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UpWind

Project UpWind

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"Integrated Wind Turbine Design"

SALFORD SUMMARY ON WP 6.1, WP.6.2, WP 6.3 AND WP 6.4

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Contents

Abstract

Within the Upwind project the University of Salford provided development work for SODAR instruments in relation to the next generation of wind turbines. The main focus of the work was on the identification and proposal of design improvements, the development of a calibration device and the novel design of a bi-static SODAR to overcome limitations in the use of remote sensing in complex terrain.

Data accuracy and availability of SODARs suffers during rain. Therefore an algorithm to detect data affected by rain and to extract the wind information has been developed and successfully tested to determine the scope of the technique. In mountainous terrain another source of inaccurate wind estimates is the separation of measurement volumes which results in inaccuracy of up to 5%. A simple flow model has been proposed and evaluated for a case study showing that the applied corrections can improve accuracy.

A calibration transponder and a new bi-static Sodar design with vertical transmission and three scanning receivers have been designed and successfully tested.

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

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

1. Introduction

Within the remote sensing work package of the Upwind consortium the use of wind speed and wind direction measurements with the ground based remote sensing technologies Sodar and Lidar has been investigated. The general aim of the Sodar related work was to make improvements to the 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 extended from a previous project. It describes the relevant aspects of the interaction of the sound beam with the atmosphere.

To enable the comparison between the measured results of commercial Sodars theoretical beam pattern calculations, transponder and beam pattern measurements have been evaluated. Integration of these methods to a standard procedure is proposed to remove measurement bias.

One of the largest inaccuracies in ground based remote sensing measurements occurs in complex terrain due to the separation of measurement volumes between the different SODAR beams. In WP 6.3 this was addressed in simple hill flow simulations allowing corrections to be applied to measurements. Within this work package an algorithm to improve Sodar measurement during rain fall has also been developed.

Additionally, a bi-static Sodar was designed and tested which demonstrates the potential of receiver arrays using beam-forming to measure a wind profile within a vertical atmospheric column.

2. WP 6.1 End-to-end measurement description and WP 6.3 Improvements to SODAR performance

An end-to-end measurement description has been adapted from documents produced for the FP6 WISE project (Antoniou et al. 2003, Bradley et al. 2005) to include the results of WP 6.3 on the improvements in Sodar performance.

For WP6.3 a sensitivity analysis has been conducted to identify the major error sources of Sodar wind speed estimates. The results are shown in Figure 2.1 where the main sources of error are identified as wind speed bias due to poor set-up, the presence of reflecting structures leading to reduced wind estimates, beam separation problems over complex terrain, erroneous wind estimates due to scattering from rain and reduced data availability in neutral meteorological conditions. Scientific contributions have been made during Upwind to estimate and address performance problems in the presence of rain and in complex terrain.
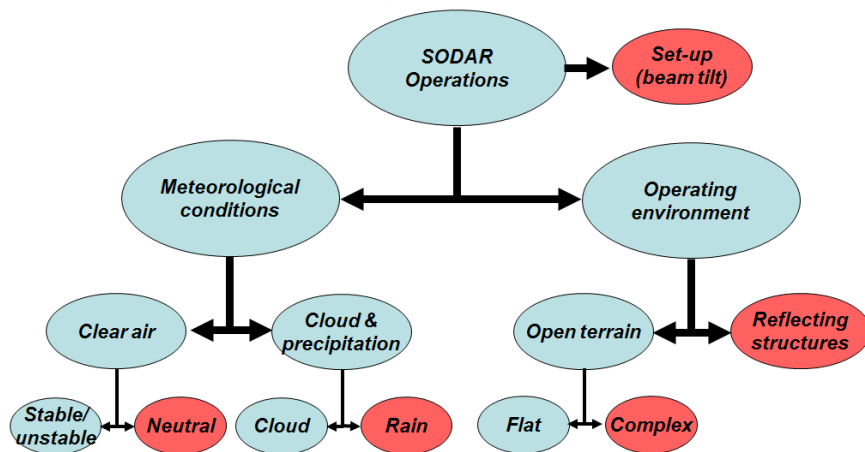
Figure 2.1 Error sources in Sodar wind speed estimates. The red circles denote the most important problem areas.

Sodar algorithm to enable measurements during rain

This method, proposed by Little (1972), makes use of the strength of acoustic scattering from turbulence having a $\lambda^{-1/3}$ dependence on wavelength λ, whereas scattering from rain has a λ^{-4} dependence. Based on this differential wavelength dependence, an algorithm was developed to fit the turbulence and rain components of a simulated backscattered signal (Legg, 2007). A multi-frequency sodar was developed to trial the algorithm. Since the algorithm relies on the differential backscattering strength on frequency, it was essential that all factors that might cause the SODAR's gain to vary with frequency be allowed for.

Both simulations and preliminary field data have been analysed in the work of Legg (2007). This method appears to offer some promise when at least two frequencies are transmitted and received simultaneously, so that the same rainfall intensity is recorded at each range gate. There are a number of design challenges in doing this properly:

1. The beam width (and beam direction for non-vertical beams) is likely to be different at different frequencies
2. Power spectra need to be expressed as a function of radial velocity, not as a function of frequency, since the Doppler frequency shift is proportional to transmitted frequency
3. The antenna characteristics need to be known at the various transmitting frequencies, or at least the *ratio* of the antenna gains known.

The proposed algorithm will work well for high frequency Sodars (transmit frequency >3 kHz). Low frequency Sodars often suffer from low signal to noise ratios in rain situations which can only be addressed by a different Sodar design. The proposed bi-static Sodar will also have fewer problems with rain as the rain signal is particularly strong in the backscattered signal.

Corrections over complex terrain

A simple potential flow model has been developed to give flow over hills of approximately Gaussian shape, together with a mono-static remote sensing instrument (Bradley, 2008a). This cylindrical hill model is shown in Figure 2.1a Winds derived using the actual atmospheric volume locations which would occur in practice have been compared with the wind vectors at the same range but directly above the SODAR to estimate the deviation. Figure 2.1b shows that the errors are small near the ground where the beams are close together and that the errors decrease towards larger heights because the flow is more uniform at larger range. The errors found are

typically in the range of 5-20%. Such errors are *huge* in comparison with errors with which investigators are usually concerned. While this early investigation has mainly served to demonstrate the severity of the problems of obtaining quality wind measurements in complex terrain with remote sensing instruments later measurements conducted outside of Upwind (Behrens, 2010, Gomez 2010) have supported these predictions. Some possible solutions have been suggested one of which is the design of a bi-static Sodar as described in Chapter 5.
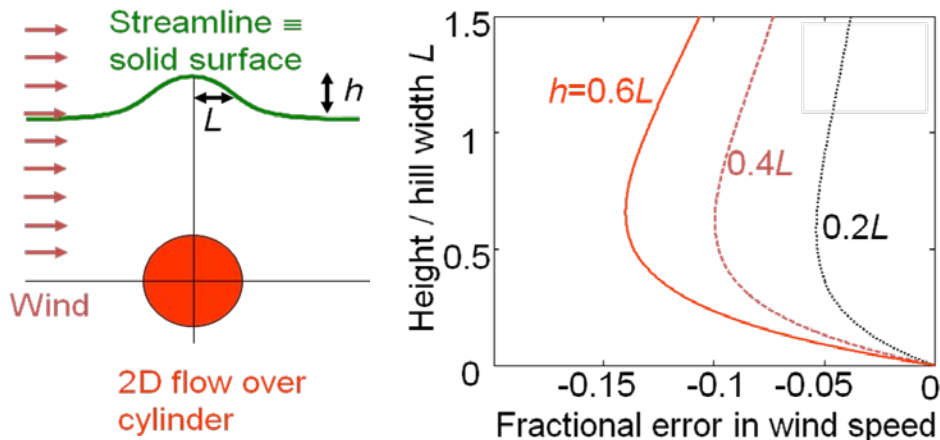
Figure 2.2 Simple potential flow model schematic a) to derive a first estimate of the error b) expected from Sodar measurements due to beam separation over the hill.

The simple analytic tool described here can readily be used for simulations on beam configurations, and it is also possible to obtain analytic expressions such as the height of maximum error, the orientation giving minimum error, or the slope of error versus height at low heights. It has in the meantime shown to give surprisingly accurate error predictions given the simplicity of the model (Bradley et al, 2011).

# 3. WP 6.2 Sodar Comparison Methods for Comparable Wind Speed Estimation

Aims

To address inconsistencies between wind estimates from different Sodar models comparisons between instruments are required to the point that gives a traceable calibration. The status quo at the start of the project was to place a Sodar close to a meteorological mast in flat, uniform terrain and compare the results at a number of heights. Because mast mounted anemometers have their own measurement errors and measure in a very different volume of air this is an unsatisfactory approach. The current project therefore aimed to

1. theoretically compare Sodar characteristics based on their design
2. design a transponder system that would record the Sodar signal and produce an artificial atmospheric echo to allow the comparison between wind estimates from different types of Sodars
3. compare methods to measure the beam patterns / tilt angles because they potentially introduce significant errors
4. propose an integration of these methods to increase measurement accuracy

Results from that work are published in Piper (2011).

Theoretical results

From the loudspeaker directivity patterns and the array geometry simple beam forming models beam patterns can be calculated at the height of the baffle edge as shown in Figure 3.1. This allows systematic fixed echo optimisation by avoiding side lobes intersecting the baffle edge and causing diffraction. Currently fixed echoes are treated during the instrument setup in an empirical fashion and very often this is poorly done.
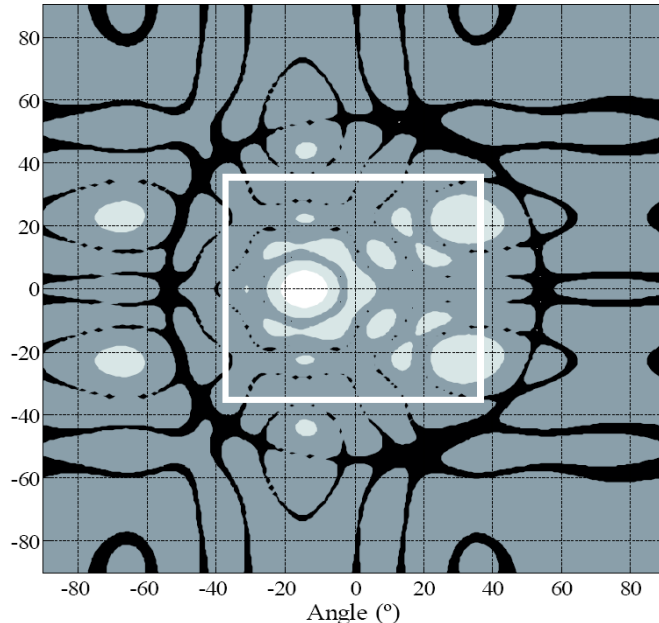
Figure 3.1 Beam pattern calculated at top edge of the acoustic shield to indicate side lobe diffraction over the baffle edge. Bright colours denote high acoustic intensities that would potentially cause fixed echoes in beam direction. These will be particularly strong when intersecting the Sodar baffles.

In addition to 2 dimensional beam patterns, effective measurement volumes based on beam forming calculations have also been calculated. They have been shown to be approximately 15% of the effective cone section depending on the window functions use for pulse shaping at the receiver. Two Doppler equations are widely published and used to calculate the wind components in beam direction. The wind estimates between the two equations differ systematically by about 2%.

In summary it has been shown that using simple theoretical analysis of a Sodar design and operating parameters can already give valuable information on the accuracy of the wind estimates. Therefore we propose to request manufacturers to at least provide simple analytical tools to both choose the optimum Sodar orientation and operating frequency of a Sodar at a particular site to allow users to minimise fixed echo effects.

Beam pattern measurements to include the effects of diffraction

The theoretical beam pattern analysis described in the section on theoretical results has given useful information to avoid fixed echoes but is does not describe the effect of baffle diffraction fully. Where baffles have triangular edges or where vertical loudspeaker arrays are used in combination with reflectors the geometry becomes complicated to calculate analytically and it is easier to measure beam patterns. Therefore a number of methods have been tested for their suitability to determine a full beam pattern including effective tilt angles:

- Near field acoustic holography (laboratory)
- Direct beam pattern measurements using a tilting platform (outdoors, on site)
- Bradley(2008b) tilt calibration (outdoors, on site)

The latter method has been newly developed during Upwind. It makes use of the relation between beam angle and wind speed. The Sodar is placed on a platform that is tilted to a number of different angles. At each angle the wind speed is measured over a suitable averaging interval. In situations where the wind speed and direction are steady this technique has given accurate measures of the tilt angle to about 0.2°. As this method relies on steady wind conditions another simple way to measure beam angle has been shown. It uses a microphone on a 10 m mast in combination with the tilting platform and achieves a similar accuracy without the limitations of the Bradley method.

Transponder design and tests

To be able to compare the results of different Sodars under standard operating conditions a transponder system was designed that would record the Sodar signal and produce an artificial atmospheric echo. The transponder shown in Figure 3.2 uses the input horn to detect and analyse the transmitted Sodar signal. A realistic echo is then calculated based on typical atmospheric scattering conditions and wind profiles. The noise background can also be varied. The transponder is designed to transmit the signal into the Sodar in real time in the respective beam direction as shown in Figure 3.3.
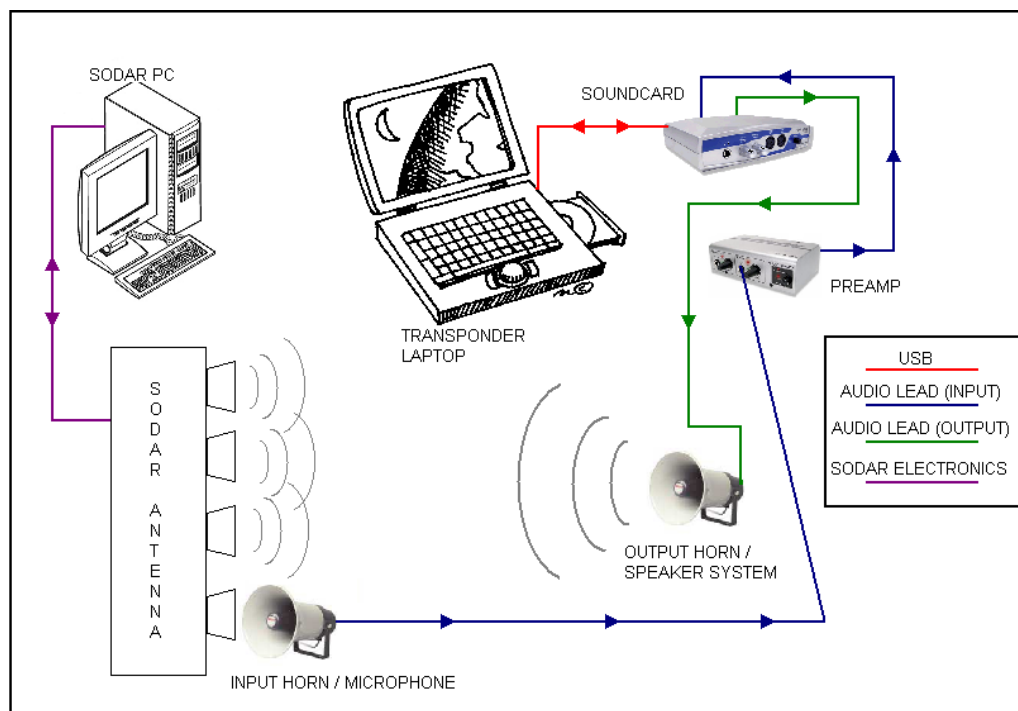
Figure 3.2 Simplified transponder schematic. The SODAR consist of the Sodar antenna and PC whereas the transponder consists of a microphone with preamplifier, loudspeaker and laptop with an external soundcard.
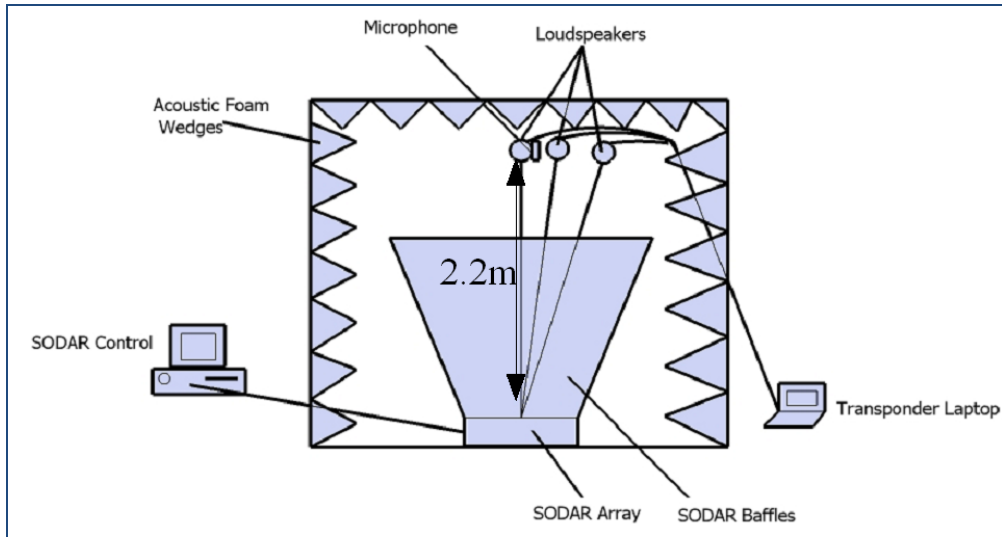
Figure 3.3 Transponder setup in semianechoic chamber Note that the extended transponder transmits sound from three different directions.
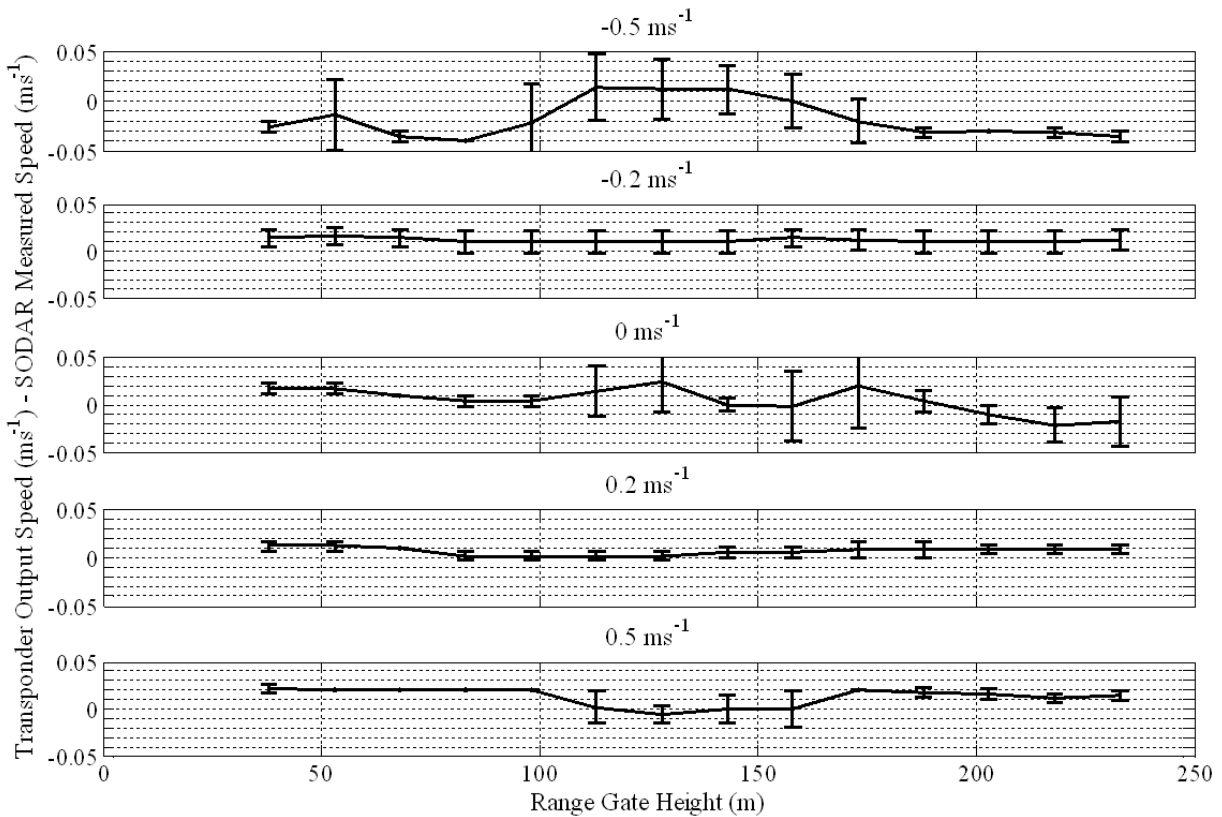
Results:

Figure 3.4 Typical laboratory results. Vertical beam profiles at different wind speeds.

The transponder has been tested in a semianechoic chamber; a laboratory environment which best reflects the operating conditions outside. Figure 3.4 shows an example of achievable results. The vertical wind profile is fully reproduced for constant model wind profiles at different wind speeds. The laboratory test results have found that the transponder is useful for diagnostics. It can detect which Doppler equation is used, if the Sodar algorithms use undocumented time and

spatial averaging. The performance of different analysis techniques such as cluster and spectral averaging as well as sets of operating parameters can be compared. Data accuracy in noisy conditions can be analysed.

At the moment the transponder works well for the type of Sodar that it has been developed for but more development work is needed to make it useful for other systems. Further development should include
- echo broadening to make the return signals more realistic compared to atmospheric returns
- automatic beam synchronisation to avoid the transponder going out of synchronisation with the Sodar and
- real times pulse recognition to avoid a pulse recording cycle before the actual transponder experiment. This would improve time efficiency and flexibility of the transponder use.

First results from field tests suggest that the transponder is most efficiently used in the laboratory rather than outdoors where the atmospheric echo interferes with the transponder signal.

The transponder experiments have shown that diagnostic measurements that are independent of the Sodar manufacturers can be useful to optimise Sodar operating parameters.

Conclusions

Under Work Package 6.2 "Traceable calibration methods for the monostatic SODAR and the LIDAR" a transponder prototype for the comparison of different Sodar models has been designed and tested and analytical methods as well as measurement methods of beam patterns/tilt angles have been tested and compared.

For Sodar performance optimisation the different analytic methods need to be combined in a systematic way. A preliminary suggestion has been made in Piper (2011). This proposal acknowledges that other work that has been conducted during the Upwind project like the simple complex terrain correction suggested ealier or the CFD approach proposed by Bingöl (2010) will also need to be included to address the fact that Sodars cannot be placed in the direct vicinity of turbines or masts. Although these methods are expected to improve Sodar results it will take time until they are firmly established and comparisons with masts will therefore remain an import means of traceable calibration for some time to come.

Salford University has commercial facilities and – following the Upwind project – the expertise suitable for development into an internationally recognised laboratory for Sodar diagnostics.

4. WP 6.4 Bi-static Sodar for complex terrain

Aims

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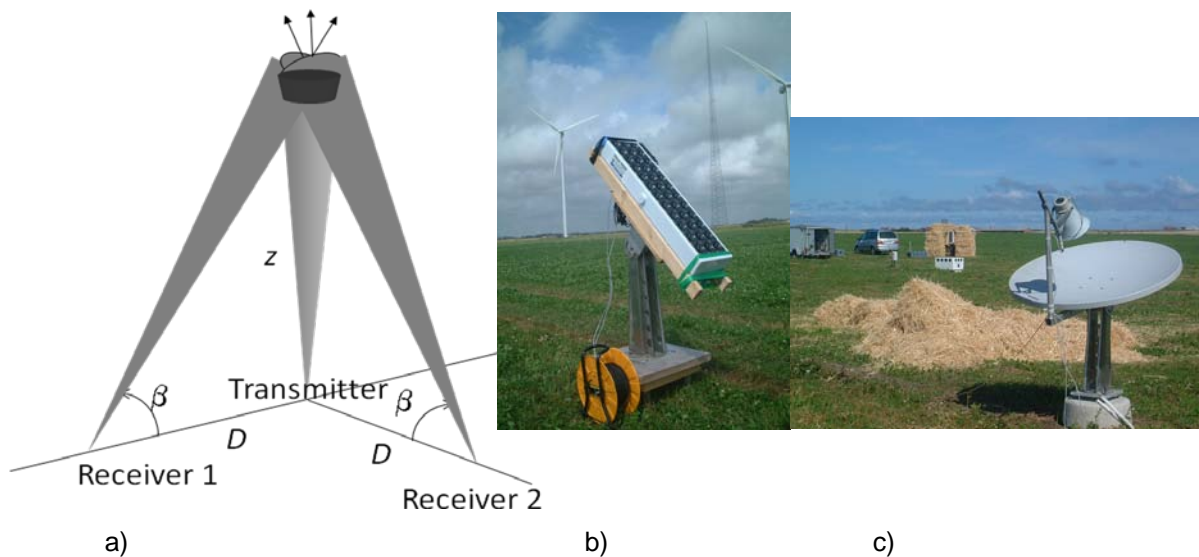

a)   b)   c)

Figure 4.1 Bistatic set-up a) schematic, b) receiver and c) transmitter in field setup at Høvsøre, DK, July 2008

Figure 4.1a) shows in a schematic diagram how transmitter and two receiver beams overlap to give measurements from one volume. Basic tests have been conducted proving the concept of wind profiling with this set-up. Figure 4.1c) shows the transmitter pointing vertically while the receiver is inclined for best results.

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

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

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

The relevant theory for each of these factors is developed, and how to design a scanning sodar which has good spatial resolution. In particular, it is important to use a pulsed system to avoid the multiple overlapping spectra experienced by previous continuous-transmission instruments. In fact, the pulse length largely determines the vertical resolution in the scanned bistatic system. The spectral processing needs to be done rather carefully, and certainly is rather more complicated than for a monostatic system. Nevertheless, it was found all spectral processing, and post-sampling beam steering, can readily be completed in MATLAB in a small fraction of the profiling time, and effectively gives real-time performance.

After doing some preliminary tests using a monostatic sodar as a receiver, a prototype scanning bistatic sodar was designed using a dish antenna transmitter and 12 x 3 arrays of microphones for the receivers. The baseline used in all experiments was 38 m, but this is somewhat arbitrary and there should be further exploration of the optimum configuration. No acoustic baffles (except for crude use of some hay bales) were used in the prototype. Significant improvements in performance can be expected if properly-designed acoustic shielding is used.

A number of preliminary experiments are described in this work. An experiment was set up to obtain profiles of the ratio of the structure function parameters, C_V^2/C_T^2. Since this is a useful atmospheric boundary layer parameter, more detailed results will be published in due course. The profile of the turbulent scattering intensity is found to closely approximate what is expected from theory, giving some confidence in the instrument design and scanning (see Fig. 4.2).
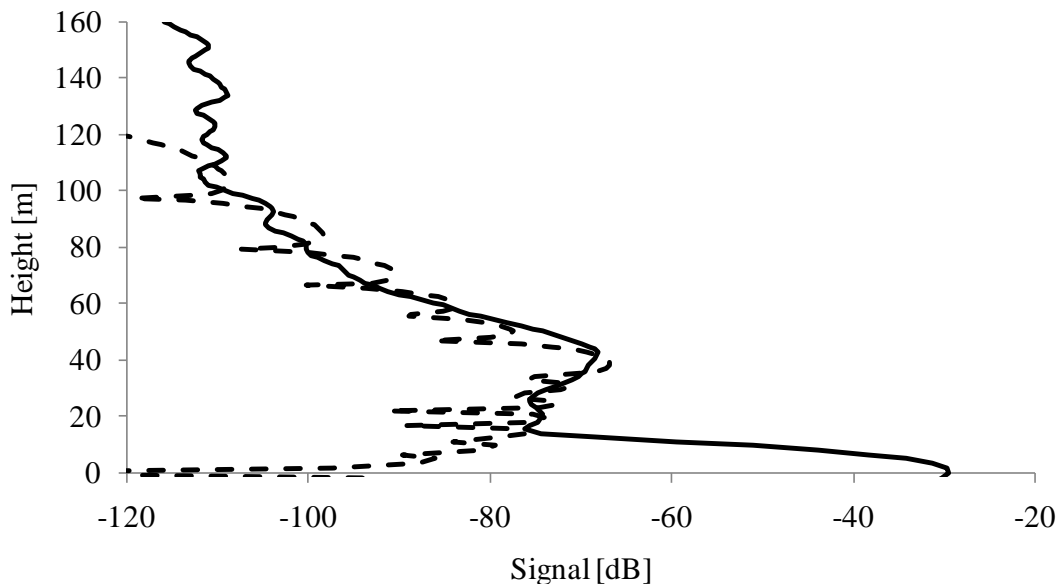
Fig. 4.2 The variation of received signal amplitude with height. Measurements (solid line), and modelled (dashed line).

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

improvements obtained through continuously transmitting, rather than the usual monostatic situation of transmitting for, say 0.1 s, then waiting 2 s for data to return from 300 m or so.
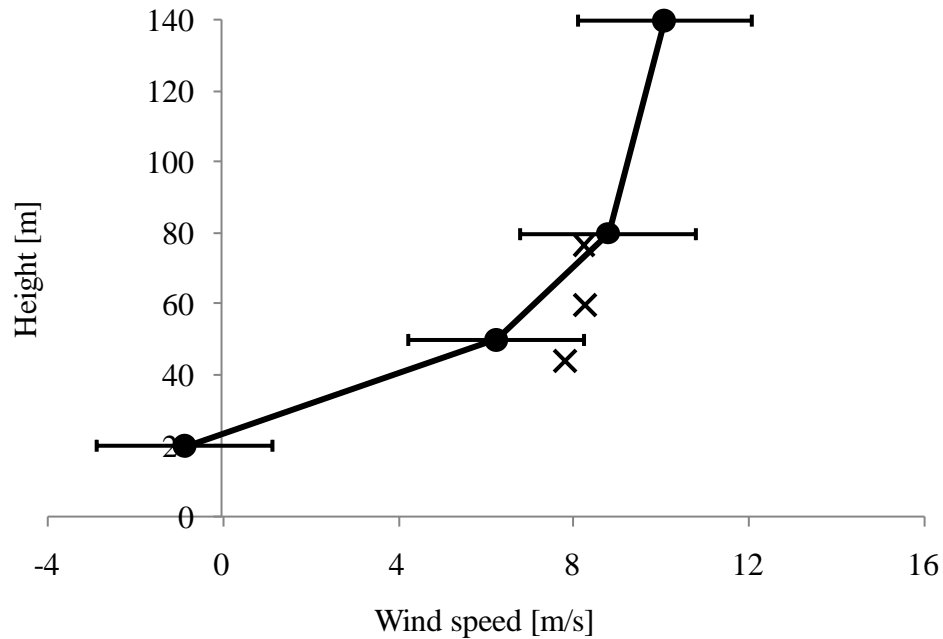
Figure 4.3 Wind speeds from the bistatic sodar (solid line and dots) compared with wind speeds from mast instruments (crosses).

Work is now progressing, outside of Upwind but motivated by the success of the bistatic trials, to design microphone-based arrays as an optional addition to a commercial monostatic sodar. This configuration will allow both monostatic and bistatic configuration to operate simultaneously, or sequentially, thereby providing considerable self-checking of the instrument, since the two velocity estimation schemes are quite different.

5. References

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