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SODAR measurements in tilted position

Investigation in the use of SODAR in a tilted position as a possibility for use in offshore wind parks

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Acknowledgement/Preface

This report has been written with the co-operation of colleagues from the group “Experiments” who have contributed during set-up, measurements and analysis. Special thanks goes to Rob Nijdam for designing and making the tilting mechanism, without which the measurements could not have been done as well as they have been done and to Erik Korterink for doing the measurements. Also thanks goes to KNMI for allowing us to perform measurements and for making the data from the meteorological mast at Cabauw available.

Abstract

In this project the goal was to establish whether a normal, off-the-shelf SODAR could be used in an offshore wind farm in a tilted position at the base of a turbine. Measurements in tilted position have been carried out before but no valid data was received. Problems encountered in the first measurements were related to the setting of the tilt angle to avoid fixed echoes, and to the fact that the SODAR did not produce any data.

In this project a tilting mechanism has been constructed which allows the tilting of the SODAR between 40 and 70 degrees with a resolution better than 1 degree. This is accurate enough to adjust the instrument in such a way as to avoid fixed echoes from certain tilt angles if possible. The next step was to establish a working set of parameters with which the SODAR does produce data. After some tests this was achieved.

Two different measurements were carried out and compared to the data from the 213 metres high meteorological mast at Cabauw (NL). In general the SODAR produced data in the same order of magnitude as the anemometers fixed to the mast, and the data were also correlated. However, absolute and relative differences were very high.

We also found that fixed echoes in both measurements affected the data (in the direction of 340 degrees) this could not be corrected by adjusting the tilt angle because the reflection was caused by the guy-wires, and these go up to high tilt angles as well. In the direction of 250 degrees the fixed echoes could be avoided by changing the tilt angle but in this direction the measuring beam was at right angles to the wind direction and therefore no good data could be measured either. Because of the vicinity of the mast and trees in all other directions no other tests were possible at the Cabauw site. A more open site would probably give better results. We also saw that the SODAR software did not always detect the fixed echoes and that the fixed echoes also affected data below and above the altitude of the fixed echo.

From a design perspective we have drawn the conclusion that operating an off-the-shelf, commercially available SODAR is probably not going to work at all for a normal wind speed range. Because the SODAR has been designed for operation in a vertical position, measurements with a tilt angle will always be affected and give data with less quality and for a much smaller wind speed range. This will be unacceptable for wind energy purposes. A possibility to use the SODAR close to a meteorological mast has been described, but whether this will also work at the base of a turbine can only be answered after further research.

Novem project number: 224.721 - 0012
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1. EXECUTIVE SUMMARY

In this project the goal was to establish if a normal, off-the-shelf SODAR can be used in an offshore wind farm in a tilted position at the foot of a turbine. Measurements in tilted position have been tried before but no valid data were received. Problems encountered in the first measurements were with setting the tilt angle to avoid fixed echoes, and with the fact that the SODAR did not produce any data.

In this project a tilting mechanism has been constructed which allows the tilting of the SODAR between 40 and 70 degrees with a resolution better than 1 degree. This is accurate enough to adjust the instrument in such a way as to avoid fixed echoes from certain tilt angles if possible. The next step was to establish a working set of parameters with which the SODAR does produce data. After some tests this was achieved.

Figure 1: SODAR tilted towards 250 degrees

Two different measurements were done and compared to the data from the meteorological mast. In general the SODAR produced data in the same order of magnitude as the mast, and the data was also correlated. Absolute and relative differences were very high.
The results were the best for the first measurement as there was a much better alignment between sound beam and wind direction than for the second measurement. Results can be found in the next table.

Table 1: Cabauw and SODAR wind speed compared for the first measurement, tilted towards 340 degrees. SODAR wind speed is corrected for the tilt angle and the difference between the measurement direction and the wind direction.

Cabauw altitude (m)	**Cabauw wind speed** (m/s)	**Distance along beam** (m)	**SODAR measured wind speed** (m/s)	**SODAR corrected wind speed** (m/s)
200	6.4	283	1.3	2.0
170	n/a	240	3.7	5.6
140	6	198	2.6	4.2
80	5.7	113	0.7	1.2
40	4.4	57	1.0	1.9
20	2.9	28	0.1	0.3
10	2	14	-0.3	-0.6

We also found that fixed echoes in both measurements affected the data (in the direction of 340 degrees). This could not be corrected by adjusting the tilt angle because the reflection was caused by the guy-wires, and these go up to high tilt angles as well. In the direction of 250 degrees the fixed echoes could be avoided by changing the tilt angle but in this direction the measuring beam was at right angles to the wind direction and therefore no good data could be measured either. Because of the vicinity of the mast and trees in all other directions no other tests were possible at the Cabauw site. A more open site would probably give better results. We also saw that the fixed echoes were not always detected by the SODAR software and that the fixed echoes also affected data below and above the altitude of the fixed echo.

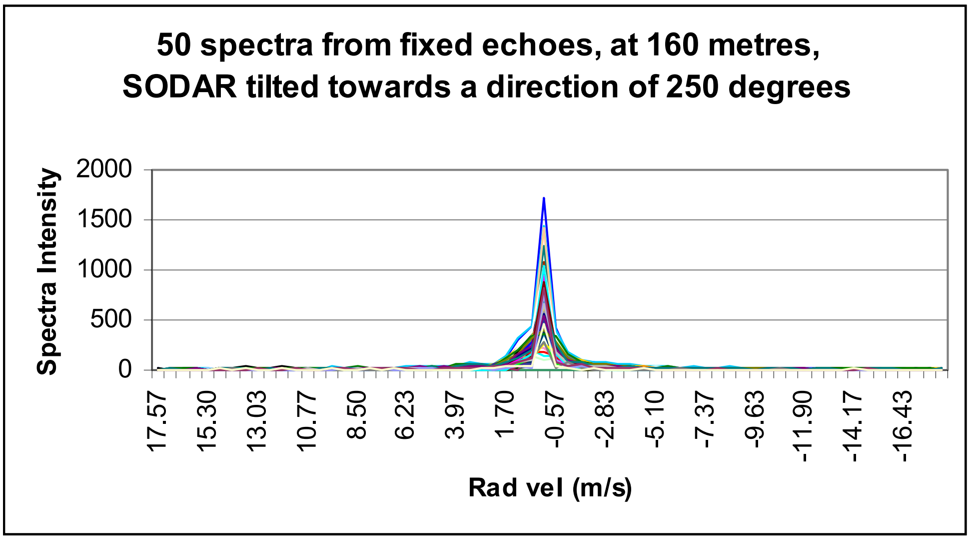

Figure 2: 50 subsequent spectra, each showing a clear peak at zero Doppler shift.

From a design perspective we have drawn the conclusion that operating an off-the-shelf, commercially available SODAR is probably not going to work at all for any normal wind speed range. Because the SODAR has been designed for operation in a vertical position, measurements with a tilt angle will always be affected and give data with less quality and for a much smaller wind speed range. A possibility to use the SODAR offshore close to a meteorological mast has been described, but if this will also work at the foot of a turbine can only be answered after further research.

2. INTRODUCTION

As part of the project SODAR Wind measurements Offshore (SWO), funded by Novem, the possible use of SODAR in an offshore wind park has been investigated. This question first came up during a previous Novem project “Mini-SODAR for wind energy applications, explorative experimentation” [Van Dam, 1999] (Novem project number 224.750-9857, ECN project number 7.4078).

During this project two main problems came up:
1. The SODAR is very sensitive for reflections from hard objects (buildings, turbine tower), especially when operated in a tilted position. To get measurements without echo from fixed objects, the tilting angle has to be very well under control and has to be adjusted as needed, with a resolution of one or two degrees.
2. The SODAR did not return any wind speed results in a tilted position. As these measurements were only explorative measurements the SODAR settings were not well understood. However, attention should be given to adjust these settings in such a way that normal wind speed results are measured.

The main goal of this project is to establish if measurements with a normal of-the-shelf SODAR can be operated in tilted position. A possible use of the SODAR would be to use the SODAR at the foot of a wind turbine in a tilted position. Before this is done it should be established that wind speed data can be obtained from a SODAR in tilted position. Another application could be to have a SODAR on top of a wind turbine, looking upwind, with a tilt angle of 90 degrees. Instead of a vertical beam the SODAR now operates in a horizontal direction. Whether such applications are possible is investigated in this project.

The first step in the SWO project is to solve the problems with adjusting the tilt angle and to make sure that the SODAR settings are such that data is retrieved. After this has been done successfully some measurements will be done to measure wind speeds in tilted position and compare these to data from the mast. The above mentioned problems have been addressed and the results will be reported here. This report has the following set-up:

- Overview of the tilting of the SODAR and how this has been achieved
- Discussion of the settings used during the tilted measurements
- Discussion of the results of the tilted measurements
- Discussion of problems inherent in operating a SODAR in tilted position
- Discussion of the use of SODARs at the base of an offshore mast or turbine

3. SODAR TILTING

The tilting mechanism consists of three separate parts:
1. One part is the fixing rod, which is a long metal rod to create a fixed distance for the ground plate and the support rod so it does not slip.
2. The second part is a ground plate with a hinge so that the support rod can be fixed to the ground plate under various angles. The ground plate stops the support rod from being pressed into the ground.
3. The third part is the support rod itself, which is a rod with a thread. On the thread is a nut with handles. The rod supports the SODAR when it is in tilted position and the thread allows the tilting angle to be changed with very small increments. The minimum increments are not defined by the thread but by the measuring equipment used to determine the tilt angle.

The fixing rod is fixed to the base of the SODAR and to the ground plate. The support rod is fixed to the top of the SODAR with one end, and the other end is connected to the ground plate. By turning the nut of the fixing rod a gradual change of the tilting angle can be made. When the nut has reached the end of the thread the distance between the ground plate and SODAR can be changed by changing the length of the fixing rod (a number of holes are made by which the fixing rod can be attached to the ground plate).

In this manner two persons can create tilt angle between 30 and 75 degrees. The system is based on gravity pull, so it only works when the SODAR has first been tilted past the dead point. However tilting angles up to 23 degrees can be made during normal operation, so only angles larger than 77 degrees are interesting. After the SODAR has been tilted the angle is determined with a digital level, and small changes can still be made to get the required angle of tilt.

Figure 3: SODAR tilted towards a direction of 340 degrees

In figure 3 the first successful attempt at getting data from a SODAR in tilted position is shown, and the SODAR has been tilted towards a direction of 340 degrees. In the distance along the line of sight of the SODAR the guy-wires for the Cabauw mast can be seen.

Figure 4: SODAR tilted towards 250 degrees

In figure 4 a different direction was tried to avoid echoes from the guy wires, by tilting the SODAR towards 250 degrees.

Figure 5: View along the line of sight of the SODAR when tilted towards 250 degrees. A small building can be seen in the distance.

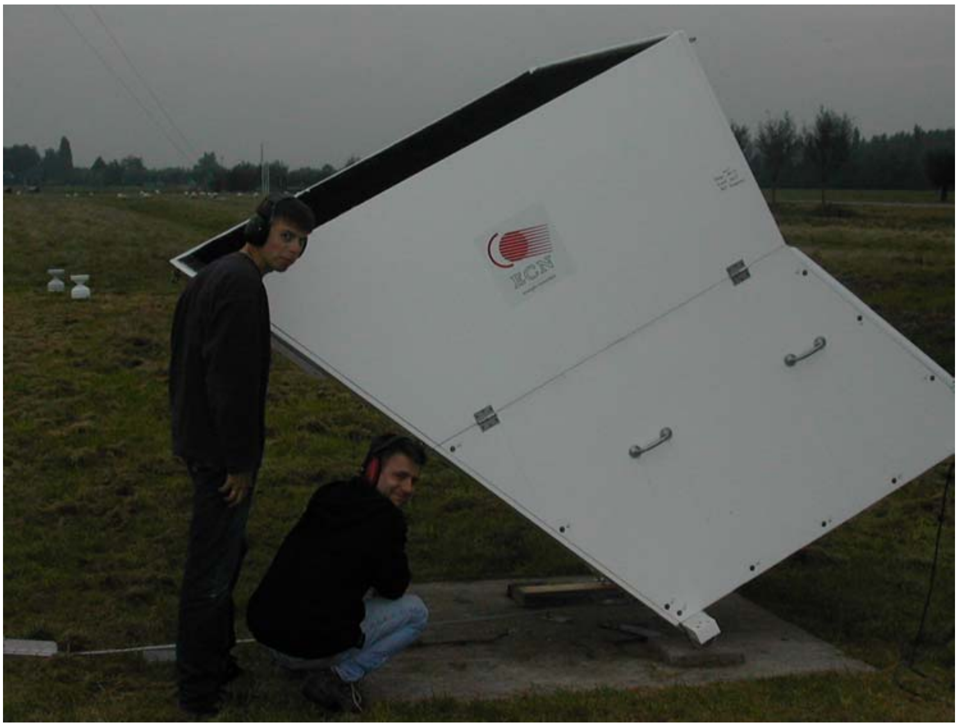

Figure 6: ECN personnel working on tilting the SODAR

Figure 7: A measurement of the tilting angle is taken with the digital level.

4. SODAR SETTINGS DURING TILTING

As seen in the previous Novem project, the SODAR has its own algorithm to decide if the measurements are reliable. If this algorithm deems the measurements of insufficient quality, then no results are reported, which is represented with the number 99.99 in the wind speed table. During the previous attempt by Jeroen van Dam and Erwin Werkhoven the SODAR only produced wind speed tables with 99.99 values and no real wind speeds were measured. Although Aerovironment (the manufacturer of the SODAR) was certain that he could adjust the settings in such a way that the SODAR would produce results, Aerovironment did not communicate the solution to van Dam and Werkhoven, who then had to end the measurements without satisfactory results.

The first step in trying to find out the correct settings for the SODAR to make it operate in tilted position was to contact again Aerovironment, this time at an early stage of the project. Again we were promised a solution soon, and again nothing has been received. To get measured wind speed results instead of 99.99 ECN personnel had to investigate which combination of settings would work.

The problem with this is that there are over 100 software settings (parameters), which can be changed independently. The following three effects complicate matters:

1. some of these settings are mutually dependent (which has not been documented by Aerovironment),
2. the influence of the parameters on the quality control algorithm is badly documented
3. we have found that the documentation that exists is sometimes inaccurate, especially with regard to the quality control algorithm

It is possible that the documentation is kept vague on purpose as the ability to produce data of high quality (and therefore the quality control algorithm) can be regarded as a company secret and can therefore not be documented extensively. Whatever the reason is, these documentation problems mean that finding a working combination is more a trial and error process than a straight forward logical process based on technical documentation.

In the table below the settings we have arrived at (with the trial and error process) are shown next to the recommended settings by Aerovironment. These recommended settings were given for normal operation (i.e. not tilted) for the 3000 array. These settings have been adapted for the 4000 array with information from Aerovironment (frequency, reflector enclosure, and altitude-increment). The main differences with the recommended settings are as follows:

- The number of beams used has been decreased from 2 to 0 (0 means one beam, 2 means three beams). Only the Z beam (normally vertical) is used.
- Radial velocities have been increased from 4 m/s to 6 m/s for the Z beam, as the SODAR is tilted a higher velocity than normal can be expected on the Z beam, where as normally the vertical wind speeds are low.
- The maximum vertical wind speed has been set to 10 m/s (this is a different settings than the radial velocity).
- The analogue bandwidth has been increased from 600 to 800, also to allow for higher wind speeds on the Z-axis.
- The total span has been increased; recommended was 40 to 200 metres, and this has been increased to a span of 10 to 350 metres. If there is data present in the signal it will be measured.
- Signal to noise threshold has been reduced from 7 to 5, to increase the chance of getting a signal. The quality of the signal may be worse, however.

Table 2: Settings overview for tilted operation

Location		Cabauw **Recommended settings by Aerovironment adapted for 4000 array**	Cabauw **Final settings used with tilted angle**
Sodar Pro version		5.22	5.22
Met Sampling			
Maximum Altitude	Mht	200	350
Altitude Increment	Avdst	10	10
Averaging Time	Sec	60	60
Wind Gust detection interval	Ngav	5	5
Percent acceptable data	Gd	5	5
W Magnitude Threshold	Wmax	400	1000
Temperature Table	Degc	10	10
Minimum Altitude	Min Alt	40	10
Digital Sampling			
Digital sampling rate	Srate	960	960
Number of FFT points	Nfft	64	64
Signal-to-Noise threshold	Snr	7	5
Amplitude threshold	Amp	7	15
Adaptive noise threshold	Back	-120	-120
Analog bandwidth	Bw	600	800
Clutter rejection	Clut	6	6
Noise time constant	Nwt	1	10
Days to archive on ASP disk		n/a	n/a
SODAR parameters			
Audio amplitude	Damp	80	80
Pulse length	Pulw	110	110
Pulse transition time	Rise	20	15
Operating frequency	Freq	4500	4500
Antenne rotation angle	Ptdir	340	340
X beam (antenna) tilt angle	TiltC	15	15
Y beam (antenna) tilt angle	TiltB	15	15
Number of beams	Axes	2	0
Reflector enclosure	Refl	Y	Y
M4000 Antenna		Y	Y
M3000 Antenna		N	N
DOPPLER Limits			
X axis min radial vel	Mincr	-800	-1200
X axis max radial vel	Maxcr	800	1200
Y axis min radial vel	Minbr	-800	-1200
Y axis max radial vel	Maxbr	800	1200
Z axis min radial vel	Minar	-400	-600
Z axis max radial vel	Maxar	400	600
Peak detection limits	Nbini	5	5
Raw Data			
Data collection axes	Specm	7	0
Lowest sampling range gate (0 based)	Specs	4	2
Number of sampling range gates (0 based)	Specl	15	40
Sampling range gate (0 based) increment	Speci	1	2
Number of pulses per sample	Specn	-1	0
Facsimile Data			
Sampling height resolution	Cdid	10	10
Number of pulses averaged	Cdin	2	2
Layer detection threshold (milliVolts)	Cdia	0	n/a

The amplitude threshold and noise-time-constant have also been changed but these changes are inconsequential for the tilting measurement. Also the changes in the raw data collection and facsimile data are of no importance.

With our increased understanding of the operation of the SODAR and when using the settings as above, we were able to overcome the previous problems of not measuring any data at all and only getting values of 99.99 in the wind speed table.

5. RESULTS OF MEASUREMENTS WITH SODAR IN TILTED POSITION

After finding settings that gave data, two measurements were done with these settings. Both measurements were done with a tilt angle of 45 degrees from the vertical. Only the W beam was used during tilted measurements.

As the measurements were done over relative short periods of time (ECN personnel had to stay near the equipment during the measurement) the average values for wind speed and wind directions from the Cabauw mast are accurate enough to compare the SODAR data with.

These values can be found in table 3.

Table 3: Average values from Cabauw mast for tilted measurements one and two.

	First measurement	**First measurement**	**Second measurement**	**Second measurement**
Altitude (m)	**Cabauw wind speed** (m/s)	**Cabauw wind direction** (deg)	**Cabauw wind speed** (m/s)	**Cabauw wind direction** (deg)
200	6.4	160	7.3	190
140	6.0	154	7.0	181
80	5.7	146	6.1	165
40	4.4	139	4.6	148
20	2.9	130	3.2	138
10	2.0	126	2.4	134

The first measurement was done with a 45-degree tilt angle from the vertical towards a direction of 340 degrees. All measurements done in this direction gave results similar to those in the following figure.

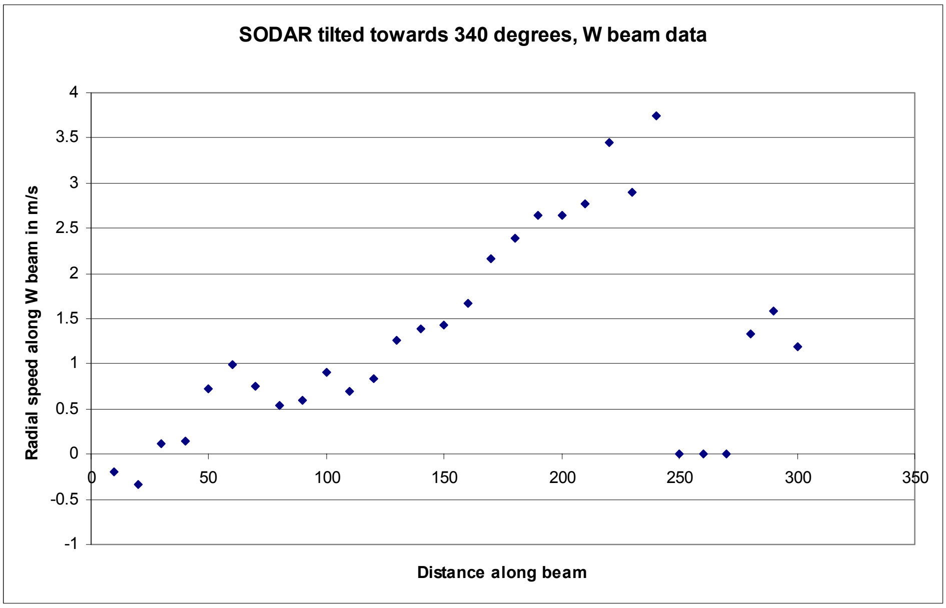

Figure 8: Radial velocities along the W beam with a 45-degree tilt angle.

For the first measurement with the tilt angle the comparison with the Cabauw mast is summarised in table 4.

Table 4: Cabauw and SODAR wind speed compared for the first measurement, tilted towards 340 degrees. SODAR wind speed is corrected for the tilt angle and the difference between the measurement direction and the wind direction.

Cabauw altitude (m)	**Cabauw wind speed** (m/s)	**Distance along beam** (m)	**SODAR measured wind speed** (m/s)	**SODAR corrected wind speed** (m/s)
200	6.4	283	1.3	2.0
170	n/a	240	3.7	5.6
140	6	198	2.6	4.2
80	5.7	113	0.7	1.2
40	4.4	57	1.0	1.9
20	2.9	28	0.1	0.3
10	2	14	-0.3	-0.6

Conclusions from table 4 are that the SODAR is too low in the wind speed measurement. The values for 170 metres has been added to compare this value to the Cabauw measurement of 140 and 200 metres. The reason that the SODAR measurement for 170 metres has been added is that the SODAR suffers from fixed echoes. As can be seen in figure 8 the measurements at a radial distance of 250 to 270 metres are at zero; this is because the SODAR did not give a value for this altitude. All the data in measurement one misses the points around a radial distance of 250 metres. Therefore the last value before the fixed echoes at an altitude of 170 metres has been reported. What can also been seen is that the data (if not affected by fixed echoes) does correlate with the Cabauw data, i.e. both show an increase in wind speed with altitude between 10 and 170 metres.

What is also clear is that the SODAR does not recover after altitude with the fixed echo. Below the fixed echo there is a clear increase of wind speed with altitude, but after the echoes the measured wind speeds are lower in value. From the tower data we know that the real wind speed was in fact higher in value, and the discrepancy is attributed to the fixed echoes. If the same fixed echoes also affect the signal t lower altitudes (by decreasing the measured wind speed) is unknown but not impossible. The quality control algorithm of the SODAR has determined that there are fixed echoes between 250 and 270 metres, but this does not mean that there are no effects at lower or higher altitude. In fact it is very likely that there is an effect also below the fixed echoes.

To get more information about the fixed echoes a spectral measurement has been done, which is the recommended method [Warmbier, 2002] to determine fixed echoes.

A general result of such a measurement is presented in figure 9. The large peak at zero Doppler shift (which gives a wind speed of zero) is obvious. A strong indication for fixed echoes is if this peak stays at the same position during subsequent measurements. This has been plotted in figure 10. From these figures at is obvious that the SODAR data is suffering from fixed echoes. After finding these fixed echoes we have checked which object was making these echoes and it appeared that at a distance of about 270 metres the guy-wires of the Cabauw mast were in the sound beam (see figure 3). Most likely the fixed echoes were from these guy-wires.

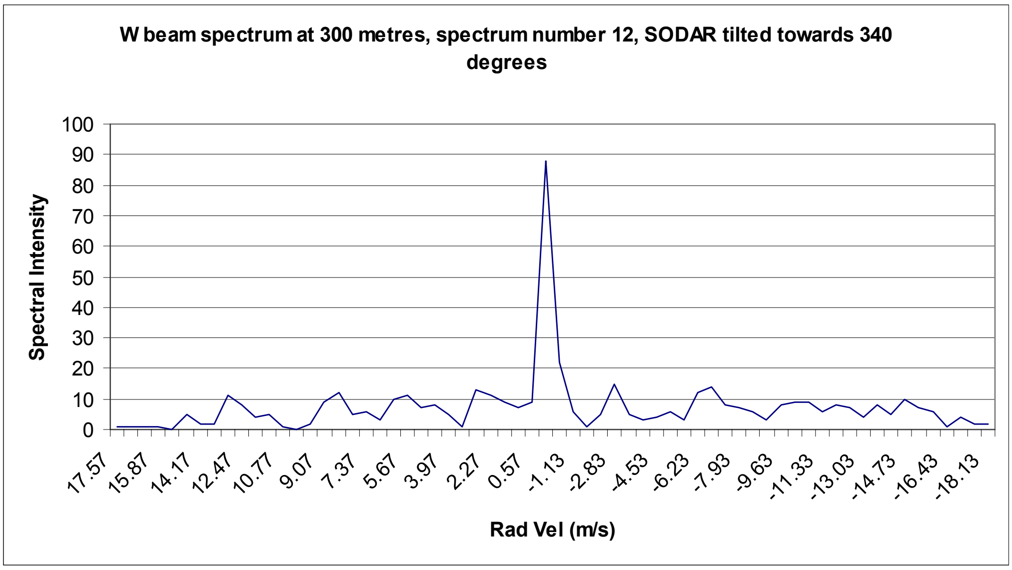

Figure 9: Spectrum of the twelfth spectrum during the first tilted measurement, direction 340 degrees.

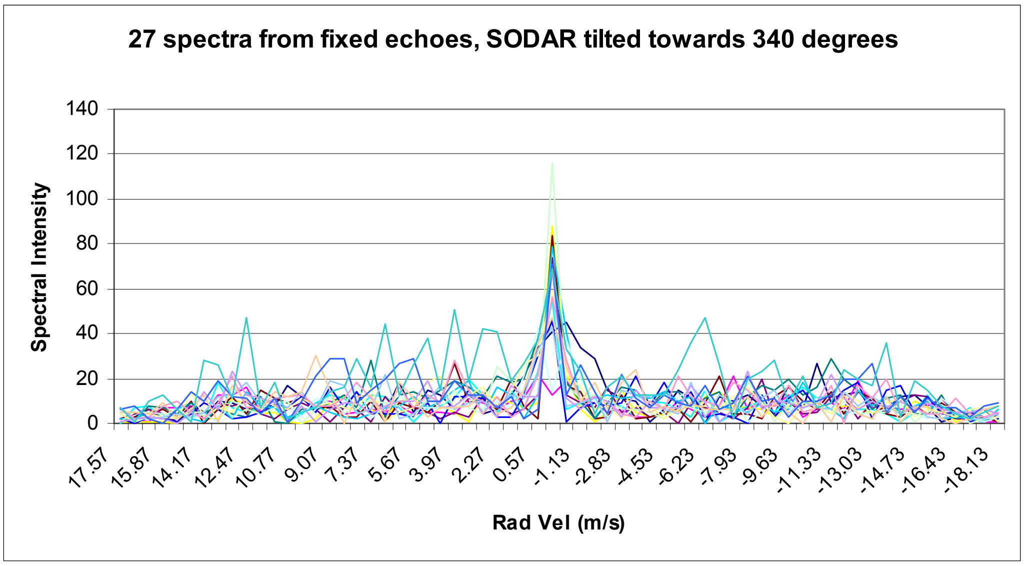

Figure 10: 27 subsequent spectra showing a clear peak at zero Doppler shift.

After finding these fixed echoes in the beam a second measurement was done towards a direction of 250 degrees with respect to North. This was the only direction that was left as all other direction than 340 and 250 were either towards the Cabauw mast or towards rows of trees.

The measurement in the direction of 250 degrees had an angle with the wind direction of 60 to 100 degrees depending on the altitude. This means that wind speed comparisons are very difficult as the SODAR beam picks up only a small fraction of the wind speed.

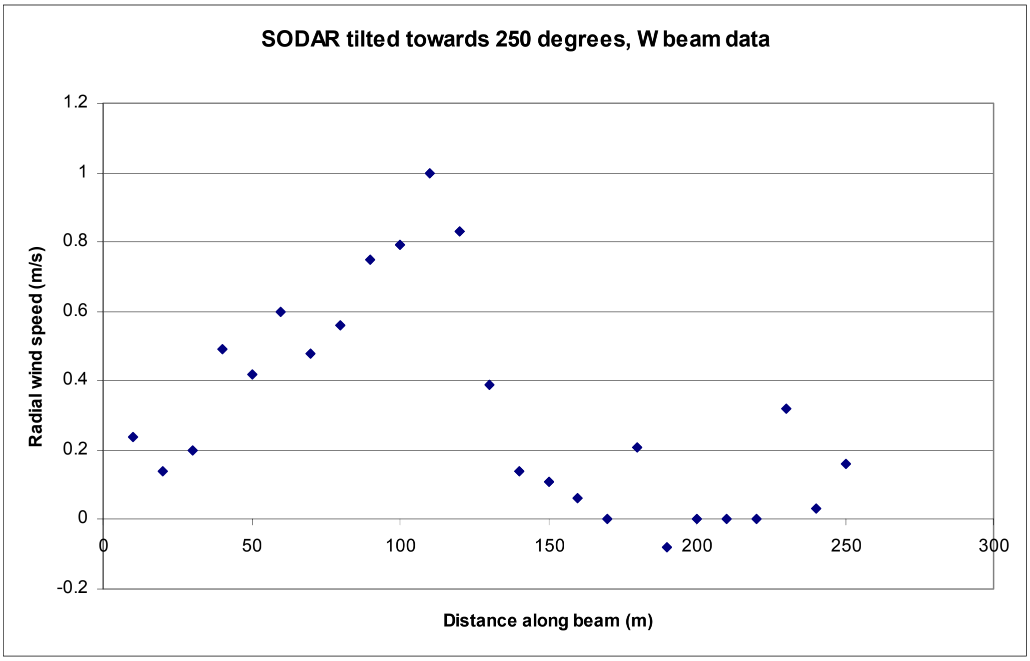

Figure 11: Radial velocities along the W beam with a 45 degree tilt angle.

The comparison for the second measurement is presented in table 5:

Table 5: Cabauw and SODAR wind speed compared for the second measurement, tilted towards 250 degrees. SODAR wind speed is corrected for the tilt angle and the difference between the measurement direction and the wind direction.

Cabauw altitude (m)	**Cabauw wind speed** (m/s)	**Distance along beam** (m)	**SODAR measured wind speed** (m/s)	**SODAR corrected wind speed** (m/s)
200	7.3	283	NaN	NaN
140	7	198	-0.08	-0.32
80	6.1	113	1.00	16.23
40	4.6	57	0.60	-4.08
20	3.2	28	0.20	-0.76
10	2.4	14	0.19	-0.61

In table 5 can be seen that the highest altitude has not been measured by the SODAR. The reason for the low wind speed at 140 metres is a fixed echo, which will be presented in more detail below. The values for 80 and 40 metres are the correct order of magnitude but have a high uncertainty due to the large correction for the angle between beam and wind direction. The multiplication factor is roughly 16 and 7 times for 80 and 40 metres respectively and the result is only an approximation of the wind speed. The values for 40, 20 and 10 metres are negative, which is correct, as the angle between the measurement direction and the wind direction becomes larger than 90 degrees.

Also in this measurement fixed echoes influenced the SODAR measurements. During the whole measurement no data was measured between 200 and 220 metres radial distance and above 260 metres.

What is more interesting however, is that all profiles gives a value of less than 0.03 m/s at 170 metres, but the data is not indicated as unreliable. In this case it seems that the quality control algorithm of the SODAR did not function well.

The difference can be seen clearly in the next table, which shows the W beam data for one profile. Values of 99.99 have been converted to NaN (not a number).

Table 6: Profile of W beam on 02/10/02 at 16:52 to 16:53

Distance along beam (m)	W beam radial velocity (m/s)	Intensity of W beam	Number of good returns for W beam	Signal to noise ratio of W beam
(m)	(m/s)	(mA)		
350	NaN	135	0	3
340	NaN	126	0	5
330	NaN	135	0	4
320	NaN	135	0	4
310	NaN	136	0	5
300	NaN	140	0	3
290	NaN	142	1	3
280	NaN	137	0	3
270	NaN	141	1	5
260	NaN	111	0	6
250	0.16	132	6	5
240	0.03	129	8	5
230	0.32	97	2	41
220	NaN	77	0	3
210	NaN	78	0	4
200	NaN	83	1	5
190	-0.08	92	7	5
180	0.21	89	7	5
170	0	237	13	8
160	0.06	750	13	13
150	0.11	731	13	13
140	0.14	123	9	4
130	0.39	59	2	3
120	0.83	69	10	4
110	1	95	13	7
100	0.79	126	14	8
90	0.75	222	13	11
80	0.56	239	13	12
70	0.48	255	13	15
60	0.6	318	15	14
50	0.42	415	21	16
40	0.49	397	20	15
30	0.2	883	26	16
20	0.14	2383	26	17
10	0.24	1957	26	14

In this table can be seen that the intensity at 160 metres is very high compared to neighbouring values, but that the data is not set to NaN. The data at the next level (170 metres) becomes zero although the peak in intensity is at 160 metres and already at 140 metres the intensity starts to rise. In this way fixed echoes can influence large parts of the measurements, and they are especially insidious if the SODAR does not detect the fixed echoes and reports zero wind speed. This is why a skilled SODAR operator is needed to assure good quality of SODAR data.

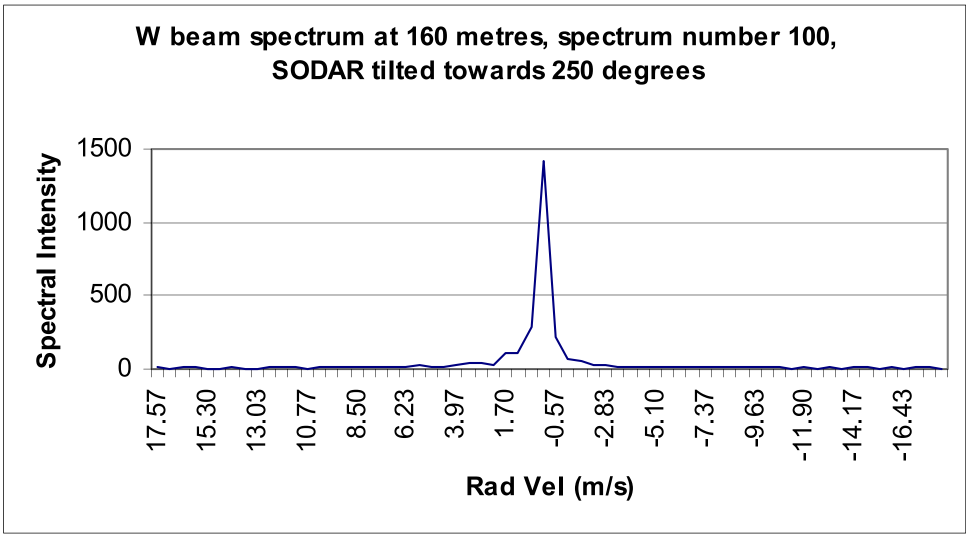

Figure 12: Spectrum of the twelfth spectrum during the second tilted measurement, direction 250 degrees.

These peaks are very stable, as can be seen in the next figure.

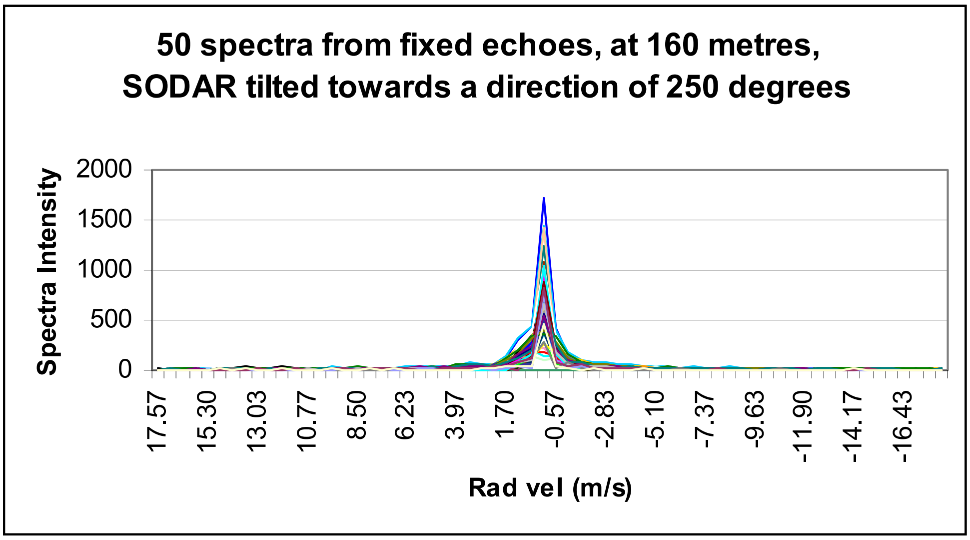

Figure 13: 50 subsequent spectra, each showing a clear peak at zero Doppler shift.

In the data (see figure 11) can be seen that not only there is a zero value at 170 metres, but the data from 130 to 190 metres distance along the beam is affected and lower values are reported. Also from 230 to 250 the data is extremely low and this is probably also caused by fixed echoes.

As can be seen in figure 5 there is a small building at a distance of 160 metres, which is the cause of the fixed echoes. The cause of the NaNs at 200 and 260 metres is not immediately obvious. Either this is caused by other structures farther away (other buildings in the background, the line of trees) or there is a residual effect in the electronics from the very strong reflection of the building at 160 metres.

To finish the measurements some different angles were tested with the SODAR tilted towards 250 degrees. The test was to see if a change in tilt angle would decrease the fixed echoes from the building. In the following table an overview of tilt angle against maximum spectral amplitude is presented.

Table 7: Tilt angle against spectral intensity.

Tilt angle	Spectral intensity
degrees	
45	1026
56	152
60	12

From these measurements can be seen that a careful adjustment of the SODAR tilt angle is very important, as it can decrease the effect from fixed echoes. This test was done with the SODAR tilted at 250 degrees as the top of building was at a lot lower angle than the guy-wires from the mast and therefore there was more chance of a decrease in fixed echo with increased tilt angle. Further measurements of the wind speed were not useful due to the fact that the wind direction was almost at square angles with the beam direction so that no good wind speed measurements could be done.

As a result of these measurements it is clear that the SODAR can produce data when tilted under an angle, with the settings as described in chapter 3. A well adjustable tilting mechanism with small resolution (as documented in chapter 2) is also important to decrease fixed echoes. Normally fixed echoes are from objects on the ground (such as the building during the second tilted measurement) and we have shown that choosing a good tilt angle can reduce these fixed echoes.

Due to the nature of the site at Cabauw (mast with guy-wires, trees and buildings around) all the measurements suffered from fixed echoes but better results are expected when the horizon is more open and if the SODAR is therefore not affected by fixed echoes.

6. INHERENT PROBLEMS WHEN USING A SODAR IN TILTED POSITION

When this project was started the main focus was to solve the technical problems encountered during previous attempts to operate a SODAR in tilted position and to compare measurements in tilted position to data from the Cabauw mast.

However, during the work we have done with the SODAR in the SWO project our understanding of the SODAR increased and as a result a number of theoretical problems with the whole approach became apparent.

- One very large problem with having a SODAR tilted at 45 degrees or even at 90 degrees is that of the side lobes. In normal operation the sound beam is reflected by turbulence in the atmosphere. There may also be hard objects around (trees, buildings) that give a much stronger reflection and can be considered "perfect reflectors". Normally, with the SODAR in vertical position the SODAR design ensures that side lobes of the main sound beam at low angles (i.e. below 70 degrees from the vertical) are at least 40 dB weaker than the main beam. Even if there are perfect reflectors the signal from the hard reflectors is still a lot weaker than the main beam. Add to this the fact that the signal from the perfect reflectors is further weakened by the SODAR baffles (extra shielding on the sides of the SODAR with acoustic foam). This gives a total picture with a viable situation for the SODAR, as the signal from hard reflectors is sufficiently smaller than the signal from turbulence to be able to do measurements.

  As soon as the SODAR is being tilted two effects make the situation worse:
  1. The protection by the baffles depends on the angle from the vertical. How larger the angle with the vertical is, the less the baffles protect against echoes from fixed objects close to the ground (or from echoes from the ground itself).
  2. The side lobes are more and more suppressed when the angle with the main lobe increased. By tilting the SODAR more and more side lobes can produce echoes from fixed objects, and these side lobes also get increasingly stronger.

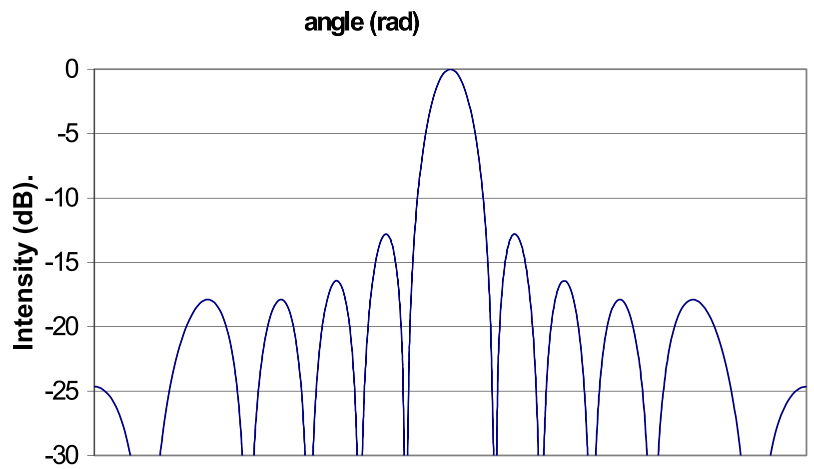

Figure 14: Side lobes of the SODAR sound beam, with the main beam in the middle.

- Also the hardware design is a problem. In the design is built in that the SODAR operates in a vertical position. Switching to a tilted position can give good data, but the wind speed range for this data is very limited. There are three reasons for this:
  1. This is because of the hardware limits of the bandwidth where the measurement takes place. As this limit can not be changed in an off-the-shelf SODAR this also limits the wind speed range that can be measured.
  2. Further decreasing the angle of the beam with regards to the wind vector also reduces the maximum wind speed range. For instance if we take a horizontal wind from North to South this can be measured by pointing the U beam in this direction. The measured wind speeds depend on the angle of the beam and the Doppler shift:

$$u = -\frac{\Delta\omega_1}{2k\sin\theta} - \frac{w}{\tan\theta} \tag{1}$$

$$v = -\frac{\Delta\omega_2}{2k\sin\theta} - \frac{w}{\tan\theta} \tag{2}$$

$$w = -\frac{\Delta\omega_3}{2k} \tag{3}$$

     where u, v and w are orthogonal wind speeds in m/s,
     $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3$, are the Doppler shifts for the u, v and w beams, respectively,
     k is the wave number,
     θ is the angle the sound beam makes with the wind. For a SODAR in vertical position this is 16 to 23 degrees (depending on SODAR model).

     From the above formulas it can be seen that the term with the sine will increase as θ goes from 16 to 45 to 90. The Doppler shift is limited by the hardware design, and so for larger tilt angles smaller maximum wind speeds can be measured.
  3. The third reason why the wind speed is limited in tilted position is that the settings for tilted operation only use one beam. In normal operation a horizontal wind speed can be made by adding wind speeds along U and V beam, so that the maximum wind speed is $\sqrt{2}$ times the maximum per beam. This factor is lost when only using one beam.

- Another problem with the hardware design is that there should be no wind pressure on the sound transducers. If the wind is directly blowing against the speakers this will affect the measurement and produce unreliable data.

- The reaction time is problematic, especially if the tilted SODAR should be used for gust detection. The idea is that the SODAR detects a strong oncoming gust and gives a signal to the turbine control, so that the turbine can react before the gust actually hits the turbine. If we take a gust of 30 m/s as an example, then we get the following picture. If we use a 4000 model SODAR we know that 70% of the time an altitude of 150 metres is reached [Ormel 2002]. If we take this 70% as sufficiently reliable to see gusts, then one pulse might “detect” the gust at a distance of 150 metres. The pulse returns after 0.5 seconds, then the data has to be analysed, the turbine control has to be warned and the turbine has to react. If we assume all this can happen in two seconds, then there still is 2.5 seconds before the gust hits. This is the optimum situation.

To measure at 150 metres, the maximum height has to be set higher, for instance to 200 metres. With one beam this gives a repetition rate of 1.5 seconds per pulse. So it is possible the gust is detected 1.5 seconds later than as optimum. Further the SODAR either operates at the foot of the turbine at an angle of 45 degrees, or on top of the turbine at an angle of zero degrees. At the foot of the turbine the reaction time is decreased with $\sqrt{2}$, which is 0.6 seconds. At the top of the turbine the SODAR has to wait for blades passing when sending the beam, and also the returned beam will be affected.

Finally, the data acquisition will be worse than normal, as the analysis has to be done per pulse whereas normally this is done per 10 minutes. Averaging pulses together increases the data, and this improvement is now lost. Expert opinion however suggests that the minimum number of averages would be 10 averages. This means that by the time the gust has been detected it is already at the turbine.

Tilting a SODAR has been done before on three occasions [Bradley, 2003]:

1. Some Russians have done tilted measurements on a high cliff face, and were successful in their attempts. It is unknown what type of SODAR they used but most likely it was not a standard model that are commercially available these days.
2. Aerovironment has done some measurements with a SODAR on or near a wind turbine. The SODAR was pointing upwind in a horizontal direction. To limit negative effects from fixed echoes and wind pressure on the speakers the SODAR hardware had been adapted to operate in a horizontal position. The measurements have not been reported.
3. Professor Bradley from the University of Salford has done measurements with an Aerovironment SODAR in horizontal position with the beam pointing over a large area of water. Although the water makes the fixed echoes less diffuse, the results were not good.

All in all there are so many problems that it is clear these problems will not be solved in the contact of the SWO project. Either the concept has to be re-thought or much more emphasis should be put on adapting the SODAR for horizontal operation and not rely on standard hardware.

7. POSSIBILITIES TO USE A SODAR IN AN OFFSHORE WINDPARK

Although the measurements done with a SODAR in tilted position were successful, our increased understanding of the SODAR has lead to the conclusion that tilting the SODAR is a lot more complex than previously assumed. For the moment there is no clear understanding if and how a SODAR could be used in an offshore wind farm in tilted position.

This still leaves the question how SODARs can be used offshore, as offshore masts are expensive, and the costs increase exponentially with height [Ormel, 2002]. Of course it is possible to create a platform just for the SODAR, but this costs a lot of money and we tried to find a solution that would give better results.

We have contacted Professor Bradley from the University of Salford, to see if we could come to a useful approach. With a lot of input from Professor Bradley, we have come up with the following suggestion to use SODARs offshore.

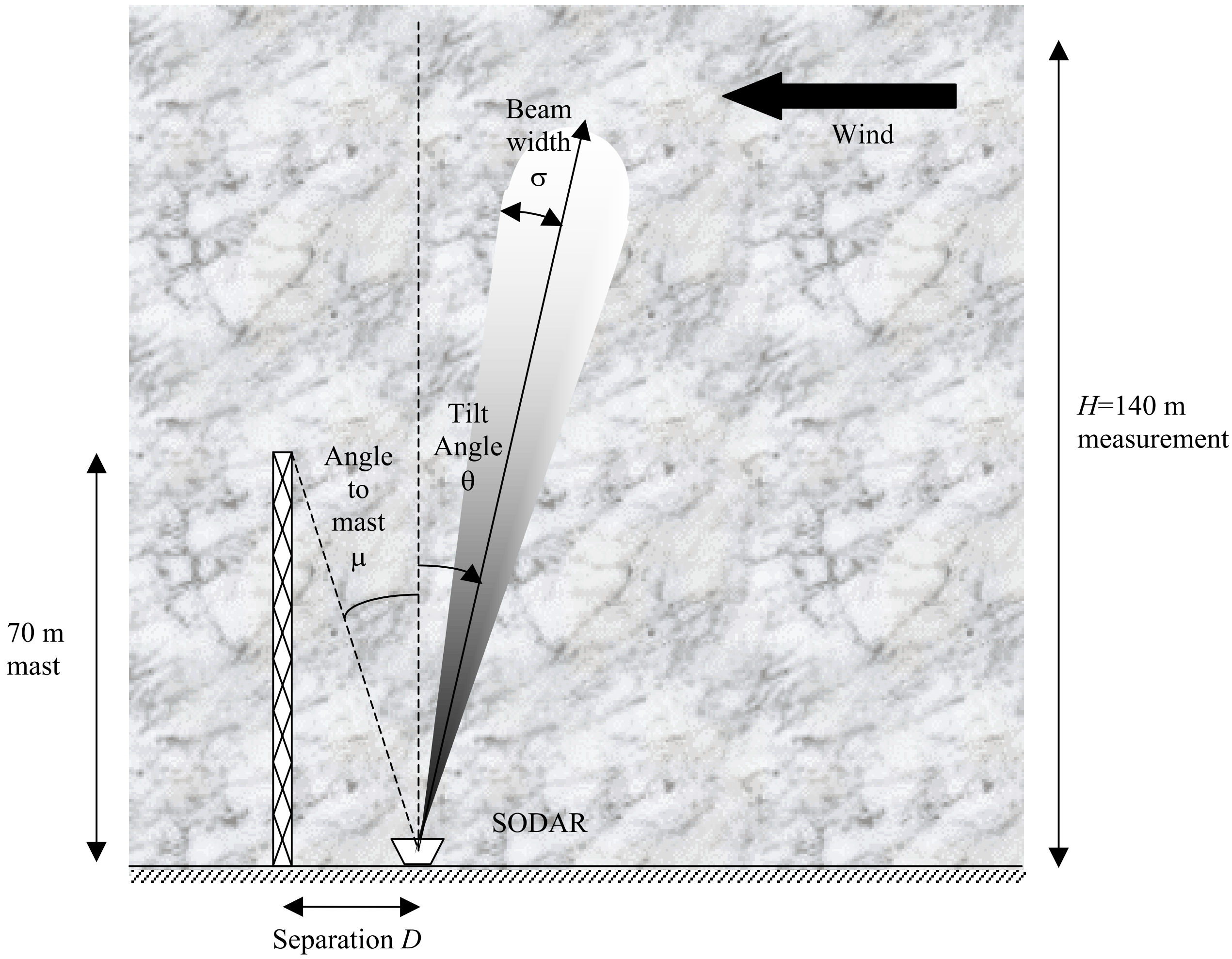

Figure 15: Schematic of an Aerovironment model 4000 SODAR

The figure above shows an AV4000 SODAR operating at horizontal distance *D* from the base of an instrumented mast. It is assumed the mast is near a wind turbine.

Typically, the tilt angle for an AV4000 is $\theta = 16°$ from the vertical, and the beam width angle $\sigma = 6°$ on either side of the beam axis. In practice, two beams will be used, tilted in planes at 90° (e.g. one could be toward the North and the other toward the East, but both only 16° off vertical). In this configuration, both beams are directed away from the mast, minimising acoustic reflections from the mast. The two-beam configuration gives estimates of two horizontal wind components, but no vertical wind is obtained. Typically vertical winds over the sea are a few cm/s: any vertical wind will give an error in the estimated horizontal wind but in practice the vertical wind would need to be about 15 cm/s to produce a detectable error. It is unlikely that such a high vertical wind will occur near the sea surface except in storm conditions (e.g. thunderstorm downdrafts).

If the SODAR is for instance D = 5m from the 70 m mast, then the angle between the tilted beam axis and the line from the SODAR to the top of the mast is $\theta + \mu = 16° + 4° = 20°$. The SODAR acoustic baffles intercept sound which is more than about 10° off-axis, so any sound reaching the mast will be mainly from diffraction over the top of the baffles, but the reflection from this source could still be significant compared with the very weak reflections from turbulence. However, experience operating near several very different 35m masts has shown no problems providing the mast is not of heavy construction (i.e. of large cross-section). In fact, the strongest mast reflection may be from sound leakage through the baffles and from the back of the speaker enclosure: in this case there would be signal loss for the lowest 5-10m. Note that any reflections from a mast structure are likely to be much less significant than the usual unwanted echoes from nearby buildings, since the mast structure is largely empty.

In summary, the geometry of an AV4000 SODAR distance 5m from a 70m mast, and using acoustic beams tilted away, appears to give a reasonable margin to avoid signal contamination from mast reflections. In addition, field experience with both low frequency and high frequency SODARs has demonstrated satisfactory operation within a few meters of 35m masts.

The mast data can be used to “calibrate the SODAR at an altitude equal to the top of the mast. The required height of the mast depends on the accuracy distribution of the SODAR with altitude (Research has shown that the measurement accuracy of the AV3000 and AV4000 SODARs depend strongly on the measurement altitude [Ormel et al, 2003]). Obviously, the mast should be as short as possible for commercial reasons. The AV4000 SODAR gives unreliable results at 20 metres, but from 40 to 80 to data quality is roughly stable and towards 140 metres the reliability gets worse again. If the required measurement heights are between 40 to 100, a 40-metre mast with an AV4000 can be used for this purpose.

The AV3000 is not reliable at 20 and 40 metres, but does very well at 80, 140 and 200 metres, although data loss is high at 200 metres. If measurements are needed between 80 to 200 metres, a solution with a 80-metre mast and a AV3000 would be the best option to perform these measurements reliably.

Depending on the platform of a turbine a similar solution may be possible by placing a SODAR in normal (vertical) position at the foot of a turbine. In this case only the U and V beams should be used because the W beam will be completely useless because of fixed echoes from the turbines and the blades. As final conclusion on this can only be taken after further research because of the following reasons:

1. The geometry of the problem is much more complicated than with a simple meteorological tower and the rotating blades give a shifting configuration as well.
2. The turbine has rotating blades (which can give fixed echoes that are not at zero Doppler shift over a large range in the spectrum, since across the blade span the speed of the blade ranges from zero to tip speed).

3. The noise production from the turbine itself can disturb the measurements.
4. The SODAR needs to be adapted as it is currently impossible to operate the SODAR with U and V beam switched on and the W beam switched off. The W beam must be switched off to prevent echoes from contaminating the spectra for the U and V beam.

8. REFERENCES

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