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WISE
WIND ENERGY SODAR EVALUATION
FINAL REPORT

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Acknowledgement/Preface

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Abstract

Measuring the wind speed is a very important matter in wind energy development. Measured wind speed is necessary for siting future wind farm locations, estimating local wind regimes and potential wind energy output, the determination of wind turbine characteristics and for all kind of operational purposes. This report is the Final report of the WISE project (WInd energy Sodar Evaluation). Within this project partially funded by the EC it has been investigated whether a Sodar (Sound Detecting and Ranging) measurement system is an acceptable alternative to measure wind speed at higher altitudes and remote areas. The research results are given regarding the theory of Sodar measurements, calibration of Sodars for wind energy applications, operational characteristics, measurements in difficult circumstances and wind turbine Power Performance measurements using Sodars.

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EXECUTIVE SUMMARY

Measuring the wind speed is a very important matter in wind energy development. Measured wind speed is necessary for siting future wind farm locations, estimating local wind regimes and potential wind energy output, the determination of wind turbine characteristics and for all kind of operational purposes.

Up to now the sensor applied to measure the wind speed is a cup anemometer. This kind of sensor is even prescribed in standards for the determination of wind turbine characteristics. The growth of wind turbine size and moving offshore limits the possibilities to measure wind on the relevant heights (80m - 150m) in mountainous and offshore areas. For that reason wind energy institutes are looking for alternative ways to determine the wind speed under those circumstances.

Within the EC funded WISE project (WInd energy Sodar Evaluation) it has been investigated whether a Sodar (Sound Detecting and Ranging) measurement system, among the remote sensing devices, is an acceptable alternative to measure wind speed at higher altitudes and remote areas.

Applied methodology and Results

As a start the theoretical basis of the Sodar system has been described (see Chapter 3). A number of issues regarding Sodars and the measurement of the atmospheric wind speed with the use of either these devices or/and cup anemometers have been addressed during the theoretical considerations.

The measurement principle is different between Sodars and cup anemometers with the largest difference being that of a point and a volume measurement. A theoretical comparison of the Sodar wind speed and the wind speed measured with the cup anemometer has been made. The analyses showed that there will always be a systematic bias of 0.5% - 2% that the Sodar wind speed will be lower than the wind speed measured with the cup anemometer. This has been confirmed with several experimental comparisons at different locations. This point is important in the sense that it adds to the uncertainty of the measurement.

The Sodar presents a number of advantages in the measurement of the wind speed in connection with wind energy applications, relative to the use of a cup anemometer. These advantages are related to the ability of the Sodar to measure the wind speed profile simultaneously at more heights. Also the expenses associated to the purchase of a met mast increase considerably as the height of the mast increases.

Finally, among the drawbacks of the measurements when using the Sodar are the limitations due to the background noise at high wind speeds or the neutral condition of the atmosphere.

In the last five years the WISE project partners made several experimental comparisons between Sodar and cup anemometer. The results of these experiments and additional experimental comparisons, against meteo mast of 60 - 120m, within the present project have been used to determine:

- A calibration procedure to improve the accuracy of Sodar measurements (Chapter 4);
- The operational and external conditions influencing the resulting Sodar measured wind speed (Chapter 5).

Calibration of a Sodar system for wind speed measurements, in the context of wind engineering, means generating a set of instructions on how to obtain, from the Sodar data, wind speed and direction at a number of heights and with known and sufficient accuracy. The calibration result is not simply a regression equation, but includes also how to set the Sodar up and apply any necessary data filtering so that the regression equation applies.

Sodar uncertainties in calibration, which arise from Sodar design and operation are summarised on the basis of an exhaustive theoretical analysis. Additionally, descriptions and evaluations are made of calibration procedures applied to three different Sodar models. These procedures are tested at different sites and with different Sodars, as well as with Sodar-Sodar comparisons. The uncertainty analysis showed that the Sodar design, regarding i.e. applied beam width and tilt angle, can improve the output. Suggestions are made as to improvements in Sodar design, specifically for the wind energy applications.

Several calibration methods have been considered. The result of the calibration investigation is to show that, with appropriate care and knowledge, Sodars can provide wind speed and direction profile data to the same degree of accuracy as mast-mounted cup anemometers, providing there is a reference cup anemometer mounted on a nearby 40m mast. Specifically, variations of wind speed calibration slope of less than 1% can be expected, with rms residuals of typically 0.4 m/s. Wind direction variations are typically 1° or 2°. Clear guidance on how to apply this calibration procedure is given and how such results might be achieved.

The various potential calibration methods were surveyed and a decision was made to calibrate three different monostatic Sodar models simultaneously and in close proximity against cup anemometers and vanes mounted at various levels on a 120m mast situated about 70m from the Sodars. The major calibration was the Profiler Intercomparison Experiment (PIE), but a subsidiary calibration with only one Sodar was undertaken at a different site as a check on portability of results. It was shown that calibration is necessary for wind energy applications. Without calibration against a reference cup anemometer on a small meteo mast, Sodar output is unreliable. The three Sodars showed different calibration results on the same location.

Besides Sodar calibration to reduce measurement uncertainty it is equally important to take appropriate care and gain knowledge on how the Sodar is applied and data is processed. Operational characteristics like external conditions and instrument settings influence the output data. The most important parameters are:

- Under neutral atmospheric conditions the data yield decreases;
- Precipitation leads to erroneous data, especially if the speed of the particles differs from the speed of the air mass;
- Very strong winds lead to additional noise production, reducing the SNR (signal to noise ratio);
- Fixed echoes from surrounding structures and objects result in a well-known draw back of the remote sensing technique.
- Background noise disturbs the backscatter intensity.

The unreliable data have been discarded using filtering techniques by using SNR thresholds and backscatter levels. Filtering needs to be carried out together with the calibration method.

The resulting calibration procedure, applying a reference cup anemometer in a nearby 40m meteo mast, together with the appropriate data filtering has been used in three power performance measurements using a Sodar system beside the regular cup anemometer set up. The experiments were performed at the three European Wind Turbine Test Stations of ECN, RISØ and WindTest KWK. The power performance measurements were carried out where possible according to the existing standard IEC 61400-12 ed.1.

After filtering the data according to the agreed methods, deviations with respect to the mean wind speed measured by the cup anemometer were too large to get comparable P-V curves and Annual Energy Production (AEP) numbers, especially at high wind speeds. In two cases the Sodar systems overestimated the wind speed at hub height by a factor of 5% to 10%, resulting in an underestimation of the P-V curve and AEP. In the third case the Sodar underestimated the wind speed by a factor of around 6%, resulting in overestimation of the P-V curve and power coefficient Cp of the wind turbine, the latter by a factor of more than 25%.

The uncertainties in Sodar measurements after calibration are still larger than in conventional cup anemometer measurements. This is a consequence of the applied calibration method. The type B uncertainty of the Sodar will never be smaller than the uncertainty of the cup anemometer used for the calibration. The reason for this is that the uncertainty of the cup anemometer, used in the calibration procedure, is part of the entire uncertainty. Nevertheless calibration reduces the uncertainty considerably compared to stand alone operation.

Within this WISE project a separate work package was included regarding the application of a Sodar system under difficult circumstances like complex terrain situations. Measurements in complex terrain using a Sodar have been performed that consisted of a site calibration at several wind turbine locations in a commercial wind energy project. These measurements were used in preparation of power performance measurements and were performed using an autonomous power supply system.

When performing a site calibration either two Sodars systems or one Sodar together with the permanent meteo mast for power performance measurements can be used. In the first case a proper calibration of both Sodars is missing, furthermore it is required to ensure that the two Sodars do not interfere with each other. In the second case it can be argued that the various comparisons of Sodar versus meteo mast data in non-complex terrain, with proven high correlation of the wind measurements at the same height, have shown that the measurement characteristics of the individual Sodar have an influence at the site. It is concluded that a Sodar based site calibration under these circumstances is not feasible.

Although the Sodar with the current technology has its limitations, the instrument remains an attractive alternative to expensive large meteo masts for wind measurements with large wind turbines and measurements at offshore locations. However improvements regarding calibration, design and software are required.

INTRODUCTION

Within the framework of the FP5 a joint research project WISE (Wind Energy Sodar Evaluation), funded by the European Community has been carried out during the period May 2002 until November 2004. Participants in this project were:

- Energy research Centre of The Netherlands, ECN (NL) (co-ordinator)
- National Laboratory, RISØ (DK)
- WINDTEST Kaiser-Wilhelm-Koog GmbH (DE)
- University of Salford (UK) / University of Auckland (NZ)
- IMK-IFU Forschungszentrum Karlsruhe (DE)
- DEWI German Wind Energy Institute (DE)

The general aim of the project is to develop the application of the Sodar measuring technique for wind speed measurements in relation to the main characteristics of large wind turbines.

The present final report on the WISE project has been drawn up from the detailed technical reports established in the different project work packages. The main reports are:

1. Antoniou I, H. E. Jorgensen, F. Ormel, S. G. Bradley, S. von Hünerbein, S. Emeis and G. Warmbier. On the theory of Sodar measurement techniques, RISØ-R-1410 (EN), April 2003, 59pp.

2. Bradley S. G., Antoniou I, S. von Hünerbein, D. Kindler, M. de Noord, E. Jørgensen, Sodar calibration procedure, The University of Salford, UK, March 2005, 67pp.

3. Antoniou I, H. E. Jorgensen, D. Kindler, S. Emeis and M. de Noord, 2005. Sodar Operational characteristics, RISØ-I-xxxx (EN), 21pp.

4. Noord M. de, A. Curvers, P. Eecen, I. Antoniou, H. E. Jørgensen, T.F. Pedersen, , S. G. Bradley, S. von Hünerbein, D. Kindler, Sodar Power Performance Measurements, ECN-C--05-041, April 2005.

5. Mellinghoff H., M. de Noord, S. von Hünerbein, Sodar Measurements under difficult circumstances, DEWI SO 0205-100.2, March 2005, 72pp.

These reports are available at the institutes responsible for editing.

The present report summarises all the work done within the WISE project and established in the reports mentioned above. In the following chapters the main results achieved in the project work packages are reported. The work packages comprise:

- the theory of the Sodar measurement technique;
- the proposed Sodar calibration procedure for wind energy applications;
- the operational and external parameters influencing the measurements;
- experience on applying the calibration procedure and operational characteristics in wind turbine power performance measurements;
- experience in applying Sodar systems under difficult circumstances.

In the final chapter the conclusions per work package are summarised, extended with overall conclusions and recommendations on the continuation of the development of the Sodar measurement technique for wind energy applications.

1. OBJECTIVES AND STRATEGIC ASPECTS

1.1 Background

Wind measurements for wind energy applications are generally done with cup anemometers mounted on meteorological masts. This is becoming increasingly difficult due to the following reasons:

- Due to the increasing height of wind turbines and the placement of wind turbines offshore masts are becoming extremely expensive so that in the near future they are no longer a practical solution. Remote sensing measurements with Sodar systems are possibly a more affordable alternative.
- Instrumentation of large masts is becoming increasingly difficult.
- Getting building permits for large masts are becoming very time consuming and sometimes impossible.

At the moment Sodar equipment can be bought commercially “off the shelf”. However, the Sodar was designed to operate in different conditions than can be encountered for wind energy applications. Specific problems are:

- For wind energy applications stricter requirements exist for uncertainty, reliability and validity of the data than for other Sodar applications.
- Calibration of Sodar systems (output wind speed against verified input wind speed) has never been done and there exists no calibration procedure; different brands of Sodar use different measurement techniques and may give different data.
- At the moment low wind speeds (below 4 m/s), high wind speeds (over 18 m/s) and other atmospheric phenomena cause difficulties with Sodar measurements. This needs to be addressed because power performance measurements require wind speeds up to 30 m/s. Furthermore, it introduces arbitrary decisions from the operator about dubious or missing data which is undesirable for wind energy purposes.
- Sodar is designed for use on land. Offshore use introduces vibrations from supporting structures and an increased level of background noise, which can influence the measurements.
- Sodar is designed to send a near vertical sound beam. To use Sodar to see oncoming gusts it will have to work with a near horizontal beam. At the moment this is not immediately possible with commercially available Sodars, though possibly only small changes have to be made to the design in order to enable this.
- Historically Sodars are used for example near airports and nuclear power plants with easy access for maintenance. For wind energy applications there may be problems with easy access to equipment and data (especially with Sodars at remote sites), electricity from the grid and operation in complex terrain. Autonomous operating Sodar systems are not yet common practice.

Therefore a lot of work needs to be done before Sodar is an accepted and practical alternative for measurements with a meteorological mast with cup anemometers. Sodar needs a thorough theoretical basis for wind energy applications including work on calibration and filtering techniques for data analysis. Sodar needs to be tested in difficult circumstances such as complex terrain and offshore use. Technical issues like data communication and power supply have to be solved for operation in remote sites. Furthermore, the possibility to use Sodar measurement techniques to detect oncoming gusts has to be explored.

1.2 Objectives

The scientific objectives of the WISE project are:

1. To establish a good theoretical basis for Sodar measurements for wind energy applications and to be able to measure wind speed in a reliable way with Sodar, including:
    - Interaction of the sound beam with the atmosphere
    - Sodar measurement algorithm
2. To establish if and how Sodars can be calibrated.
3. To compare different types, including effects of calibration.
4. To establish a general filtering technique for detection and treatment of unreliable data.
5. To test Sodar measurements in difficult circumstances such as offshore and complex terrain.
6. To carry out a Power Performance (P-V) measurement with Sodar, including new possibilities such as using wind speed data for the whole rotor instead of only at hub height and to establish criteria for such Sodar P-V measurements.
7. To quantify the effects of vibrations in supporting structures and increased background noise on offshore Sodar measurements.
8. To test if Sodar systems can be used to detect oncoming gusts.

The technical objectives are:

9. To test and develop an autonomous power supply for Sodar operation at sites with weak or no electricity grid.
10. To test and develop a good data communication method for Sodar operation at remote sites.

1.3 Community added value

In order to reach the goal within the EU-policy of doubling the share of renewables until the year 2010, bottlenecks hindering the exploitation of wind energy have to be overcome. The contribution and the spin off of the proposed project are:

1. The commercial exploitation of a method to identify suitable sites for wind farm operation by enhanced micro siting methods focussed on offshore and complex terrain situations.
2. Application of Sodar systems for the characterisation measurements of multi-megawatt wind turbines, both off- and onshore, through which extremely expensive large meteorology masts can be avoided. Offshore applications for large turbines are a major issue of the proposed work.

It is particularly important that this work is carried out on a European level because the Sodar technique to measure the wind speed will not succeed without an implementation of the technique into European and International standards. In that perspective the support of MEASNET for this research project is extremely important. Each MEASNET member, within its own country, has many years of experience in wind speed measurement techniques. All MEASNET members started or will start the development of Sodar measurement techniques, to be able to characterise multi-megawatt wind turbines in the future at any location. Adoption of alternative wind speed measurement techniques is being discussed within MEASNET and the international standardisation maintenance group. Up to now only cup anemometers are allowed in wind turbine characterisation measurements. The result of the present project is important to adopt possible new measurement techniques within MEASNET and international standards.

A developer, Sodar manufacturer or research institute alone cannot perform the project. It brings together the critical mass in human and financial terms. Five of the project partners are involved in standardisation in the field of power performance and are members of MEASNET.

The results of ongoing activities like commercial measurements, demonstration projects in the field of Sodar measurements and off- and onshore micro siting at European level are directly used as input for the proposed methodology. Application and acceptance of Sodar in the wind energy field requires intense discussions within the scientific community due to complexity of the Sodar technique.

1.4 Community social objectives

The WISE project will help to promote the use of wind energy in European regions where the economical risk of operating a wind farm has been considered too high. It will become easier to assess the wind regimes in areas with difficult accessibility, like offshore and mountainous areas, to carry out micro siting including resource measurements. Performance verification of wind turbines within wind farms will become possible. The reduced financial risks due to the application of the Sodar technique will increase the total amount of wind power installations. Furthermore this will stimulate the wind power implementation within Europe resulting in reduced environmental impact due to GHG emission.

1.5 Economic development and scientific and technological prospects

The scale of future wind turbines, like hub height and rotor diameter, will be over 100 metres. This implies that the overall height of the turbine will be over 150 metres. To understand the behaviour of the wind turbine it is not sufficient to know the wind speed only at the rotor centre, as is done now. The wind shear over the whole rotor should be known. Masts up to 150 metres high are extremely expensive, impractical and not flexible. The investment cost of Sodar systems which can measure up to 150 metres are about € 55,000.-. Masts with which wind speed can be measured up to the same height may cost ten times that amount of money, or even more depending on the accessibility of the location. Masts for offshore locations cost several millions Euros. Also, Sodars are quickly placed and moved and in general do not need a building permit.

If the results of the WISE project show that the Sodar system is a reliable tool for accurate and reliable wind speed measurements it will be applied by a broad users group: wind farm developers, wind farm operators and measurement laboratories and institutes:

- The developers will have a powerful tool for site assessment both off- and onshore, and the prediction of the wind farm performance.
- Wind farm operators, the measurement institutes and laboratories can offer reliable measurement and testing procedures against lower costs due to the fact that expensive masts and time consuming building permits can be avoided. These measurements can be carried out at wind turbines that are placed in a wind park configuration for performance verification purposes.
- The manufacturers of Sodar systems become more competitive because of this new market area.

All the present project partners are end-users and will directly benefit from the work.

The results will directly transfer into European and international standardisation work. The co-ordinator itself and four of the partners are members of MEASNET, CENELEC and IEC working group for power performance standards and IEA members of the working Group Wind Speed Measurements. The developed methodology can be introduced into a quality assurance system as accredited laboratories according to international standards can apply the measurement procedure. Accreditation on this point is obliged within MEASNET.

Results will be communicated with the European Sodar Industry (manufacturers and suppliers) via a special non-scientific report. The project results will also be presented through presentations and papers at regular European Wind Energy Conferences.

It is expected that the proposed methodology will soon find a way into daily application since the demand has already been phrased in several cases. Several wind farms have shown poor power performance in the last years due to insufficient micro siting. Wind turbines reach hub heights up to 100 meters so alternative wind speed measurement methods are desired to make performance verification accessible.

Finally, research and development institutes will apply Sodar systems as a measurement tool. All these applications will stimulate the market for these devices, reduce the costs of Sodar systems and thus lead to a further dissemination of the technique. If the number of sold Sodar systems will be increased by a factor five (which could be easily achieved by the end of the proposed project), the costs for a Sodar system could be reduced by about 50 %.

2. THE THEORY OF SODAR MEASUREMENT TECHNIQUE

This chapter deals with the "standard" Sodar algorithms. It is not aimed at a specific make of Sodar but generalised to be valid for general phased array Sodars. The chapter is divided in four parts: general, beam sending, signal receiving and parameter interdependence.

The general part introduces some general ideas of the interactions between the Sodar and the atmosphere. The sending and receiving are focussed on sending the beam and receiving the back-scattered signal and the last part (parameter interdependence) explains the relations between a number of variables encountered earlier.

The aim of this chapter is

- to give insight into the conditions that affect the Sodar,
- to show how the settings can change the measurement results and
- to give a basic understanding of the relationships between settings in order for the reader to be able to make a complete set of Sodar settings that takes these interdependencies into account.

2.1 Generally on phased array Sodars

To measure the wind profile with a Sodar, acoustic pulses are sent vertically and at a small angle to the vertical. A thus transmitted sound pulse is scattered by fluctuations of the refractive index of air. Those fluctuations can develop through temperature and humidity fluctuations and gradients as well as wind shear. Due to the scattering angle of 180°, the commercially available monostatic Sodars are mainly sensitive to the thermal fluctuations. As reflected sound intensity depends strongly on the size of the fluctuations, scattering is restricted to turbulent patches of size $\lambda/2$. In other words changes of the transmitted sound frequency lead to scattering from differently sized fluctuations.

Turbulent fluctuations move with the wind. Therefore the Doppler effect shifts the sound frequency during the scattering process. The amount of frequency shift is proportional to the velocity of the scatter in the beam direction. If the beam is directed vertically, the vertical wind speed w can be calculated directly from the Doppler shift. The horizontal components however need to be determined by tilting the beam also by a small angle θ_0 from the vertical into two horizontally perpendicular directions whose wind components we will call u (East) and v (North). This gives three Doppler shifts, which are a function of the wind components u, v, and w.

The pulse is assumed to be confined to a conical beam of half-angle θ. For a system having pulse duration τ and with speed of sound c, the pulse is spread over a height range of $c\tau$. As the pulse is scattered, it is detected at any one time from a volume $V = \pi\left(z\theta\right)^2 c\tau/2$ where $c\tau/2$ is the height range and $\pi(z\theta)^2$ is the horizontal extension with z being the height above the antenna array.

Note that the centres of the scattering volumes for the three beams are separated by a horizontal distance of up to 88m at a typical tilt angle of $\theta_0 = 18^\circ$ and a range of 200 m. At the same time the horizontal beam cross section is 35 m. This means that two respective scattering volumes do not even overlap. Therefore the assumption of homogeneous turbulence and a homogeneous wind field within the volume of all three beams is necessary.

Even if turbulence is strong the scattered signal power is extremely weak in comparison to the transmitted power: The ratio between received and transmitted powers at a height of a 100 m above ground and for a 4500 Hz Sodar is typically of the order of 10^{-14} Therefore absorption in the atmosphere is an important factor restricting the range that is the maximum height from which scattered signals can be detected. The Sodar equation (Eq. 2.1) shows that the ratio of received to transmitted power is proportional to the absorption term: $\frac{P_R}{P_T} \propto e^{-2\alpha z}$

The absorption coefficient α is the sum of classical absorption, α_c, and molecular absorption, α_m. Classical absorption is due to viscous losses when sound causes motion of molecules, and is proportional to frequency squared. Molecular absorption is due to water vapour molecules colliding with oxygen and nitrogen molecules and exciting vibrations, which are dissipated as heat. At low humidity there is little molecular absorption. At high humidity O_2 and N_2 molecules are fully excited without acoustically enhanced collisions, and there is again little extra absorption. Absorption also depends on temperature and pressure since these affect collisions. The resulting equation shows a complicated dependence on the mentioned parameters as well as on the sound frequency. However, in the frequency range of interest for Sodars that is between 1 and 10 kHz the following rule is valid: The higher the frequency of a Sodar the more limited its range due to absorption. For a detailed treatment of sound absorption in air see Salomons, E. M. (2001).

2.2 Beam Sending:

There are five basic parameters that determine how the Sodar sends the beam. These are:

1. Transmit frequency (f_T)
2. Transmit power (P_T)
3. Pulse length (τ)
4. Rise time (up and down) ($\beta\tau$)
5. Time between pulses (T)

There are some further parameters necessary to describe the three different beams of the antenna but these depend on other parameters and cannot be set. These further parameters are:

6. The tilt angle
7. Half beam width

The following drawing shows the relationship between these parameters. The basic pulse shape is shown in Figure 2.1 and the pulse repetition pattern in Figure 2.2.

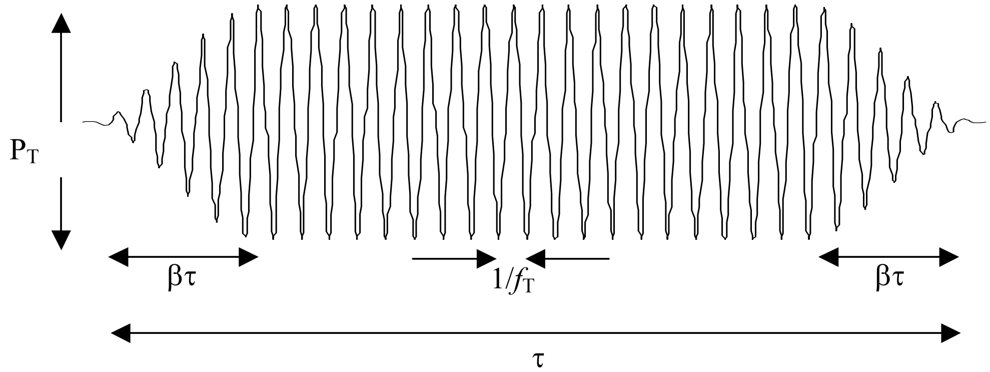


Figure 2.1 Basic pulse shape of the Sodar

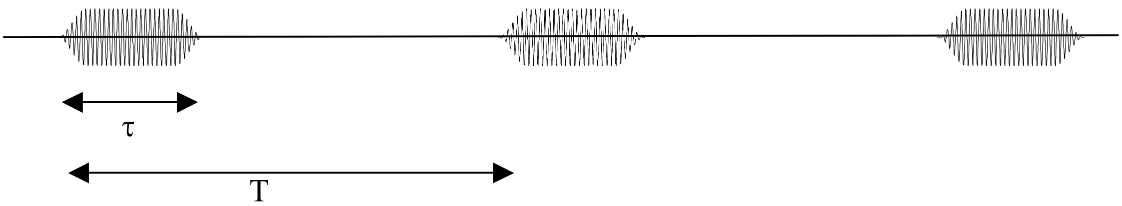


Figure 2.2. The pulse repetition

2.2.1 Frequency

The frequency of a standard phased array Sodar is determined in the design process. There is little room for changing the frequency once the Sodar has been assembled. For example, a 4500 Hz mini Sodar can usually be adjusted between 3000 and 6000 Hz. Outside this frequency band the loudspeaker performance is too bad to be used. For lower frequencies the bandwidth is generally smaller such as 1500-2500 Hz (for a Sodar that is normally operated at 2000 Hz). The choice for the frequency is a basic parameter in the maximum altitude reached. This is because the background noise decreases when the frequency increases but the absorption in the atmosphere increases with frequency: The atmospheric absorption basically depends on three parameters: temperature T, relative humidity RH and frequency f. Of these three only the frequency is a design parameter for the Sodar. In Figure 2.3 and Figure 2.4 can be seen that the absorption increases exponentially with the frequency. This limits the maximum height that the Sodar can reach.

On the other hand the background noise level tends to decrease with increasing frequency, especially during the day. This can be seen in Figure 2.5. A lower background noise level for a specific frequency would mean that the Sodar can reach a higher altitude with the measurements.

From these two considerations can be concluded that there is an optimal frequency depending on the application. A last point to be considered in the choice of frequency is the radial wind speed resolution, which depends on the frequency. The formulas can be found later in this chapter, but the higher the frequency, the better the resolution. This can be influencing the choice for a higher frequency, which means lower sampling depth but higher resolution.

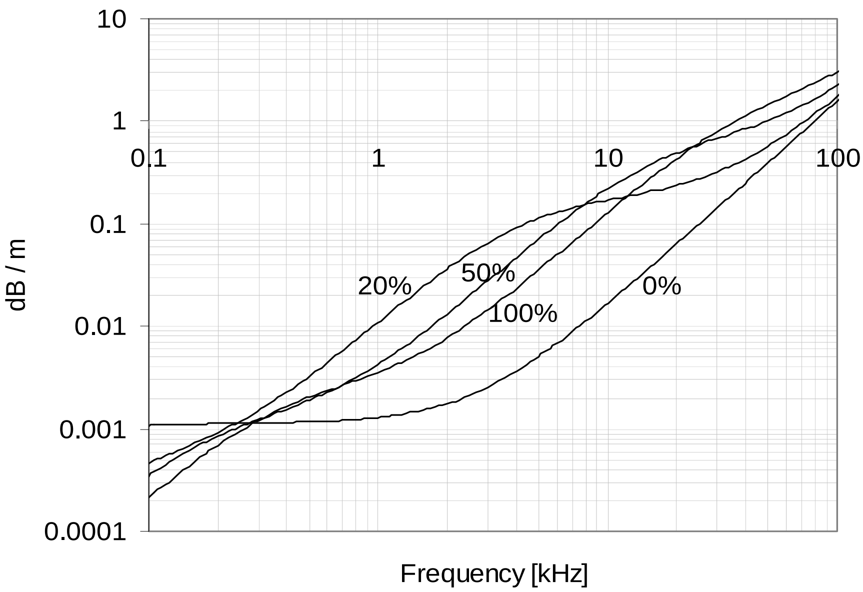


Figure 2.3. Atmospheric absorption (at T = 283 K) for different values of Relative Humidity.

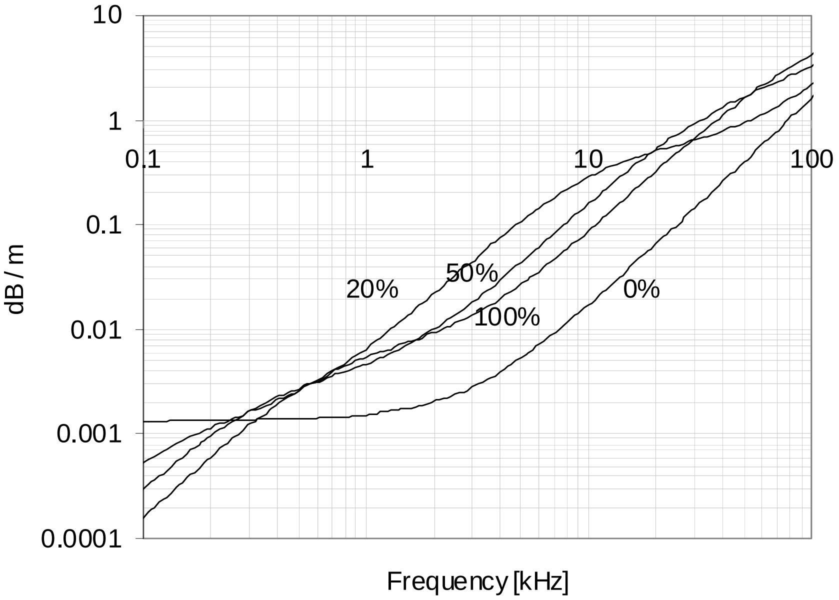


Figure 2.4. Atmospheric absorption (at T = 293 K) for different values of Relative Humidity.

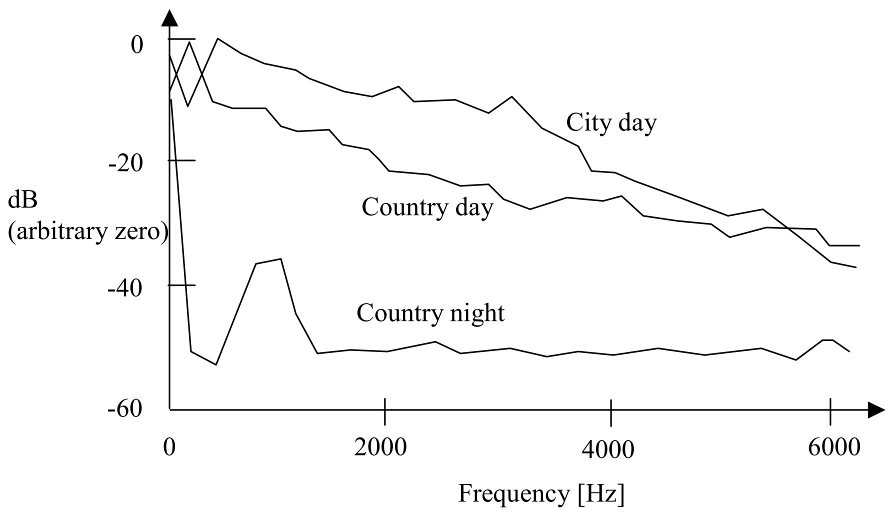


Figure 2.5. Background noise levels for different surroundings

2.2.2 Power

This is one of the simpler parameters: the power should be set to such a level that the speakers just are not damaged by the voltage signal. This can be clearly seen from the Sodar equation:

$$P_R = P_T G A_e \sigma_s \frac{c\tau}{2} \frac{e^{-2\alpha z}}{z^2} \qquad (2.1)$$

With:

P_T the transmitted power
G the antenna transmitting efficiency
A_e the antenna effective receive area
τ the pulse duration
z the height
α the absorption of air
σ_s the turbulent scattering cross section
c the wind speed in air ($\pm$ 340 m/s)

The more power is put into the beam, the more power is received back. Therefore the only consideration is how much power the speakers can deliver without damage.

2.2.3 Pulse length

The pulse length is the length of the pulse (either in milliseconds or in meters). Normally only the effective pulse width with respect to power output is used in calculations; this is the pulse width without the rise time plus half the rise time (up and down). So a pulse length of 100 ms with a rise time (up and down) of 15%, will have an effective pulse length of 85 ms.
The pulse length influences the following:

- power received from the atmosphere from Sodar equation (Eq. 2.1, longer transmit pulse means more received power)
- $$\frac{P_R}{P_T} \propto \tau \qquad (2.2)$$
- frequency resolution (and therefore radial wind speed resolution)
- $$\Delta f_V = \frac{1}{\tau} \qquad (2.3)$$
- height resolution
- $$\Delta z = \frac{c\tau}{2} \qquad (2.4)$$

2.2.4 Rise time

The rise time means that the signal is attenuated by a Hanning filter, which means it gets a ramp up and ramp down at the beginning and end of the signal. This protects the speakers from too quick rise in voltage that could damage them. Assuming a pulse shape $p(t)$ and duration τ, determining the Hanning shape is defined as follows:

$$(1-\beta)\,p(t) = \begin{cases} \frac{1}{2}\left[1-\cos\left(\frac{\pi}{\beta\tau}t\right)\right] & 0 < t < \beta\tau \\ 1 & \beta\tau < t < \tau(1-\beta) \\ \frac{1}{2}\left[1-\cos\left(\frac{\pi}{\beta\tau}\{\tau - t\}\right)\right] & \tau(1-\beta) < t < \tau \end{cases} \qquad (2.5)$$

Time series of the pulse shapes are shown in Figure 2.6, for β = 0, 0.2, and 0.5. The pulses become more round with increasing β. The frequency spectra for these three pulse shapes are shown in Figure 2.7 (in practice the pulse is the *product* of the envelope and a sine wave at the transmit frequency f_T, and so the pulse spectrum is *convolved* with a spectrum line at f_T, and so has the shape shown centred on f_T).

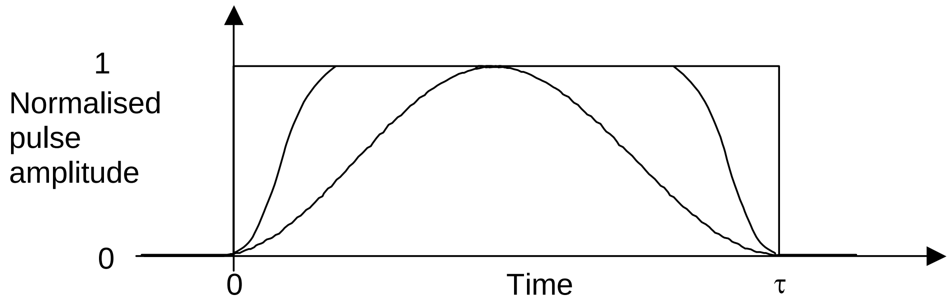


Figure 2.6. Time series of square window compared to Hanning shaped pulse with different ramp times.

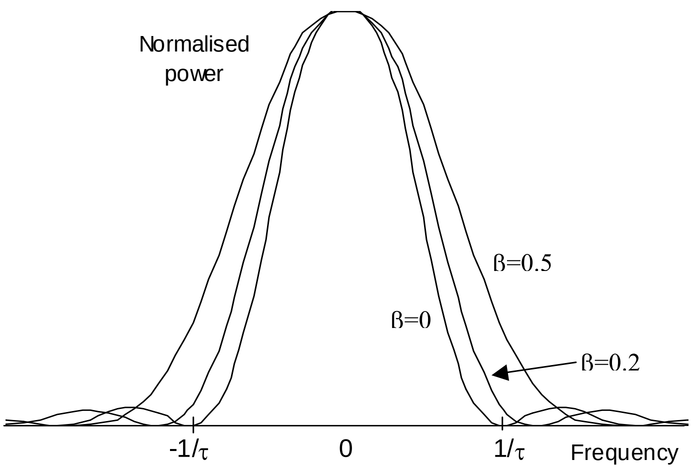


Figure 2.7. Frequency spectra of a square pulse compared to Hanning shaped pulse with different ramp times.

An ideal pulse (β=0) would have all the energy in the main lobe of the sine function (around the y-axis) and decay to zero with no ripples. However, the rectangular pulse introduces ripples into the frequency domain. These are unwanted contributions, which could be aliased back into the spectrum.

With increasing β, the pulse has a broader and deeper main lobe, which means that more of the energy is in this main lobe and less is in the ripples. If there is less energy in the ripples then it means that the frequency response will also have less ripples, therefore a better function for windowing data. The broadening of the main lobe is unwanted as the transmit frequency is less well defined.

Therefore, the user needs to find a trade-off between "ripples", pulse power, and well defined transmit frequency.

2.2.5 Time between pulses

There is a direct relation between the time between pulses T and the maximum height the Sodar attempts to measure. Any measurement of backscatter must be finished before the next pulse is sent; therefore the maximum height is cT/2.

Another consideration is the danger of getting backscatter from the previous pulse in the measurements. If the Sodar has a general sampling depth of 500 metres, and the maximum height is set at 150 metres, then we get the following situation:

If we assume that the phased array Sodar has three beams, then it will listen to backscatter from one beam for 0.88s. After this 0.88s it will do the same for the other two beams. So after 2.65s it will come back to the first beam. When it starts to listen for the backscatter from the second pulse of the first beam (2.65s after the first pulse was sent) then there will also be backscatter from 450 metres high. This means that the wind speed at 450 to 600 metres is represented as wind speed for 0 to 150 metres. But also the backscatter from the second pulse will give a wind speed for these altitudes, and so there will be two peaks in the spectrum. This is a very unwanted situation that can spoil the measurements. As a rule of thumb the maximum height should be set to ½ or ⅔ the maximum sampling depth the Sodar can reach. As this maximum depth depends on the atmospheric boundary layer, it is best to set the maximum height to a value on the safe side.

2.2.6 The tilt angle

Although the tilt angle of the U and V beam relative to the W beam is important to know in order to be able to calculate the wind speed, it is not a parameter that can be set by software. The tilt angle θ is defined by the loudspeaker spacing d of the antenna array, by the number of speakers N and by the transmit frequency f (or wave number k). The resulting intensity pattern can be compared to optical interference patterns:

$$I \propto \left[\frac{\sin\left(Nk \frac{d}{2} \sin\theta \right)}{\sin\left(k \frac{d}{2} \sin\theta \right)} \right]^2 \tag{2.6}$$

This is the intensity for a loudspeaker array of N speakers in a line showing the general principle. An example for 8 speakers and two different tilt angles (vertical – thick line, 15˚ from vertical – thin line) is shown in Figure 2.8.

Note that there is a second maximum as high as the first at about 95˚ from the main lobe. There are two important issues connected with this second maximum:

a) the second maximum could lead to strong reflections from surrounding hard objects like buildings, tarmac, and trees. This is prevented by a Sodar baffle which is a sound absorbing shield inside the Sodar enclosure.
b) the second maximum restricts the tilt angle: If the main beam is tilted too much then the second maximum acts as a new main beam and the scattered signal becomes ambiguous.

Theoretically, the beam could be steered by a variable phase-shift between 0 and π/2 between two respective loudspeaker groups. To simplify the design however, Sodar manufacturers fix the progressive phase-shift at π/2. In practice this leads to tilt angles of 16° - 30° for higher to lower transmit frequencies respectively. The practical limit on the beam tilt angle is

$$\Delta\theta_{tilt} \leq \frac{2\pi}{4dk} \tag{2.7}$$

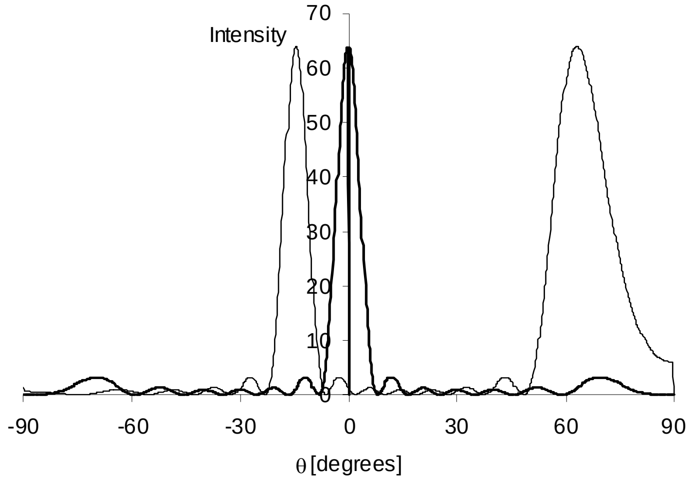


Figure 2.8 Antenna beam pattern for a line array consisting of 8 speakers with a speaker spacing of 0.95λ and at a transmit frequency of 4500 Hz. The vertical beam corresponds to the thick line, the tilted beam to the thin line.

2.2.7 Half beam width

A final aspect of the beam being sent up that should be discussed is the half beam width. This is also not a parameter that can be set, but it follows from the speaker, array and baffle design.

Again the transmit frequency determines the beam opening angle as can be seen in Figure 2.9. This is the same linear array consisting of 8 speakers as in Figure 2.8. The transmit frequencies are 4500 Hz (blue) and 2000 Hz (green) for constant speaker spacing which is unrealistic as speakers for a 2000 Hz Sodar are larger and thus have to be spaced wider. However, it can be seen that the beam-opening angle roughly doubles.

In effect spectral broadening results from and is proportional to the finite beam width. The broadening may be of the same order as finite pulse effects. However, the finite-beam broadening is different, in that it scales with the wind speed.

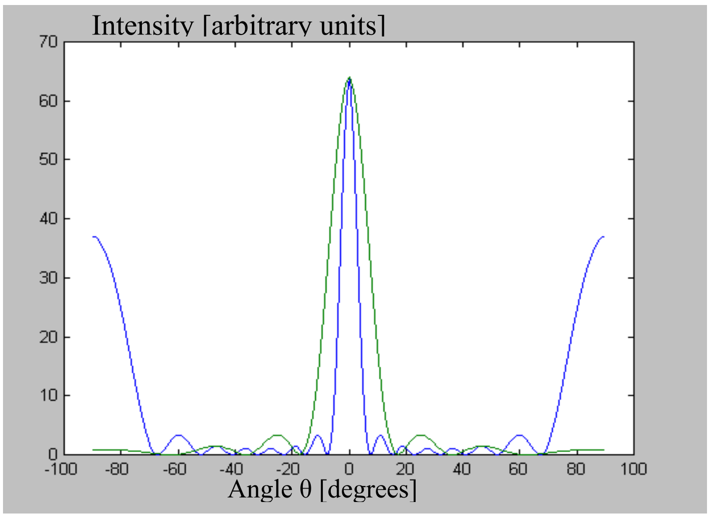


Figure 2.9 Antenna beam pattern (for details see Fig. 6) at two different transmit frequencies: Blue – 4500 Hz, green – 2000 Hz.

Finally it should be mentioned that the Sodar baffle, which was mentioned in 2.2.6, adds an extra level of complexity to the intensity pattern as it acts as an additional circular hole with its own diffraction pattern. A more realistic example with the transmit frequency f_T = 2 kHz, and the array diameter $2a$ =1 m is given in Figure 2.10. In this case, the angle plotted is $\theta^*=\theta - \tan^{-1}(a/h)$ with the baffle height h. The intensity at low elevation angles is around 25 dB below that of the main vertical beam.

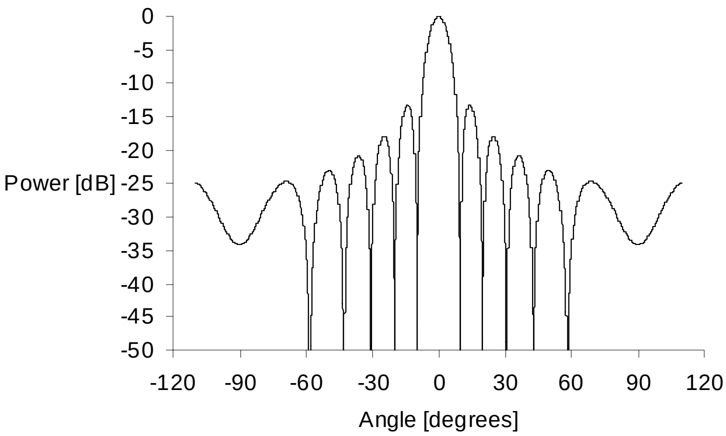


Figure 2.10 Antenna beam pattern with baffle.

For phased array Sodars, the baffle needs to have a wider exit so that tilted beams do not intersect the baffle edges too much. The top rim of the baffle will be in the near field of the Sodar beam (rays from different parts of the antenna to a point on the rim will not be parallel). However, detailed calculations have shown that the far-field approximations applied above are generally sufficient to optimise a design. Baffles can have a circular cross-section or be some polygon: for the following we just consider the rim as if it were a circle.

The height of the baffle has to be chosen with care, as the enhanced diffraction at the rim of the baffle can lead to enhanced sensitivity to the reflection from surrounding hard objects. The optimum baffle height is determined by:

$$\frac{a}{h} = \tan\theta_{\min} \qquad (2.8)$$

Where θ_{min} is the angle where the antenna pattern has its first minimum. Unfortunately, this angle changes with both, transmit frequency and tilt angle. Therefore baffle design is still mostly empirically done in practice.

2.3 Signal receiving

After the beam has been transmitted it interacts with the atmosphere. This is described in another chapter in this report. This second section deals with what happens when the back-scattered signal reaches again the speakers. These speakers have now been switched and act as microphones. In the following section, the parameters related to the receiving of the back-scattered signal will be explained.

2.3.1 The hardware sequence:

The following hardware components can be identified in the receive chain:

1. Microphone
2. Low noise amplifiers
3. Bandwidth filters
4. Ramp gain
5. Mixer
6. Low pass filter

2.3.1.1 Low noise amplifier:

When the back-scattered signals reach the speakers (now acting as a microphone), the typical signal strength that the microphones produce is 0.1 to 1 mVrms. This means that an amplification of around 1.000.000 times is needed to get a signal strength of around 1Vrms.

2.3.1.2 Bandwidth filter

After the amplification, the noise has to be filtered out. This is done because only a small part of the frequency spectrum contains meaningful backscatter information but most of the spectrum contains noise. If we filter out this noise then we can get a cleaner spectrum later. The bandwidth that is necessary depends on the maximum wind speed to be measured. The typical value of around 400 Hz on each side of the transmitted frequency corresponds to a wind velocity of about ± 15 m s^{-1} along the beam. As even the tilted beams have a huge vertical component and tend to be in the order of 1 m s^{-1} of horizontal winds, actual measurable horizontal winds can be of the order of 50 m s^{-1}. This example was chosen for a transmit frequency of 4500 Hz and a tilt angle of 16°.

2.3.1.3 Ramp gain

The received signal decreases with the distance it travelled in the atmosphere. Therefore the backscatter that returns from higher altitudes is both weaker and later in time. A ramp gain is therefore introduced which amplifies the signals from higher altitudes more than it amplifies signals from lower altitudes.

2.3.1.4 Mixer

To keep the sampling rate down, the frequency of the signal is mixed down from around the sending frequency to around zero. If before mixing the interesting frequency range is from 4300 Hz to 4700 Hz (with a sending frequency of 4500 Hz) then after the down mixing this interesting frequency range will be from 0 to 200 Hz. In this case the difference between a positive and a negative Doppler shift is indicated by the in-phase trace and the 90° phase trace. As such, it is possible to distinguish between positive and negative Doppler shift also after down mixing.

2.3.1.5 LP filter

After the mixing a low pass filter is applied in order to remove all the higher frequency components still present in the signal. After the LP filter the frequency content in the signal represents the Doppler shift in the received signal. The LP filter therefore also limits the maximum wind speeds that can be seen with the Sodar.

2.3.2 Switching time

When the transducers are switched from speaker to microphone, the main problem is that the transmitted noise will "ring" for some time in the antenna and enclosure. During this time signal levels from ringing are higher than from back-scattered signals from the atmosphere and this makes it very difficult to measure meaningful data from low altitudes. Even though the antenna and enclosure is designed to reduce this ringing time by using "soft" materials and acoustic foam in the enclosure, the ringing can affect data quality for the lowest 6 – 10 m (at a pulse length of 40 ms). A typical transient from an Aerovironment Sodar can be seen in the next figure:

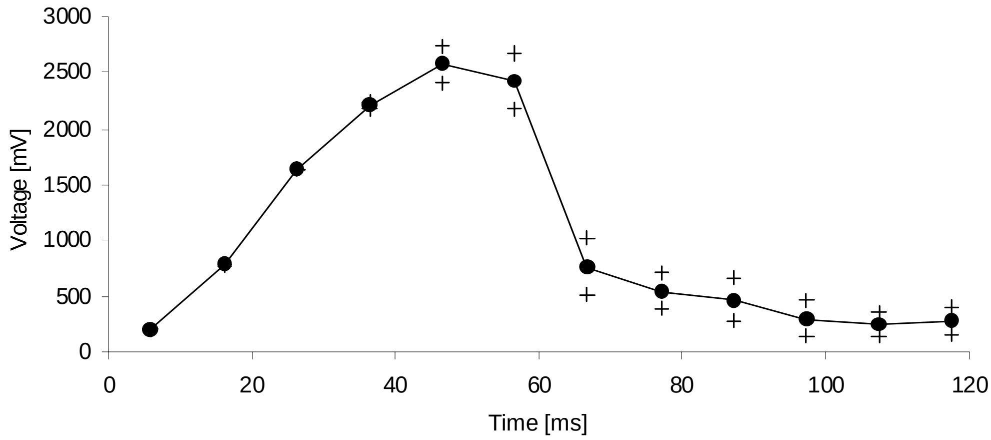


Figure 2.11 Transducer signal due to ringing where time = 0 ms is the time when the pulse has finished being sent.

2.3.3 Sampling time

The maximum height is defined by the time the Sodar measures back-scattered signals. To measure up to a height of 200 meters, the Sodar will have to measure during 1.2 seconds. This sampling time should not be set too short, as otherwise the possibility exists that back-scattered signals from a certain pulse will contaminate the signal from the next pulse.

2.3.4 Range gates

The Sodar measures wind speeds at various heights. These heights are also called range gates. The maximum resolution that can be obtained for these range gates is given by two formulas:

$$\Delta z_V = \frac{c\tau}{2} \qquad (2.9a)$$

$$\Delta z_V = \frac{cN_s}{2f_s} \qquad (2.9b)$$

With Δz_V the height resolution, c the sound speed in the air, τ the pulse length in m, Ns the number of samples of an FFT in a time series, and *fs* the sampling rate.
Equation 2.9a represents the maximum height resolution due to the pulse length whereas Equation 2.9b represents the maximum height resolution due to the FFT sampling.
The maximum height resolution is equal to the larger value of Δz_V in the above formulas. Often Sodars will present data at finer spatial resolution. This can be done either by doing FFTs using overlapping sequences of samples or by using a higher sampling rate if resolution is limited by Eq. 2.9b. While this may look good on a profile plot, no extra information is gained.

2.3.5 FFT

When the back-scattered signal has been sampled, an FFT is done. This FFT is usually done with either 64 or 128 points, at a sampling rate of normally 960Hz. The spectral resolution is 15 Hz (64 points over 960 Hz) which corresponds to a wind speed resolution of 0.55 m s^{-1} along the beam. The sampling frequency also determines the range of wind speeds that can be measured along the beam (f_s = 960 Hz: v_{max} = ± 18 m s^{-1}). As we have seen earlier this amounts to horizontal winds of more than 50 m s^{-1} for a transmit frequency of 4500 Hz and a tilt angle of 16°.

2.3.6 Peak detection

Once the FFT is done for a specific height, the frequency of the peak has to be determined. The following methods can be used to determine peaks:

- By determining the average noise level of that part of the spectrum where no wind speed signal is expected, the background noise can be estimated. The peak is determined through its height above the background noise level
- Averaging of power spectra can also be used. Averaging will not change the signal. The noise (because it is random) will be reduced by the square root of the number of averaged spectra.
- Very often the wind speed is not exactly zero, and reflections from hard objects (fixed echoes) will always be at zero frequency shift. Therefore very often peaks at zero Doppler shift can be ignored.
- The spectrum can be fitted with a specific shape. Based on knowledge of pulse length and other characteristics, this shape can be determined. The part of the spectrum that gives the best fit is the most likely position of the peak.

2.3.7 Consistency checks

If the wind speed is calculated from the instantaneous peaks detected from the spectra, one important problem becomes apparent: The higher the range gate the lower is the signal-to-noise ratio as the sound is absorbed in air and the scattered power decreases. This result in erroneous peak positions from the peak finding algorithm and the resulting wind profiles look “jumpy” both in space and in time. Therefore, it is very common to apply consistency checks and/or averaging. As the essence of a good Sodar system is in how it handles data quality and consistency in a noisy environment, not much is know about the algorithms and techniques actually employed by the manufacturers. However, there are some typical techniques that are commonly used in research instruments and it is therefore likely, to find those in commercial systems as well:

The easiest technique is a straight geometrical average over either the calculated wind profiles or over the Doppler shift along the beam. How to do that will be explained in the section about wind component calculation, as it is very important for the actual information content of the resulting data set. The user can usually choose the averaging time. Typical values range between 1 minute and 60 minutes.

Alternatively, a moving average can be applied where the profiles become interdependent. Although the resulting wind field looks smoother to the eye, no new information is obtained.

Real consistency checks assume that there is certain inertia of wind profiles in time or a maximum vertical wind shear that is physically possible. In this case for each range gate of a profile the wind or frequency shift can be compared with one or more previous profiles and if a certain maximum difference is exceeded the respective value can either be rejected or smoothed out. The same principle applies to the vertical consistency check where a value is compared with one or more upper and lower neighbours and a certain maximum wind shear is defined. If some level of sophistication is applied the difference values are scaled with the wind speed.

In practice it is likely, to find every possible combination of these basic techniques in commercial Sodar systems. Very few manufacturers go as far as to extrapolate the wind profiles according to some meteorological model, which depends on the stability classification that is also determined by the Sodar. The big disadvantage of this approach is that model data cannot be distinguished from measured data and therefore data quality cannot be judged. Therefore, this technique is not normally applied.

Every single technique mentioned above has some level of randomness such as the choice of the averaging time or the definition of a maximum level of permitted wind shear. For the future, it is necessary to develop and evaluate a systematic algorithm for both consistency checking and smoothing, allowing for poor data points, and combining several profiles and points within a profile as consistency check resulting not only in the wind profile but also in a general measure of how trustworthy the result is.

2.3.8 Data rejection

Besides data rejection through consistency checks there are other measures for data quality: Signal-to-noise ratio, Number of valid returns within an averaging interval, a measure for clutter that is the strong echo signal from fixed echoes, and vertical wind speed as a measure of scatter from rain.

2.3.8.1 AD-converter overload

For each range gate the incoming signal is tested for overload in the AD-converter. If there is an overload this would have uncontrollable effects on the spectrum, therefore the respective signals are discarded.

2.3.8.2 Signal-to-noise ratio

The signal-to-noise ratio (SNR) is either defined as a ratio of powers or as a ratio of logarithmic powers. It is straightforward to find the SNR below which, the signal is equal to the noise or smaller. Therefore no valid peak can be found and the data point is rejected. However, most systems allow the user to choose a higher SNR thus defining an empirical value when the peak-finding algorithm is supposed to become unreliable and data points are rejected.
To compare the SNRs of different types of Sodars is generally very difficult because of the different ways the noise level is determined. While some systems determine the noise level from every spectrum, others do one or more noise measurements after every pulse or every measurement cycle (three to five beams). Averaging of the noise level of up to several minutes is also common.

2.3.8.3 Clutter flag

If part of the signal is scattered by fixed objects like houses or trees a second strong peak will show up in the frequency spectrum at zero Doppler shift. The peak finding algorithms often mistake this peak for the wind peak. These so called fixed echoes can be detected assuming that the fixed echo does not extend over more than a couple of range gates. Simple vertical consistency checks are normally sufficient to reject fixed echoes.

2.3.8.4 Vertical wind speed

High frequency Sodars are sensitive to the scattering from rain droplets and again the Sodar spectrum is contaminated with a second peak. However, medium to large rain droplets fall with vertical velocities above the usual atmospheric vertical wind speed of not more than 1 ms^{-1}. Therefore, the peaks can in theory be separated and the real wind speed found. In practice, data points with high vertical wind speeds are often ignored.

2.3.8.5 Number of valid returns within an averaging interval

So far, all data rejection parameters were introduced during spectrum analysis. After this, wind components or vectors are usually averaged over times typically ranging from 1 to 60 min.

When a high percentage of data points is missing for a certain averaging interval the reliability suffers and the average value can be rejected. The threshold is mostly chosen empirically.

Kirtzel and Peters 1999 describe additional checks of the spectrum. They also check the spectrum for the minimum power level of the spectrum defining a threshold that should not be exceeded. This is possible because the bandwidth of atmospheric echoes is small in comparison to the bandwidth of the whole spectral width of the FFT spectrum. Kirtzel and Peters reason that only noise or interfering signals can be wide enough to increase the minimum power value of the spectrum.

A last spectral feature used by Kirtzel and Peters is the fact that the spectral width of the signal is known to a certain extend: It cannot be smaller than the width defined by the acoustic beam width, the finite pulse length and the Hanning shaping of the pulse. On the other hand if the spectral width is too large, then the frequency resolution is too poor to give accurate wind speeds. Therefore the threshold is determined by the application.

2.3.9 Wind component calculation uvw

The signal transmitted from a Sodar is a travelling wave with components like sin(ωt-kz) or cos(ωt-kz) When the wave is scattered at turbulence which is moving with vertical speed w then the returning signal is frequency-shifted due to the Doppler effect. The total Doppler shift is

$$\Delta\omega = -2\mathbf{kw}\,. \qquad (2.10)$$

If the Sodar beam (Figure 2.12) is tilted at a zenith angle θ from the vertical, and directed at azimuth angle ϕ with respect to East, and the wind has components $V = (u,v,w)$ then:

$$\Delta\omega = -2k\left(u\sin\theta\cos\phi + v\sin\theta\sin\phi + w\cos\theta\right) \qquad (2.11)$$

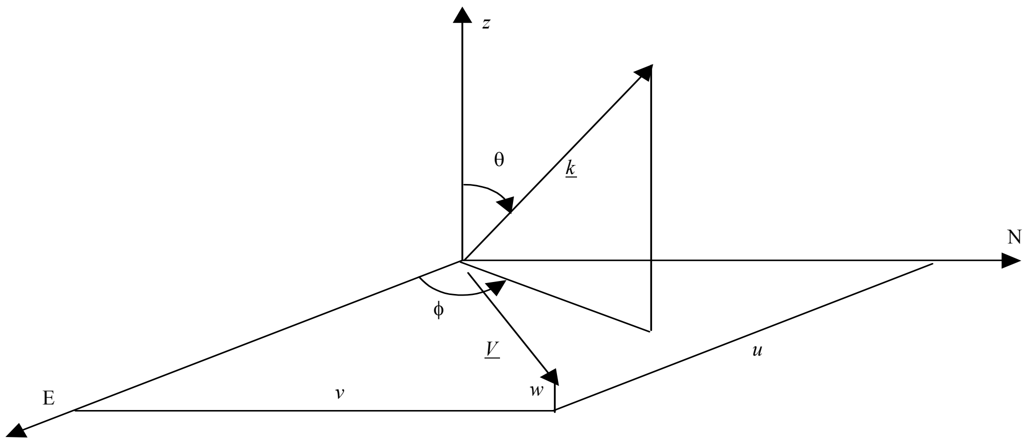


Figure 2.12 Orientation of the Sodar beams

The *easterly* wind component is u and the *northerly* wind component is v, so an easterly or northerly wind gives a *lower* frequency. Generally Sodars are designed so that they direct two tilted beams in orthogonal planes, say with $\theta_1=\theta_2=\theta_0$, $\phi_1=0$ and $\phi_2=\pi/2$. A third beam is vertical with $\theta_3=0$.

Then, at each range gate height, three Doppler shifts are recorded

$$\begin{array}{lcl} \Delta\omega_1 & & -2ku\sin\theta_0 - 2kw\cos\theta_0 \\ \Delta\omega_2 & = & -2kv\sin\theta_0 - 2kw\cos\theta_0 \ . \\ \Delta\omega_3 & & \qquad\qquad -2kw \end{array} \qquad (2.12\ \text{a-c})$$

Solving for u, v, and w gives the three wind components

$$\begin{array}{lcl} u & & -\dfrac{\Delta\omega_1}{2k\sin\theta_0} - \dfrac{w}{\tan\theta_0} \\ v & = & -\dfrac{\Delta\omega_2}{2k\sin\theta_0} - \dfrac{w}{\tan\theta_0} \\ w & & \qquad -\dfrac{\Delta\omega_3}{2k} \end{array} \qquad (2.13\ \text{a-c})$$

Since w is usually much smaller than u or v, the w component in the tilted beam Doppler shifts is sometimes simply ignored in calculating u and v. For example, if w = 0.1 m s^{-1}, then for $\theta_0 = \pi/10$ the error in u is 0.3 m s^{-1}. This compares with a typical measurement uncertainty in u of 0.5 m s^{-1}.

Each tilted beam also has finite width $\delta\theta_0$. This causes an extra spectral broadening in the Doppler signal of

$$\frac{\delta\Delta\omega_1}{\Delta\omega_1} = 2\frac{\delta\theta_0}{\tan\theta_0} \qquad (2.14)$$

(ignoring the w term). Typically $\delta\theta_0 \sim \pm\pi/40$, $\theta_0 \sim \pi/10$, so if k=80 m^{-1} and u=5 m s^{-1}, then $\Delta\omega_1$ =250 rad s^{-1} (Δf_1 = 39 Hz), and $\delta\Delta\omega_1$ =160 rad s^{-1} ($\delta\Delta f_1$ = 26 Hz).

2.3.10 Horizontal wind vector calculation WS, WD

Wind speed WS, and wind direction WD can be directly calculated for each measurement cycle from the wind components:

$$WS = \sqrt{u^2 + v^2} \qquad (2.15)$$

$$WD = \tan^{-1}\frac{u}{v} \qquad (2.16)$$

However, the standard deviation of these single shot wind speeds can exceed 1 m s^{-1}due to finite beam width, finite pulse length, Hanning shaping and other effect. This is too large for most applications and therefore averaging is necessary to increase the accuracy.

There are two basic averaging methods: a) Averaging of power spectra before calculating the wind vector and b) calculating the wind vectors, and average wind speed and wind direction separately. The first method gives lower average wind speeds as changes in wind direction result in smaller wind components. The maximum available wind energy can therefore be measured with the second method. Both methods are described below.

2.3.10.1 Averaging of power spectra from successive profiles.

The noise power fluctuates more than the signal, providing the averaging time is not too long (say no longer than 20 minutes, but this signal autocorrelation time will depend on the environment). Noise powers P_{Ni} from the ith profile, at a particular range gate, are summed in the averaging process:

$$\overline{P_N} = \frac{1}{n}\sum_{i=1}^{n} P_{N_i} \tag{2.17}$$

and

$$\sigma_{av}^2 = \sum_{i=1}^{n}\left(\frac{\partial \overline{P_N}}{\partial P_{N_i}}\right)^2 \sigma_{P_{N_i}}^2 = \sigma_{P_N}^2 \sum_{i=1}^{n}\left(\frac{1}{n}\right)^2 = \frac{\sigma_{P_N}^2}{n} \tag{2.18}$$

so the standard deviation of the noise goes down as the square root of the number of averages.

2.3.10.2 Averaging winds to obtain wind energy

Here we are interested in the wind energy, represented by mean WS^2 .

We assume there are N measurements u_i, v_i, i=1,2,..,N where the u_i and v_i are measured with individual uncertainties σ_{u_i} and σ_{v_i} . Assume that these uncertainties arise from taking the mean of n_{u_i} values of u, and n_{v_i} values of v, each with variance σ_1^2, so that

$$\sigma_{u_i}^2 = \frac{\sigma_1^2}{n_{u_i}} \tag{2.19}$$

$$\sigma_{v_i}^2 = \frac{\sigma_1^2}{n_{v_i}} \tag{2.20}$$

where σ_1^2 arises from error in estimating the position of the spectral peak at each range gate, and is essentially the same for each estimation.

Now:

$$\begin{aligned}\sigma_{S_i}^2 &= \left(\frac{\partial S_i}{\partial u_i}\right)^2 \sigma_{u_i}^2 + \left(\frac{\partial S_i}{\partial v_i}\right)^2 \sigma_{v_i}^2 \\ &= \left[\frac{1}{n_{u_i}}\left(\frac{u_i}{S_i}\right)^2 + \frac{1}{n_{v_i}}\left(\frac{v_i}{S_i}\right)^2\right]\sigma_1^2 \;. \\ &= \frac{\sigma_1^2}{\alpha_i}\end{aligned} \tag{2.21}$$

is the variance of a single speed S_i , and

$$\sigma_{\theta_i}^2 = \left(\frac{\partial\theta_i}{\partial u_i}\right)^2 \sigma_{u_i}^2 + \left(\frac{\partial\theta_i}{\partial v_i}\right)^2 \sigma_{v_i}^2$$

$$= \left[\frac{1}{n_{u_i}}\left(\frac{v_i}{S_i^2}\right)^2 + \frac{1}{n_{v_i}}\left(\frac{u_i}{S_i^2}\right)^2\right]\sigma_1^2 \qquad (2.22)$$

$$= \frac{\sigma_1^2}{\beta_i}$$

is the variance of a single direction θ_i.

The mean $\overline{S}$ and $\overline{\theta}$ are required over the N measurements, allowing for the variable uncertainties. These means are found by following the usual procedures for modelling $y = a + bx$, but here we have only one parameter $a = \overline{y}$, so the one-parameter weighted least-squares fit has the form $y = \overline{y}$.

The single parameter, $\overline{y}$, is found by minimizing

$$\chi^2 = \sum_i \left(\frac{y_i - \overline{y}}{\sigma_i}\right)^2 \qquad (2.23)$$

where σ_i^2 is the variance in measurement y_i, giving

$$\overline{y} = \frac{1}{\sum_i \frac{1}{\sigma_i^2}} \sum_i \frac{y_i}{\sigma_i^2} \qquad (2.24)$$

and

$$\sigma_{\overline{y}}^2 = \frac{N}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}}. \qquad (2.25)$$

In the context of wind-averaging of N=10 one-minute values, this gives:

$$\overline{S} = \frac{1}{\sum_{i=1}^{10} \alpha_i} \sum_{i=1}^{10} \alpha_i S_i \qquad (2.26)$$

and

$$\overline{\theta} = \frac{1}{\sum_{i=1}^{10} \beta_i} \sum_{i=1}^{10} \beta_i \theta_i \qquad (2.27)$$

where the weights are:

$$\alpha_i = \left[\frac{1}{n_{u_i}}\left(\frac{u_i}{S_i}\right)^2 + \frac{1}{n_{v_i}}\left(\frac{v_i}{S_i}\right)^2\right]^{-1} \qquad (2.28)$$

and

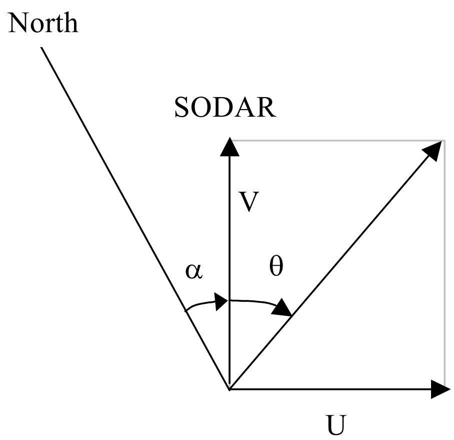
$$\beta_i = \left[\frac{1}{n_{u_i}}\left(\frac{v_i}{S_i^2}\right)^2 + \frac{1}{n_{v_i}}\left(\frac{u_i}{S_i^2}\right)^2\right]^{-1}. \qquad (2.29)$$

Similar considerations can be used for any other averaged quantities.

An example taken from an AeroVironment 4000 return from 90 m with averaging over 150 s, has measured values of u_i = -3.4 m s^{-1}, σ_{u_i} = 0.8 m s^{-1}, n_{u_i} = 38, v_i=3.7 m s^{-1}, σ_{v_i} =0.9 m s^{-1}, and n_{v_i} =36. This gives S_i =5.0 m s^{-1}, θ_i =313°, and σ_1 =5 m s^{-1}. Then α_i =36 and β_i =920 radian^{-2} m^2 s^{-2}. This means that the standard deviation in wind speed for this averaging period is σ_{S_i} =0.83 m s^{-1} and the standard deviation in wind direction is σ_{θ_i} =9.5°.

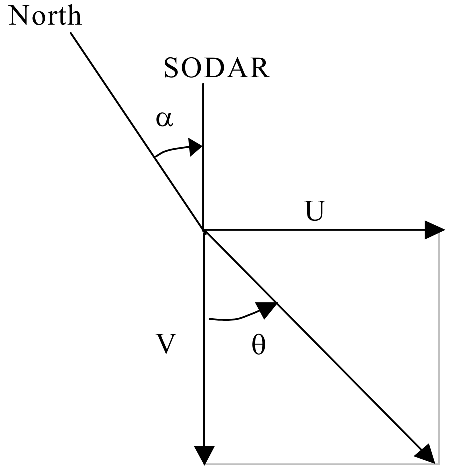
2.3.10.3 Wind direction with rotated Sodar

Whereas we have looked at Sodars as being perfectly aligned in North–East orientation so far, Sodars will normally have an input for antenna rotation angle, to allow for an antenna that does not have its tilted beams facing north and east. The Sodar display software, using the following algorithm, should correct for antenna rotation.

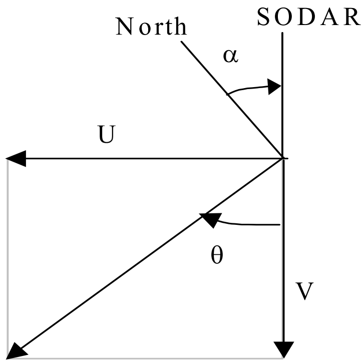


Antenna rotation angle = α

Wind direction : $a+\theta = a+\tan^{-1} U/V$ (2.30a)



Wind direction = $a+\pi-\tan^{-1} U/V$ (2.30b)



Wind direction = $a + \pi + \tan^{-1} U / V$ (2.30c)

2.4 Conclusions on parameter interdependence

From the descriptions above the conclusion is that some of the variables are affecting each other. For instance, by setting the number of sample points to a higher value also the range resolution of the Sodar is decreased. Therefore the settings of these variables should be decided by taking into account these relations.

The following variables depend on each other:

1. Height resolution Δz_V – pulse length τ – sampling rate f_S– number of sample points N_S

   Range resolution Δz_V = the larger of $\frac{c\tau}{2}$ and $\frac{cN_s}{2f_s}$ (2.9a and 2.9b)

   Wind speed spectral resolution: Δf_V = the larger of $\frac{f_s}{N_s}$ and $\frac{1}{\tau}$ (2.31 and 2.3)

   Uncertainty product for winds: $\Delta z_V \Delta f_V = \frac{c}{2}\frac{f_s\tau}{N_s}$ if $f_s\tau > N_s$ (2.32)

   $\Delta z_V \Delta f_V = \frac{c}{2}\frac{N_s}{f_s\tau}$ if $f_S\tau < N_S$ (2.33)

2. Rise time β – effective pulse length $\tau_{eff}(\beta)$?

3. In terms of the power output the effective pulse length changes with the rise time as:
   $\tau_{eff}(\beta) = \tau(1-\beta)$ (2.34)

4. Receive power P_R – pulse length τ

   Via Sodar equation (Eq. 2.1) $P_R \propto \tau$ (2.2)

5. Range z_{max} – pulse repetition rate T – transmit frequency f_T

There is no simple relation between Sodar range, transmit frequency, and pulse length as the range is determined by the absorption, the turbulence strength and distribution as well as the noise levels. These parameters change with the meteorological conditions and the environmental activity. As a rule of thumb one can assume a range of :

$z_{max} \approx 2822 \times f_T^{1.76}$ (2.35)

where the transmit frequency is given in kHz.

This corresponds to a pulse repetition rate of

$$T = \frac{2z_{max}}{c} \qquad (2.36)$$

with sound speed c which is also changing slightly with temperature.

When taking these relations into account, the following settings for the AV4000 Sodar is recommended (Table 2.1):
Because of these dependencies the following settings are recommended for measurements with Aerovironment Sodars. Other Sodars (METEK, Scintec) should follow this re-commendation as close as possible.

Table 2.1 Recommended settings for the AV4000 Sodar

Sodar settings		**Advised value**	**Comments**
Met Sampling			
Maximum Altitude	Mht	4000 array = 150 m 3000 array = 250 m	Preventing backscatter from a previous pulse
Altitude Increment	Avdst	4000 array = 10 m 3000 array = 20 m	
Averaging Time	Sec	600 s	
Wind Gust detection interval	Ngav	Not important	
Percent acceptable data	Gd	At least 10 %	
W Magnitude Threshold	Wmax	500 cm/s	Should be adjusted in complex terrain
Minimum Altitude	Min Alt	1	
Digital Sampling			
Digital sampling rate	Srate	960	Together with the nfft gives this a range resolution of 22.6 m. The frequency resolution is 15 Hz.
Number of FFT points	Nfft	64	
Signal-to-Noise threshold	Snr	7	Should be 6 to 8
Amplitude threshold	Amp	Not important	This parameter is not important in the cases that the Back parameter is not equal to 0
Adaptive noise threshold	Back	-120	Noise threshold is 120 % of the noise measured after the pulse
Analog bandwidth	Bw	800 Hz	
Clutter rejection	Clut	6	Only clutter rejection on the U and V beams
Noise time constant	Nwt	10 s	
Sodar parameters			
Audio amplitude	Damp	As high as possible	
Pulse length	Pulw	100 ms	Taken into acount the range resolution of 22.6 m which follows from Srate and Nfft and Rise
Pulse transition time	Rise	15 %	Together with Pulw = 100 ms gives this an effective pulse length of 70 ms
DOPPLER Limits			
X axis min radial vel	Mincr	-800 cm/s	
X axis max radial vel	Maxcr	800 cm/s	
Y axis min radial vel	Minbr	-800 cm/s	
Y axis max radial vel	Maxbr	800 cm/s	
Z axis min radial vel	Minar	-400 cm/s	
Z axis max radial vel	Maxar	400 cm/s	
Peak detection limits	Nbini	5	

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3. SODAR CALIBRATIONS FOR WIND ENERGY APPLICATIONS

3.1 Objectives

The method traditionally used for measuring the wind speed and direction for wind energy purposes is to record the output from cup or propeller anemometers and vanes at several heights on a mast. As turbines have grown in height, this method has become increasingly more expensive and difficult, and new methods have been sought.

One alternative method for measurement of wind speed and direction over depths of around 200m is the Sodar (SOund Detection And Ranging) instrument that is installed on the ground and which uses sound to remotely sense winds. Sodar technology is well established as a tool for visualising and quantifying atmospheric dynamics in the lowest few hundred meters. At the same time, use of a Sodar as a replacement for cup or propeller measurements in wind energy applications has a number of potential drawbacks. These include the need to calibrate much more rigorously than generally required for other applications, and the requirement that the Sodar operates with well-specified performance over the full range of atmospheric conditions relevant to wind turbine operations. Furthermore, Sodar performance should be portable from one physical site to another, and instruments supplied by a variety of manufacturers should be able to be deployed with known characteristics.

A Doppler Sodar is an instrument that measures wind speed and direction within a number of vertically contiguous volumes above the ground. Transmitting a pulse of sound upward into the atmosphere and then measuring the change in pitch of sound reflected from the combination of turbulent density fluctuations within each distinct volume obtain each measurement. Transmission of acoustic pulses is done sequentially into several directions tilted slightly off-vertical so that separate wind vector components can be estimated in these directions and both wind speed and direction estimates can be inferred in each height range. Some post-processing using consistency algorithms may mean that data obtained from each volume are not strictly independent, but essentially a wind profile is obtained.

At each height range, the wind speed estimate $\hat{V}$ and the wind direction estimate $\hat{\theta}$ are obtained from inputs comprising

- knowledge of the transmitted sound frequency
- an estimated speed of sound
- an estimate of the angle of transmission from the vertical
- a set of frequencies at which echo strength is measured: the frequency at which peak echo power occurs is a measure of wind speed component in the direction of sound transmission
- an estimation of the compass orientation of the plane containing the transmitted beam and the vertical.

The height range at which $\hat{V}$ and $\hat{\theta}$ are obtained is estimated from

- an estimated speed of sound
- an estimate of the angle of transmission from the vertical.

These inputs fall into four categories:

1. Inherent in the Sodar design, and assumed constant and known
2. Established during setting up of the Sodar, and assumed constant and known for a particular site
3. Determined from auxiliary measurements
4. Determined from echo signals which contain variable background noise

In order to provide accurate, repeatable, and well-understood wind measurements for the wind energy sector, it is important that uncertainties in the various inputs, and the underlying assumptions in their use, be well understood and verified through robust calibration. Within the WISE project, work package WP3 therefore has as objectives:

a) An estimation of the uncertainties in calibration, which arise from Sodar design and operation.
b) Description of calibration procedures established by the WISE project and an evaluation of their limitations.
c) Testing of the calibration procedures against other methods of measurement.
d) Suggestions for improvements in Sodar design.

Items (a), (b), and (c) comprise Project deliverable D4 (Report on calibration of Sodar and inter-comparison before and after calibration). Item (d) comprises Project deliverable D5 (Notes on possible improvements of Sodar hardware/software for easier and better calibration).

3.2 Results of calibration studies

The results of the WP3 Sodar calibration study are in two basic parts: theory of Sodar wind retrievals, and factors which might cause uncertainties in wind speed and wind direction results; and designing and carrying out a calibration trial. These two parts are then combined to produce estimates of calibration errors, insight into Sodar implementation best practice, and recommendations as to Sodar design improvements.

3.2.1 Theory of Sodar wind retrievals

A typical Sodar transmits sound as a short (typically 60 ms) single-frequency pulse sequentially into each of three or five beam directions, as shown in Fig. 1 (variations using multiple frequencies and/or other beam combinations are also possible). After each pulse transmission, the echo signal is analysed within a series of successive time intervals, each typically 0.1 s long. Using the assumed speed of sound, these time intervals are associated with contiguous *range gates* or range intervals in the atmosphere. Within each range gate, the echo power is found in a set of closely spaced frequency intervals, centred on the transmitted frequency.

The frequency interval having the most echo power gives a measure of signal frequency shift due to the Doppler effect: the frequency shift gives the wind speed component lying along the direction of the transmitted acoustic beam. Echo signals from a particular transmission are analysed until negligible echo remains, and then sound is transmitted into the next beam direction. Typically the time interval between pulse transmissions into successive beam directions is 2 – 8s. The wind components *u*, *v*, and *w* in the Easterly, Northerly and vertical directions are found by combining radial wind component estimates from all the beam directions at each range gate height.

The important components in retrieval of winds are therefore the speed of sound, the beam directions, estimation of the frequency shift in the presence of background noise, and combining multiple beam information to obtain vector winds.

As seen from
Figure 3.1, beam direction information involves

- the zenith angle, or *tilt angle*, φ, both for signal transmission and signal reception
- the beam width $\Delta\varphi$
- the Sodar orientation angle ϕ

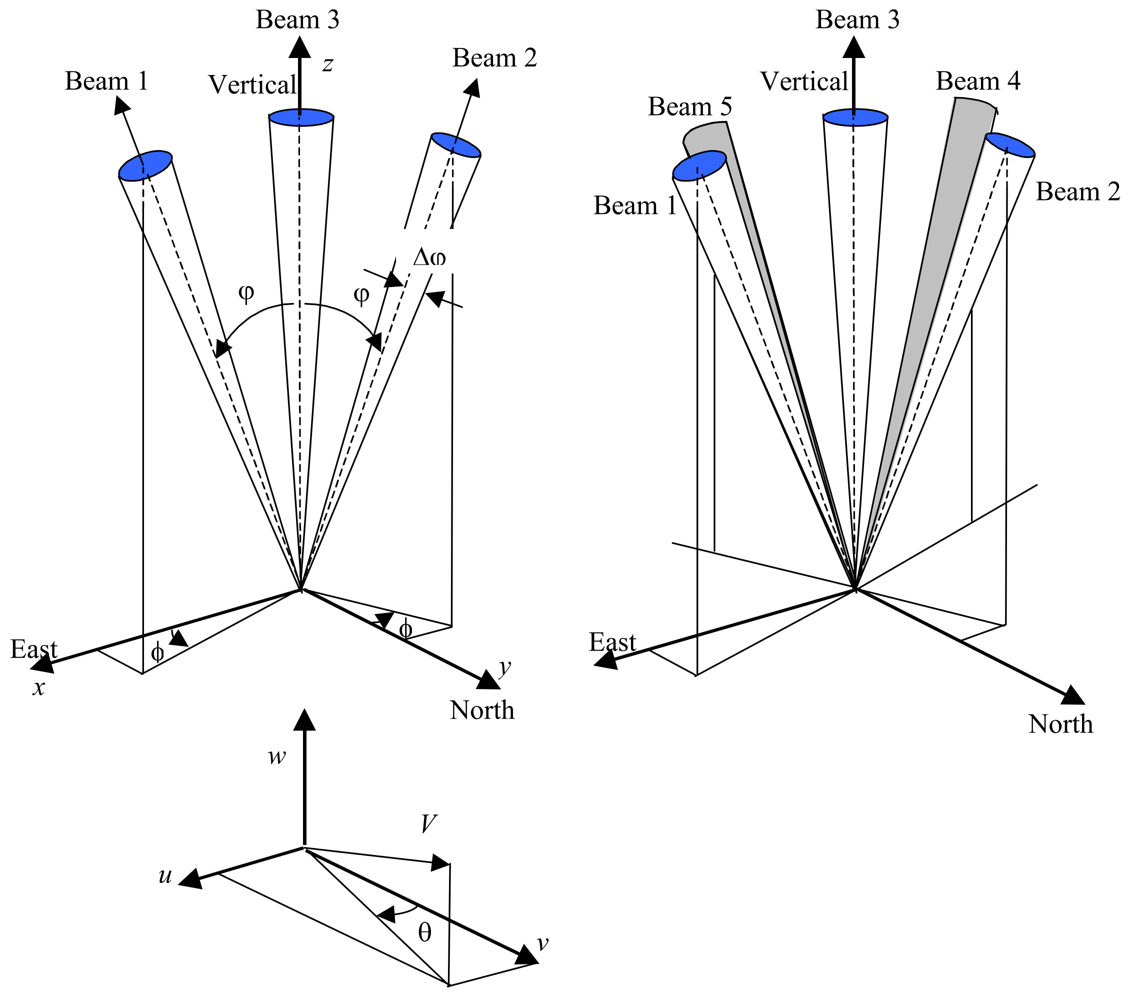


Figure 3.1 Typical beam geometries for a 3-beam and a 5-beam system, showing the relationship to wind components.

It is generally assumed that φ and Δφ are determined by Sodar design, possibly with allowance for temperature effects, but ϕ is determined by Sodar setting up.
The relationship between the frequency shifts Δf_1, Δf_2, Δf_3, Δf_4, and Δf_5 and the wind velocity components *u*, *v*, and *w* is usually assumed to be:

$$
\begin{aligned}
\Delta f_1 &= -\frac{2f_T}{c}\left(u\sin\varphi\cos\phi + v\sin\varphi\sin\phi + w\cos\varphi\right) \\
\Delta f_2 &= -\frac{2f_T}{c}\left(-u\sin\varphi\sin\phi + v\sin\varphi\cos\phi + w\cos\varphi\right) \\
\Delta f_3 &= -\frac{2f_T}{c}w \\
\Delta f_4 &= -\frac{2f_T}{c}\left(-u\sin\varphi\cos\phi - v\sin\varphi\sin\phi + wco\right)s\varphi \\
\Delta f_5 &= -\frac{2f_T}{c}\left(u\sin\varphi\sin\phi - v\sin\varphi\cos\phi + w\cos\varphi\ \right)
\end{aligned}
\qquad (3.1)
$$

where f_T is the transmitted frequency and *c* is the speed of sound. These equations can be inverted to find *u*, *v*, and *w*. From these components, the wind speed *V* and direction θ are found from

$$V = \sqrt{u^2 + v^2 + w^2} \qquad \theta = \tan^{-1}\frac{u}{v}. \qquad (3.2)$$

Because of background noise, the Δf have some associated uncertainty, and so the inversion of these equations produces *u*, *v*, and *w* estimates which also contain random errors. Estimation of the Δf values is therefore a central concern in Sodar signal processing performed by manufacturers' software. An analysis of the peak-finding process used to find the Δf values showed that $\sigma_{\Delta f} \propto \frac{1}{SNR}$ where *SNR* is the ratio of the signal amplitude to the noise amplitude. The behaviour of the signal strength under various atmospheric conditions was then examined. For the same level of background noise, comparable levels of *SNR* occur for constant $\frac{C_T^2}{z^2}$, where C_T^2 is the structure function for turbulent temperature fluctuations and *z* is the height. It was shown that C_T^2 has a direct relationship with two measures of atmospheric stability: the Richardson number *Ri*; and the Monin-Obhukov length *L*. One formulation is

$$C_T^2 \propto L^{-\frac{20}{3}} Ri^{-\frac{14}{3}} (Pr - Ri)^{-\frac{1}{3}} \qquad (3.3)$$

Although, since it was also shown that $L \bullet Ri \propto \left(\frac{dV}{dz}\right)^{-\frac{1}{2}}$, other formulations are possible. For the first time, this theory gives a connection between the generally observed reduction in Sodar data quality during conditions of near-zero temperature gradient, and atmospheric parameters which can be measured or predicted through models. An example is given in Figure 3.2.

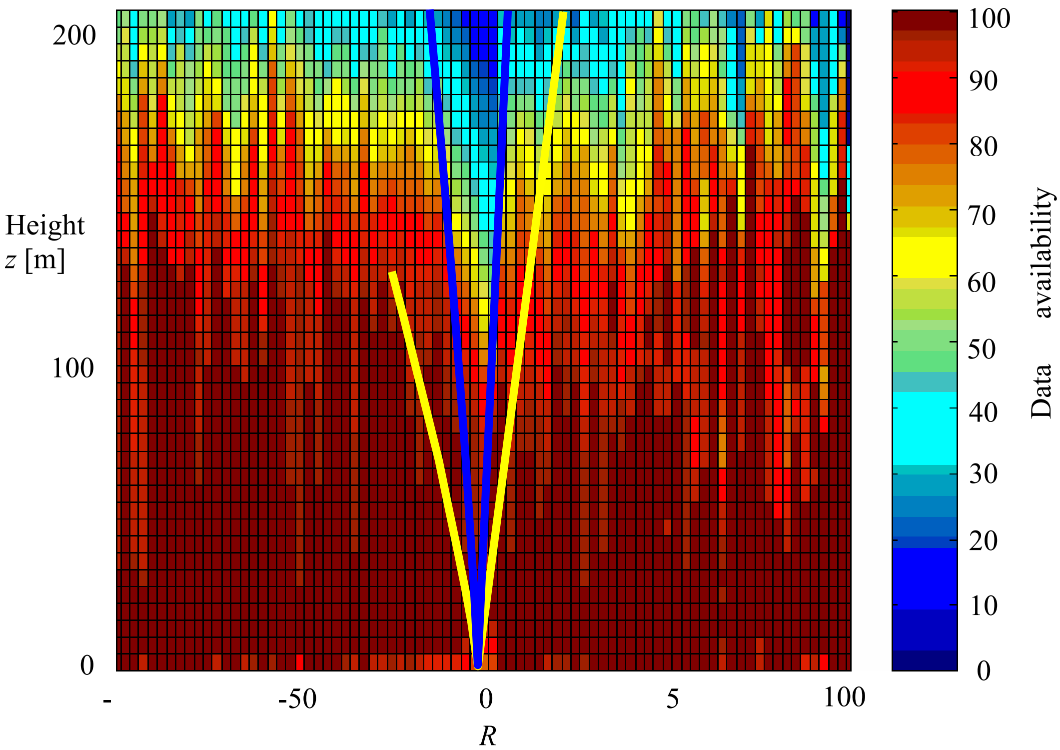


Figure 3.2 Percentage of relative data yield of Scintec Sodar receptions, plotted against height z of the Sodar range gates and against the Richardson number *Ri* based on meteorological mast measurements at 100 m. The solid yellow and blue lines are two contours of constant $\frac{C_T^2}{z^2}$ based on the theory developed in WP3.

In the presence of noise, the peak-fitting process used to find the most likely frequency interval in which the most echo power resides, or other consistency and noise-level checks, will reject some Δf values. This means that at a particular range gate some of the equations in (3.1) will not be part of the inversion to find *u*, *v*, and *w*. Error propagation formulae from $\sigma_{\Delta f}$ into σ_u, σ_v, and σ_w were found for every possible combination of available beams for 3-beam and 5-beam Sodars. Based on this analysis, the relative merits of 3-beam and 5-beam systems were investigated, given that *u*, *v*, and *w* values are generally averaged over 20-60 profiles. There is a trade-off between the greater chance of having a set of solvable equations for a 5-beam system, and the lower numbers of values in each average.

Overall, it was found that the ratio of acceptable 5-beam wind speeds to acceptable 3-beam wind speeds would be:

$$\frac{3}{5}\left(4-5f+3f^2-f^3\right) \tag{3.4}$$

where *f* is the fraction of spectra at a particular range gate which produce acceptable data (this fraction relates to the earlier theory on *SNR*). This implies that a 3-beam system will generally give better quality data when data availability is higher (for example, closer to the ground), but worse when data availability is reduced (for example, further above the ground). It is concluded that an arbitration algorithm should be used in 5-beam systems to reduce down to 3 beams if conditions of high *SNR* are occurring over the height range of interest.

The averaging over N_s = 20-60 profiles reduces σ_u, σ_v, and σ_w by $\sqrt{N_s}$. However, the number of points in each average is variable and so σ_u, σ_v, and σ_w are will be different. The error propagation into σ_V and σ_θ was investigated when there are different numbers N_u, N_v, and N_w of points in the average for each wind component. In the case where *only* those values of *u* and *v* are kept when *both* are available, $N_u = N_v = N_V$ and:

$$\begin{aligned}\sigma_{\overline{V}}^2 &= \frac{1}{N_V}\left(\sigma_u^2+\sigma_v^2+\overline{u}^2+\overline{v}^2-\overline{V}^2\right)\\ \sigma_{\overline{\theta}}^2 &= \frac{1}{N_V}\frac{\sigma_u^2+\sigma_v^2\tan^2\overline{\theta}}{\overline{v}^2\left(1+\tan^2\overline{\theta}\right)^2}\end{aligned} \tag{3.5}$$

This shows the familiar reduction in variance with increasing N_V but also that the uncertainties depend on the mean values.

As pointed out by Antoniou and Jørgensen (2003) cup anemometers measure wind run and divide by averaging time to obtain wind speed. A more extensive analysis of scalar and vector averaging was undertaken in WP3. It was found that:

$$V_{cup} = V_{SODAR} + \frac{\sigma_u^2+\sigma_v^2}{2\overline{V}} \tag{3.6}$$

and so the differences decrease with increasing wind speed. However, neither this dependence nor the height dependence predicted by Antoniou and Jørgensen (2003) on the basis of the parameterisation by Panofsky et al. (1977) was observed in practice.

Apart from Sodar orientation at the chosen site, and temperature dependence of sound speed *c*, the other major factor in accurate wind retrievals based on (2.1) is the tilt angle φ. The origin and meaning of the tilt angle was examined closely in WP3. For an individual beam, and a typical beam tilt angle of 18°, each 1° error in tilt angle represents a 5% error in horizontal wind speed, so accurate estimation of this angle appears to be paramount. Most Sodars form their acoustic beams using a phased 2D matrix of speakers/microphones. For this configuration the change in tilt angle with temperature is about 1º tilt change for 33ºC change in temperature (1.5% wind speed error for every 10ºC change in temperature). This affects *all* tilted beams, but such errors should readily be corrected by either measuring the surface air temperature or using a climatology. At first sight, (3.1) would appear to imply that poor levelling of the Sodar will give rise to similar errors. However, careful error analysis shows that, for both 3-beam and 5-beam systems, if the entire Sodar is tilted, then the change in radial velocity component on a tilted beam is accompanied by a change in the radial velocity on beam 3: when the *w* contribution is subtracted from a tilted beam, the tilt error is largely cancelled. The conclusion is that if the beam 3 signal is considered unreliable then it is better to NOT include the calculation from (3.1) in forming an average.

From the analysis in WP3 it is clear that beam direction errors are important only when the tilt angle of *all* tilted beams in either increased on decreased from the value predicted. This predicted value is generally based on both calculations of the beam pattern from a phased array of speakers and on anechoic measurements, so the actual beam pattern produced by the Sodar is generally quite well known. However, WP3 identified two potential mechanisms by which the *effective* beam direction could be changed. The first of these was beam refraction due to wind and temperature gradients. Georges and Clifford (1972) first gave a treatment and then extended this with examples (Georges and Clifford, 1974). Unfortunately their formula for Doppler shift does not reduce to the simple 1D text book case when the transmitter, receiver and wind are in line. This means also that numerical simulations based on the Georges and Clifford formulae by Phillips et al. (1977) and Schomburg and Englich (1998) are suspect. More recently, another approximate treatment was given by Ostashev (1997). An exact formulation based on fundamental principles was produced in WP3. It was found that, for individual beams, there is a small quadratic dependence of estimated radial wind speed on true radial wind speed. For a 3-beam system there is some cancellation of this effect and the errors in wind speed are only ±0.3 % at V = 5 m s^{-1}, rising to ±1.3 % at V = 20 m s^{-1}. The opposing beams on a 5-beam system mean that there is no refraction error. In contrast, if the vertical beam in *not* used in the wind retrieval for a 3-beam system, serious errors result (±7 % at V = 5 m s^{-1}, rising to ±27 % at V = 20 m s^{-1}) emphasising again that good quality vertical beam data is important!

As shown in Figure 3.1, the acoustic beams have finite spread. In practice, the echo power received is an integration over the entire volume covered by transmitted sound, weighted according to antenna angular gain. This means that the right hand side of (3.1) is also a weighted integral, so the beam pattern is important. The theoretical analysis in WP3 shows that the estimated wind $\hat{V}$, ignoring beam spread, is related to the actual wind V through

$$\hat{V} = V\left(1 + \frac{2\sigma_\varphi^2}{\sin^2 \overline{\varphi}}\right) \tag{3.7}$$

This means the error in wind estimation increases with beam width and is less for greater tilt angles. For example, assuming a typical phased array Sodar configuration with a nominal tilt angle of 18.3°, the weighted tilt angle is 19.6°, giving a 7% overestimate of wind speeds.

Finally, the actual calibration process itself contributes errors and uncertainties. An analysis was done of the errors expected due to spatial separation of the sampling volumes in different Sodar beams. These errors depend on the spatial correlation between winds measured at horizontally separated points. The important finding is that these errors are only significant if (3.1) is solved for *u*, *v* and *w* each profile, and then these components averaged over a number of profiles. In practice, Sodar manufacturers appear to average the radial components (equivalent to the left hand sides of 3.1) and no significant beam separation error results.

3.2.2 Field calibrations

The various potential calibration methods were surveyed and a decision made to calibrate three different Sodar models simultaneously and in close proximity against cup anemometers and vanes mounted at various levels on a 120 m mast situated about 70 m from the Sodars. The major calibration was the Profiler Intercomparison Experiment (PIE), but a subsidiary calibration with only one Sodar was undertaken at a different site as a check on portability of results. The PIE test site is shown in Figure 3.3.

Figure 3.3 The test site, the met tower and the Sodars (wind blowing from the east)

Temperature data were also available form the mast and from a RASS temperature profiler. Rain gauges were used to detect rain and to reject rain-contaminated data. Sodar data was filtered for measurement sector (based on mast location), rain contamination, and echoes from the mast.

The calibration focussed on wind speed estimation, since this is most significant for wind power estimation. Based on physical arguments, a linear model without offset was chosen for the calibration

$$V_s = mV_c + \varepsilon \tag{3.8}$$

where V_s is the wind speed measured by the Sodar, V_c is the wind speed measured by the cup anemometer, m is the calibration slope, and ε is the combined measurement and model error. An analysis shows that the best estimate of the true wind speed is $\hat{V} = \frac{V_s}{\hat{m}}$ and $\sigma_V^2 = \frac{\sigma_{V_s}^2}{\hat{m}^2} + \hat{V}^2 \frac{\sigma_m^2}{\hat{m}^2}$ so the calibration procedure requires estimation of m and σ_m. Wind speeds are of course not uniformly distributed, but an analysis showed that the slope estimation is relatively insensitive to wind speed distribution and, for the meteorological conditions encountered during PIE, the dependence of σ_m on wind speed distribution was not high.

Around 9500 10-minute averages were analysed at each of five heights (40 m, 60 m, 80 m, 100 m, and 115 m), but this number was different at different heights and for different Sodars depending on data quality, correct functioning of the instruments, and filtering used.

The regression results generally showed:

- Scatter of data increases with height
- There are fewer data points and fewer high-wind points at greater heights
- Slopes are not within 5%
- Correlation is high with values of ≥ 0.96.

Figure 3.4 shows residuals for one Sodar and a cup anemometer mounted on the mast at 60 m height. Also shown are residuals from the regression between 60 m and 80 m cup anemometers. There is essentially no difference, and this is validated from 0 -12 m s^{-1} through an F-test on the rms residuals in each 1 m s^{-1} interval. This suggests that most of the uncertainty either lies with the cup anemometers (this is considered unlikely given other data) or is due to the physical separation of the mast and Sodars. Sodar manufacturers generally quote the uncertainty in wind speed measurement expected with their system. For example, Metek estimate σ_{V_s} = 0.4 ms^{-1}, which is consistent with the residuals found in PIE. Also, the standard deviation of residuals for the AV4000 at 40m is 0.40 m s^{-1}. Scintec specifications quote 0.1 to 0.3 m s^{-1} accuracy for their horizontal winds, but the PIE comparison gave values similar to the other Sodars. The important finding is that the Sodar is measuring winds to at least as high reliability as the mast cup anemometers.

The values of slope *m* show 6% underestimation of wind speed for the Metek Sodar, 8% overestimation for the AeroVironment Sodar, and variation with height of 0% at 40 m to underestimation by 6% at 115 m for the Scintec Sodar. The Scintec Sodar uses a combination of asymmetric opposing beams and a range of transmitted frequencies, with the lower frequencies being used preferentially for obtaining winds at greater heights. This could mean that the way in which data is handled is different at different heights (in the sense that different hardware is used and the software uses different parameters), and that this somehow causes the calibration change with height. The slope error for the other two Sodars is within the range of calibration errors discussed above in Section 2.1.

If the 40 m cup is used to correct slopes at other heights,

$$\frac{V_s(z)}{V_s(40)} \approx \frac{m(z)}{m(40)}\frac{V_c(z)}{V_c(40)}$$

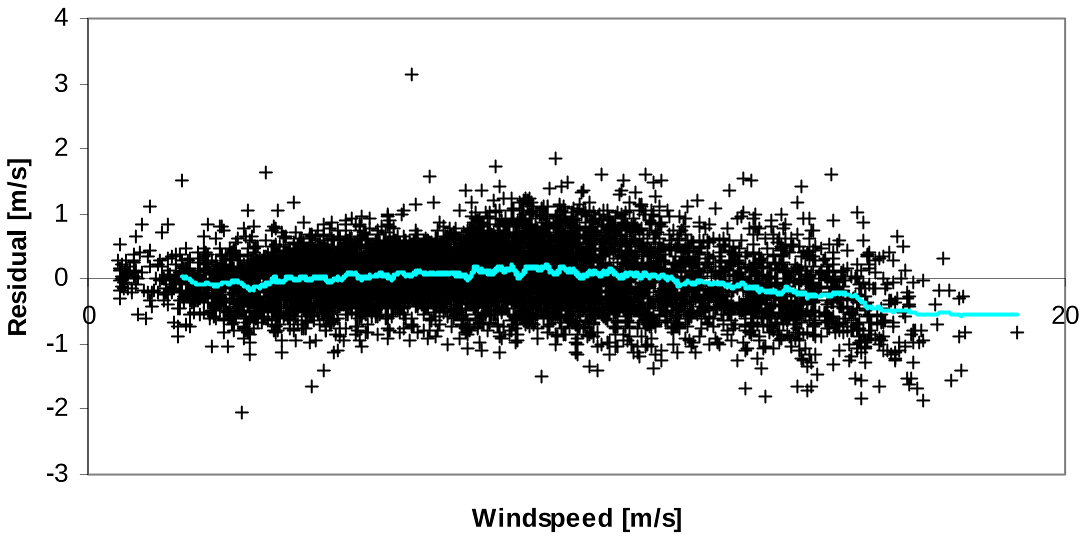
or

$$V_s(z) \approx \frac{m(z)V_s(40)}{m(40)V_c(40)}V_c(z) = m'(z)V_c(z) \qquad (3.9)$$

The profiles of $m'(z)$ are shown in Figure 3.5 for the AeroVironment and Metek Sodars.

It can be seen that calibrations within 2% can be realised over all heights. In fact a persistent echo from the mast in the range of 80 m to 100 m existed in the Metek data, so with some further care in beam orientation it is expected that both Sodars could give wind speeds accurate to 1% over all heights.

Sodar wind directions were found to be consistent with vane directions to within 1-2°.



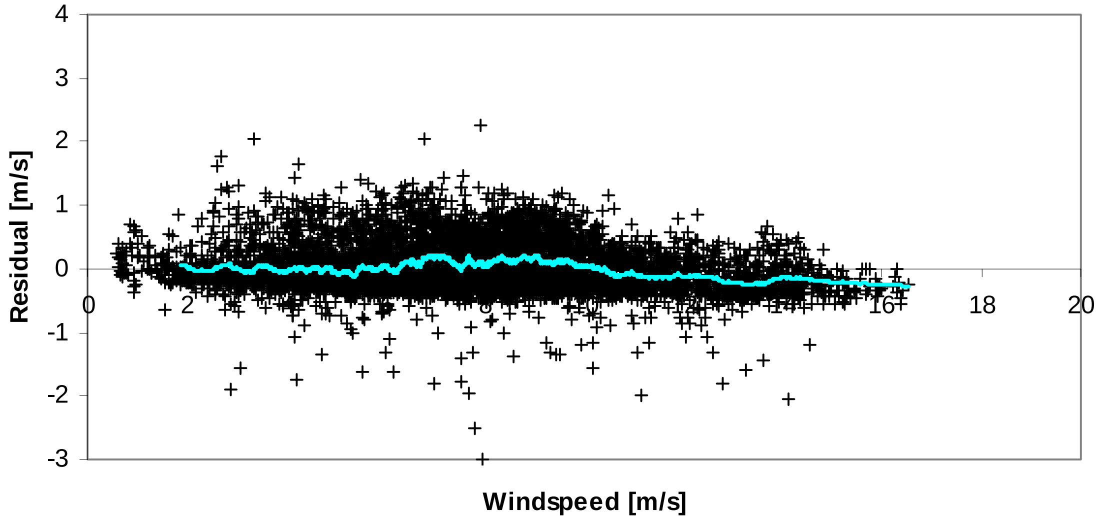


Figure 3.4 Upper plot: Residual plots for AV4000 Sodar and cup at 60m. Lower plot: Residuals in a linear fit of 80 m cup wind speed to 60 m cup wind speed. Superimposed line: running average of 100 points.

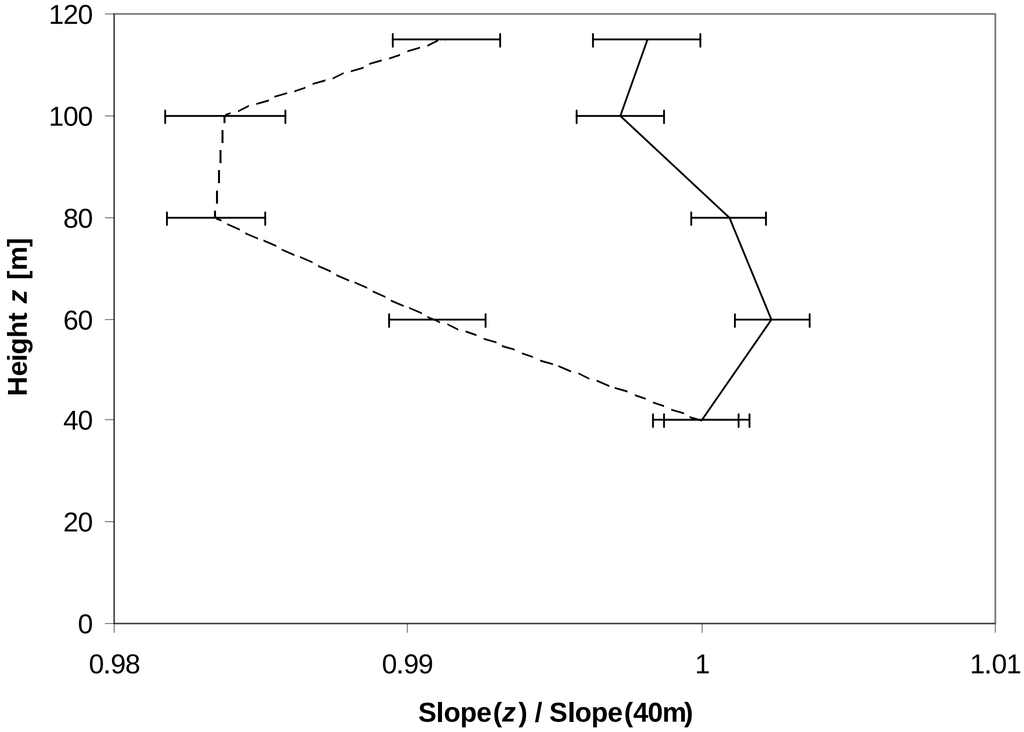


Figure 3.5 Variation in slope *m'* with height. Metek (dashed line), AeroVironment (solid line).

3.2.3 Robustness of calibrations

Five checks were performed on the robustness of the calibration to variations in conditions:
1. divide the data set into even and odd hours. This should give two data sets with negligible difference in conditions, and is simply a test of the robustness of the regression process.
2. divide the data set into even and odd days. This should still provide considerable homogeneity in meteorological conditions.
3. divide data into different wind sectors. This would be expected to give very different meteorological conditions within the various sub-sets, and so is a good check that the calibration is not peculiar to a particular set of conditions.
4. divide the data into the first part of the PIE period and a later part. General seasonal climate differences can be tested.
5. perform calibrations elsewhere, using a Sodar similar to one of those in the PIE trials.

All these tests showed *m* variations of typically 0.1%.

Sodar-Sodar regressions were also computed from the PIE data. These showed agreement with ratios of Sodar-mast regression slopes to within 0.5%. This result emphasizes the reliability of the calibrations.

3.2.4 Estimates of calibration error budget

An estimate of Type A and Type B uncertainties was completed, based on the theoretical treatment and the calibration results. Type A and Type B uncertainties contribute approximately equally when a Sodar is operated without calibration support from a 40 m mast. When a Sodar is routinely calibrated against a cup anemometer and vane mounted on top of a 40 m mast, the Type B uncertainty becomes negligible.

Type A standard uncertainties of 0.31 m s^{-1} in wind speed and 4.7° in wind direction are dominated by:

- Non-colocation of Sodar and cup
- Loss of signal in low acoustic reflectivity atmospheres

Type B standard uncertainties in stand-alone operation are 0.31 m s^{-1} in wind speed and 1° in wind direction and are dominated by:

- Uncertainties in the effective angle to the vertical into which sound is transmitted and from which sound is received

Type B uncertainty when a Sodar is calibrated against a 40 m mast is negligible.

The relative contributions, as fractions of the totals, are shown in the table below.

	Stand-alone operation				**Calibrated against 40 m mast**			
	Type A		Type B		Type A		Type B	
Cause of uncertainty	$\frac{s_{V,A}}{s_V}$	$\frac{s_{\theta,A}}{s_\theta}$	$\frac{s_{V,B}}{s_V}$	$\frac{s_{\theta,B}}{s_\theta}$	$\frac{s_{V,A}}{s_V}$	$\frac{s_{\theta,A}}{s_\theta}$	$\frac{s_{V,B}}{s_V}$	$\frac{s_{\theta,B}}{s_\theta}$
Sodar-mast separation	0.21	0.72			0.42	0.76		
Loss of signal	0.29	0.23			0.58	0.24		
Beam direction			0.50					
Orientation				0.05				

3.2.5 Sodar implementation best practice

For calibration using a short mast to be successful:

1. The mast must extend above the lowest couple of range gates of common Sodars. This is to ensure that valid data is obtained at mast top, unaffected by antenna ringing or ground interference problems. In practice this means a mast height of around 40 m.
2. A high-quality well-calibrated cup and vane be installed at the top of the mast.
3. The tall-mast calibration should prove that the calibration obtained at 40 m can be extended reliably to above hub height through knowledge of generic Sodar characteristics.
4. If the tall-mast work demonstrated calibration dependence on wind or temperature extremes, then the short-mast calibration will need to encompass a similar range of weather.
5. The Sodar be placed within about a mast height of the mast (40 m, say). Closer than this will be likely to cause fixed-echo errors; further away could cause larger residuals.
6. Filtering be applied for bad data (low SNR), rain, excluded sector influenced by the mast, and low wind speeds below the cup calibration recommendations.
7. Care be applied in setting up the Sodar.

3.2.6 Recommendations as to Sodar design improvements

The WISE WP3 Report has shown that:

1. Sodars can be calibrated to within the standard required for wind energy applications, and which is currently provided by mast-mounted cup anemometers.
2. There are differences between Sodar designs which may limit applicability of some designs
3. The proposed technique of calibrating against a 40 m mast cup anemometer is successful providing care is taken with siting of the Sodar, setting it up, and filtering of the Sodar data.

What can be done to develop even better calibration techniques and/or more reliable and continuous Sodar operation?

1. Development of a means of self-calibration
2. Improved SNR by simultaneous transmission on several beams to obtain more averages per unit time and to improve data availability particularly in near-neutral conditions
3. More sophisticated digital signal processing and filtering to remove bad data
4. A rain rejection scheme (and preferably a scheme to obtains valid winds during rain)
5. Good diagnostics and information dissemination to the user
6. Automatic measurement of air temperature for beam tilt calculations
7. Detection of out-of-level
8. Designing with 5-beam capability
9. Attention to beam separation errors in tilt design

3.3 Relationships with other WISE work packages

The WP3 Report draws on and significantly extends the *Theory of Sodar Measurement Technique* (WP1). WP3 is reliant on the data sets produced in PIE and elsewhere, and these are described in some detail in *Supporting Measurements and Creating Datasets* (WP2). Although discussed with the view to obtaining reliable and understandable calibrations, considerable portions of the WP3 Report are concerned with operational characteristics of Sodars. This includes site selection, setting up, and filtering of data. These aspects have substantial overlap with *Operational Characteristics* (WP4), and some of the Sodar features appear in both Reports. Results from WP3 are used in *P-V Measurements* (WP5), together with other data. Finally, it should be noted that WP3 does not address siting Sodars in complex terrain or on marine platforms: these aspects are treated exclusively in *Measurements in Difficult Circumstances* (WP6).

3.4 Conclusions on Sodar Calibration

The WP3 Report *Sodar calibration for wind energy applications* comprises an exhaustive theoretical analysis of Sodar uncertainties in calibration which arise from Sodar design and operation. Additionally, it describes and evaluates calibration procedures applied to three different Sodar models, and tests these procedures at another site and on another Sodar, as well as with Sodar-Sodar comparisons. Suggestions are made as to improvements in Sodar design, specifically for the wind energy applications.

The result of the calibration investigation is to show that, with appropriate care and knowledge, Sodars can provide wind speed and direction profile data to the same degree of accuracy as mast-mounted cup anemometers, providing there is a reference cup anemometer mounted on a nearby 40 m mast. Specifically, variations of wind speed calibration slope of less than 1% can be expected, with rms residuals of typically 0.4 m s^{-1}. Wind direction variations are typically 1° or 2°. Clear guidance is given on how such results might be achieved.

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4. OPERATIONAL CHARACTERISTICS OF SODAR SYSTEMS

4.1 Introduction

The subject of the following paragraphs is circumstances that cause unreliable wind data from Doppler-Sodar measurements, and how these data might be detected and filtered a posteriori. The following discussion assumes that the Sodar has been set up perfectly (horizontally and azimuthally correct, no interference between the baffles and the main acoustic beam, all loudspeakers and receivers work as designed). The general remark and points on well-mixed boundary layer in the late afternoon and precipitation mainly relate to the determination of mean wind speeds and are therefore especially important for wind energy site evaluations. The points on very strong winds, external noise, and fixed echoes can also influence power performance measurements.

The important point with remote sensing devices is that they are related somehow to the state of the atmosphere, and therefore, they are likely correlated with the measured variable itself. This means, that the statistics may become more or less biased, if there are appreciable gaps in the data (Peters 2001).

4.2 Operating conditions

4.2.1 Well-mixed boundary-layer in the late afternoon

A drawback of monostatic Sodars is that the atmosphere does not produce acoustic backscatter in the 180° direction if primarily mechanical forces produce the atmospheric turbulence, and buoyancy forces are very small (Maughan et al. 1982). This frequently happens when the atmospheric stratification changes from stable to unstable in the morning hours and even more pronounced when the atmosphere becomes very well mixed in the later afternoon. A comparison between Sodar and RASS measurements shows clearly (Emeis et al. 2004) that the acoustic backscatter from a CBL decreases rapidly in the afternoon while the backscatter for electromagnetic waves in the same range gates is still there (or even becomes stronger). This is clearly seen in Figure 4.1, where the Richardson number that is a measure of the atmospheric stability, is plotted vs. the data yield. In Sodar data records this situation is signalised by weak backscatter intensities and decreasing signal-to-noise ratios while the variance of the vertical velocity component remains still high.

The automatic filter algorithms eliminate these data. The effect of the elimination of data due to well-mixed temperature stratification on the measured daily mean wind speeds is probably height dependent. In the surface layer, the wind speed is higher during the afternoon than during the night on days when a convective boundary layer evolves. On these days the diurnal course of the wind speed is opposite in the lower Ekman-layer above. Therefore this drawback of monostatic Sodars probably leads to too low mean wind speeds in the surface layer and to too high wind speeds in the lower Ekman-layer. The only way to avoid this problem is probably to use bistatic Sodars.

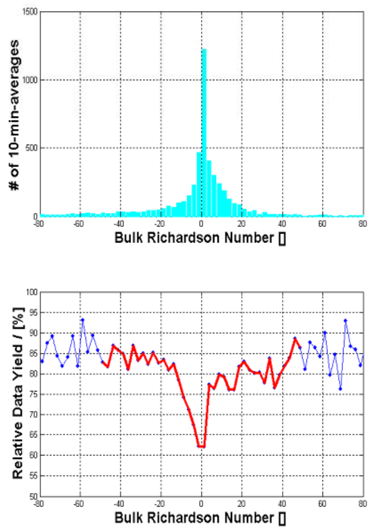

Figure 4.1. Upper panel: Distribution of Bulk Richardson number as observed from 2003-05-23 to 2003-07-23. Lower panel: Percentage of relative data yield of Sodar receptions for the same period, plotted versus the Bulk Richardson number.

4.2.2 Precipitation

Different forms of precipitation have various influences on the recorded acoustic backscatter by Sodars. Especially if the speed of the precipitation particles differs from the speed of the air mass through which they are falling, precipitation can lead to the detection of wrong wind speeds. An example is given in the Figure 4.2 below, where the correlation between the mast and the Sodar readings becomes worse during precipitation. Eventually heavy precipitation will result in total loss of data, see figure 4.3.

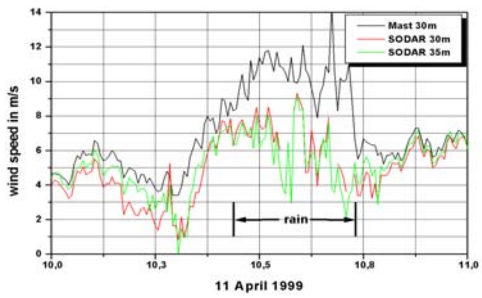

Figure 4.2. Sodar and met tower readings during dry and rain weather

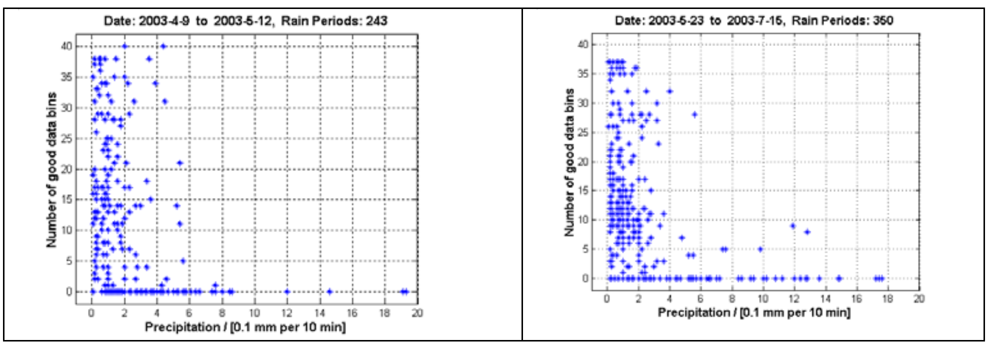

Figure 4.3. Dependency of the number of valid data returns on the precipitation rate

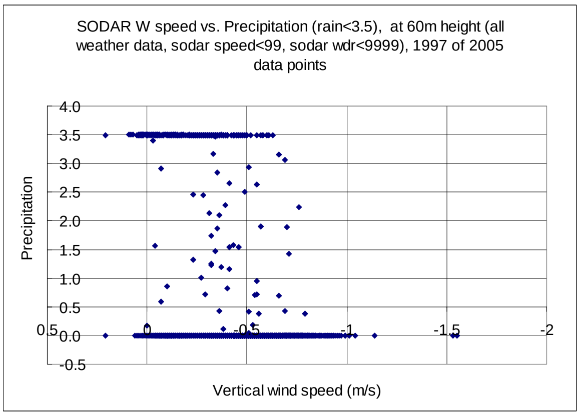

Figure 4.4. The Sodar vertical wind speed vs. the precipitation

In figure 4.4, it is indicative that higher vertical wind speeds are observed during rain periods relative to the dry weather data. Rain leads to considerable noise due to the impact of the drops on the instrument and in the surroundings. On the other hand, due to their smaller size (compared to snow flakes) they are not so good reflectors for sound waves. Therefore, during rain the signal-to-noise ratio declines and the Doppler detection of wind speed ceases while it rains. Hail has even worse effects than rain.

4.2.3 Falling snow

It induces the detection of a considerable – though spurious – downward velocity in the order of 2 m/s. As larger snowflakes provide a good reflectance and the impact of snow flakes on the instrument is loudless the signal to noise ratio stays high and normal filtering algorithms may let pass such signals. Longer snowfalls on Sodars without heating lead to a nearly perfect insulation of the instrument and a failure of further measurements until the snow melts again. In Sodar data records snowfall can be detected from constant downward vertical velocities while the backscatter intensity is high and the variance of the vertical velocity is usually small. The usual filters do not eliminate data from periods of snowfall. The determination of wind speeds is usually eliminated in periods of rainfall by the filtering procedure. They are marked by high backscatter intensities in all range gates and low signal-to-noise ratios in the remaining data. At least for convective showers and thunderstorms there is a correlation between precipitation and higher wind speeds. Thus, the elimination of rain episodes might lead to too low wind speed averages.

4.2.4 Very strong winds

Very strong winds lead to noise production in the surroundings of the instrument and also at the edges of the instrument, enclosure. The consequence is a drastic decrease in the signal-to-noise ratio, which may result in the total loss of signal after a certain point where the background noise dominates. The design and the acoustic sheltering of the instrument may have beneficial effects for wind speed measurements of very high wind speeds.

4.2.5 External noise

Apart from meteorologically induced noise like rain and high wind speeds other – external – noise sources disturb the backscatter intensity and wind speed measurements considerably. The results of the measurement are spuriously high backscatter intensities and low signal-to-noise ratios. As external noise sources are usually not correlated with the wind speed the elimination of data by the filtering algorithm should not have systematic influences on the measured wind speeds. External noise results from the surroundings (birds, highway traffic, air traffic).

In Sodar data records the events can be identified from high background noise levels, high backscatter intensities in all range gates and low signal-to-noise ratios. The influence of external noise sources might be minimized by a suitable choice of the measurement location, as far as this is possible.

4.2.6 Fixed echoes

A well-known drawback of acoustic remote sensing techniques are so-called fixed echoes, i.e. reflections from structures and objects that do not move (or move with a speed different from the wind speed) in the surroundings of the instrument. As backscatter intensities are very high from these structures and objects, they influence Sodar measurements even if side lobes of the Sodar beam only hit them. Fixed echoes lead to wrong wind speeds, which are – in the most usual case of not moving objects – too low.

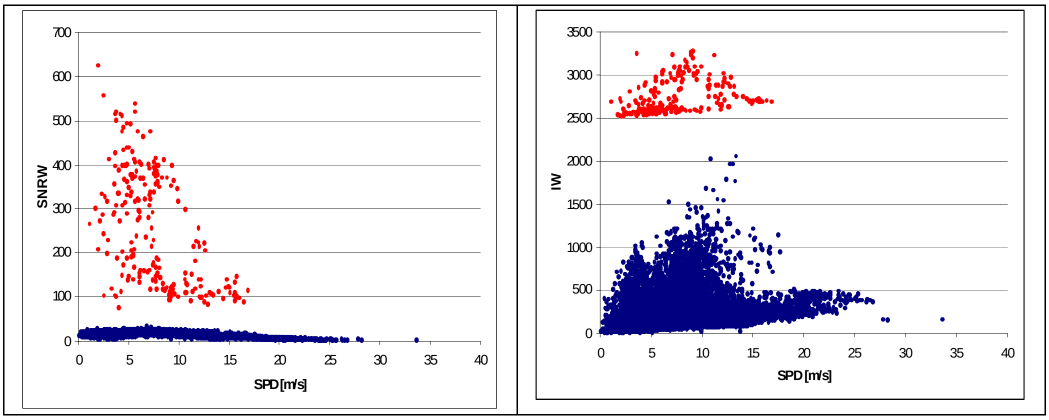

Figure 4.5 The signal to noise ratio and the signal intensity vs. the wind speed

In Sodar data records fixed echoes can most easily be detected from time series of the backscatter intensity and time series of the wind speed. Fixed echoes produce too high backscatter intensities in certain range gates during the whole measurement period (although they might change their intensity with the wind direction), Figure 4.5. Simultaneously too low wind speeds are determined from the data from these range gates. This can most easily be detected from time-mean vertical wind profiles. The usual filters let pass fixed echoes because the signal-to-noise ratio stays high. The influence of fixed echoes might be minimized by a suitable choice of the measurement site. Alternatively, the common practice is to exclude SNRs, which exceed a certain threshold as in Figure 4.5.

4.3 Filtering using the SNR

The data below (Figure 4.6) are from an analysis of some AV4000 Sodar results which was made in combination with data from a near by met mast, which is instrumented at heights 60m, 80m, 100m and 116m. The filtered and non-filtered wind speed data at 60m and 100m are presented relative to the mast wind speed. The filtering took place by using the same filtering conditions (7<SNR (U,V,W)<30) at all heights. Note that the data are presented for both rain and dry weather periods together. In the upper right of the figure the results are also presented as dry and rain weather data.

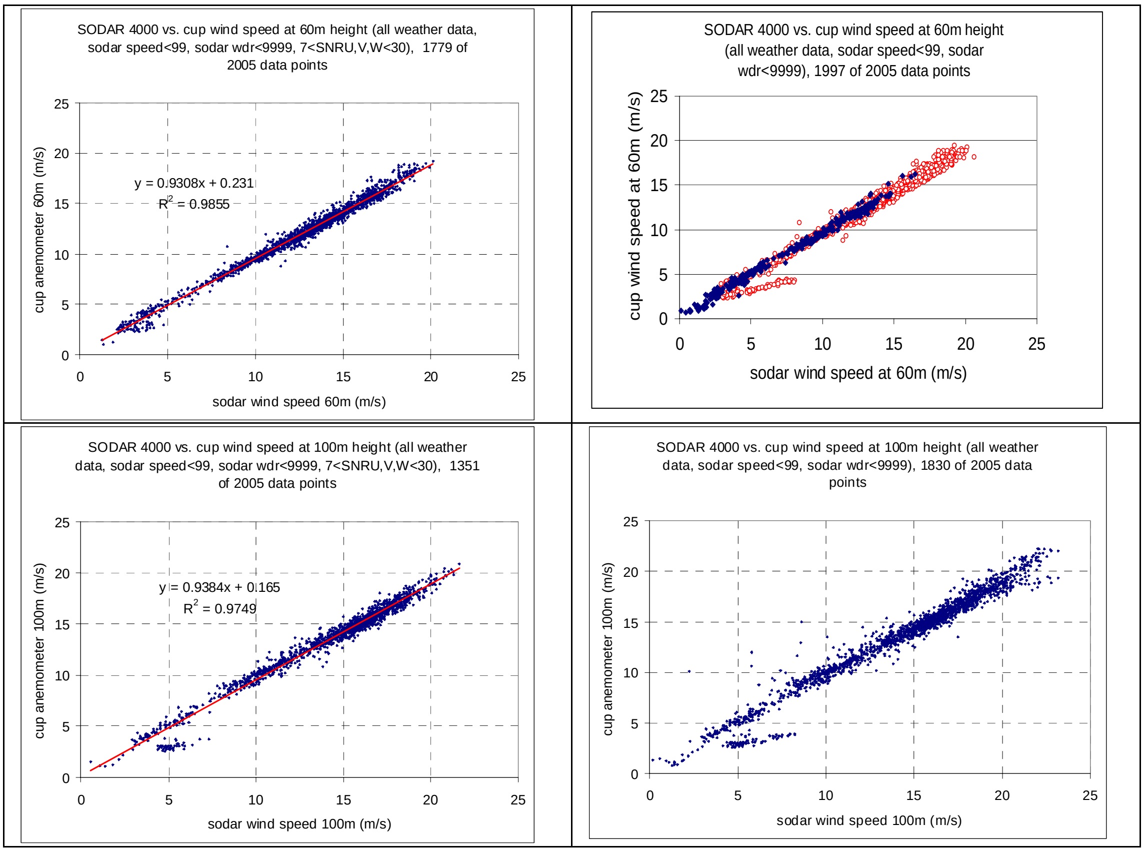

Figure 4.6 Filtered and non-filtered Sodar wind speed data at 60m and 100m height. In the right upper figure results are shown as rain (red circles) and dry (blue solid) weather data.

The main filtering, at least for the AV4000, takes place with the help of the SNR parameter after the wrong 999 data have been excluded. In the figure above the rain and dry weather data do not show any significant differences and as seen the deviations from the main data are due to rain incidents. Comparing to the figure to the left, some of the obviously wrong data are removed by using the SNR filter, but not all. Clearly the filtering of the data is not adequate using the SNR and therefore additional filtering methods should be used. This is however difficult, as this demands access to a closed commercial software and development of additional corrective algorithms.

In Figure 4.7, the SNR and the number of signal returns are presented for the 60m and up to 100m heights, both filtered and non-filtered data. Both the SNR and the number of signal returns are seen to fall with the increase of the wind speed and the height. Thus it seems that the information given by these quantities is highly interconnected. This illustrates that the use of other parameters from the existing software does not introduce new possibilities for data filtering. The figures below illustrate also that the SNR attenuates with increasing height and that it attenuates different for the three velocity components, remaining higher for the w-component.

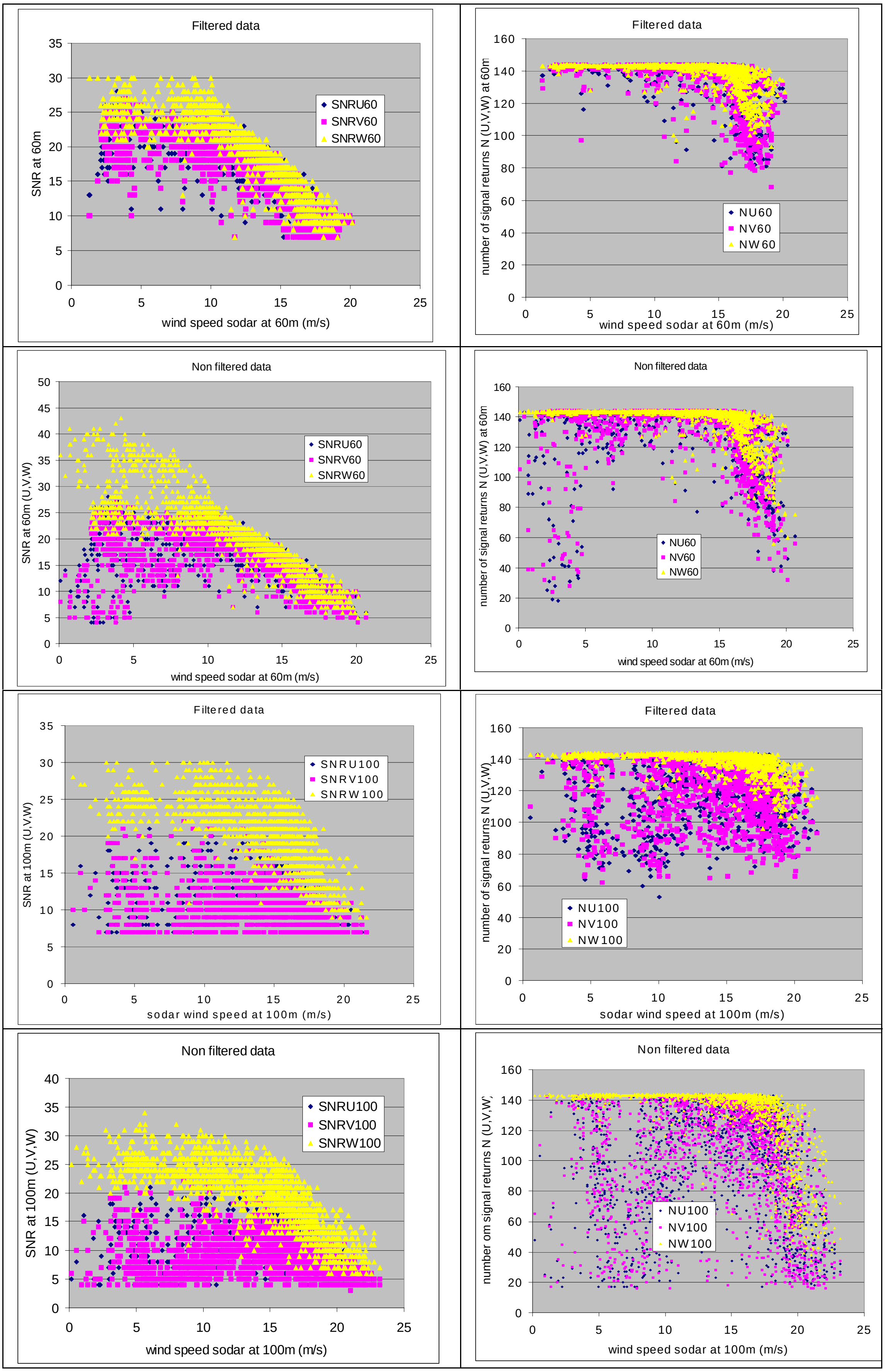

Figure 4.7. The SNR and the number of signal returns (filtered and non-filtered data) at 60m and 100m height.

In order to filter the above results a SNR was used between 7 and 30 for all three wind speeds and for all heights. This leads to an over-filtering of the data at higher heights, as the SNR becomes less. By looking in Figure 4.6, the consequence of this filtering is that a large amount of high-speed data, not obviously wrong, are removed together with outliers.

4.4 Conclusions on Operational Characteristics

A number of parameters influence the phased array Sodar operation either due to weather conditions or conditions at the site of deployment. These conditions are:

1. Neutral atmospheric conditions
2. Rain-snow
3. Background noise
4. External noise
5. Fixed echoes from surrounding objects

The available filtering techniques offered by the software of the instrument do not seem to be adequate as they either fail to remove the wrong data or filter away sound data especially at high wind speeds. To develop corrective routines to be able minimize data losses and make filtering techniques more efficient, there is a strong need for insight in the instrument software. Manufacturers of Sodar systems should be aware of this.

4.5 References

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5. POWER PERFORMANCE MEASUREMENTS WITH SODAR

5.1 Introduction

Within the framework of the WISE project three experiments using Sodars have been carried out at three European wind turbine test sites. The purpose of these experiments was to conduct power performance analyses using Sodar measured wind speed data. Power Performance curves and Annual Energy Productions from the test turbines at the three sites from Sodar measured data and cup anemometer measured data are compared. Filtering methods determined in [WP3] and [WP4] have been applied to the data to enhance the accuracy. Since the used Sodars in this project had to be calibrated (see also the reports of [WP3] and [WP4]), simultaneous calibration measurements have been carried out using cup anemometer measured data at small meteo masts of around 40m height. Uncertainties in measurement are a very important issue in power performance tests, hence an analysis is given of uncertainties involved in P-V measurements with a stand alone Sodar and measurements with a calibrated Sodar. In the following section a summary is given of this uncertainty analysis. In the next three sections the power performance results from RISØ, ECN and WINDTEST are summarised.

5.2 Uncertainties in Sodar measurements

The WP3 Report recommends that a Sodar shall be routinely calibrated against a cup anemometer and vane mounted at the top of a 40m meteo mast. It should be noted that the calibration must be executed during the entire measurement period. In that case, the simultaneous calibration significantly reduces the measurement uncertainties. In the next section the type B uncertainties will be given for Sodar stand alone operation. In Section 5.2.2 an analysis is given in case the Sodar is simultaneously calibrated against a calibrated wind speed measurement using a smaller (for example 40m high) mast mounted with a cup anemometer.

5.2.1 The uncertainties of Sodar measurements by stand alone operation

The uncertainties of the Sodar at stand-alone operation are given below. These uncertainties are treated as type B uncertainties, since these do not involve direct statistical information from the measurements.

Uncertainty in estimating the centre of the height range over which Sodar winds are estimated gives $s_{V,B1} = 0.06$ m/s.

The beam tilt angle of the Sodar might be different from the beam tilt angle that is used in the determination of the wind speed and direction. The uncertainty in beam tilt angle has various origins:

a) Due to incorrect estimate of the speed of sound, this gives $s_{V,B2a} = 0.015V$ m/s

b) Due to poor levelling of the Sodar: $s_{V,B2b} = 0.03V$ m/s

c) Due to finite beam spread: $s_{V,B2c} = \frac{0.07}{2}V$ m/s.

d) Due to refraction of the beam path: $s_{V,B2d} = 0.005V$ m/s.

Combination of uncertainties $s_{V,B2a}$, $s_{V,B2b}$, $s_{V,B2c}$, and $s_{V,B2d}$ gives a combined standard error of

$$s_{V,B2} = V\sqrt{0.015^2 + 0.03^2 + 0.035^2 + 0.005^2} = 0.049 \text{ V m/s.}$$

Uncertainty in Sodar orientation s_ϕ due to misalignment of the Sodar. This does not affect $s_{V,B}$ but contributes an estimated $s_{\theta,B3}$ = 2°.

Uncertainty s_f in the frequency *f* at which the frequency spectrum peaks. The FFT algorithm of the Aerovironment Sodar has a resolution of 0.55m/s along the beam, which is around 2m/s in the horizontal plane. This leads to a standard deviation in wind speed of $2/\sqrt{N_s}$ m/s, where N_s is the number of peak estimates in an averaging interval.
For N_s = 100, the standard deviation in wind speed is 0.21 m/s. Error propagation gives a standard deviation in wind direction of $s_{V,B4}/V$. Assuming a wind speed *V=10m/s,* $s_{\theta,B4}$ = 0.02 radian or $s_{\theta,B4}$ = 1.1°.

The uncertainties $s_{V,B1}$ $s_{V,B2}$ and $s_{V,B4}$ lead to the total Type B combined standard errors of

$$s_{V,B} = \sqrt{s_{V,B1}^2 + s_{V,B2}^2 + s_{V,B4}^2} = \sqrt{(0.049V)^2 + (0.21)^2} \text{ m/s.}$$

$$s_{\theta,B} = \sqrt{s_{\theta,B3}^2 + s_{\theta,B4}^2} = 2.3°.$$

5.2.2 Sodar type B uncertainty analysis with calibration against a small mast

A first uncertainty analysis approach for the use of Sodars for power performance measurements could be based on a relative calibration of the Sodar in flat terrain combined with a meteorology mast equipped with cup anemometers to provide wind speed measurements at several heights. The subsequent use of the Sodar is with a smaller reference mast for the power performance measurement.

A Sodar is operated next to a mast in which a calibrated cup anemometer is installed. The Sodar and cup anemometer measure simultaneously, where the Sodar measurements at higher altitudes are used for the power performance measurements. In this case the Type B uncertainties $s_{V,B2}$ and $s_{\theta,B3}$ from the previous section are largely removed, leaving $s_{V,B1}$ and $s_{V,B4}$ together with uncertainties associated with cup and vane.

The uncertainty of the cup anemometer being used for the RISØ experiments for WISE at Høvsøre, the RISØ P2546, is in general:

$$u_{M,lower} = u_{M,upper} = \sqrt{u_{cal}^2 + u_{ope}^2 + u_{mount}^2} = \\ = \sqrt{(0{,}07 m/s)^2 + (0{,}06 m/s + 0{,}006 U_{M,lower})^2 + (0{,}011 U_{M,lower})^2} \quad (5.1)$$

The operational uncertainty of the cup anemometer was analysed for the conditions during the measurements at Høvsøre. It was found that the cup anemometer on average seems to under-predict the wind speed by -0.14%, and the general standard uncertainty could be set to 0.2%.

Sodar calibration and uncertainties
The relative calibration should produce correction factors for the Sodar for extrapolation to higher heights:

$$\alpha = (U_{M,upper} / U_{M,lower}) / (U_{S,upper} / U_{S,lower}) \quad (5.2)$$

It must be assured that the filtering of measurement data takes away erroneous data, and that the operational characteristics of the Sodar do not change in such a way that its response would be influenced. The statistical uncertainty in equation (5.2) is small and can be neglected.

For the power performance measurement, the cup anemometer on the small meteorology mast measures the wind speed at the lower level as a traceable wind speed and the Sodar measures the extrapolation profile. The hub height wind speed is thus:

$$U_{hub} = U_{upper} = \alpha\,\beta\,U_{S,upper} \tag{5.3}$$

The relation β between the lower met mast measurement and the Sodar measurement at the same height should be determined during the power performance measurement:

$$\beta = U_{M,lower} / U_{S,lower} \tag{5.4}$$

The uncertainty of the relation β is taken as:

$$u_{\beta} = \sqrt{s_{\beta}^{2} / N_{\beta}} \tag{5.5}$$

and is calculated between 4m/s and 16m/s. The uncertainty due to different vector and scalar averaging at different height can be derived, but is in the present case small and is neglected. As a result the uncertainty of the wind speed measurement U_{hub} by the Sodar at hub height of the turbine can now be summarised as:

$$u_{hub} = \sqrt{u_{\alpha}^{2} + u_{\beta}^{2} + u_{M,lower}^{2}} \tag{5.6}$$

The reader should be aware that in the above analysis, the variation in the number of samples over which the average value is taken within a 10 minutes period, has not been discussed.

5.3 RISØ Power Performance analysis

The RISØ Sodar power performance measurements took place during two campaigns at the National Danish Test Station for Large Wind Turbines, which is situated in the northwest of Denmark close to the North Sea. The site is flat and a site calibration, although not needed, has taken place in the first campaign in order to confirm the way the boundary layer develops. The site calibration took place using two mast instrumented at a number of heights which confirmed that no profile changes occur between the location where the met tower and the turbine are situated.

In a second field experiment at the same site, the Sodar was deployed near a heavily instrumented met tower and a nearby wind turbine and power curve measurements were made using both instruments. The calibration method for the Sodar was applied to the results of this campaign. An inter-comparison of the wind speed results and the wind turbine power curve is determined together with annual energy production results.

The Sodar used during the measurements campaigns was the AeroVironment mini Sodar. The Sodar was a combination of a 50-element 4000-antenna operating at 4500Hz installed in a 3000 enclosure. The hub height of the turbine used for the power performance analysis is 80m.

5.3.1 Filtering of data

To filter the data for the Power Performance analysis the criterion 7<SNR<35 at both 40m and 80m height was used, together with filtering erroneous data and rain weather data. From experience it has been found that common filtering rules should be applied at both heights. The largest drawback from using the SNR criterion is that it decreases with increasing height and because of this, there is a risk of excluding sound data at higher heights. The removal of data contaminated by fixed echoes is a more tedious task, as it requires investigation of the spectral results in order to determine their presence. Alternatively outliers can be removed artificially by limiting the allowable difference between the Sodar and the cup anemometer data at 40m height and excluding the corresponding data also at the 80m (hub height). As fixed echoes do not necessarily appear simultaneously at more heights, the application of this filter does not remove all outliers at the hub height. In Figure 5.1 the effect of filtering on the data availability is shown.

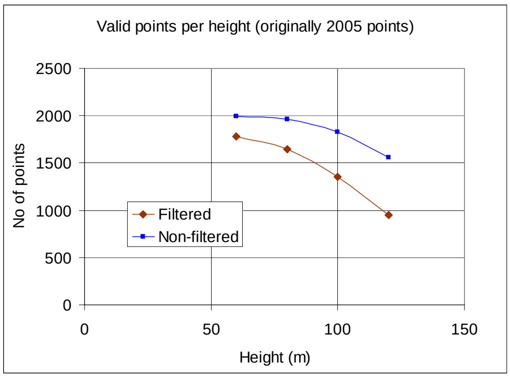

Figure 5.1 The number of data points before and after filtering.

5.3.2 Power Performance curve

The power curve of the wind turbine as measured during the second campaign is presented as a function of the wind speed for the three instruments in Figure 5.2.

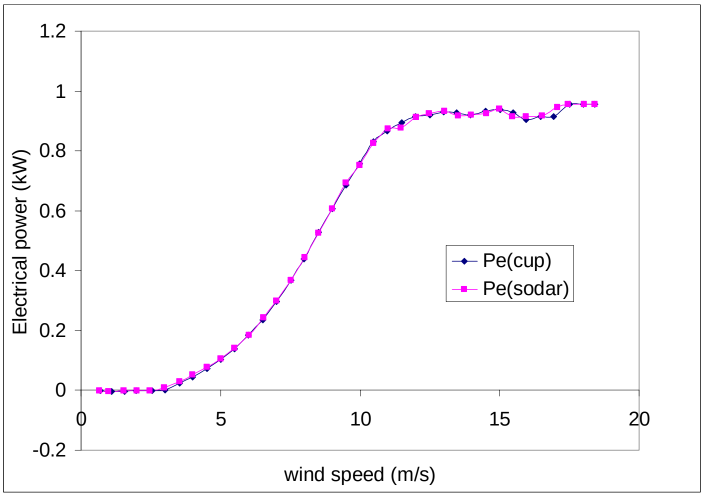

Figure 5.2 The power curve as a function of the wind speeds measured by the cup and the Sodar.

The power curve is normalised and consists of data where the turbine has been operating at two different nominal power configurations. Thus the power curve presented is not representative of the turbine's commercial power curve. Starting point for the calculations has been the common measurement period for the Sodar and the cup anemometer. As the figure shows, the Sodar wind speeds at the high end have been filtered or the Sodar has not been able to measure. No attempt has been made to change the filtering conditions in order not to exclude the higher wind speeds but certainly this is a subject of future investigation.

5.3.3 The annual energy production

The AEP of the turbine as a function of the cup anemometer and the Sodar is seen in the table below. The uncertainty associated to the Sodar is higher than the corresponding one for the cup anemometer.

Table 5.1 The AEP [MWh] as a function of the Sodar and the cup anemometer

	cup anemometer		Sodar	
[m/s]	AEP measured	Uncertainty AEP measured	AEP measured	Uncertainty AEP measured
4	1747	192	1799	249
5	3263	264	3310	345
6	4940	312	4977	407
7	6509	334	6536	436
8	7780	339	7798	440
9	8667	332	8679	429
10	9174	319	9181	409
11	9362	301	9365	385

5.3.4 Conclusions RISØ Power Performance analysis

The results from both campaigns compare well to the theoretical analysis concerning the changes in the slope as a function of height above the ground level, yet they deviate considerably from the results expected following the theory (Antoniou, 2003) as the Sodar values are higher than the cup anemometer values. Earlier measurements, using an AV4000 Sodar (a 4000 model with a 32 element antenna, operating at 4500Hz in a 4000 enclosure) have produced results, which agree with equation the theory. Therefore the present deviations are attributed to the different geometry of the 3000 enclosure and an error in the Sodar software which did not allow compensation for the difference in the geometry of the enclosures. In any case the above results confirm the need for control and calibration of the function of the Sodar during every measurement campaign.

During the second campaign the power curve of a turbine was measured and presented as a function of both the Sodar and the cup anemometer. The operation of the Sodar is limited by a number of external factors and atmospheric conditions such as background noise, signal attenuation with height, rain, atmospheric stability and others. Filtering of the data through SNR, removes both erroneous and high wind speed data and thereby reduces the instrument availability, extending in principle the necessary measurement period. Filtering of the data proved to be a tedious task and cannot be performed in a satisfactory way with the help of the front view software. Access in the source code and further insight in the instrument needs to be gained.

Based on a theoretical analysis and the experimental results, a calibration method has been applied for the Sodar which consists in finding the relation of the Sodar to two nearby cup anemometers mounted on a met mast and transfer of this relation to a higher height. This relative calibration neutralizes effectively a number of inherent Sodar uncertainties.

5.4 ECN Power Performance analysis

The ECN Sodar P-V measurements have been carried out during two measurement periods between December 2003 and August 2004 at the ECN test site EWTW. The periods are a selection from a total set of measurement periods performed by the ECN Sodar within the framework of the WISE project. Power measurements were taken from a prototype wind turbine at the same time, whereas comparative wind speed and direction measurements were performed at a meteo tower nearby on the test site. The procedures and requirements according to the standard IEC-61400-12 have been followed where possible.

The Sodar which is used for the measurements is a Model 3000 Sodar system from AeroVironment Inc., USA. ECN has acquired two speaker arrays with the system, the AV3000 and AV4000 arrays. Both arrays could be operated with the Model 3000 enclosure, however AeroVrionment advised to use the AV4000 array since it would provide better results.

In the calibration period a cup anemometer at 45m in the meteo mast came available for calibration measurements. The calibration parameters from this period were also applied to the first period to determine the difference between a one-time calibration and a simultaneous calibration.

The P-V measurements during the calibration period have been carried out with Sodar, meteo mast and turbine in operation simultaneously. The Sodar is calibrated using the measured data from the 45m height sensors in the meteo mast. The calibration information is transferred to turbine hub height, which is 70m.

5.4.1 Filtering of data

Before the Sodar measured data can be used in a P-V analysis the data need first to be filtered. In the table below the applied filtering methods are shown.

After filtering the Sodar data at 45m height is used to determine the calibration parameters by linear regression. The calibration parameters are subsequently applied to the Sodar measured data at 70m. The resulting corrected Sodar data are used to perform the P-V analysis.

Table 5.2 Applied filtering methods to meteo mast and Sodar data

General filters	Settings
Data availability	Speed and direction <> -999
Rain	Rain intensity < 0.01
Measurement sector	40º > DIR > 260º
Max. standard deviation of U,V,W beams Sodar	2.7 m/s
Filter on Signal to Noise ratio Sodar	7 < SNR < 35

Additional filters for calibration and P-V analysis	Settings
Max. difference |Sodar-Cup| at calibration height	2 m/s
Minimum wind speed meteo mast	4 m/s

5.4.2 Results of the Power performance analysis

In Figure 5.3 the Power Performance curve from the calibration period is shown. The curve from the cup anemometer is shown together with the curves from the Sodar measurements before and after applying the calibration correction. It can be seen from the figure that the calibration has a corrective effect but the correction is too strong, i.e. the calibrated Sodar curve is shifted to the left of the cup P-V curve in both periods. It is clear from Figure 5.3 that there is a lack of high wind speed data during the calibration period. Wind speeds and power are normalised in the figure.

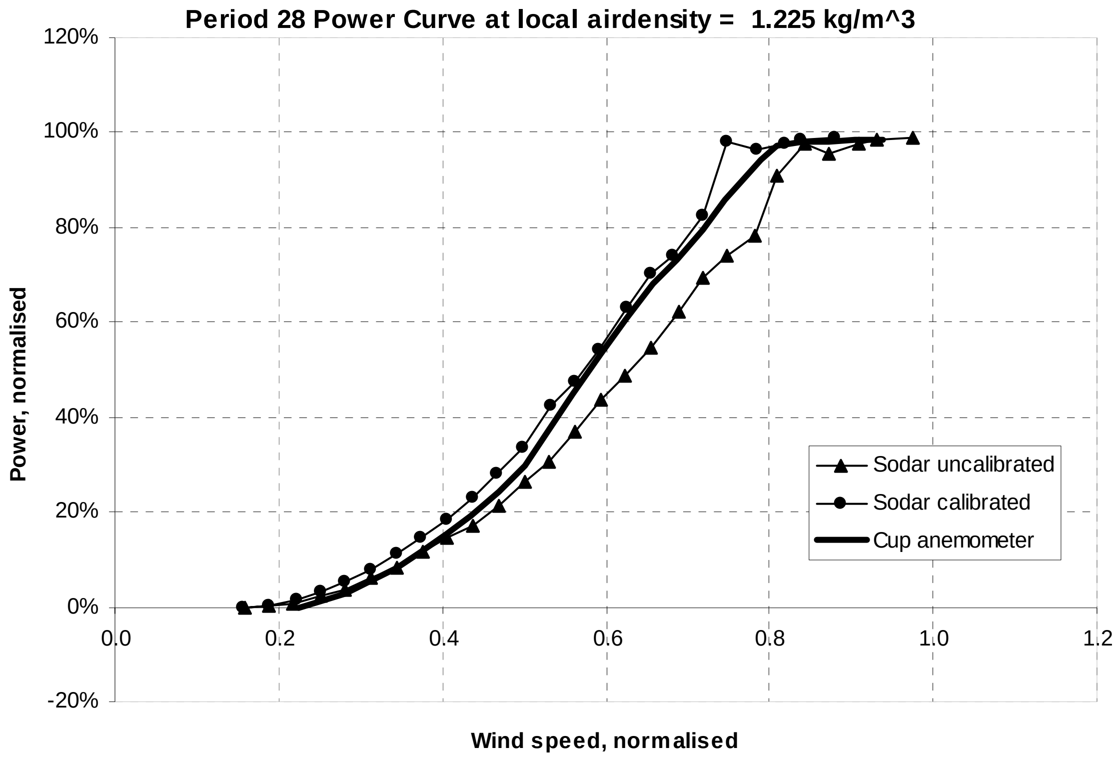

Figure 5.3 Power curves for the calibration period.

5.4.3 Annual Energy Production

In this section the Annual Energy Productions resulting from the P-V analysis are compared. To get a better comparability the comparison have been carried out with the extrapolated AEP's instead of the measured AEP's, since for both periods no wind speeds have been measured up to the wind turbine cut-out wind speed. The measured AEP in the official test report of the wind turbine at a wind speed of 4 m/s is taken as a reference and set to 1000 MWh. All values in the table are related to this reference value.

In Table 5.3 the extrapolated AEP's and their uncertainties are shown for the calibration period.

Table 5.3 Extrapolated AEP's for the calibration period

Wind	Cup anemometer		Sodar calibrated		Sodar uncalibrated	
speed [m/s]	AEP [MWh]	Uncertainty [%]	AEP [MWh]	Uncertainty [%]	AEP [MWh]	Uncertainty [%]
4	1006	11.6	1263	12.2	952	19.9
5	2117	8.5	2447	9.2	1896	14.7
6	3496	6.8	3871	7.5	3096	11.7
7	4958	5.7	5353	6.5	4422	9.9
8	6358	5.0	6753	5.9	5742	8.8
9	7602	4.6	7986	5.5	6956	8.0
10	8639	4.3	9002	5.2	7996	7.5
11	9440	4.1	9779	5.0	8820	7.1

5.4.4 Conclusions ECN Power Performance analysis

During two campaigns in the period between 19 December 2003 and 12 August 2004 measurements have been carried out with the ECN AV3000 Sodar with a 4000 speaker array from AeroVironment Inc. at the ECN test site EWTW. The purpose of these measurements was to establish a comparison between P-V analyses using Sodar and cup anemometer wind speed measurements. Power measurements were taken from a prototype wind turbine at the test site.

Wind speeds measurements were taken from the ECN meteo mast nearby the tested wind turbine. During the first period only wind speed measurements at hub height were available. During the second campaign the Sodar system was calibrated using a cup anemometer in the meteo mast from a boom at 45m height. The measurements complied with the IEC 16400-12 standard.

The Sodar system was serviced prior to the measurements and was fully operational during the measurement periods. AeroVironment Inc. advised to use the 4000 speaker array instead of the 3000 array since it would provide results which should be better comparable with the cup anemometer measurements.

Stand alone operation
During both campaigns it became clear that the Sodar measurement results in stand-alone operation were not comparable with the measurements from the meteo mast. Without calibration the ECN Sodar overestimates the wind speed by a factor of around 10% to 12% with an offset of around -0.3 to -0.6 m/s. This means an increasing difference from 0 m/s at a wind speed of 5 m/s to 1.75 m/s at a wind speed of 20 m/s. These results will lead to an underestimation of the P-V curve and AEP calculation. The underestimated Sodar AEP's are outside the lower uncertainty boundaries of the AEP calculations using cup anemometer measurements. Therefore measurements with the ECN Sodar need a calibration with an extra instrumented mast for wind turbine P-V measurements.

Calibration against a small meteo mast
During the second campaign the Sodar is calibrated against a boom in the meteo mast at 45m height. Measurements of Sodar, wind turbine power and cup anemometers at 45m and at the wind turbine hub height at 70m in the meteo mast were carried out simultaneously. Unfortunately not many high wind speeds were measured during this specific measurement.

The simultaneous calibration improved the Sodar measurements. By calibrating the Sodar at 45m the differences with the cup measured power curve at 70m were reduced. However the corrected Sodar measured wind speeds resulted in an overestimation of the P-V curve and AEP calculations. The difference in the AEP calculation between cup and calibrated Sodar is still higher than the uncertainty ranges of the cup anemometer for annual average wind speeds lower than 10 m/s, but much better than using the Sodar in stand alone operation. However to achieve a more accurate calibration the calibration measurements should cover an equally distributed number of data points for every 0.5 m/s wind speed interval up to wind speeds above the nominal wind speed of the wind turbine.

Calibrated Sodar in stand alone operation
The calibration settings of the second period were applied to the measurements of the first period to see if calibration settings can be applied to periods without simultaneous calibration. Likewise the situation in the calibration period the corrected Sodar measurements resulted in an overestimation of the P-V curve and AEP. Here the differences in AEP were also higher than the uncertainty ranges using the cup anemometer measurements. The correction of the measurements in this period using the calibration parameters was less effective than the correction in the calibration period. This result supports the recommendation to carry out simultaneous calibration against an instrumented meteo mast.

Not many high wind speeds were measured during the calibration period. For that reason it cannot be concluded that the calibration for both periods was successful or not. However the deviations between Sodar and cup anemometer measured wind speeds at hub height were different for both periods. During previous Sodar measurements within the framework of WISE equal regression parameters were never found between cup anemometer and Sodar for different measurement periods. This means that using calibration parameters for a period of stand alone operation will lead to less accurate results than during a campaign with a simultaneous calibration. This leads to the conclusion that a 'calibrated' Sodar cannot be used in stand alone operation.

5.5 WINDTEST Power Performance analysis

For the power curve measurement a location on WINDTEST's test site at Kaiser-Wilhelm-Koog was chosen, which is close to the North Sea at the west coast of Schleswig-Holstein in northern Germany. The used Sodar was a Scintec SFAS - Small Flat Array Sodar. The turbine on the test site used for the power performance analysis had a hub height of 80m.

5.5.1 Relations between Sodar and cup wind speeds and filtering

Based on experiences from earlier comparisons within the WISE project between wind speeds from the Sodar (of SFAS type) and from cup/met mast measurements a persistent underestimation by the Sodar was well known. Hence a correction of the Sodar data towards the cup data needed to be done in order to get comparable power performance results at hub height.

The first data processing steps for the merged and synchronized data set as yielded from the two data sources (Sodar system and met mast/wind turbine system) were to establish relationships between the cup anemometer readings and the corresponding Sodar wind speed values at 40 m and at 80 m above ground level.

Prior to the correlation analysis the data set was filtered according to the following parameters: quality of Sodar receptions in terms of the mentioned Sodar error flag (see above) wind direction, i.e. for winds coming from the undisturbed sectors (taken from 80m wind vane) turbulence within a range according to IEC 61400-12 standard (taken from the cup data) periods to be excluded due to change of wind turbine settings and turbine performance experiments periods to be excluded when turbine settings were altered (like limited maximum power output below rated power). From this filtering a total of 1063 wind speed values remained usable for the regression analysis and hence for the power performance analysis. The application of the regression results from the 40m correlation to the Sodar data measured at 80m was necessary, in order to get wind speed values being comparable to cup measurements at 80m.

5.5.2 Power performance curve

The power performance curve (PPC) data were taken from a measuring campaign lasting from 2003-09-23 until 2003-11-20. In Figure 5.4 the P-V curves are shown for three cases, namely using the uncorrected Sodar data, the corrected Sodar data using the calibration parameters and using data from the cup anemometer. The lower wind speeds in the uncorrected Sodar case (caused by the prescribed underestimation) resulted in a significantly better power curve than the one from the cup measurements.

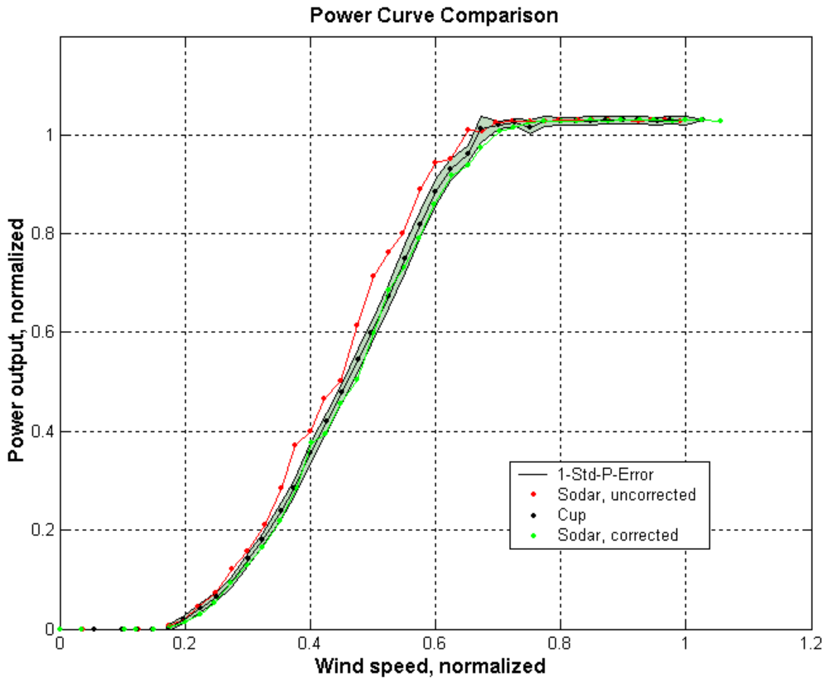

Figure 5.4 Power performance curves for the three prescribed approaches. Grey shaded tube represents the 1-std-error-bar for the PPC as recorded by the cup anemometer at the met mast.

5.5.3 Annual Energy Production results

The mentioned overestimation of the power curve by the pure Sodar results can again clearly be seen in the comparison of AEP values as shown in Table 5.4. Looking at the AEP values of the "Corrected" power curve reveals that it is well within a 4% range of the "CUP" power curve for reasonable annual mean wind speeds above 6 m/s. Note that for anonymity reasons the absolute values are arbitrarily scaled.

Table 5.4 Comparison of Annual Energy Production (AEP) values as derived from the three mentioned power curve versions, calculated for different annual mean wind speeds, based on a Rayleigh distribution and on a 100% availability of the turbine.

Annual Mean Wind Speed [m/s]	Annual Energy Production CUP [MWh]	Sodar [MWh]	Corrected [MWh]	Percentage Rel. To Cup %
4	605.0	699.7	562.3	93.0
5	1213.1	1380.2	1156.0	95.3
6	1944.5	2170.9	1876.1	96.5
7	2700.7	2961.5	2627.6	97.3
8	3388.7	3659.5	3321.9	98.0
9	3942.3	4204.7	3893.3	98.8
10	4333.1	4576.2	4310.0	99.5
11	4565.4	4783.9	4571.2	100.1

5.5.4 Conclusions WINDTEST Power Performance analysis

During a 2-months measuring campaign in a flat near coastal terrain a new approach to record a power performance curve (PPC) at a multi-megawatt wind turbine was tested by using a Sodar for wind speed measurements. Simultaneously, a classical PPC – using cup anemometers installed at a nearby erected met mast – was performed. The comparison of wind speed measurements by Sodar and by cup and the comparison of the resulting power performance curves yielded the following conclusions.

From the significant underestimation of the wind speed using a Sodar (of type Scintec SFAS in our case) compared to the cup wind speeds at 40m and 80m a stand alone Sodar PPC measurement without a cup reference seems not to be recommendable. It was shown that using the uncorrected Sodar wind speeds in 80m to produce a PPC would lead to far too high values in terms of power performance and power coefficients.

Using the 40m cup measurements to reference the Sodar wind speeds, it was shown that for future Sodar-PPC applications a solution could be, to erect a smaller met mast in order to get a cup reference for Sodar wind speeds at lower range. In the currently analysed measurement the validity of a low altitude wind speed relation (between Sodar and cup) for higher altitudes was proved. This allowed us to correct the Sodar wind speeds at 80m by using the regression slope from 40m. The resulting so-called corrected Sodar PPC shows a much better agreement with the cup PPC. This is even more pronounced when comparing the annual energy production of those two power curve versions.

In this PPC comparison only those classical cup measurements (in terms of 10-minute averages) were used, which coincided with useable Sodar receptions at the altitude of the hub height. The number of those data points amounted to only 1063. This is low compared to a significantly larger number of data points which could have been used if the power curve was calculated based on the cup/met-mast data at 80m alone. This may underline that in general it will take much more time to record a complete PPC using a Sodar compared to a classical measurement.

5.6 Conclusions on Power Performance Measurements

Within the scope of the WISE project three experiments at three different locations have been carried out to measure the power performance of wind turbines using currently available off-the-shelf monostatic Sodar systems. These experiments are described and analysed in this report of WISE WP5. The experiments took place at test sites that were fully equipped for power performance testing according to the standard IEC 61400-12. Results of the Sodar measurements were compared to cup anemometer measurements using large meteo towers, which is up to now the only accepted method for certified wind speed measurements for wind energy purposes.

The operation of the Sodar system is limited by a number of external factors and atmospheric conditions such as background noise, signal attenuation with height, precipitation, atmospheric neutral condition, high wind speeds and others. The effect of these disturbing factors is twofold: the availability of data is reduced (high fall-out rates) and the data quality is affected. This has been reported extensively in the WP3 and WP4 report of this WISE project. It means that Sodar measured data, as provided by the supplied software of the Sodar manufacturers, first need to be processed by filtering out inappropriate data. However the present data format of the output from the supplied data acquisition and processing software is not directly usable to apply the filtering methods. Reorganising the data is required first to obtain a dataset that is suitable for a database structure.

Filtering of data
The Sodar measured raw data had to be filtered to obtain more reliable data since many data points deviate considerably from the mean values. The causes of these deviations are due to background noise and atmospheric conditions such as precipitation and near neutral stability or due to fixed echoes from nearby objects. Filtering takes place by removing erroneous values and applying limiting values to the Signal to Noise Ratio SNR of the returned signal and the standard deviation of the 10-minute averaged wind speed. The SNR and also the data availability of the raw measured data decreases with height and with wind speed. Therefore filtering reduces the availability of high wind speed data above ca. 15 m/s even more. Some of the high wind speed data are removed although they do not deviate considerably from the mean values. Furthermore the data has to be filtered to exclude data points in periods with precipitation. Since the used Sodar systems did not have a precipitation sensor the sensors from nearby meteo masts had to be deployed.

In combination with the necessity of reorganising the raw data due to the output format of the software, the data filtering proved to be a tedious task. Access to the source code by the user or a more user-friendly version of the software is therefore required to improve the data output.

The availability is considerably reduced due to the filtering of data, in some cases this was far more than 50% especially at high wind speeds. Knowledge of the operator in Sodar measurement technique and insight in the influencing factors due to atmospheric conditions, atmospheric stability and the effect of background noise is required to enhance the data quality of the raw measured data from the Sodar.

All measurements showed a good similarity between the resulting wind direction measurements of the Sodar and the meteo mast direction sensors.

Power performance in stand alone operation
At three European wind turbine test locations Sodar systems were used to carry out power performance analyses of wind turbines. After filtering the data using the methods mentioned above, deviations from the mean wind speed measured by the cup anemometer were too large to get comparable P-V curves and Annual Energy Production AEP numbers, especially at high wind speeds. In the cases of ECN and RISØ the Sodar systems overestimated the wind speed by a factor of 5% to 10%, resulting in an underestimation of the P-V curve and AEP. In the situation at WINDTEST the Sodar underestimated the wind speed by a factor of around 6%, resulting in overestimation of the P-V curve and power coefficient Cp of the wind turbine, the latter by a factor of more than 25%.

Furthermore the uncertainty analysis in Chapter 2 shows that the type B instrument uncertainties in stand alone operation are currently far too high to perform P-V analyses with an accuracy comparable to cup anemometer wind speed measurements. This is confirmed by the measurements.

Power performance with a small meteo mast
The WISE WP3 report deals with issues regarding calibration of Sodar systems. The recommended method to perform wind energy related measurements with currently available Sodars is to calibrate the Sodar with the simultaneous use of a small meteo mast of 40m. This calibration is to be carried out during the power performance measurements. In case of a P-V measurement of a wind turbine the actual Sodar measurements at hub height are derived from simultaneous calibration measurements of Sodar and cup anemometer and vane at a lower height. During the three experiments at the test sites of ECN, RISØ and WINDTEST this calibration is carried out during a power performance test with cup anemometers at around 40m height in meteo masts which were fully suitable for certified P-V measurements (IEC 61400-12).

In general the correction of the measured Sodar wind speeds at hub height with the use of the calibration at lower height worked well. The deviations between Sodar and cup anemometer at hub height were largely corrected. However the effect of the correction depends heavily on the number of available data points for the calibration. Since filtering is required due to unfavorable atmospheric conditions, background noise and fixed echoes this means that the measurement period required to obtain a P-V curve complying with the standard IEC 61400-12 will be considerably longer than the required period when using cup anemometer measurements.

The uncertainties in Sodar measurements after calibration are still larger than in conventional cup anemometer measurements. This is a consequence of the applied calibration method. The uncertainty of the Sodar will never be smaller than the uncertainty of the cup anemometer used for the calibration, although calibration reduces the uncertainty considerably compared to stand alone operation.

The AEP results from RISØ and WINDTEST show that the calibrated Sodar derived AEP's are within 4% deviation from the AEP's calculated using cup anemometer measurements. However the uncertainties in AEP's calculated by calibrated Sodar measurements are a factor 10% to 30% higher than AEP's calculated by cup anemometer measurements. The P-V and AEP calculations from ECN show different results, here the P-V curve is overcorrected and the resulting AEP's, by calibrated Sodar, are outside the uncertainty range of the cup measurements for most wind speeds. This is most presumably due to the fact that the calibration period appeared too short to measure enough data points at high wind speeds.

The calibration results were also applied to a measurement period without simultaneous calibration measurements against a small meteo mast at the ECN site. Although the calibration period was too short, in this case the P-V curve was overestimated to a larger extend than the P-V curve resulting from the calibration period. This means that the calibration parameters cannot be simply transferred to a situation without a calibration meteo mast and stresses the conclusion that simultaneous calibration is required when performing wind energy related measurements.

Usability for wind energy related measurements
The mobility and flexibility of Sodar systems are larger compared to fixed meteo masts. The costs involved in high meteo masts increase exponentially with height. Especially with the increasing sizes and heights of modern wind turbines, measurements with Sodar systems could become a good alternative to measurements with meteo masts. Advantages are a mobile measurement system, the capability of measuring wind speeds and directions at selected height intervals and the absence of flow distortion.

Measurements are carried out with Sodar systems at three locations during several years in the WISE project. It has been shown that using currently available Sodars systems power performance measurements cannot be carried out comparable to cup anemometer measurements in stand-alone operation without a proper calibration. The operation of a Sodar system appeared to be limited by a number of external factors and atmospheric conditions. Filtering of the dataset is necessary to obtain a data quality comparable to data from cup anemometer measurements. Due to the data filtering the measurement period may become considerably longer compared to power performance analyses with cup anemometers.

During the WISE project a new calibration method was developed using a small meteo mast with a height of 40m. This will reduce however the mobility and will increase the costs of the measurements. By applying a simultaneous calibration the measurements increased considerably in accuracy. The AEP calculations show comparable results with cup anemometer measurements on the condition that the calibration provides sufficient information at wind speeds preferably up to the cut-out wind speed of the test turbine. Also an equivalent number of datapoints per 0.5 m/s wind speed interval over this range is required.

The uncertainties in power performance and AEP calculations using calibrated Sodar measurements are however higher than in the case of cup anemometer measurements due to the necessary calibration of the Sodar against a cup anemometer on a small mast.

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6. APPLICATION OF SODAR IN DIFFICULT CIRCUMSTANCES

6.1 Sodar measurements under extreme conditions - Introduction

With wind energy growing mature the dimensions and places change. Hub heights of 100 meters and more are becoming common. Rotor areas have exceeded the size of football field in the meantime. Offshore wind energy is about to enter the dimensions of nuclear power plants in terms of rated power. Wind turbines are installed in complex terrain in rural mountainous sites. While the dimensions change dramatically the methods of assessing the site potential or measuring a power curve are still oriented on the ideal measurement conditions with wind described by a logarithmic profile undisturbed of terrain or stability effects. It also favours the idea of a point measurement performed on hub height. But with the increasing hub heights and the upcoming offshore wind farms this is much harder to fulfil then it was only ten years ago. The costs for installing a mast based wind measurement offshore are at least 100 times more expensive then on the land. Therefore remote sensing of a wind field is becoming more and more interesting. It also allows exploring the wind profile much better and opens the door to a new definition of the wind conditions that are driving a wind turbine.

The effects of wind profile deformations are also a major reason why a Sodar can be interesting in complex terrain. For these sites the classical wind farm study reaches its limits following from the used theoretical model for the determination of the flow. Putting up a met mast with wind profile measurements at several heights is one possible answer but again it is a very expensive method. A remote sensing tool that could be easily brought to the site of interest would be a major improvement. Here the Sodar seems to be very promising with its capability to measure not only the horizontal wind speed like the cup anemometer but also the vertical component of it.

Finally the general idea of measuring the wind speed along a straight line is not limited to vertical measurement approaches. It should also be possible to measure the wind in horizontal direction. This would be interesting for wind turbines that are subjected to an environment with gusty wind conditions. A wind gust can introduce huge structural loads on a turbine. The situation could be eased if the state of the machine could be prepared for what is coming a few seconds in advance for example by pitching the blades.

To summarize a Sodar could be the tool to go to heights of modern turbines without the need to install a tall wind met mast. It could do this also at places where it is extremely hard to install a tower such as offshore or in complex terrain. Finally it allows linking the power output of the turbine to a more complex definition of the wind field acting on the rotor and thus allows making the classical power curve measurement more independent from site effects and the state of atmospheric stability.

These advantages are contrasted with a number of practical problems with this type of measurement. The Sodar data is an average of several vector measurements over a volume while all wind data in the wind energy industry is referring to cup anemometer measurements at a point.

Other disadvantages of the Sodar follow from the complex data treatment and the numerous factors that influence the result. The manufacturer does often not disclose the details of the internal data processing and therefore the decision if a certain data set can be used is based on the experience of the operator with the measurement system.

Since Sodar is a remote sensing tool that relies on the backscatter on small fluctuations of the thermal refractive index, there will always be situations when the data is on the edge of rejection. In these unclear cases the setting of the filters becomes critical. Otherwise too much useful data is rejected or noisy data included in the data set. A Sodar data set will therefore seldom be as complete as a cup anemometer time series. For all other situations it will be required to find a solution how to work with the data even if the availability is reduced and the data rate changes with height.

Next to the practical problems with the comparison of data with the wind speed definition based on cup anemometers there are practical problems when a Sodar is used in field measurements. One of them is the question of power supply. Since the power consumption of a Sodar is higher than a wind mast, it must be operated at 230 Volts, which has a set of implications for a power supply system. The technical aspects must therefore follow new paths to provide the power of a Sodar.

6.2 The measurement situation in complex terrain

Sodar measurements have been performed in combination with a commercial project that consisted of a site calibration at several turbine locations at 80 m hub height in preparation of the later power performance measurement. The met mast had been equipped with calibrated cup anemometers at 80 and 40 m height. These two heights correspond to the hub height and the approximate lower tip position height.

A moderate slope to towards the South and a steeper slope in the North characterize the terrain. There are two major wind directions at the site. The first one around North and the second one around SSE direction. So the two major flow conditions correspond quite well to the terrain structure. The vegetation is very similar in all directions; mainly fields and grassland with only a few bushes and no trees. A special directional influence from this structure must not be expected. The terrain slopes to the North have been determined to been determined between 0 and - 17 degrees. Towards Southern directions slopes ranged between -2 and -9 degrees.

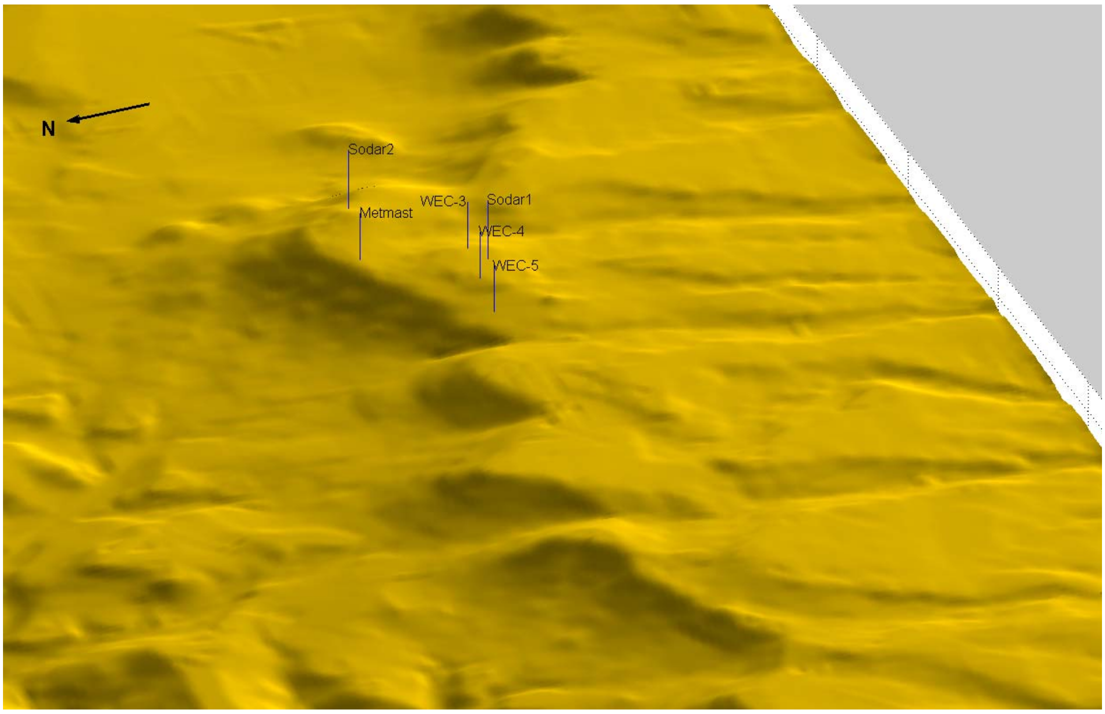

Figure 6.1 Height contour of the site in 3D view.

A total of four measurements have been performed. Due to reasons discussed later only two of them could be evaluated. They are labelled with Sodar1 and Sodar2 in the diagram and relate to the second and third measurement (working titles Wimcay2 and Wimcay3) at the site.
The first three measurements have been performed using an autonomous power supply system consisting of a diesel generator and a large lead battery bank, the fourth one was performed with power supply from the public 230 V grid since infrastructure works in the farm have made that possible at that time.

6.3 Obstructions in the Sodar measurements

A Sodar has significantly higher power consumption than a classical logger based wind measurement. It has also a higher degree of technical complexity that requires using PCs and specialized signal processor units for the data processing, storage and transmission. The over all increase in power consumption and computing infrastructure on site make the system more vulnerable to disturbances and interruptions.

There was a set of obstructions that affected this campaign and even when it is unsatisfactory to deal with these problems they can still be used to learn how to avoid them. Part of these considerations has been used for the recommendations for the design of a Sodar with autonomous power supply.

The first campaigns have been conducted during the wintertime. The site experienced snowfall and icing conditions. This affected the power supply in two ways: The batteries capacity was reduced due to the cold temperatures and the ventilated diesel engine housing, located some 50 meters away from the Sodar, was filled with snow during times when the system was running on batteries. The system of electric and diesel engine was affected and the engine would not crank any more. Once the power of the system was down and three starting attempts had failed, the system would be stopped until service was available at the site. This caused significant interruptions, because service could not be made available on short notice. It could also be that a trip to the site needed to be repeated since the first site visit was required for the diagnostics and that spare parts needed to be organized. This emphasizes the need to monitor the state of the system remotely in order to minimize the time needed for service and travel.

Further problems of the Sodar measurement were also related to the snowfall. The system has a heater that would increase the temperature of the reflector plane in order to melt all snow and ice and reduce the damping effect of the snow in the horn. However, this feature has a power consumption of several kW and that can not be provided from a reasonable stand alone system that has to be optimised for one load case, in this case an average power consumption between 100 and 200 Watts.

Another drawback resulted from sabotage. One of the cables that connect the Sodar horn with the electronics compartment had been forcefully removed from its position and the repair required reworking the connections of the 16 wires that were connected to that plug. This is a point where the advantage of a Sodar, its mobility and quick installation, can also be a disadvantage in comparison to the mast-based measurement. They provide some type of natural protection simply because they allow to place the sensitive parts in heights that cannot be easily reached. A Sodar with its ground based installation of all parts, the Sodar itself and possible other components for its power supply like a generator, wind charger or solar panels, are much more vulnerable.

A particular form of sabotage has come from a mouse that had entered the electronics compartment through one of the ventilation holes, damaged several wires and finally seems to have died from electrical shock. Rodents have also damaged the connection between Sodar trailer and diesel engine compartment at another occasion. The distance between the Sodar and the trailer was considered important to reduce the background noise during the charging process of the batteries. The engine itself cannot be placed on the trailer since the sound transmission over the common structure would spoil the measurements. This experience suggests to minimize the amount of cables that can be reached from the outside or to take additional safety precautions for them.

To make the list of drawbacks complete there must have been a problem with the electronics during the fourth campaign that resulted in very poor height range and high noise levels. It had first been thought that the wind next turbine had disturbed the measurement but a fixed echo had not been detected and the problem did not vanish when the machine was stopped. Speaker damage is also not likely since a complete overhaul of the system led to the replacement of only 3 of 63 speakers, a remarkably low number of them after the time that these speakers had already been in operation. The reason for this unusual low number is likely to be attributed to the amplifier of the system, it featured almost 20 % less power output than the standard version of the model due to a 12 V DC power supply. Parts replaced during the service were the power supply and the amplifier. Furthermore a unit that is designed to monitor the speaker performance has been removed from the system. So it is likely that the problem had been in one of the parts.

6.4 Proposal for a system with autonomous power supply

Based on the experiences it has been proposed that a Sodar for remote operation in wind energy should not just be an off the shelf system mounted on a trailer but be integrated in a power supply system. The general idea is that the autonomous Sodar should be a system that consists of one or several sources that provide electricity (Generator, Wind charger, Solar panels) that charge a battery bank and provide power to a sine wave inverter who runs the electrical components of the Sodar and the data communication. In addition there should be a programmable controller unit that is aware of the state of the components of the system and can take action, for example to reboot a PC, and most important, can send information on the state of the system on a separate data channel. Ideally it should also be able to accept commands, for example to start the generator externally.

Such a system would notify the operator if problems occur or refuelling can be expected in a certain time. The chance for a person that goes to the site to be able to do the required works would be much greater. It might not be required at all if the remote control possibilities allow taking the required steps. In order to develop the Sodar to a tool in the commercial wind industry it is required to make the amount of service competitive with the existing mast based measurements. If service means to fly in a specialist then this can easily blow every budget that must be avoided.

A separate document (DEWI SO 0205-100.1) describes the system proposal in more detail. The scheme is printed in Figure 6.2.

Data communication is a second task handled in a separate document. The general question is how to get the data of a system in remote locations regularly to an operator to be able to check it for consistency and quality.

Here it makes sense to assume that it will not be required to transfer the raw data of the spectral moments but the final wind speed tables that are calculated from the local computer system. The information is in a much higher degree of density available then and the data amount can usually be transferred over already existing GSM cell phone connections. Other approaches like broadband UMTS and satellite links might be gaining importance in the future, but there are two considerations that make it likely that GSM will be important in the next years also. Satellites are quite expensive and they will require special antennas and modems. It is also possible that so called low earth orbit satellites will be used but for those systems the response time can be up to 20 minutes since it is not guaranteed that a satellite will always be in view of the target. The problem with any cell phone high-speed accesses is that with increasing bandwidth the cells will be becoming smaller. And it is unlikely that such a system will be installed in the rural areas that wind energy siting usually enters.

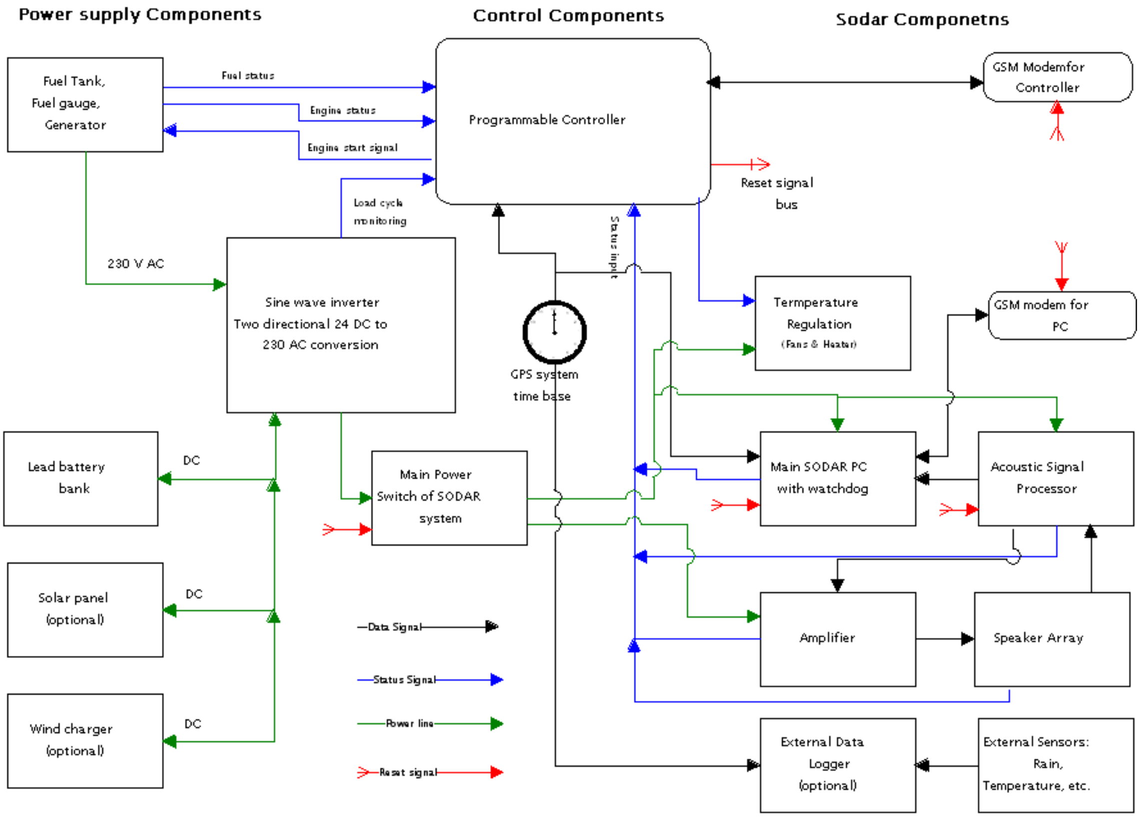

Figure 6.2. Scheme for a Sodar with autonomous power supply.

It can be concluded that the complexity of a Sodar systems, especially with an autonomous power supply featuring a combustion engine, motivates a separate unit in charge of monitoring the state of the system and capable to issue resets, send status reports and receive commands to change system settings. The decision if such a system shall be used depends on the costs of the installation vs. the cost of sending a person to the site for maintenance. The system can be avoided, if a person with some expert knowledge is available near the site. But this condition is not easy to fulfil since the wind energy industry is increasingly active on a global scale.

Another option to avoid complexity at the site is to operate the Sodar on public power supply usually from a long cable. In this case it is important to protect the system against over voltage between ground potential and neutral potential of the power supply. This could for example happen if lightning hits the ground near the Sodar location. Any cable must be selected such that an amplifier suffering from a low input voltage does not obstruct the peak power demand during beam emission.

6.5 Data evaluations

The evaluation of the data for complex terrain was mainly following the following questions:

- Can any of the expected special flow conditions be found in the data set?
- Can the calibration method, developed for the measurement of power curves in the WISE project, be also applied here?
- What sort of flow can be expected and how does that fit to the results of the Sodar measurement? In order to assess this question a three-dimensional flow model has been applied in comparison with the results of the Sodar campaign.

6.6 Scatter diagrams

The Sodar itself has a set of filtering rules like signal to noise ratio or number of successive returns that are used to decide if a data set will be presented or an error value is reported. In order to be flexible these results should not be too strict to allow an individual decision. The data presented here follows the settings for the Aerovironment Mini Sodar that has been agreed upon by the project partners.

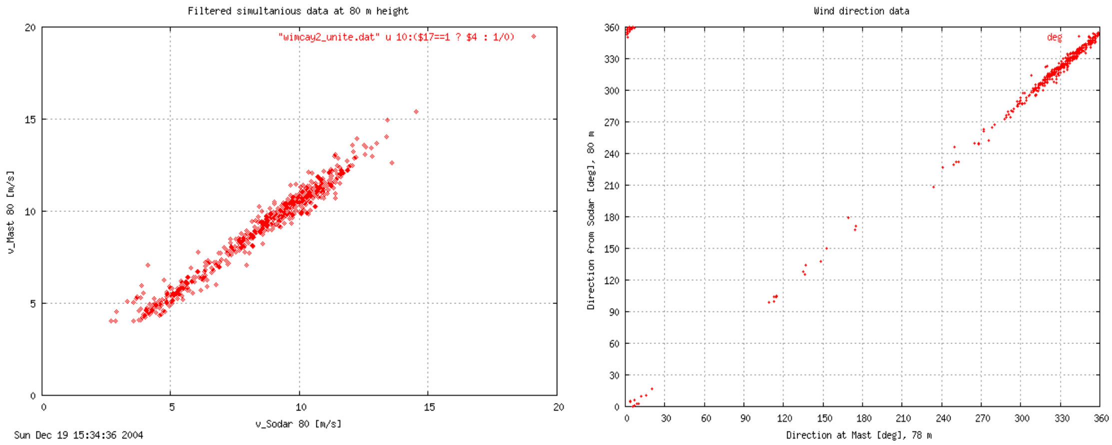

Figure 6.3 Example of a filtered data set for 80 meters height in comparison with the met mast data.

The diagram shows the wind speed on the left and the wind direction on the right in a scatter diagram. Especially in the wind speed there is a obvious scatter around 10 m/s but it must be noted that there is a distance of approx. 300 meters between the two locations.
It can also be seen that the direction measurement is in good agreement, an observation that can be made quite often with Sodar measurements. This is an important feature for complex terrain since small changes in flow direction can lead to very different flow patterns.

The good agreement with the wind direction measurement has been observed in other Sodar campaigns also. It must be noted that a precise wind direction measurement can be essential in complex terrain since flow situations can occur where small changes of the wind direction on a medium range scale have large implications on the wind direction at a specific turbine location. This highly non-linear pattern can be observed in the wake of hills or mountains. In these occasions a Sodar measurement with a careful antenna orientation adjustment can deliver important wind direction information.

6.7 Averaged Profiles

One of the major drawbacks of Sodars is the feature that they seldom deliver complete time series. This makes it hard to use them for wind measurements without the need to fill in the gaps. The problem is increased with height. A possible work around is the use of a subset of the data that fulfils a number of extra requirements, assuming that these measurements may be generalized. It also allows comparing the result against a flow model, which usually assumes a certain wind filed as an input and calculates the equilibrium condition.

The report shows the average profiles distinguishing between night and day. Here it can be expected that for night time the chance of stable stratification is much higher and therefore the wind speed will increase much more over height during the night than it is the case during the day. The evaluation has been performed for the two major wind directions at the site. As an example the sector NNE is presented here.

Normalization means that an average for a subset of the profile data fulfilling the requirements has been calculated and presented with a reference to the value in 80 meters height.

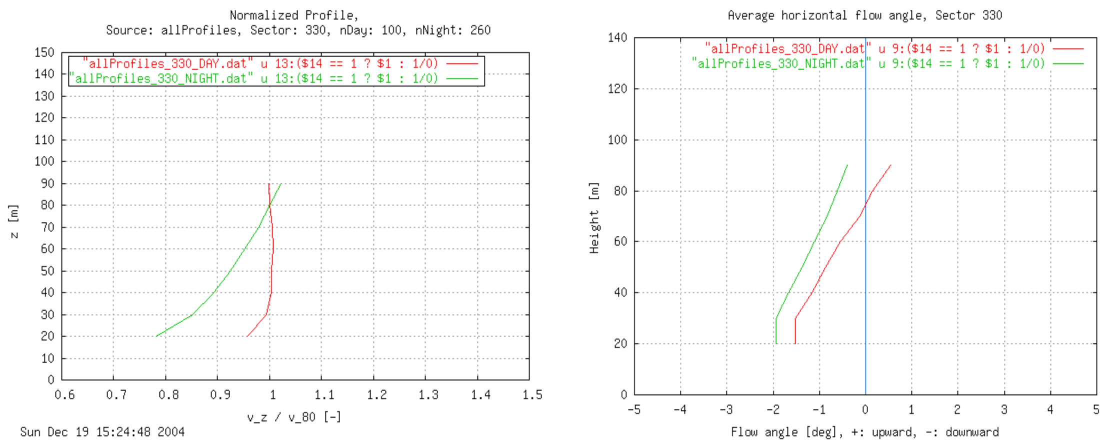

Figure 6.4 Normalized profiles for day and night and wind direction from NNE.

Figure 6.4 shows that there are strong differences between night and day that can be expected. However, it is also clear that the wind gradient during the day (red lines) is quite small or even negative which does not fit to the expected picture.

The second diagram shows the flow inclination over height, also averaged but not normalized with respect to a certain value. Here day and night variations should not have a significant influence, instead the terrain is the dominating factor. In this case the Sodar was located on a sloped terrain with 9 degrees. It can be seen that the Sodar also reports a downward flow inclination, but its magnitude is smaller and also decreases with height.

The diagram also shows that the number of successive measurements for a profile significantly increases during the night. This is an observation that is quite common with Sodar measurements that experience better measurement conditions under the more often stable stratification and reduced background noise conditions.

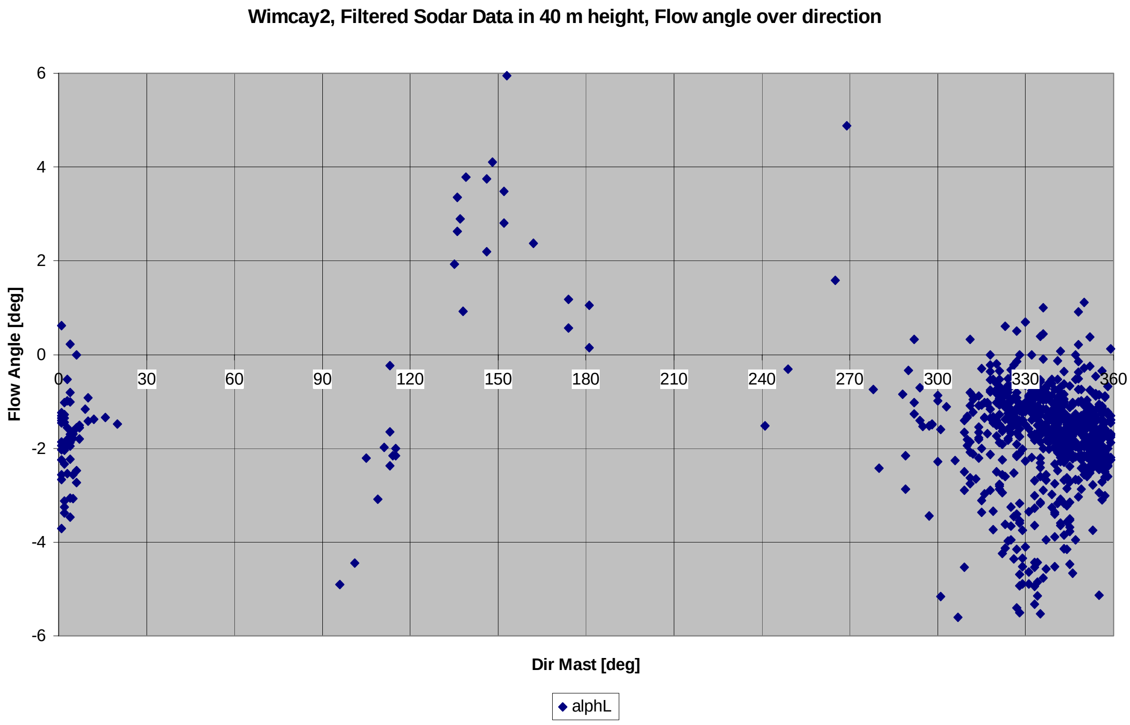

Figure 6.5. Example of flow inclination measurement with the Sodar.

The following diagrams present the 10-minute average of the flow angle with the horizontal plane for the 40-meter height level after filtering. Wind speeds below 4 m/s are not considered. The convention of the angle is for upwards-pointing wind vectors positive, otherwise negative. Angles are given in degrees.

The Sodar reports a downward flow in 40 m height from NNW direction on the order of 1 to 2 degrees at 40 m height. The same analysis for the 80 m level shows, that the flow approaches the horizontal plane as the height over ground increases. The finding is in order with the slope of the terrain. The Sodar is placed on a slope falling off towards SSE (150 deg).

It is concluded that flow angle measurements with the Sodar in terrain of medium complexity deliver results that are in agreement with the expectations.

6.8 Application of the WISE calibration method

In the framework of the WISE project the partners have developed a procedure to calibrate a Sodar against a 40 m met mast by determining a factor from the wind speed relation and using it on the Sodar data at hub height. The procedure has been proposed for power curve measurement conditions that did not require a previous site calibration. The relation therefore contains the influences from the site, the measurement characteristics of the Sodar and the cup anemometer. Influence from sensor mounting and obstacles should be minimized from the measurement sector selection procedure.In the case of application of the procedure in complex terrain the relation should also contain the effects that are usually described by a site calibration.

The evaluation is also interesting since the Sodar used is a unit with the Aerovironment housing and antenna from the 4000 model series, where the other two Aerovironment Sodars in the project were combinations of a model 3000 housing and model 4000 antenna that lead to a bias in the reported wind speed values.

The linear factor at 40 meters height is determined to be of magnitude 1.083 with a correlation of 0.965. The same analysis for the 80 m level delivers a factor of 1.070 and a correlation of 0.974.

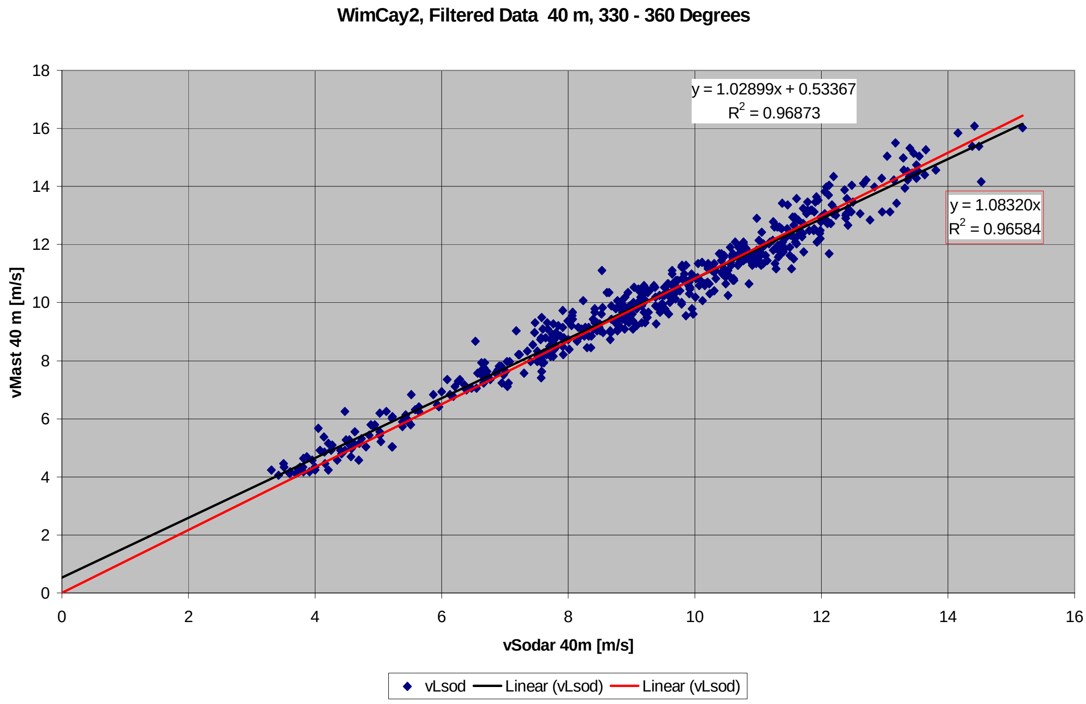

Figure 6.6. Fit of a linear factor and linear equation to the data set in 40 m height.

It can be seen that the correction on the order of 7 to 8 percent in wind speed is significant for this experiment set up. It is also interesting that the correlation is a bit better for the 80 m data set, but this might also be due to the reduced data amount that has been available at this height.
The Sodar delivers considerably smaller values than the cup anemometer, but with the application of the relation gained at 40 meter there is a correction possible that on the average deviates only 1.1 % from the cup anemometer measurement. It must be noted that the standard deviation after the application of the fitted factor is in this case 3.9 % so the scatter is quite broad. This is a good result since there are limitations in the size of the data set at 80 meters. Furthermore it can be seen from the profile evaluations that the terrain influence decreases with height. It is therefore likely, that the site calibration factor, included in the relation, depends on height also.

Therefore it can be concluded that this approach can be used for terrains of medium complexity for an approximation to the wind speed with accuracy less then 1 percent. At the present state it cannot be used to replace a cup anemometer measurement at hub height. The database should not be too small in order to be able to gain meaningful averages.

6.9 Comparison to numerical flow model

The Sodar offers one interesting method to look into the flow of the near surface atmosphere in complex terrain. Another interesting view can be gained from a comparison of recent three dimensional flow models that calculate the wind field for a certain wind direction and wind speed driving the atmosphere at the top of a virtual box with the terrain a small part of it inside.
The model has been set to consider average conditions for the stability, which means that day and night patterns are not simulated. In order to make the result comparable with the simulation, averaged profiles have been calculated using a weight according to the day and night time hours during the measurement period.
The red line gives the wind speed profile computed from the model, also normalized to wind speed at 80 meters. The pink line is the result of the weighted Sodar data. For the height range 30 to 90 meters the two results do not differ for more than 1.5 %.

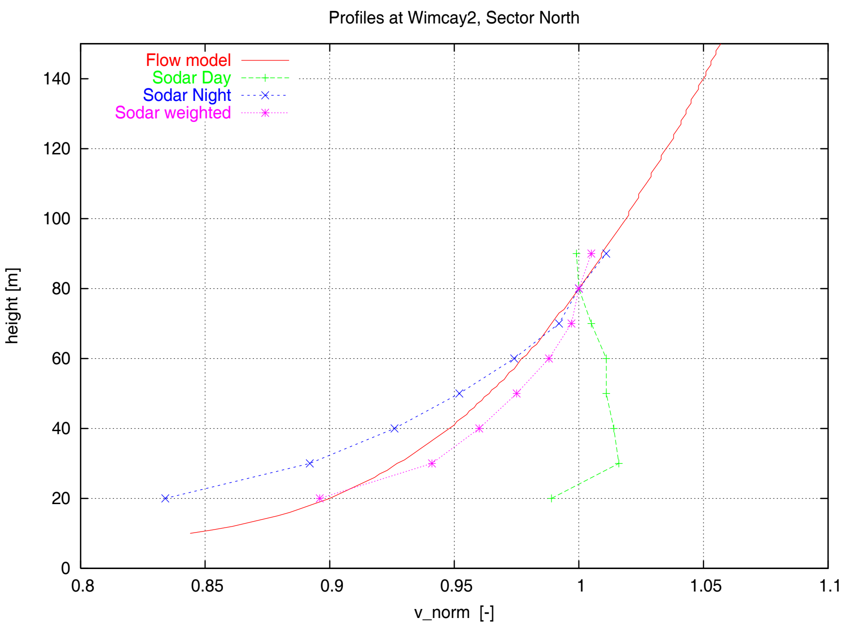

Figure 6.7. Normalized profile as computed with flow model and derived from the Sodar data.

This is a remarkable result given the different approaches, the relatively thin database and the strong day / night variations that contribute to the wind speed profile.

In terms of verification of the flow inclination over height a general agreement between calculated and measured flow has been found but an offset on the order of 1.3 degrees has been reported. In order to evaluate the differences it would be required to assess many more situations. In this case the deviation of the average flow angle is uncritical since it is small if compared to the typical rotor tilt axis angle of 4 to 5 degrees.

It is therefore concluded that complex flow modelling offers an interesting additional tool for assessing the atmospheric conditions with comparable results to Sodar wind profile measurements.

6.10 Considerations on Sodars for site calibrations

Site calibrations are a field of increasing importance in the wind energy business. A typical wind farm in complex terrain requires performing site calibration measurements for all three turbines and with the arrangement of the IEC 61400-12 this usually means to install three pairs of met towers of hub height. This is an expensive task for modern wind turbines of hub heights 100 meters and more. Furthermore it requires delicate timing in cooperation with the park installation schedule. If this procedure could be streamlined, it would be a very interesting method when putting up a wind farm.

In general two set-ups can be considered:

- Two Sodars for site calibration
- One Sodar and a met mast for site calibration.

However, both approaches have their limitations that will make the use of a Sodar in this field impossible.

In the case of using two Sodars it would be required that the parties agree to use the relation as if it was measured with a pair of cup anemometers. This can be a significant obstruction since the current procedure requires the use of the same anemometer type for site calibration and later power performance measurement. But even when this is accepted (for example because the power curve will be measured with the Sodar also) two problems remain.

Two Sodars of the same type will use the same frequency, assuming the simplest case of single frequency devices, and therefore the two Sodars will disturb each other. One could also think of using two different Sodars or alternatively one that can be operated at different frequencies but in this case it must be argued that the results of the PIE experiment in the framework of this project have shown that significant differences in Sodar measurements at the same location exist that are on the same order of magnitude as the effect that should be measured, namely the site calibration.

The second option is the combination of a Sodar with a met mast but again it must be argued that the various comparisons of Sodar vs. mast data in non complex terrain with proven high correlation of the wind measurements at the same height have shown that the measurement characteristics of the individual Sodar have a influence at the site. These differences must be assessed for every site and can therefore not be transferred from other measurements.

Finally the effect of data filtering should not be neglected. It is possible that the specific filter rules for a Sodar introduce a bias in the site calibration relation that makes the relation useless for the measurement of a power curve.

6.11 Gust detection with a Sodar

University of Salford has contributed to the work package with a chapter on considerations concerning the gust detection using a Sodar that is nacelle mounted and is pointing towards the wind.

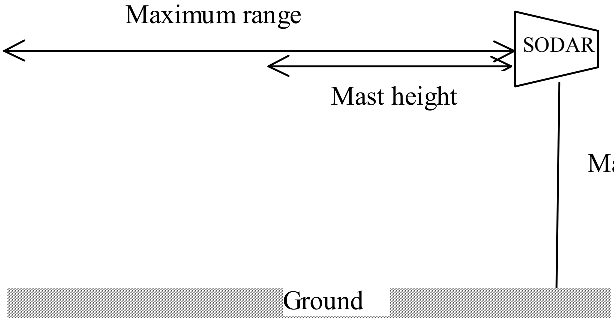

Figure 6.8. Scetch of a nacelle or mast based Sodar.

However there is a number of arguments why this will lead to significant problems that will be discussed shortly.

Limitations are seen by the measurement range that a Sodar would need to cover. Considerations assuming a gust approaching at 25 m/s lead to a measurement range of around 800 meters where the gust must be detected the first time. In total three successful measurements should be made to be sure that it is a real gust and not just noise. However, the experience shows that the data rate decreases significantly with distance respectively measurement height. As an example a low frequency Sodar like the Metek RASS System, reaches it full measurement range (here 500 meters) only in 5%-8% of all cases. Therefore measurement limitations in distance and wind speed range of interest are poorly fitting to the considered task.

Other considerations relate to the nature of a gust as a three dimensional turbulent eddie that should travel faster than the average wind speed in order to be detected as an outstanding wind speed. This is however not always the case since the eddie contains a large number of wind speed an is a three dimensional flow. The averaging of the Sodar is performed over a volume that is at first order of comparable size as the eddie itself. Therefore the reported value will be much smaller than the maximum value of interest and the detection of the potentially dangerous eddie is not straightforward.

A final argument against a Sodar use for gust detection comes from geometrical considerations. A Sodar pointing horizontally will always pick up signals from the ground that has a much higher reflection rate than the moving turbulent air that is of interest. Therefore this fixed echo will affect all signals in a greater distance then the mounting height of the Sodar. Even with turbine heights of 100 to 140 meters this is far to close to allow for an effective gust detection and reaction of the turbine.

6.12 Sodar measurements offshore

ECN had the change to work with data that had been collected at the Dutch offshore station "Meetpost Noordwijk". The offshore platform features a 10-meter mast and allowed for the installation of an Aerovironment 4000 Mini Sodar that had been on place for more than two years in different configurations.

Figure 6.9. Meetpost Noordwijk (MPN), 8 km out of the Dutch shore, at the top right side of the platform the meteorological mast is located.

The met mast on the platform was standard meteorological height of 10 meters. It is the lowest level of the Sodar but it is the only possible combination that could be assessed in direct comparison.

The Sodar had been operated in four different settings which mainly considered height range, vertical spacing, filter setting with respect to signal to noise threshold and pulse length duration.

The comparison of the wind speed data showed large differences between Sodar and mast at the available height level when a direct comparison has been possible (Measurement campaigns 1 and 3). Large deviations on the order of 50% have been found between the two wind data sources. The situation improved when the 20 m data has been used for comparison. Therefore it is concluded that the 10 m data should not be used for this model.

Very large deviations up to 30 m/s have been found in some occasions. This effect can be explained with the overestimation of the wind speed from the Sodar, which has been influenced from heavy rain.

An interesting picture has been gained for the height level that had the highest number of successful readings. The most often reached height was 80 meters independently of the season or the setting. The over all height performance was also limited. Only in 55% of all cases the height of 80 meters had been exceeded. The evaluations also showed that during the measurement period the performance was decreasing.

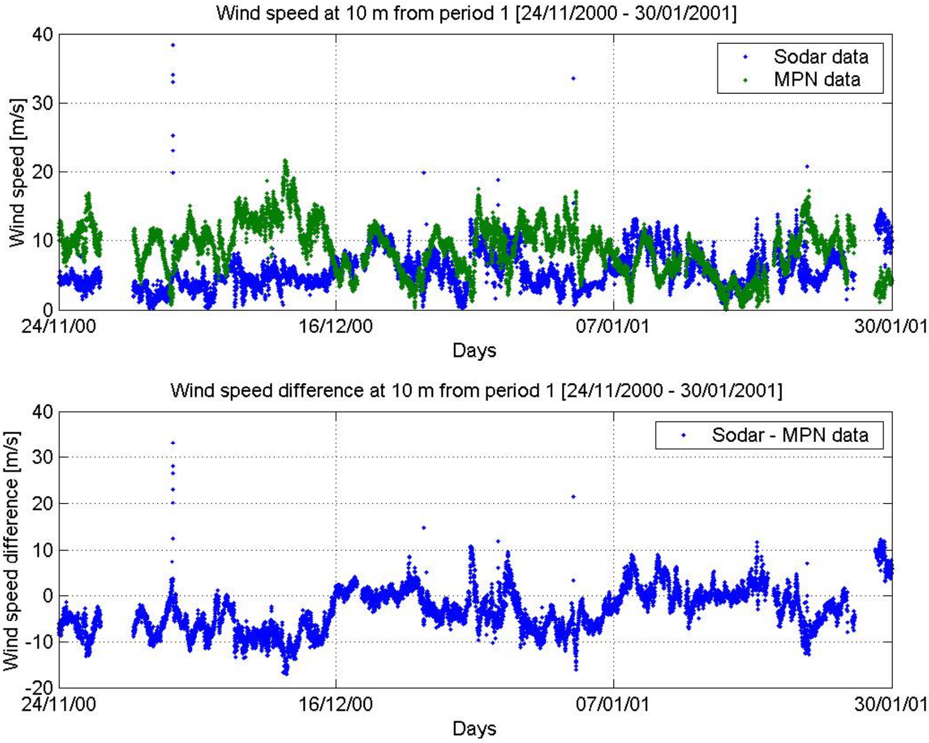

Figure 6.10. Example of a data plot of the wind speeds.

This behaviour can be explained with the long operational time without maintenance of the system, especially the speakers. Following the manufacturers manual the speakers should be checked every three months. In this case this has been done at the end of the measurement period. It is likely that this procedure would have detected worn out speakers and an additional electronics problem that seems to have occurred during the last two measurement campaigns. It must be noted that this type of service is hindered by the fact that going to the site will not always be possible and has higher costs than a land based measurement.

The author therefore concludes from the experiences with the measurement that the service intervals should be met if possible. He furthermore argues that the offshore conditions increase the failure rate of the speaker and the electronics. Three possible causes have been named for this effect. One was the high operational voltage of the specific Sodar in the measurement, the second one the marine environment and finally the noise that is transmitted from the platform structure to the Sodar housing. Most likely a combination of all three components is responsible for the limited information gained from the measurement.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

Within the WISE research project the use of wind speed and wind direction measurements with Sodar systems for wind energy applications have been investigated. The general aim of the project was to investigate the application of Sodar measurement technique for wind speed measurements in relation to the determination of large wind turbine characteristics. Therefore an accurate model of the theoretic background of the Sodar has been developed that describes the relevant aspects of the interaction of the sound beam with the atmosphere and the applied processing techniques. During the project several measurement campaigns were conducted by the project partners to create a data set for research purposes. The dataset extends to several years of measurements next to large meteorological masts.

Measurements in complex terrain were carried out during the project to investigate the possibilities of using Sodars for site calibration. The main wind energy related activity in the project however was to carry out power performance measurements of wind turbines with the use of Sodars and meteorology masts. In order to perform these measurements insight was required in operational characteristics that affect Sodar measurements. Also an adequate Sodar calibration method was required and has been designed.

7.2 Theoretical basis

A theoretical basis for Sodar measurements with respect to wind energy applications has been established to be able to measure wind speed with Sodars in a more reliable way by describing the Sodar measurement algorithm and by determining the interaction of the sound beam with the atmosphere. A number of issues regarding Sodars and the measurement of the atmospheric wind speed with the use of either Sodars or/and cup anemometers have been addressed. The measurement principle is different between Sodars and cup anemometers with the largest difference being that of a point versus volume measurement.

The wind speed measurement at the centre of the wind turbine rotor disk is not always representative of the wind speed over the whole rotor area and the differences are increasing with the increase of the wind shear. The Sodar presents a number of advantages in the measurement of the wind speed in connection with wind energy applications, relative to the use of a cup anemometer. These advantages are related to the ability of the Sodar to measure the wind shear profile directly.

Following the theoretical basis several Sodar parameter interdependencies have been addressed. For example by setting the number of sample points to a higher value the range resolution of the Sodar decreases. The settings of these parameters should therefore be taken into account when setting up the system to perform wind energy related measurements. This has led to a list of recommended parameter settings for Sodar measurements.

Among the drawbacks of the Sodar measurements are the limitations due to the background noise at high wind speeds or during neutral conditions of the atmosphere. The systematic bias in the measurements, between the cup anemometer and the Sodar results, which both the experimental analysis and the theoretical results point at, is important in the sense that it adds to the uncertainty of the measurement.

7.3 Sodar calibration

An exhaustive theoretical analysis has been performed of Sodar uncertainties in calibration, which arise from Sodar design and operation. Additionally, calibration procedures applied to three different Sodar models are described and evaluated. These procedures have been tested at different sites and different types of Sodars with field calibrations, as well as with Sodar-Sodar intercomparisons during a major calibration experiment called PIE (Profiler Intercomparison Experiment).

In general the regressions between Sodar and cup anemometers in the nearby meteo mast showed a good correlation between Sodar and cup anemometer measured data. However the scatter between Sodar and cup increases with height. Also less Sodar measured high wind speeds were available and the regression slopes had deviations of more than 5% compared to the cup anemometer. These results illustrate the necessity of a Sodar calibration procedure.

Several calibration procedures have been considered, each with advantages and limitations. The method of calibration against a cup anemometer mounted in a small mast appeared however to be most effective concerning elimination of geometric errors, reduction of the estimation bias and reduction of the total uncertainty in Sodar measurement. In addition several error sources in Sodar measurements in stand alone operation have been identified, such as the effect of air temperature changes, bad positioning of the instrument and the accuracy of peak frequency detection in the back-scattered acoustic signal.

The result of the calibration investigations has shown that, with appropriate care and knowledge, Sodars can provide wind speed and direction profile data in non-complex terrain to a comparable degree of accuracy as mast-mounted cup anemometers, providing there is a reference cup anemometer mounted on a nearby 40m mast. Specifically, variations of wind speed calibration slope of less than 1% can be expected, with RMS residuals of typically 0.4 m/s. Wind direction variations are typically 1° or 2°.

7.4 Operational characteristics

Sodar operation is influenced by a number of factors determined by weather conditions and/or the surroundings where the system is installed. These factors have been identified and their influence on Sodar operation has been explained. To reduce the effect of these factors recommendations are given regarding the optimisation of the settings of the system. In addition to this, filtering procedures have been established to be able to distinguish the reliable from the unreliable data as measured by the Sodar, and to minimise data losses due to excessive filtering.

Circumstances that can cause unreliable Sodar data are a well-mixed boundary layer of the atmosphere in the late afternoon, precipitation, very high wind speeds, external noise and fixed echoes. Filtering techniques can be based on the SNR ratio and intensity of the back-scattered signal, the measured vertical velocity and the background noise level.

During field experiments a remarkable loss of usable Sodar receptions of almost 40% was observed during near neutral atmospheric stratification conditions. A significant amount of data loss seems to happen at heights above 100m. Below this height range however the back-scattered signal might be strong enough to ensure good quality receptions. For power performance measurements of large wind turbines such data loss will generally result in longer measurement campaigns in case of frequently occurring near neutral atmospheric stratification conditions at the test site.

Precipitation can influence the Sodar measurement results, since the emitted sound will be back-scattered from falling raindrops or snowflakes causing outliers in the measured data. Although rain sensors from nearby meteo masts were used during the measurements, no clear filtering technique have been found yet to determine data points with precipitation using only Sodar measured data, such as the intensity and the SNR ratio of the back-scattered signal.

Fixed echoes can occur in the data when the acoustic signal is back-scattered from a fixed object. This can cause a high value of the back scatter intensity and the SNR ratio of the back-scattered signal, while the vertical velocity component of the wind speed is zero. An effective filtering method appeared to accept datapoints with a SNR of lower than 35.

Filtering of data is required to enhance the data quality of the measured Sodar data. This is done using external precipitation sensors and with the help of the SNR parameter after erroneous data points i.e. 999 have been excluded. Good results are obtained taking the SNR of each of the back-scattered sound beam between 7 and 30. However, additional filtering methods should be used, since a relative high scatter in the regression between Sodar and cup anemometer can remain. The available filtering techniques offered by the software of the instrument do not seem to be adequate as they either fail to remove the erroneous data or filter away sound data especially at high wind speeds. The development of additional filtering methods requires access to the Sodar data processing software and the development of additional corrective algorithms.

7.5 Measurements in difficult circumstances

Measurements in complex terrain using a Sodar have been performed that consisted of a site calibration at several wind turbine locations in a commercial wind energy project. These measurements were used in preparation of power performance measurements and were performed using an autonomous power supply system. During the campaigns several obstructions affected the measurements. Besides vandalism, these were related to malfunctions in the autonomous power supply in combination with bad weather conditions such as snowfall and icing. These issues are however not Sodar specific.

Based on the experiences with the autonomous power supply a proposal has been presented which includes a battery bank powered by several optional sources of electricity supply including a diesel generator. The proposal deals also with the data communication and a warning system to notify the operator in case of power problems.

The measured Sodar data were analysed to characterise the complex terrain using a three-dimensional flow model. The wind direction measurements were in good agreement with the meteo mast, this is considered as essential in complex terrain measurements. Using averaged wind profiles the measurements showed strong differences between day and night due to the typical daily pattern in atmospheric stratification. It is concluded that flow angle measurements with the Sodar in terrain of medium complexity deliver results that are in agreement with the expectations.

When performing a site calibration either two Sodars systems or one Sodar together with the permanent meteo mast for power performance measurements can be used. However there are some special problems to be considered. In the first case a proper calibration of both Sodars is missing, furthermore it is required to ensure that the two Sodars do not interfere with each other. In the second case it can be argued that the various comparisons of Sodar vs. mast data in non-complex terrain, with proven high correlation of the wind measurements at the same height, have shown that the measurement characteristics of the individual Sodar have an influence at the site. It is concluded that a Sodar based site calibration under these circumstances is not feasible.

The possibilities to use a Sodars for detection of approaching gusts in front of offshore wind turbines have been investigated. Limitations of the possibilities are caused by the decrease of the data rate with the distance in front of the turbine. Therefore approaching gusts cannot always be detected. Furthermore the nature of a gust can cause smaller reported wind speeds than the maximum wind speed occurring in the gust, which means that the detection of a potential dangerous gust is not straightforward. It can also be expected that the sound beams will cause fixed echoes against the sea surface, resulting in higher scatter in the data.

In the framework of measurements in complex terrain measured data from a Sodar system installed on an offshore platform were analysed. The data were compared to cup anemometer measurements from a small meteo mast on the platform. Unfortunately it appears that the system had a long operational time without proper maintenance, hence the dataset was not usable to perform further analyses.

7.6 Sodar power performance measurements

At three European wind turbine test sites power performance measurements have been carried out with the use of Sodar systems and cup anemometers in meteo towers. On these three sites also Sodar calibration experiments were performed using a small meteo tower of about 40m, or boom at an equivalent height in the existing meteo mast. The power performance and AEP results (Annual Energy Production) from uncalibrated Sodar (stand alone), calibrated Sodar and cup anemometer data as measurement at the hub height of the wind turbines were compared.

All measurements showed a good similarity between the resulting wind direction measurements of the Sodar and the direction sensors in the meteo masts. However the Sodar measured raw wind speed data had first to be filtered to obtain more reliable data since many data points deviated considerably from the mean values. Filtering took place by removing erroneous values and applying limiting values to the SNR ratio of the returned signal. Furthermore the data had to be filtered to exclude data points in periods with precipitation. Since the Sodar systems did not have a precipitation sensor the sensors from nearby meteo masts had to be deployed. The SNR and also the data availability of the raw measured data decreases with height and with wind speed. Therefore filtering reduced the availability of high wind speed data above ca. 15 m/s even more, by up to 50%. Some of the high wind speed data are removed although they do not deviate considerably from the mean values. In combination with the necessity of reorganising the raw data due to the output format of the software, the data filtering proved to be a tedious task. Access to the source code by the user or a more user-friendly version of the software is therefore required to improve the data output.

After filtering of the Sodar data from stand alone operation the deviations from the mean wind speed measured by the cup anemometer were too large to get comparable P-V curves and AEP numbers, especially at high wind speed. In two cases the Sodar systems overestimated the wind speed by a factor of 5% to 10%, resulting in an underestimation of the P-V curve and AEP. In the other case the Sodar underestimated the wind speed by a factor of around 6%, resulting in overestimation of the P-V curve and power coefficient Cp of the wind turbine, the latter by a factor of more than 25%. The uncertainty analysis shows that the type B uncertainties in stand alone operation are currently far too high to perform P-V analyses with an uncertainty comparable to cup anemometer wind speed measurements. This is confirmed by the measurements.

The recommended method to perform wind energy related measurements with currently available Sodars is to calibrate the Sodar with the simultaneous use of a small meteo mast of 40m. In case of a P-V measurement of a wind turbine the actual Sodar measurements at hub height were derived from simultaneous calibration measurements of Sodar and cup anemometer and vane at a lower height. During the three experiments this calibration is carried out during a power performance test with cup anemometers at around 40m height in meteo masts which were fully suitable for certified P-V measurements (IEC 61400-12). In general the correction of the measured Sodar wind speeds at hub height with the use of the calibration at lower height worked well. The deviations between Sodar and cup anemometer at hub height were largely corrected. However the effect of the correction depends heavily on the number of available data points for the calibration. Since filtering is required due to unfavorable atmospheric conditions, background noise and fixed echoes this means that the measurement period required to obtain a P-V curve complying with the standard IEC 61400-12 will be considerably longer than the required period when using cup anemometer measurements.

The uncertainties in Sodar measurements after calibration are still larger than in conventional cup anemometer measurements. This is a consequence of the applied calibration method. The type B uncertainty of the Sodar will never be smaller than the uncertainty of the cup anemometer used for the calibration. The reason for this is that the uncertainty of the cup anemometer is part of the entire uncertainty, although calibration reduces the uncertainty considerably compared to stand alone operation. On the other hand, the type A uncertainty, basically consisting of the scatter in the bins of the wind speed versus turbine power scatter plot can be smaller due to the volume measurements of the Sodar that theoretically resembles the win conditions in the rotor swept area more accurately.

The AEP results from two experiments show that the calibrated Sodar derived AEP's are within 4% deviation from the AEP's calculated using cup anemometer measurements. However the uncertainties in AEP's calculated by calibrated Sodar measurements are a factor 10% to 30% higher than AEP's calculated by cup anemometer measurements. The P-V and AEP calculations of the other experiment show different results, here the P-V curve is overcorrected and the resulting AEP's, with calibrated Sodar, are outside the uncertainty range of the cup measurements for most wind speeds. This is most presumably due to the fact that the calibration period in this case appeared too short to measure enough data points at high wind speeds.

Analysis of applying the calibration parameters to data obtained from uncalibrated measurements stresses the conclusion that simultaneous calibration is required when performing wind energy related measurements.

7.7 Usability for wind energy related measurements

The mobility and flexibility of Sodar systems are larger compared to fixed meteo masts. The costs involved in high meteo masts increase exponentially with height. Especially with the increasing sizes and heights of modern wind turbines, measurements with Sodar systems could become a good alternative to measurements with meteo masts. Advantages of a Sodar system are being a mobile measurement system, the capability of simultaneously measuring wind speeds and directions at selected height intervals and the absence of flow distortion from a mast.

Measurements have been carried out with Sodar systems at three locations in the WISE project for several years. It has been shown, using currently available Sodars systems, that power performance measurements cannot be carried out comparable to cup anemometer measurements in stand-alone operation without a proper calibration. The operation of a Sodar system appeared to be limited by a number of external factors and atmospheric conditions. Filtering of the dataset is necessary to obtain a data quality comparable to data from cup anemometer measurements. Due to the data filtering the measurement period may become considerably longer compared to power performance analyses with cup anemometers.

During the WISE project a new calibration method was developed using a small meteo mast with a height of 40m. This will reduce however the mobility and will increase the costs of the measurements. By applying a simultaneous calibration the measurements increased considerably in accuracy. The AEP calculations show comparable results with cup anemometer measurements on the condition that the calibration provides sufficient information at wind speeds preferably up to the cut-out wind speed of the test turbine. Also an equivalent number of datapoints per 0.5 m/s wind speed interval over this range is required.

The uncertainties in power performance and AEP calculations using calibrated Sodar measurements are however higher than in the case of cup anemometer measurements due to the necessary calibration of the Sodar against a cup anemometer on a small mast.

7.8 Recommendations

The main recommendation based on the research done in the WISE project is the use of a small and sufficiently instrumented meteo mast to calibrate Sodar systems simultaneously during the measurements. To carry out power performance measurements with a Sodar and simultaneous calibration with a lower meteo mast the following steps are recommended:

1. Install the Sodar according to the instructions of the manufacturer.
2. Install the 30-40m meteo mast sufficiently equipped with top and reference anemometer and sensors for wind direction, precipitation, temperature and air pressure, (all instruments traceably calibrated).
3. Start the measurements and synchronise the two systems in time.
4. Check data during the measurements for possible influences of fixed echoes, background noise, speaker degradation and improper parameter settings.
5. After the end of the measurements, collect all points in a database.
6. Filter away all the erroneous data points from both met mast and Sodar and keep only simultaneous points.
7. Filter away all the SNRs below and above a given threshold.
8. Verify that the cup anemometer has been working satisfactorily.
9. Verify that outliers in the Sodar are due to precipitation.
10. Find the regression of the relation between Sodar and cup.
11. Filter all outliers outside a certain band.
12. Find the slope of the regression relation again between the Sodar and the cup.
13. Calibrate the wind direction of the Sodar using the mast direction for the low height.
14. Apply the relations at the hub height for the cup and the wind direction.
15. Apply the relation for pressure and temperature using the adiabatic relation and the pressure change with height.

The requirement to use a small meteo mast reduces however the advantages which can be involved in the use of a stand-alone Sodar. Therefore improvements are required regarding calibration, system design and the data acquisition software.

The data acquisition software must be improved to enhance the accessibility for storage in a database structure. Furthermore there is a strong need for insight in the instrument software to develop corrective routines in order to minimize data losses and make filtering techniques more efficient.

To develop even better calibration techniques and/or more reliable and continuous Sodar operation the following is recommended:

1. Development of a means of self-calibration technique
2. Improved SNR by simultaneous transmission on several beams to obtain more averages per unit time and to improve data availability particularly in near-neutral conditions
3. More sophisticated digital signal processing and filtering to remove bad data
4. A rain rejection scheme (and preferably a scheme to obtain valid winds during rain)
5. Good diagnostics and information dissemination to the user
6. Automatic measurement of air temperature for beam tilt calculations
7. Detection of out-of-level
8. Designing with 5-beam capability
9. Attention to beam separation errors in tilt design

Since Sodar systems are not plug and play devices, knowledge of the operator in Sodar measurement technique is required. Insight in the influencing factors due to atmospheric conditions and the effect of background noise is required to enhance the data quality of the raw measured data from the Sodar.

Although the Sodar with the current technology has its limitations, the instrument remains an attractive alternative to expensive large meteo masts for wind measurements with large wind turbines and measurements at offshore locations. However improvements regarding calibration, design and software are required.