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"Integrated Wind Turbine Design"

UpWind WP6 – Remote Sensing

Final Report – Deliverable D6.17

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Abstract: This is the final report for the Remote Sensing work package (WP6) in the UpWind project. The deliverables are summarised and important, wind-energy related results are highlighted. Some ideas concerning the direction of future work for remote sensing as related to wind energy are given. The dissemination activities of WP6 are reported and a bibliography is given.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY									
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	x		**R0**	General public	x		Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	x
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
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PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

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2. Objectives

As wind turbines get larger, making hub-height wind measurements becomes ever more costly when using conventional, mast-mounted instrumentation. Even for resource assessment, minimizing the uncertainty associated with the vertical extrapolation of the wind speed requires higher and higher masts. The challenge of Work Package 6 (WP6) is to research into remote sensing methods as a more cost effective alternative to tall measuring masts. Two such alternatives are sodar and lidar. A sodar measures wind speed by detecting the Doppler shift of sound waves backscattered from atmospheric temperature in-homogeneities. Lidars are based on a similar technique but use instead coherent light backscattered from suspended particles (aerosols). They are much faster and potentially much more accurate than sodars. Recently new wind lidars have appeared on the market, designed for performing wind measurements over height ranges relevant to wind turbine applications.

More specifically, the objectives of WP6 are to answer the questions – can remote sensing techniques substitute conventional towers with the precision required by the IEC standards, and - how do we best exploit the freedom to measure detailed profiles offered by remote sensing techniques.

3. Goals

The following fields of research within remote sensing were identified as relevant to wind energy and pursued during the course of the project:

Topic	Relevant deliverables
Calibration techniques for both lidar and sodars	6.2.2, 6.2.3, 6.2.4
Optimisation and improvements for lidars and sodars	6.3.1, 6.1.2
Bi-static sodars	6.4.1
Mast comparisons of lidars and sodars	6.5.1, 6.13.1
Power curve testing using lidars	6.5.1, 6.15.1
Lidar error sources	6.1.3
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Lidar availability as related to aerosol statistics	6.14.1
Inclusion of remote sensing instruments in international standards	6.2.1, 6.12.1, 6.13.1
Nacelle-based lidar measurements	6.7.1

4. Results from the work tasks

4.1 WP6.1 A description of the measurement at all stages

A description of the measurement at all stages has been reported for both the remote sensing instruments (lidar and sodar) by QinetiQ and USAL. These reports describe the underlying technology used for each type and an end-to-end description of how wind speeds are sensed and processed.

Deliverables:

D6.1.1 Description of the Lidar measurement method.

This report provides a detailed description of the measurement process for a Doppler lidar that measures wind speed and direction. Emphasis is on continuous wave lidars, with QinetiQ's ZephIR TM lidar as the main example. Pulsed lidar operation is more briefly discussed.

D6.1.1p LEOSPHERE Pulsed Lidar Principles Contribution to UpWind WP6 on Remote Sensing Devices.

Whilst not a formal deliverable, this document has been included as a complement to *D6.1.1.*It contains a complete description of the measurement method for the Windcube pulsed lidar. This work has been written free-of-charge by Leosphere, the manufacturers of the Windcube.

D6.1.2 Description of the Sodar measurement method.

A comprehensive description of the sodar measurement method is provided. The deliverable also contains results for the sodar optimisations, notably for enhanced performance in rain, previously designated for the separate deliverable *D6.3.2*.

D6.1.3 Uncertainties in remote wind sensing with lidars

This comprehensive report describes the error sources inherent in measuring with lidar profilers. Both hardware error sources such as tilt, cone angle errors and chirp together with the effect of the atmosphere are analysed. In particular, the effect of wind shear is described. This is the most significant contributor to differences between the volume measurement of a lidar and the point measurement of a cup. It is found that only non-linear shear will give a bias error.

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4.2 WP6.2 Traceable calibration methods

This task concentrates on developing and describing traceable calibration methods for both sodar and lidars. With such methods documented and proven, it will be possible to introduce remote sensing instruments to international standards. Here the most relevant to UpWind is the ongoing revision of the IEC 61400-12 power curve standard where inclusion of remote sensing instruments for profile measurements is anticipated.

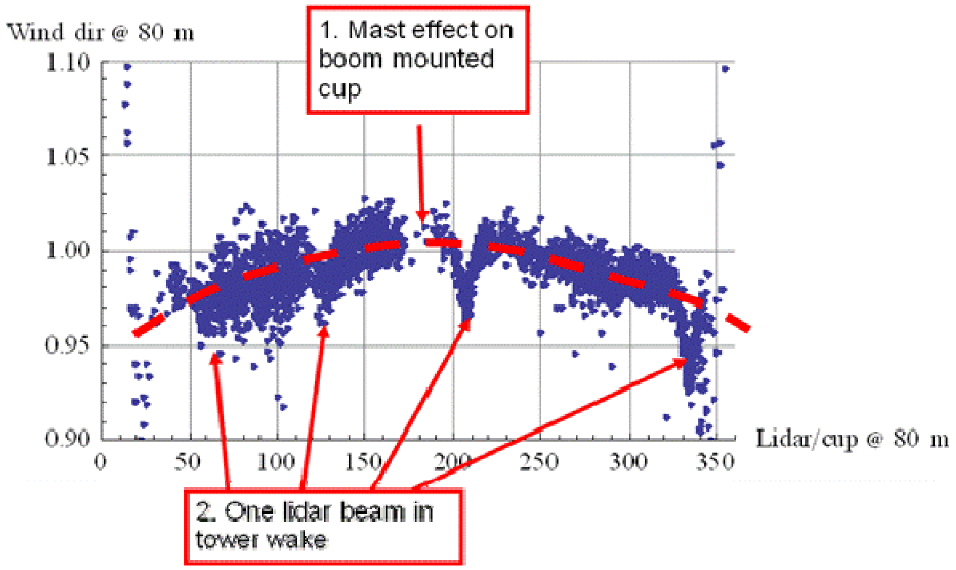


Figure 1 Plot of lidar speed normalised by cup anemometer speed as a function of wind direction. Both the effect of the mast on the boom-mounted cups and the effect of the mast wake on the lidar can be clearly seen.

In terms of calibration, sodar and lidar are very different devices. Whilst lidars can be placed close to measurement masts, this is not so feasible for sodars since echos from the mast itself degrade the sodar measurements. Therefore this task has concentrated on stand-alone calibration methods for the sodar whilst for lidars the effort has been to perform measurement comparisons traceable mast-mounted anemometry.
Figure 1 illustrates an important advance in lidar-mast comparisons – both the effect of the mast wake on the cup anemometer and the lidar itself are now taken account of. This is from the work on lidar uncertainties reported in *D6.1.3*, where this knowledge is being used to improve our comparison techniques.

Deliverables:
D6.2.1 A note with considerations with respect to the acceptance of remote sensing in IEC power performance measurements.
This deliverable describes the relationship of the WP6 work to the upcoming revision of the IEC 61400-12 power curve standard. The tasks identified lead directly from much of the work already performed in WP6. Some new tasks were defined.

D6.2.2 Transponder based sodar calibrations
For sodar, the approach is to develop an active calibration system that analyzes the sound pulses emitted by a sodar and generates a simulated atmospheric response for nominal heights, wind speeds and atmospheric conditions. The speeds reported by the sodar can then be compared with nominal values input to the calibration system.

Laboratory and field testing of the transponder system has shown that it can provide valuable insight into the operation of a sodar in the laboratory but that the practical difficulties of establishing a semi-anechoic chamber outdoors restricts its relevance in the field.

D6.2.3 A description of the principles of the lidar calibration method.
This deliverable describes the methods used to test and calibrate the CW ZephIR lidar during the manufacturing process. Since this lidar type discriminates height through an active focusing of the laser beam, correct calibration of the focusing system is crucial to system performance. Other tests, including use of a calibrated running machine, are used for plausibility checks on system performance.

D6.2.4 In situ Calibration of SODARs via Level Perturbation
A complementary system for in-situ sodar calibration has been identified and tested. The idea of this technique is to determine the precise beam angles of the sodar by performing measurements using different perturbations of the tilt angle. Tests at Høvsøre were made in July 2008.

4.3 WP6.3 Improvements to the Monostatic SODAR and the LIDAR

This task aims at identifying areas where the design of sodar and lidars can be improved or optimised. For the sodar, much attention has been paid to the effect of rain. Work in this area is ongoing.

Deliverables:
D6.3.1 IDENTIFY POSSIBLE IMPROVEMENTS TO SODARS
This report, written early in the project, concentrated on improvements to sodars. It was concluded that improvements could be made in the following areas of sodar design:

- Baffle design
- Use of multiple (redundant) beams
- Use of level sensors
- Improved signal processing for rain detection
- Bi-static designs

D6.3.1 QinetiQ Report on Cloud Removal Algorithm
For the lidar, the work on improvements has concentrated on the sensitivity of the continuous wave lidar to cloud and mist. After considerable testing at the Høvsøre test site, where a ceilometer is available to report cloud height, it was confirmed that the continuous wave lidar was indeed sensitive to extraneous backscatter from cloud, usually giving a positive bias. In addition, it was determined that the cloud-correction algorithm originally implemented in the ZephIR lidar to mitigate this effect, had the unfortunate side-effect of negatively biasing the reported wind speeds in periods where no clouds were present. A more sophisticated cloud-correction algorithm was clearly required. Based on work performed to screen ZephiR lidar data measured at the Horns Rev offshore wind farm (Penas et al), a new cloud correction scheme has been devised with selectivity and proportionality determined by the ratio of back scatter detected at a fixed low height (38m) and a fixed high altitude (800m). In the presence of cloud, this ratio will be much higher than 1 and the cloud correction can be made as before. As the ratio falls, so too does the degree of cloud correction until beneath a certain threshold, corresponding to clear sky conditions, no correction is made at all. This modified algorithm is now implemented on production ZephIR lidars. A description of this work is available on the web.

D6.3.2 Optimization of the sodar measurements including Operation of Monostatic sodars in rain.
Improving the performance of monostatic sodars in the rain will increase both the availability and accuracy of this instrument type. This deliverable has been combined in to the end-to-end sodar description D6.1.2.

D6.3.3 An analysis of the influence of volume integration and sampling frequency (contained in D6.1.3).
In flat terrain where the assumption of horizontal flow homogeneity is fulfilled, the vertical wind shear will be the main cause of discrepancies between the measurements of mean wind speed for a cup anemometer (point) and a remote sensing profiler (lidar or sodar). This effect is described in deliverable 6.1.3. Sampling frequency influences the uncertainty of the mean speed and should not cause a bias.

The standard deviation of the wind speed (or equivalently, the turbulence intensity) will be much more affected by both the volume averaging and sampling frequency. This is an important subject to understand, particularly if lidar anemometry is ultimately to replace cup anemometry. It is the subject of deliverables 6.3.3, 6.3.4 and 6.16.1.

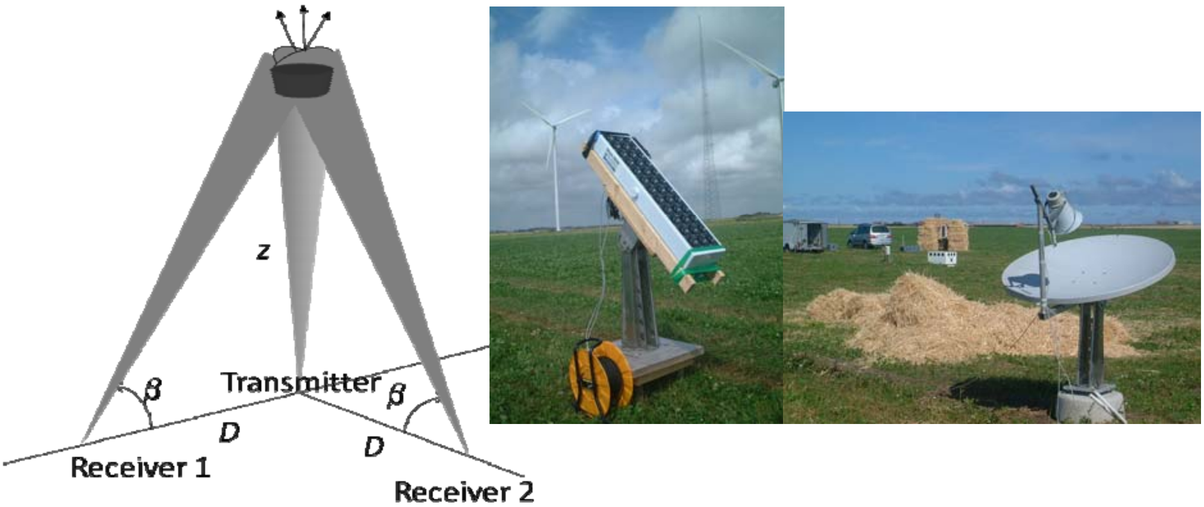
D6.3.3 Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer.
This is the first known attempt to measure wind speed and turbulence by using three lidar beams crossing at a point in space. Results from the experiment were fundamental in confirming our models for the spatial averaging due to the finite probe volume of both pulsed and CW lidars. This 'along-the-line' attenuation is one important component of the more complex case of how a lidar profiler senses atmospheric turbulence.

D6.3.4 Measurement of turbulence parameters through remote sensing in both flat and complex terrain.
This work has concentrated on relating the turbulence reported by a conically-scanning CW lidar to that reported by a cup or sonic anemometer. A mathematical model including the horizontal and vertical attenuation of the volume averaging has been derived and compared to measurements. Comparison with experimental data shows that the mathematical model has many of the correct features but can not explain the large scatter in the data.

6.3.5 Simultaneous sodar measurements at different frequencies with focus on the optimization of the instrument.
This deliverable had to be abandoned due to the operational difficulties with the available sodars.

4.4 WP6.4 Work on Bistatic SODARs

Deliverables:
D6.4.1 Bi-static sodar
In response to measurement inaccuracies in complex terrain, an entirely new remote-sensing technology, a scanning bi-static sodar, was developed and tested. The prototype was designed to give wind profiles from measurements within a single atmospheric column and over a height range from the ground to more than 200m, using receiver beam scanning. The transmitted signal is pulsed to give high spatial resolution and to reduce problems with direct beams (Bradley et al;, 2011b).



a) b) c)

Figure 2 Bistatic set-up a) schematic, b) receiver and c) transmitter in field setup at Høvsøre, DK, July 2008.

The design and first field tests of the first scanned bistatic sodar have been described. This new technology has significant advantages over previous bistatic sodars, all of which used a 'staring mode' in which wind data could only be obtained from a confined height range. The main motivation for designing a scanning bistatic sodar, described in the first section, is to avoid errors arising in all current sodars and lidars when they sample non-horizontally-uniform winds. This situation arises generically in complex terrain and, without a solution such as the new bistatic sodar, wind estimates in such regions are considerably compromised.

The result is single-column, or 'mast-like' sampling of the wind profile. But there are other advantages which have been identified in this work. These include

- improved SNR because of the extra scattering from velocity fluctuations
- much improved performance in neutral lapse conditions, where the turbulent temperature fluctuation contrast is low
- improved rejection of rain echoes through an advantageous scattering pattern
- larger Doppler shift reducing the possibility of erroneous velocity estimates arising from echoes from fixed structures

Comparisons were performed against mast-mounted instruments, and the velocity profile obtained with the bistatic sodar agreed with the 'standard' instruments to within measurement uncertainties (see Fig. 4.3). Finally, it is described how a step-chirp pulse sequence can be used to continuously profile the atmosphere and to obtain enhanced SNR. It was found the improvement in SNR to be close to the theoretical, the difference probably being due to the noise not being Gaussian, and to the signal (the wind velocity components) not being static. At this stage the Bradley et al. (2011b) manuscript only describes the new process for averaging spectra from different transmitted frequencies. A following publication will describe the large SNR improvements obtained through continuously transmitting, rather than the usual monostatic situation of transmitting for, say 0.1 s, then waiting 2 s for data to return from 300 m or so.

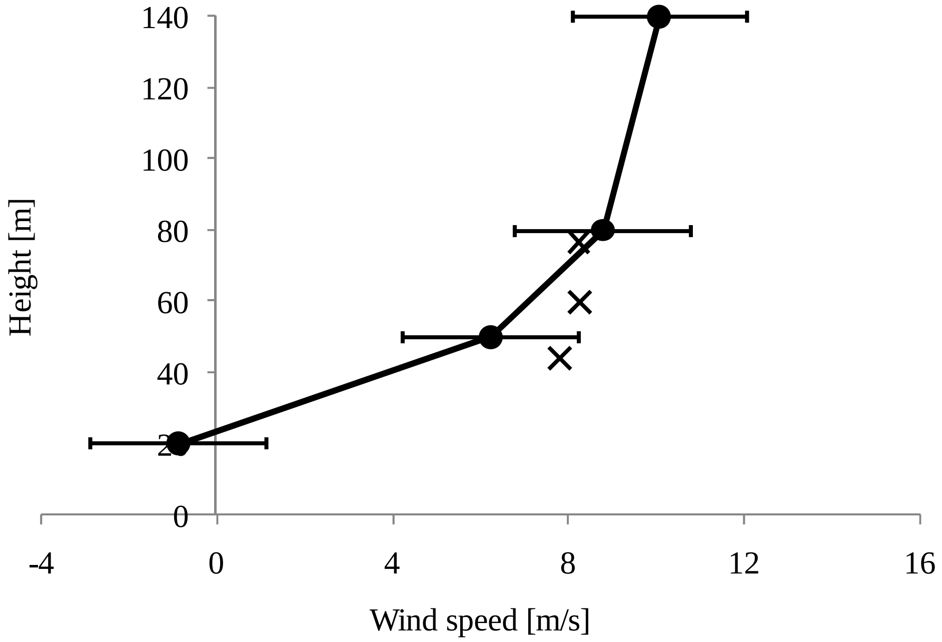


Figure 4.3 Wind speeds from the bistatic sodar (solid line and dots) compared with wind speeds from mast instruments (crosses).

4.5 WP6.5 Measurements -comparisons in flat terrain

Comparisons of measurements from remote sensing devices with mast measurements are our main tool for assessing the performance of lidars and sodars. In flat terrain, the assumption of flow homogeneity inherent in the design of sodar and lidar profilers, is fulfilled, giving the best possible comparison to mast-mounted instruments.

Deliverables:

6.5.1: Measurements in flat terrain using a sodar, a lidar and an instrumented met mast in front of a wind turbine.

Extensive testing of different lidar types (ZephIR, Windcube and recently Galion) has been carried out at the Høvsøre test station. In conjunction with Task 2, the methods for testing have been refined as performance and the repeatability of the lidars has improved. The state-of-the-art for lidar performance and our ability to perform repeatable measurements is illustrated in Figure 2.

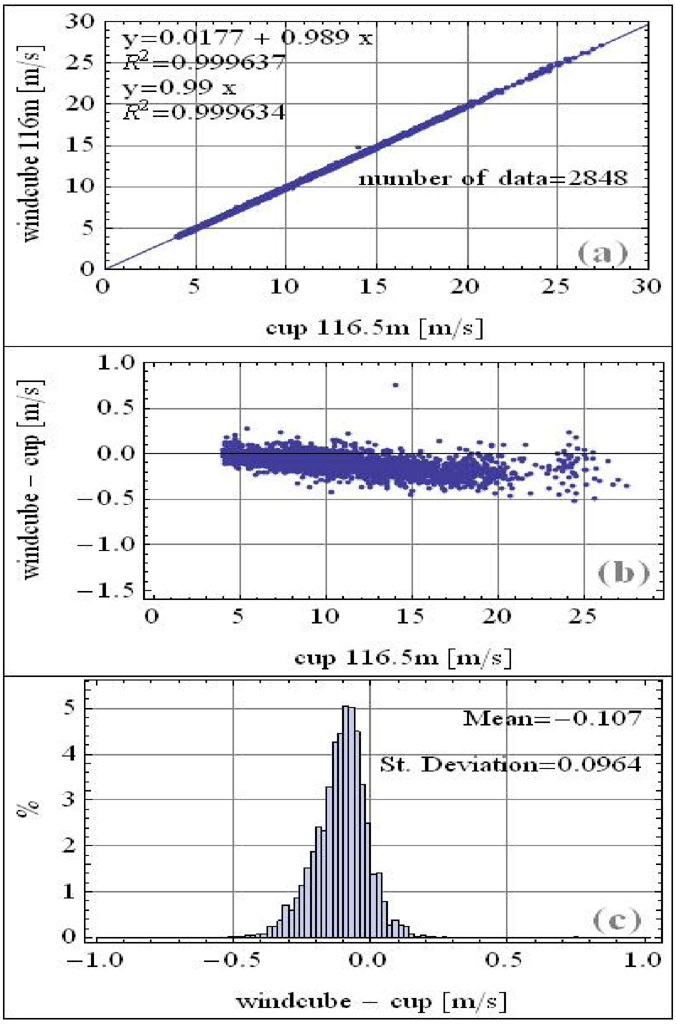


Figure 2 Comparison of simultaneous lidar (Windcube) and cup anemometer measurements. The data are presented as a) linear regression, b) error as a function of wind speed and c) distribution of error.

Investigation of the use of lidars and sodars for power performance measurements has also been performed. An initial experiment is reported. This experiment demonstrates that for normal profile types, a power curve measured using the wind speed profile measured by a lidar, combined into an equivalent wind speed is at least as good as a conventional measurement. Results using a sodar showed an increase in the scatter in the power curve, suggesting that only good lidar profile measurements will actually decrease the power curve uncertainty. Initial indications were that the equivalent speed method could result in significant reduction in the power curve scatter. Ultimately this will lead to more repeatable power curve measurements.

The importance of this work was recognised and a new task, WP6.15 was defined to further analyse the application of the so-called equivalent wind speed to power curve testing.

D6.5.2 Inter-comparison of two lidars closely situated next to each other.

An important task in the introduction of a new measuring technology is inter-comparisons with both existing measuring techniques and inter-comparisons amongst the new devices. This report is concerned more with the latter – inter-comparison of both nominally identical devices (e.g. two ZephIR’s measuring simultaneously) and comparison of two different lidar devices (ZephIR and WindCube measuring simultaneously).

By looking at data from two supposedly identical devices, in particular by looking at the similarities and correlations of the errors in relation to mast measurements, we can gain a better understanding of the applicability and maturity of the new technology. This will give an idea about how repeatable two versions of the same device really are and therefore how much 'calibration' of individual systems is necessary. In the case of perfect repeatability, it would only be necessary to measure one example of a given design. Due to manufacturing differences and component tolerances, this will probably not be the case in practice.

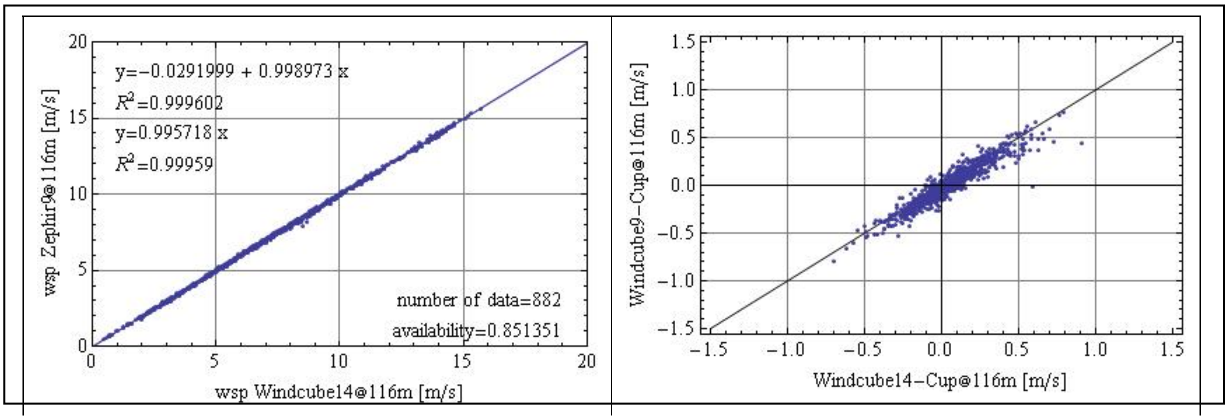


Figure 3 Scatter plot of simultaneous 10 minute wind speeds measured by two adjacent Windcubes (left) and scatter plot of the simultaneous errors (lidar speed - cup speed) for the two systems (right).

placed side-by-side. This indicates that most of the difference between lidar and cup anemometer is truly due to the difference in probing method rather than due to random noise.

4.6 WP6.6 Measurements -inter-comparisons in complex terrain

Lidar and sodar profilers measure with intrinsic errors in complex terrain since the requirement for homogeneity, inherent in their methods of extracting the horizontal wind speed, is not fulfilled. The aim of this task is to quantify these errors and to investigate means of dealing with this problem. Lidar and sodar measurements have been performed by CRES at two complex sites in Greece. Measurements in Spain, performed by CENER are now completed , after both technical and site access problems.

Initial results confirm that at most sites in complex terrain (with convex flow), the profilers will underestimate the true horizontal wind speed. Errors of up to 15% have been observed. Although it was initially presumed that smaller cone angles (measuring more nearly vertical) would minimize the errors, it was shown theoretically that this is in fact not the case. For symmetrical flow patterns, the error is independent of the cone angle used. This has been confirmed from simultaneous measurements using two Windcube lidars, one with a 15° and one with a 30° cone angle (Foussekis D., *Investigating wind flow properties in complex terrain using 3 lidars and a meteorological mast*, EWEC 2009, Marseille).

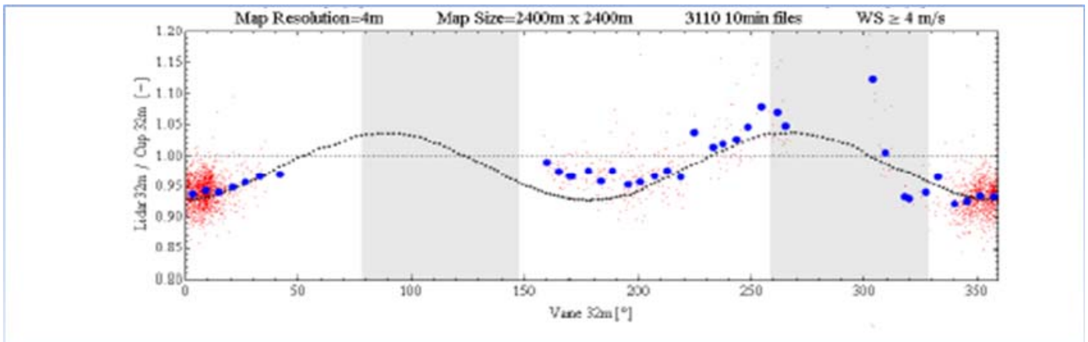


Figure 4: Predicting lidar error in complex terrain. Speed ratio (lidar/cup) as a function of wind direction. Red dots - measurements, Blue dots - binned averages, Hashed line - model prediction.

A method of predicting the lidar measurement error in complex terrain has been developed using flow modeling (BINGÖL, F., J. MANN, D. FOUSSEKIS, 2009: *Modeling conically scanning lidar error in complex terrain with WAsP Engineering.* – Meteorol. Z. , April 2009). A script for the WAsP Engineering flow model is now available for this purpose. Figure 4 shows an experimental verification of this method for a complex site in Greece.

Deliverables:

D6.6.1 Measurements in complex terrain using a sodar, a lidar and an instrumented met mast.

A report version of the above mentioned paper is contributed at part of deliverable 6.6.1. In addition, CRES have prepare a full report of the measured data from Greece, including comparisons with the theoretical error predictions.

6.6.2 Measurements in complex terrain using a lidar and an instrumented met mast in front of a wind turbine.

CENER have prepared a full report of the complex terrain measurements from Albacete in Spain. Comparisons with the theoretical error predictions are given.

4.7 WP6.7 LIDAR on the turbine nacelle

Measurements with lidars mounted on the wind turbine nacelle were investigated. The idea is to take advantage of the information on the upstream wind speed, which the turbine will experience at a later stage in order to optimize production and minimize the loads. Power curve measurements using the nacelle mounted lidar will be attempted in order to test the practicality of this attractive option.

Deviation from plan

An initial measurement campaign with a lidar mounted on a Vestas owned V110 wind turbine at the Høvsøre test station was conducted. Initial analysis of the data at the end of the campaign revealed data of very poor quality due to malfunctioning of the lidar (pitted fibre connectors). Due to the large resources required, it has been decided not to analyse this data set further.

Figure 5 The Risø V27 wind turbine with the ZephIR prototype CW lidar mounted on the top of the nacelle.

A second measurement campaign with a nacelle mounted lidar was attempted in 2009. In order to better match the range specifications of the available cw lidar, it was decided to make these measurements on a V27 turbine (27m diameter) situated at the main Risø-DTU site, see Figure 5.

Although it was originally envisaged to integrate the lidar output directly into the turbine control system, this is no longer a realistic ambition within the scope of the UpWind project. Allowing a lidar to control a wind turbine requires a degree of reliability and robustness in the lidar measurement that we are unable to provide at the present time. However, the measurement campaigns being carried out do have turbine control as one of the ultimate aims.

Deliverable:

D6.7.1 Doppler lidar mounted on a wind turbine nacelle – UPWIND deliverable D6.7.1

The measurements on the V27 were a partial success although only about 1 month of usable data were obtained before the data quality again deteriorated. Due to the limited data availability, it was not attempted to perform power curve or load measurements using the nacelle lidar dataset.

In this report the spectral characteristics of the wind speed as measured by two different instruments, a ZephIR prototype lidar and a METEK sonic anemometer were investigated. The ZephIR prototype lidar was mounted on the nacelle of a Vestas V27 wind turbine, while the METEK sonic anemometer was installed on a nearby located meteorological mast. The data analysis was focused on time intervals where the wind flow coincided with the line-of-sight of the lidar, thus minimizing the effect of the wind direction fluctuations to the detection of the wind speed turbulence.

Spectral analysis of the lidar wind speed measurements displayed a lower temporal resolution than those measured by the sonic anemometer. It was observed that the lidar was adequately measuring the turbulence fluctuations with wave-numbers below 0.01 - 0.03 m^{-1}. This limitation is attributed to the fact that the lidar measurements result from a convolution of the wind speed with a spatial weighting function, which acts in a similar fashion to a low pass filter.

4.8 WP6.12, 6.13 and 6.15 - Contributions to the IEC 61400-12-1 revision

A major priority in the final period of the project has been to make the knowledge gained in this work package available to the bodies engaged in revising international standards. Of particular relevance is the on-going revision of the important standard for power curve measurement, IEC 61400-12-1. Participants from work package 6 have participated as observers in meetings of this revision process. Three areas were identified where the experience from WP6 could be brought to bare, classification and uncertainty, mast verification and equivalent wind speeds. New deliverables were defined to highlight these topics:

Deliverables:

D6.12.1 Uncertainties in measuring wind from the viewpoint of a lidar calibration

Part of the work is concerned with an interpretation of the lidar uncertainty in a manner parallel to that for cup anemometers. This will form the basis of a future lidar classification scheme. Central issue of this report are the concepts of bias and uncertainty with regard to the proposed lidar verification scheme. The final aim is to set up an appropriate uncertainty budget for the lidar measurements, taking into account observed biases and inherent uncertainties (ie the scatter in the data) appropriately.

D6.13.1 Lidar profilers in the context of wind energy – A verification procedure for traceable measurements

This is a consolidation of the work already reported in 6.1.3, specifying a more formal procedure for traceable mast calibrations. The deliverable is a paper submitted to the journal Wind Energy.

D6.15.1 Power curve measurements using RS profile information

This deliverable is concerned with further documentation of the equivalent wind speed method applied to power curve measurements. It is anticipated that the IEC will adopt the equivalent wind speed based on a kinetic energy flux approach proposed in this report.

An indication of the power of this method can been seen by comparing Figure 6 with Figure 7. In the former, two distinct power curves from two groups of profile are seen. By applying the equivalent wind speed method to the same data, Figure 7, the two curves collapse to one.

The deliverable is a PhD thesis submitted and defended on this topic. This work is also submitted for publication in the journal Wind Energy.

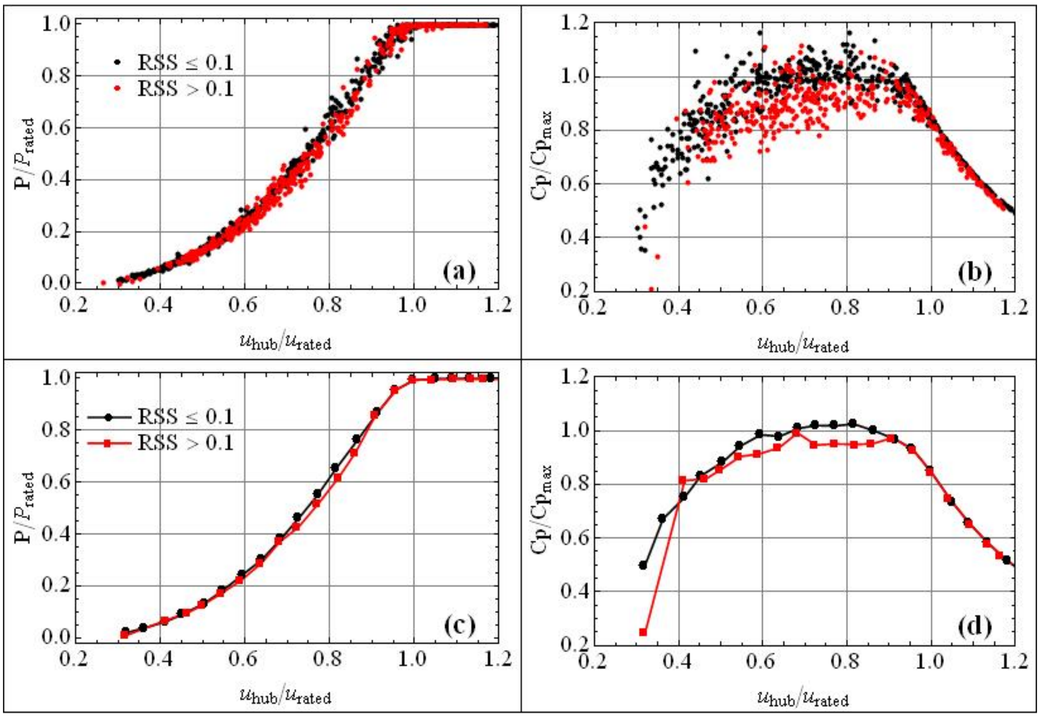


Figure 6 Power curves for different profile types ignoring the effect of wind shear. Two different power curves are apparent.

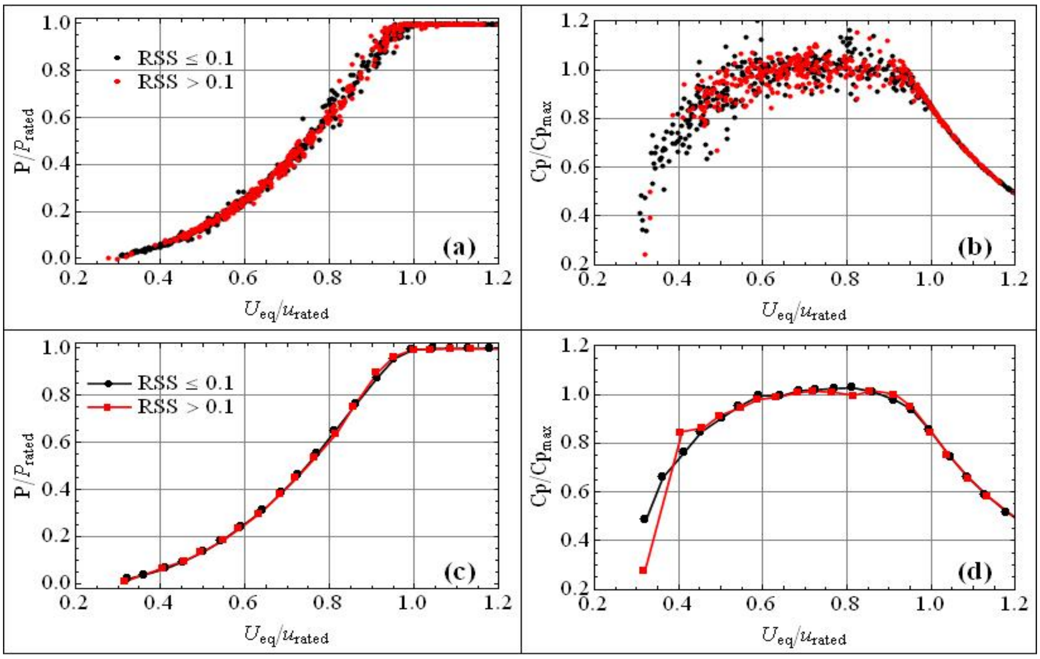


Figure 7 Power curve for two different groups of profile using an equivalent wind speed to include the effect of shear. The two curves collapse to one.

4.9 WP6.14 Aerosol backscatter statistics

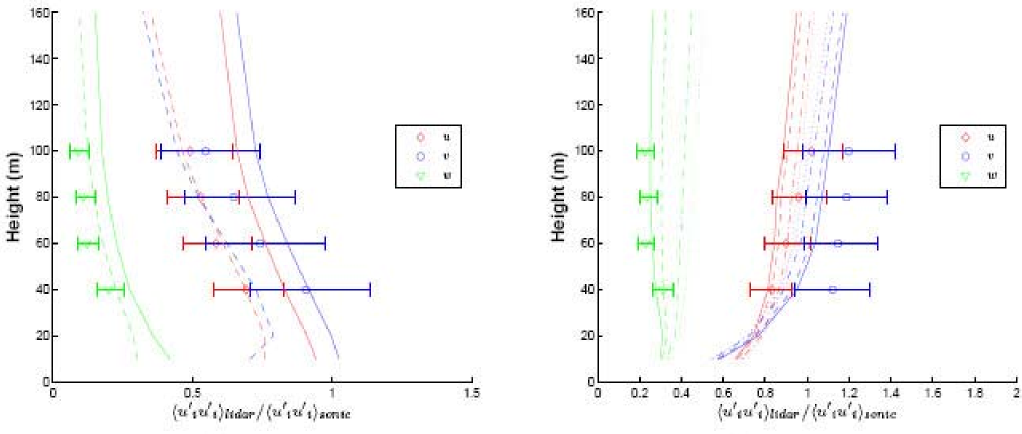
Use of lidars is always dependant on the presence of sufficient aerosol in the atmosphere to give the necessary backscatter. Aerosol concentration varies greatly – from very high in densely populated industrial areas (eg Japan) to very low in remote mountainous regions. Even in a given location, the aerosol concentration can vary significantly according to wind direction and atmospheric conditions. If lidars are ever to be used operationally on wind turbines, it is necessary to have a better understanding of how great these concentration variations can be at different locations.

Deliverables:
D6.14.1 QinetiQ Lidar Availability Report
This report summarises the factors that affect availability of lidar systems for wind measurements worldwide. The main factors are environmental tolerances, weather obscurants (cloud/rain/fog/snow), and aerosol backscatter. It is found that almost everywhere on the Earth, the boundary-layer backscatter is sufficient for > 95 % availability from current commercial lidar wind profilers. Dust particles, aerosols and pollutants are maintained in the atmosphere by natural and artificial processes: volcanoes, vehicle and powerplant emissions, forest fires etc. The air must be extremely clear (polar regions, high altitudes) for current commercial wind lidars to fail.

4.10 WP6.16 Lidar turbulence measurements

For wind turbine siting measurements, the turbulence intensities that can be experienced at the site is often as important to determine as the mean wind speed. From our earlier work in WP6, we had seen that our understanding of how lidar profilers sense atmospheric turbulence was incomplete. We had identified that the ratio between the turbulence measured by a cup anemometer and a lidar varies considerably and that this was not accounted for by the existing mathematical models. A new task was formulated to address this particular problem and to put lidar profiler turbulence measurements on a firmer footing.

Deliverables:
D6.16.1 Estimating the systematic errors in turbulence sensed by wind lidars
The goal is to model the systematic errors in the turbulence sensed by the CW and pulsed lidars using the VAD technique of lidar scanning. The line-of-sight averaging and the full extent of conical scanning is considered. Figure 8 shows that the modelled systematic errors for the u, v and w variance agree well with the measurements. This work has also been submitted to JTech [19].



(a) ZephIR (b) WindCube

Figure 8 ZephIR and WindCube systematic errors under neutral conditions. The markers indicate measurements.

5. Specific results - Impact on the wind energy community

WP6 has contributed very significantly to the development of remote sensing for wind energy. Important results have been accomplished, in particular in the areas of sodar calibration, bi-static sodar design, lidar testing, the use of lidars in complex terrain, power curve testing using remote sensing and the understanding of the turbulence sensed by lidars. Ultimately many of these advances have contributed to the improvement and modernization of standards and best practices, most notably the IEC 61400-12-1 power performance standard revision.

Apart from the more formal work, WP6 has functioned as an important European remote sensing forum, especially within the field of lidar development. Work package meetings have included a number of participants from outside the project group, both from industry and other research institutes.

5.1 Sodar –calibration and design improvements

A central aim has been to develop techniques for the in-situ calibration of sodars. One idea that has been developed in the project is to build a transponder system that simulates in a pre-defined manner, the acoustic response of the atmosphere to the transmitted signal under different speed and shear conditions [1]. This system has been found to be a useful tool for laboratory quality control and investigation of sodar behavior but has practical limitations in real-life field environments. A much simpler system that can measure the effective beam tilt angles by using in-situ tilting of the lidar, has been proposed and tested with promising results [2].

Bi-static sodar designs, where the transmitter and receiver are physically separated, are much more sensitive than mono-static sodars and can have significant advantages in complex terrain. Under the auspices of WP6, a scanning bi-static sodar design has been proposed [3]. Successful testing has been carried out in flat terrain and the system will soon undergo trials in mountainous landscape. Several commercial bi-static sodar designs are now beginning to emerge [20].

5.2 Lidar testing in flat terrain

Comparisons of measurements from remote sensing devices with mast measurements are our main tool for assessing the performance of lidars and sodars. In flat terrain, the assumption of flow homogeneity inherent in the design of sodar and lidar profilers is fulfilled, giving the best possible comparison to mast-mounted instruments. Especially concentrating on wind lidars, that are still rather new and technologically immature, this has been a major task in WP6 and has provided important synergy to other EU projects using lidars, notably NORSEWInD and SafeWind.

Indisputably, the lidar testing carried out under WP6 has provided important feedback to the lidar manufacturers. For example it has been identified that the deflection angles of the prisms used in both the major wind lidar types were too imprecise. New procedures for individually measuring the prism cone angles have resulted in significant improvements in lidar precision. Another important example is the improvements made to the cloud correction algorithm in the ZephIR lidar, a direct result of the work within UpWind. Thorough analyses of lidar error sources have been undertaken within WP6 [6] and these findings used both to improve lidars and to improve the lidar testing procedure. In flat terrain, pulsed wind lidars provide consistently high correlations to reference cup anemometers [7].

As lidars have improved, so too has the demand for accurate testing. Especially the need to validate a whole wind speed profile as opposed to a speed at a single height imposes unprecedented demands on the accuracy of boom mounted cup anemometers. A new scheme using two cup anemometers mounted on two identical but differently pointing booms at one height has recently been proposed [8] which significantly reduces the uncertainty of boom mounted cup anemometer measurements.

Figure 10 Commercial lidars undergoing test at Høvsøre, Denmark. WP6 has contributed significantly to wind lidar development and testing.

5.3 Lidar measurements in complex terrain

Wind lidars use an assumption of horizontally homogeneous flow in order to calculate the horizontal wind speed. Whilst this is a good assumption in flat terrain, in complex terrain the flow is rarely horizontally homogeneous and consequently significant errors can occur in the measurement of the horizontal wind speed. A major result for WP6 has been to propose a scheme using flow models to predict and correct for the error [9]. Major wind lidar manufactures now offer such an error correction scheme based on CFD modeling as optional services for their products.

5.4 Power curve testing

Power curve measurements require wind speed measurements at the hub height of the wind turbine. As wind turbines increase in size and height, this requirement alone makes ground-based lidar or sodar anemometry more attractive. At the same time, with increasing rotor diameter, the concept of correlating wind turbine power production to a single, hub-height wind speed becomes more and more suspect. It is now well accepted that the wind speed profile has a significant effect on the power production and an equivalent wind speed method has been proposed to include the influence of the speed shear [12]. Measurements have shown a significant reduction in scatter when the power is plotted as a function of the equivalent wind speed rather than the hub-height wind speed [13]. Uncertainty budgets show that a remote sensing device with a very high correlation to the reference cup anemometer is required.

5.5 Lidar turbulence measurements

At a prospective wind energy site, the turbulence intensity is often as important to ascertain as the actual wind resource. Lidar testing has shown that, even when the mean wind speed is highly correlated to a reference cup anemometer measurement, the standard deviations of wind speed are much less well correlated between the lidar and reference. In WP6, this has been examined both theoretically and experimentally.

Firstly, the turbulence measured by a ‘staring’ lidar (one constant line of sight as opposed to scanning) has been compared with that measured from an adjacent sonic anemometer [15]. Good agreement was found. For a conically scanning lidar, several mechanisms combine to attenuate the wind speed standard deviation observed by the lidar. A model including the spatial averaging both along the lines of sight and around the scanning circumference has been proposed and compared to experimental measurements [16]. Whilst generally good agreement is found, the lidar and cup anemometer standard deviations are still very scattered. An even more rigorous model including the contribution from all 3 components of turbulence has recently been proposed [19]. Here it is found that the ratio between lidar and cup anemometer turbulence intensity varies markedly both with height and atmospheric stability. Using current lidar designs it is impossible to accurately measure the horizontal turbulence intensity unless a sonic anemometer, giving the ratio between the 3 turbulence components, is present.

5.6 IEC 61400-12-1 revision

Many of the results from WP6 are contributing to the modernization of the strategically important power curve standard, IEC 61400-12-1. Most importantly, the equivalent wind speed method is proposed as a central component for the revised standard. Since remote sensors are obvious tools for measuring wind speed profiles, WP6 is also contributing concepts and methods for lidar verification including a rigorous proposal for lidar uncertainty [14].

6. Future developments in Remote Sensing for wind energy

In the space of the 5 years spanned by the UpWind project, we have seen a colossal change in the impact of remote sensing on wind energy. Today whole new breeds of instruments exist – fully autonomous sodars and 2nd generation wind lidars. Remote sensing is commonly used in site assessment and is also being introduced to the new power curve standard. In the research community, especially for lidars, the centre of interest is shifting from ground-based profilers to embedded-lidars for control and nacelle-mounted systems for power and load certification. From this vantage point, we will attempt to predict future developments and briefly highlight areas of special interest.

6.1 Autonomous sodars

Completely new designs of sodar, specifically targeted to wind energy, are emerging. Common amongst them is that they are fully autonomous, requiring no external power or communication connection. Power is provided by a combination of solar, wind and generator together with a suitable battery bank. Communications are based on satellite or terrestrial 3G links, often with dedicated web services for the data management. We will see a continuation of this trend with falling power consumptions. This level of autonomy and low power consumption (some systems use less than 10W), together with a relatively low price, give a substantial competitive advantage over current lidars, even though measurement performance and availability can not be matched.

6.2 Monostatic-Bistatic combined sodars

In WP6 we have had a task specifically dedicated to bi-static sodars (where transmitter and receivers are separated in space). It has been shown that the bi-static design, despite its increased complexity, can offer significant performance enhancements. In part influenced directly by the work performed in WP6, a new generation of combined monostatic/bistatic sodars is emerging, where the original monostatic system is supplemented by auxiliary receivers when the improved performance of the bi-static method is required [20]. This is especially suited for measurements in complex terrain. It will be fascinating to see if the performance advantages outweigh the extra cost, complexity and power consumption.

6.3 Better Lidars- less power and less expensive

The first generation of lidars was not renowned for their reliability. With time, the situation has improved considerably where it is now a good assumption that the lidar will work on deployment rather than the opposite! Indeed there are several examples of measurement campaigns in fairly demanding locations (e.g. offshore on oil platforms) where well over one year of continuous lidar operation has been achieved.
New models of both pulsed and CW lidars appeared in 2010 and it is remarkable how much attention has been paid to improving reliability and also to reducing power consumption. A

contemporary lidar profiler has a power consumption of around 50W, nearly a reduction by a factor of 3 on the first generation. However this is still a sizable amount of power to generate in a truly remote location. Taking the example of the sodars, a further significant reduction may well be needed if lidars are to become commonplace in the wind industry. Ultimately it is economics that determine if a lidar if truly worthwhile. Lidars still cost in excess of 100k€ and without some very clear demonstrations of the added value of a lidar profiler to a wind project, this is possibly still the largest disincentive to their more widespread use.

6.4 Lidar's ability to measure turbulence

As part of the work of WP6 has shown, current lidar profilers are unable to measure the horizontal turbulence intensity with the same accuracy as a cup or sonic anemometer. Since turbulence and extreme wind speeds are important secondary parameters in a wind farm site assessment, it is important to improve lidar accuracy in this respect. Risø DTU is proposing a new scan configuration using six different beam directions [25], which is theoretically shown to give a significantly lower uncertainty in the horizontal turbulence estimation. This will be experimentally tested in course of 2011.

6.5 Lidars mounted on wind turbines

Only a small amount of the work in WP6 has been concerned with lidars mounted on a wind turbine. Had the project started only recently, a much higher proportion of the work would have concerned this exciting area. Five years ago, lidars did not have the technological maturity to be used in the challenging nacelle-top environment. Today they are much more suited and a lot of experimentation is taking place or is planned.

There are two very distinct ways of employing a lidar on a wind turbine. The first is to use the lidar measurements to predict the incoming wind and pass this information to the control system which is then able to proactively regulate the blade pitch, either to reduce loads or to increase power capture. Such a use requires a lidar embedded somewhere on the wind turbine – possible locations are the nacelle top, inside the spinner or maybe even in the blade root. Thus the lidar becomes an integrated part of the wind turbine and requires an intimate connection to the control system. This is a highly competitive area of research, much of which is probably undertaken by turbine manufacturers under strict confidentiality.

A second, very different application is to place the lidar on the nacelle top and measure either the incoming wind or the turbine wake. This can have obvious experimental benefits, providing detailed flow descriptions. In the longer term, nacelle-top lidars may well prove to be an excellent replacement for upstream measuring masts as recent power curve measurements using this technique have shown. This is an exciting area for research, subsequent demonstration and ultimately application to the international standards.

6.6 Windscanners

Windscanners (or multi-lidars) are lidars with steerable beams, operating in consort. By separating the lidars, the individual beams can be arranged to coincide at one point in space with different angles, see Figure 9. A schematic of the Windscanner (multi-lidar) system being developed at Risø DTU.. Such an arrangement, in contrast to a single lidar profiler, can give the total 3D wind vector without the resort to the assumption of homogeneity. Using a sophisticated control system the beams (usually 3 for a complete 3D vector) can be steered through space together, providing a complete 3D scan of the wind field.

Such systems are being built in the Risø DTU Windscanner.dk project [39]. Both a short range CW system capable of scanning at 500 Hz at ranges up to 150m and a long range pulsed system with a 5km maximum range, are being built. Recently, the project was included on the ESFRI roadmap and is the first wind energy project to be a candidate for the large scale funding associated with ESFRI.

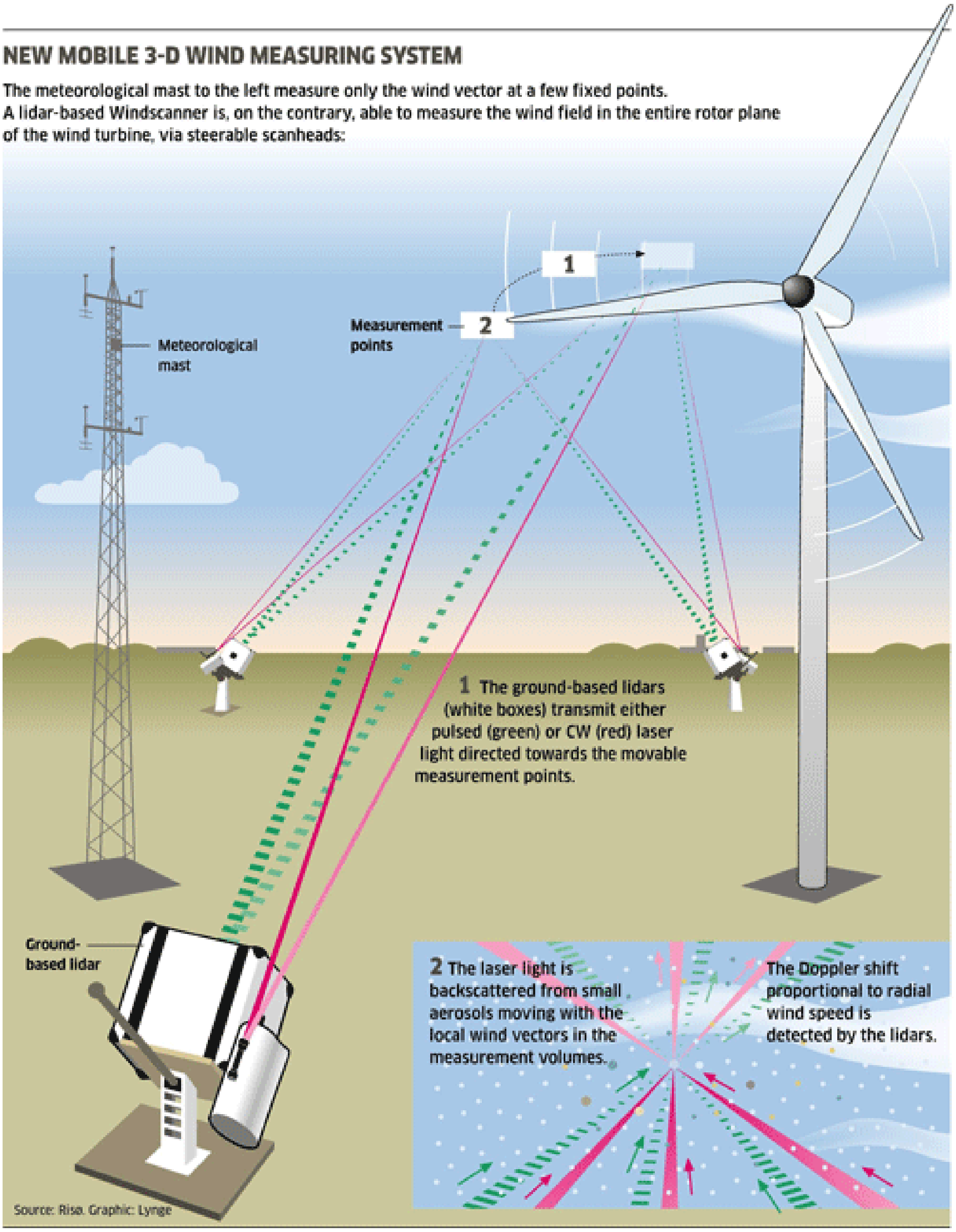


Figure 9 A schematic of the Windscanner (multi-lidar) system being developed at Risø DTU.

7. Dissemination

7.1 Contributions to conferences

EWEC 2007

Ioannis Antoniou, *REMOTE SENSING THE WIND USING LIDARS AND SODARS*
Dimitri Foussekis, *WIND PROFILE MEASUREMENTS USING A LIDAR AND A 100M MAST*
Hans Ejsing Jørgensen, *LIDAR AS A VIRTUAL MET-TOWER*

ISARS 2008

S Bradley, *Robust, 'blind', in-situ calibration of SODARs.*
P Behrens, *A scanning bi-staic SODAR.*
J Mann,*Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer.*
M. Courtney,*Testing and comparison of lidars for profile and turbulence measurements in wind energy.*
P Lindelöw, *Wind shear proportional errors in the horizontal wind speed sensed by focused, range gated lidars.*
B Piper, *The Development of a transponder based technique for the acoustic calibration of SODARs.*
M Sjöholm, *Time series analysis of continuous-wave, coherent Doppler Lidar wind measurements.*

EWEC 2008

D Foussekis, *Lidar and sodar measurements in complex mountainous areas.*
Michael Courtney, *COMMERCIAL LIDAR PROFILERS FOR WIND ENERGY. A COMPARATIVE GUIDE.*
H Jørgensen. *Upwind progress in the remote sensing of the wind using lidars and sodars.*
Rozenn Wagner**,** *WIND CHARACTERISTICS MEASUREMENT FOR LARGE WIND TURBINE POWER CURVE*
Stuart Bradley, *PRECISION WIND PROFILING USING NEW ACOUSTIC TECHNOLOGIES*

EWEC 2009

Stuart Bradley, *NEXT-GENERATION ACOUSTIC WIND PROFILERS.*
Ferhat Bingöl, *LIDAR PERFORMANCE IN COMPLEX TERRAIN MODELLED BY WASP ENGINEERING.*
Dimitri Foussekis, *INVESTIGATING WIND FLOW PROPERTIES IN COMPLEX TERRAIN USING 3 LIDARS AND A METEOROLOGICAL MAST.*
Alfredo Peña, *EXTENDING THE WIND PROFILE MUCH HIGHER THAN THE SURFACE LAYER.*
Stuart Bradley, *ESTIMATION AND CORRECTION FOR WIND SHEAR WITH SODAR AND LIDAR REMOTE SENSING IN COMPLEX TERRAIN.*
Petter Lindelöw, *ARE LIDARS GOOD ENOUGH? ? ACCURACY OF AEP PREDICTIONS IN FLAT TERRAIN GENERATED FROM MEASUREMENTS BY CONICALLY SCANNING WIND SENSING LIDARS.*
Torben Mikkelsen, *WIND AND TURBULENCE PROFILE MEASUREMENTS FROM GROUND-BASED LIDARS: ON THE DIFFERENT TIME AND SPACE RESOLUTION PROPERTIES OF CONTINUOUS WAVE AND PULSED LIDAR SYSTEMS - A REVIEW.*
Rozenn Wagner, *INVESTIGATION OF TURBULENCE MEASUREMENTS WITH A LIDAR.*

AWEA 2009

Michael Courtney, *Lidar Profilers in Wind Energy - The State of the Art.*
Rozenn Wagner, *Power curve measurements using sodar and lidar.*

EWEC 2010

Rozenn Wagner, *IMPROVEMENT OF POWER CURVE MEASUREMENT WITH LIDAR WIND SPEED PROFILES.*
Dimitri Foussekis *INVESTIGATING THE DEVIATIONS OF VERTICAL WIND SPEED COMPONENT, MEASURED BY SONICS AND LIDARS, IN COMPLEX TERRAIN.*
Dimitri Foussekis, *LIDARS DEPLOYMENTS IN COMPLEX TERRAINS.*
Julia Gottschall, *APPLICATION-ORIENTED CLASSIFICATION OF LIDAR PROFILERS – OR: INTRODUCING LIDARS TO POWER PERFORMANCE TESTING.*

ISARS 2010

BRADLEY S.	Integration of a scanning bistatic option into a commercial SODAR
GOMEZ P.	Power curve with lidar in complex terrain
MANN J.	Systematic error in the estimation of the second order moments of wind speeds by lidars

7.2 Journal publications (accepted and submitted)

BINGÖL, F., J. MANN, D. FOUSSEKIS, 2009: *Modeling conically scanning lidar error in complex terrain with WAsP Engineering.* – Meteorol. Z. , April 2009

Sjöholm, M; Mikkelsen, T; Mann, J; Enevoldsen, K; Courtney, M. *Spatial averaging-effects on turbulence measured by a continuous-wave coherent lidar*. Meteorologische Zeitschrift, Volume 18, Number 3, June 2009 , pp. 281-287(7).

Mann, J; Cariou, Jean-Pierre; Courtney, Michael S.; Parmentier, Rèmy; Mikkelsen, Torben; Wagner, Rozenn; Lindelöw, Petter; Sjöholm, Mikael; Enevoldsen, Karen. *Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer*, Meteorologische Zeitschrift, Volume 18, Number 2, April 2009 , pp. 135-140(6)

J. Mann, A. Pena, F. Bingöl, R.Wagner, and M S. Courtney. Lidar scanning of momentum flux in and above the surface layer. Journal of Atmospheric and Oceanic Technology, 27(6):792 806, 2010. DOI:10.1175/2010JTECHA1389.1

Wagner R, Antoniou I, Petersen SM, Courtney M, Jørgensen HE. *The influence of the Wind Speed Profile on Wind Turbine Performance Measurements*, Wind Energy, 12, issue: 4, 348-362, (2009).

Lindelöw-Marsden P. et al. *Investigation of flow distortions on boom mounted cup anemometers on a lattice tower – proposal of correction algorithm and in-field calibration method*, submitted to Wind Energy, September 2010.

Wagner R, Courtney M, Gottschall J, Lindelöw –Marsden P. *Accounting for the wind speed shear in wind turbine power performance measurement*, submitted to Wind Energy, July 2009, currently under revision.

Gottschall J, Wagner R, Courtney M, Jørgensen H, Antoniou I, *Lidar profilers in the context of wind energy – A verification procedure for traceable measurements*, submitted to Wind Energy, September 2010.

Sathe A, Mann J, Gottschall J, Courtney MS, *Estimating the systematic errors in turbulence sensed by wind Lidars.* Submitted to JTECH, September 2010.

Bradley S, Von-Hunerbein S, Mikkelsen T, *A bi-static sodar design for precision wind profiling in complex terrain.* Submitted to JTech, January 2011.

8. Conclusion

The work performed in WP6 has had a major influence on the use of ground-based remote sensing in wind energy. Amongst the highlights are:

- Development of a new robust method to be calibrate SODAR’s in-situ.
- Bi-static Sodar systems built based on phased array.
- Lidar testing against masts providing valuable feedback.
- Improved cloud corrections scheme developed for the Zephir CW lidar.
- Error corrections based on flow modelling for lidars measuring in complex terrain.
- New methods of determining sensing height errors in remote sensors.
- Measuring power curves with lidars based on profile measurements.
- Better understanding of how lidars sense turbulence.
- Major contributions to introducing remote sensing to the power curve standards.
- An overview of how aerosol affects lidar availability.

Members of WP6 have been busy in disseminating their results with over 30 conference contributions and 10 journal articles.

Figure 10 Group photo from the last WP6 meeting at the Vestas R+D headquarters in Aarhus, Denmark.

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11. Table of deliverables

Del. No	Orig. Del. No.	Document name	Pages	Partner	Comment
D6.1.1	New	LEOSPHERE pulsed Lidar principles.pdf	33	Leosphere	End-end description of pulsed lidar
D6.1.1	D6.1	QinetiQ Lidar measurement report_September 2010.pdf	37	QinetiQ	End-end description of CW lidar
D6.1.2	D6.1	D6.1.2_Sodar_measurement_description.pdf	50	USAL	End-end description of sodar
D6.1.3	D6.1	D6.1.3_Uncertainties_in_wind_measurements_with_Lidar	54	Risø DTU	Lidar error sources
D6.2.1	D6.2	D6.2.1_Remote_sensing_in_IEC_power_ performance.pdf	6	Risø DTU	Note on including lidars in IEC61400-12-1
D6.2.2	D6.2	D6.2.2_Sodar_Comparison_methods.pdf	210	USAL	Transponder calibration for sodars
D6.2.3	D6.2	QinetiQ Lidar calibration report_September 2010.pdf	9	QinetiQ	Lab calibration of CW lidars
D6.2.4	New	D2 In_situ_Calibration_of SODARs_via_Level_Perturbation.p	13	USAL	Field calibratioin of sodars by tilting
D6.3.1	D6.3	QinetiQ Cloud removal algorithms_September 2010.pdf	6	QinetiQ	CW cloud-correction improvement
D6.3.1	D6.3	UpWind_Improvements_18month.pdf	11	USAL	Areas of improvements for sodars
D6.3.2	D6.3	Contained in D6.1.2	0	USAL	Sodar optimisation
D6.3.3	D6.3	D6.3.3_3D_lidar_turbulence_measurements.pdf	19	Risø DTU	3D Turbulence measurements using 3 lidars
D6.3.4	D6.3	D6.3.4_Turbulence_measurements_from_a_CW_Lidar.pdf	26	Risø DTU	How CW wind lidars sample turbulence
D6.4.1	D6.4	D6.4.1_Bistatic_Sodar.pdf	31	USAL	Design of a scanning, bistatic sodar
D6.5.1	D6.5	D6.5.1_Power_curves_using_lidars_and_sodars.pdf	35	Risø DTU	RS mast comparisons and power curves
D6.5.2	D6.5	D6.5.2_Simultaneous_measurements_on_two_lidars.pdf	22	Risø DTU	Simultaneous dual lidar measurements
D6.6.1	D6.6	D6.6.1_Modelling_Lidar_errors_in_complex_terrain.pdf	20	Risø DTU	Modelling lidar errors in complex terrain
D6.6.1	D6.6	D6.6.1_Complpex_terrain_lidar_sodar_CRES.pdf	36	CRES	Lidar and sodar in complex terrain - Greece
D6.6.2	D6.6	D6.6.2_Complex_terrain_lidar_Spain.pdf	36	CENER	Lidar in complex terrain - Spain
D6.7.1	D6.7	D6.7.1_Doppler_Lidar_mounted_on_WT_risoe-r-1757.pdf	46	Risø DTU	CW lidar mounted on a wind turbine

Continues....

Del. No	Orig. Del. No.	Document name	Pages	Partner	Comment
D6.8	D6.8	UpWind WP6 D6.3 Risoe_12month_report02.doc	35	Risø DTU	12 month report
D6.8	D6.8	UpWind WP6 D6.3.b CRES 12month report.doc	22	CRES	12 month report
D6.8	D6.8	UpWind WP6 D6.3b 1st Year Progress report_CENER.doc	41	CENER	12 month report
D6.8	D6.8	UpWind WP6 D 6.3.a 12 month reportUSAL.doc	12	USAL	12 month report
D6.8	D6.8	UpWind WP6 D 6.3_Vestas.doc	3	Vestas	12 month report - flat terrain measurements
D6.8	D6.8	UpWind WP6 D6.7 a Vestas.doc	3	Vestas	12 month report - Nacelle lidar
D6.8	D6.8	UpWind WP 6 D 6.3b QQ 12-month report v2.doc	6	QinetiQ	12 month report
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