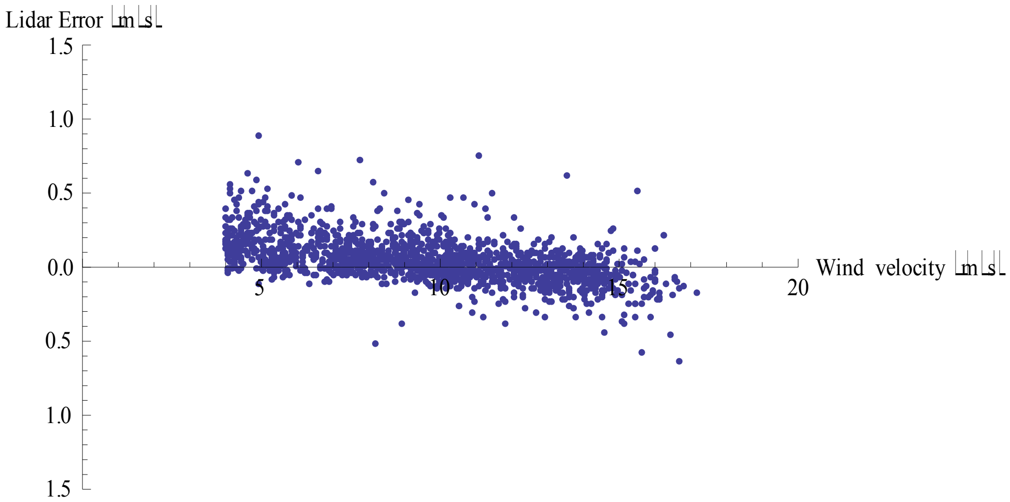


Figure 34 : Lidar-cup vs cup wind speed at 116 m. Note the strong slope and the significant offset.

The coefficients of lidar –cup vs cup speed regression, means and standard deviations can be found in Table 4.

Height [m]	**Regression offset [m/s]**	**Gain**	**R^2**	**Standard Deviation [m/s]**	**Mean [m/s]**
116	0.20 ± 0.03	0.982 ± 0.003	0.999	0.11	0.04
100	0.08 ± 0.02	0.993 ± 0.002	0.999	0.08	0.02
80	0.03 ± 0.03	0.984 ± 0.003	0.998	0.12	-0.12
60	0.08 ± 0.03	0.993 ± 0.003	0.999	0.10	0.02

Table 4 : Regression coefficients, mean and standard deviation form the lidar-cup comparison. The uncertainty ranges are the 90% confidence interval.

In this experiment a cone angle deviation error can not be excluded. The highest cup accuracy is at 116 m since the cup is top mounted. However, it is not unlikely that this coincides with the lowest lidar accuracy. Although this data set has been screened for low shears and veers a multiparametric regression would decrease the uncertainties in the estimation of the cone angle error if the lidar suffers from large sensing range or estimator errors. This lidar used a cruder variant of the bump corrected estimator. A never version of the estimator has been developed and it could have less errors.

These cone angle errors should lead to a lidar which underestimates the wind velocity, even so the mean are predominantly positive, see Figure 35, which is reflected in quite large regression offsets. This could be due to significant altitude errors, i.e. that the lidar measures at a higher height than intended. However, as will be seen in the following chapter this does not seem to be the case at 116 m.

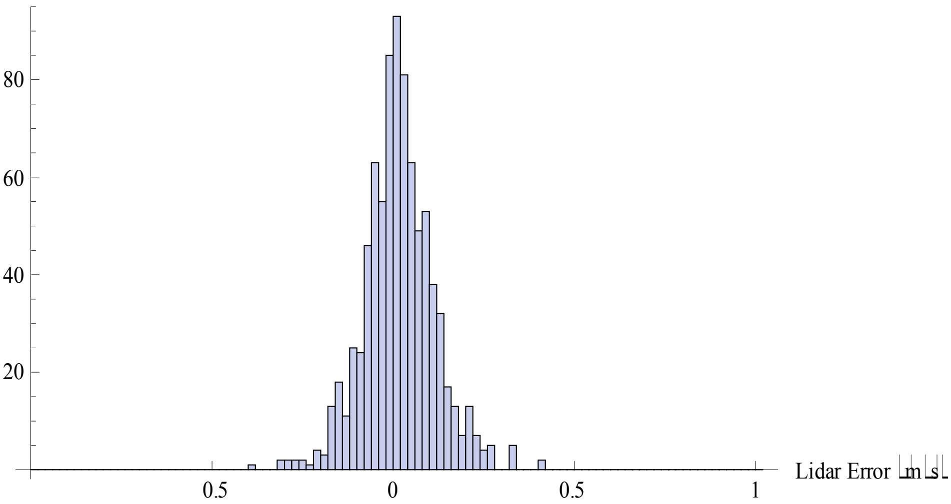


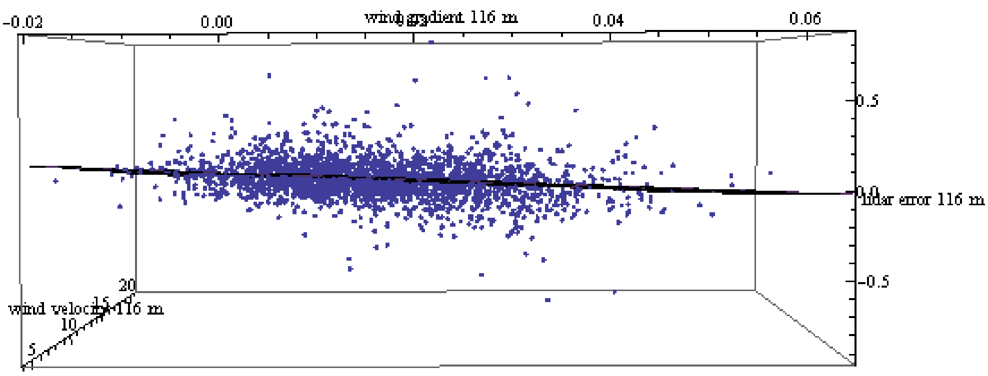
Figure 35 : Histogram of the lidar-cup at 60 m obtained in low shear from the ocean sector, 220 to 290°.

Shear

The wind shear studies so far done in Høvsøre have high uncertainty since the data from the wind sector with significant spread in wind shear is contaminated with mast and turbine wakes both on cups and lidar. The top cup which has a free sector also for the sectors with high wind shear spread does only have a measurement from the light tower at 160 m to calculate the shear from. In addition is the shear at this height is typically limited in Høvsøre.

The wind shear was calculated as the derivative of a windprofile fitted to the cup measurements at 10, 40, 60, 80, 100 and 116 m. A high level wind shear model, u(z) = `A + Bx + Cx2 + DLog[x]`, was chosen to get a good fit to the measured ten minute averages.

At 116 m the 2-parametric regression analysis in is obtained for a Windcube cup comparison in June to September 2008. The screening conditions follow: no rain +-30 min, veer < 3 degrees from 60 to 100 m, CNR > -15, availability > 80%. Wind sector 100-290 degrees and wind speed > 4 m/s. Data is collected with the first bump corrected Windcube from June to September.



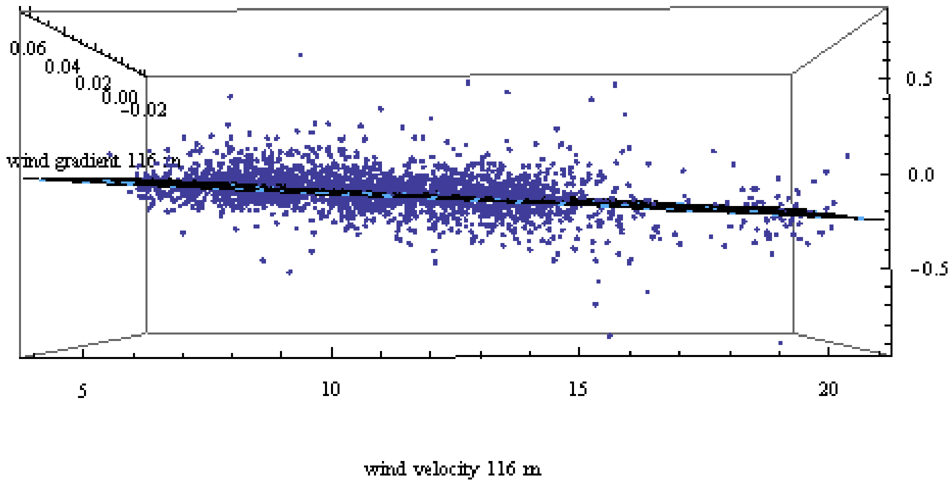


Figure 36 : Lidar-cup as function of wind shear and wind speed for a Windcube sensing at 116 m height in Høvsøre June to September 2008.

Parameter	**Estimate**	**90%-confidence interval**
Offset [m/s]	0.17	[0.15..0.19]
Wind shear dependency, k_s [m/s per m]	-2.0	[-4.4..-2.8]
Wind velocity dependency, k_u [%]	-1.3	[-1.6 ..-1.1]

Table 5 : Coefficients from the 2-parametric regression analaysis of the lidar error as a function of wind shear and speed.

The Lidar-cup as a function of wind shear will only reveal the combined effect of sensing range errors and estimator errors. The uncertainties due to sensing range errors and estimator errors cannot be estimated individually in cup comparisons. However, the wind shear dependency has in most comparison looked predominantly linear.

The 2-parametric regression analysis still indicates a slight negative dependency to the wind speed as in 0.0, -1.3% as compared to -1.8 %. It also indicates that the lidar measures at 2 m below the set measurement height.

Larger errors, up to 8 m, have been observed at lower altitudes. The windcubes tend to measure above the set height for heights below the focus distance of about 100 m while they tend to measure below the set height above. However, this needs further confirmation.

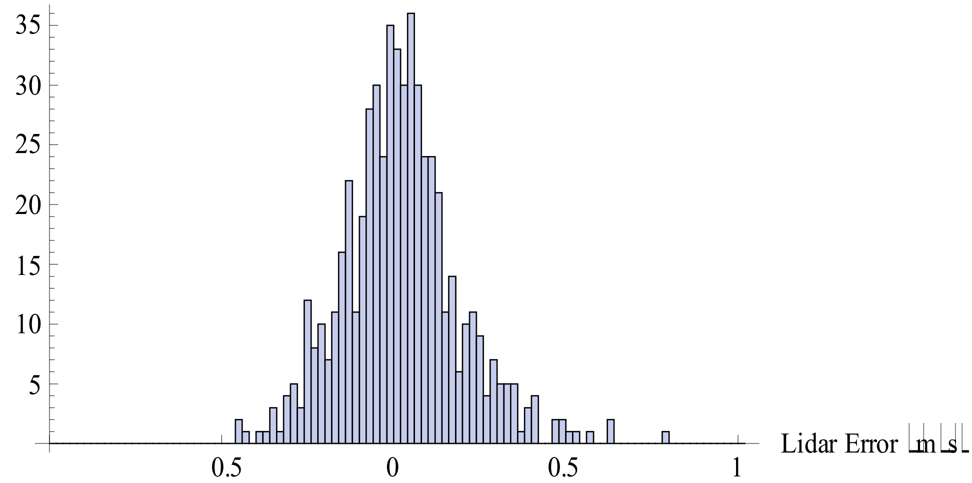


Figure 37 : The histogram of the lidar-cup in mixed shear from the land sector, 100 to 180°.

The histogram of the lidar-cup in mixed shear from the land sector, 100 to 180°, has a higher spread than that obtained with wind over land, see Figure 37. The data set has been screened on veer. The standard deviation, 0.17 m/s, is larger as compared to that obtained with wind from the ocean, 0.11 m/s. Most likely this is due to the larger spread in shear which gives a higher variability in errors due to the altitude error. The mean error is slightly lower 0.02, as compared to 0.04 m/s, which would be typical for a lidar which measures at a lower altitude than expected. However, the mean is still positive, reflected in the relatively large regression offset, although two sources of errors show on an underestimation of the wind speed measured by lidar at 116 m. This ends up in the slight paradoxical fact that if the lidar was corrected for the suspected cone angle and altitude errors it would in fact measure an even stronger offset in mean.

This paradox could possible be explained by outliers in the analyses, due to spurious errors in the cup or the lidar. However, it cannot be excluded that other errors which are fairly well spread with wind speed and shear are the source of a significant positive bias.

Veer

Most of the strong shear comes from the east. However, some of this wind also contains considerable veer, sometimes with more than 20° clockwise from 60 to 100 m height, see Figure 23 : Summertime wind veer, i.e wind direction at 100 m – wind direction at 60 m as a function of wind velocity and direction, only for velocities above 4 m/s. Note that there seems to be an offset of about 3° between the two wind vanes. Measurements are taken at the metrology mast in Høvsøre.

Note that a lidar would make the same kind of errors if the veer is clockwise or counterclockwise. In our dataset there is only significant clockwise veer and that the errors in the linear regression analysis are therefore avoided.

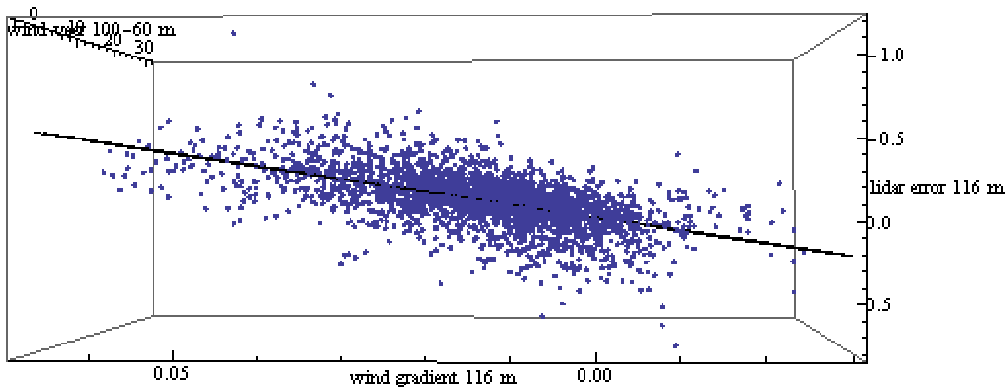
Since wind speed, veer and shear are correlated the effects on the lidar has to be studied in multiple regression analyses. Wind conditions with large spread in shear and veer are limited from the sector where the lidar is free from mast wakes and in comparisons with the top mounted cup the accuracy of the shear measurement is lower. Furthermore it is assumed that the veer is linear between 60 and 100 m and that it continues so past 116 m. The accuracy of the regression of lidar-cup as a function of wind speed, shear and veer is therefore limited.

If all veer and shear values are included the following plot of lidar/cup vs direction is obtained. Large veer and shear is predominantly occurring when the wind comes from the east, i.e. direction 100 to 150 or so. It is evident that the standard deviation and errors for these conditions are higher. Table 6 gives the regression coefficients of the analyses of data collected with a Windcube at 116 m from June to September 2008. In Figure 38 a visualization of the Windcube-cup as function of veer and shear can be seen. The data collected with the Windcube was corrected with the -1.4% dependency on wind speed given from the 3 parametric regression analyses. From the vizualisation it is evident that more acceptable veer data is necessary for a better estimation of the veer influence.

The screening conditions follow: no rain +- 30 min, CNR > -15, availability > 80%, wind sector 100-290 degrees and wind speed > 4 m/s. In addition, data where the shear fit goodness was low has been screened.

Regression coefficient	**With 90% confidence interval**
Offset	0.20 ± 0.02 m/s
Shear	-3.2 ± 0.5 m
Veer	-0.004 ± 0.001 m/s per veer from 60 to 100 m height
Speed	-1.4% ± 0.2%

Table 6 : Regression coefficients of Windcube-cup at 116 m during June to September 2008.



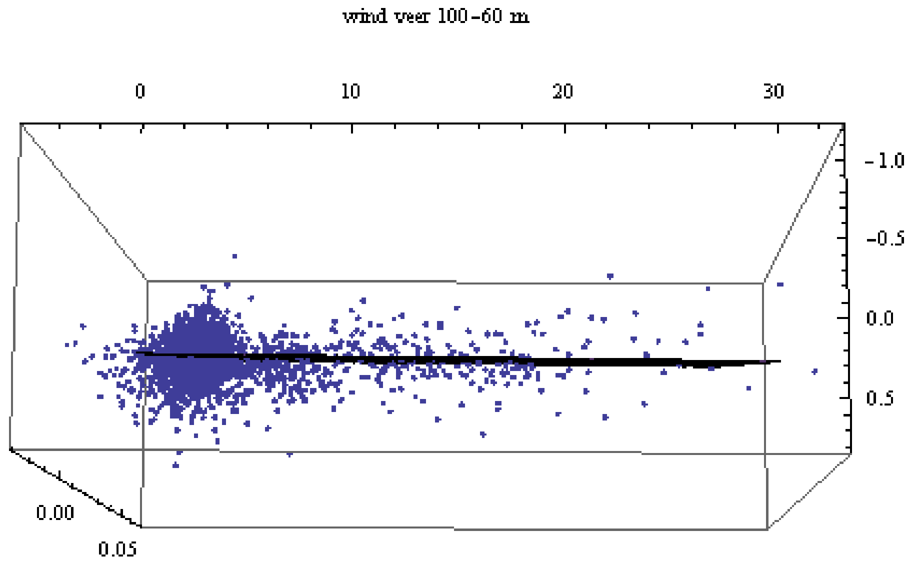


Figure 38 : Visualization of the Windcube-cup as function of veer and shear. The data collected with the Windcube was corrected with the -1.5% dependency on wind speed given from the 3 parametric regression analyses.

The lidar error found in the previous studies, of about -1.5% with wind speed, and -2 m on altitude, is still reflected in this expanded analyses which includes wind with strong veer. The error dependency with veer is limited, but not insignificant. For example will a veer of 30°, which is approximately the highest veer recorded in Høvsøre, over 40 m only induce an error or 0.12, which is comparable to the error induced by a speed dependent error of 0.5% at a quite extreme 25 m/s.

Also veer will have an underestimating effect of the lidar measurement. But the mean error is still positive in this data set, 0.02 m/s, with a standard deviation of 0.15 m/s, see . Again the conclusion is that if the lidar was corrected for cone angle and altitude errors and veer dependency it would overestimate more in mean than it does uncorrected. The possible source for the positive mean in this lidar-cup comparisons has to be further investigated.

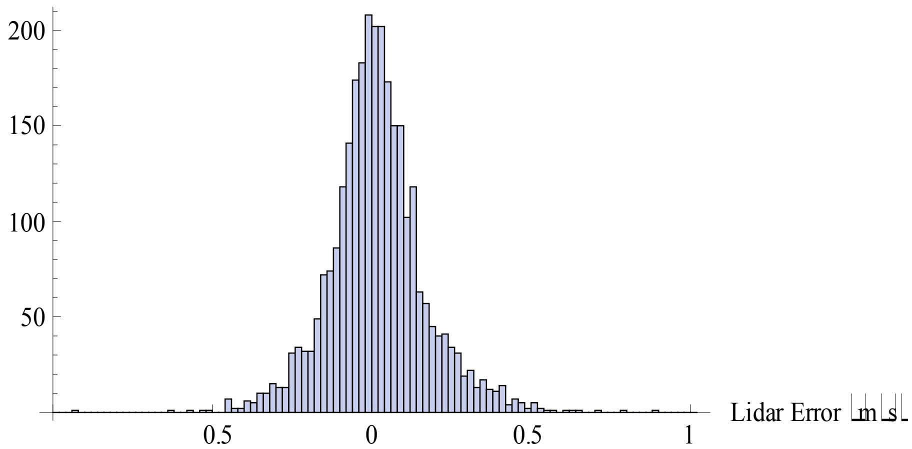


Figure 39 : Windcube-cup at 116 m in mixed veer and shear conditions. The comparison shows on a slight positive bias although three error sources indicate on an underestimating lidar.

Rain

Rain has a strong influence on the vertical velocity but according to cup comparisons in rainy weather it does not seem to introduce large biases on the horizontal wind velocity, -0.01 to -0.04 m/s. The standard deviation increases drastically though, from 0.15 to 0.46 m/s, see Figure 40.

This analysis is done without corrections for cups but the data is screened for low shear and veers, wind speed higher than 4 m/s and the wind sector used is 200-290°. To obtain sufficient amounts of data the four heights 60, 80, 100 and 116 m are analyzed together.

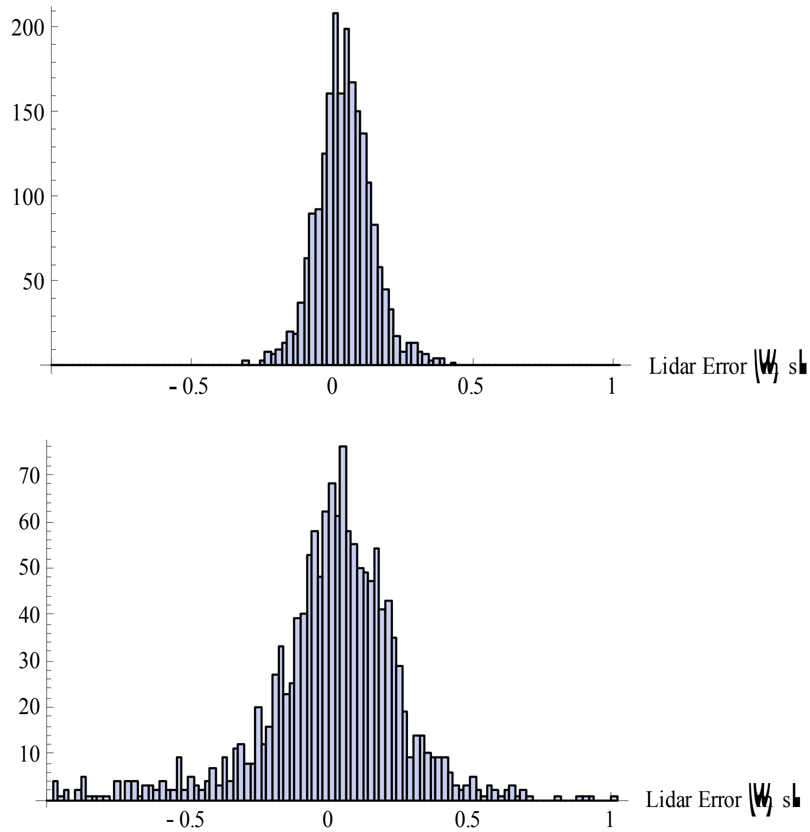


Figure 40 : Histogram over lidar error in rain conditions, lower, and no-rain conditions. Rain does not significantly influence the mean estimate, however the standard deviation in rain increases significantly.

However, the analysis is not fully conclusive since large negative bursts are sometimes experienced in rain at 80 m, Figure 41. The source of these events is unknown but it is probably connected with the low CNR connected to rainfall.

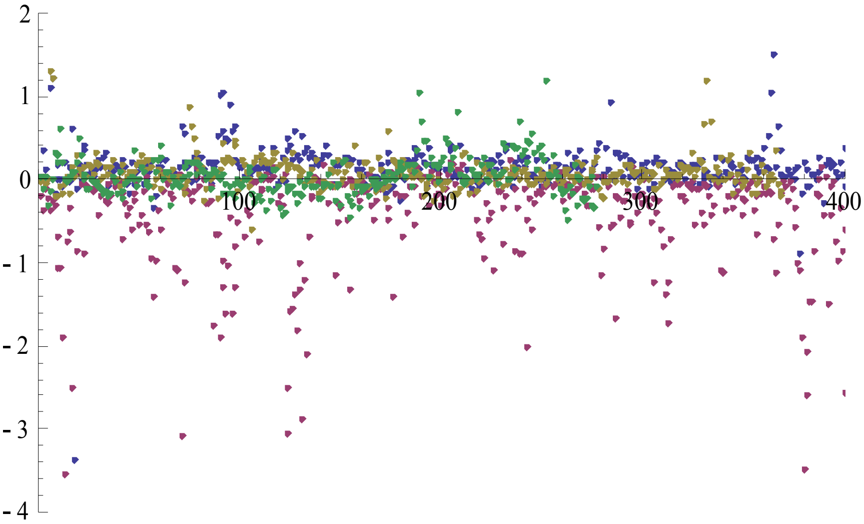


Figure 41 : None-consecutive time serie of windcube-cup in rainfall. Green is at 116 m, yellow at 100 m, purple 80 m and blue is for 60 m. Note the negative bursts at 80 m.

Since the lidar is quite sensitive to rain it is important in error analyses to screen for rain, but in long site assessments it is probably not necessray and it is possibly more accurate to include rain data in Annual Energy Production estimates. It cannot be excluded that rain is the source of some of the outliers.

RIN

Relative Intensity Noise introduces problems in lidars which do not use an offset on the local oscillator line, like the Zephir. The RIN and the wind signal are overlapped during low wind speeds. This has been mitigated by filtering sensed radial velocities lower than about 1 m/s. At high wind speeds this only affects the cross wind sensing directions for which the fit is very insensitive. However, during low wind speed also some of the important wind signal is lost from the lower part of the Doppler spectra. The extracted radial wind velocity is therefore overestimated, see Figure 42.

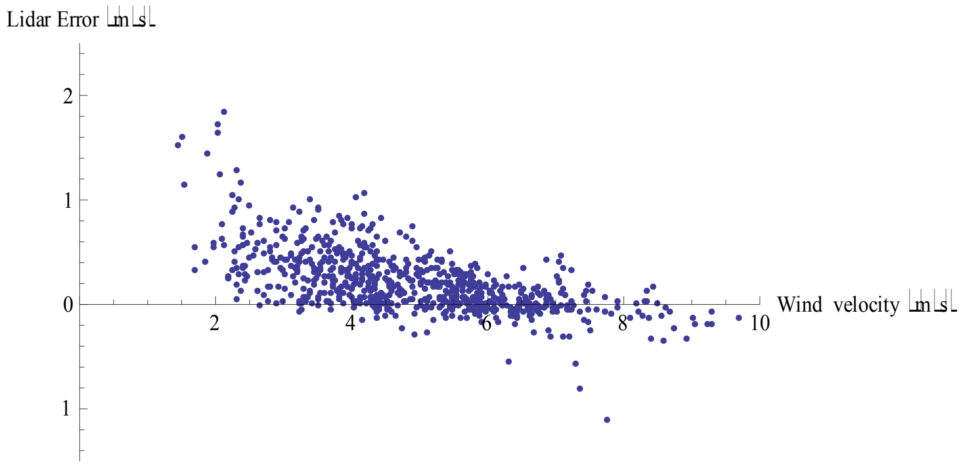
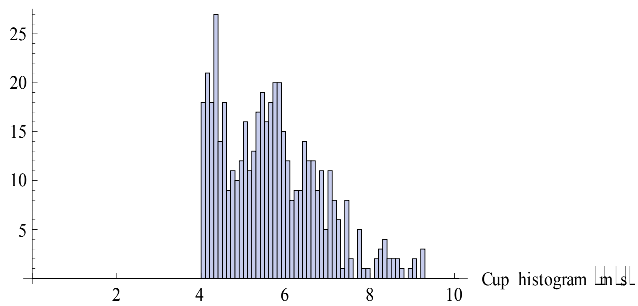


Figure 42: The lidar error of the Zephir during low wind velocities. Note that the ldiar under test was expected to be slightly linearly underestimating in comparison to the cup so the effects of overestimation at low wind speeds could be slightly overexagerated.

The initial idea has been to screen on > 4 m/s measured by the lidar, which typically are uninteresting winds for the wind energy industry, but for the versions up till spring 2008 some lidars have had problems also above 4 m/s. It is likely that partly employed improvements and tighter control of the RIN in the fiber lasers in the Zephir will mitigate these problems.

The low winds are slightly overestimated in lidars with RIN problems but at the same time more low winds would be accepted into the data set. The mean in this test almost stayed the same, see Figure 43. However, Weibull distribution fits will become quite different.



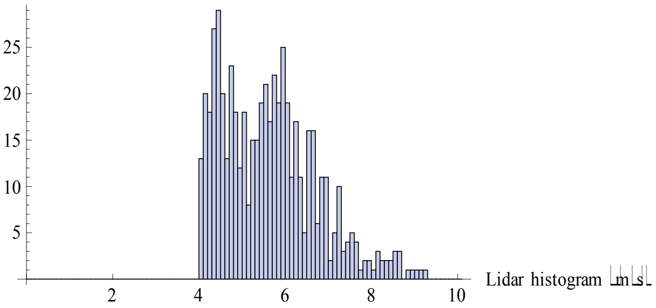


Figure 43 : Top : Histogram of 489 ten minute averages measured with a cup anemometer screened on 4 m/s, mean = 5.7 m/s. Bottom : Histogram of 554 ten minute averages measured with a Zephir screened on 4 m/s, mean = 5.6 m/s.

Clouds

A lot of attention has been given to the influence of clouds on variable focus continuous wave lidars. A cloud correction scheme has been developed at Qinetiq, the initial developer of the Zephir, and it has later been improved in cooperation with Risø DTU. Histograms of Zephir-cup in cloud and cloud free conditions can be seen in Figure 44. The Zephir used the second version of the cloud correction algorithm. The standard deviation and mean are comparable.

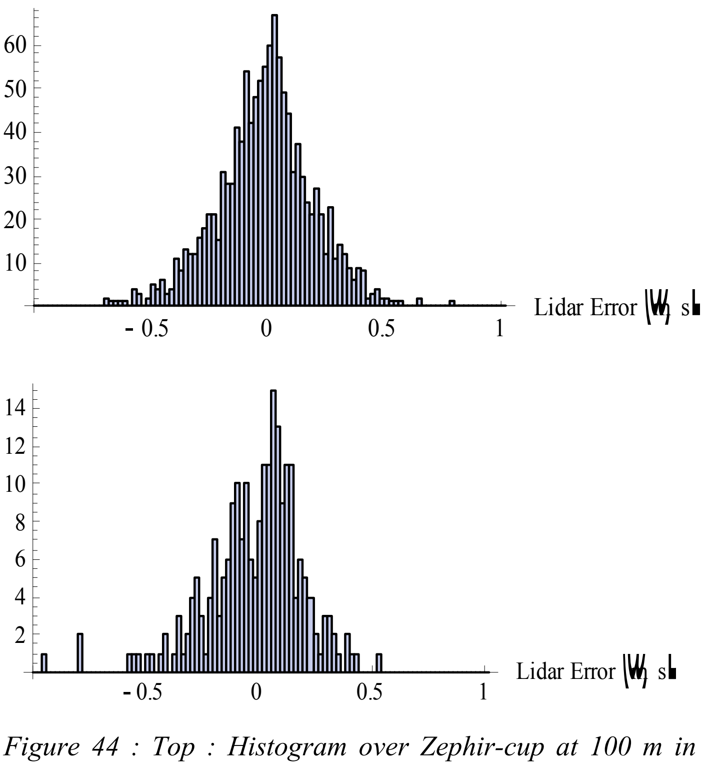


Figure 44 : Top : Histogram over Zephir-cup at 100 m in cloud free conditions, i.e. ceilometer measures cloud base above 2.5 km. σ = 0.20 and m = -0.01. Bottom : Histogram over Zephir-cup at 100 m in cloudy conditions, i.e. ceilometer measures cloud base below 1 km. σ = 0.22 and m = -0.02.

5.4 Uncertainty with height.

Although it could be expected that lidar uncertainty should increase with sensing range, since the distance over which the radial velocities are interpolated becomes longer, and in the case of the Zephirs; signal to noise ratios lower and sampling volumes bigger. In addition wind velocities are typically stronger at higher altitudes so the uncertainty in cone angle would give larger absolute errors. However, this has not been observed, see for example Table 4 for Windcube standard deviations or Figure 45 for a Zephir comparison.

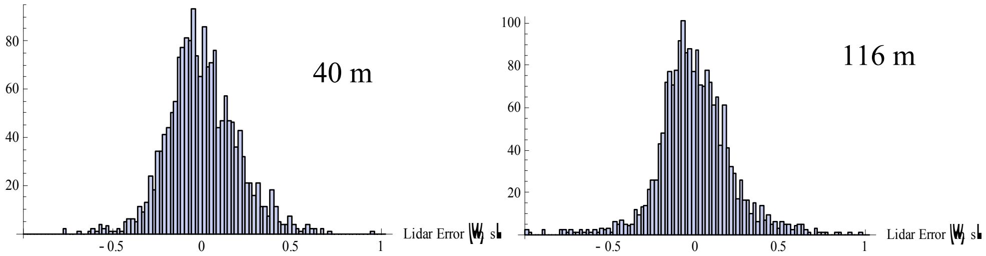


Figure 45 : Histogram of Zephir-cup at 40 resp 116 m.

There are several factors which could give large deviations at lower altitudes. For example that the boom mounted cups suffer from higher uncertainties than the top mounted cup, that the horizontal turbulence and shear and veer decreases as the height increases. Further more, wind speed at low height is normally much lower and this means that possible RIN effects on the Zephirs are larger at these sensing ranges.

5.5 Comparison of brands

Windcubes have generally shown on slightly lower standard uncertainty in cup comparisons, see for example figure Figure 46. The experimental extraction of cone angle errors and range errors are therefore of higher quality. From comparisons in Høvsøre it is estimated that the difference in accuracy between the two systems is due to a higher sensitivity to inhomogeneous aerosol concentration and a non-optimal extraction of the significant wind velocity from the Doppler spectra. However, as an outcome of this work the test conditions and the Zephirs have improved since the most recent Zephir was tested in Høvsøre.

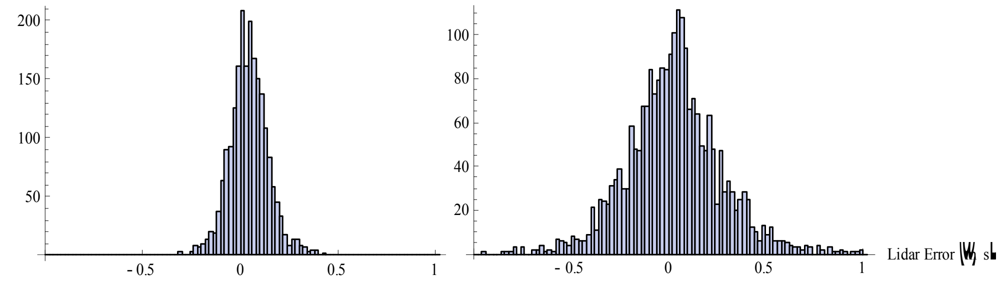


Figure 46 : Histogram of the lidar-cup at 100 m height for a Windcube, left σ =0.11 m/s, and a Zephir, right σ =0.22 m/s. Note that these data sets where taken at different time periods, the Zephir was tested during higher variability in wind shear.

6 Conclusions on uncertainty in lidar anemometry

Lidars have improved much since 2005 and now show impressive accuracy as remote wind sensors, see Figure 47. The deviations in the ten minute average horizontal wind velocity are so small that they can only be properly evaluated if the test conditions are extremely well defined.

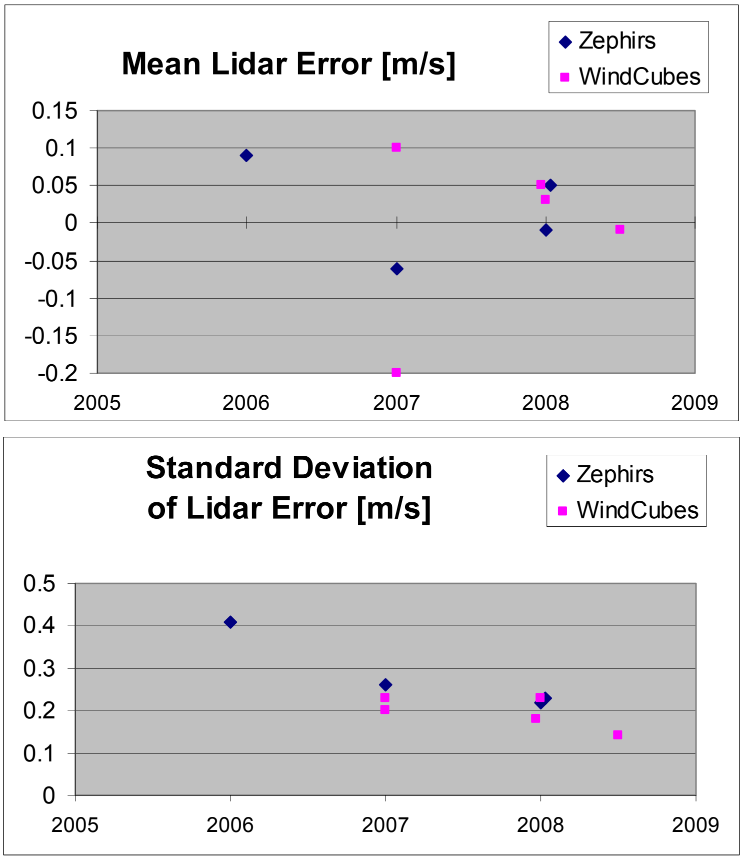


Figure 47 : Development of lidar anemometry in 2005 to 2008.

Høvsøre has in the course of the last three years developed to the leading test site for lidars. The site is flat and the surrounding roughness is fairly simple. The wind conditions at the site are well known, the class 1 cup anemometers are well maintained and mounting effects are to the highest degree mitigated. During these tests surprisingly larger errors on boom mounted cup anemometers have been observed. By cup to cup comparison these errors has to a large degree been mitigated. Høvsøre is an almost ideal site for debugging new models and for making fair comparisons between different remote sensing techniques, configurations and systems. It will most likely play an important role for acceptance testing and pre and post verifications of remote sensors in between measurement campaigns.

6.1 Lidar Precision in 2008

A rough estimate of the uncertainties of lidar anemometry can be made from the results of twenty lidar systems studied in Høvsøre. It is likely that Windcubes can extract the horizontal wind velocity in homogeneous flow with a higher than ±2% deviation with wind speed and with better than 10 m accuracy in sensing height. The mean error in typical flat coastal conditions is expected to lie within ±0.05 m/s with a standard deviation in mixed shear conditions of about 0.15 m/s

Windcubes have generally shown on slightly lower standard uncertainty in cup comparisons when compared to Zephirs. From comparisons in Høvsøre it is estimated that the difference in accuracy between the two systems is due to a higher sensitivity to inhomogeneous aerosol concentration and a non-optimal extraction of the significant wind velocity from the Doppler spectra. However, it is likely that the Zephir is less prone to make biases due to wind shear. As an outcome of this work the test conditions and the Zephirs have improved since the most recent Zephir unit was tested in Høvsøre.

6.2 Commercial application of lidar anemometry.

The results in this report indicate that lidars can be used for stand alone wind assessment in homogeneous flow. Considering the current state of accuracy, demand on flow homogenity, system maturity and price a likely first commercial use of lidar anemometry is pre-assessment of large MW wind farm sites before the permit application and construction of a hub height mast is complete. If the lidar measurement later correlates well with the mast measurements the initial stand alone data, probably a couple of months, can be calibrated and trusted with high certainty. The lidar can during the time it stands beside the hub height mast also be used as a reference and reveal errors, for example due to icing or degradation on cup anemometers, and wind vanes. In such cases the lidrar data can be used to fill in the time gaps.

However, several system failures have been experienced during testing, both due to hardware and software issues and the long term stability has not yet been confirmed. It is therefore recommended that lidar ability, also in the following years, are regularly verified with cup anemometers. Although lidar anemometry probably has matured sufficiently as a measurement principle it is not sure that the price and reliability is sufficient for stand alone campaigns.

In addition more work is needed to asses the accuracy and best practice in complex terrain. It will also be important to make guidelines for developers regarding what kind of terrain that gives sufficiently homogeneous flows for low errors on the interpolated horizontal wind velocity.

[i] S. Henderson, P. Gatt, D. Rees and M. Huffaker, “Wind Lidar”, Chapter 7 in Laser Remote Sensing edited by T. Fujii and T. Fukuchi, Taylor and Francis, pp. 469-722 (2005)

[ii] P. Lindelöw, ”Fiber Based Coherent Lidars for Remote Wind Sensing”, PhD thesis DTU, ISBN 978-87-911-8482-6 (2007)

[iii] V. A. Banakh, I. N. Smalikho, F. Köpp and C. Werner, ”Representativeness of wind measurements with a CW Doppler lidar in the atmospheric boundary layer”, Appl. Opt., vol. 34 No. 12, pp. 2055–2067 (1995)

[iv] P. Lindelöw, M.Courtney R. Parmentier and J. P. Carriou, ”Wind shear proportional errors in the horizontal wind speed sensed by focused, range gated lidars”, 14. International symposium for the advancement of boundary layer remote sensing, Risø (DK), 23-25 Jun 2008. IOP Conf. Ser.: Earth Environ. Sci. (2008) **1** , 012051 (6 p.)

[v] R.Frehlich and M. Yadlowsky, “Performance of Mean-Frequency Estimators for Doppler Radar and Lidar”, J. Atmos. Oceanic Technol., Vol 11, pp 1217-1230 (1994)

[vi] C. Werner, F. Köpp and R. L. Schwiesow, “Influence of clouds and fog on LDA wind measurements”, Appl. Opt., vol. 23 No. 15, pp. 2482-2484 (1984)

[vii] M. Harris, D. Smith and A. Coffey, “Laser radar device and method”, Patent Application WO 2005/ 114253 A1 (2005)

[viii] IEC 61400-12-1 Standard for power performance measurements, Appendix E.5.3

[ix] T. Friis Pedersen, “Characterisation and Classification of Risø P2546 Cup Anemometer” Risø-R-1364 (ed. 2), Risø National Laboratory, Roskilde (2004)

[x] L. Kristensen, O. Frost Hansen “Distance constant of the Risø cup anemometer “ *Risø-R-1320(EN)*, Risø National Laboratory, Roskilde G X (2001)

[xi] M. Courtney, R. Wagner, P. Lindelöw, “Testing and comparison of lidars for profile and turbulence measurements in wind energy” , 14. International symposium for the advancement of boundary layer remote sensing, Risø (DK), 23-25 Jun 2008. IOP Conf. Ser.: Earth Environ. Sci. (2008) **1** , 012051 (6 p.)

[xii] Mann, J.; Cariou, J.-P.; Courtney, M.S.; Parmentier, R.; Mikkelsen, T.; Wagner, R.; Lindelöw, P.; Sjöholm, M.; Enevoldsen, K., Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer. 14. International symposium for the advancement of boundary layer remote sensing, Risø (DK), 23-25 Jun 2008. IOP Conf. Ser.: Earth Environ. Sci. (2008) **1** , 012012 (6 p.)

[xiii] Sjöholm, M.; Mikkelsen, T.; Mann, J.; Enevoldsen, K.; Courtney, M., Time series analysis of continuous-wave coherent Doppler Lidar wind measurements. 14. International symposium for the advancement of boundary layer remote sensing, Risø (DK), 23-25 Jun 2008. IOP Conf. Ser.: Earth Environ. Sci. (2008) **1** , 012051 (6 p.)

[xiv] F. Bingöl, 14. International symposium for the advancement of boundary layer remote sensing, Risø (DK), 23-25 Jun 2008. IOP Conf. Ser.: Earth Environ. Sci. (2008) **1** , 012051 (6 p.)