

Noise and Vibrations Measurements

External noise and vibrations measurements for offshore SODAR application

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Acknowledgement/Preface

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Abstract

The partners in the WISE project are investigating whether application of the SODAR measurement technique in wind energy experimental work is feasible as a replacement for cup anemometers, wind direction sensors and tall meteorological masts both from the view of accuracy and costs. In Work Package 2 of the WISE project extensive controlled experiments with the SODAR have been performed. For example, SODAR measurements have been compared with measurements from nearby masts and different brands of SODARs have been compared. Part of the work package is the measurement of vibration and noise on an offshore SODAR system. The results of these measurements are presented in this report.

ECN have performed measurements at an offshore location to investigate the influence of noise and vibrations on the performance of a MiniSODAR measurement system. The aim of the measurements was to quantify the effect of these external noise and vibrations disturbances on the MiniSODAR's performance. Measurements on an identical SODAR system onshore have been carried out to compare the disturbances of offshore and onshore external conditions.

The effect of background noise on SODAR operation has clearly been established in literature. Therefore, measurements have been performed only to establish the absolute background sound pressure levels. This has been done at the Measuring Platform Noordwijk (MPN) located in the North Sea, nine kilometres out of the coast at Noordwijk, The Netherlands, and at two locations onshore.

At the MPN-platform, the SODAR has been moved from the middle deck to the upper deck to diminish the influence of the diesel generator needed for the electric powering of the island. Although the absolute sound pressure level became higher at the new location, this level became lower at the most important frequencies inside the SODAR, due to the use of absorbing foam. With regards to the sound pressure level the move improved the situation. The sound pressure levels measured offshore were 6 to 15 dB higher than for the two locations measured onshore. Therefore, under offshore conditions a negative effect of the background noise on the SODAR measurements is expected.

The vibrations in the metal structure of the offshore island are expected to have an influence on the SODAR performance. The vibration measurements showed that the effects are negligible with regards to the normal SODAR measurement uncertainties.

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SUMMARY

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.
- Instrumentation of large masts is becoming increasingly difficult.
- Getting building permits for large masts is becoming very time consuming and sometimes impossible.

For these reasons, it would be advantageous to use MiniSODAR for these wind measurements. At the moment SODAR equipment can be bought commercially “off the shelf”. However, the SODAR is not yet an accepted device to be used for wind energy applications.

The general aim of the WISE project is to investigate whether application of the SODAR measurement technique in wind energy experimental work is feasible as a replacement for cup anemometers, wind direction sensors and tall meteorological masts. Measurements for wind energy applications such as power performance testing, load measurements and site assessment are standardised, carefully calibrated and controlled. Up to the beginning of the WISE project some trials with SODAR have been held but due to various reasons this has not resulted in the general acceptance of SODAR for wind energy applications. What is needed is development of a calibration technique for SODAR, a good understanding of SODAR operational characteristics and its limitations. Afterwards, SODAR should be tested by performing a power performance measurement including a rigorous uncertainty analysis. Also the operation of the SODAR in difficult conditions (complex terrain, offshore) has to be tested. The WISE project will attempt to do this and thus help to make SODAR an accepted method in the wind energy field.

In Work Package 2 of the WISE project extensive controlled experiments with the SODAR are performed. Part of the work package is the measurement of vibration and background noise on an offshore SODAR system. The results of these measurements are presented in this report.

ECN performed measurements at onshore and offshore locations to investigate the influence of background noise and vibrations on the performance of a MiniSODAR measurement system. These measurements are described chapter 2. The aim of the measurements is to quantify the effect of these external noise and vibrations disturbances on the MiniSODAR’s performance. Measurements on an identical SODAR system onshore are carried out to compare the disturbances of offshore and onshore external conditions.

The noise measurements are done at the Measurement Platform Noordwijk (MPN) location offshore and at two locations onshore. The SODAR has been relocated on the offshore platform. The background noise at these two locations is compared. From these measurements, it is recommended to limit negative effects of background noise offshore by performing noise measurements in advance and by choosing a position for the SODAR equipment based on these measurements. Because of the A-weighted filtering of the human ear, it is recommended to select the best position on an offshore island using instruments and not just by listening. The measurements show that the sound pressure levels were 6 to 15 dB higher than for the two locations measured onshore [7]. Research showed that background noise has a negative effect on the SODAR performance. Therefore, under offshore conditions a negative effect of the background noise on the SODAR measurements is expected.

The vibration measurements on the metal structure of the offshore island show that the effects of the vibrations are negligible with regards to the normal SODAR measurement uncertainties.

1. INTRODUCTION

SODARs are affected in their operation by the presence of background noise. This has already been reported by Crescenti [2]. In his article a number of different problems with background noise are reviewed. A distinction is made between active and passive noise sources as well as between broadband and narrow-band noise. For instance, noise from a car is active noise and the reflection of noise from a building is passive noise. Broadband noise is noise with random frequency such as heavy machinery. Narrow-band noise is noise with a fixed frequency such as the noise from birds. Another disturbance affecting SODAR operation can be the vibrations on offshore platforms. The placement of SODAR on these platforms provides less stable underground for the SODAR than placement onshore. In principle, the vibrations could influence the accuracy of the SODAR.

The offshore SODAR equipment (from Ecofys [5]) placed at the Measurement Platform Noordwijk (MPN), nine kilometres out of the coast before Noordwijk, The Netherlands, is provided with electricity from a diesel generator located elsewhere on the island. The SODAR may be influenced by active broadband noise from the generator and possibly by active narrow-band noise from seagulls and other birds that visit the island. The position of the SODAR on the MPN platform was such that no other object, with the exception of a 10 meter high meteorological mast, were located higher than the SODAR. For this reason passive noise sources were not expected to have an influence on the SODAR measurements.

In order to analyse the noise levels of the offshore SODAR equipment, two other SODARs have also been tested. One site is concerned with the KNMI meteorology mast in Cabauw, The Netherlands, (SODAR equipment of ECN, measurements performed by ECN) and at the Samlesbury military airfield, UK, (SODAR equipment of the University of Salford, measurements performed by ECN). The results obtained from the measurements at the three sites are presented in chapter 2.

1.1 Measurement locations

The vibration and background noise measurements on the MPN platform have been performed at two different locations and at two positions in each location.

Due to the presence of a diesel generator in the neighbourhood of the SODAR equipment, the exact location of the SODAR on the measuring island may influence the results obtained. Therefore, the SODAR equipment was moved from an 'old' location to a 'new' one. Figure 1 and Figure 2 show the 'old' location of the SODAR equipment. The SODAR was placed on the walkway. Figure 1 and Figure 3 show the 'new' location.

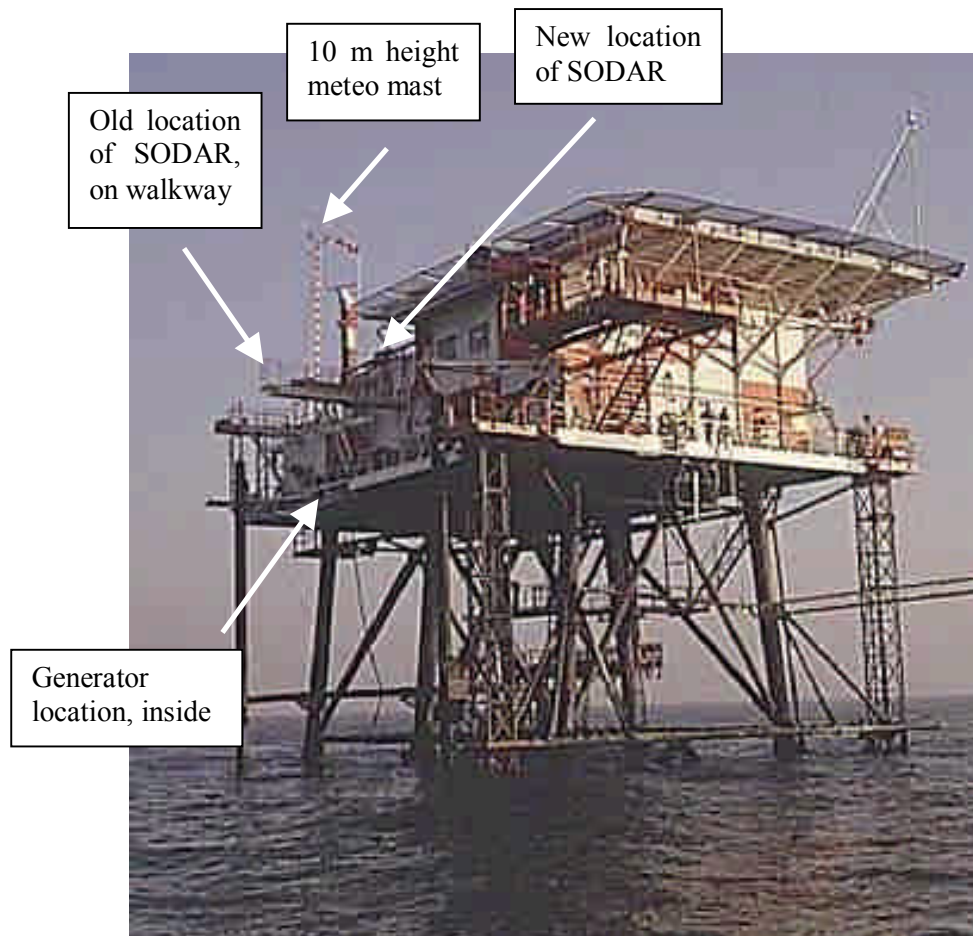


Figure 1. Southwest side of the MPN island



Figure 2. Old SODAR location, on the walkway.

Figure 3 shows the ‘new’ location for the SODAR. The old SODAR location is off to the left (not on the picture), and the lower part of the 10 metres meteorological mast can be seen just next to the SODAR.



Figure 3. New SODAR location.

2. BACKGROUND NOISE INFLUENCE

2.1 Overview of Measurements

For the background noise determination, measurements have been carried out at three locations:

- 1) MPN, an offshore island with a SODAR equipment from Ecofys [5] (AeroVironment 4000 model);
- 2) Samlesbury military airfield, near Manchester, with a SODAR equipment from the University of Salford (prototype AeroVironment 4000 model);
- 3) Cabauw, where a meteorological mast from the KNMI is placed, and where ECN operates a SODAR (AeroVironment 4000 model).

At these sites relevant measurements were performed (calibration measurements have not been listed in this report). Table 1 gives an overview of locations, dates and descriptions of eight measurements. The duration of the measurements and the sensitivity of the equipment (in Volts) have also been included.

Table 1. Overview of SODAR measurements for noise analysis.

#	Sitename and date	Description	Time (sec)	Sensitivity (V)	Remarks
1	MPN 08-04-02	Measurement next to generator	665	5	Measurement needed to establish the “fingerprint” of the generator.
2	MPN 08-04-02	Measurement at old SODAR position	665	2	Old location of SODAR was on a metal structure on the side of the island.
3	MPN 08-04-02	Measurement at new position, inside SODAR.	910	5	New location of SODAR is on top of the MPN-island
4	MPN 08-04-02	Measurement at new position, outside SODAR	910	5	New location of SODAR is on top of the MPN-island
5	Samlesbury 15-07-02	Measurement at Samlesbury airfield, outside SODAR	660	2	Measurement performed on an unused runway of the British army.
6	Samlesbury 15-07-02	Measurement at Samlesbury airfield, inside SODAR	660	2	Measurement performed on an unused runway of the British army.
7	Cabauw 30-09-02	Measurement at Cabauw, inside SODAR	600	2	Measurements next to a 213 m high meteorological tower
8	Cabauw 30-09-02	Measurement at Cabauw, outside SODAR	600	2	Measurements next to a 213 m high meteorological tower

All ‘inside’ measurements have been performed with the microphone hanging inside the SODAR casing. The microphone was located in front of the speaker array, to represent as good as possible the sound ‘heard by the SODAR’. Outside measurements have been performed with the microphone placed just next to the SODAR. During the measurements the SODAR equipment has been turned off. The following equipment was used:

Table 2. Equipment used during noise analysis of SODAR.

Site name	Equipment type:	Equipment model / number	Remarks
MPN	SODAR	Model 4000	
	Microphone	DEGL0436	
	Pre amp	DEGL0168	
	Amplifier	DEGL0202	
	DAT recorder	DEGL0200	Tape name: 08-04-02 MPN-1
	Calibrator	DEST0004	
Samlesbury	SODAR	Model 4000	prototype model
	Microphone	DEGL0432	
	Pre amp	DEGL0169	
	Amplifier	DEGL0202	
	DAT recorder	DEGL0200	Tape name: Data Stuart Bradley 150702
	Calibrator	DEST00010	
Cabauw	SODAR	Model 4000	
	Microphone	DEGL0432	
	Pre amp	DEGL0169	
	Amplifier	DEGL0202	
	DAT recorder	DEGL0200	Tape name: Geluid Cabauw 30-09-02 4000 model
	Calibrator	DEST0004	

The analysis has been done using the DAT recorder DEGL0167, a PULSE front end DEGL0629 and a Toshiba Satellite Pro laptop P3166 running Pulse LabShop software version 6.1.4.4 2002-03-08.

The first analysis was performed to determine an average of 40 FFT spectra, each 0.25 seconds long. In total a 10-second interval was averaged. The spectra consisted of 3200 lines of 4Hz width, with a total span of 12.6 kHz. Also a third-octave band spectrum was made, between 20 and 20.000 Hz, again with a 10-second average. The 10-second time frame was chosen because it is of the order of magnitude a SODAR takes to cycle through three beams. For each measurement at least 10 minutes of data were analysed to see possible variations between the 10-second periods. With the third-octave band spectrum the sound pressure level was determined for the same frequencies and time span.

The frequency range most interesting for the Aerovironment model 4000 SODAR is the range from 4200 to 4800 Hz. The pulses this SODAR sends have a frequency of 4500 Hz, and there is a band pass filter that filters away frequencies below 4200 Hz and above 4800 Hz. Frequencies outside this band will therefore influence the SODAR much less than frequencies inside the frequency range. For this reason a twenty-fourth-octave band spectrum was made between roughly 4200 and 4800 Hz and an FFT spectrum with 6400 lines of 1Hz width, with a total span of 6.4 kHz. For the range between 4200 and 4800 Hz also the sound pressure level was calculated.

In the following sections, the measurement results for each of the locations as described in Table 2 are shown. For each location a third-octave spectrum and a FFT are shown, together with a 1/24th-octave spectrum from 4200 to 4800 Hz and an FFT from 0 to 6.4 kHz.

The figures in the following sections are directly inserted from the analysis program and therefore some non-standard terms are used in the titles. MB1 or MB2 in the titles refer to the memory buffers the data is stored during analysis. These are of no further importance to the assessment of the results. The decibels are reported as dB/20.0u Pa, which should be read as dB/20 µPa. Finally, all the third octave band spectra have “CPB” as title, which stands for Constant Percent Bandwidth. This is the same as a normal third octave band spectrum.

2.2 Measurement #1: Broadband Spectrum

These measurements have been performed on the MPN platform, next to the generator. The SODAR model used was of the 4000 type. The background noise measurements were done to establish a “fingerprint” of the noise from the diesel generator.

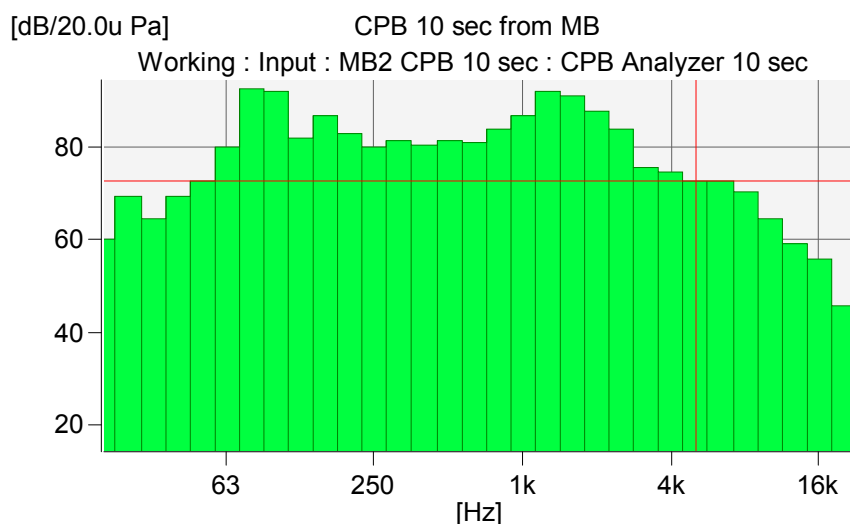


Figure 4. Broadband CPB 10 seconds measured next to the generator at MPN.

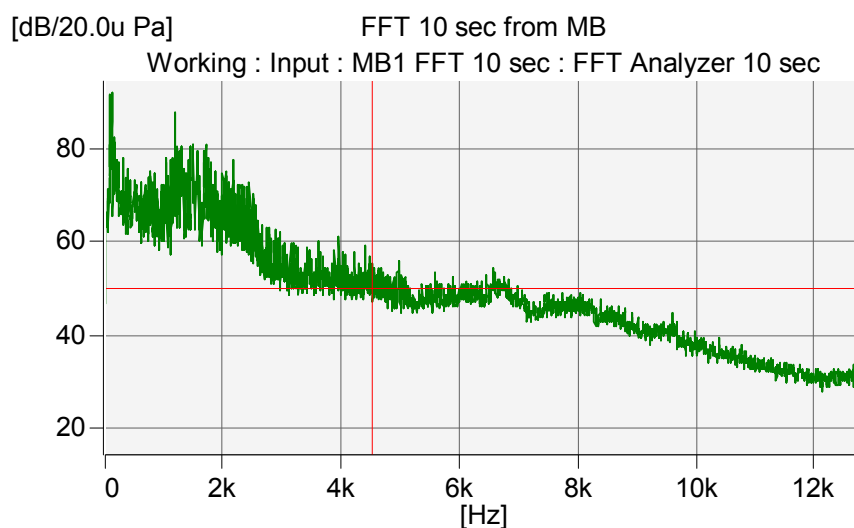


Figure 5. Broadband FFT 10 seconds measured next to the generator at MPN.

From Figure 4 (measurements next to the generator) it can be seen that some peaks in the noise level occur at 100 Hz and at 1 kHz. Figure 5 shows that behind the 2 kHz frequency, the noise levels decrease.

2.3 Measurement #1: Narrow-band Spectrum

These measurements have also been performed on the MPN platform, next to the generator. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

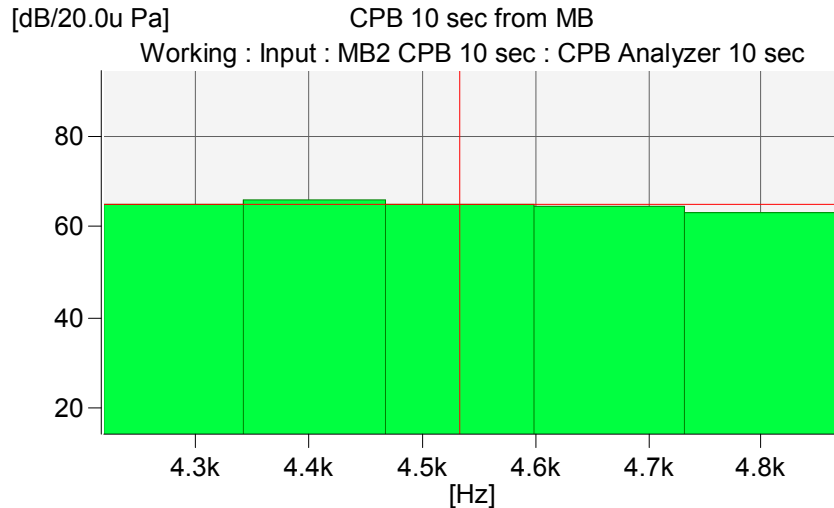


Figure 6. Narrow band CPB 10 seconds measured next to the generator at MPN.

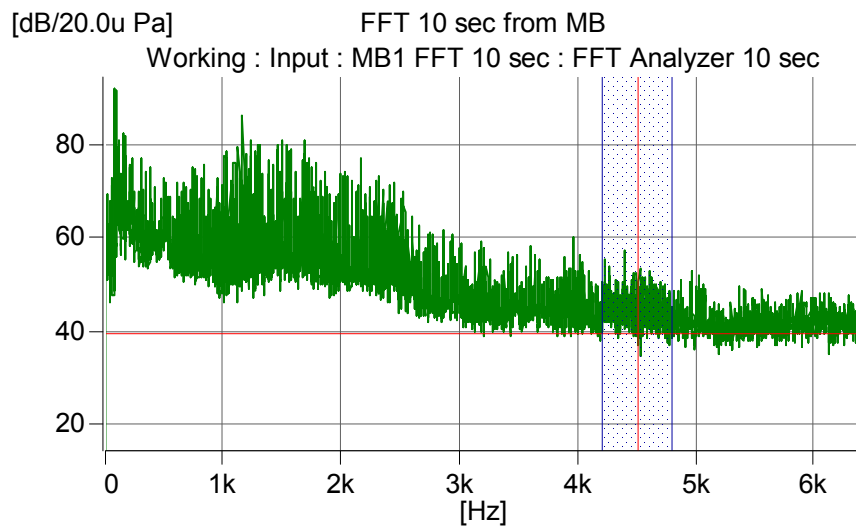


Figure 7. Narrow band FFT 10 seconds measured next to the generator at MPN.

From the figures it can be seen that the generator noise level is fairly constant within the 4200 – 4800 Hz frequency band.

2.4 Measurement #2: Broadband Spectrum

These measurements have been performed on the MPN platform, at the old SODAR location. The SODAR model used was of the 4000 type.

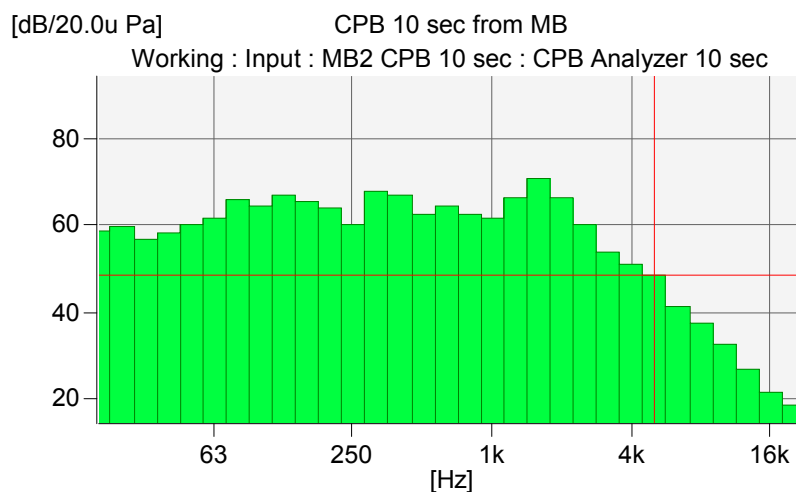


Figure 8. Broadband CPB 10 seconds measured at the old SODAR location at MPN.

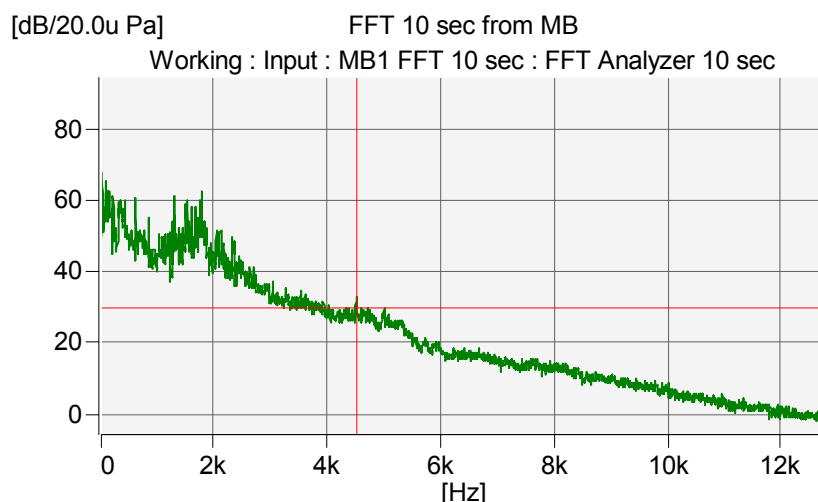


Figure 9. Broadband FFT 10 seconds measured at the old SODAR location at MPN.

Figure 8 and Figure 9 show that the noise levels at the old SODAR location are significantly lower than the levels measured next to the generator. Compared to the same reference, the noise level falls off quicker above 2 kHz. The peak around 1 kHz is still present, the peak at 100 Hz is less pronounced than directly next to the generator.

2.5 Measurement #2: Narrow-band Spectrum

These measurements have also been performed on the MPN platform, at the old SODAR location. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

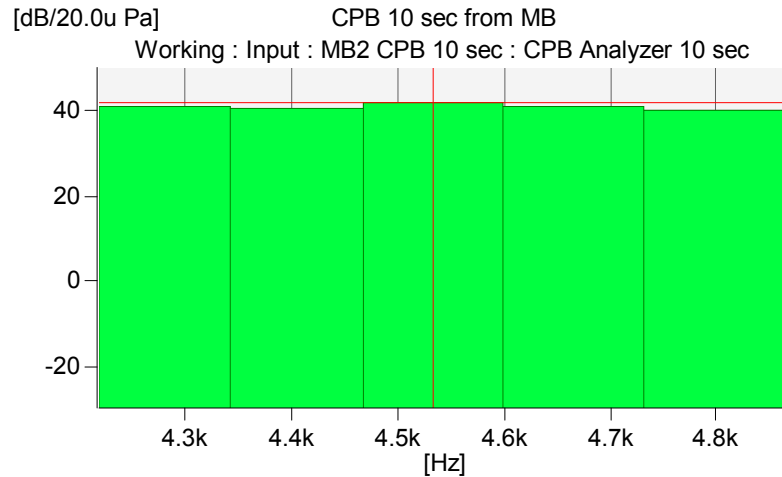


Figure 10. Narrow band CPB 10 seconds measured at the old SODAR location at MPN.

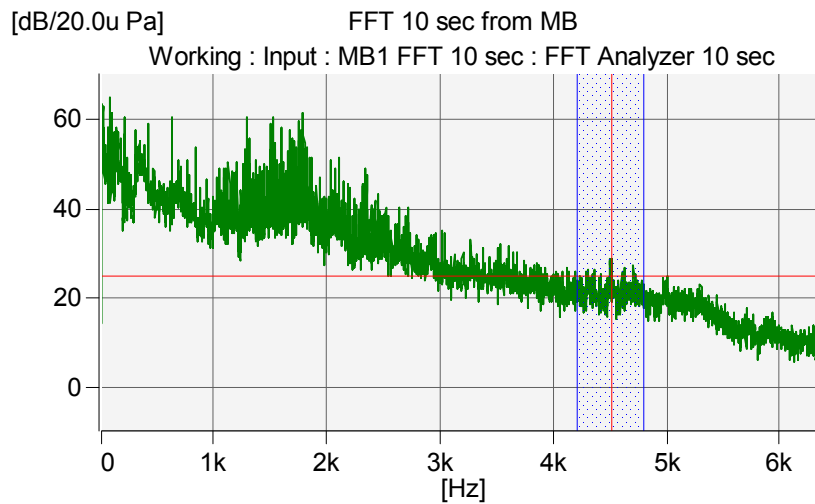


Figure 11. Narrow band FFT 10 seconds measured at the old SODAR location at MPN.

Compared to the measurements performed next to the generator, these figures show only a lower noise level. No other significant characteristics can be observed.

2.6 Measurement #3: Broadband Spectrum

These measurements have been performed on the MPN platform, at the new SODAR location, inside the SODAR casing. The SODAR model used was of the 4000 type.

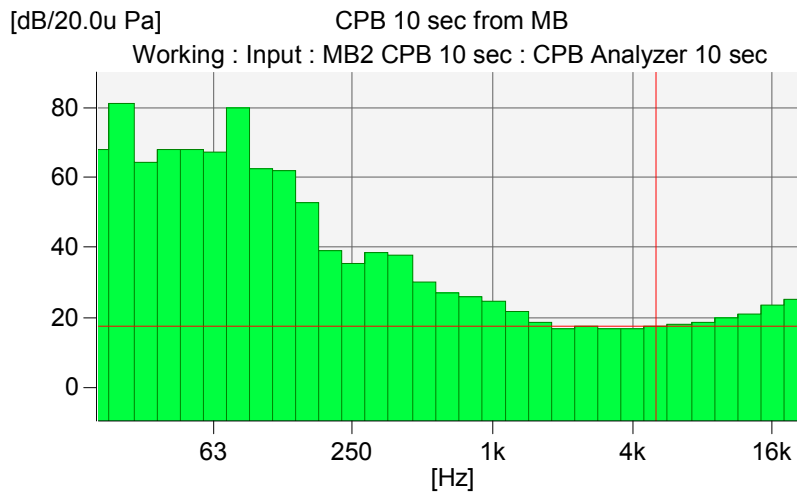


Figure 12. Broadband CPB 10 seconds measured at the new SODAR location at MPN inside the SODAR casing.

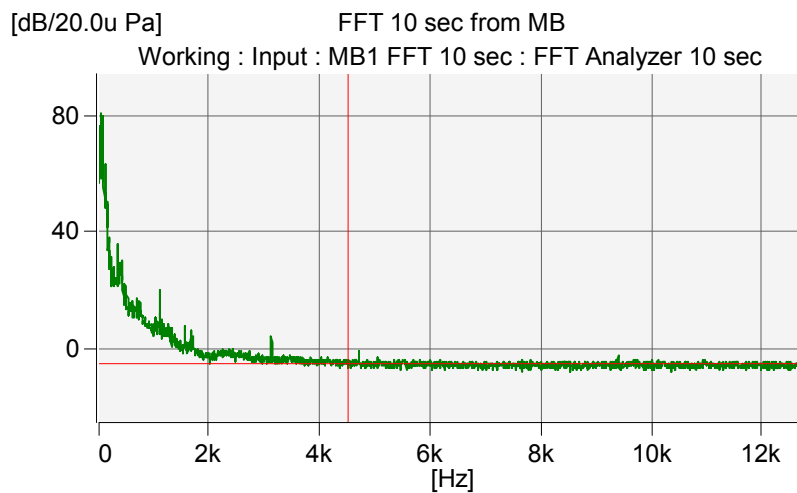


Figure 13. Broadband FFT 10 seconds measured at the new SODAR location at MPN inside the SODAR casing.

In the above figures, the effect of the noise absorbing material placed inside the SODAR casing can easily be observed. To shield the SODAR from background noise (and to shield the surroundings of the SODAR from the very loud sound pulse) the inside of the SODAR is covered with absorbing foam, especially effective in the 4200 – 4800 Hz frequency band. This effect can clearly be seen in the third-octave band spectrum (Figure 12) where the bands between 4200 and 4800 Hz are suppressed and where the bands at 16 kHz are increasing again. This is partly due to the fact that also outside the SODAR the last two bands increase slightly, but the effect is stronger inside the casing and mainly due to the absorbing foam.

Although the FFT spectrum does not show this dip around 4200 Hz, in the comparison with the outside measurement it can be seen that the levels inside are also suppressed. Also the peak at 100 Hz is very pronounced and a new peak at low frequencies appears.

2.7 Measurement #3: Narrow-band Spectrum

These measurements have also been performed on the MPN platform, at the new SODAR location, inside the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

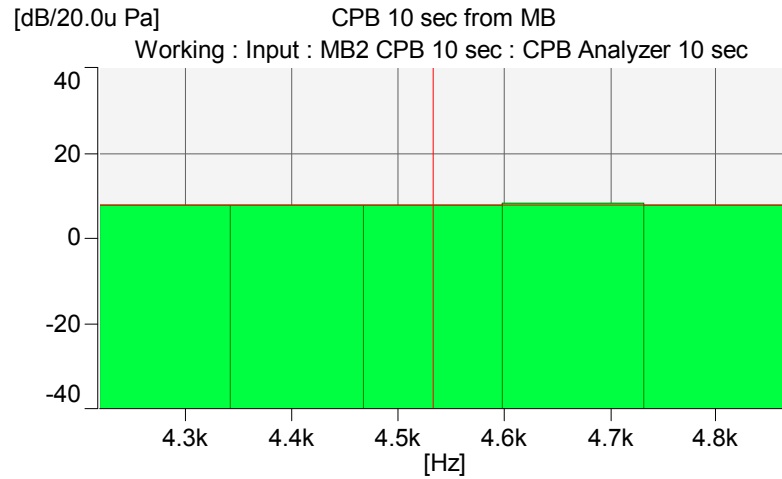


Figure 14. Narrow band CPB 10 seconds measured at the new SODAR location at MPN inside the SODAR casing.

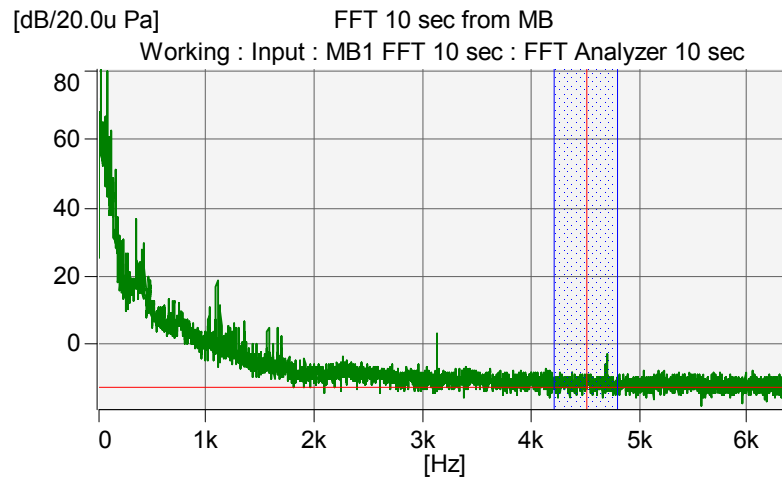


Figure 15. Narrow band FFT 10 seconds measured at the new SODAR location at MPN inside the SODAR casing.

2.8 Measurement #4: Broadband Spectrum

These measurements have been performed on the MPN platform, at the new SODAR location, outside the SODAR equipment. The SODAR model used was of the 4000 type.

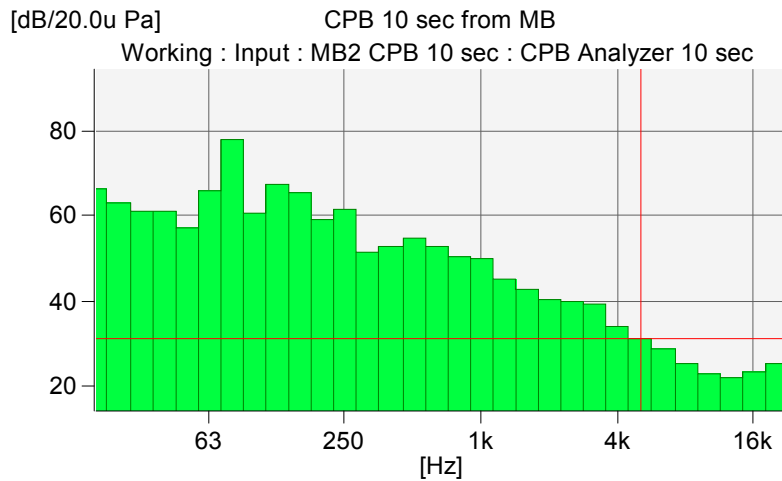


Figure 16. Broadband CPB 10 seconds measured at the new SODAR location at MPN outside the SODAR casing.

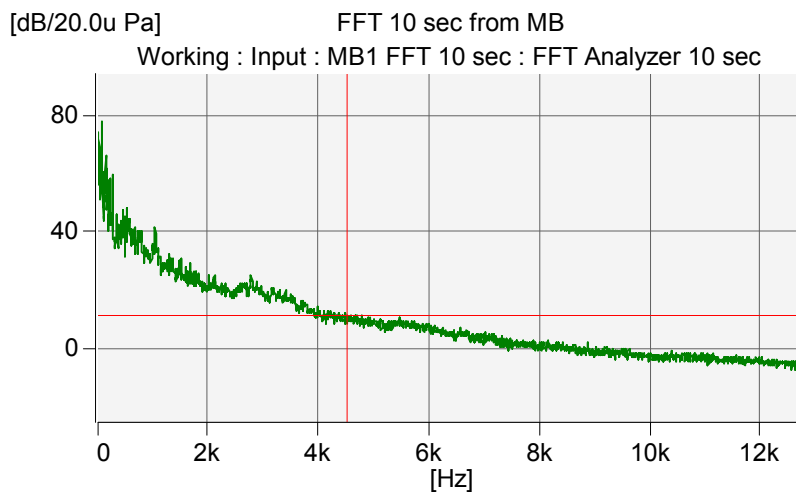


Figure 17. Broadband FFT 10 seconds measured at the new SODAR location at MPN outside the SODAR casing.

In the measurements outside the SODAR especially the peak at 100 Hz is strong whereas the peak at 1 kHz has disappeared. The signal's strength decreases almost linearly with the frequency. This is different than inside the SODAR where the lower part of the spectrum around 4500 Hz is extra suppressed. Inside the SODAR the level decays much faster and thereafter remains almost stable from 2 kHz to 16 kHz.

2.9 Measurement #4: Narrow-band Spectrum

These measurements have also been performed on the MPN platform, at the new SODAR location, outside the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

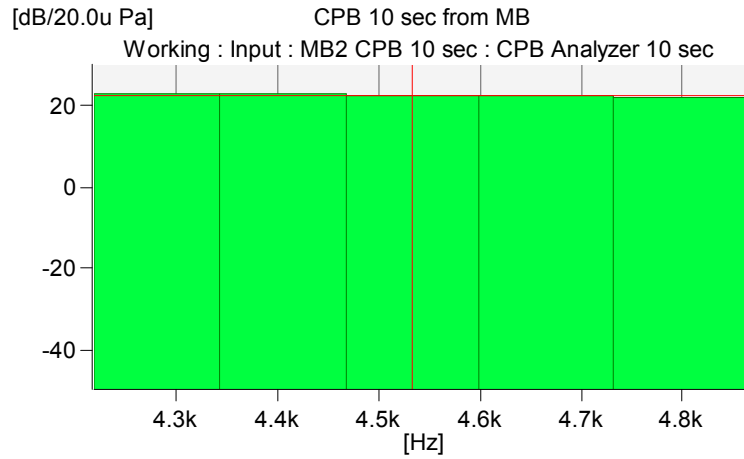


Figure 18. Narrow band CPB 10 seconds measured at the new SODAR location at MPN outside the SODAR casing.

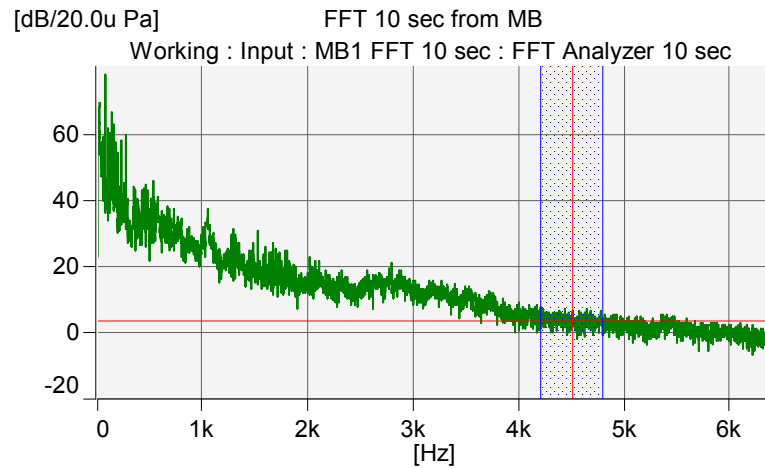


Figure 19. Narrow band FFT 10 seconds measured at the new SODAR location at MPN outside the SODAR casing.

2.10 Measurement #5: Broadband Spectrum

These measurements have been performed at the Samlesbury airfield, at the outside of the SODAR equipment. The SODAR model used was of the 4000 type.

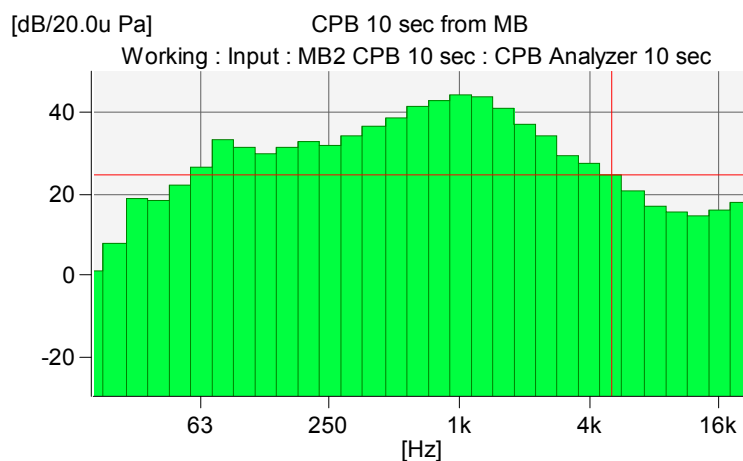


Figure 20. Broadband CPB 10 seconds measured at the Samlesbury airfield, outside the SODAR casing.

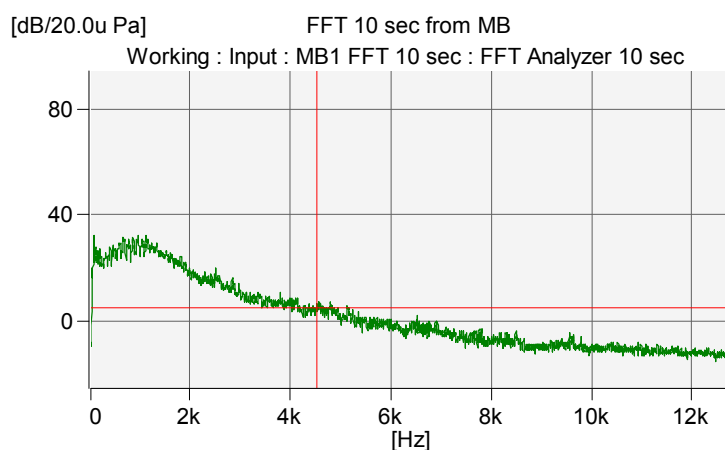


Figure 21. Broadband FFT 10 seconds measured at the Samlesbury airfield, outside the SODAR casing.

In both the FFT spectrum and the third-octave band spectrum the differences between offshore (see Figure 10 and Figure 11) and onshore (Figure 20 and Figure 21) are very clear. Offshore the largest noise source was low frequency originated from the generator. The onshore noise level spectrum measured at the Samlesbury airfield peaks at 1 kHz.

2.11 Measurement #5: Narrow-band Spectrum

These measurements have also been performed at the Samlesbury airfield, at the outside of the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

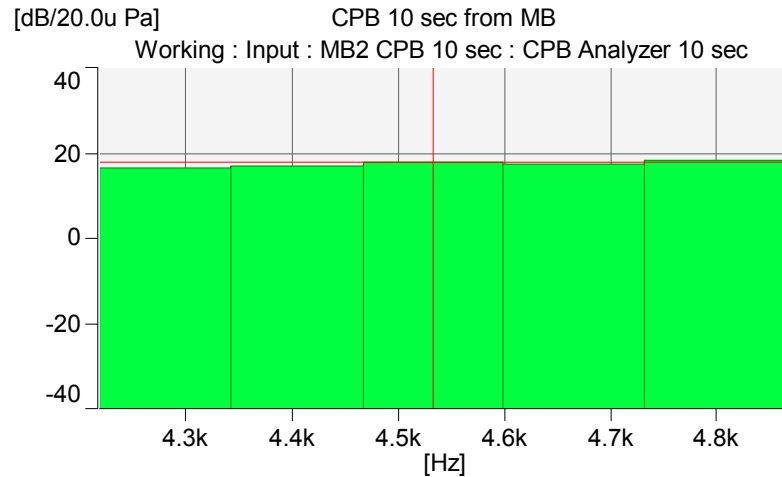


Figure 22. Narrow band CPB 10 seconds measured at the Samlesbury airfield, outside the SODAR casing.

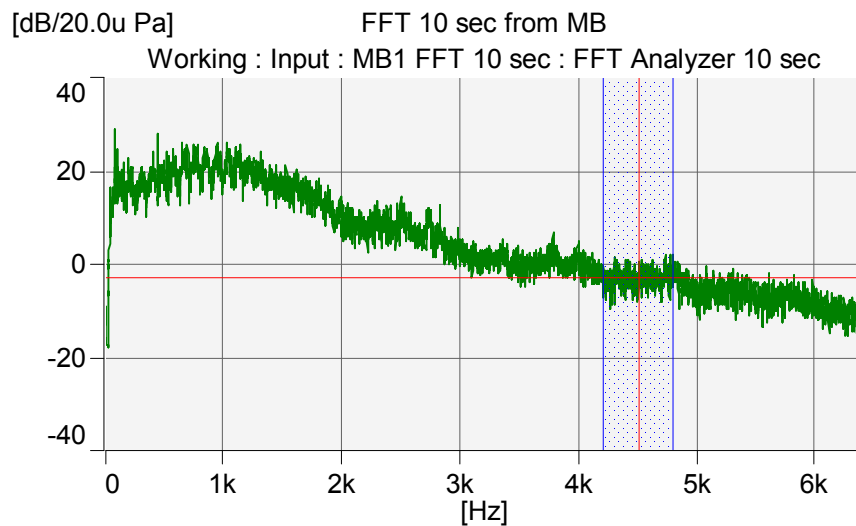


Figure 23. Narrow band FFT 10 seconds measured at the Samlesbury airfield, outside the SODAR casing.

2.12 Measurement #6: Broadband Spectrum

These measurements have been performed at the Samlesbury airfield, at the inside of the SODAR equipment. The SODAR model used was of the 4000 type.

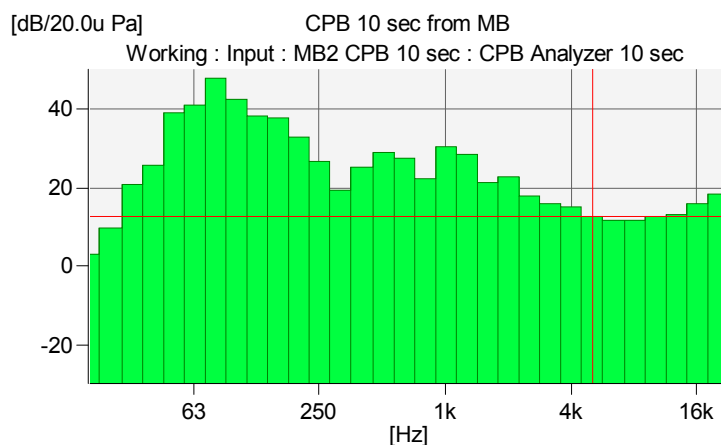


Figure 24. Broadband CPB 10 seconds measured at the Samlesbury airfield, inside the SODAR casing.

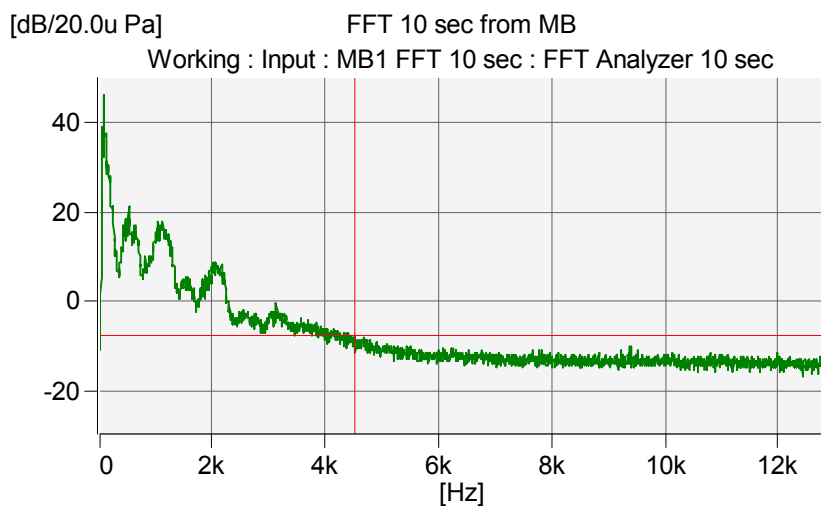


Figure 25. Broadband FFT 10 seconds measured at the Samlesbury airfield, inside the SODAR casing.

Also in this measurement inside the SODAR the effect of the absorbing foam is observed when compared to the measurements outside the SODAR (Figure 20 and Figure 21). The peak around 1 kHz outside the SODAR is not present anymore and has been replaced by a peak around 100 Hz. If this increase is caused by a higher noise level during the measurements or due to vibrations in the SODAR shielding itself is not clear.

2.13 Measurement #6: Narrow-band Spectrum

These measurements have also been performed at the Samlesbury airfield, at the inside of the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

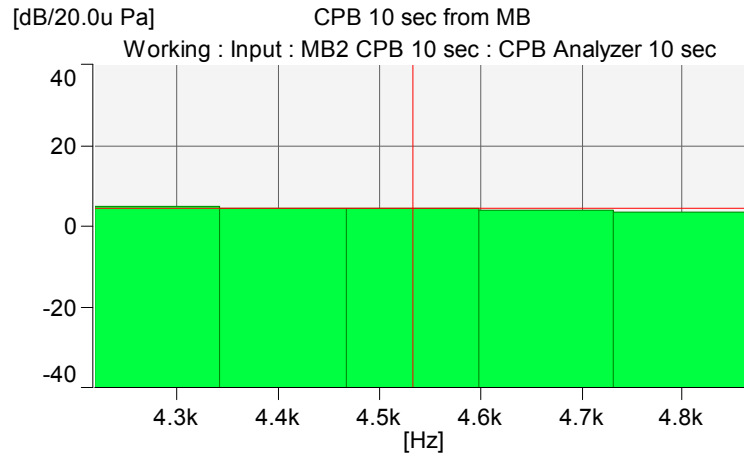


Figure 26. Narrow band CPB 10 seconds measured at the Samlesbury airfield, inside the SODAR casing.

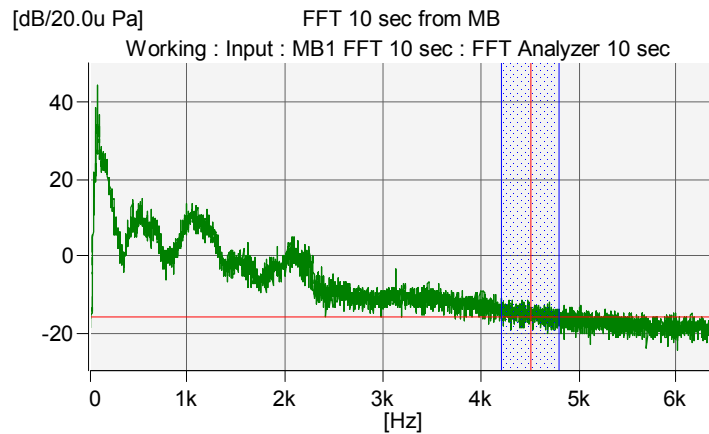


Figure 27. Narrow band FFT 10 seconds measured at the Samlesbury airfield, inside the SODAR casing

2.14 Measurement #7: Broadband Spectrum

These measurements have been performed at Cabauw, at the inside of the SODAR equipment. The SODAR model used was of the 4000 type.

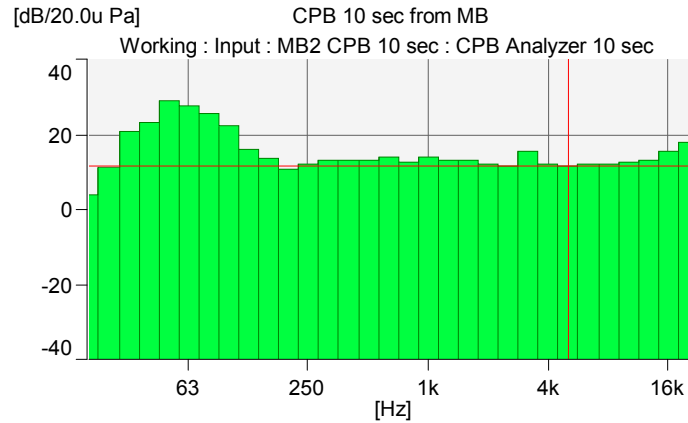


Figure 28. Broadband CPB 10 seconds measured at Cabauw, at the inside of the SODAR casing.

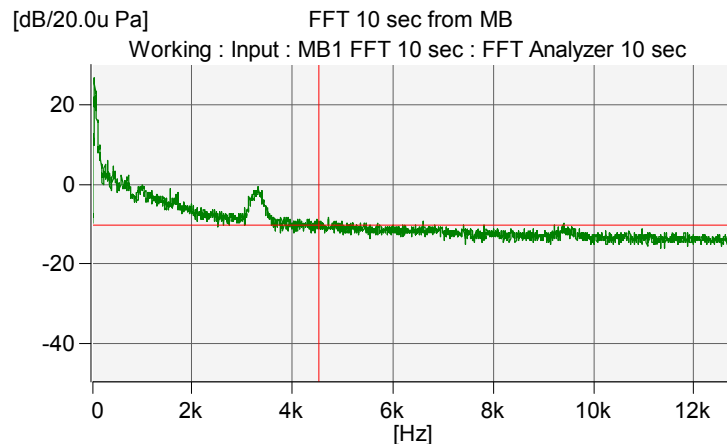


Figure 29. Broadband FFT 10 seconds measured at Cabauw, at the inside of the SODAR casing.

When comparing the inside measurements (Figure 28 up to Figure 31) and the outside measurements at the Cabauw site (Figure 32 up to Figure 35), the effect of the absorbing foam is again observed very clearly. The third-octave spectrum is very levelled, with exception of a peak at 60 Hz. With the absorbing foam the frequencies between 200 Hz and 4kHz are suppressed so that an almost levelled third-octave spectrum results between 200 Hz and 16 kHz. Also at 16 kHz the levels increase slightly. Furthermore, a peak in the FFT spectrum is observed at around 3200 Hz, which shows in the third-octave band spectrum as a heightened level in one band.

2.15 Measurement #7: Narrow-band Spectrum

These measurements have also been performed at Cabauw, at the inside of the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

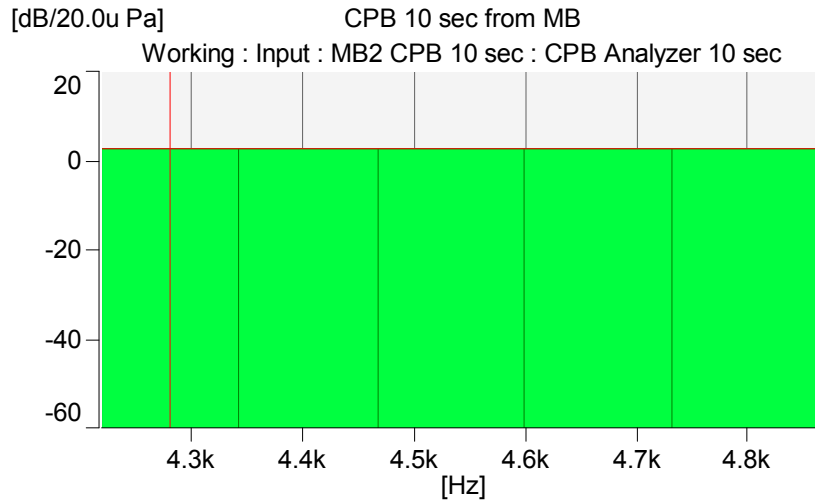


Figure 30. Narrow band CPB 10 seconds measured at Cabauw, at the inside of the SODAR casing.

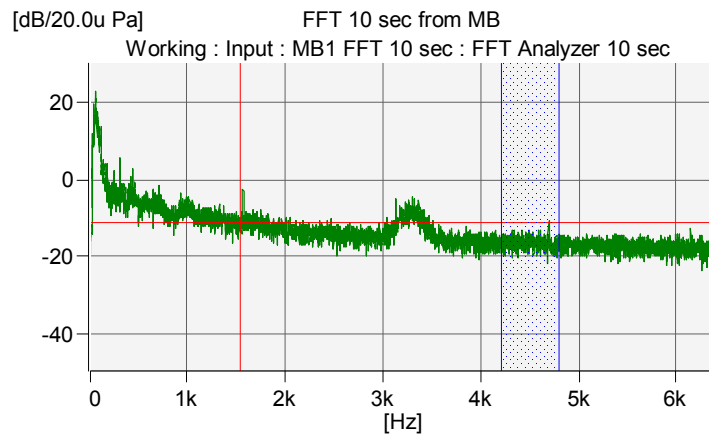


Figure 31. Narrow band FFT 10 seconds measured at Cabauw, at the inside of the SODAR casing.

2.16 Measurement #8: Broadband Spectrum

These measurements have been performed at Cabauw, at the outside of the SODAR equipment. The SODAR model used was of the 4000 type.

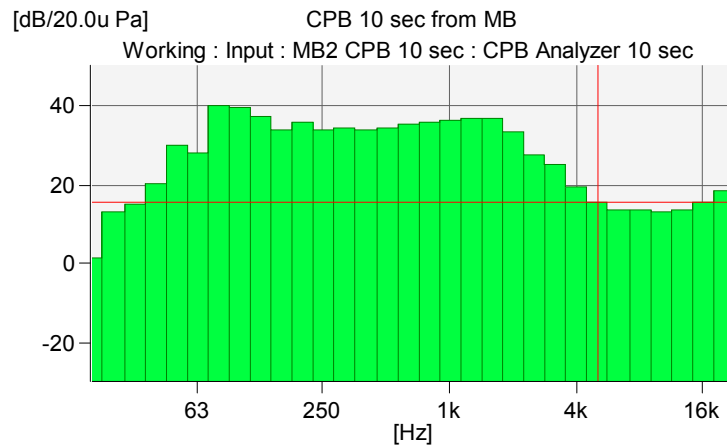


Figure 32. Broadband CPB 10 seconds measured at Cabauw, at the outside of the SODAR casing.

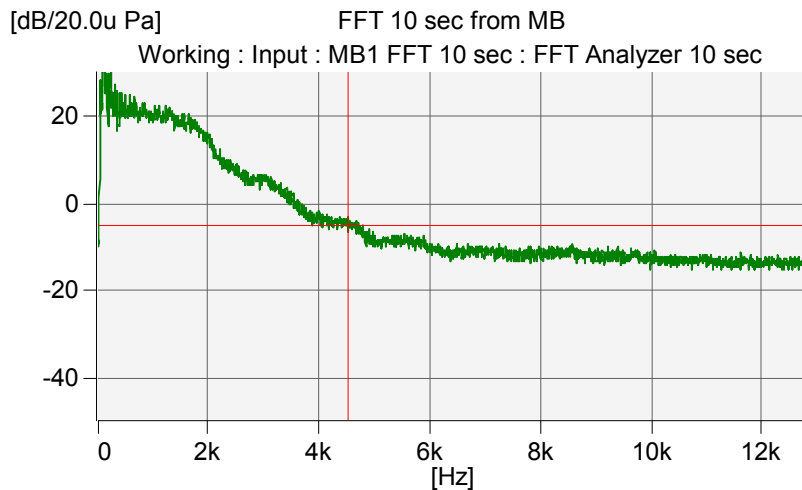


Figure 33. Broadband FFT 10 seconds measured at Cabauw, at the outside of the SODAR casing.

Figure 32 and Figure 33 show also a clear difference between the offshore and onshore measurements (compare these figures with Figure 8 and Figure 9). Again the low frequencies are not present, and the spectrum is fairly levelled between 100 Hz and 2 kHz in the third-octave band spectrum. The FFT spectrum decreases almost linearly until 6 kHz. Later it levels off and stays almost stable until 12 kHz.

2.17 Measurement #8: Narrow-band Spectrum

These measurements have been performed at Cabauw, at the outside of the SODAR equipment. The spectrum analysed comprises the 4200 – 4800 Hz range. The SODAR model used was of the 4000 type.

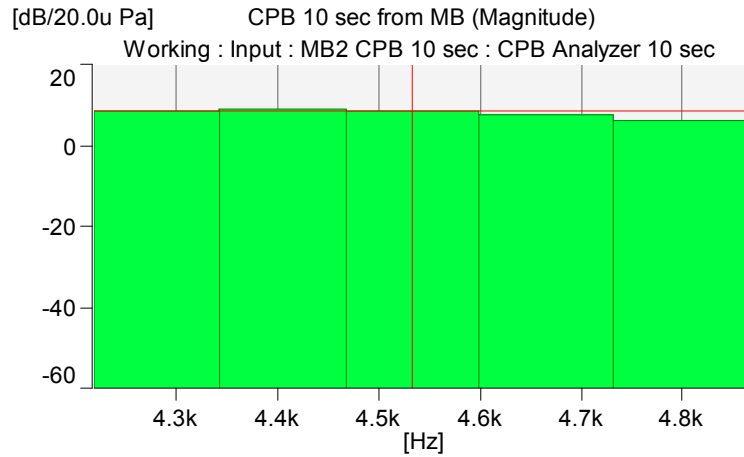


Figure 34. Narrow band CPB 10 seconds measured at Cabauw, at the outside of the SODAR casing.

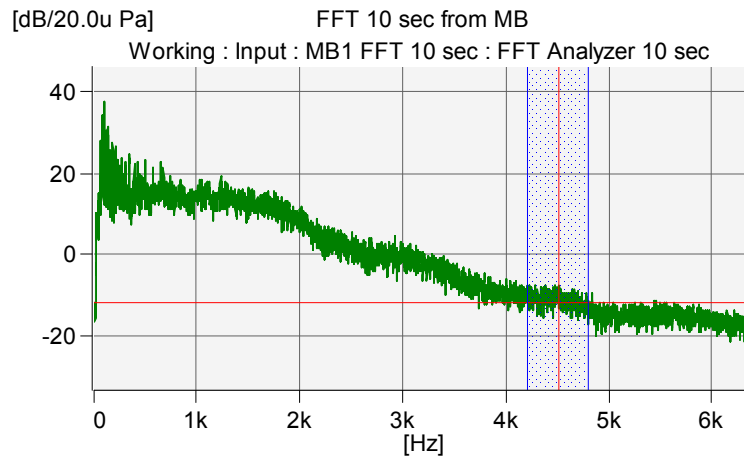


Figure 35. Narrow band FFT 10 seconds measured at Cabauw, at the outside of the SODAR casing.

2.18 Overview of Sound Pressure Levels

In addition to the spectra given above, Table 3 gives an overview of the Sound Pressure Levels that have been measured at the various locations.

Table 3. Overview of the measured Sound Pressure Levels

Measurement number #	Site	Location / position	Timeframe	A (dB)	L (dB)	L-narrow (dB)
1	MPN	Next to generator	3	96.8	99	71.1
2	MPN	Old location	5	75.1	78.1	47.5
3	MPN	New location, inside SODAR	0	56.9	84.5	14.2
4	MPN	New location, outside SODAR	0	61.4	80.5	29.4
5	Samlesbury	Outside SODAR	2	50.3	50.3	23.0
6	Samlesbury	Inside SODAR	2	36.3	50.2	10.7
7	Cabauw	Inside SODAR	5	24.9	33.5	9.1
8	Cabauw	Outside SODAR	3	44.1	47.8	14.5

NOTES:

A is the A-weighted sound pressure level

L is the unweighted sound pressure level

L-narrow is the unweighted sound pressure level between 4200 and 4800 Hz.

All sound pressure levels are given with respect to a sound level of 20 µPa

In Table 3 the various sound pressure levels can be seen for the different measurements. The timeframe is the number of the 10-second interval that has been chosen to present in this report, from the longer period of measurements. The 'L'-values are unweighted sound pressure levels. However, the human ear does not respond equally strong to all frequencies. For instance a tone of 100 Hz or 1 kHz of equal strength will not be perceived as equally strong. Therefore many noise measurements are presented as A-weighted, which is a weighting according to the frequency response of the human ear.

The results in Table 3 are graphically presented in Figure 36.

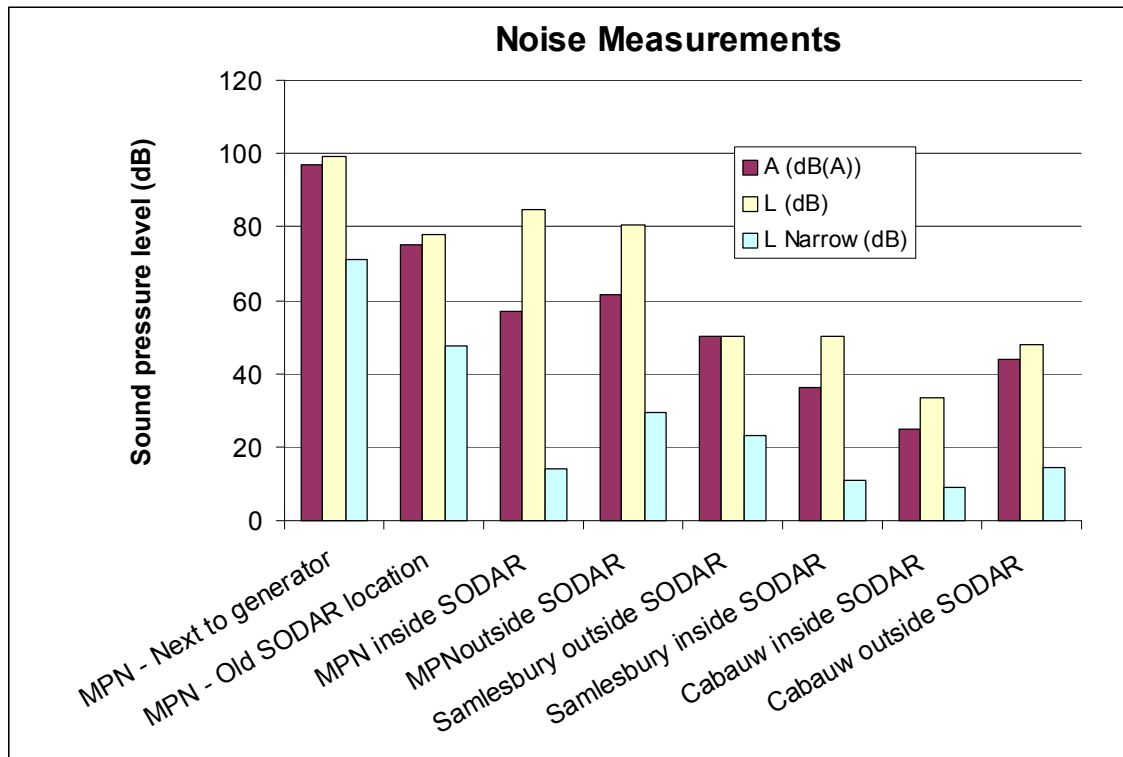


Figure 36. Results from noise measurements as presented in Table 3.

2.19 Conclusions with regard to Noise Measurements

From the presented measurement results the following conclusions are drawn:

- With respect to the measurements at MPN, it is seen in Table 3 that the new measurement location at the MPN island is more quiet for the human ear than the old location (compare the A-weighted values for measurements 2 and 4). However, a higher sound pressure level is observed at the new site with respect to the old one. So the new chosen location had a higher sound pressure level, originated by the low frequency noise from the generator. The human ear filters out this low-frequency noise and therefore the new location is experienced as being quieter, although this is not true.
- With respect to the measurements at MPN, looking at the most interesting frequencies for the SODAR, it has been shown that the sound pressure level at the new chosen location was 15 dB lower compared to the old SODAR location. The conclusion is therefore that the new chosen SODAR location has indeed decreased the background noise in a narrow band around the SODAR operating frequency, although the absolute sound pressure level went up.
- These results show that it is advisable to base decisions about the lowest sound pressure level on measurements, as it can be clearly seen that the human ear can give erroneous information on absolute sound pressure levels.
- The measured sound pressure data show that the sound pressure level at the outside the offshore SODAR is 6 to 15 dB higher than at Samlesbury airfield or at Cabauw. Inside the SODAR this difference is 3.5 to 5 dB respectively. The higher background level influences the SODAR performance at the offshore island, and therefore it is expected that the offshore SODAR produces less reliable results. Especially, the maximum height reached by the SODAR is expected to be lower, as reported by Crescenti [2].
- The sound absorbing material in the SODAR significantly reduces the noise inside the casing. Thus it helps to get rid of excess noise in the narrow band. As it is expected that sun, rain and sea salt will degrade the absorbing material, care must be taken to control the quality of this material often and to replace it in case of damage.

3. VIBRATION MEASUREMENTS

The influence of vibrations on the SODAR is less easy to deal with than the influence of background noise on the SODAR. The latter has been well documented in the SODAR literature, but the former often does not occur when the SODAR equipment is placed directly on land. Vibrations are possible when a SODAR is placed on a supporting structure, such as a metal offshore island. This has only very seldom happened, and as such no documentation has been found regarding the influence of vibrations on the SODAR.

If vibrations would cause tones or noise in the audible spectrum, this would have (and may have) been registered during the background noise measurements. In this section the attention is focussed on low frequency vibrations.

3.1 Geometry

To have a good frame of reference for the description of the vibrations, a clear description of the SODAR and the supporting structure is given.

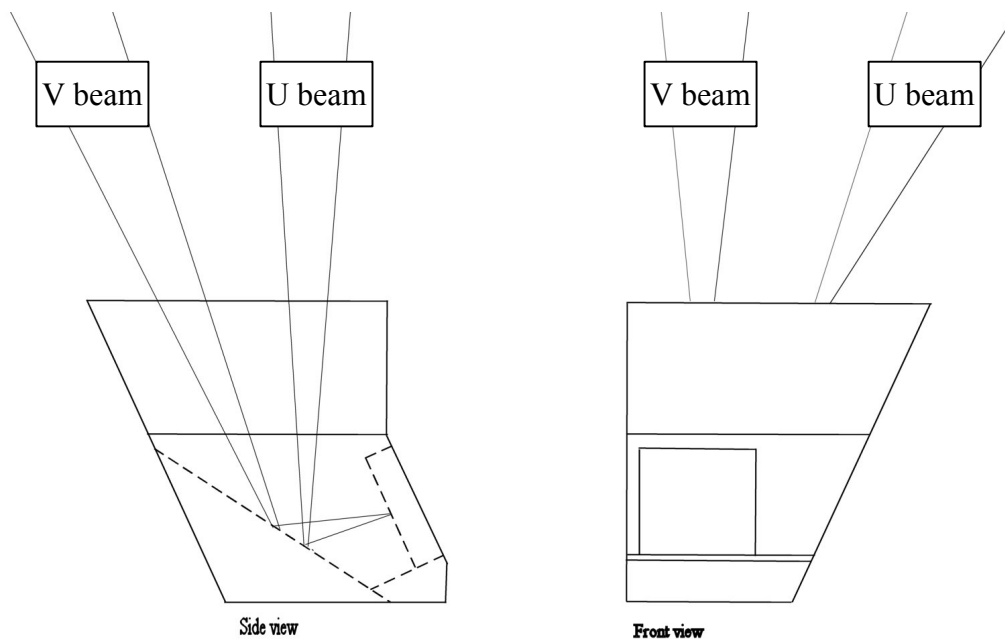


Figure 37. Schematic of SODAR beams with respect to the W beam.

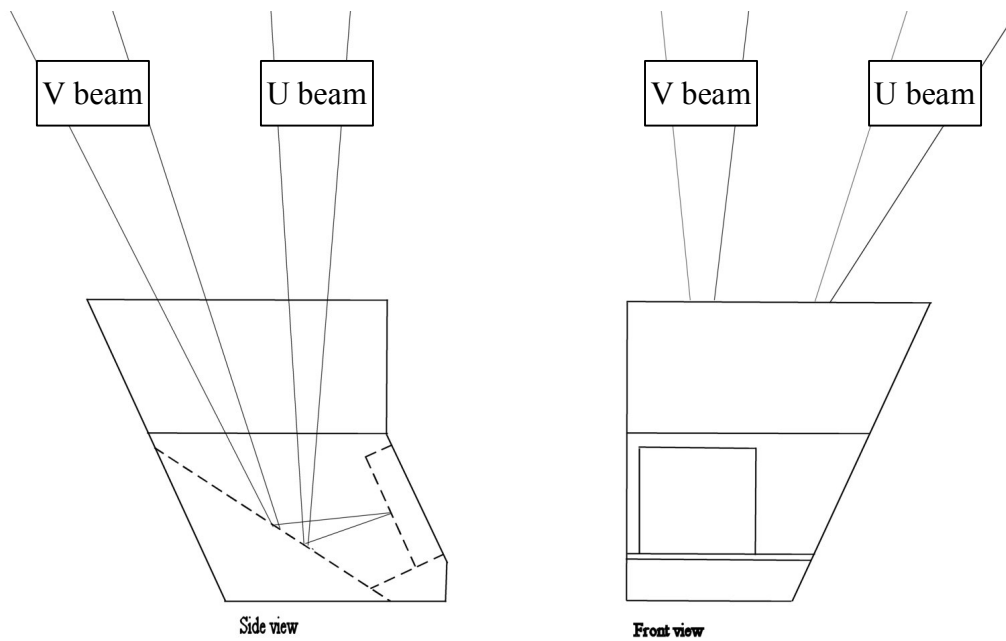


Figure 37 shows that the W-beam is always pointed in a vertical direction if the SODAR is aligned correctly. The two other beams have a 16-degree angle with the vertical and a 90-degree angle with respect to each other. For instance, the V-beam can make a 16-degree angle with the vertical towards the North, and the U-beam can make a 16-degree angle with the vertical towards the East.

It is important to note the naming conventions of the different beams. The beams themselves are non-orthogonal and orthogonal wind speed vectors are calculated from them. The non-orthogonal beams are designated as the X, Y and Z-beam. Respectively, the orthogonal wind speed vectors are referred to as the U, V and W-vectors. Although the X, Y and Z-beams correspond with the U, V and W vectors respectively, they refer to a different geometry. In many texts (including this one) often the term U-beam is used. Normally this is acceptable as it will not lead to confusion, but where the geometry asks for a clear reference the definitions from this paragraph are used.

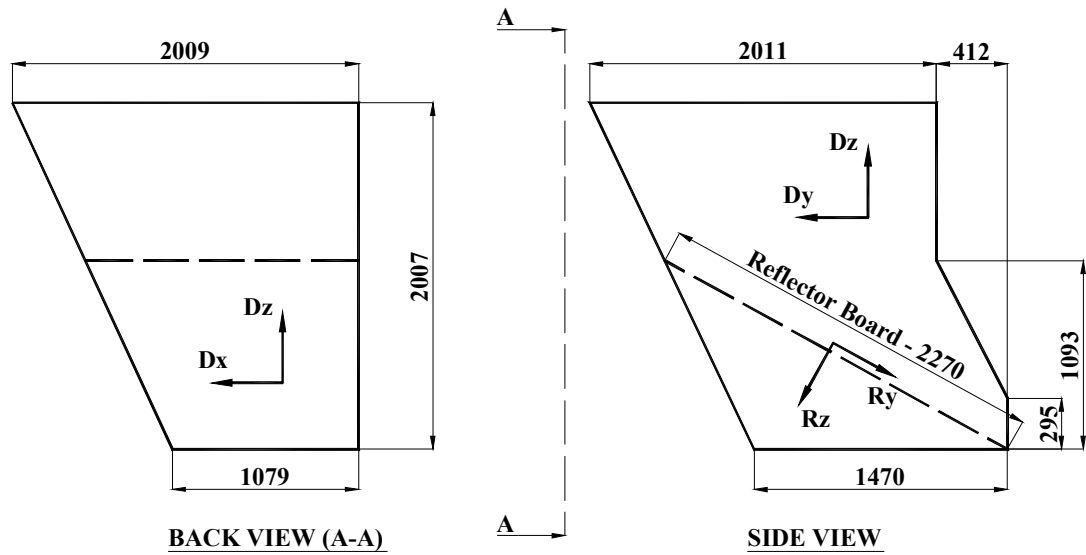


Figure 38. Schematic of SODAR

With exception of the two references for the SODAR beams and vectors, two orthogonal reference systems are also defined to describe the measurements more clearly.

- One frame of reference is specified as (D_x, D_y, D_z) , which is the system with reference to the supporting platform of the MPN island (the D stands for the deck of the platform). The X-axis and Y-axis are parallel to the sides of the platform and form a horizontal plane parallel with the deck of the platform. The Z-axis is perpendicular to this plane and points upwards. D_y is the direction in which the sound pulse travels from the speaker board to the reflector board.
- The second frame of reference is specified as (R_x, R_y, R_z) . These axes are relative to the reflector board of the SODAR. R_x and R_y form the plane of the reflector board while R_z is perpendicular to it.

In the D_y - D_z plane the Z-axis goes from bottom to top and the Y-axis goes from right to left (see Figure 38). In the D_x - D_z plane the X-axis goes from left to right and the Z-axis goes from bottom to top.

Although a detailed analysis of the vibrations would have to take into account the exact beam shape and the near-field approximations, these considerations are outside the scope of this report. The analysis in this section is limited to an estimation of the most important effects on the measurements.

3.2 Measurement Locations

The vibration measurements on the MPN platform have been performed at two different locations and at two positions in each location. In section 1.1 the choice of these locations has been already presented. Figure 39 shows the diesel generator to which vibration measurements are performed. Although in the figure the accelerometers are on top of the generator, during the measurements they were placed at one of the sides.



Figure 39. Vibration measurements at the generator.

Figure 40 shows the SODAR equipment at the new location with the accelerometers mounted on the reflector board.

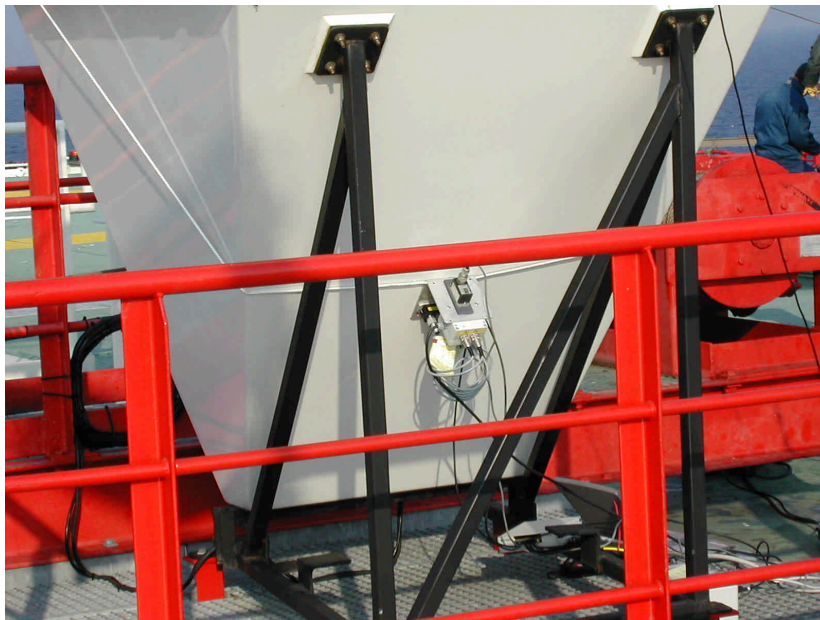


Figure 40. Vibration measurements at the SODAR equipment

3.3 Overview of Possible Influences

Vibrations may occur along any axis of (Dx, Dy, Dz) or (Rx, Ry, Rz). They result in accelerations given as A(Dx) (if along the Dx-axis), speeds given as V(Dx) and displacements given as S(Dx). Each of these accelerations, speeds and displacements may influence the SODAR.

Estimation of influences along the (Dx, Dy, Dz) axes:

1. Accelerations A(Dx), A(Dy) and A(Dz) are not expected to influence the SODAR measurements;
2. V(Dz) can cause a frequency shift because it is a speed along the sound beam;
3. V(Dy) can cause a frequency shift because it is a speed along the sound beam;
4. V(Dx) is not expected to have an influence because it is not aligned with the sound beam;
5. S(Dz) could cause an error in the measured altitude because the SODAR is moving up and down;
6. S(Dx) and S(Dy) are not expected to influence the measurements because they are displacements perpendicular to the sound beams.

Estimation of influences along the (Rx, Ry, Rz) axes:

7. Accelerations A(Rx), A(Ry) and A(Rz) are not expected to influence the SODAR measurements;
8. V(Rz) can cause a frequency shift in the measured signal and thus a change in the measured speed because the vibrations are perpendicular to the reflecting surface;
9. V(Rx) and V(Ry) are not expected to have an effect because the vibrations are in the plane of the reflecting surface;
10. S(Rz) can have an effect through distortion of the reflector board. The effect would be on the beam shape and direction;
11. Displacements S(Rx) and S(Ry) are not expected to influence the SODAR measurements because they do not distort the reflector board.

3.4 Assessment of the Importance of Influences

From the list above the points 2, 3, 5, 8 and 10 may disturb the measurements. An important influence is defined as an influence that is of the same order of magnitude as the SODAR's established uncertainty. If such an effect exists, it should not be neglected in the uncertainty calculations and is therefore important. Effects that are of a smaller order of magnitude will not contribute to the uncertainty of the SODAR and are not considered important. With these considerations the seriousness of such an influence is assessed.

Point (2), V(Dz): The possible influence of a speed component along the Dz-axis on the measured wind speed will be of the order of magnitude of the speed resulting from the vibration. To quantify this effect the maximum speed caused by the vibrations that has been seen during the measurements has been used.

Point (3), V(Dy): The only way the speaker board can cause a frequency shift is under the assumption that the speaker board vibrates but that the reflector board does not. Since the whole SODAR is mounted on the same support structure, this is very unlikely. However, conservatively the maximum speed along the Dy-axis has been calculated as an estimate of the maximum influence of the SODAR measurement.

Point (5), S(Dz): Because the SODAR is vibrating in the Dz-direction, this will cause some inaccuracy in the height determination. However, this inaccuracy is five orders of magnitude smaller than the measured signal (roughly 1 mm on 100m). Therefore, measurable changes are not expected and this effect is neglected.

- Point (8), V(Rz):** The same considerations as for point (2) apply. However, the magnitudes of V(Dz) and V(Rz) can be very different and this will determine the importance.
- Point(10), S(Rz):** A displacement of the centre of the reflector board (assuming that the rest of the SODAR remains fixed) would mean that the board is distorted. Because the board is fixed along the sides we only expect first order distortions: either the board is concave or convex. If there is an effect on the direction of the beam this would affect the resulting wind speeds. If there is an effect on the beam shape instead (widening of the beam), this would mean the acoustic power density will decrease and this would mean that the SODAR becomes less accurate.

This assessment leads to the conclusion that the analysis should be further concentrated on quantifying the influence of:

- Point (2), V(Dz)
- Point (3), V(Dy)
- Point (8), V(Rz)
- Point (10), S(Rz)

3.5 Measurement Results

In this section the results from the measurements are presented. The measurements have been performed at four locations on the MPN island. These locations are

1. Next to the generator, for a “fingerprint” of the vibrations caused by the generator.
2. At the old location of the SODAR
3. At the new location of the SODAR, next to the SODAR
4. At the new location of the SODAR, on the reflector board

At the first three locations the measurements have necessarily been done in the reference frame D. At the fourth location the measurements have been done in reference frame R. These measurements have been done with the following equipment:

Table 4. Vibration measurement equipment

Equipment	Brand	Type	Serial	Identification
Accelerometer	Schaevitz	A223-0001	111454	DEFR0572
Accelerometer	Schaevitz	A223-0001	111453	DEFR0573
Accelerometer	Schaevitz	A223-0001	5742	DEFR0574
AD converter	National Instruments	AI-16XE-50	B3D6ED	DEAD0603
Laptop	Toshiba	Tecra 530 CDT	87019534	P1880

3.6 Measurements at the Generator

For the measurements next to the generator especially the “fingerprint” is important. Therefore only the acceleration spectra are shown for Dx, Dy and Dz-axis. The speeds and displacements are not important at this location.

In the following graphs the spectra are shown for a frequency range of 0 to 100 Hz. As the vibrations are expected to have an influence at low frequencies, the spectra were optimised for these frequencies and the higher frequencies are not shown. This is because the expected effects are from speeds and displacements in a metal structure. In a stiff structure as the MPN island any large displacements or speeds over a longer time (around 0.1 second) are not expected.

Although the accelerations are higher for higher frequencies, the higher frequencies will be suppressed when integrating from acceleration to speed, and from speed to displacement. Therefore, the accelerations in the lower frequencies are expected to be more important.

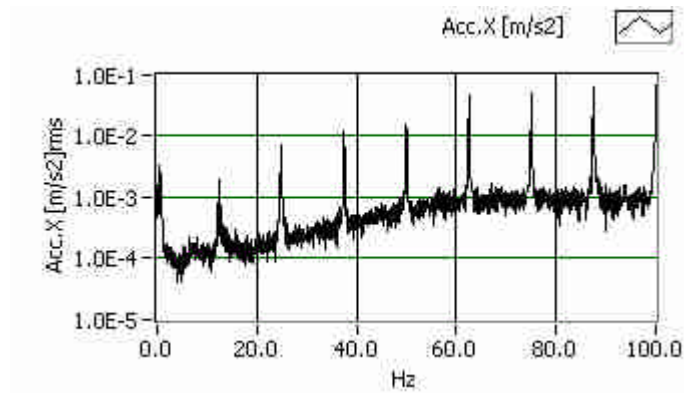


Figure 41. Acceleration spectrum along Dx-axis, next to the generator

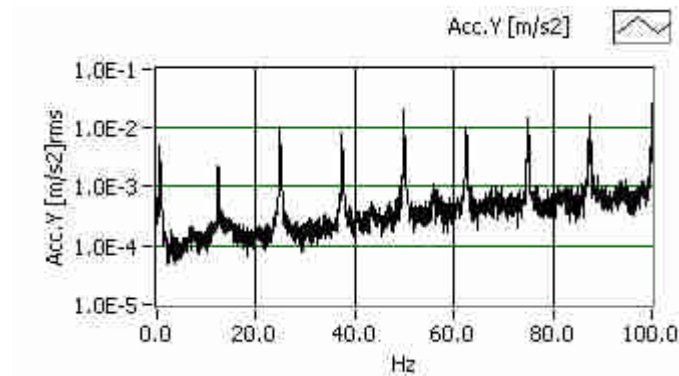


Figure 42. Acceleration spectrum along Dy-axis, next to generator

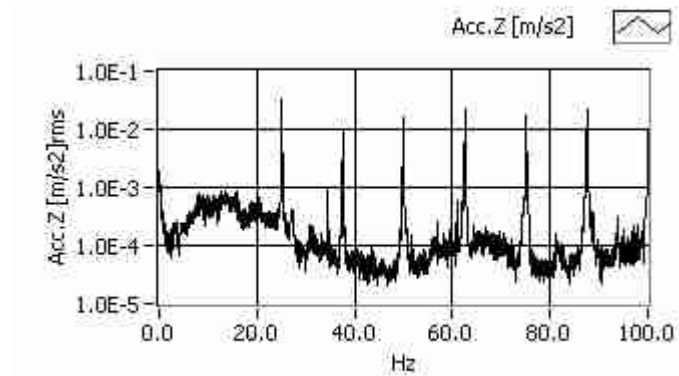


Figure 43. Acceleration spectrum along Dz-axis, next to generator

As is shown in the graphs above, all spectra peak at multiples of 12,5 Hz, as can be expected from a generator. For the Dx-axis there is also a peak at 12.5 Hz. For the Dz-axis there is a peak more spread out at 12.5 Hz. All three axes also have a peak at around 1 Hz.

3.7 Measurements at the old SODAR location

At the old location the SODAR was placed at a walkway, at the same side as the generator on the offshore island. Speeds have been measured the in Y and Z-direction.

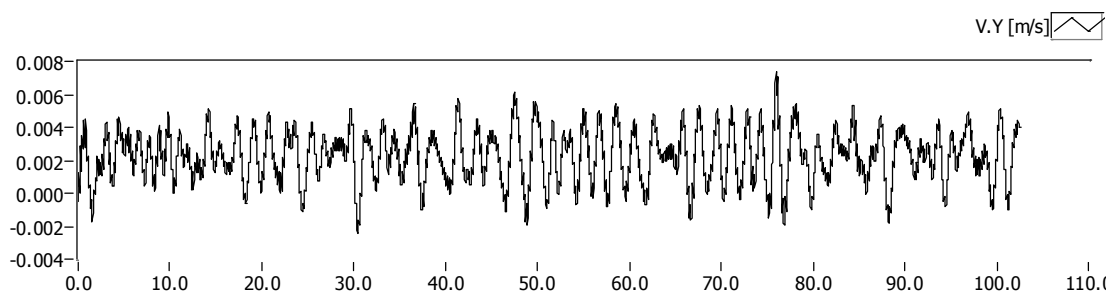


Figure 44. Speed time series along Dy-axis, at the old SODAR location

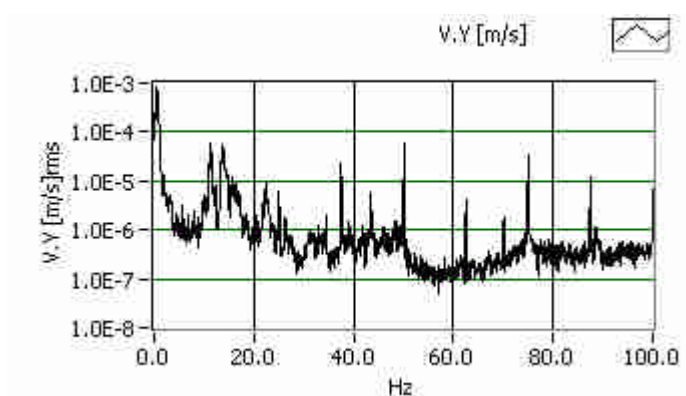


Figure 45. Speed spectrum along Dy-axis, at the old SODAR location

In the spectrum it can be seen that especially at low frequencies the speeds are higher, as expected. However, the maximum speeds are still very small.

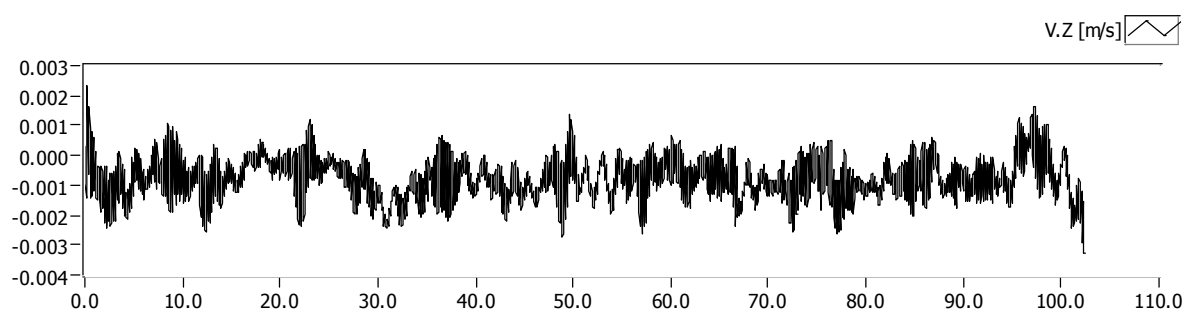


Figure 46. Speed time series along Dz-axis, at the old SODAR location

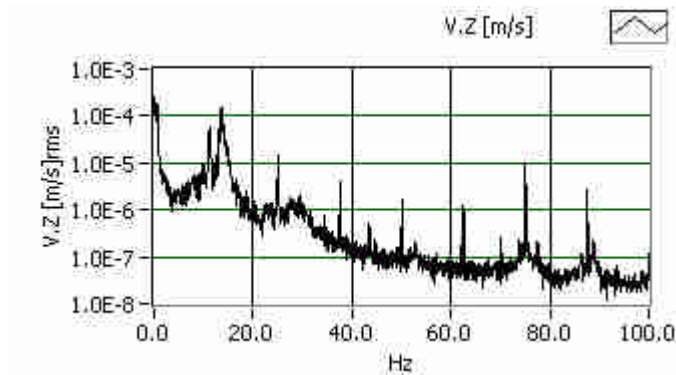


Figure 47. Speed spectrum along Dz-axis, at the old SODAR location

Figure 46 and Figure 47 show that the speeds are also low (less than 0.1 m/s) along the Dz-axis.

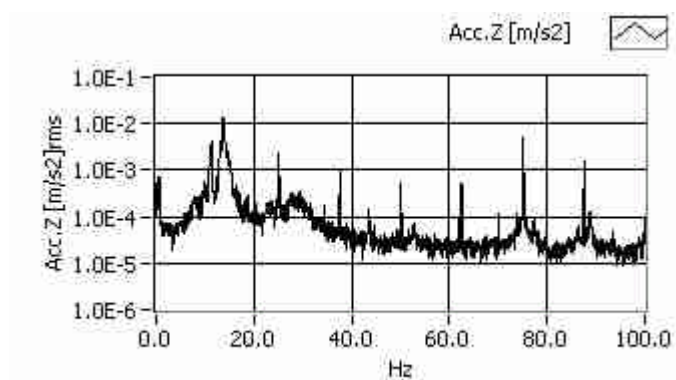


Figure 48. Acceleration spectrum along Dz-axis, at the old SODAR location

In Figure 48, differences with the original spectrum next to the SODAR in the acceleration spectrum are shown. Although the measurement has been done further away from the SODAR, it was performed on a walkway extending outside the structure of the island, which has less structural support. The spectrum shows this with increased vibrations around 12.5 Hz.

3.7.1 Measurements next to the SODAR

The measurements next to the SODAR have been done with the accelerometers mounted on the horizontal support beam of the SODAR structure. Although the maximum values in the time series between the speeds at the old location are not very different from those at the new location (compare Figure 49 with Figure 46), the spectrum in Figure 50 shows lower values around the 12.5 frequency. This is because the higher frequencies are suppressed when integrating from accelerations to speeds. Only at very low frequencies the speeds are still comparable.

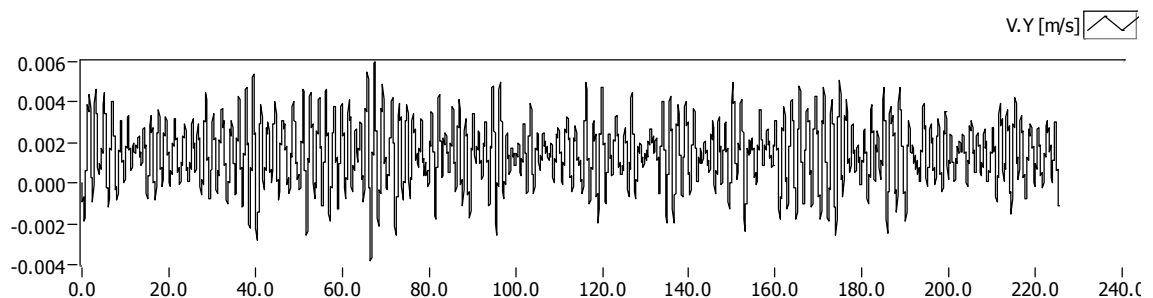


Figure 49. Speed time series along Dy-axis, next to the SODAR

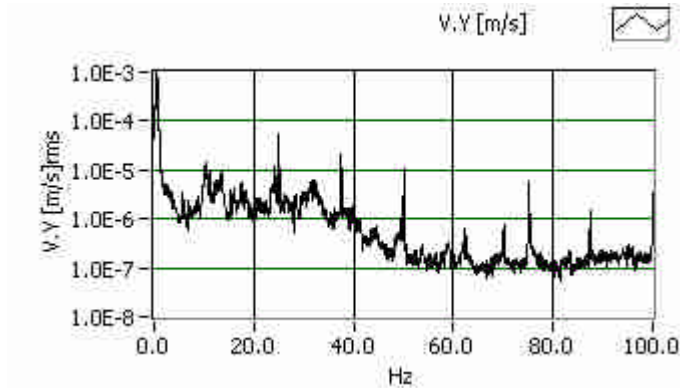


Figure 50. Speed spectrum along Dy-axis, next to the SODAR

The speeds along the Dz-axis show the same course as along the Dy-axis. Compared with the old locations the speeds at all frequencies have been reduced, except for those at very low frequencies.

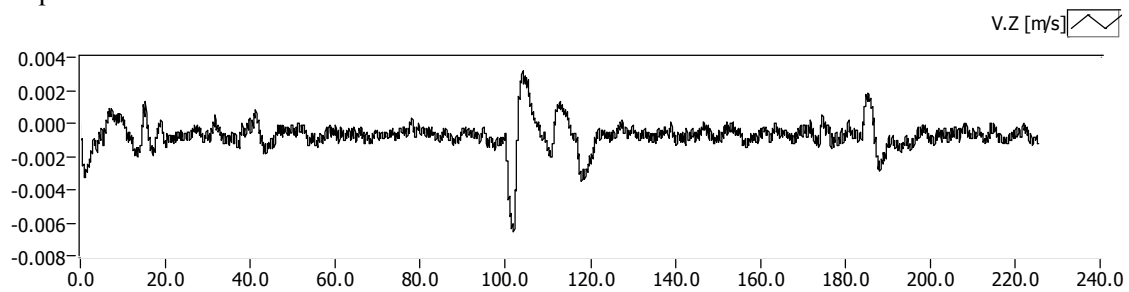


Figure 51. Speed time series along Dz-axis, next to the SODAR

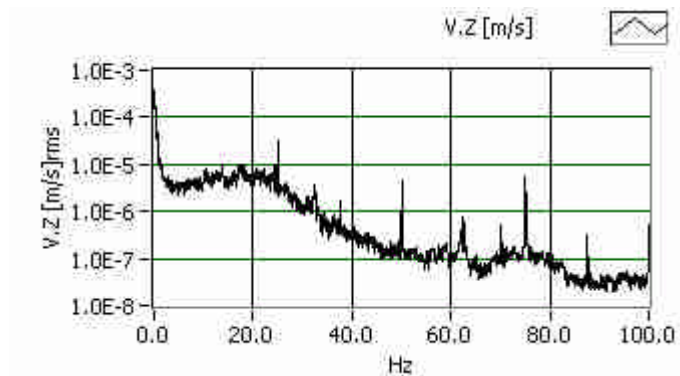


Figure 52. Speed spectrum along Dz-axis, next to the SODAR

The acceleration spectrum along the Dz-axis (Figure 53) shows a less steep peak at 12.5 Hz compared to Figure 48.

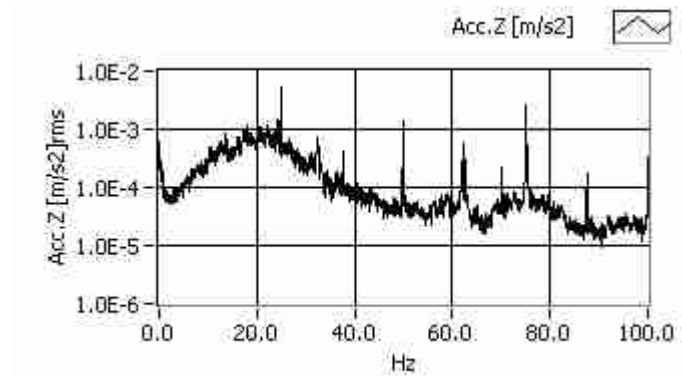


Figure 53. Acceleration spectrum along Dz-axis, next to the SODAR

3.7.2 Measurements on the reflector board of the SODAR

To perform measurements in the R reference frame the accelerometers are mounted at the underside of the SODAR reflector board. This board is roughly 3 by 1.5 metres and only supported at the sides, not in the middle. Especially the speeds and displacements along the Rz axis (perpendicular to the board) were of interest.

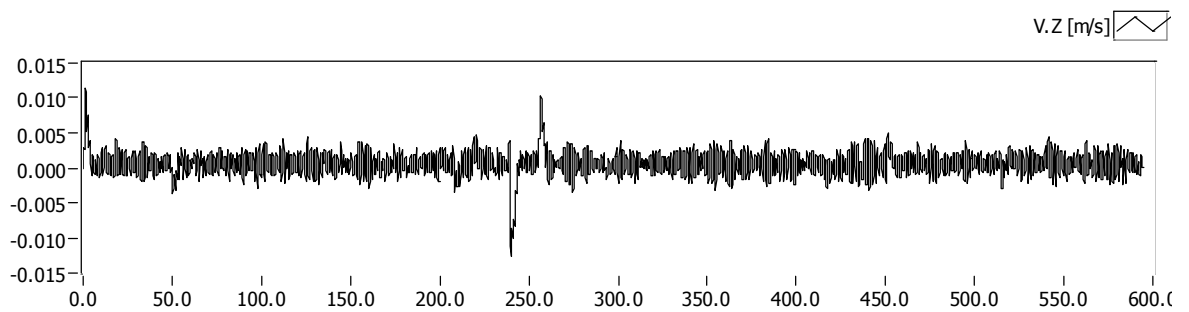


Figure 54. Speed time series along Rz axis, on the SODAR reflector board

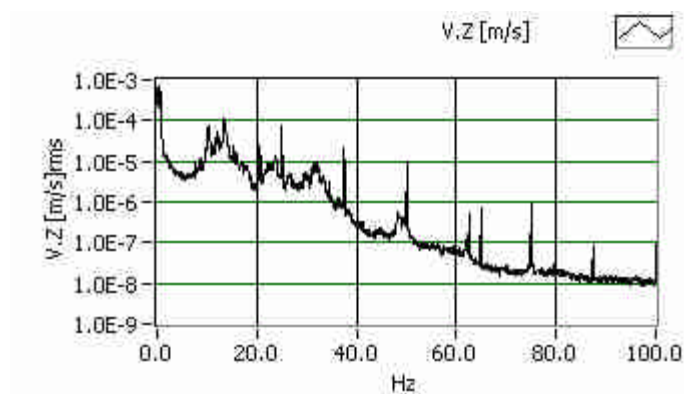


Figure 55. Speed spectrum along Rz axis, on the SODAR reflector board

In the above figures the speed time series and spectra are shown. Although larger vibrations were expected and therefore also larger speeds and displacements, this is not seen in the measurements. At the beginning of the time series and in the middle sudden large speeds are seen, and it is unknown if this is due to the wind, the generator or another effect. We have therefore included these anomalies in our analysis.

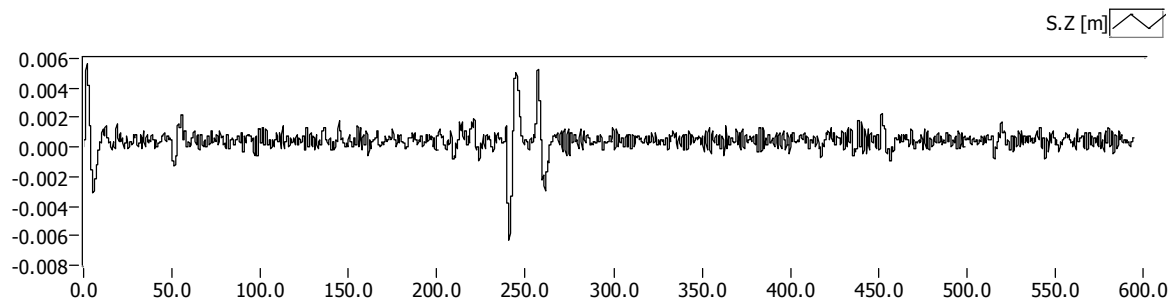


Figure 56. Displacement time series along Rz-axis, on the SODAR reflector board

Comparing Figure 54 with Figure 56, it can be seen that where the large speeds were measured also large displacements occur, in the order of 6 millimetres. It is not known if these large displacements are caused by effects from wind or waves. Conservatively, it has been assumed that the large speeds and displacements are also often present during the normal operation of the SODAR.

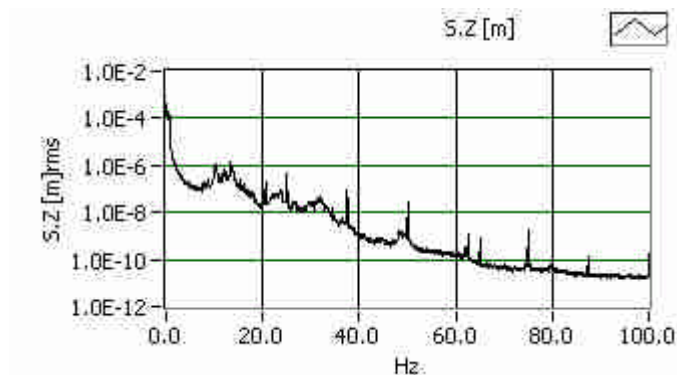


Figure 57. Displacement spectrum along Rz-axis, on the SODAR reflector board

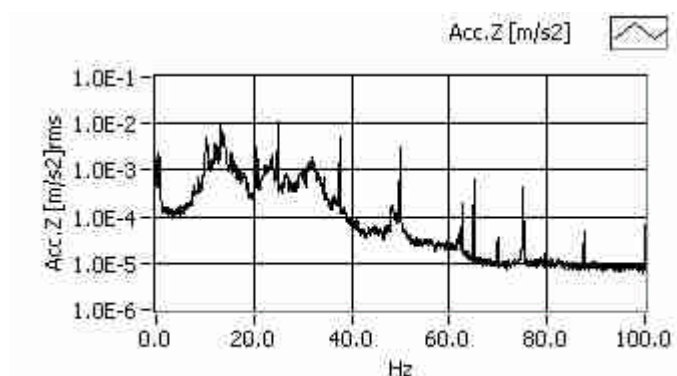


Figure 58. Acceleration spectrum along Rz-axis, on the SODAR reflector board

At the lower frequencies the amplitude is of the same order of magnitude as next to the SODAR (Figure 53). At higher frequencies the way the reflector board is mounted has probably affected the acceleration spectrum.

3.8 Compilation of Results

The following table gives an overview of the different measurements:

Table 5. Overview of accelerations, speeds and displacements, taken as RMS-average over 0.1 second.

Location	Variable	Ref. frame	A(x) [m/s ²]	A(y) [m/s ²]	A(z) [m/s ²]	V(y) [m/s]	V(z) [m/s]	S(z) [m]
Generator	average	D	0.2060	0.2060	10.0749	0.003	0.003	0.002
Generator	absolute maximum	D	0.2649	0.3139	10.0945	0.012	0.020	0.010
Old location	average	D	0.0589	0.1766	10.0847	0.002	0.001	0.000
Old location	absolute maximum	D	0.1177	0.2354	10.1141	0.007	0.003	0.001
Next to the SODAR	average	D	0.3728	0.0196	10.0749	0.002	0.001	0.000
Next to the SODAR	absolute maximum	D	0.4022	0.0392	10.0847	0.006	0.006	0.004
Reflection board	average	R	0.1962	0.0098	0.0294	0.003	0.001	0.001
Reflection board	absolute maximum	R	0.2943	0.0294	0.0785	0.008	0.012	0.006

This table has been prepared by performing a calculation at each location, for each axis (x, y, z) and for each variable (acceleration, speed and displacement). These calculations were performed over a time of 0.1 second to get the mean values, standard deviations and RMS-mean values.

The whole data set contained data over a longer period of time. From this data set, the mean RMS and maximum RMS values are shown. The value of 0.1 second has been chosen because this is roughly the duration of the beam and also because it is a typical time in which the SODAR gets returns from a certain altitude. RMS-averages over longer periods are expected to be lower than those over 0.1-second. As we were interested in maximum values, we have not looked at longer periods.

After the analysis it appeared that the vibration levels were (very) low. If we therefore concentrate on the measurements with the highest values and if we can show that these are not affecting the SODAR significantly then this could also be assumed to be true at other times. As the RMS-mean is always larger than the normal mean, we have focussed on the RMS-mean. We have also calculated the maximum RMS-mean that we have encountered for the various signals. The measurements in the R-reference frame had to be treated differently. As this measurement was performed under a 45-degree angle from the vertical, both the X-axis and Z-axis registered a mean acceleration of approximately 6.8 [m/s²]. This mean had to be subtracted from the obtained values to get the true vibrations along these axes.

As can be seen from Table 5, all measured speeds are lower than 1.5 [cm/s] and thus the effect of the speeds can be neglected. This is because the speeds are small with reference to the other SODAR measurement uncertainties, which are in the order of 50 [cm/s]. Also the displacement of the reflector board is small, less than 6 [mm] at the centre. As the whole reflector board is more than three metres long and over 1.5 metres wide, the displacement is less than 0.4% in either direction. This displacement has a negligible effect on the SODAR beam.

Another consideration that must be taken into account for assessing the influence of vibrations on the SODAR, is that the above data has been taken with respect to a single beam and for a single return. The SODAR produces normally 10-minute average values and as such this consists of 6000 times a 0.1-second period. In 10 minutes many different vibrations will

affect the SODAR thus that the cumulative effect will be almost zero. Any effect on 0.1-second will be averaged away at 10 minutes. This is another reason why no influences from vibrations are expected.

It should not be forgotten that these measurements are indicative and only represent the situation at the MPN island under mild wind and wave conditions. At other structures and with different weather conditions the results will be different. However, the resulting speeds and displacements from our measurements are so small that no large effect from vibrations on the SODAR is expected.

3.9 Conclusions with regard to Vibrations

From the results of the measurements the following can be concluded:

- Speeds caused by vibrations in the SODAR hardware do not affect the SODAR measurements. The maximum speed observed was less than 1.5 cm/s. This value is about 33 times smaller than the SODAR measurement uncertainty as reported by the manufacturer.
- Displacements caused by vibrations in the SODAR hardware also have a negligible effect on the wind speeds measured by the SODAR. The maximum displacements do not exceed 0.4% of the reflector board size.
- Because the SODAR measurements are normally reported as 10-minute averages, all vibration effects (which are determined on 0.1-second periods) on the SODAR equipment will be zero on average.

4. CONCLUSIONS AND RECOMMENDATIONS

The partners in the WISE project investigate whether application of the SODAR measurement technique in wind energy experimental work is feasible as a replacement for cup anemometers, wind direction sensors and tall meteorological masts. In Work Package 2 of the WISE project extensive controlled experiments with the SODAR are performed. Part of the work package is the measurement of vibration and noise on an offshore SODAR system. ECN performed measurements at onshore and offshore locations to investigate the influence of noise and vibrations on the performance of a MiniSODAR measurement system. The aim of the measurements is to quantify the effect of these external noise and vibrations disturbances on the MiniSODAR's performance. Measurements on an identical SODAR system onshore are carried out to compare the disturbances of offshore and onshore external conditions.

Noise measurements

The effect of background noise on SODAR operation has clearly been established in literature. Therefore, measurements have been performed only to establish the absolute sound pressure levels. This is done at the MPN location offshore and at two locations onshore. At the MPN-island, the SODAR has been relocated from the middle deck to the upper deck to diminish the influence of the diesel generator needed for the electric powering of the island. Although the absolute sound pressure level became higher at the new location, this level became lower at the most important frequencies inside the SODAR, due to the use of absorbing foam. With regards to the sound pressure level the relocation improved the situation.

It is found that the sound pressure levels measured offshore were 6 to 15 dB higher than for the two locations measured onshore. Research showed that background noise has a negative effect on SODAR performance [7]. Therefore, under offshore conditions a negative effect of the background noise on the SODAR measurements is expected.

Vibration measurements

The vibrations in the metal structure of the offshore island might have influenced the SODAR, although measurements showed that the effects are negligible with regards to the normal SODAR measurement uncertainties.

4.1 Recommendations on Offshore SODAR Operation

It is recommended to limit negative effects of background noise offshore by performing noise measurements in advance and by choosing a position for the SODAR equipment based on these measurements. As the most important frequencies lie in a frequency band of approximately 4500 ± 300 Hz and because of the limited A-weighted filtering of the human ear, it is recommended to select the best position on an offshore island using instruments and not just by listening.

5. REFERENCES

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