Verification of wind energy related measurements with a SODAR system

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Trailer-based SODAR system during a measurement within a wind farm

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Abstract

Complex terrain and growing wind energy converters (WEC) in wind parks generate increasing interest in determining wind profiles and turbulence besides the general forecast of annual energy production. Increasing hub heights and growing rotor diameters of advanced WEC make SODAR systems a valuable alternative to meteorological towers. SODAR systems provide wind profiles as well as turbulence information over the entire height of large turbines. With SODAR measurements at WEC testing field in Grevenbroich in comparison to sonic and cup anemometers the usability of qualified wind and turbulence data from a SODAR are verified.

Results from simultaneous measurements of cup anemometers, ultra-sonic anemometers and the SODAR system show the differences and the compatibility between them. But they also show their suitability for wind measurement and turbulence determination. Site calibration with 2 ultra-sonic anemometers at 50 m height above ground level and an ultra-sonic anemometer and the SODAR thereafter prove the close agreement between these different measuring methods. The same result can be drawn from a comparison of a SODAR and a calibrated cup anemometer at 50 m height.

To complete the spectrum of comparisons in wind speeds an experiment of a European project (WISE) is quoted for profiles at 5 different heights.

The relationship between turbulence data of the different devices (cup and ultra-sonic anemometers with SODAR) referring to accepted guidelines like IEC 61400-1 allow the conclusion that it is possible to check a site for turbulence intensity and intensity profile with a SODAR to make sure that mechanical loads are resumed well.

Finally a power performance curve of a cup anemometer and a SODAR are compared.

1. Introduction

The results presented here are mainly based on the results of a common research project (“WIPRO” – partly funded by the German state of North Rhine-Westphalia) of WINDTEST Grevenbroich GmbH (WTG) and GWU-Umwelttechnik (GWU) with the goal to analyze and optimize SODAR measurements for the demanding requirements of wind energy applications.

GWU has been involved in meteorological measurements for more than 20 years with one major focus on wind energy related wind and wind profile measurements.

WTG is acting worldwide as an accredited technical consulting and service company in the wind energy sector. They operate the largest inland test field for wind energy systems hosting several prototypes of wind turbines from different manufacturers. This well known test site was used for some of the basic investigations and experiments presented in this paper.

1.1 What is a SODAR?

SODAR (Sound Detection and Ranging) is a remote sensing technique using audible acoustic pulses which are emitted into at least 3 different directions. While the sound travels upwards it interacts with atmospheric turbulence and a fraction of it is backscattered. The radial movement of the scattering air volume causes a frequency shift proportional to (radial) speed (Doppler shift). The SODAR collects the backscattered signal as a function of time (which is used to determine the height) and analyzes it for Doppler shift.

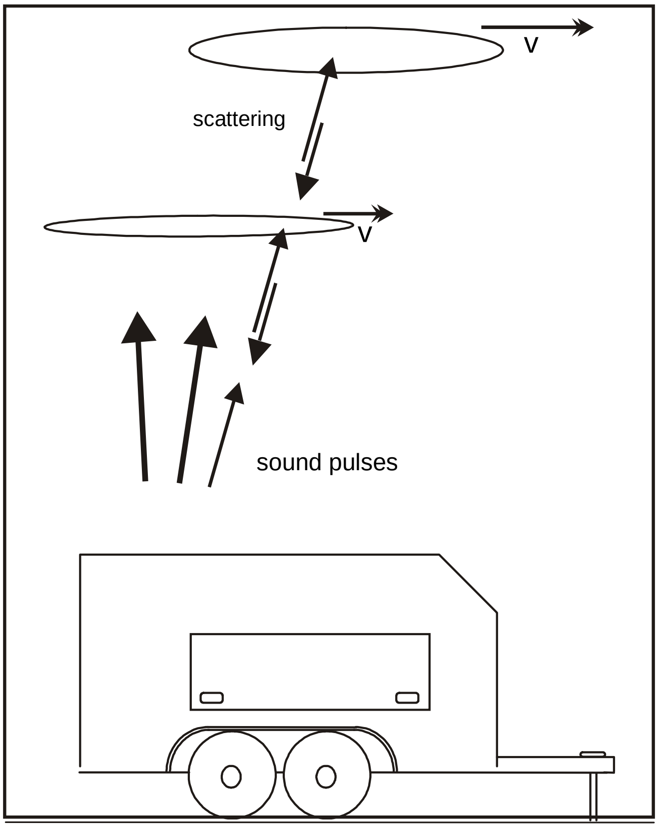

Fig. 1: SODAR operating principle

As the Doppler shift is directly proportional to the transmit frequency it is easier to quantify this shift at higher transmit frequencies. The crucial demands for accuracy with wind energy applications require a frequency as high as possible. On the other side higher frequencies are affected by a stronger attenuation in the atmosphere than lower frequencies. This leads to a compromise between accuracy and resolution on one hand and maximum height that can be reached on the other. For our experiments we selected a miniSODAR from AeroVironment (this products line has been meanwhile transferred to Atmospheric Systems Corp.).

1.2 Applications of SODARs in wind energy

In wind energy we find various applications in which SODARs can be used instead or as a compliment to wind towers. This can be wind site assessment or micrositing for planning a wind farm. For the latter a typical procedure is to setup a mast at a central position of the projected wind farm and move the SODAR around to the different locations of the turbines.
The fact that continuous wind profiles instead of a few discrete levels from towers can be measured allows quantifying the effect of wind shear across the rotor area on power performance.
Other applications are measurement of turbulence and turbulence profiles as well as verifying power curves e.g. of individual wind turbines within a wind farm.

When it comes to the point to discuss the method to measure wind with at a certain height and SODAR comes into the discussion usually the question arises how good the data quality is or how well data compare to more conventional assumed proven technologies

Before comparing data from SODAR with anemometer data we should keep in mind the basic differences of the methods involved.

SODAR is a vector measurement that reports the three components independently from each other while cup anemometers sense a scalar that even can be affected by the vertical component (i.e. the speed reported can be the magnitude of the three-dimensional or two-dimensional wind vector depending on the individual layout of the sensor). All mechanical sensors show some inertia with their moving parts whereas SODARs are basically inertia-free (like ultra-sonic anemometers). Another major difference is the measuring volume of the SODAR which typically is tens of cubic meters of air compared to the extremely small measuring volume of any in-situ sensor.

2. Verification of wind speed and wind profile measurements

2.1 Wind speed measurement verification

2.1.1. Comparison SODAR with cup anemometer

Recently we had a chance to compare the SODAR to a 50 m mast about 6-8 km on land at the French west coast. The mast was equipped with a calibrated cup anemometer. The data base of each point in Fig. 2 and Fig. 3 is a 10-min-average value of wind speed. The linear regression shows a slope of about 1.04 and a bias of -0.21 m/s (Fig. 2). Both measurements are highly correlated showing a correlation coefficient of slightly below 0.96.

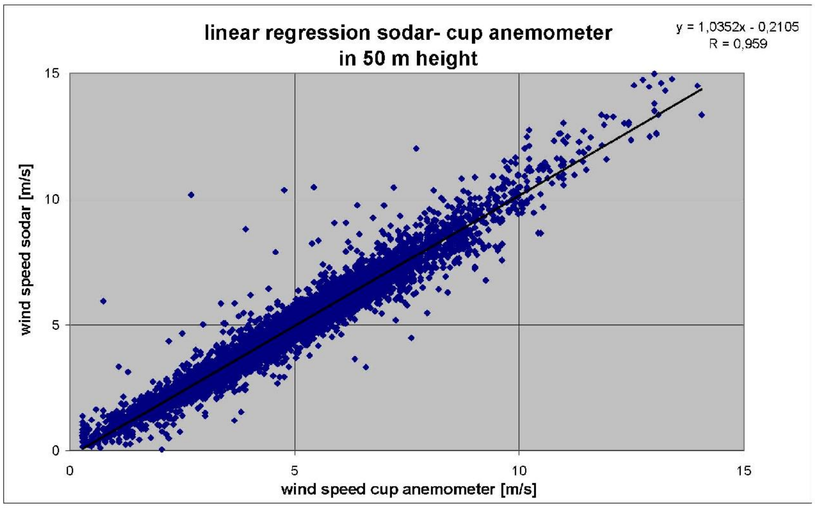

Fig. 2: Linear regression SODAR vs. cup anemometer with offset

Looking at the low speed end of the data one can notice that the cup never reaches 0 which is caused by the offset from the calibration procedure of the cup anemometer. As this is at one end of the curve the influence cannot be neglected. There are 2 possibilities to reflect this in data processing: reject all data below a certain threshold or force the regression line through zero (origin). We decided to use the latter method and got the curve in the next graph (Fig. 3) as a result. While the correlation coefficient stays almost unchanged slightly below 0.96 the slope of the regression line reaches almost 1.

This example shows that it is important to look critically at the statistical means used in intercomparisons like this.

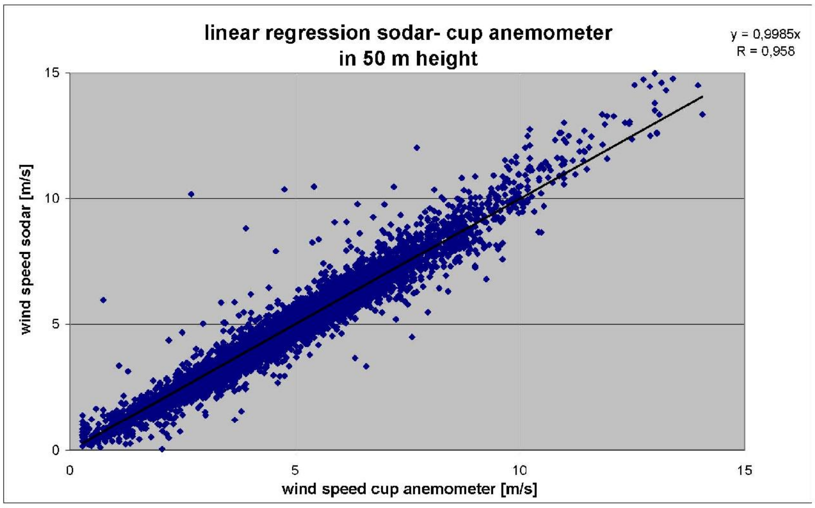

Fig. 3: Linear regression SODAR vs. cup anemometer forced through the origin

2.1.2 Site calibration with ultrasonic anemometers and SODAR

On the WINDTEST test field we used 2 80 m telescopic masts to compare the SODAR to an ultrasonic anemometer (SONIC) mounted in 50 m height. These masts were separated by a distance of about 400 m. The first part of the experiment compared the 2 sites by using 2 calibrated SONICs of the same type (R.M. Young 3D Model 81000). After several weeks of measurements we removed one of the masts and deployed the SODAR at this spot instead. The result is shown in Fig 4. The solid black line shows the normalized frequency distribution of the difference between the SONICs whereas the dashed blue line shows the same for the differences between the ultrasonic anemometer and the SODAR. The similarity between the curves proves impressively the compatibility between both measuring techniques. All calculations were based on 10-min-averages of wind speeds and only for direction sectors without influence from the wind turbines.

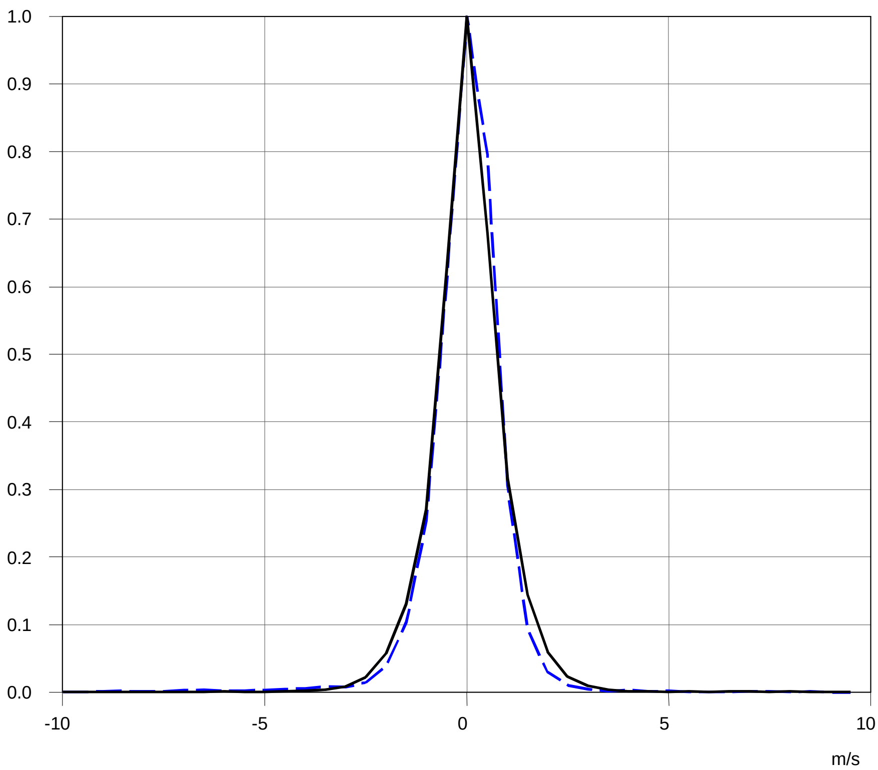

Fig. 4: Normalized frequency distribution of differences in wind speed SONIC-SONIC (solid, black), SONIC-SODAR (dashed, blue)

The same data sets for the SONIC and the SODAR are used for the graph in Fig. 5 as frequency distributions as a function of wind speed (similar to Weibull distribution). Again the similarity and especially the agreement of the long-term averages are convincing ($v_{avg,sonic}$ = 5.46 m/s, $v_{avg,SODAR}$ = 5.43 m/s).

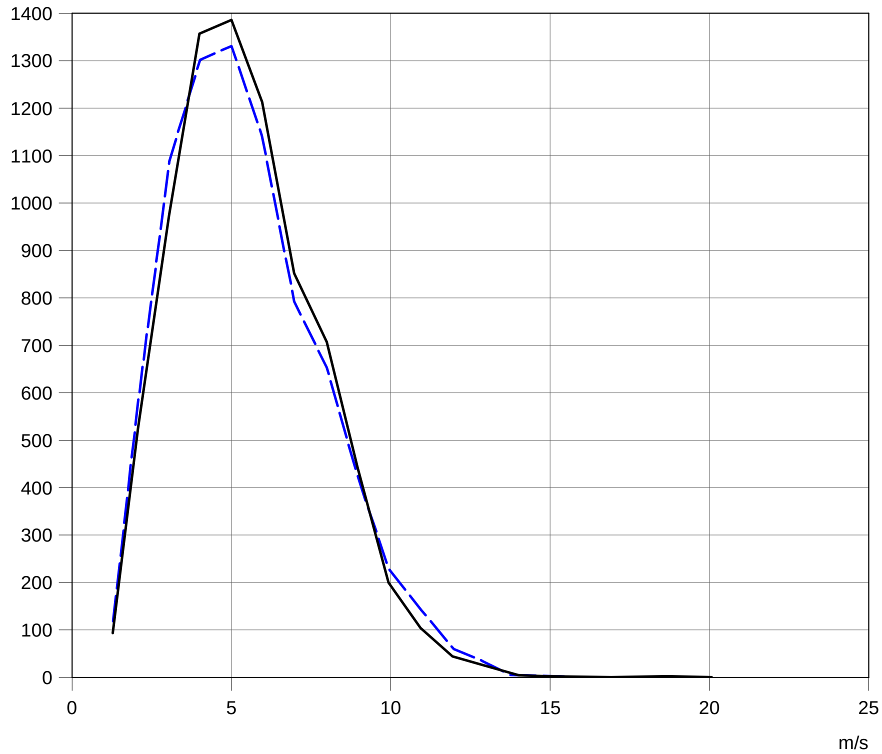

Fig. 5: Frequency distribution of wind speed SONIC (black) and SODAR (blue)

2.2 Windprofile verification

After the verification of wind measurements of a SODAR in a selected height the behaviour of the SODAR as a function of height has to be looked at. As the WIPRO project did not allow performing this in a sufficiently wide height range some results of a European project (WISE) are quoted [1].
In a field experiment at the Risø test site in Høvsøre close to the North Sea in flat terrain 3 different SODARs were installed side by side and compared to a heavily equipped meteorological mast in 5 different heights.

As a result the slope of the regression lines for all three SODARs and all available heights within the measuring range of the SODARs were calculated and plotted as a function of height as shown in Fig. 6. The behaviour of the three systems shows big differences. Most consistent results are provided by the AeroVironment instrument. Fig. 7 shows the change of the slopes with height with respect to the 40 meter level. This change stays within +/- 0.3 % (!). Taking the uncertainties into account it can be stated that there are obviously systems available that can be calibrated with a relatively low reference mast. This is especially of interest for situations where cup or ultrasonic anemometers are mandatory due to demands by banks or project developers.

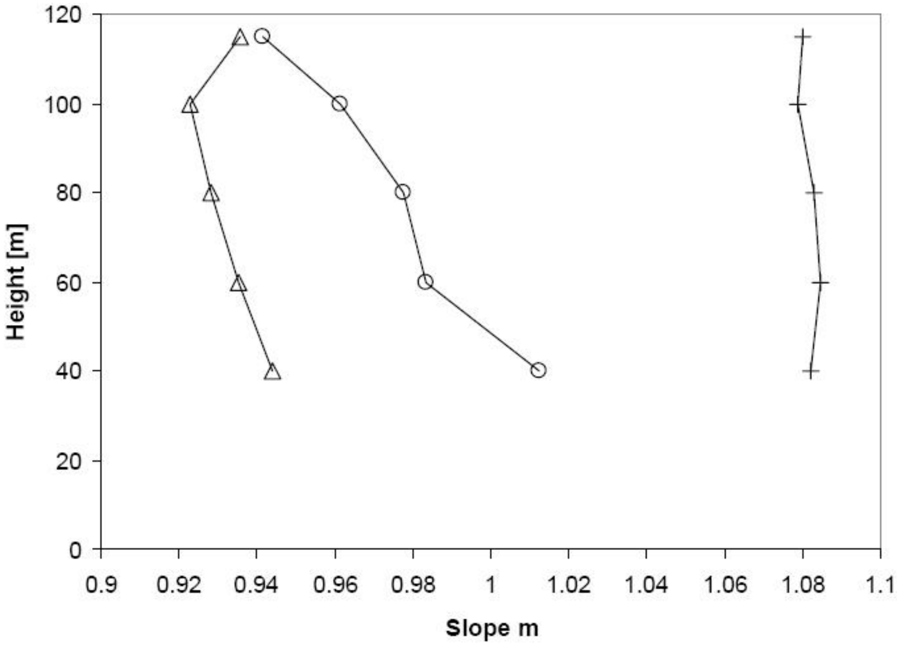

Fig. 6: Height dependence of regression slope vs. mast for 3 different SODARs
O Scintec, Δ Metek, + AeroVironment (ASC), source: EU project WISE

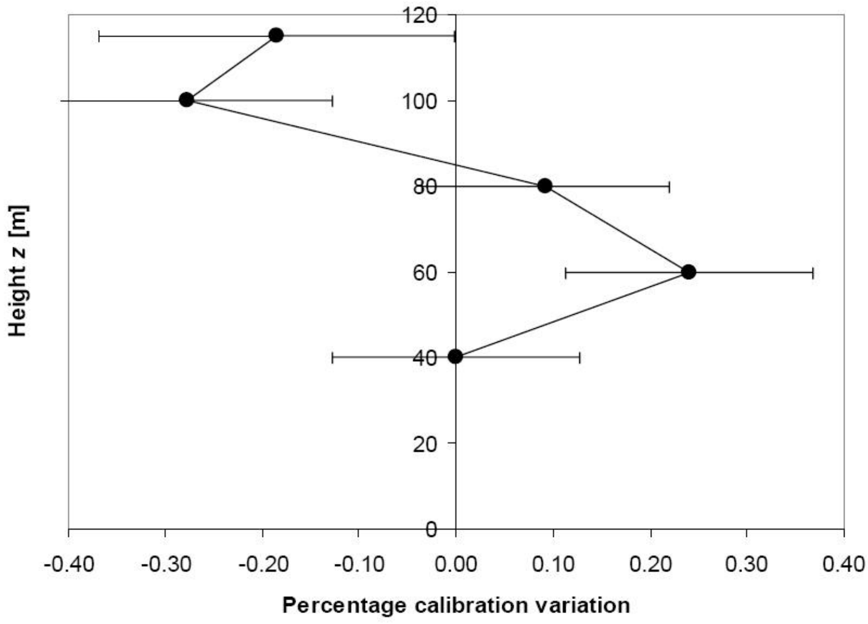

Fig. 7: Height dependence of the variation in calibration for AeroVironment (ASC)
source: EU project WISE

3. Verification of turbulence measurements by a SODAR compared to other references

3.1 Comparison of SODAR turbulence with anemometer turbulence measurements

Besides wind vector information the SODAR reports variances for all three wind components over the selected averaging periods (typically 10 minutes). These variances were used to determine the turbulence intensities and compared to turbulence intensities of cup and ultra-sonic anemometers on the WINDTEST test field in Grevenbroich.

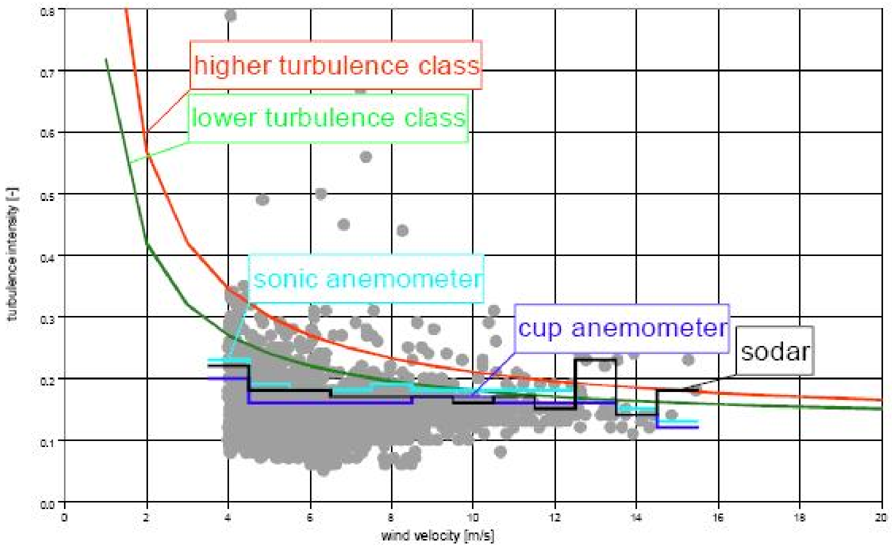

Fig. 8: Comparison of measured turbulence intensity data and IEC parameterisation (80 % percentiles)

The graph in Fig. 8 shows turbulence intensity versus wind speed as a result. The solid green and red lines represent turbulence intensity according to IEC61400-1 [2] where green is the lower turbulence and red the higher turbulence class of a normal turbulence model (NTM). The IEC turbulence parameterization is presumed as independent from height.
The SODAR measurement data, which is given as grey dots representing 10 minute average SODAR measurements each, is compared to cup and sonic anemometers installed at 50 m height. To compare parameterization with measurements 80 % percentiles of each data base are presented according to [2].
The given step functions for wind classes of 1 m/s width of the different measuring techniques agree very well up to 12 m/s. Above 13 m/s the data collective doesn't reach extension to give statistically approved evidence. Data below 4 m/s has been rejected as common in wind energy considerations.

3.2 SODAR turbulence measurements at different sites

The turbulence intensities (80 % percentiles) at different sites in 50 m, 100 m, 150 m heights obtained in many field measurements show the general characteristics according to wind speed coincident with IEC parameterization. At higher wind speeds the curves converge due to turbulent mechanical mixture. Especially at lower wind speeds the differences between the sites are significant. Normally turbulence intensity decreases with height due to the influence of vegetation or other obstructions (some results have been published in 2004 at the German Wind Energy Conference) [3].

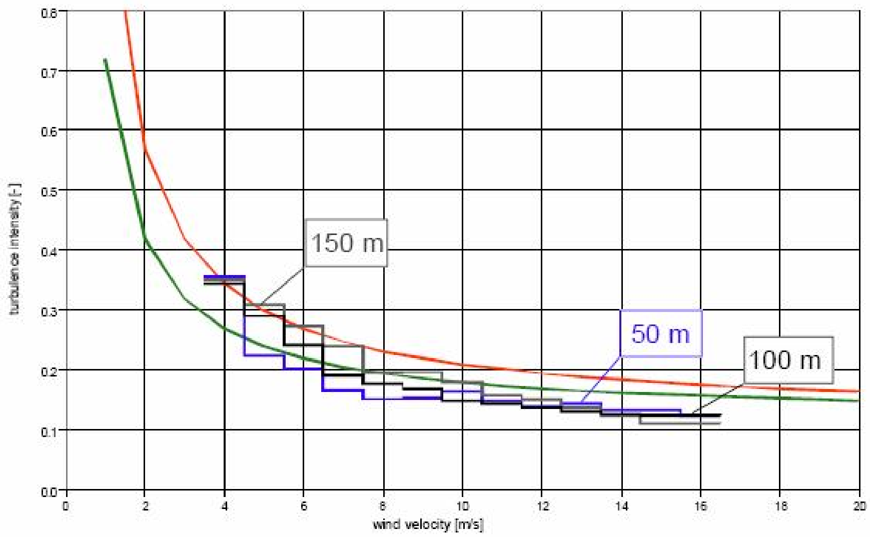

Fig. 9: Turbulence measured in Spanish Highland at a complex site

The example in Fig. 9 shows that it can be very useful to monitor turbulence profiles especially in complex terrain. This specific site in the complex Spanish Highlands shows an increase of turbulence intensity with height at lower wind speeds which is in contradiction to the most frequently observed slight decrease with height observed on most other sites. Turbulence intensities still follow closely the parameterized curves. Above 11 m/s the behaviour becomes “normal” and the turbulence intensities at the different levels converge.
The effect observed here may be induced by orographic effects.

Referring to the figures above the data quality of the SODAR is proven to be good and compares very well to conventional cup anemometers and even ultrasonic sensors. Examples of this presentation, mostly based on short term measurements (6-10 weeks), show the presumption of collecting enough measurement data especially for higher wind speeds above 12 m/s and choosing the measuring period dependent on e.g. seasons and site conditions. SODAR measurements under various conditions of complex sites have been proven to be a good alternative to turbulence measurements with a mast. Especially for measurements at higher altitudes SODAR technology offers advantages in terms of installation and operation. The SODAR gives a continuous wind and turbulence profile with a height resolution of 5 to 10 m up to 150 – 200 m. Thus it enables a more realistic and reliable information about the turbulence distribution all across even large rotors or advanced WEC than measurements with a mast at only a few discrete heights. Individual profiles of measured turbulence sometimes show values even exceeding the higher turbulence class of IEC parameterization at some heights. With WEC in operation SODARs can be used to check the site concerning turbulence intensities to make sure that inherent mechanical loads are assumed correctly.

4. Verification of a power performance curve

Wind turbines with hub heights in excess of 100 metres and rotor diameters of nearly 100 metres are no longer a rarity, for example. In particular in this part of the atmosphere there are frequently severe wind speed and wind direction gradients, resulting in high turbulence intensities. Measurements at least at hub height are needed in order to forecast reliably expected energy yields, but also to verify the power curves of existing installations. The installation costs involved with mast-based sensors increase disproportionately with the measuring height required. The SODAR system dispenses entirely with the costly installation of wind measuring masts (WMM) together with the sensors that are currently standard – calibrated cup anemometers and vanes. We used SODAR and a cup anemometer at the test site in Grevenbroich/Germany to determine the power performance of a wind turbine following IEC 61400-12 [4]. The solid curve in Fig. 10 shows the result from SODAR measurements in comparison to the cup anemometer power curve. Above 12 m/s we had not enough data for a stable and statistically significant evaluation (oscillation of the SODAR and anemometer curve). Below 12 m/s the curves coincide within about 3 %.

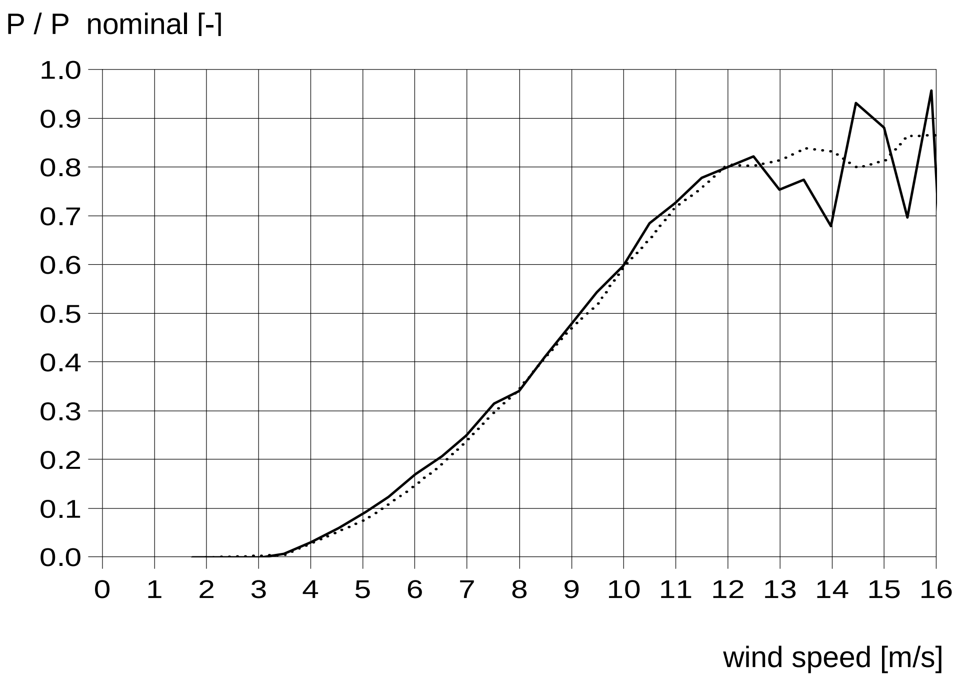

Fig. 10: Power performance curve of a cup anemometer (dotted line) and SODAR (solid line)

5. Recommendations and conclusion

The work presented here along with experience from measurements at many different sites (several of them with the presence of a tower that could be used as a reference) it can be stated that at least advanced SODAR systems optimized for the lowest layer of the atmosphere can meet even the demanding requirements of wind energy applications. This includes wind and wind profile measurements as well as turbulence classification.
A basic requirement is that the systems used are well serviced and maintained as it is mandatory for every other sensor and that the site and the way of installation do not affect data quality. Fixed echoes and interfering noise sources can deteriorate the measurements of these acoustic devices. If carefully following these rules and in doubt consulting an experienced SODAR user or consultant SODARs will provide the results that can be expected from a high quality and accurate measuring system.
Most of the results presented here were obtained within the research project WIPRO partly funded by the German state of North Rhine-Westphalia.

References:

[1] Stuart Bradley (ed.) et al., 2005, SODAR calibration for wind energy applications (final report on WP3, EU WISE project NNE5-2001-297), University of Salford, ISBN 0-9541649-1-1

[2] IEC 61400-1: Wind turbine generator systems Part 1: Safety requirements (IEC 61400-1:1999, modified); German version EN 61400-1:2004

[3] DEWEK 2004, 7th German Wind Energy Conference; Poster 5.4: Measurement of Atmospheric Turbulence with SODAR system, Wilhelmshaven 2004

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