

TNO report**TNO 2013 R11916****Underwater noise measurements in the North
Sea in and near the Princess Amalia Wind
Farm in operation****Technical Sciences**

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Summary

The Princess Amalia Offshore Wind Farm (in Dutch: Prinses Amaliawindpark, or PAWP) is one of the first two operational offshore wind farms near the Dutch shore. One of the conditions imposed by the legislator is to monitor the underwater noise during operation of the wind farm. This report covers the execution, analyses and results of the acoustic monitoring of PAWP in operation.

The measurements were conducted according to an operational plan, which has been approved by the authorities. Ambient sound pressure levels were determined at a location 100 m distance from a turbine and at the same time, at a location further away at 3.8 km distance. In order to check if the turbine contributes to the ambient noise levels, the sound pressure levels at both locations are compared for three wind speed ranges between 4 and 14 m/s at hub height. In total 24.4 hours of data has been collected for wind speed range 1 (4-6 m/s) and 77.7 hours for range 2 (6-12 m/s). For the highest wind speed range (12-24 m/s) 2.2 hours of data could be recorded during the selected monitoring period.

The ambient noise levels at sea can be caused by various sound sources, like wind and shipping noise. The offshore wind farm could contribute to the ambient noise through turbine noise, generated by rotating shafts and transmission gears, and increased shipping noise, from the wind farm service ships. The measured noise levels depend on environmental conditions. Meteorological, operational, environmental and shipping traffic conditions were therefore monitored and documented in this report.

The time-average broadband sound pressure levels on both locations show no significant differences. Only a narrow band analysis of the sound measured at the location close to the operational turbine reveals some tonals, which are caused by the gearbox transmission of the turbine. Even at the location close to the turbine, these tonals do not dominate the broadband sound pressure level. At a distance of 3800 m, these tonal contributions of the turbine to the underwater noise were not found. Hence, the noise from the operational wind turbines in the PAWP is too low to be of use for the validation of underwater sound propagation models.

The 95% exceedance level L_{95} is the sound pressure level which is exceeded for 95% of the time. The increase of L_{95} with increasing wind is equal within 1 dB for both measurement locations, which indicates that L_{95} is probably determined by distant shipping and surface waves. For the location close to the turbine, L_{95} is partly affected by turbine noise in the lower frequency range.

It is likely that the measured underwater noise up to 500 Hz can be perceived by harbour seals, but not by harbour porpoises. This includes wind turbine related noise at a close range of 100m.

The data set for the highest wind speed range was limited to 2 hours, due to the prevailing weather conditions during the monitoring period. The available data do not show clear differences between the underwater noise at the two measurement positions. It is highly unlikely that additional measurements in the highest wind speed range will lead to a different conclusion. Hence it is considered unnecessary to undertake an additional campaign to collect more acoustic data in the highest wind speed range.

Abbreviations

AIS	Automatic Identification System
CPA	Closest Point of Approach
HSS	High Speed Shaft
LSS	Low Speed Shaft
PAWP	Prinses Amaliawindpark
SESAME	Shallow water Extendable Stand-alone Acoustic Monitoring Equipment
SPL	Sound Pressure Level
WTG	Wind Turbine Generator

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1 Introduction

The Princess Amalia Offshore Wind farm (in Dutch: Prinses Amaliawindpark, or PAWP) is one of the first two operational offshore wind farms near the Dutch shore, see Figure 1.1. One of the conditions imposed by the legislator is to monitor the underwater noise both during construction and operation of the wind farm. The acoustic monitoring during the construction phase has already been conducted and reported by TNO in 2007 [1]. This reports covers the execution, analyses and results of the acoustic monitoring of PAWP in operation.



Figure 1.1 Overview of Princess Amalia Offshore Wind Farm [ref. beeldbank.rws.nl].

The aim of the monitoring is to quantify the ambient underwater noise levels in and near PAWP at nearly 4 km distance at different wind speed conditions. Ambient noise levels at both locations are compared in order to check if the turbines contribute to the noise levels at close and at larger distance. For this purpose the influence of shipping on the ambient noise levels is quantified as well. Additionally, the operational and environmental conditions during the measurements are reported.

Vibrations induced by rotating shafts and gear wheels of the turbine are transmitted to the tower structure and can radiate into the water [7]. Wind turbine related noise levels are expected to depend on the output power of the turbine, which is a function of rotational speed and torque. These parameters are controlled by governing wind speed and by settings of the controllable pitch of the blades. The turbines at PAWP are of type Vestas V80 with a maximum output power of 2 MW.

The underwater noise levels that are measured near a wind turbine in the North Sea are not only caused by the wind turbine, but also by shipping noise, wind generated and precipitation noise. Therefore, the measured noise levels depend on environmental conditions, such as shipping density, and weather conditions. Meteorological, operational, environmental and shipping traffic conditions, including service ships for PAWP, were also monitored and are documented in this report.

In 2012 TNO wrote an operational plan for the determination of the noise level and the type of noise during operation of PAWP [2]. This plan has been approved by the

authorities. The acoustic monitoring was conducted between July 11th and July 23rd 2013 according to this operational plan.

One aim of the measurements was to obtain data of the sound generated in operational wind farms, for use in the future to produce sound maps in and around the wind farm. The sound exposure to sea mammals and fish due to wind farm related activities can then be assessed. Such studies may result in input for the formulation of future legislation conditions. These extra analyses are not within the scope of this report, which only covers the results of the monitoring exercise and its statistics.

Chapter 2 explains the main definitions that have been used for the analyses. In Chapter 3 the underwater noise measurements are covered. The way of data analysis is covered in Chapter 4, and results are shown in Chapter 5. Finally in Chapter 6 conclusions are drawn.

2 Definitions

2.1 Sound pressure level

The sound pressure level (SPL) is a measure of the average squared acoustic pressure defined by

$$\text{SPL}(T) \equiv 10 \log_{10} \left[\frac{1}{T} \int_0^T \frac{p^2(t)}{p_{\text{ref}}^2} dt \right], \quad (2.1)$$

where T is the duration of considered time interval in [s] and p is the acoustic pressure in units of μPa ($p_{\text{ref}} = 1 \mu\text{Pa}$ is the reference pressure). The SPL is expressed here in units of dB re $1 \mu\text{Pa}^2$.

2.2 1/3 octave bands

There are two ANSI and ISO approved approaches to determine the exact centre frequencies for 1/3-octave bands [3]. Both approaches use a centre-band frequency of 1000 Hz as a basis. In the first approach (the so-called base-ten approach) the ratios of centre-band frequencies for adjacent bands equal $10^{\pm 1/10}$. In the other approach (the so-called base-two approach) the ratios of centre-band frequencies equal $2^{\pm 1/3}$. The lower and upper edge-band frequencies are obtained by multiplying the centre-band frequencies by $2^{-1/6}$ and $2^{1/6}$, respectively. The differences between the centre-band frequencies of both approaches are maximally in the order of 1% in the considered frequency range between 20 Hz and 80 kHz. In the present analysis the base-two approach is used to determine the 1/3-octave bands. According to the standards, the frequency bands are indicated by nominal rather than exact centre-band frequencies.

2.3 Exceedance Levels

During the study, the exceedance levels according to ISO 1996-1 are applied: L_5 , L_{50} and L_{95} in dB re $1 \mu\text{Pa}^2$, see also [4]. Each exceedance level indicates the percentage (5%, 50%, and 95%) of measurements for which the SPL has a higher value than the exceedance level.

3 Underwater Noise Measurements

3.1 Introduction

The underwater noise measurements were conducted according to the operation plan [2]. During one period of 12 days the underwater noise was recorded at two locations in and near PAWP. The noise was recorded at three ranges of wind speed conditions: 4-6 m/s, 6-12 m/s and 12-24 m/s. For each range it was aimed to record at least 24 hours of data.

3.2 Measurement method

3.2.1 *Measurement locations*

The underwater noise measurements were recorded simultaneously at two locations, see also Figure 3.1:

H1 at the edge of the wind farm, at 100 m distance from turbine WTG1, see also Figure 3.4.

H2 at a distance of 3780 m from WTG1 in North Eastern direction .

Exact locations of the measurement points are listed in Table 3.1.

Both measurement locations were selected North-East of PAWP. In this way, both locations have about equal distance to shipping lanes and are away from anchor locations South and South-West of PAWP. Figure 3.2 gives an overview of the location of main shipping lanes relative to the measurement locations.

The measurement systems were deployed at 100 m distance from an anchored marking buoy.

Table 3.1 GPS locations (WGS84 coordinates) of WTG1 and the measurement locations H1 and H2.

WGS84	N [deg]	E [deg]
H1	52.60549	4.24107
H2	52.63231	4.27295
WTG 1	52.604579	4.240736

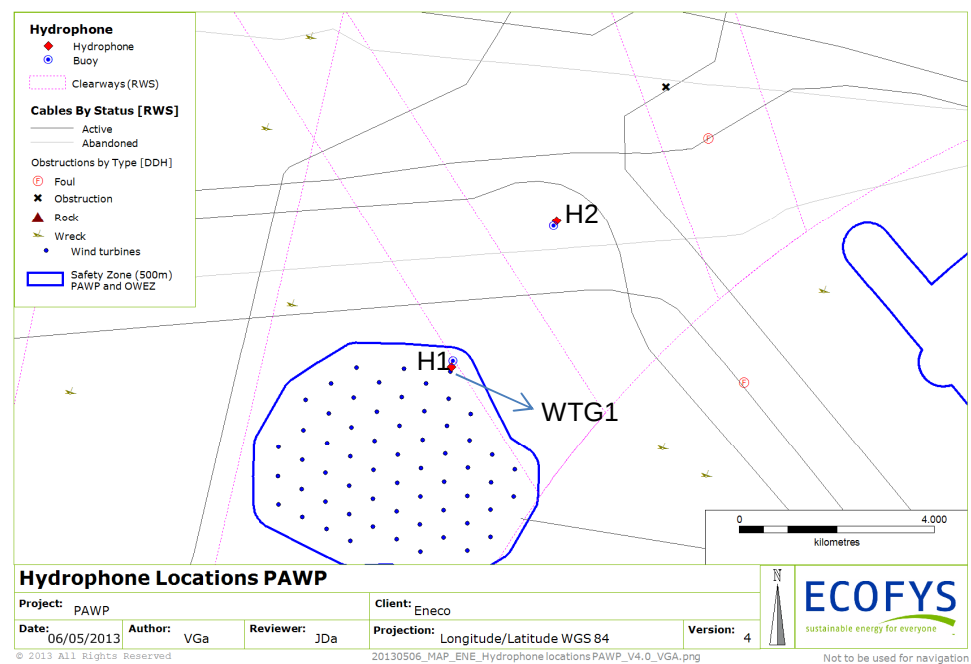


Figure 3.1 Locations of wind turbine WTG1 and measurement locations H1 and H2 in red. The marking buoys are shown as blue concentric circles.

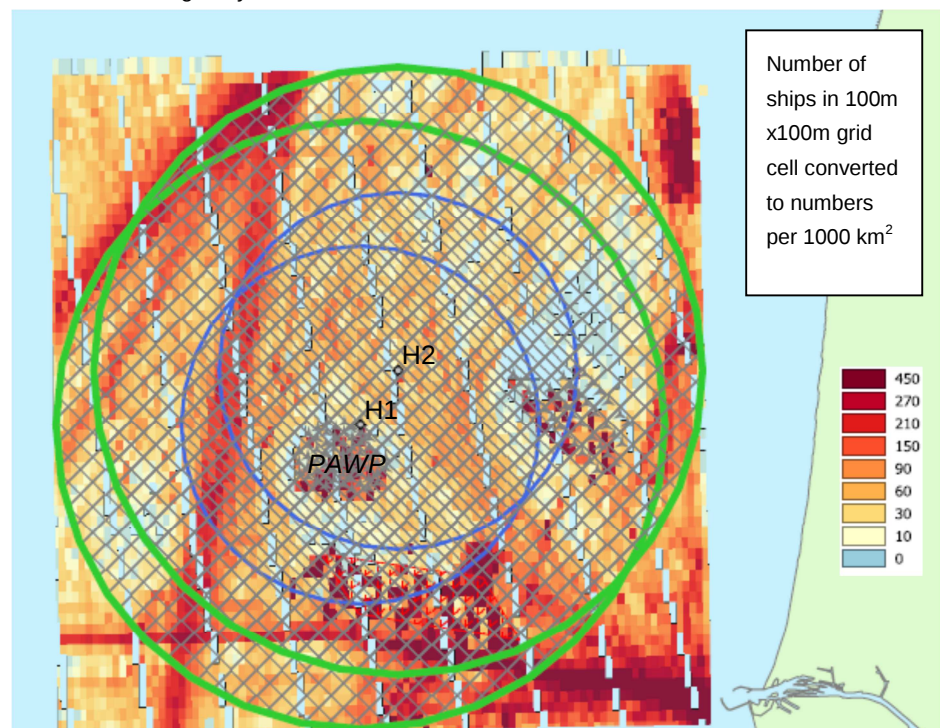


Figure 3.2 Shipping map of the area around the measurement locations, indicating the main shipping lanes [ref. Marin]. The map is based on real AIS data, monitored over the measurement period of 12 days. The number of ships are presented as a fraction of time (one minute intervals) in which one or more ships were present in a cell (e.g. 450 implies during 78 out of 17,280 minutes ships were present in the cell). The green circles indicate the area around both measurement locations, with 17 km radius, for which AIS and radar data has been obtained. Blanks in the data are due to the required limited size of the cells.

3.2.2 *Measurement systems*

Two different autonomous measurement systems were applied during the monitoring. The TNO system SESAME was deployed at location H1 near the turbine, see appendix A for more details. For the second measurement point TNO commissioned the Germany company *Institut für Technische und Angewandte Physik GmbH* (ITAP). More details about the their systems can be found in appendix B.

3.2.3 *Time scheme measurements*

The monitoring period started 11 July 2013 at 13:00 local time and ended 23 July 2013 at 11:00, resulting in a monitoring period of almost 12 days.

According to [3] (p.41): 'In order to reduce the amount of data to be stored, observation periods may be divided into intermittent measurement periods of e.g. 5 s per minute'. Here 6 s samples are taken.

Both measuring systems were synchronized by GPS time prior to the measurements.

Prior to deployment, the Sesame system at position H1 was started at exactly the beginning of a minute, according to GPS time. In this way the first 6 seconds of every minute were recorded (10% duty cycle).

The applied ITAP systems have a maximal duty cycle of 10 minutes recording time every 30 minutes. In order to increase the duty cycle, two identical measurement systems were installed, with two separate hydrophones. Prior to deployment, the first ITAP recorder was started at exactly the beginning of a minute. The second recorder was started exactly 15 minutes after the first, resulting in an effective duty cycle of 67% (10 minutes recording every 15 minutes).

Due to some technical problems with the cold start of the recorders at location H2, they did not record noise during the entire measurement period. For both recorders, some time frames were not present. Since the recordings on both locations require synchronous analysis, recordings of Sesame in the missing time frames were not addressed for the analysis per wind speed condition, see Section 4.1.

3.2.4 Measurement set-up

Figure 3.3 shows a schematic overview of the measurements, with the locations of the measurement systems and hydrophones relative to wind turbine WTG1.

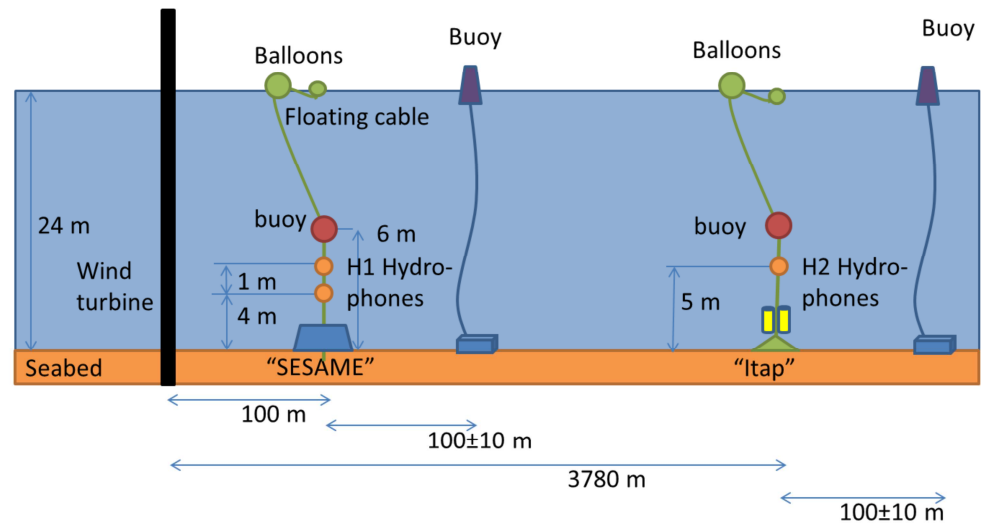


Figure 3.3 Schematic overview measurement set-up.

3.2.5 Monitoring of environmental conditions

Additionally to the recording of the underwater noise the following conditions were also stored or collected during the measurements time:

Operational conditions turbines

- Rotational speed input shaft [rpm];
- Power [kW];
- Orientation nacelle [degrees];
- Number of turbines surrounding WTG1 in operation. All turbines were monitored.

Environmental conditions

- Bathymetry and tide;
- Properties seabed;
- Speed of sound over water depth [m/s], measured at both locations by TNO;

Meteorological conditions

- Wind speed and wind direction (10 min intervals), measured on top of turbine at 60m height;
- Wave height [m] (10 min intervals);
- Precipitation;

Shipping traffic

- AIS data in combination with radar (1 min intervals); GPS locations of ships (WGS84) within 17 km range from the two measurement locations, speed [knots], length [m].



Figure 3.4 Deployment and recovery vessel 'Terschelling' near WTG1 Vestas V80 turbine. The orange and yellow floats, within the red circle, indicate position H1 with Sesame deployed.

4 Data Analysis

4.1 Data selection

The aim was to record the underwater noise in three wind speed ranges: 4-6 m/s, 6-12 m/s and 12-24 m/s. For each range it was aimed to record at least 24 hours of data. PAWP provided the measured wind speed of WTG1 as a function of time for the entire measurement period. From this data, the required acoustic data was determined according to the following criteria:

- Wind speed is within one of the three defined speed ranges;
- WTG 1 is operational; production output power > 0 kW;
- All measurement systems on both locations were operational and recording acoustic data;

The SPL at location H1 was determined for every minute throughout the measurement period and is shown in Section 5.1. However, for the averaging of the SPL over the various wind speed ranges, Section 5.2, the data on both locations has been analysed with the 67% duty cycle, as determined by the measurement systems at location H2.

4.2 Determination of sound pressure levels in 1/3-octave bands

4.2.1 *Measurement system at location H1*

From the data recorded by the measurement system at location H1 (with two hydrophones), sound pressure levels (SPLs) in 1/3-octave bands were determined. The following steps were taken to convert the stored 16-bit data into SPLs for 1/3-octave bands:

- The 16-bit data were converted to time series of voltages by using the information on the set voltage range of the ADC and the sample frequency. The resulting time series for each measurement corresponds to a time interval of 6 seconds.
- The 1/3-octave band SPL spectra were determined in the time domain by using digital filters fulfilling ANSI S1 [3].
- The frequency components of the voltages were converted to frequency components of the acoustic pressures registered by the hydrophones. This was done by accounting for the frequency dependent filter (see Appendix A) and the applied amplification factor.
- The SPL's of both hydrophones were energy averaged.

4.2.2 *Measurement system at location H2*

From the data recorded by the measurement systems at location H2 (with two separate hydrophones on the separate recorders), sound pressure levels (SPLs) in 1/3-octave bands were determined. The following steps were taken to convert the stored 16-bit data into SPLs for 1/3-octave bands:

- The 16-bit data (wave files) contain voltages. The 1/3-octave band SPL spectra were determined in the time domain by using digital filters fulfilling ANSI S1 [3].
- The frequency components of the voltages were converted to frequency components of the acoustic pressures registered by the hydrophones.

For both measurement systems, each determined SPL value is based on a time interval of the first 6 seconds of a minute.

4.3 Measures of shipping conditions

Information on all shipping, including service ships of PAWP, within a 17 km range of H1 and H2 was provided by PAWP using an AIS (Automatic Identification System) receiver in combination with radar data. *Shipping density measures* [5] were determined from the available information on the positions and speeds of ships. The distances of all ships within this range, relative to the measurement locations were determined every minute. By using these distances, the following shipping density measures were determined for each minute of the recording period:

- The distance to the nearest ship (ND)
ND can be used to identify service ships entering the wind farm and passing the measurement station H1 at very close range.
- Weighted sums N_n over a selection of ships:

$$N_n = \sum_i r_i^{-n}, \quad \text{with } n = 2 \quad (4.1)$$

where i labels the selected ships, and r_i is the distance of each ship relative to the location of the measurement. These measures take into account the number of ships in the vicinity of the measurement as well as the distances of these ships relative to the measurement location. In the analysis of earlier background noise measurements [5], it was found that the N_2 measure, with r_i^{-2} -weighting, exhibited a correlation with the measured noise. The N_2 measure gives a very rough estimation of the potential contribution of ships to the measured background noise, based the following assumptions:

- all ships have the same source level
- propagation loss is due to spherical spreading only.

In this report, N_2 will be used as an indicator of the relevant shipping density in the vicinity of the hydrophone. In the analysis, only moving ships were included. Selected ships were required to have a speed higher than 1 m/s.

4.4 Wind noise

In order to investigate to what extent the factor wind has affected the measured background noise, the correlation between the wind speed and the measured noise levels were determined. For this purpose wind speed information, measured on top of the turbine at 60m height, was provided by PAWP. The provided wind speed data represents the 10 minute averages of the wind speed in units of m/s.

The correlation of measured SPL and governing wind speed is investigated.

For this purpose, the wind speed measurement points are plotted against the underwater sound pressure levels, averaged over the same time window.

In case wind generated noise is dominating the SPL, both parameters will show correlation.

5 Results

The former chapter discussed the way in which the measurement data has been analysed. This chapter shows all results of the analyses.

5.1 Overview sound pressure levels

Figure 5.1 shows the overall broadband SPL as a function of time for the entire monitoring period of 12 days. The broadband SPL is determined in the frequency range between 20 Hz and 63 kHz for location H1 and 20 Hz and 16 kHz for location H2. According to the operation plan, the frequency range for the location close to the turbine, was selected to be from 50 Hz. However, since a detailed analysis of the noise indicated tonals of the turbine to be present between 25 Hz-28 Hz, see Section 5.3, it was decided to extend the frequency range for location H1 down to 20 Hz. The effect of the high-pass filter was taken into account, see appendix A.

Per minute, the SPLs are averaged over a time duration of the first 6 seconds of that minute. For the measurement system of location H1 the results of the two hydrophones are energy averaged. Due to the limited duty cycle of the measurement system at location H2, there is a 5 minute blank in the data after every 10 minutes.

The dynamic range of the total sound pressure levels is large, about 40 dB at both locations. The maxima are caused by pass-by of near-by shipping traffic, resulting in local maxima at the *closest point of approach* (CPA) of individual ships to the location of the measurement systems, see also Section 5.5.

Figure 5.2 show histograms of the broadband SPL, for all wind conditions, showing a similar distribution.

Figures 5.3 show spectrograms of the SPL, which show the frequency content of the SPL in 1/3 octave bands as a function of time (one spectrum averaged over the first 6 seconds of each minute). Whereas the upper two figures cover the entire measurement period, the lower two figures cover the first day only. In this way individual ships passing-by can be recognized for both measurement locations. Both measurement systems can be seen to have recorded synchronously. The white vertical stripes in the spectrogram of H2 are caused by the data blanks due to the applied duty cycle and limited operation time of the measurement system at location H2.

It should be noted that in Figures 5.1 and 5.3 SPL data is shown for every minute on location H1. In the same figures the applied duty cycle of the systems at location H2 can be seen by the blanks in the dataset. Only the data of H1 in the periods that overlap with the recordings of H2 have been used for the averaging of SPLs per wind speed range.

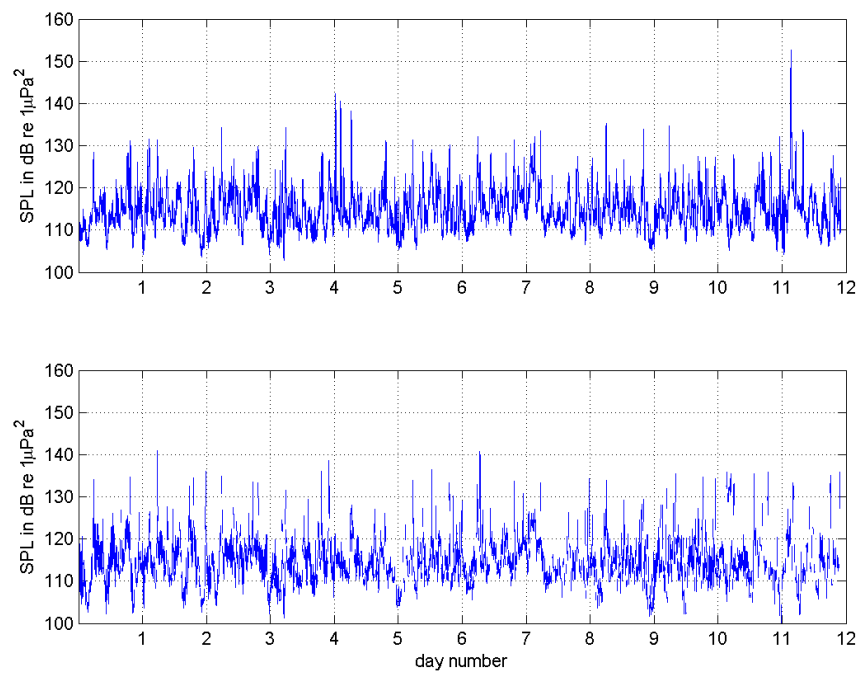


Figure 5.1 Broadband sound pressure levels as a function of time, resolution of one minute, at both measurement locations (upper H1; lower H2).

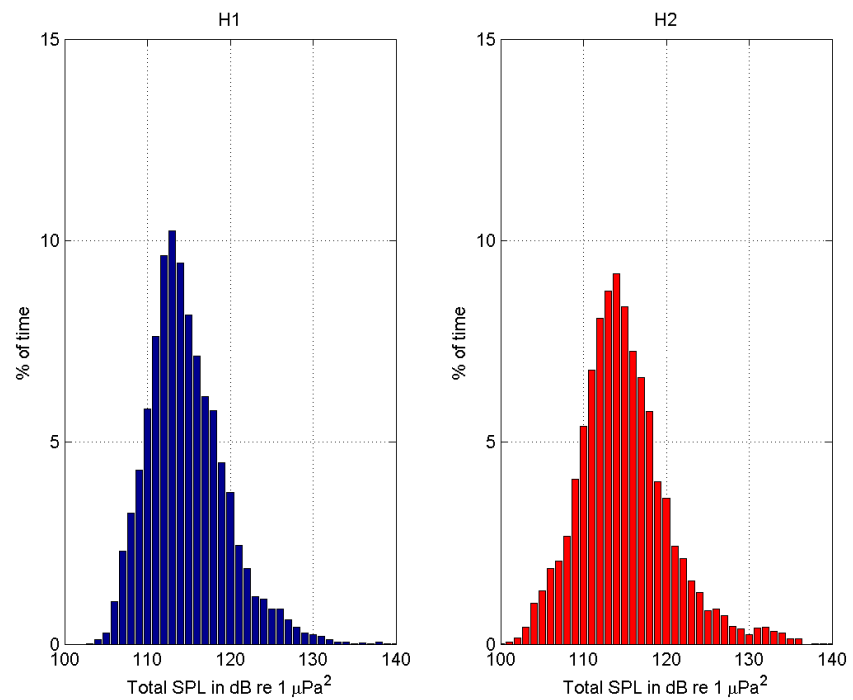


Figure 5.2 Histograms of the broadband sound pressure levels (in 1 dB steps) for all wind condition at locations H1 and H2.

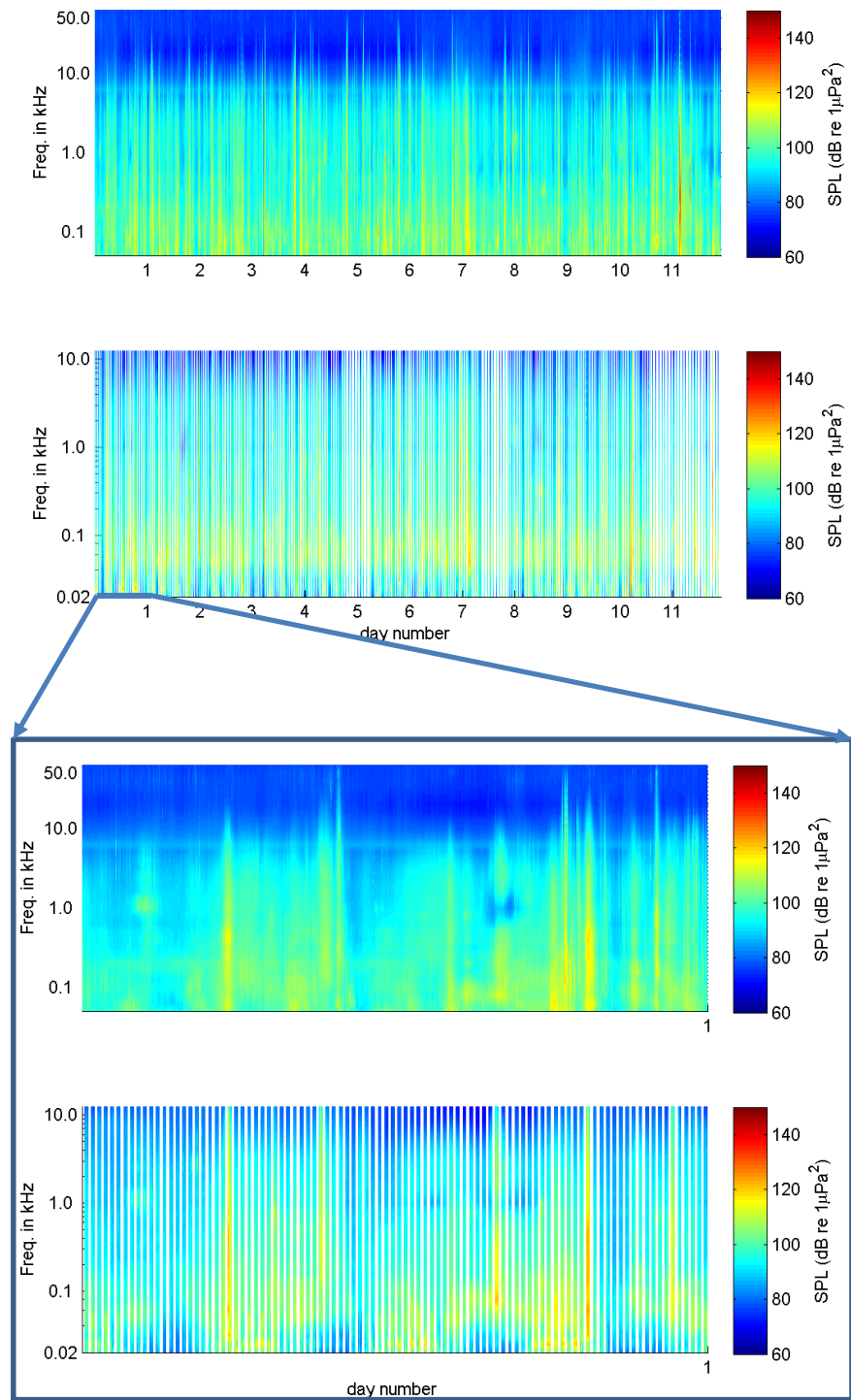


Figure 5.3 Sound pressure levels in 1/3 octave bands as a function of time, resolution of one minute, at both measurement locations (H1 upper, H2 lower). The lower plot shows a spectrogram zoomed in on the first measurement day.

5.2 Sound pressure levels per wind speed range

Next, the SPLs are determined per wind speed range. As discussed in session 4.1, the aim was to record the underwater noise in three wind speed ranges: 4-6 m/s, 6-12 m/s and 12-24 m/s for at least 24 hours. PAWP provided the wind speed of WTG1 as a function of time for the entire period. The wind speed is measured on top of the turbine at a height of 60 m above the waterline. From this data, the time frame for which acoustic data could be used was determined according to the following criteria:

- Wind speed is within one of the three defined speed ranges;
- WTG is operational, which implies that the output power > 0 kW;
- All measurement systems were operational and recording data.

Figure 5.4 shows the wind speed, rotational speed of the generator input shaft and output power of WTG1, during the monitoring period. This data was provided by PAWP, at 10 minute intervals. The colour coding shows which of the data points was used per wind speed conditions, based on the criteria above. In total the usable data set consisted of 24.3 hours for wind speed range1, 77.7 hours for range 2. For the highest wind speed range (12-24 m/s) only 2.2 hours of data could be recorded during the selected monitoring period, during which the turbine produced at maximum output for about 15 minutes.

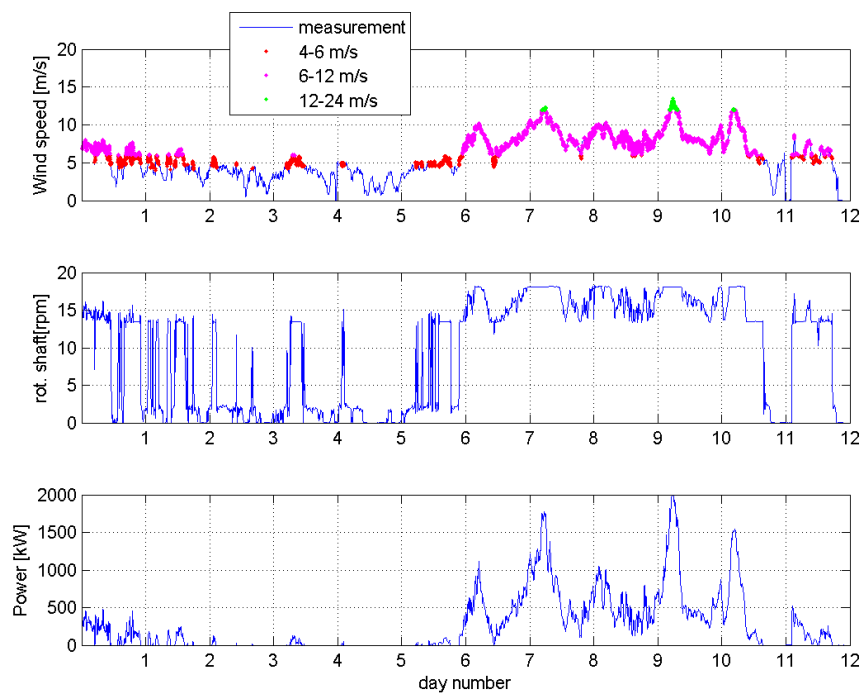


Figure 5.4 Measured wind speed, turbine input shaft rotational speed and produced power for WTG1 during the monitoring period (source PAWP). Colour-coded data points indicate usable data, based on wind speed, turbine's operational conditions and availability of acoustic data.

Figure 5.4 shows that the rotational speed of the turbine is limited to 18.1 rpm at a governing wind speed of about 10 m/s, which is in the second wind speed range (6-12 m/s). However, the output power does reach its maximum at a wind speed of about 13 m/s, in the highest wind speed range. This can be explained by some

basics on variable-speed pitch-regulated turbines, as clarified by PAWP in the next paragraph.

The Vestas V80 – 2 MW offshore wind turbine is a variable-speed wind turbine. A variable-speed wind turbine can control generator torque and blade pitch in order to maintain the necessary rotational speed. Since the rotational speed of a wind turbine is related to its power output as: $\text{Power} = \text{Torque} \times \text{Rotational speed}$, power can increase with constant speed and increasing torque. At lower wind speeds (e.g. $< 9 \text{ m/s}$), the wind turbine control system aims to capture as much power as possible. Thus, the rotor speed increases proportionally to the wind speed, see also appendix D. This control strategy is used until the rotational speed reaches its nominal value – which in the case of the Vestas V80 – 2 MW offshore wind turbine is 18.1 rpm. Above this wind speed (and below rated power), the wind turbine controller maintains a nearly constant rotational speed and increases torque, resulting in increasing power. Above rated power (2 MW), the wind turbine controller pitches the blades to maintain constant generator torque and rotational speed, so constant power, [6].

In the lowest wind speed range, the rotational speed is very low (2 rpm) for wind speed smaller than 5 m/s, which is nearly stationary. For wind speeds larger than 5 m/s, the rotational speed is higher (14 rpm), see also Figure D.1 and D.2 in appendix D.

Next, the measured SPLs are categorized per wind speed condition. Figure 5.5 shows the distribution of SPL and wind speed for the selected data points per wind speed range by histograms. Also, the distribution of the shipping density (N_2 factor of eq.4.1) is shown. For this purpose the shipping density is presented in dB re 1 km^{-2} ($10\lg(N_2/\text{km}^{-2})$). A high value implies that ships are closer to the measurement locations (eg. 0 dB: $N_2=1 \text{ km}^{-2}$; -10 dB: $N_2 = 10 \text{ km}^{-2}$). High values for $10\lg(N_2/\text{km}^{-2})$ ($>5 \text{ dB}$) are related to PAWP service ships, entering the wind farm at close range. PAWP has confirmed that all service ships sail in a straight line from IJmuiden harbour to the wind farm. Therefore, the tracks of these ships are much closer to measurements location H1 than to H2. The variation in distribution of shipping density between the wind speed ranges and measurement locations is small.

The histogram for the highest wind speed range is based on only 2 hours of data (120 SPL data points). The SPL histograms do not show a smooth (Gaussian) distribution like for the other wind speed ranges at both locations. For this, a longer monitoring period would be required.

Table 5.1 lists the total values of the exceedance levels, derived from the spectra, as shown in Section 5.4 by taking the energy sum in frequency range from 20 Hz to 16 kHz for location H2 and 20 Hz to 63 kHz for location H1.

L_{95} is governed by the wind turbine, wind effects and distant shipping. Table 5.1 shows that L_{95} is equal within 1 dB for wind speed ranges 1 and 2 for both locations. For wind speed range 3, L_{95} on location H1 is 3 dB higher relative to the lower wind speed ranges. At location H2, L_{95} is 2 dB higher than for the lower wind speed ranges. So the contribution of turbine noise and other wind farm related noise contribution to L_{95} appears to be less than 1 dB. It can be concluded that the noise

generated by the operational wind farm does not significantly increase the local ambient noise due to shipping and surface waves.

L_5 can be expected to be a good indicator for shipping noise of near-by traffic, since L_5 captures the outliers of data. These outliers are caused by the pass-by of shipping traffic, as is shown in Section 5.5. The variation in L_5 levels is small, within 2 dB, for various wind speed ranges at the two measurement locations, even though the averaging time for wind speed 3 range was small.

Figure 5.5. shows that the limited amount of data (only 2h) in the highest wind speed range results in a less clear estimation of the shape of the statistical distribution of the data. Therefore the estimation of L_{95} and L_5 are less accurate for wind speed range 3. However, the distributions are clear enough to have confidence in the order of magnitude of the measured SPLs in this wind speed range.

Table 5.1 also contains the energy average (equivalent sound pressure level) over all wind speed conditions. The average level at H2 (120 dB re $1 \mu\text{Pa}^2$) is 2 dB higher than at H1 (118 dB re $1 \mu\text{Pa}^2$). This suggests that the ambient noise measured at H1 is not dominated by turbine noise and that the average noise level at both locations is dominated by shipping noise.

Since differences of L_5 and L_{eq} between both measurement locations are small, it can be concluded that the no increase of the noise level due to PAWP service ships has been found.

Since the wind turbine noise is expected to be maximal at the highest wind speed range (based on maximum output power and maximum rpm), it will be further investigated in the next section to what extent the wind turbine contributes to the broadband SPL in this wind speed range.

Table 5.1 Total broadband values for three exceedance levels and for the mean square sound pressure level (L_{eq}) per wind speed range at the two measurement locations in dB re $1 \mu\text{Pa}^2$.

	Location	range1	range2	range3	All ranges
L_5	H1	123	124	124	124
	H2	124	125	126	124
L_{50}	H1	113	113	116	113
	H2	112	113	115	113
L_{95}	H1	107	107	110	107
	H2	105	105	107	105
L_{eq}	H1	118	118	118	118
	H2	119	120	121	120

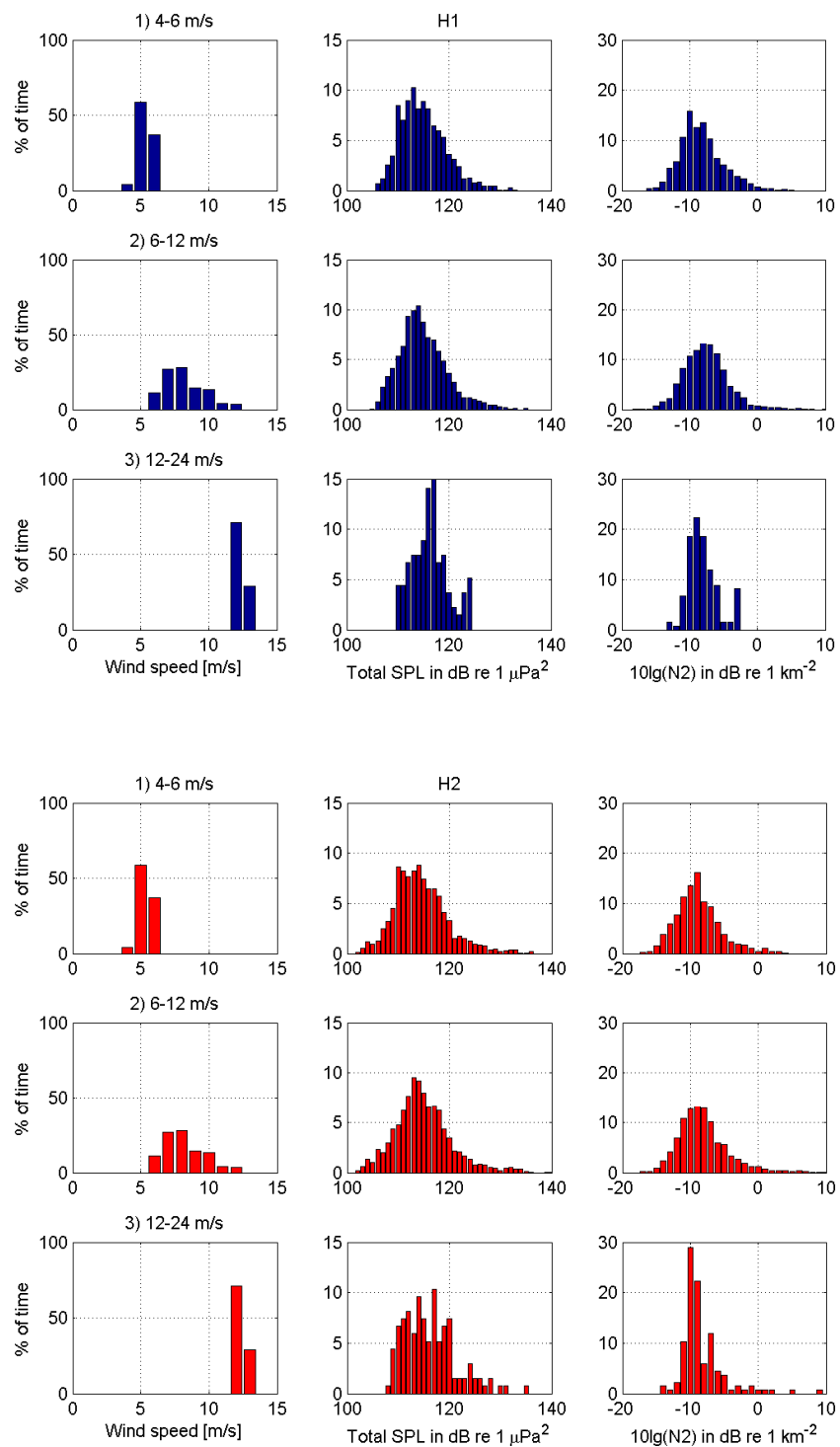


Figure 5.5 Histograms of wind speed and SPL's and shipping density N_2 for all applied measurement points per wind speed range for both locations (H1, upper, H2, lower).

5.3 Narrow-band analysis

Previous studies have shown that the underwater noise radiated from operational wind turbines is dominated by tones at frequencies associated with the rotation of the gears in the nacelle, see e.g. [7]. In order to be able to identify such tonals, a discrete Fourier-transform was applied to the time series covering 6 s for both measurement locations. In the Fourier-transform a time weighting was performed by using a Hanning window, and with a 50% overlap. The block size equals the sample frequency, resulting in a 1 Hz frequency resolution.

Table 5.2 shows the tones of the gears at various rotational speeds of the low speed shaft (LSS). The rotational speed of the high speed shaft (HSS) is calculated from the gear transmission ratio. The gearbox of the turbine is of type EH804A Offshore (ZF/Hansen), and has a transmission ratio of 1:92.3. Also, the gear meshing frequency of the gear wheels on the HSS is listed, which have 26 teeth. Tonal noise at this frequency is expected for the gear transmission noise. The transmission gearbox of the turbine, which is a multi-stage transmission with a planetary gear from the low speed shaft to an intermediate shaft, and another gear transmission to the high speed shaft, will generate multiple tones. Exact details on all transmission stages are not available at TNO.

Figure 5.6 shows a narrowband spectrogram of the underwater noise levels over the entire monitoring period at H1, for a frequency range between 20 Hz and 1 kHz. Also, the turbine rotational speed is shown again in the upper figure. For rotational speeds higher than 13 rpm, the time dependency of the rotational speed of the LSS in the upper figure (indicated by the dotted box) can also be recognized in the underwater noise spectra in the lower figure, although heavily disturbed by ambient shipping noise. The yellow lines inside the dotted box represent the varying tonals in the sound pressure level generated by the wind turbine. For lower speeds, no speed related components can be found in the underwater noise. The varying tone in the underwater noise can be identified as the HSS rotational frequency, which is the transmission ratio of the gear transmission times the rotational speed of the LSS.

Since the varying tones in the underwater noise of the wind turbine might not be clearly visible for the reader from Figure 5.6, this effect will be further explained by showing narrow band spectra from the spectrogram separately. Considered are 4 time windows (see captions) over which the narrow-band SPL is averaged, indicated in figure 5.6 by the red dotted lines:

1. Average LSS speed of 15.4 ± 0.4 rpm, wind speed range 2, no interference of ship pass-by, Figure 5.9.
2. Average LSS speed of 2 ± 0.1 rpm, wind speed range 1, no interference of ship pass-by, Figure 5.10.
3. Maximum output power (2 MW) and LSS speed (18.1 rpm) of WTG1, wind speed range 3, with interference of ship pass-by (2km distance), Figure 5.8.
4. Maximum output power (2 MW) and LSS speed (18.1 rpm) of WTG1, wind speed range 3, no interference of ship pass-by, Figure 5.7.

Figures 5.7 – 5.10 show the narrow-band SPL averaged over these time windows, for both locations. Also, the 1/3 octave band spectrum is calculated, showing the contribution of the tonals, and allowing comparison with the other 1/3 octave band plots in this report.

For wind speed ranges 2 and 3, tonals from the turbine can be recognized in the spectra near the turbine.

For location H2, further away from the turbine, no turbine related tonal noise components are visible in the spectra. Hence, the noise from the operational wind turbines is too low to be of use for the validation of underwater sound propagation models.

Figures 5.7-5.10 also show 1/3 octave band spectra derived from the narrow-band spectra. This allows for comparison of the turbine generated underwater noise levels with other noise levels presented in this report. The SPL in individual 1/3 octave bands measured at H1 is maximal 2.5 dB higher than that at H2, in the frequency range 100-400 Hz. The tonals are not dominant in the 1/3 octave bands because otherwise tone levels would have been equal or close to the third-octave levels. This implies that broadband noise caused by wind and shipping dominates the third-octave levels.

When a ship is passing by at close range, the contribution of the turbine cannot be seen anymore and is predominated by shipping noise.

From these narrowband analyses we can conclude that tonal noise associated with wind turbine operation (mainly at gear mesh frequencies) can be detected in the underwater noise measurements at location H1, but not at location H2. At location H1, the tonal noise has a limited contribution to the 1/3-octave band sound pressure levels, smaller than 3 dB.

Table 5.2 Frequencies of the turbine related to the rotational speed of the low speed shaft.

LSS		HSS		HSS Gear Meshing	
rpm	Hz	rpm	Hz	rpm	Hz
18.1	0.30	1671	28	43436	724
15.4	0.26	1421	24	36957	616
2	0.03	185	3	4800	80

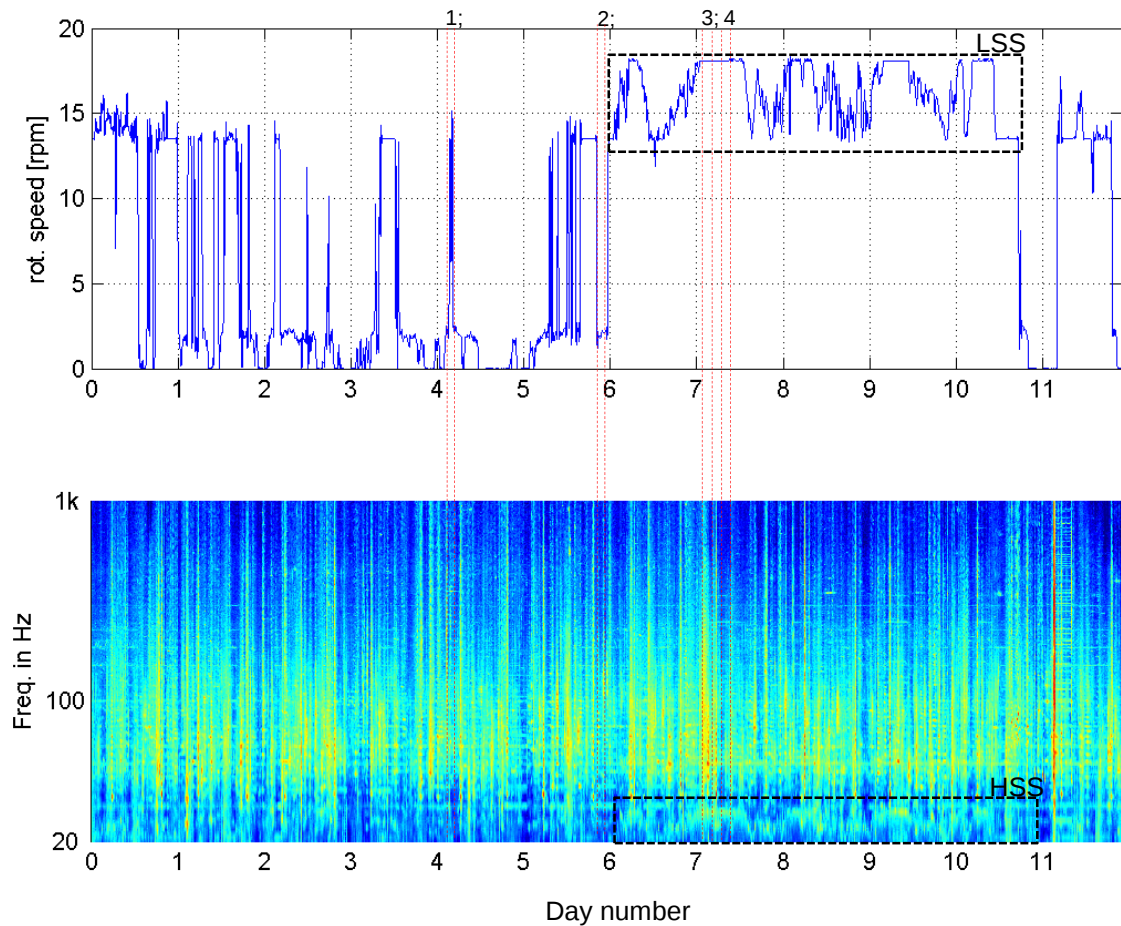


Figure 5.6 Rotational speed of WTG1 LSS (upper) and narrow-band sound pressure levels ($\Delta f=1\text{Hz}$), measured on location H1. The sound pressure levels are indicated by colours (blue low levels, red high levels). The red dotted lines show the time windows, numbered from 1 to 4, for the average narrow-band spectra shown in Figures 5.7-5.10. When the time dependency of the rotational speed of the LSS in the upper figure (indicated by the dotted box) is compared to the time dependency of the sound pressure level inside the dotted box in the lower figure, indicated by HSS, the same trend can be found. The varying tone in the underwater noise can be identified as the HSS rotational frequency, which is the transmission ratio of the gear transmission times the rotational speed of the LSS.

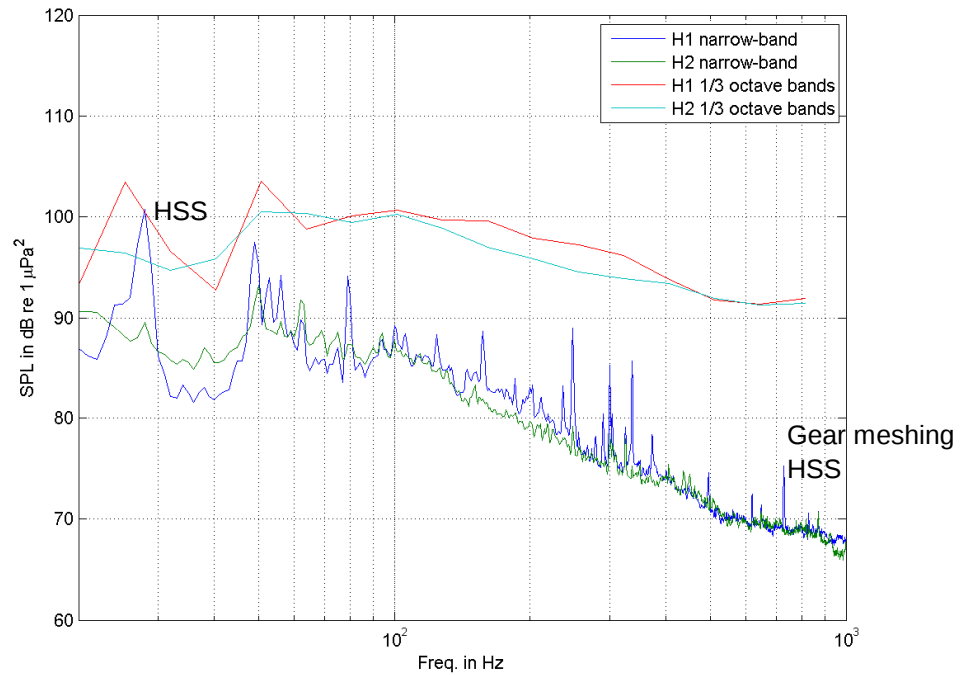


Figure 5.7 Narrow band spectrum ($\Delta f=1\text{Hz}$) of the SPL on location H1 and H2, averaged over the time window 4 as indicated in Figure 5.6 (wind speed range 3; 100 minutes). The average rotational speed of the LSS is 18.1 rpm. The SPL is also shown in 1/3 octave bands.

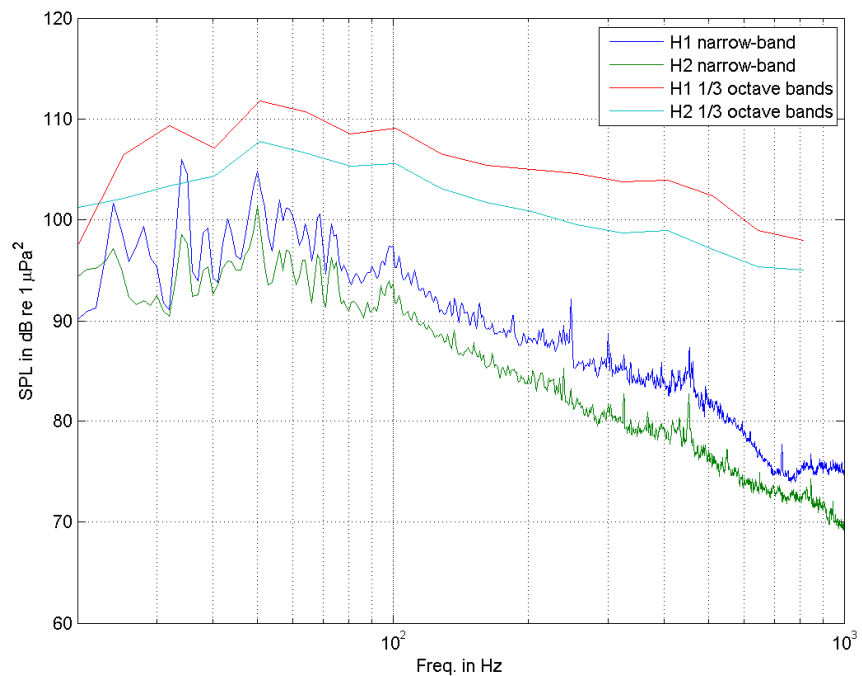


Figure 5.8 Narrow band spectrum ($\Delta f=1\text{Hz}$) of the SPL on location H1 and H2, averaged over the time window 3 (wind speed range 3; 60 minutes) as indicated in Figure 5.6. The average rotational speed of the LSS is 18.1 rpm. The SPL is also shown in 1/3 octave bands. During the time frame a ship passes-by H1 (CPA = 2km).

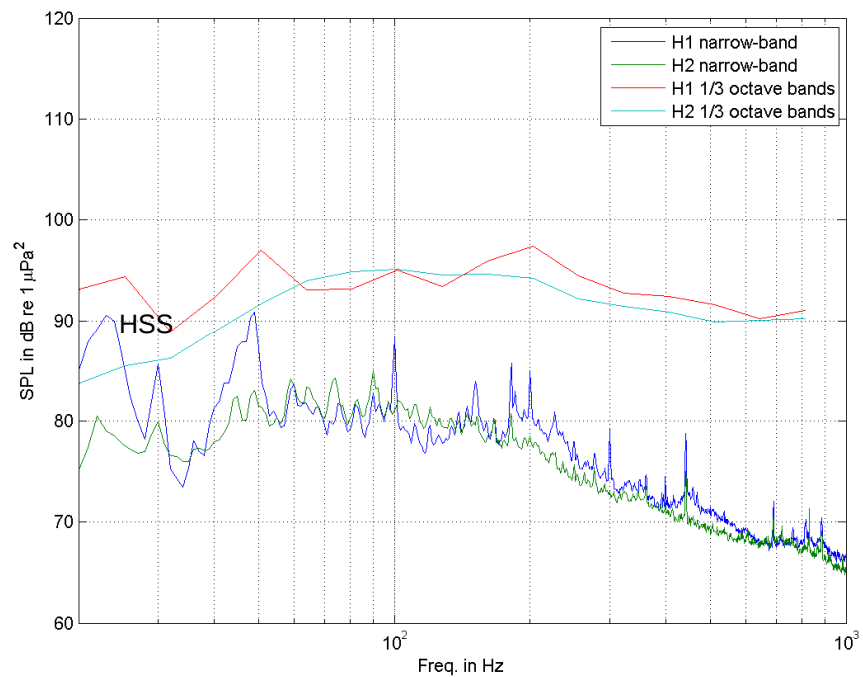


Figure 5.9 Narrow band spectrum ($\Delta f=1\text{Hz}$) of the SPL on location H1 and H2, averaged over the time window 3 (wind speed range 2; 60 minutes) as indicated in Figure 5.6. The average rotational speed of the LSS is 15.4 rpm. The SPL is also shown in 1/3 octave bands.

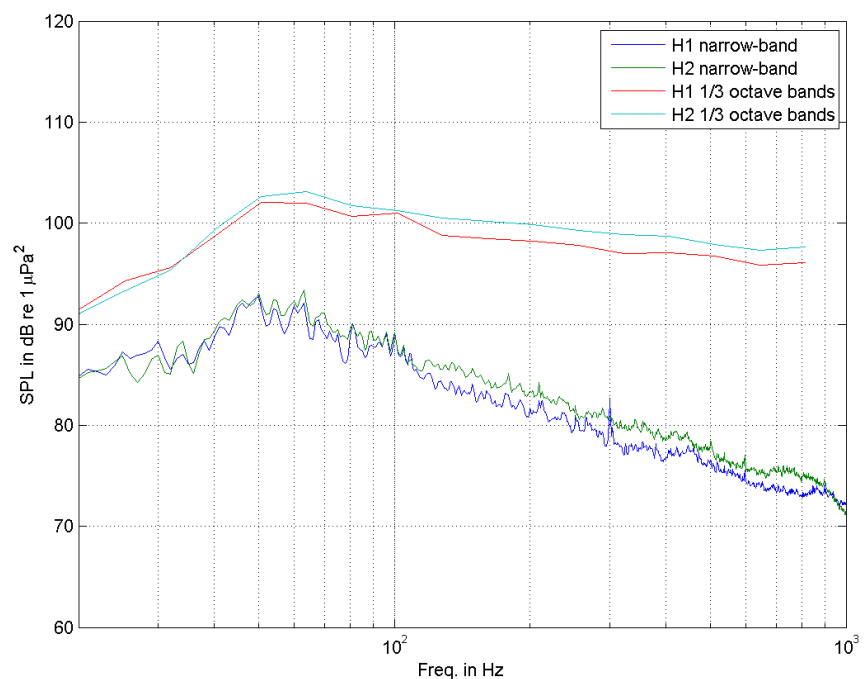


Figure 5.10 Narrow band spectrum ($\Delta f=1\text{Hz}$) of the SPL on location H1 and H2, averaged over the time window 2 (wind speed range 1; 60 minutes) as indicated in Figure 5.6. The average rotational speed of the LSS is 2 rpm. The SPL is also shown in 1/3 octave bands.

5.4 Exceedance level spectra

All measured SPLs for all wind conditions for both locations are plotted against the centre-band frequencies in Figure 5.11. The results for all individual measurements are plotted in light grey. For H1 per 1/3-octave band the difference between the minimum and the maximum value of the SPL is up to about 40 dB.

In the same figure, the corresponding exceedance levels L_5 , L_{50} , and L_{95} are drawn. Also, the energy average (based on the mean square sound pressure) is shown. From L_5 and L_{95} it follows that for a subset containing 90% of the measurements the difference between maximum and minimum SPL is maximally about 20 dB, whereas the small remaining set of only 10 % of the measurements is responsible for the larger variations.

Figure 5.12 – 5.15 show the spectra for various exceedance levels per wind speed range and measurement location. This allows for a comparison between the exceedance levels as measured near to and further away from the turbine.

For both locations, the spectra of L_{95} are about equal for wind speed ranges 1 and 2, see Figure 5.12 and 5.13. For wind speed range 1 the rotational speed of the LSS, and consequently the output power, are low. The narrow-band analysis in Section 5.3 has shown that no turbine generated tonal noise could be detected at location H1 for this range. Such tonals could be detected for wind speed range 2, but the presence of these tonals does not raise the ambient noise level in third-octave bands. Figure 5.12 shows that the increase of L_{95} on location H1 in the highest wind speed range, is partly caused in the turbine related frequency range (shaft and transmission noise, see Section 5.3). For the higher frequencies, the contribution of the noise of ships and surface waves on the ambient noise is much larger.

For location H1, all exceedance levels converge to a constant lower value of the SPL governed by the electronic noise in the measurement system itself at higher frequencies. The L_{95} at H1 appears to be noise limited at frequencies above 5 kHz. Figures 5.14 and 5.15 show the L_5 on both locations, which is probably determined by individual ship pass-by's during the monitoring period. The deviations in the L_5 curves for wind speed range 3 are probably due to the limited monitoring period and hence insignificant. The peaks in the L_5 spectra are not caused by the turbine.

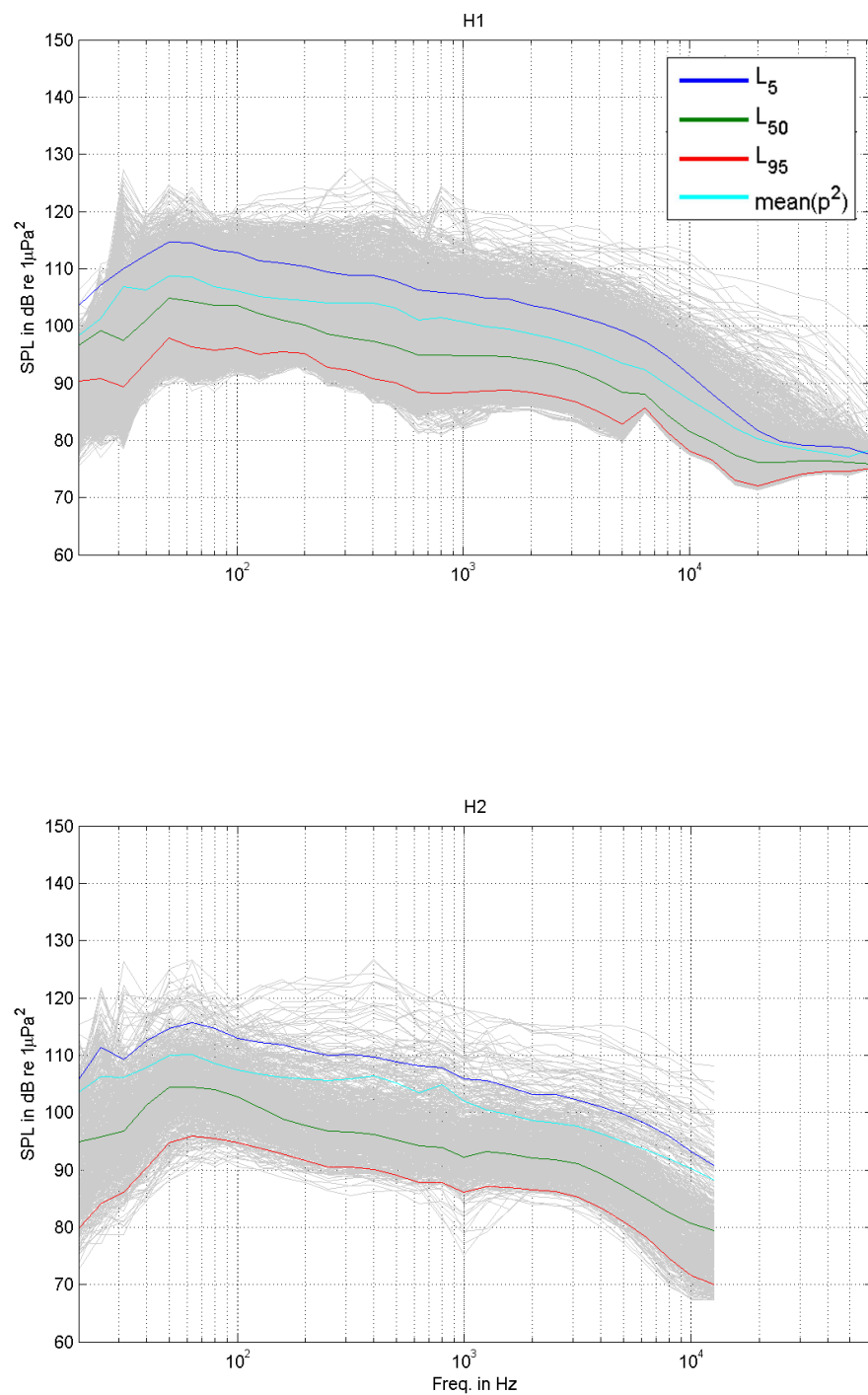


Figure 5.11 Sound pressure levels in 1/3-octave bands for H1 (upper) H2 (lower). The results of all individual measurements are represented by the light grey lines. The exceedance levels are shown by the coloured lines. Average values of the noise levels over all measurements are represented by the cyan line (average p^2) and the red solid line (average SPL).

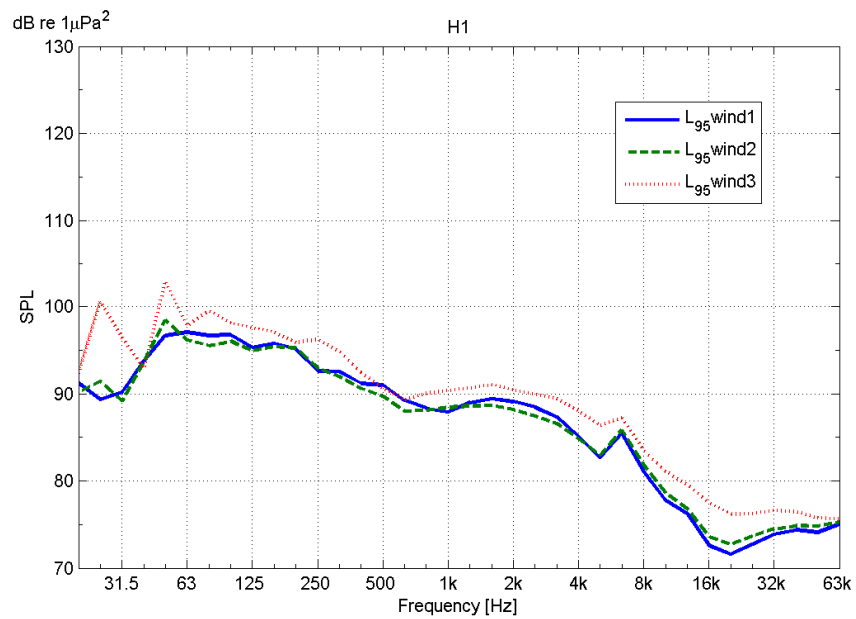


Figure 5.12 Spectra of L_{95} in 1/3-octave bands for all wind speed ranges for the location close to the turbine (H1).

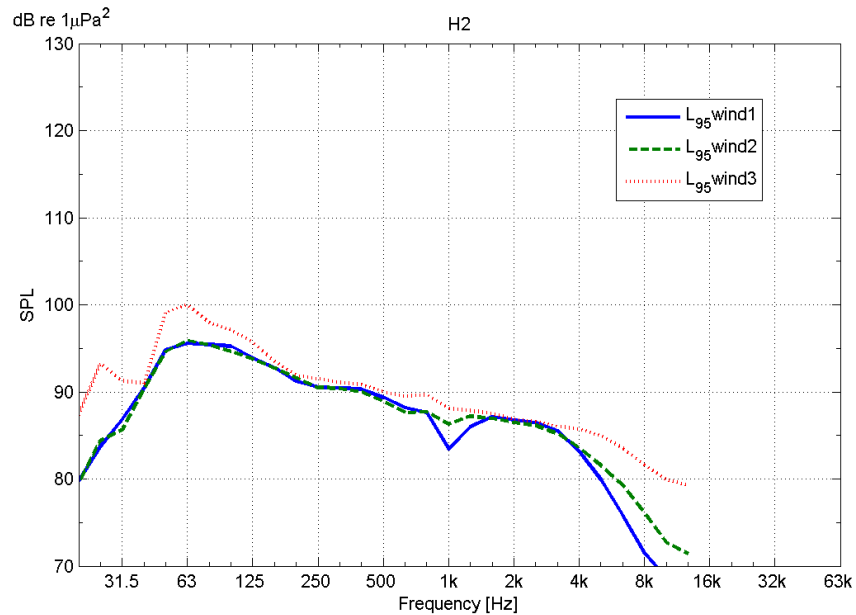


Figure 5.13 Spectra of L_{95} in 1/3-octave bands for all wind speed ranges for the location away from the turbine (H2).

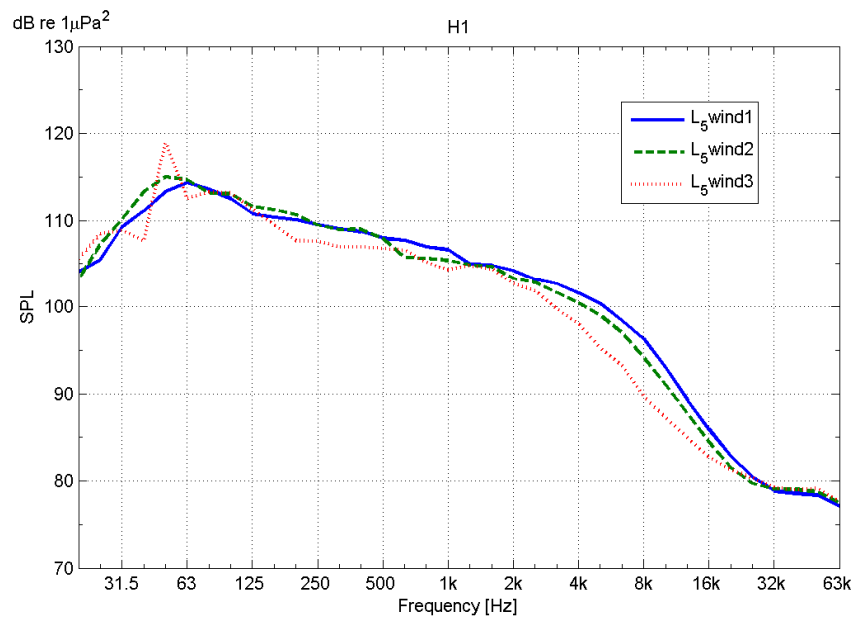


Figure 5.14 Spectra of L_5 in 1/3-octave bands for all wind speed ranges for the location close to the turbine (H1).

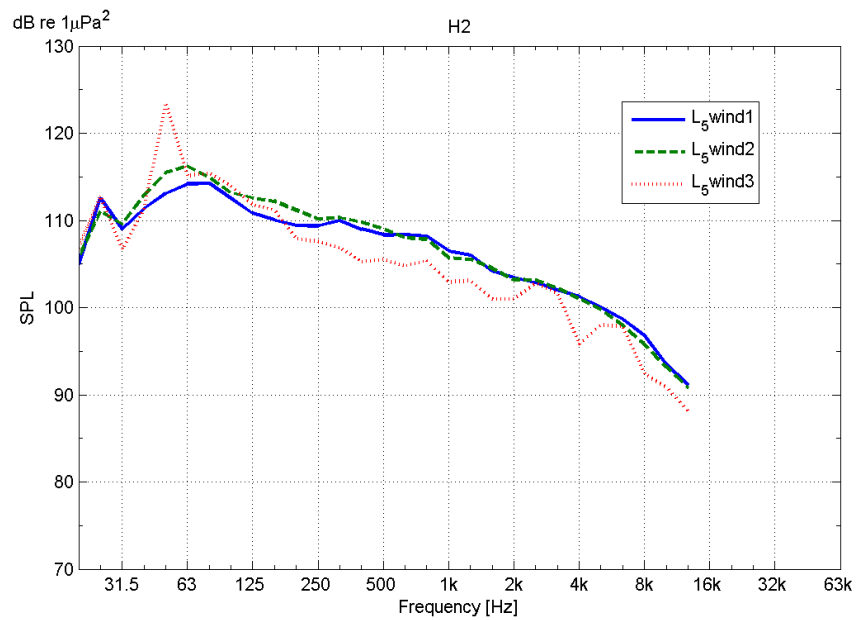


Figure 5.15 Spectra of L_5 in 1/3-octave bands for all wind speed ranges for the location away from the turbine (H2).

5.5 Shipping traffic

Following the procedure of Section 4.3, shipping density factors were determined as a function of time, from the ship positions relative to the measurement locations. Figure 5.16 shows the total SPL and Shipping density factors for both locations for each minute of the first three days of the monitoring period. A high N_2 implies either a ship pass-by at close range, or the presence of many ships in the environment of the measurement location. Local maxima in SPL seem to coincide with maxima in N_2 factors, showing that shipping noise is probably dominating the SPL for these time frames. For the other measurement days, the comparisons between SPL and N_2 can be found in appendix F.

Figure F.5 of appendix F shows the nearest distance (ND) between any ship and measurement location H1 as a function of time. In this figure spikes are visible at distances smaller than 500 m. These are pass-by's of PAWP service ships, about 19 pass-by's over 12 days. As shown in Section 5.2 these service ships pass-by's do not result in increased average noise levels.

5.6 Correlation SPL with wind speed

The effect of wind-speed dependent noise produced, for instance, by the wind generated breaking of waves is expected to lead to a positive correlation of the ambient noise with the wind speed. However, such effects are only noticeable if the background noise is not dominated by other sources, such as ship-produced noise. In this case the broadband SPL shows no clear correlation with wind speed. For individual 1/3 octave bands, the SPL shows some correlation with wind speeds above 5 m/s in the higher frequency bands, as can be seen in Figure 5.17 for the 10 kHz band as an example.

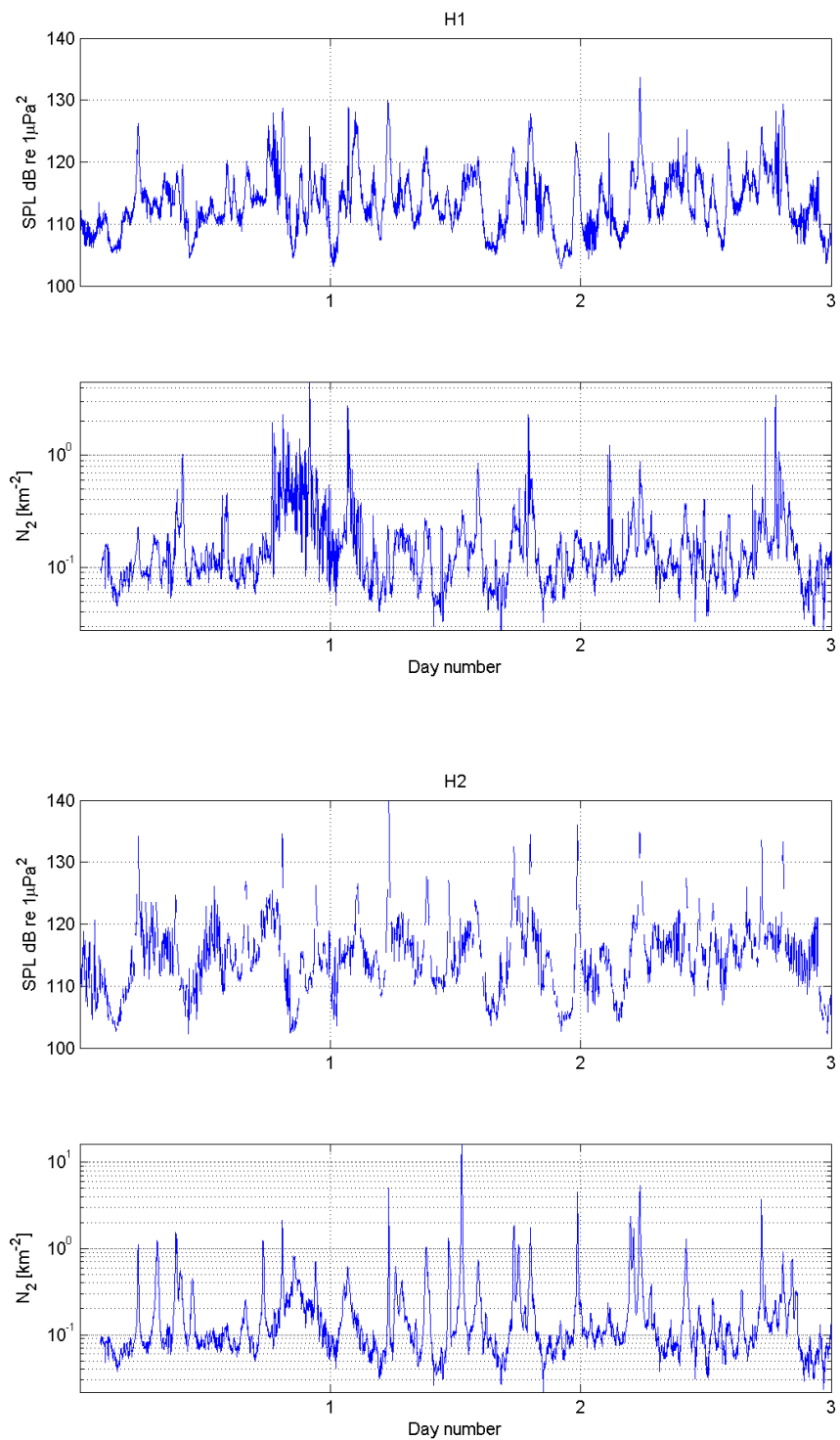


Figure 5.16 Total SPL and Shipping density factor N_2 for locations H1 and H2 for each minute of the first three days of the monitoring period.

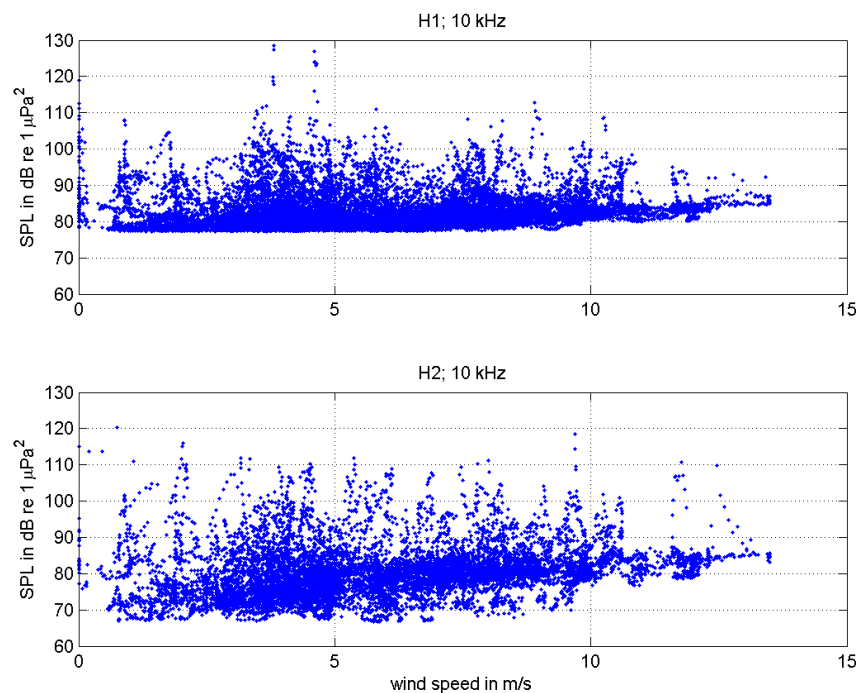


Figure 5.17 SPL of the 10 kHz 1/3 octave band as a function of governing wind speed at both locations. Note that the lower limit in the data for H1 is probably caused by electronic noise in the measurement system.

5.7 Precipitation

No rainfall was registered during the monitoring period. According to the operational plan, a comparison between predicted rain fall noise and measured noise from the wind farm is made. Rain fall noise is estimated from [8] for various rain fall rates and wind speeds, see Figure 5.18. Comparison with the measured L_{95} exceedance levels shows that the main frequency range for rainfall noise is above 10 kHz. Therefore, rainfall noise will not mask the ambient noise at lower frequencies.

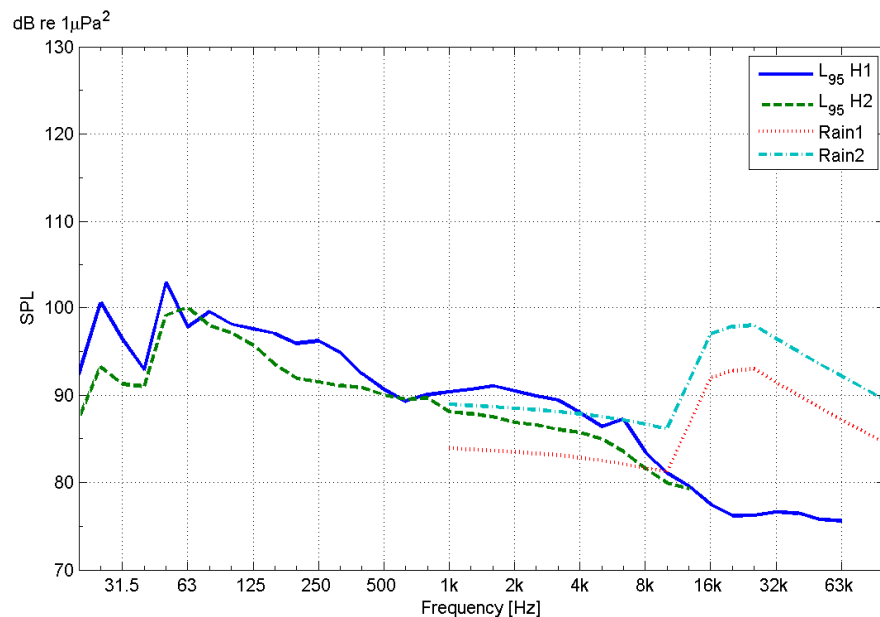


Figure 5.18 Estimations for rain noise at 20m depth in SPL in 1/3 octave bands (rain1: rate 1 mm/h, wind speed 5 m/s; rain2: rate 10 mm/h, wind 15 m/s) plotted with the L_{95} exceedance levels for wind speed range 3.

5.8 Audiograms sea mammals

In order to assess if turbine induced noise could be perceived by sea mammals, their audiograms need to be considered. These audiograms represent the tonal SPL threshold at which a sound can be detected with a 50% probability, in a situation without masking background noise. Figures 5.20 and 5.21 show the audiograms of harbour seals and harbour porpoises [9,10] plotted together with measured L_{95} exceedance levels for both measurement locations. It is likely that the measured underwater noise up to 500 Hz can be perceived by the harbour seal, but not by a harbour porpoise. This includes wind turbine related noise at a close range of 100 m. These figures do not provide direct information regarding physiological or behavioural effects of the measured sound on the animals.

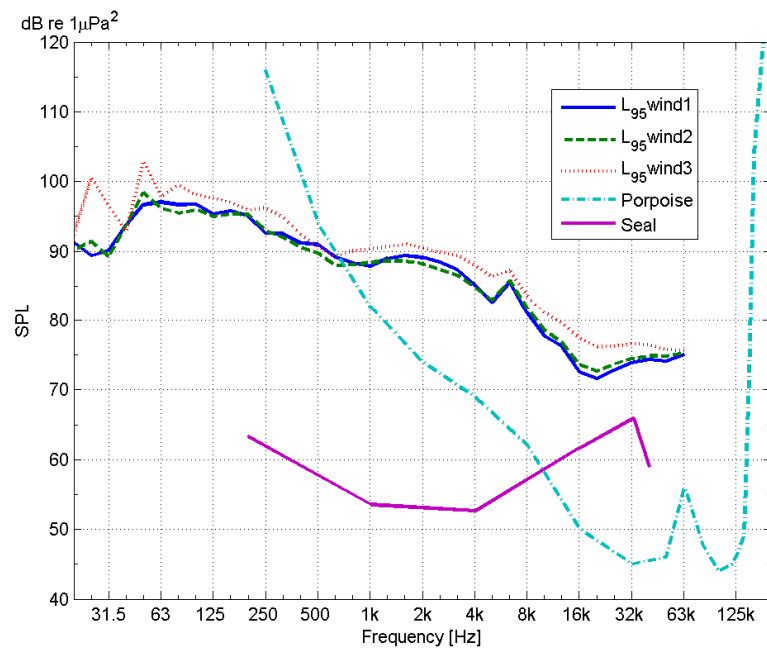


Figure 5.19 Audiogram of Harbour Seals and Porpoises (long signal durations) plotted together with L_{95} at location H1.

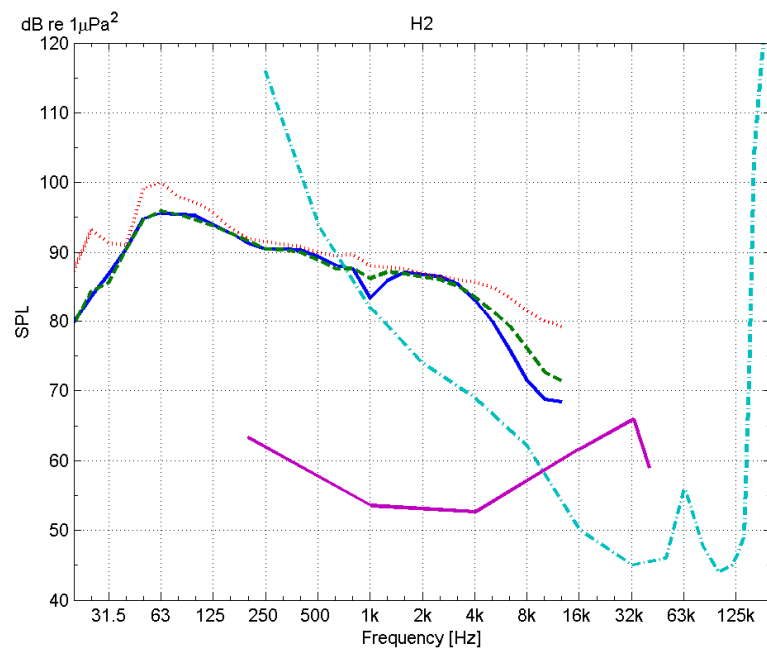


Figure 5.20 Audiogram of Harbour Seals and Porpoises (long signal durations) plotted together with measured L_{95} at location H2.

5.9 Supplementary registrations

All supplementary registrations can be found in the following appendices.

Environmental conditions (appendix C)

- Bathymetry and tide;
- Properties seabed;
- Water level;
- Speed of sound over water depth [m/s], measured before one both measurement locations, before deployment.
- Wave height [m].

Operational conditions turbines (appendix D)

- Rotational speed [rpm];
- Power [kW];
- Orientation nacelle [degrees];
- Number of turbines surrounding WTG1 in operation.

Meteorological conditions (appendix E)

- Wind speed and wind direction (10 min intervals);
- Precipitation.

Shipping traffic (Appendix F)

- Shipping density derived from AIS and radar data (1 min intervals); The data contains GPS locations ships (WGS84), speed [knots] and length [m].

6 Conclusions

At two locations, at close range of an operational wind turbine (H1 at 100 m) and at large distance (H2 at 3800 m) the underwater noise was recorded for nearly 12 days. The SPLs were averaged over periods of time within certain wind speed ranges (4-6 m/s, 6-12 m/s and 12-24 m/s). For the first range, 24.4 hours of data was available, for the second 77.7 hours. For the third range 2 hours of data was available. The wind turbine operated at its maximum output power for 15 minutes of this period.

The average broadband sound pressure levels on both locations show no significant differences. Only at the location close to the operational turbine, a narrow band analyses revealed some tonals which are caused by the gearbox transmission of the turbine. It can be concluded that even at the location close to the PAWP wind turbine, these tonals do not dominate the broadband SPL.

On both locations, the 95% exceedance level L_{95} tends to increase by about 3 dB for the highest wind speed range, in which the turbine has its maximum operating condition, from 107 to 110 dB re $1 \mu\text{Pa}^2$ for location H1, and from 105 to 107 dB re $1 \mu\text{Pa}^2$ for location H2. So the increase of L_{95} with increasing wind is equal within 1 dB for both measurement locations. L_{95} is determined by distant shipping and surface waves. For the location close to the turbine, L_{95} is also partly affected by the turbine(s). The numbers show that the differences in SPL between both locations are small. It can be concluded that the noise generated by the operational wind farm does not significantly increase the local ambient noise due to shipping and wind.

On both locations, the average sound pressure levels are equal within 2 dB (118 dB re $1 \mu\text{Pa}^2$ at H1 and 120 dB re $1 \mu\text{Pa}^2$ at H2). This is to be expected if shipping noise dominates the average broadband SPL and both measurement locations have about equal distance from shipping lanes.

The 5% exceedance level L_5 , dominated by near-by shipping noise, is about 124 dB re $1 \mu\text{Pa}^2$ on both locations. Since the PAWP service ships pass location H1 much closer than H2, it can be concluded that the presence of these ships does not lead to a significant increase of the time-average background noise level.

At a distance of 3800 m (H2), no contributions of the turbine to the underwater noise was found. Hence, the noise from the operational wind turbines is too low to be of use for the validation of underwater sound propagation models.

Background noise is dominated by wind speed dependent noise for speeds higher than 5 m/s, for frequencies higher than 5 kHz.

No rainfall was registered during the monitoring period. A theoretical prediction of rainfall noise indicates that rainfall during the measurements would not have affected the results, since the main frequency range for rainfall noise is much higher than for turbine noise. Therefore, rainfall noise will not mask the noise generated by the wind farm.

It is likely that the measured underwater noise up to 500 Hz can be perceived by harbour seals, but not by harbour porpoises. This includes wind turbine related noise at a close range of 100m.

The data set for the highest wind speed range was limited to 2 hours, due to the prevailing weather conditions during the monitoring period. However, the available data do not show clear differences between the underwater noise at the two measurement positions. It is highly unlikely that additional measurements in the highest wind speed range will lead to a different conclusion. Hence it is considered unnecessary to undertake an additional campaign to collect more acoustic data in the highest wind speed range.

7 Referenties

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A SESAME (location H1)

The autonomous acoustic measurement system SESAME was used for the recordings at location H1. SESAME stands for 'Shallow water Extendable Stand-alone Acoustic Monitoring Equipment' and is installed on the seabed. The system weighs about 850 kg in air. An illustration of the measurement system can be found in Figure A.1. The electronics and the power supply of the measurement system are housed within a metal container supported by a metal frame.

During the full measurement period SESAME was positioned at a fixed location on the seafloor (depth about 24 m). Sound was recorded by two hydrophones. The hydrophones were attached to the frame by using a vertical cable. The cable was kept vertically above the frame by a buoy providing an upward force. The buoy remained fully below the water surface at about 6–7 m above the seafloor. The hydrophones were fixed at 5 m above the seafloor. SESAME remained on one location during the measurements.

The output of the two B&K 8101 (sensitivity of -184 dB re 1V/ μ Pa) hydrophones was conditioned by using high-pass filters and low-pass filters in order to use the available dynamic range of the data acquisition system at the best possible. The resulting signal was converted to 16-bit digital data by using a 16-bit (Sigma-Delta) ADC (Analogue-Digital Converter). The applied settings for signal conditioning and data acquisition are listed in Table A.1.

The 1st order high pass filter with a -3 dB cut-off frequency of 42 Hz was used in order to suppress the low frequency fluctuations due to wave height variations. The -3 dB cut-off frequency of the 6th order low-pass filter was set at 80 kHz. The gain of the amplifier was varied dynamically. It was automatically set in such away that the voltage offered to the ADC remained within its input range. The resulting analogue signals were sampled at 200kHz. An internal digital time scheduler was programmed to allow for recording and storage of 6 seconds of digital data per each minute (i.e., with a duty cycle of 10 %). The raw data were stored on a hard disk in binary format.

Prior to and after the measurements, the hydrophones were calibrated by a B&K Hydrophone Sound Level Calibrator 4223 + coupler UA-0547.

Table A.1: Signal conditioning and data acquisition settings applied by the SESAME system during the noise measurements.

Sample frequency	200 kHz
low-pass filter -3 dB cut-off frequency	80 kHz
high-pass filter -3 dB cut-off frequency	42 Hz, see fig A.2.
gain	automatically set between 0 dB and 60 dB, in steps of 6 dB
ADC resolution	16 bit
Duty cycle	10 % (6 s per minute)

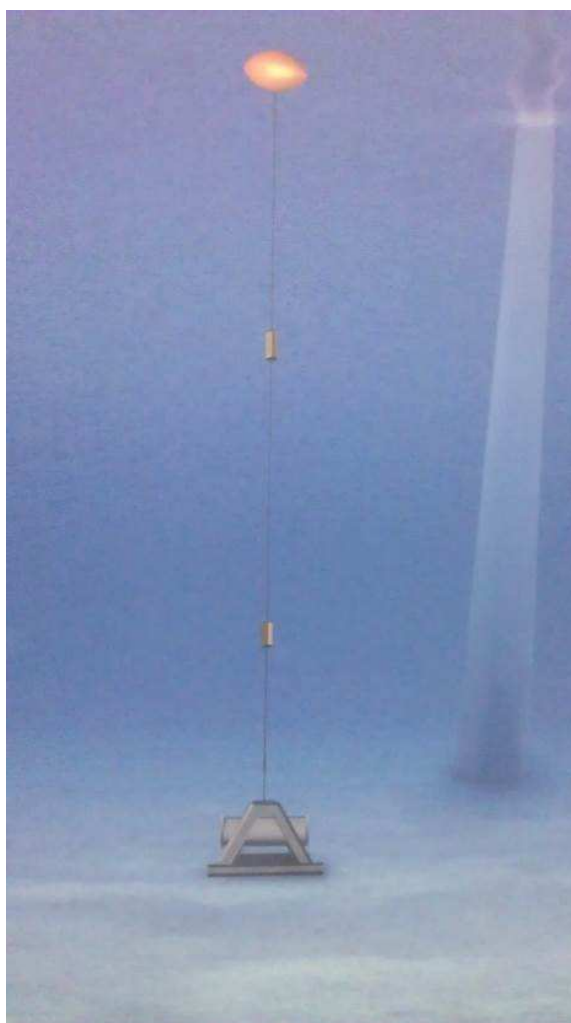
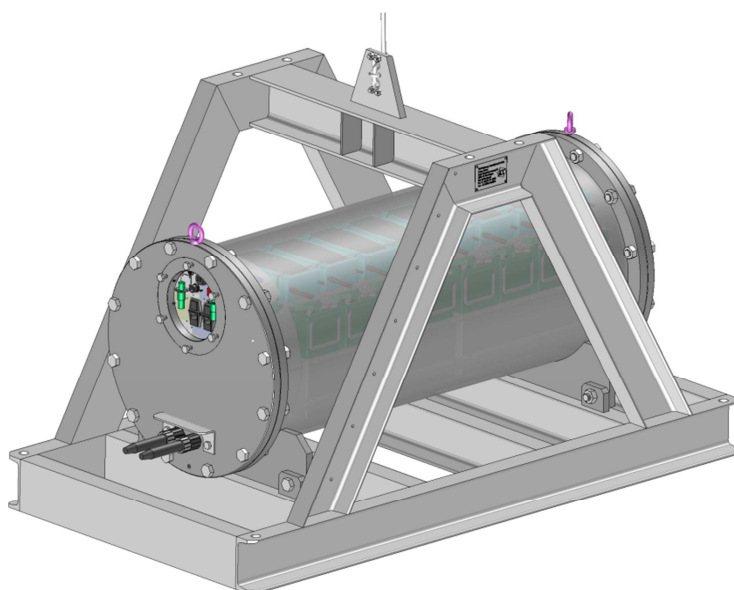


Figure A.1 Overview of Sesame.

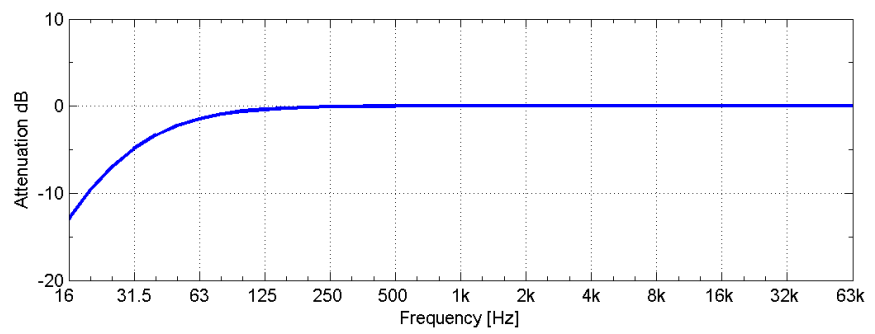


Figure A.2 High-pass filter settings of Sesame.

B ITAP systems (location H2)

The measurement system of ITAP was used for the recordings on location H2. The system consists of two Marantz PMD 620 recorders, with two B&K 8106 Hydrophones (sensitivity of 2mV/Pa), see figure B.1.

The PMD 620 recorders have a flat frequency response from 15 Hz to 19 kHz. The hydrophone preamps have an intrinsic high pass filter with 5 - 10 Hz cut off. The PMD 620 has an optional high-pass filter called "Low Cut", but this was switched off.



Figure B.1 Overview of ITAP system, two recorders with each its own hydrophone.

Table B.1: Signal conditioning and data acquisition settings applied by Marantz system of ITAP during the noise measurements.

Sample frequency	44.1 kHz
gain	0 dB
ADC resolution	16 bit
Duty cycle	66 % (10 minutes per 15 minutes)

C Environmental conditions

Bathymetry and tide

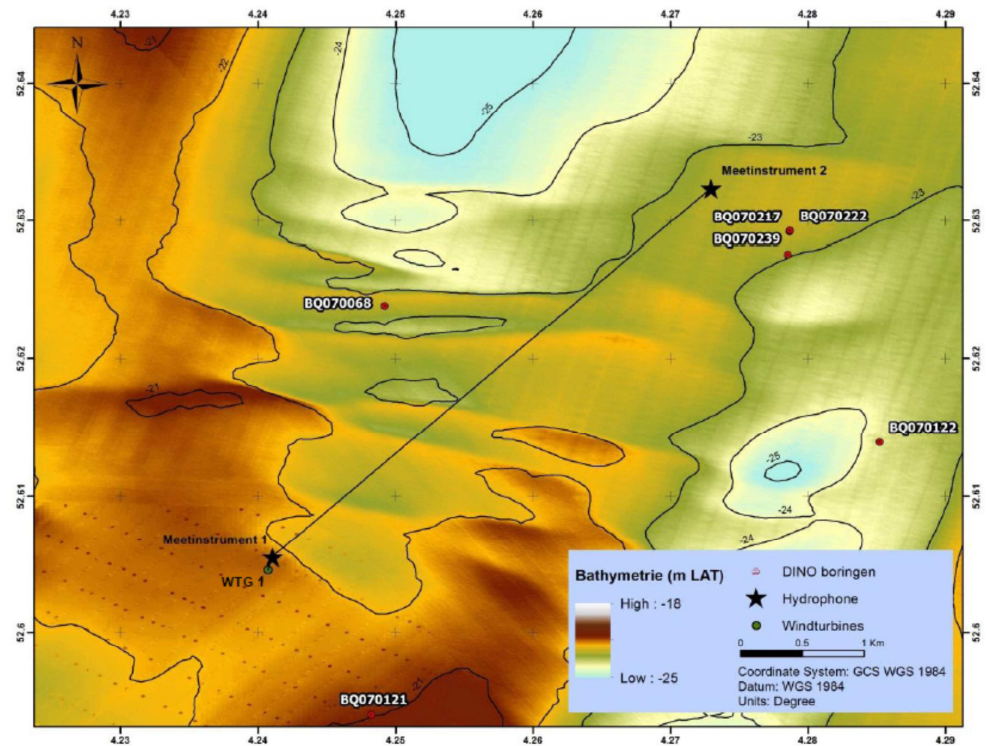


Figure C.1 Bathymetry of the area, showing the locations of the measurement systems and WTG1 [11].

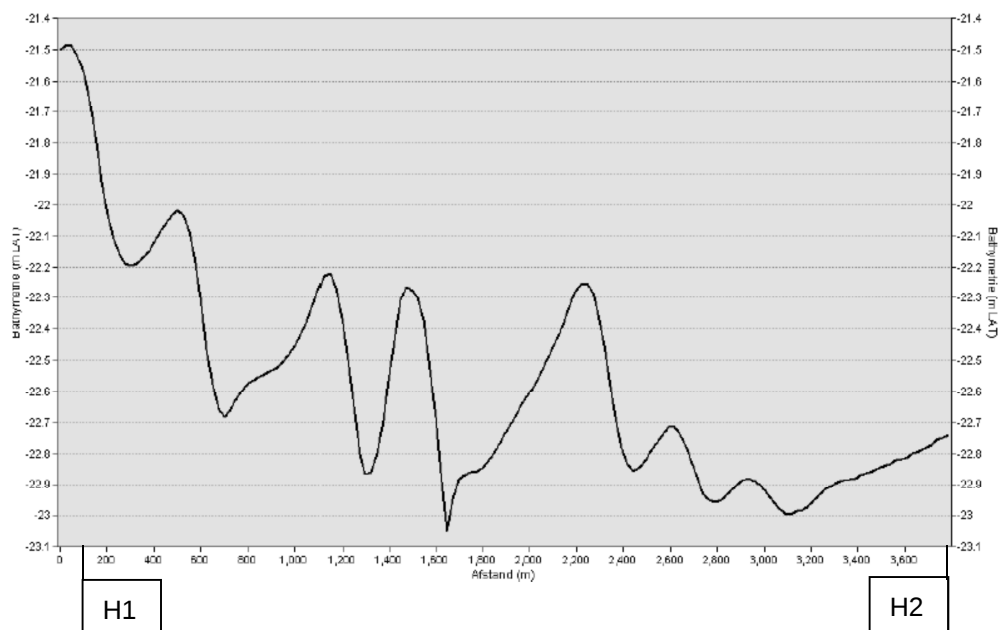


Figure C.2 Seabed profile, relative to LAT, between WTG1 and measurement systems [11].

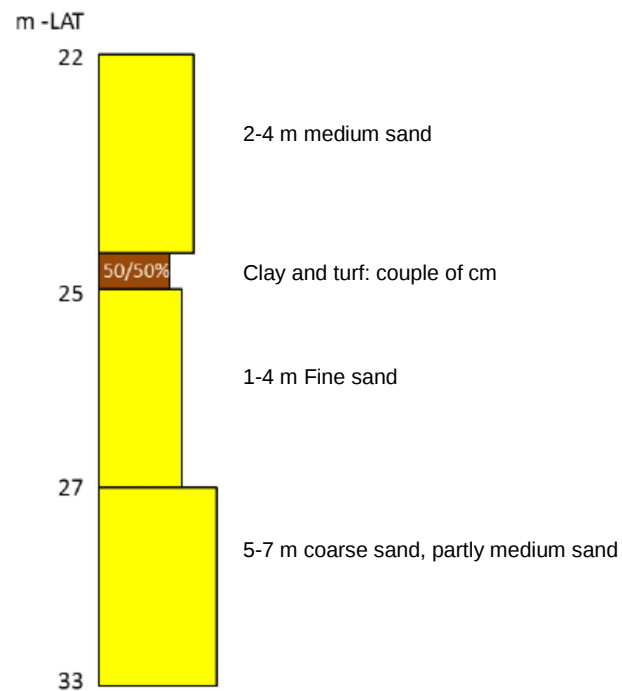


Figure C.3 Average composition of the seabed in the area [11].

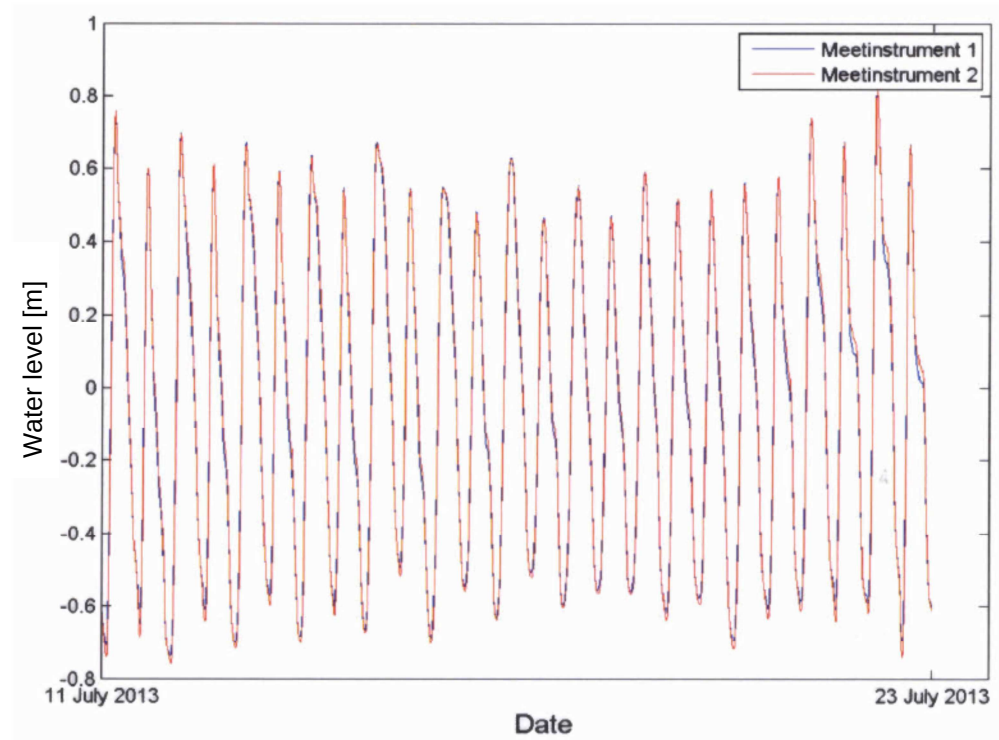


Figure C.4 Water level relative to mean sea level during the measurement period [11].

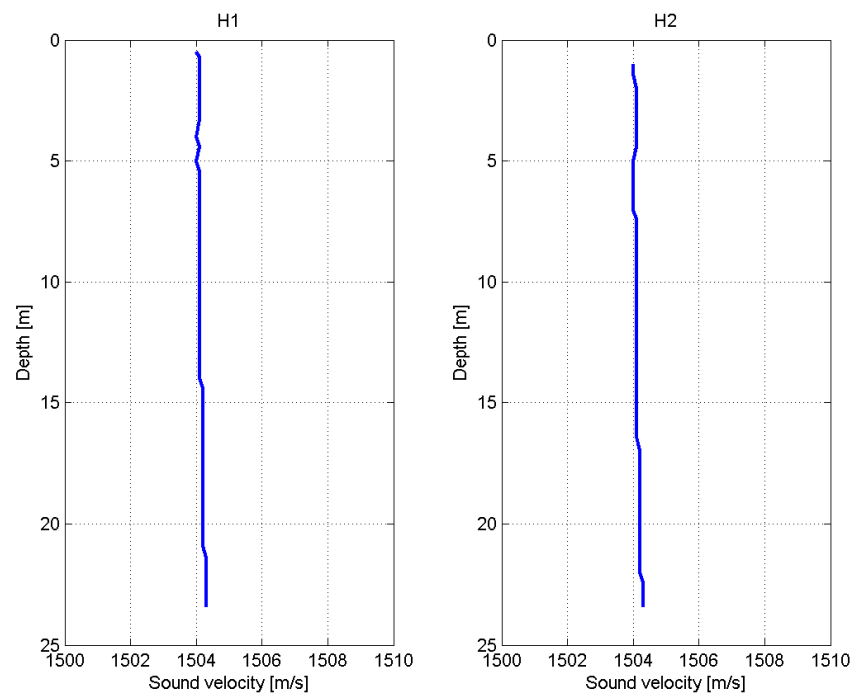


Figure C.5 Speed of sound over water depth for both locations as measured on location by TNO.

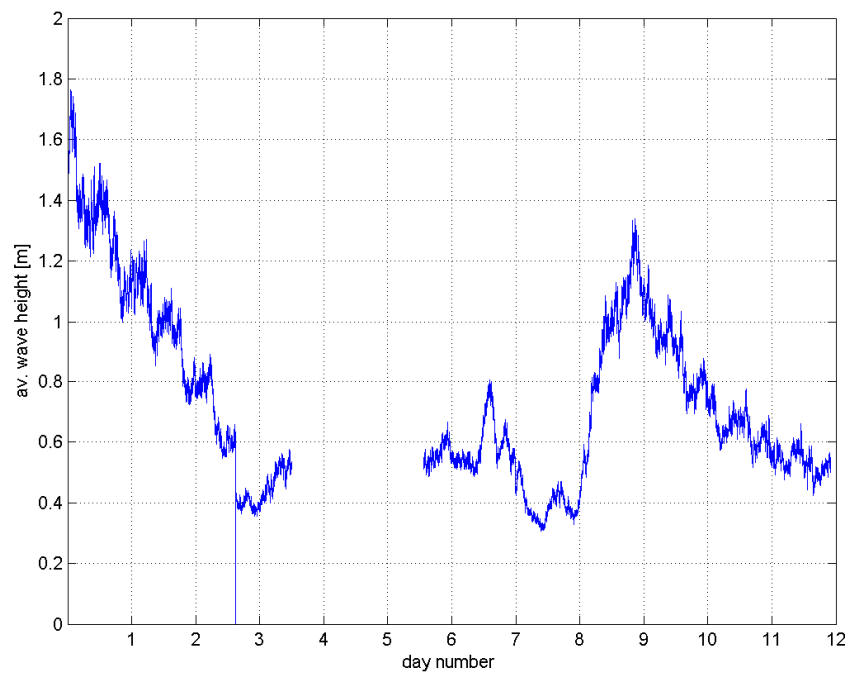


Figure C.6 Average wave height in [m] as a function of measurement days [11]. Some data is missing.

D Operational conditions turbines

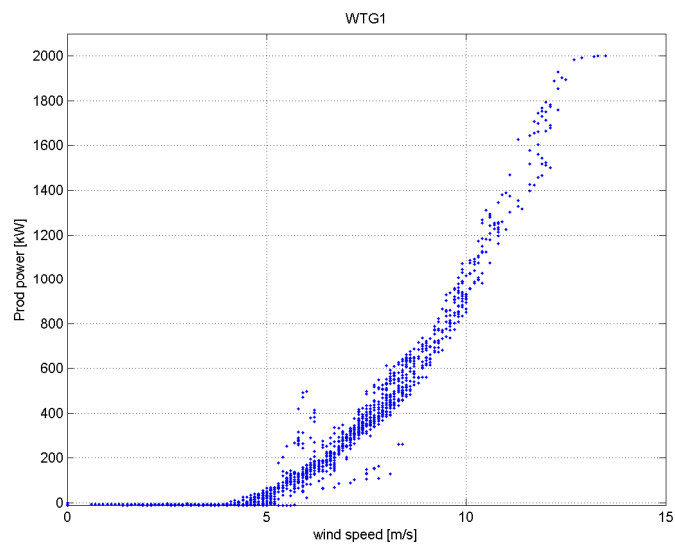


Figure D.1 Output power of WTG1 as a function of wind speed, as registered during the 12 day measurement period.

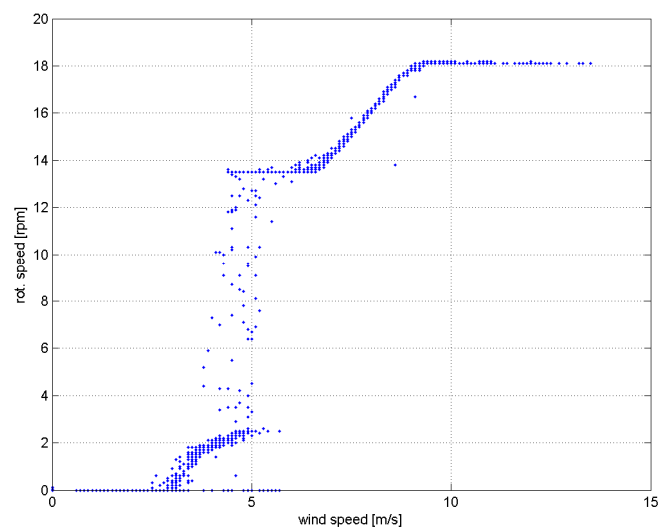


Figure D.2 Rotational speed of WTG1 as a function of wind speed, as registered during the 12 day measurement period.

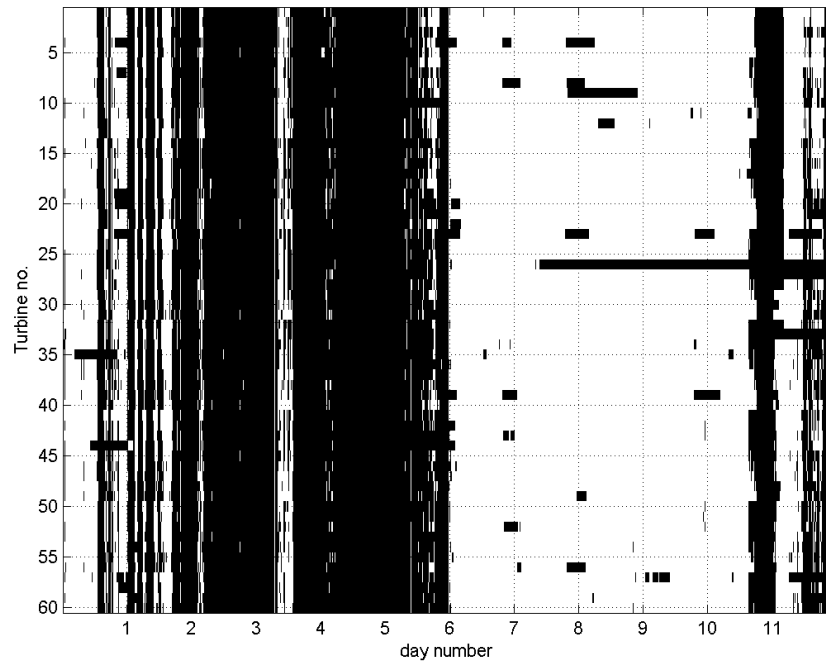


Figure D.3 Overview of the turbines that were operational during the measurement period. White indicates operational and black indicates shut-down.

Table D.1: Maintenance activities at PAWP during the measurement period

Date	Start	end	Activity	Vessels	Wind turbine, OHVS
11 juli 2013	11:45	12:30	Deployment measurement systems	MS Terschelling	1
12 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	20,35,44,01,19,10,57,22
12 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,04,41
12 juli 2013	7:15	19:00	Transferplan	Offshore Phantom	21,13,22,34,44,52,11,36,5,20,35,46,
					12,53,29,8,23,15,17,9,16,7,6,40,19
13 juli 2013	6:45	16:00	Blade repairs	Windcat 7	4,39,23
14 juli 2013	6:45	16:00	Blade repairs	Windcat 7	4,39,23
15 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	5,30,01,10,22
15 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,04
15 juli 2013	7:15	19:00	Inspections	Offshore Phantom	55,60,50,51,56,57,53,22
16 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	44,10,22,42
16 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,39,04
16 juli 2013	7:15	19:00	Inspections	Offshore Phantom	50,51,20,46,53,21,22,44
17 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	46,36,47,39,42
17 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,04
17 juli 2013	7:15	19:00	Inspections	Offshore Phantom	20,48,22,44
18 juli 2013	17:00	19:00	visit	Spike Islander	Unknown
18 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	52,43,39,56,08
18 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,04
19 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	09,26,49,56,08
19 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,04
20 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,48,39
21 juli 2013	6:45	16:00	Blade repairs	Windcat 7	23,48,39
22 juli 2013	7:00	16:00	Inspections and maintenance	Windcat 26	49,56,40,30
22 juli 2013	6:45	16:00	Blade repairs	Windcat 7	48,39
22 juli 2013	7:00	19:00	Diving activities	Zeeland	1,20
22 juli 2013	7:00	19:00	Inspecties	Offshore Phantom	OHVS
23 juli 2013	6:30	20:00	Diving activities	Zeeland	45,60
23 juli 2013	8:00	14:00	Recovery measurement systems	MS Terschelling	1

E Meteorological conditions

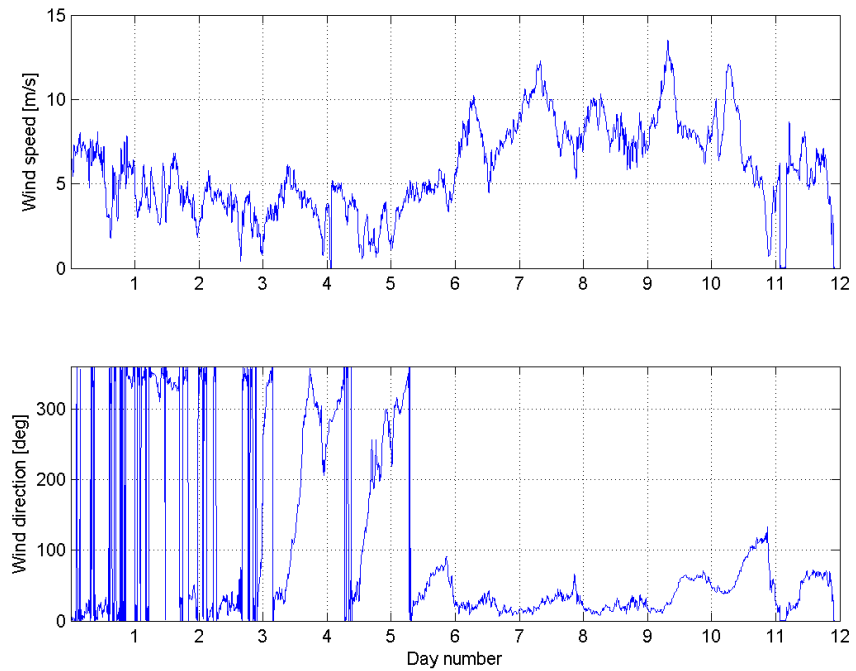


Figure E.1 Wind speed and wind direction measured on wind turbine WTG1 at 60m height as a function of time (measurement days), in 10 minute intervals.

Precipitation

No precipitation was registered during the entire measurement period.

F Shipping traffic

This appendix shows the shipping density N_2 as a function of time, as derived from AIS and radar data, see also Section 4.3. Also, the measured SPL as a function of time is shown for both measurement locations.

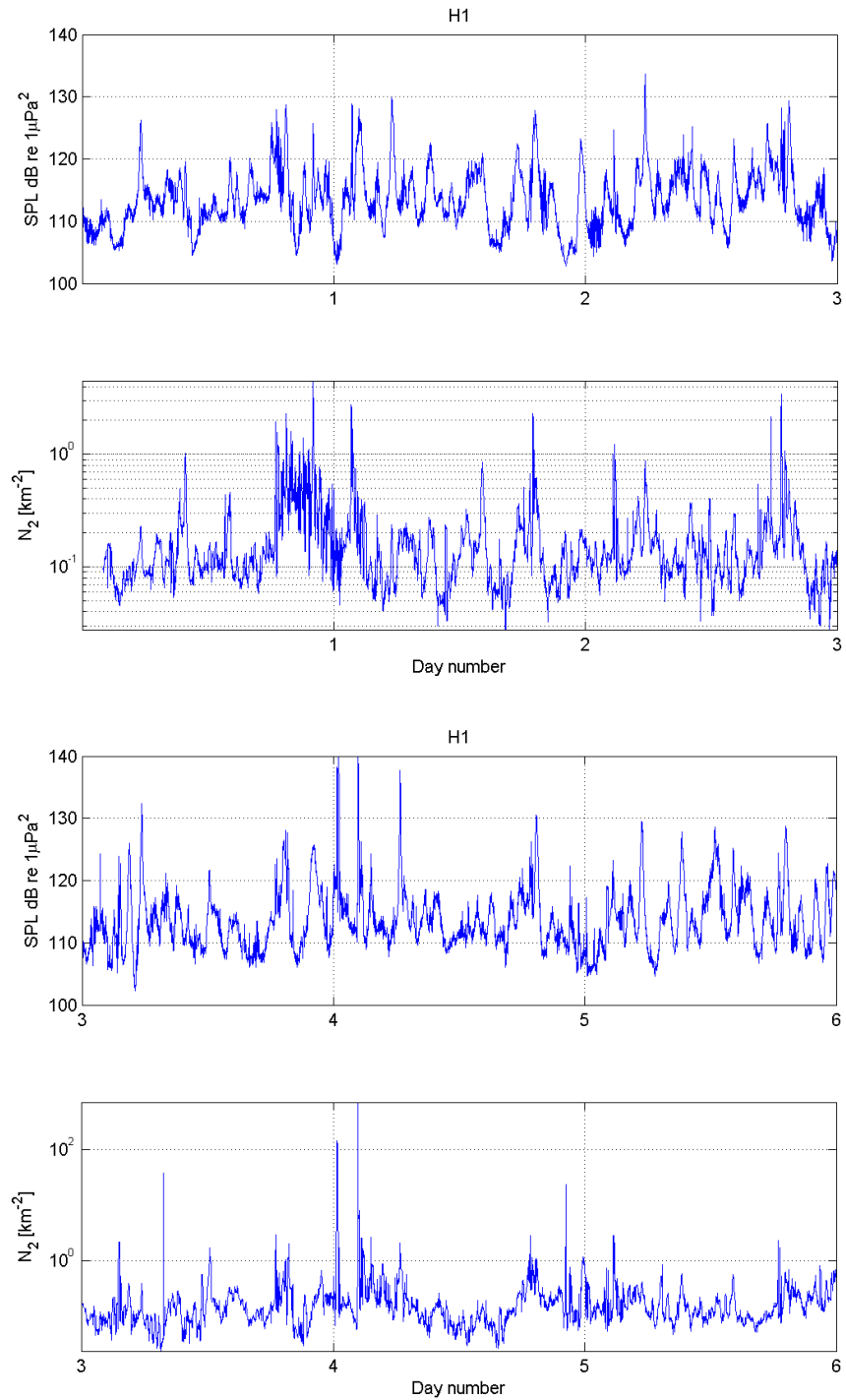


Figure F.1 Total SPL and Shipping density factor N_2 for location H1 for each minute of the day 1-6 of the monitoring period.

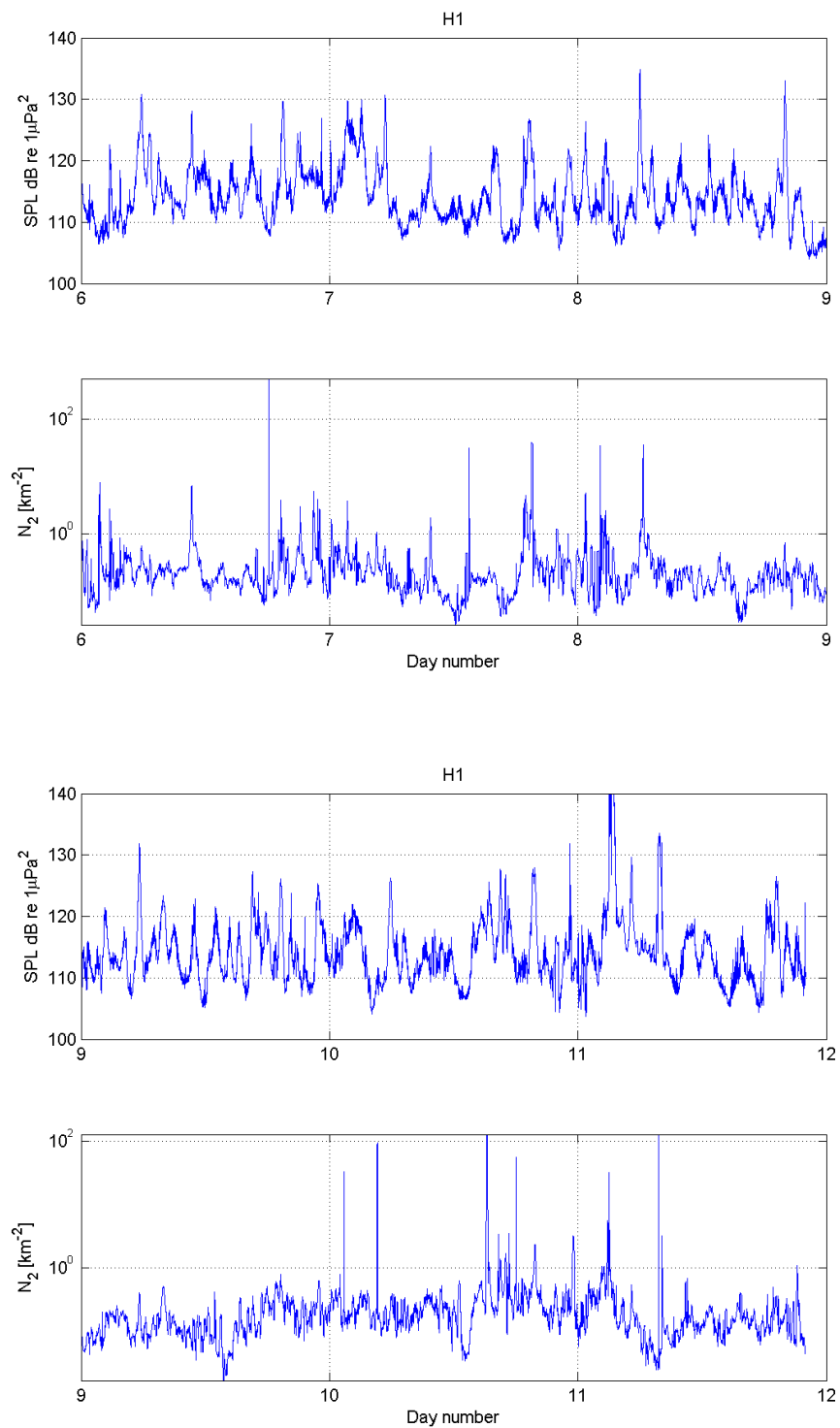


Figure F.2 Total SPL and Shipping density factor N_2 for location H1 for each minute of the day 6-12 of the monitoring period.

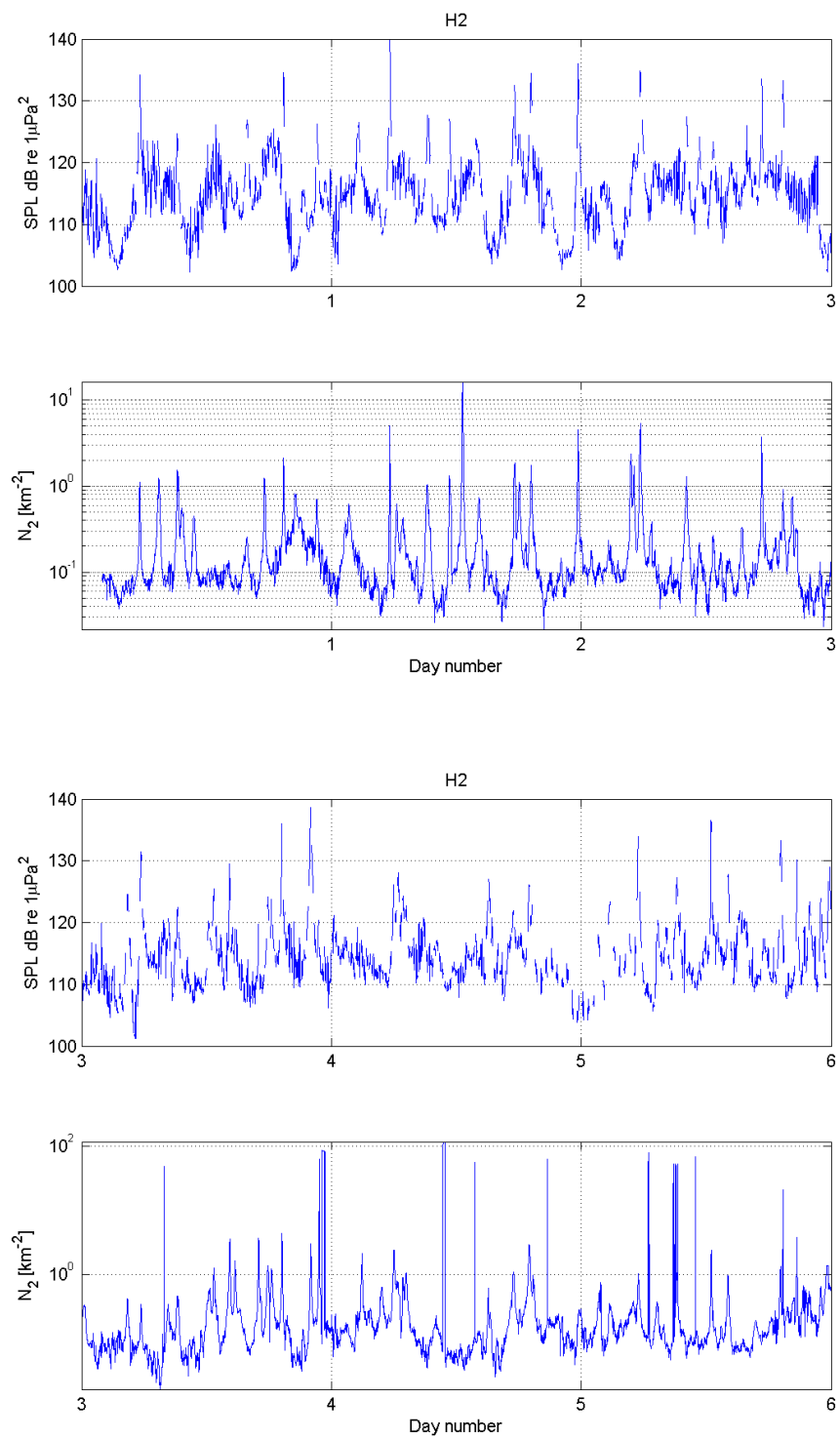


Figure F.3 Total SPL and Shipping density factor N_2 for location H2 for each minute of the day 1-6 of the monitoring period.

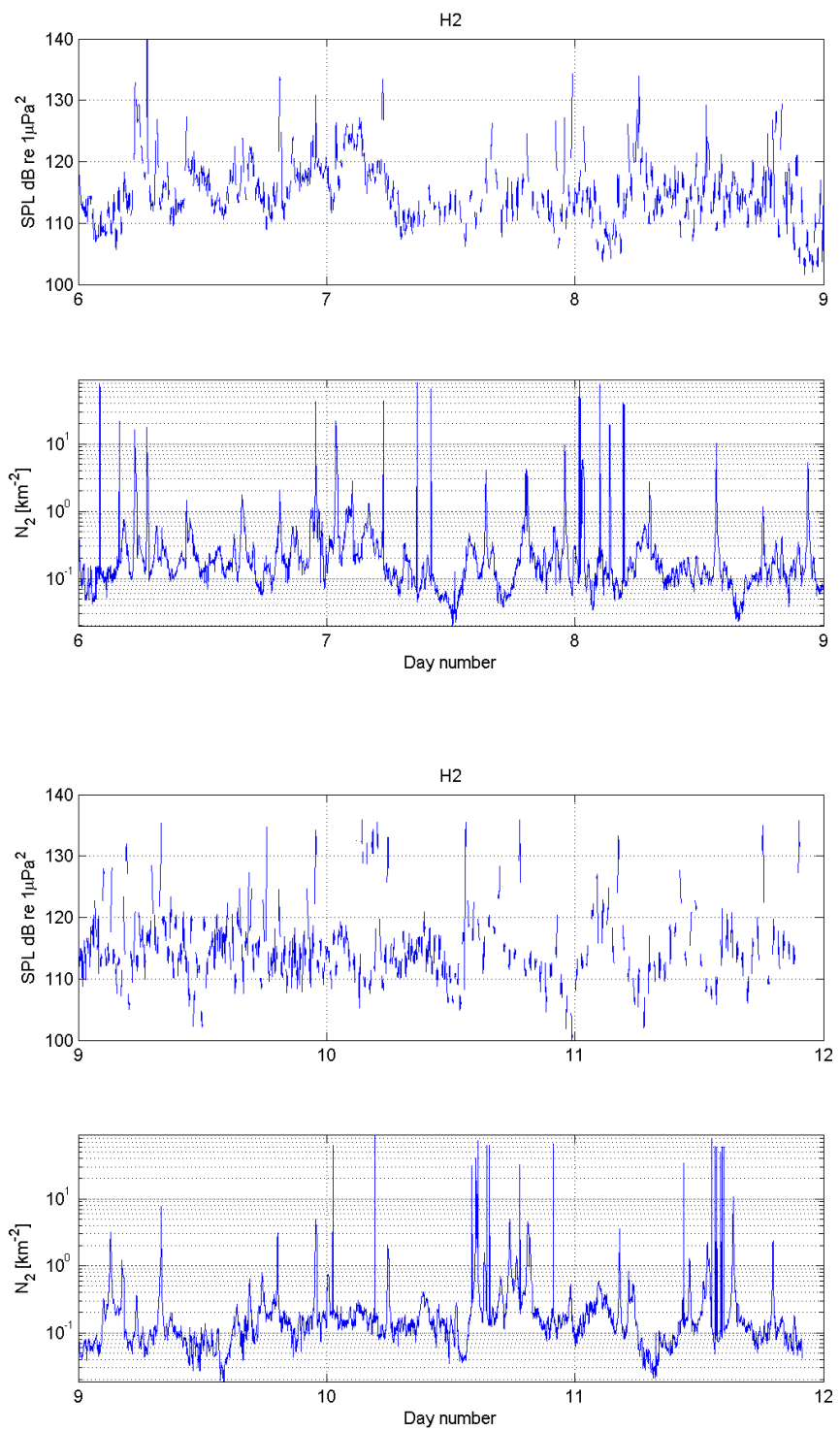


Figure F.4 Total SPL and Shipping density factor N_2 for location H2 for each minute of the day 1-6 of the monitoring period.

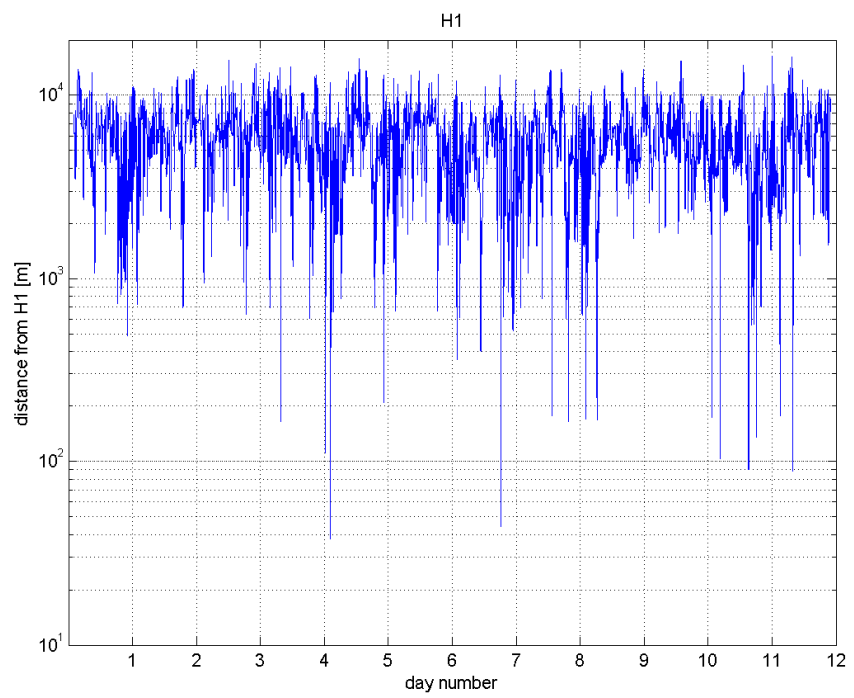


Figure F.5 Distance to the nearest ships from hydrophones at H1. Ships at very close range (< 200m) are service ships of PAWP entering the wind farm.